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Assessment of the Climate Change Impact and Adaptation Strategies on Italian Cereal Production using High Resolution Climate Data

Dr. Andrea Gallo

Direttore della Scuola	Prof. Alba Pusino
Referente di Indirizzo	Prof. Donatella Spano
Docente Guida	Prof. Donatella Spano
Tutor	Dr. Valentina Mereu

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The two defining challenges of the 21st century are overcoming poverty and avoiding dangerous climate change. If we fail on one of them, we will fail on the other. Unmanaged climate change will irretrievably damage prospects for development during the course of the century, and action on climate change which hinders development over the next two decades can never build the global coalition on which action on climate change depends.

Nicholas Stern

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ABSTRACT

The agricultural sector could suffer the impacts of climate changes projected for the coming decades with consequences varying from one region to another. Given the primary importance of wheat and maize for Italian agriculture, it is necessary to adopt the most effective adaptation strategies to climate change.

The objective of this study was to evaluate the effects of the increases in atmospheric CO_2 concentration on the phenology and yield of the main Italian cultivars of durum wheat, common wheat and maize at the national scale, considering the climate, soil and crop management features in each cultivation area, with and without adaptation.

The CSM-CERES-Wheat and CSM-CERES-Maize crop models were calibrated and evaluated at the Italian level. The assessments of climate change impacts and adaptation strategies were made using a digital platform and high resolution climate data of two climate change scenarios related to a single climate model. The uncertainty analysis of the yield outputs associated with the different resolution of the input data was also performed.

The results show increases of yield for wheat and a reduction of the maize productivity in Italy. Better results have been obtained using a fine resolution of input data. Irrigation and early sowing are the most effective adaptation strategies to climate change for wheat, while the incorporation of crop residues is an useful adaptation option for maize, especially before mid-century.

Structure of the thesis

The thesis is divided into several sections that deal with different aspects of the work that has been undertaken. After the first two sections (introduction and objectives), the following sections are organized according to the scientific scheme (introduction, objectives, materials and methods, results, conclusions, references).

The first section serves as an introduction to the chapters that follow. The first part of the introduction describes the importance of cereals for various uses (especially for food), with a particular focus on wheat and maize, which are the most important cereals in the world. In the next part, the scenarios and models used for climate change studies are discussed, with particular attention to the new generation scenarios (Representative Concentration Pathways) that were used in this work. The introduction of the thesis concludes with an overview of crop simulation models and their utility in research on climate change in agriculture (such as the study of the impacts of climate change on phenology and yield of crops and evaluation of the most effective adaptation strategies). Particular attention is given to models CSM-CERES-Wheat and CSM-CERES-Maize implemented in the Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM) that was used in this study.

The second section describes the objectives of the thesis and the methodological scheme followed in order to achieve them.

The third section relates to the first part of the thesis work: the parameterization at the Italian scale of the CSM-CERES-Wheat and CSM-CERES-Maize crop models for the considered crops (durum wheat, common wheat and maize). Detailed results of the calibration, evaluation and sensitivity analysis of these models are described for each crop.

The fourth section is dedicated to the assessment of climate change impacts on phenology and yield of crops considered in this study, through the use of crop models parameterized in the previous phase and considering two climate change scenarios (RCP4.5 and RCP8.5). In addition, the results of uncertainty analysis of the simulations output results due to two different climate data resolutions are shown in this section.

Finally, the last section shows the results of the evaluation of adaptation strategies that can be adopted in Italy in order to limit the negative effects of climate change on phenology and yield of durum wheat, common wheat and maize.

In chapters 3, 4 and 5 all the graphical and statistical results are shown separately for each crop.

1. INTRODUCTION

The issue of climate change and related impacts at the socio-economic and political level is of a very high contemporary importance, as evidenced by numerous studies in recent decades. In fact, climate change has direct and indirect effects in several areas affecting human society, like agriculture, forestry, tourism, etc. The consequent implications on food security and on land use change are of particular importance both at the local and global scale.

Among the priorities for action on climate change, we may mention the United Nations Framework Convention on Climate Change (UNFCCC) at the political level and the Intergovernmental Panel on Climate Change (IPCC) at the scientific level.

The IPCC, in its Fifth Assessment Report, defines climate change as a statistically significant change of the mean state of the climate or of its natural or anthropogenic variability persisting for an extended period (typically decades or longer) (IPCC, 2013). On the other hand, the UNFCCC (1998) defines climate change as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.

The most obvious of ongoing climate change is the warming of the climate system, as evidenced by the increase in the average temperature of the air and oceans, the progressive melting of glaciers and the resulting increase in mean sea level. Further evidence of recent changes in climate is represented by the change in the composition of terrestrial and marine ecosystems, with the appearance of new species. (IPCC, 2013).

The main drivers of climate change are the progressive increase in the atmospheric concentration of greenhouse gases (GHGs) and aerosols, the solar irradiance and land cover. They influence the various radiative processes (absorption, scattering and emission) within the atmosphere and on the Earth's surface, resulting in positive or negative changes in energy balance defined as radiative forcing and expressed in W m^{-2} (IPCC, 2013).

Nowadays it is widely recognized that changes in radiative forcing are mainly due to anthropogenic emissions of long-lived GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and halocarbons (F-gases). These gases accumulate in the atmosphere and their concentrations increase with time (Figure 1). Significant increases in emissions of all of these gases have occurred in the industrial era: +80% between 1970 and 2010 (Figure 2). The largest increases in global emissions of GHGs in the same period are due to the energy sector (+145%). The energy supply sector is the one which mostly contributes to anthropogenic greenhouse gases emissions (35% in 2010), followed by the industrial sector (31.7%), agriculture (11.2%), and forestry and other land use (12.7%) (IPCC, 2014a).

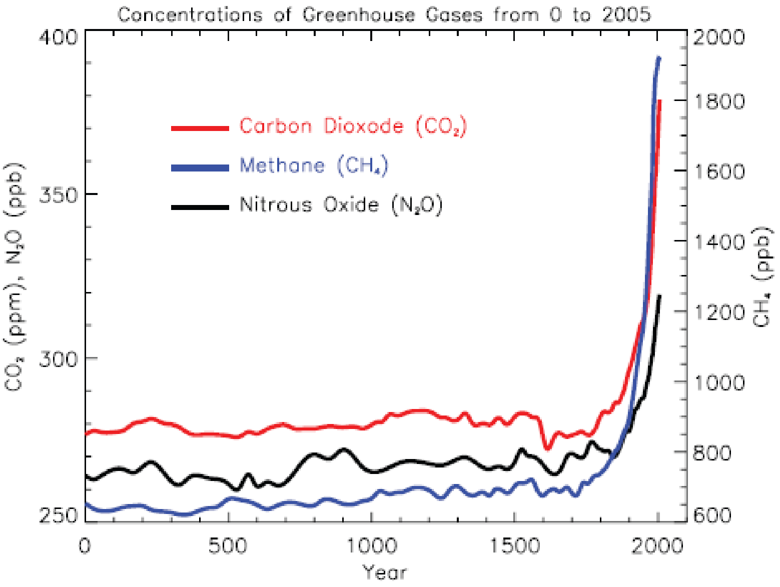

Figure 1. Trend in atmospheric concentrations of important long-lived greenhouse gases over the last 2,000 years (source: IPCC, 2007).

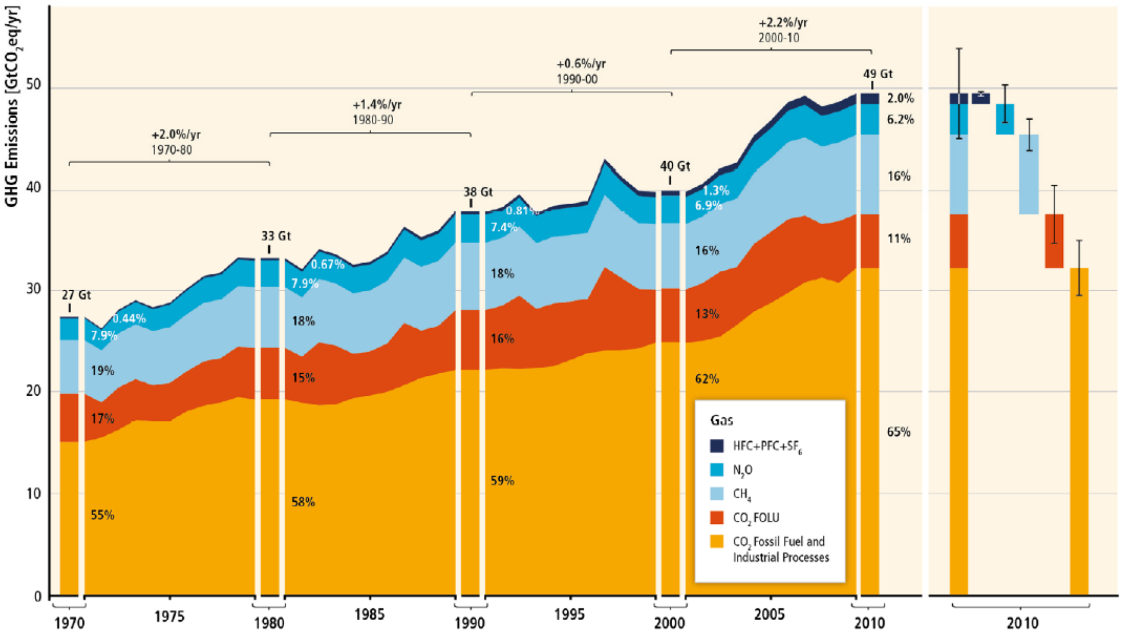

Figure 2. Trend in atmospheric concentrations of important long-lived greenhouse gases over the last 40 years (source: IPCC, 2014a).

The most important anthropogenic GHG is CO_2 (77% of total anthropogenic GHG emissions in 2010) (IPCC, 2014a). Its atmospheric concentration has increased from 280 ppm in pre-industrial era to 390.5 ppm in 2011 (+39.5%), becoming the most important component of the radiative forcing of climate change (IPCC, 2013). The main natural sinks of CO_2 are the oceans (containing 78% of the total CO_2) and fossil sediments (22%). The main source of CO_2 emissions is represented by fossil fuels (oil, coal and natural gas), followed by the phenomena of deforestation, land use change, decay of biomass, etc. (IPCC, 2013). Its average persistence in the atmosphere is high and variable between 50 and 200 years, depending on the means of absorption.

The second largest long-lived GHGs is methane (CH_4), which contributes to the total radiative forcing for more than 15% and whose emissions derive from various sources such as the production and transport of fossil fuels, wetlands, livestock, rice cultivation, biomass burning and the decay of organic waste in solid waste landfills (IPCC, 2007, 2014a). Its global atmospheric concentration has increased by about 150% compared to pre-industrial levels (IPCC, 2013). Its average atmospheric concentration is about 1.8 ppm in 2011 with an average annual increase ranging between 1% and 1.4%. Notwithstanding the low concentration, methane has a capacity to retain heat about 20 times greater than carbon dioxide. Its persistence in the atmosphere is lower than that of CO_2 (between 10 and 15 years).

Nitrous oxide (N_2O) is the third long-lived GHGs (6.2% of total GHG emissions in 2010) (IPCC, 2014a). Its atmospheric concentration is less than that of carbon dioxide and methane (about 0.3 ppm) with an average annual increase of 0.3% (about +20% compared to pre-industrial era) (IPCC, 2013). Emission sources are the agricultural sector (fertilization based on nitrogen fertilizers), the industrial sector (production of nylon), urban traffic and power plants using fossil fuels. N_2O emissions have increased by 50%, largely due to the development of the agricultural sector (IPCC, 2007, 2014a). Nitrous oxide has a capacity to absorb heat about 300 times greater than CO_2 and has an average time of persistence of about 120 years.

Figure 3 shows the linkages between the anthropogenic drivers of climate change, socio-economic and environmental impacts of climate change and possible measures (adaptation and mitigation strategies) in favor of socio-economic development.

The main effect of the increase in the atmospheric concentration of long-lived GHGs is the warming of the climate system. CO_2 is the GHG most responsible for the

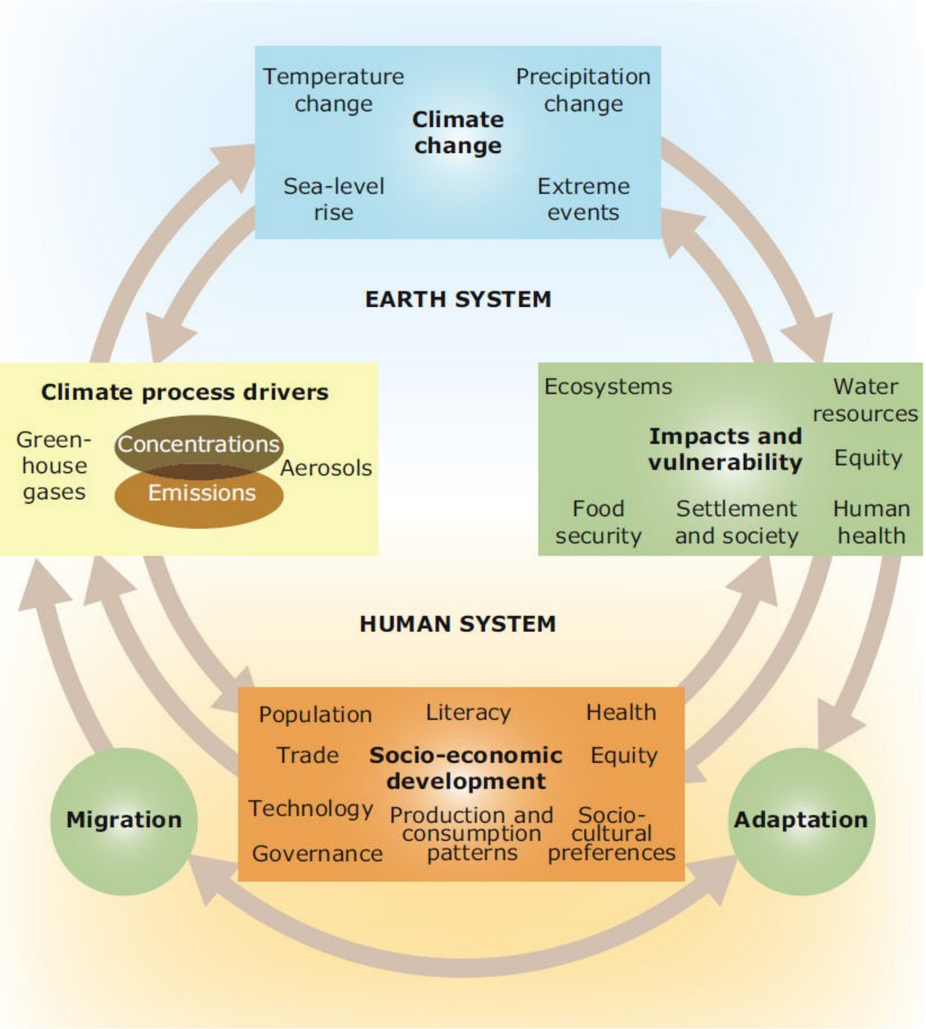

Figure 3. Schematic framework representing anthropogenic climate change drivers, impacts and responses, and their links (source: IPCC, 2007 modified by European Environment Agency, http://www.eea.europa.eu/publications/environmental-indicator-report-2012/environmental-indicator-report-2012-ecosystem/part2.xhtml).

increase in the average temperature in recent decades (+0.85 °C from the pre-industrial era to 2012) (IPCC, 2013). According to recent projections, the atmospheric concentration of CO_2 will increase to more than 700 ppm, resulting in increase of average global temperature between 1.0 °C and 3.7 °C by the end of the century, depending on the climate change scenario (IPCC, 2013). Another consequence of the increase in the atmospheric concentration of GHGs is the change in rainfall patterns, with a reduction of these and an increase in the number and intensity of extreme weather events (floods and droughts).

The impacts of climate change on the environment (water resources, land use changes, etc.) and human activities (agriculture, tourism, etc.) are inevitable, even if their amount is variable in different areas of the planet (see section 4 of this thesis). Therefore, taking into account the climate projections for the coming decades, an accurate assessment of the climate change impacts is essential to evaluate the most effective strategies for adaptation and/or mitigation to climate change. These evaluations may be a useful tool for policy makers in order to plan for priority actions at different scales (from the field to the regional scale).

1.1 THE IMPORTANCE OF CEREALS FOR HUMAN CONSUMPTION

1.1.1 World cereal production

Cereals are the main source of food supply for direct food consumption in the world. Therefore they represent the key sector for global agriculture and food security. The area cultivated with cereals in the world amounts to about 700 million hectares while total production is about 2.5 billion tons in 2012 (FAO, 2014a).

Figure 4 shows the increasing trend of production and use of cereals in the world over the past decade (FAO, 2014b). World cereal production by type in recent years is shown in Figure 5 (USDA, 2014). The most important cereals are maize, wheat and rice, which together cover about 80% of the total area cultivated with cereals with world production of 869, 657 and 472 million tons respectively in the crop year 2012-2013 (FAO, 2014a; USDA, 2014). For 2014 an increase in production is predicted for maize (+13.0%), wheat (+8.6%) and rice (+1.3%), as compared to 2013 (USDA, 2014).

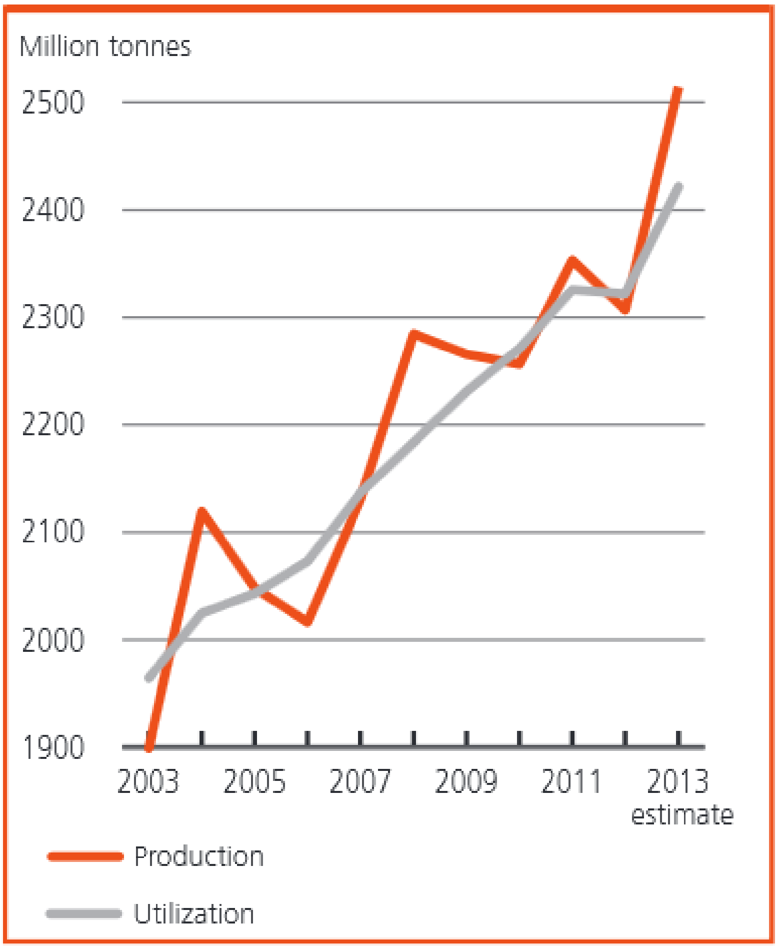

Figure 4. Evolution of the world cereal production (source: FAO, 2014b).

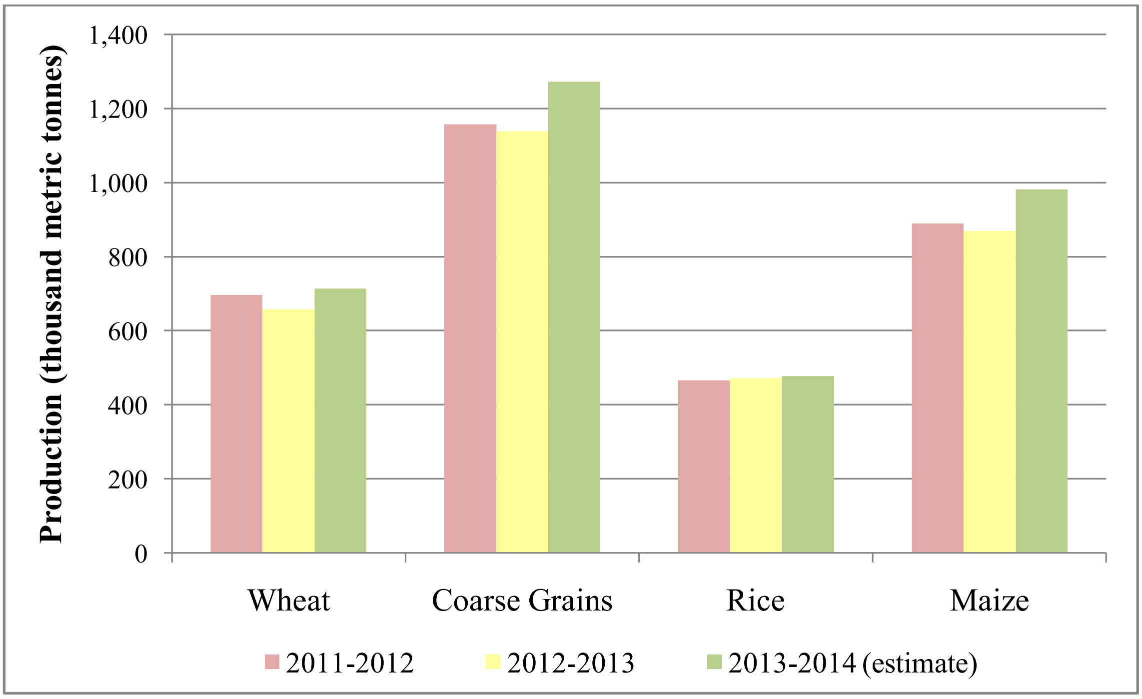

Figure 5. Evolution of the world cereal production by type (source: USDA, 2014).

The global trend of the use of cereals by type is shown in Figure 6. Cereals are mainly used for human consumption (46.2% of the total in 2012) and secondarily for animal feed (34.5%) (FAO, 2014c).

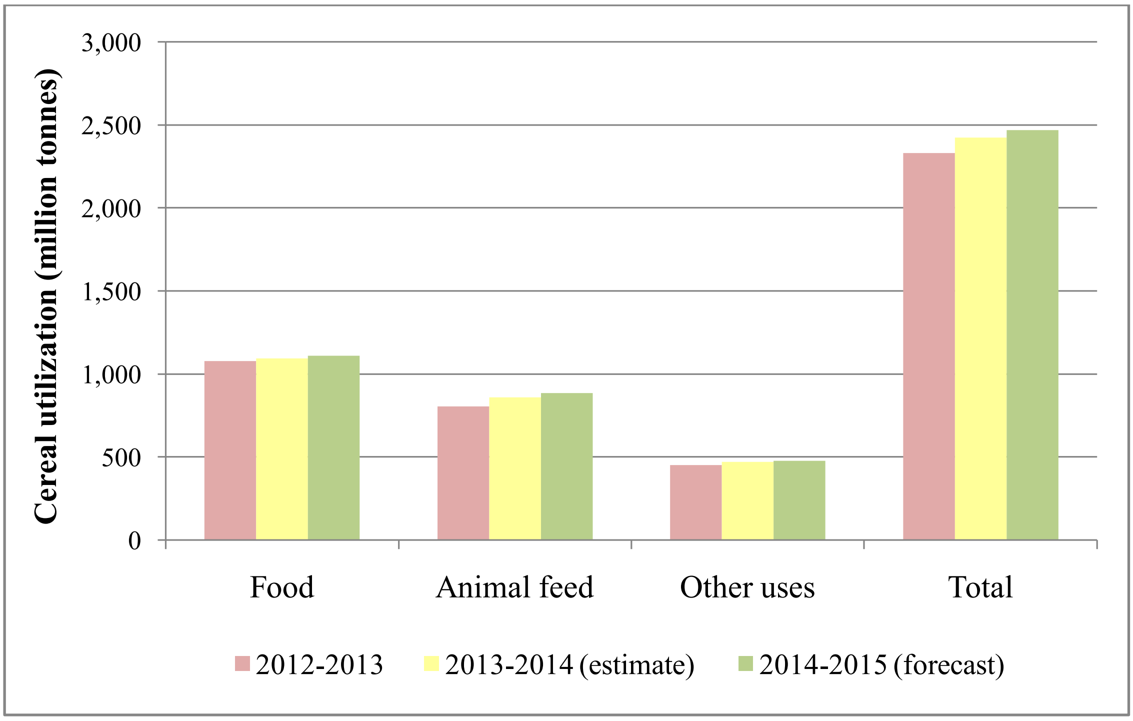

Figure 6. Global trend of cereal utilization by type (source: FAO, 2014c).

Recent studies have shown an overall increase in yields of main cereals in the medium-recent past (Hafner, 2003; Ray et al., 2012). In particular, in the period 1962-2002 the average annual increase in yields in the world was 43 kg ha^{-1} for wheat and 62 kg ha^{-1} for maize, while in Europe the average annual increase in yields for these two crops was higher (77 and 145 kg ha^{-1} respectively) (Hafner, 2003). Over the past decade (2002-2012) the annual average yields increased further at the global level (+33 kg ha^{-1} for wheat and +40 kg ha^{-1} for maize) and also in Europe for wheat (+14 kg ha^{-1}). Instead, an average annual decrease in yield was observed for maize at the European level (-42 kg ha^{-1}) (FAO, 2014a). This is due to the decrease in wheat yields in some western European countries as a result of recent climate change (Brisson et al., 2010). The increase in yield in the 1961-2008 period has affected more than half of the cultivated area in wheat and maize in the world (61.2% and 70.1% respectively) (Ray et al., 2012).

However, recent research shows that climate change will have a negative impact on cereal yield in the coming decades, to varying degrees with the type of cereal, the geographical area and the climate change scenario and will lead to the northward shift of the cultivation areas (Brown, 2002; Ciais et al., 2005; Fischer et al., 2005; Hildén et al., 2005; Parry et al., 2005; Rosenweig et al., 2005; IPCC, 2007, 2014b, 2014c; Olesen et al., 2007; Mereu, 2010; Ciscar et al., 2011; Lobell et al., 2011; Mereu et al., 2012).

Considering the steady growth of the world population and the increase in area sown to cereals for biofuels production in recent years, the impacts of climate change on the variability of cereal yields is even more important for food security, especially in semi-arid areas (e.g., sub-Saharan Africa and several areas of Southern Asia) (Brunisma, 2003; IPCC, 2007; Schmidhuber and Tubiello, 2007).

1.1.2 Wheat production

Wheat is a cereal of primary importance for human consumption and, therefore, for food safety. Its spread over time has been favored by some of the characteristics that have made it an essential element to the world economy. First, it is a crop adaptable to different environments. This has made possible its large-scale cultivation. Second, the grain of wheat is a dry product, so it is easily storable and allows the establishment of stocks usable in time. Finally, the grain has a content of proteins, lipids, minerals and vitamins that make it suitable for human consumption.

Wheat is mainly used for human consumption (flour, bread and substitutes, leavened bakery products, biscuits, pasta) (69.2% of total use) and secondarily for feeding livestock (19.3%). The remaining fraction (11.5%) is allocated for other uses (e.g., as a source of bio-energy) (Mergoum et al., 2009; FAO, 2014c).

Table 1 shows the trend of world production of wheat in recent years (2011-2013), and an estimate for 2014. The main producers are European Union, China, India, USA and Russia.

Table 1. Wheat world production in 2011, 2012, 2013, 2014 and estimates for 2015 (millions of metric tons) (source: USDA, 2014).

Country	**2011**	**2012**	**2013**	**2014 (estimate)**
Argentina	17.2	15.5	9.3	10.5
Australia	27.4	29.9	22.5	27.0
Brazil	5.9	5.8	4.4	5.3
Canada	23.3	25.3	27.2	37.5
China	115.2	117.4	121.0	121.7
Egypt	7.2	8.4	8.5	8.7
European Union	136.0	137.3	133.9	143.3
India	80.8	86.9	94.9	93.5
Iran	15.0	13.5	13.8	14.5
Kazakhstan	9.6	22.7	9.8	13.9
Pakistan	23.9	25.0	23.3	24.0
Russia	41.5	56.2	37.7	52.1
Turkey	17.0	18.8	15.5	18.0
Ukraine	16.8	22.3	15.8	22.3
USA	60.1	54.4	61.7	58.0
Uzbekistan	6.5	6.3	6.7	6.7
Others	48.2	50.4	51.4	56.9
Worldwide	652.3	697.2	657.3	714.0

Considering world population growth and the limited availability of arable land, global grain production must increase in order to meet the growing demand for food. Therefore it is necessary to increase the grain yield of the areas currently under cultivation. This objective will be achieved through genetic improvement of the varieties currently used in order to introduce new varieties with higher yields and which are stable and more resistant to main plant diseases and abiotic factors. In such a way it will be possible to obtain varieties adaptable to the different cultivation areas, a condition of considerable importance if one takes into account the impacts of climate change for the coming decades.

There are different classifications of wheat. Those most commonly used are based on the genetic characteristics, growth habits and qualitative characteristics.

The most important types of wheat currently on the market are common wheat (*Triticum aestivum* L.) and durum wheat (*Triticum durum* Desf.). Common wheat is a hexaploid type of wheat ($2n = 6x = 42$), while durum wheat is tetraploid ($2n = 4x = 28$) (Mergoum et al., 2009). Common wheat is the most cultivated one in the world (about 95% of world wheat production) (Taylor and Koo, 2013).

Depending on growth habits, there are three main classes of wheat: winter, spring and facultative. *Winter* wheat is sown in late summer or autumn and requires vernalization for flowering. Therefore, it can withstand low winter temperatures. Growth resumes in early spring and grain is harvested in early summer. Winter wheat is mostly common wheat. *Spring* wheat does not usually require vernalization to flower and cannot endure temperatures below zero. Therefore it is mainly cultivated in areas with harsh winters in which it is sown in spring and harvested in late summer. The greatest part of global wheat production is spring wheat. *Facultative* wheat is a type of wheat for which vernalization is optional. It is cultivated mainly during the winter in mild climates and cannot endure long periods with temperatures below zero (Baenziger and DePauw, 2009; Taylor and Koo, 2012, 2013).

Finally, based on the qualitative characteristics (color of the caryopsis, endosperm hardness, etc.), winter and spring wheat can be distinguished in further classes, as described in Table 2 (Baenziger and DePauw, 2009; Mergoum et al., 2009).

Durum wheat

The durum wheat (*Triticum durum* Desf.) was one of the first cereals cultivated worldwide. It is native to the Central-Eastern Africa and eventually it spread to different areas of the world, particularly in the Mediterranean basin and North America, which are the main cultivation areas. In the last forty years, the area planted with wheat decreased progressively (Belaid, 2000).

The global durum wheat is grown on over 12 million hectares (about 5.5% of the world area cultivated with wheat in 2011) (USDA, 2010). The world durum wheat production estimated to be about 35 million metric tons in 2014 (IGC).

Main production areas in 2013 are the European Union, North America and North Africa with 8.0, 6.8 and 4.6 million metric tons respectively. According to recent

Table 2. Qualitative classes of winter and spring wheat and their main uses (sources: Baenziger and DePauw, 2009; Mergoum et al., 2009).

Growth habit classes	**Classes based on the qualitative characteristics**	**Main uses**
Winter wheat	*Soft red* and *white*	Cookies, breakfast cereals, cakes, and crackers.
	Hard red and *white*	Leavened products (e.g., bread).
	Soft white	Noodles and steam breads.
Spring wheat	*Hard red spring (HRS)*	Bread wheat with superior milling and baking characteristics.
	Soft white (SW)	Cakes, crackers, pastries, cookies, quick breads, muffins, and snack foods.
	Hard white spring (HRS)	Yeast breads, hard rolls, bulgur, tortillas, and oriental noodles.

estimates, the largest producer of durum wheat in 2013 is Canada with about 4.6 million tons, followed by Italy (3.8 million tons), which is the largest exporter in the world (Eurostat, IGC).

The increase in production and reduction in the area cultivated with durum wheat resulted in a global average yield increase over the last forty years (from 1.4 t ha^{-1} to more than 2 t ha^{-1}).

The European Union is the most important area for durum wheat with a cultivated area of about 2.5 million hectares and a total production of 8.0 million tons in 2013 (Eurostat). The largest producer is Italy followed by France, Spain and Greece. 95% of European Union durum wheat production is produced in these four states (Table 3).

Durum wheat has a high resistance to water scarcity. This makes it possible the growth under rainfed conditions in areas characterized by lower annual rainfall as the Mediterranean basin (Southern Europe, North Africa and West Asia) (Nazco et al., 2012). In these regions the main factors limiting the yield of durum wheat are drought during the grain filling phase, nutritional deficiencies (especially nitrogen), plant diseases, pests, and negative soil properties.

In the Mediterranean region the most widely growth habit is winter durum wheat, while in North America (Canada and USA) spring durum wheat is grown because the climate is continental (long and cold winters, short and hot summers).

The durum wheat is almost completely used for human consumption, in

Table 3. Cultivated area and production of durum wheat in the European Union in 2011, 2012 and 2013 (source: Eurostat).

Country	**Cultivated area (thousand hectares)**			**Production (thousand tons)**		
	2011	**2012**	**2013**	**2011**	**2012**	**2013**
Austria	15.3	14.2	12.4	78.0	43.7	63.1
Bulgaria	35.7	18.7	30.0	153.3	50.2	127.0
Cyprus	11.1	8.5	9.3	24.9	22.9	17.6
France	417.2	437.0	337.3	2,022.6	2,380.0	1,777.1
Germany	15.3	11.7	8.6	72.6	57.4	52.7
Greece	403.8	400.7	410.0	1,237.1	1,090.8	1,115.2
Hungary	12.2	12.2	14.5	49.9	45.6	64.3
Italy	1,194.9	1,260.1	1,268.2	3,857.1	4,160.1	3,768.6
Portugal	2.9	3.7	1.3	3.9	4.3	3.0
Romania	3.5	8.1	4.0	10.0	18.1	12.4
Slovakia	11.7	10.5	11.2	52.4	28.6	55.5
Spain	378.1	411.1	342.5	900.4	499.5	904.0
European Union	2,501.6	2,596.5	2,450.2	8,462.1	8,401.1	7,964.7

particular for the production of pasta (80%), typical breads (about 15%) and other products (e.g., couscous). The Mediterranean countries are major consumers of these products, so they are the main importers of durum wheat.

The increase in the yield of durum wheat in the last century is due to genetic improvement programs that have made possible the gradual replacement of old cultivars with modern varieties in many production areas of durum wheat (Moragues et al., 2006). This fact, combined with the reduced number of ancestors and cultivars currently used, has determined the loss of genetic variability (genetic erosion) (Skovmand et al., 2005). Therefore, the use of modern cultivars could result in an increase of vulnerability to biotic and abiotic stresses (especially drought and high temperatures).

The development of genetic variability for durum wheat is one of the main objectives of current breeding programs. To this end, the International Maize and Wheat Improvement Center (CIMMYT) and the International Center for Agricultural Research in the Dry Areas (ICARDA), play an important role as main centers that operate internationally on durum wheat.

The possibility of exploiting the existing genetic variability is related to the collection of germplasm in gene banks (de Carvalho et al., 2013). In this way, it has been possible to obtain new cultivars with higher and more stable yield, and which are more resistant to biotic (pests and diseases) and abiotic (drought, cold, lodging) stresses and with better qualitative characteristics (De Vita et al., 2007; Royo et al., 2007, 2008; Álvaro et al., 2008). However, the Mediterranean durum wheat landraces retain high variability (especially those in eastern regions), so they can be used to improve the qualitative characteristics of the grain in the modern varieties (Nazco et al., 2012).

Durum wheat in Italy

Italy is the largest producer of durum wheat in Europe contributing 47.3% to total production in the European Union in 2013 (Eurostat). Durum wheat is the second most important cereal after maize in Italy in 2013 with a production of just under 4 million tons, accounting for 23.9% of national cereal production, and its cultivation extending over an area of about 1.3 million hectares (ISTAT).

Figure 7 shows that over the past 50 years, Italian production of durum wheat has grown progressively, from 1.8 to 3.8 million tons in the 1963-2013 period (Eurostat). During the same period, the area under cultivation has decreased from 1.4 to 1.3 million hectares. So the yield of durum wheat in Italy has increased from 1.4 to 3.0 t ha^{-1} (Eurostat).

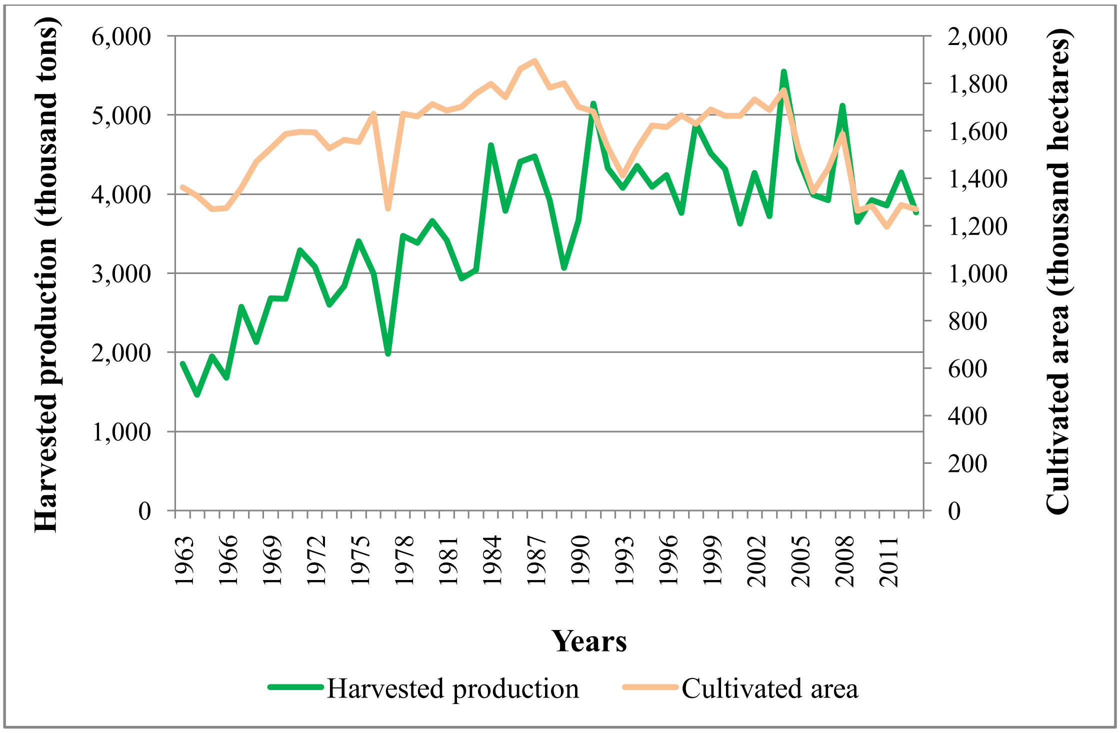

Figure 7. Trend in the production and cultivated area for durum wheat in Italy in the 1963-2013 period (source: Eurostat).

Durum wheat is the most important cereal in Southern Italy and Islands. According to estimates of 2013, the South-Peninsular and Sicily cultivation areas contribute to 65% of the national production of durum wheat (ISTAT). The most productive regions are Apulia and Sicily with 1.08 and 0.78 million tons respectively. The cultivated area in Southern Italy and Islands has declined since the 1980s (-11.4% between 1981 and 1990 and -5.0% between 1991 and 2000) and this trend was confirmed in the last years (-24.2% between 2001 and 2013) (ISTAT).

Similar trends were observed in the other cultivation areas, except in the North area (+161.2% during the 2001-2013 period). The trend of production over the same period shows a large increase in the North area (+211.3%), an increase in South-Peninsular and Sicily areas (+21.0% and +3.7% respectively) and a decrease in other areas (from -3.4% in the Centre-Italy (Tyrrhenian side) area to -39.4% in the Sardinia area) (Figure 8).

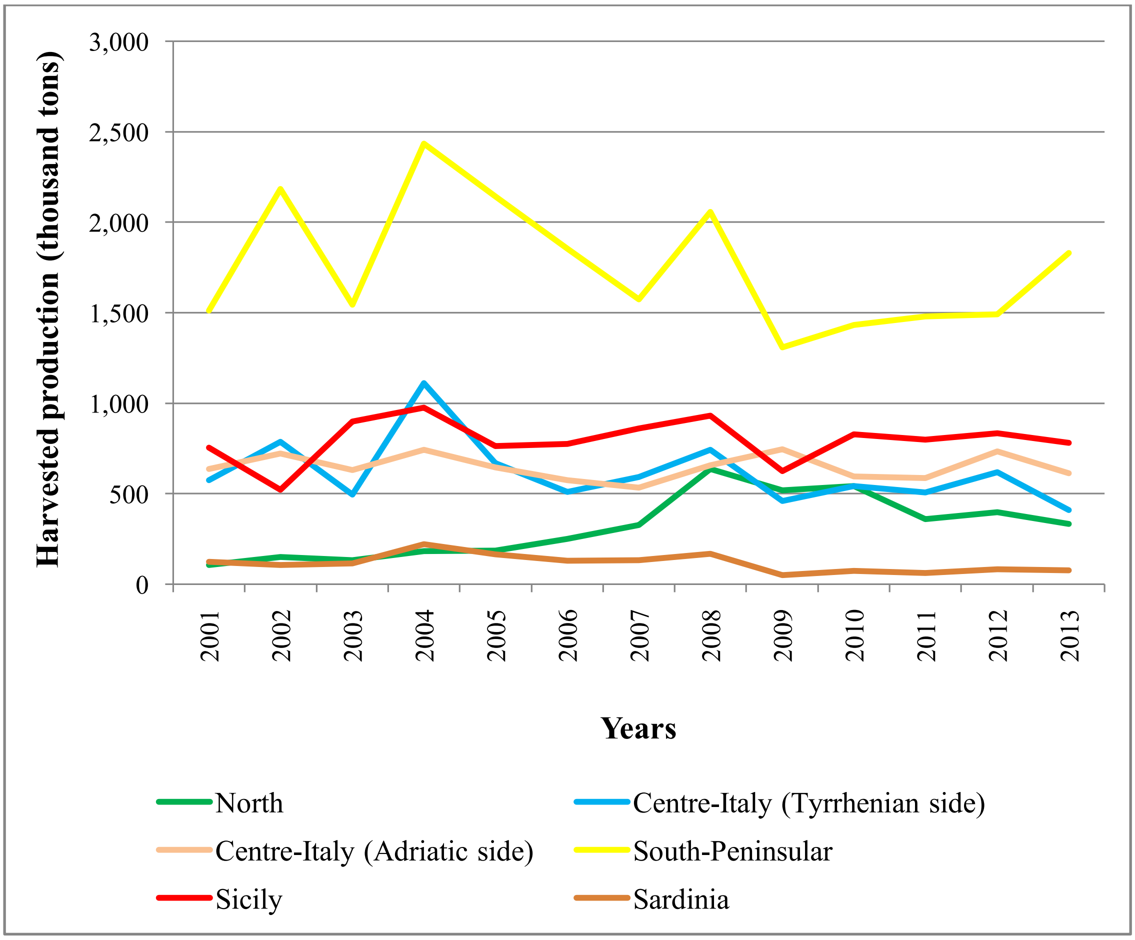

Figure 8. Trend in the durum wheat production in different cultivation areas in Italy from 2001 to 2013 (source: ISTAT).

Given the importance of durum wheat for Italian cereal production, since the beginning of the twentieth century various breeding programs have been launched for this species with the aim of restoring the genetic variability and in order to develop new better varieties in terms of yield and quality. The establishment of gene banks and the availability of a large number of Mediterranean landraces have made it possible to have many crosses (Di Fonzo et al., 2005).

In 1974, the cross between a CIMMYT dwarf line and cv 'Castelfusano' made it possible to obtain the variety 'Creso', characterized by high productivity. As a result, the productivity of durum wheat has reached similar values to those of common wheat. Since the 1980s the Italian gene pool has been enhanced with the introduction of new cultivars such as 'Simeto', 'Duilio', 'Iride', 'Colosseo', 'Ciccio', 'Ofanto', 'Grazia' and others which have spread rapidly nationwide (Di Fonzo et al., 2005).

Considering the amount of certified seeds in 2011, the varieties of durum wheat which are currently the most widespread in Italy are: 'Iride' (12.8%), 'Simeto' (9.6%), 'Saragolla' (8.7%), and 'Claudio' (7.0 %) (INRAN-ENSE).

Common wheat

Common wheat (*Triticum aestivum* L. ssp. *aestivum*) is the most important type of wheat in the world, contributing to 95% of global wheat production (Taylor and Koo, 2013). It is native to the Middle East, from which it spread to Europe during the Neolithic era. In the sixteenth century the Spanish introduced it in North America, which has become the largest exporter. Currently it is cultivated on all continents.

World production of common wheat in 2011 is of 659 million tons, according to the International Grain Council (IGC). Main producers are the European Union, China and India, which together contributing to over 45% of global production.

The area cultivated with common wheat in the European Union in 2013 is about 22 million hectares and the production is about 120 million tons (Eurostat). France is the main producer country with 37 million tons in 2013 (30.7% of the total production of the European Union), followed by Germany and the United Kingdom with 25 and 12 million tons respectively (Table 4).

Common wheat is a microtherm crop. Its high resistance to cold explains the spread of this species in regions with temperate and continental climates. Despite this, its cultivation is very important also in countries with a Mediterranean climate. The most widespread growth habit in Europe is winter common wheat (Eurostat).

Table 4. Cultivated area and production of common wheat in the European Union in 2011, 2012 and 2013 (source: Eurostat).

Country	**Cultivated area (thousand hectares)**			**Production (thousand tons)**		
	2011	**2012**	**2013**	**2011**	**2012**	**2013**
Bulgaria	1,101.8	1,166.3	1,170.0	4,305.2	4,404.9	4,970.0
Czech Republic	805.8	746.0	788.4	4,660.2	3,234.9	4,530.8
Denmark	727.3	583.2	539.5	4,745.6	4,370.8	3,990.0
France	4,975.8	4,866.4	4,958.6	33,887.5	35,540.8	36,662.2
Germany	3,172.8	2,892.7	3,066.2	22,396.3	21,396.6	24,634.1
Hungary	949.9	1,040.5	1,058.3	3,997.0	3,910.1	4,920.8
Italy	531.1	593.5	620.4	2,828.9	3,494.2	3,241.3
Poland	1,931.2	1,373.0	1,872.2	8,272.2	5,949.8	8,558.1
Romania	1,968.3	1,938.7	2,130.6	7,160.9	5,067.4	7,412.4
Spain	1,616.6	1,685.2	1,583.7	5,976.3	4,278.5	5,957.6
United Kingdom	1,969.0	1,992.0	1,615.0	15,257.0	13,261.0	11,921.0
European Union	21,102.9	21,189.5	20,854.3	122,457.7	123,275.4	119,484.8

Common wheat is mainly used for the production of bread (over 60%). The remaining part is used for the production of cakes, biscuits, pasta and other domestic purposes. The countries of the Mediterranean Basin are among the largest consumers of products made from common wheat.

As in the case of durum wheat, in recent decades several breeding programs have been undertaken for common wheat also. Therefore, were developed new cultivars that are more productive and more adaptable to different climatic conditions. CIMMYT and ICARDA are the main international centers involved in the genetic improvement of common wheat. In particular, more than 35% of new cultivars of common wheat were obtained from CIMMYT germplasm, while in marginal areas landraces are still being used (Colombo, 2006).

Common wheat in Italy

Italian production of common wheat in 2013 is 3.2 million tons, corresponding to just under 3% of the European Union total production (Eurostat). Among the different species of cereals grown in Italy, common wheat is in the third place with a cultivated area of about 611 thousand hectares and a production equal to 20.3% of total cereal production (ISTAT).

The national production of common wheat has been decreasing in recent decades, as shown in Figure 9. As can be seen, the annual production of common wheat has been more than halved, going from 6.2 to 3.2 million tons in the 1973-2013 period, while the cultivated area decreased from about 2 million hectares to just over 600 thousand hectares in the same time span (Eurostat). Instead, the yield has increased from 3.0 to 5.2 t ha^{-1}. One of the causes of reduction of the national production of common wheat is the Common Agricultural Policy (CAP) which has been applied since the 1990s and has affected to a great extent common wheat cultivation in Italy. The CAP reform of 2004 (effective from 2005), which introduced the "decoupling" of the prize from production and the "coupling" to the farm area for all crops, has not helped to reverse the trend. At the same time national needs have increased. For this reason Italy is currently one of the main importers of common wheat (USDA, 2012).

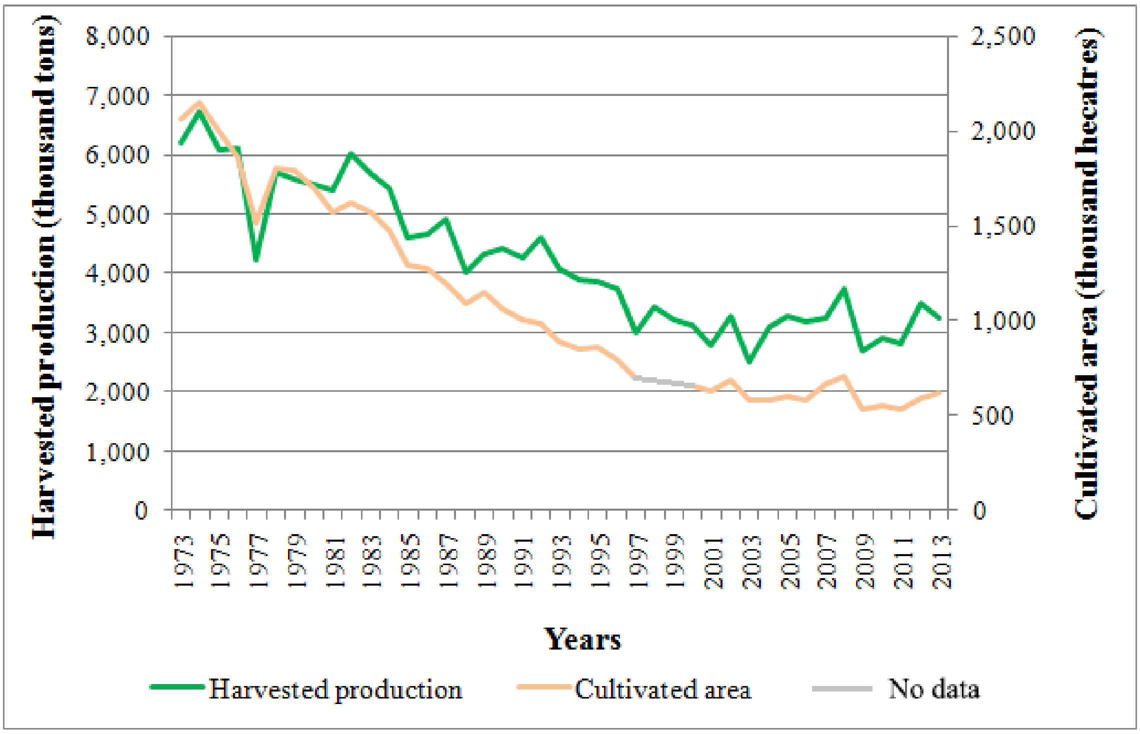

Figure 9. Trend in the production and harvested area for common wheat in Italy in the 1973-2013 period (source: Eurostat).

At the sub-national level, common wheat is mostly grown in the North cultivation area, where current production (2013) is about 2.7 million tons, accounting for 77% of national production (ISTAT). Emilia-Romagna is the most productive region with 1.1 million tons, followed by Veneto, Piedmont and Umbria with 0.7, 0.5 and 0.4

million tons respectively. Overall, the national cultivation area of common wheat remained unchanged in the 2001-2013 period, but with differences in the various areas (ISTAT). In fact, despite an increase in the North area (+13.2%), a significant reduction was observed in the rest of Italy, especially in the Centre area (-12.0%). Regarding production, an increase of +22.5% was observed between 2001 and 2013, particularly inthe North area, where common wheat production has increased by +42.3% compared to 2001. Conversely, the production trend is decreasing in the Centre area (-21.0) (Figure 10).

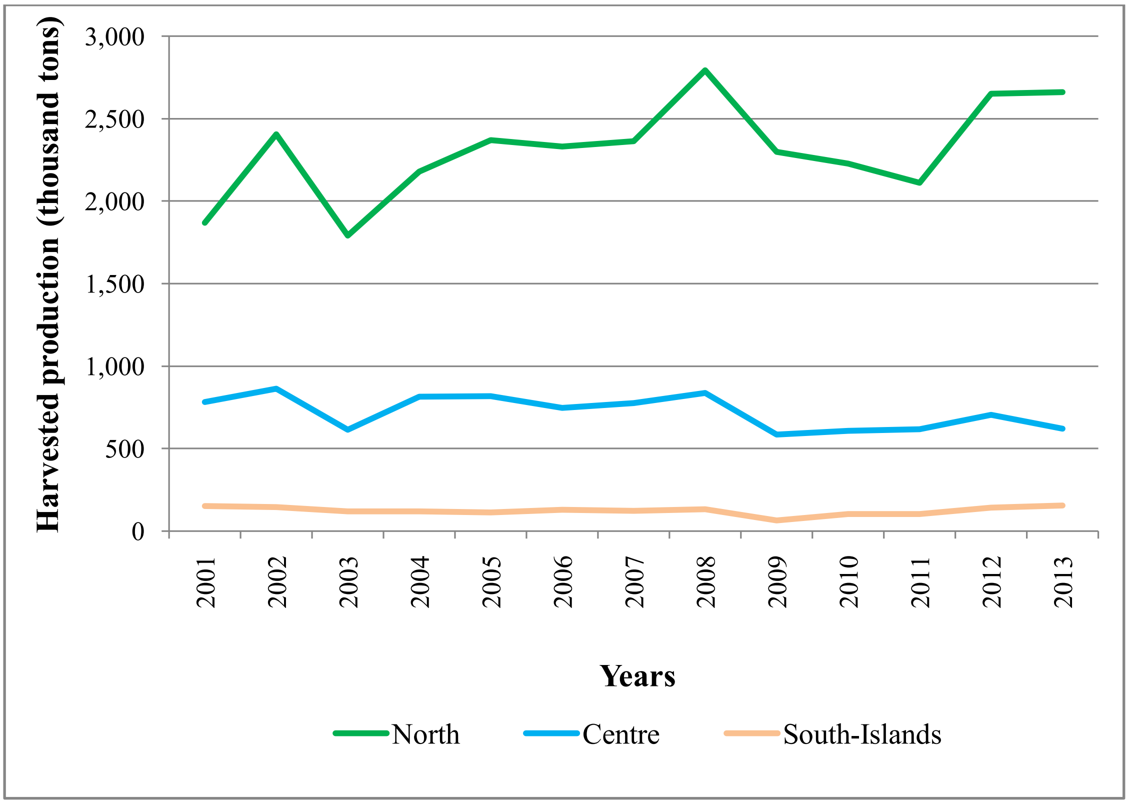

Figure 10. Trend in the common wheat production in different cultivation areas in Italy from 2001 to 2013 (source: ISTAT).

The genetic improvement of common wheat carried out in Italy has been important. At the beginning of the twentieth century a large number of crosses were carried out between the cultivar 'Rieti' and local varieties (landraces) or with other cultivars from other countries (Boggini et al., 2011). The first cultivars obtained were not very productive because they were sensitive to the high temperatures during the grain filling. Therefore the main objective of breeding programs was to advance the date of earing and maturity. For this purpose, the Japanese variety 'Akagomughi' was used, thus obtaining the cultivars 'Ardito, 'Damiano', 'Chiesa', 'Mentana', and 'Villa Glori', which became widespread in Italy and other countries. The variety 'San Pastore' was developed in 1929, which remained the most cultivated type in Italy for over 35 years and it has been used as a parent to obtain new cultivars (Boggini et al., 2011).

In recent decades new cultivars such as 'Aubusson', 'Bologna', 'Africa', 'Bolero', 'Bilancia', 'PR22R58', 'Mieti', 'Blasco', 'Palesio', 'Aquilante' and 'Antille' have been successfully introduced in Italy.

The most spread cultivars of common wheat at the national level in 2011 are 'Bologna' (17.2%), 'Aubusson' (10.8%), 'PR22R58' (6.7%), and 'Mieti' (4.4%) (INRAN-ENSE).

1.1.3 Maize production

Maize (*Zea mays* L.) is a cereal native to tropical and sub-tropical America. It was identified for the first time in Southern Mexico, from where it spread in North and South America and later in other continents. The introduction of maize in Europe came after the discovery of the Americas, but only the precocious forms, those indifferents to the photoperiod native of the tropical area, and those originating from regions with a photoperiod similar to that of the Mediterranean Basin have adapted to the climatic conditions of the Euro-Mediterranean area (Lorenzoni and Marocco, 2008). The continuous process of domestication and genetic improvement programs implemented has allowed the increase in number of varieties that can be used in different geographical areas.

Maize has high water requirements, so it is very sensitive to drought, especially in 50-60 days during the period of flowering. A prolonged water shortage in this period will significantly impair production. An example is given by the substantial loss of production that occurred in Europe in 2003, particularly in France (COPA-COGECA, 2003). For this reason, generally maize is grown in areas equipped for irrigation and in which rainfall contributes to a great extent to the crop water balance during the growing season.

One of the most common classifications of maize is that of Sturtevant modified by Kuleshov, based on the types of kernels. Based on this classification, the maize is divided into eight subspecies listed in Table 5 (Hallauer et al., 2010). *Zea mays* L. ssp. *indentata* is the most productive subspecie.

Maize is one of the most important cereals in the world for two reasons. First,

Table 5. Subspecies of *Zea mays* L. according to type of kernels and related description (source: Hallauer et al., 2010).

Group	**Description**
Zea mays L. ssp. *indurata*	Flint corn
Zea mays L. ssp. *amylacea*	Soft corn
Zea mays L. ssp. *indentata*	Dent corn
Zea mays L. ssp. *everta*	Pop corn
Zea mays L. ssp. *saccharata*	Sweet corn
Zea mays L. ssp. *amylea saccharata*	Starchy-sugary corn
Zea mays L. ssp. *ceratina*	Waxy corn
Zea mays L. ssp. *tunicata*	Pod corn

each year new hybrids that can adapt to various pedoclimatic conditions are available, thus favoring the spread of maize in areas where it did not previously exist or it was not much cultivated. Secondly, maize can have multiple uses (Dell'Orto et al., 2008). In fact, the high carbohydrate content (about 65% starch) provides a high energy value to maize that makes it suitable for human consumption (especially in developing countries) and for animal feed (in particular maize silage). Finally, maize can be used as an bioenergy crop for the production of thermal energy and/or electricity through combustion or anaerobic digestion and for the production of ethanol through fermentation. Considering the increase in population and consumption of food of animal origin, the food demand for maize has increased significantly in recent years (Delgado, 2003). Therefore maize is a very important cereal for food security (Shiferaw et al., 2011).

According to global FAO estimates for 2014, maize is mainly used for animal feed (about 56.9% of total use) and in lower quantities for human consumption (just over 30%), while only a small fraction (about 10%) is used for other purposes.

Maize is cultivated on an area of about 177 million hectares and is the cereal crop with highest global production, approximatively equal to 868.8 million metric tons in 2013 (FAO, 2014a; USDA, 2014). The main producers are the United States and China (31.5% and 23.7% of global production), followed by Brazil (9.4%) and the European Union (6.8%) (Table 6). These four producers contribute to slightly more than half of the total world area sown with maize.

The European Union is the world's fourth largest producer of grain maize in 2013 with a cultivated area of about 9 million hectares and a production of 59 million tons (Table 7). France is the first European producer of maize in 2013 (23.1% of total

Table 6. Maize world production in 2011, 2012, 2013 and estimates for 2014 (millions of metric tons) (source: USDA).

Country	2011	2012	2013	2014 (estimate)
Argentina	25.2	21.0	27.0	24.0
Brazil	57.4	73.0	81.5	76.0
Canada	12.0	11.4	13.1	14.2
China	177.2	192.8	205.6	217.7
Ethiopia	4.9	6.1	6.2	6.5
European Union	58.3	68.1	58.9	64.6
India	21.7	21.8	22.3	24.2
Indonesia	6.8	8.9	8.5	9.1
Mexico	21.1	18.7	21.6	21.9
Nigeria	8.8	9.3	7.6	7.7
Philippines	7.3	7.1	7.3	7.7
Russia	3.1	7.0	8.2	11.6
Serbia	6.8	6.4	3.8	6.4
South Africa	10.9	12.8	12.4	14.5
Ukraine	11.9	22.8	20.9	30.9
USA	316.2	313.9	273.8	353.7
Others	86.3	88.4	90.3	91.1
Worldwide	835.92	889.3	868.8	981.9

Table 7. Cultivated area and production of grain maize in the European Union in 2011, 2012 and 2013 (source: Eurostat).

Country	Area (thousand hectares)			Production (thousand tons)		
	2011	2012	2013	2011	2012	2013
Bulgaria	399.4	466.8	420.0	2,209.2	1,717.8	2,300.0
Czech Republic	121.0	119.3	96.9	1,063.7	928.1	675.4
France	1,596.7	1,718.6	1,849.6	15,914.1	15,614.1	15,053.0
Germany	487.9	526.2	497.0	5,183.6	5,514.7	4,387.3
Greece	181.9	184.0	190.0	2,165.8	2,009.8	2,185.0
Hungary	1,230.3	1,191.3	1,254.0	7,992.4	4,762.7	6,724.8
Italy	994.8	976.6	808.3	9,752.6	7,888.7	6,503.2
Poland	333.3	543.8	613.9	2,392.1	3,995.9	4,041.9
Romania	2,604.9	2,748.3	2,593.8	11,671.9	5,949.3	11,434.9
Slovakia	202.0	212.3	219.2	1,444.4	1,170.4	1,133.6
Spain	369.3	390.2	440.9	4,199.9	4,261.4	4,853.6
European Union	9,302.0	9,854.0	9,752.0	70,620.0	59,745.7	65,240.9

production), followed by Romania (17.5%), Hungary (10.3%) and Italy (10.0%) (Eurostat).

Figure 11 shows the progressive increase in maize production and cultivated area in the European Union over the last 40 years. Therefore, the annual yield has increased substantially (from 3.7 to 6.7 t ha^{-1} from 1963 to 2013) (FAO, 2014a). The genetic improvement programs and the introduction of more productive hybrids, resistant to biotic and abiotic factors were the key elements for the increase in maize yields and most likely it will be so in the coming decades so as to meet the increasing food needs related to world population growth and to cope with the reduction in yield due to climate change. In fact, an overall yield decrease from 3% to 10% by 2050 is expected for maize (Rosegrant et al., 2009).

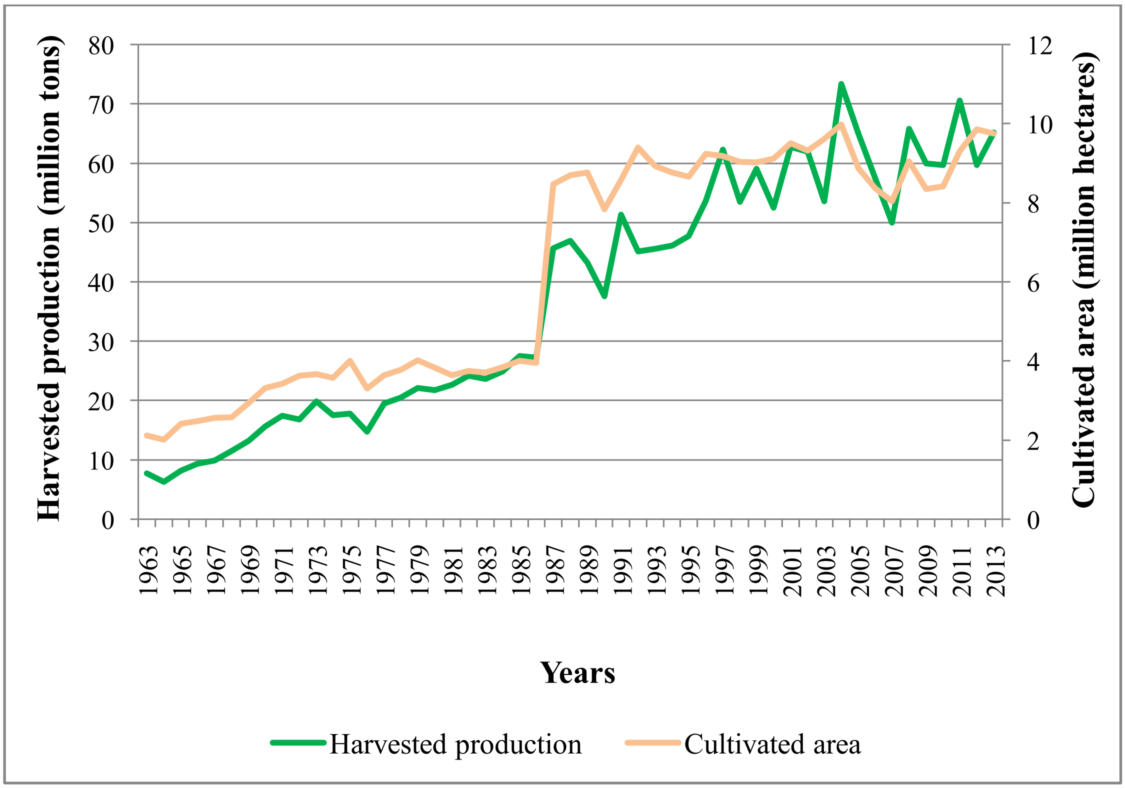

Figure 11. Trend in the production and harvested area for maize in the European Union during the 1963-2013 period (source: FAO, 2014a).

Until the early 1930s mass selection was the only technique of genetic improvement for maize, but the increase in yield was very slow over time. The varieties of the U.S. Corn Belt developed in the second half of the nineteenth century have been the basis for highly productive varieties currently available in temperate climate areas

(Lorenzoni and Marocco, 2008). A significant increase in yield was obtained with the use of hybridization techniques since the early 1930s (Duvick, 2005). Modern hybrids have also other advantages as compared to older hybrids, namely higher plant height (hence greater resistance to lodging), larger ears, greater stay green and greater resistance to abiotic and biotic stress factors (Duvick, 2005; Lorenzoni and Marocco, 2008). The most spread hybrids in the trade are simple hybrids [A x B] and double hybrids [(A x B) x (C x D)].

Currently the most used classification for maize hybrids is that of the FAO based on precocity (Table 8). The most precocious hybrids (classes 200 and 300) are used only in the case of spring dry sowing. The hybrids of intermediate precocity (classes 400, 500 and 600) are the most suitable for the production of grain. The late hybrids (classes 700, 800 and 900) are the most suitable for forage production.

Table 8. Classes of the maize hybrids based on the precocity (FAO classification).

Class	**Hybrid of reference**	**Precocity**	**Growth cycle duration (days)**
100	Wisconsin 1600	Ultra-precocious	76-85
200	Wisconsin 240	Very precocious	86-95
300	Wisconsin 355	Precocious	96-105
400	Wisconsin 464	Medium-precocious	106-115
500	Ohio M15	Medium	116-120
600	Jowa 4316	Medium-late	121-130
700	Indiana 416	Late	131-140
800	US13	Very late	141-150
900	US523W	Ultra-late	150-160

The conservation of germplasm in gene banks is fundamental for the evolution and implementation of breeding programs. The largest collection of maize germplasm in the world is that of CIMMYT with over 20,000 varieties from all over the world. Notwithstanding the commercial importance of the modern hybrids, it is necessary to point out the importance of maize landraces, as they represent a genetic resource that can be used to obtain better hybrids, with higher adaptability to different climatic conditions (Rebourg et al., 2003).

Maize in Italy

Italy is the fourth largest producer of maize in the European Union with about 6.5 million tons in 2013, accounting to 10.0% of total production (Eurostat). At the national level, maize is the most important cereal contributing to 38.5% of Italian cereal production and it is the second crop in terms of cultivation area, with about 800 thousand hectares dedicated to its production (ISTAT).

The national maize production has been increasing rather regularly, as shown in Figure 12. Since 2005, with the implementation of the reform of the Common Agricultural Policy (CAP), the cultivated area with maize has decreased leading to reduced production. Over the past 50 years, the Italian production of maize has increased of +76.1% because the yield has increased significantly from 2.9 to 8.1 t ha^{-1} in the 1963-2013 period, offsetting the decrease of the cultivated area, equal to -27.9% (Eurostat). The increase in yield in recent decades is due to the replacement of old varieties with hybrids and the improvement of cultivation techniques (Lorenzoni and Marocco, 2008).

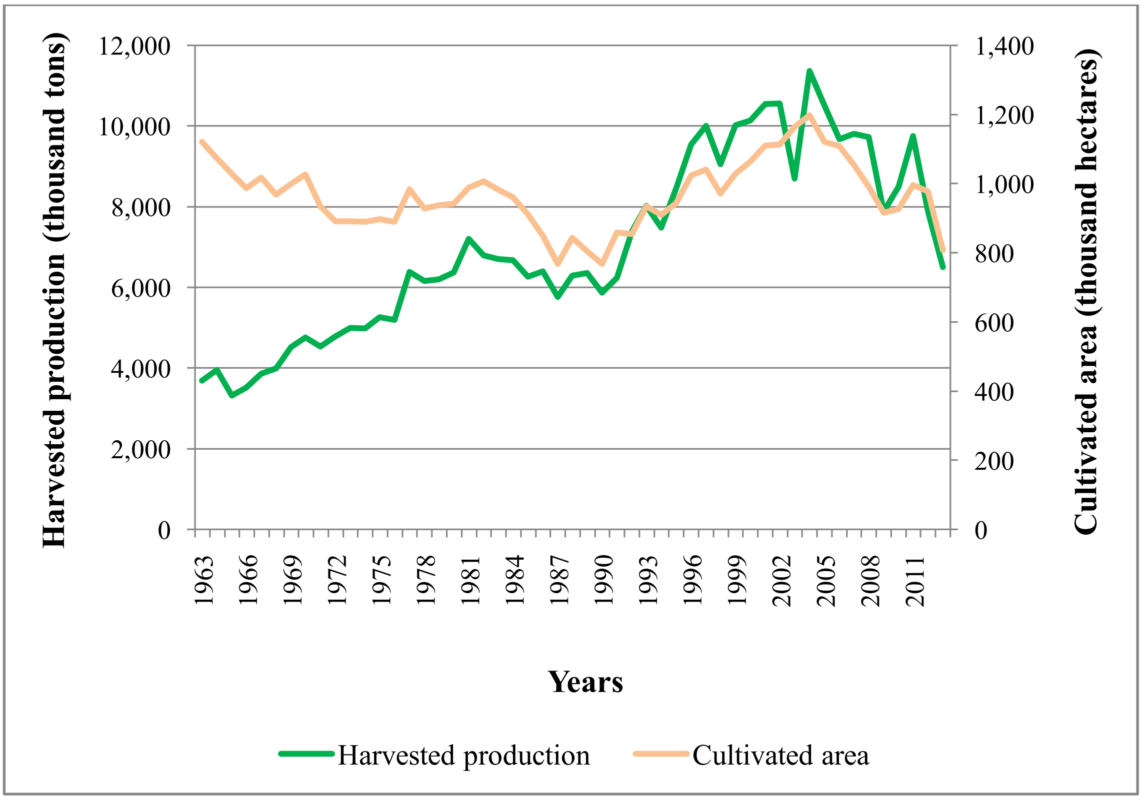

Figure 12. Trend in the cultivated area and production of maize in Italy in the 1963-2013 period (source: Eurostat).

In Italy maize is grown mainly in the plains of Northern Italy (Po Valley) where the greater availability of water resources enables irrigation during the summer. Sowing usually takes place between the end of March and mid-May, while harvest is carried out between the beginning of September and the end of October.

The regions with the highest maize production in 2012 are Lombardy and Veneto with 2.3 and 1.6 million tons respectively (Figure 13). Together, these two regions contribute to 49.4% of national maize production. Other producers are Piedmont (23.4%), Friuli-Venezia Giulia (10.5%) and Emilia-Romagna (9.3%) (ISTAT). There is little production of this crop in the Centre-South of Italy (7.4% of Italian production and 9.6% of the total cultivated area). This is due to the poor rains during great part of the crop cycle, thus resulting in lower and unstable yields.

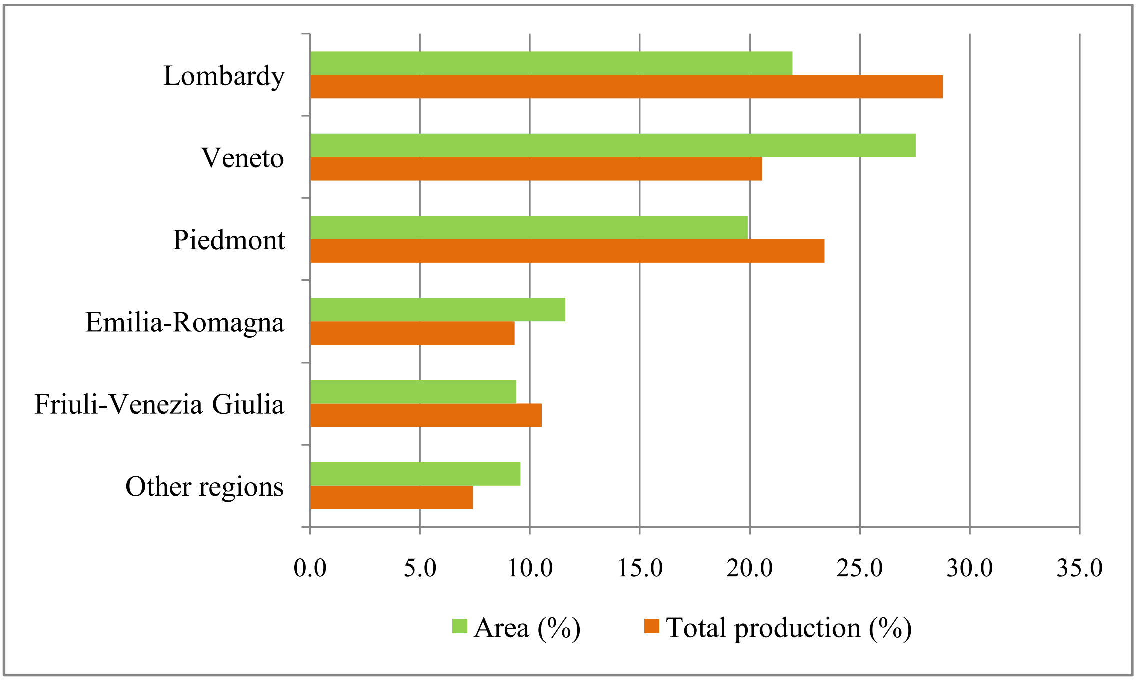

Figure 13. Cultivated area and total production for maize in Italy in 2012 (% of total) (source: ISTAT).

The cultivated area with maize in Italy has declined over the 2001-2012 period (-11.8%), particularly in Friuli-Venezia Giulia (-27.7%), Lombardy (-24.7%) and the Centre-South (-30.4%). Figure 14 shows the trends for the production during the same period. National production has decreased by about 26%, while at the regional level the largest decrease was observed in Veneto (-41.6%) and the Centre-South (-42.6%) (ISTAT).

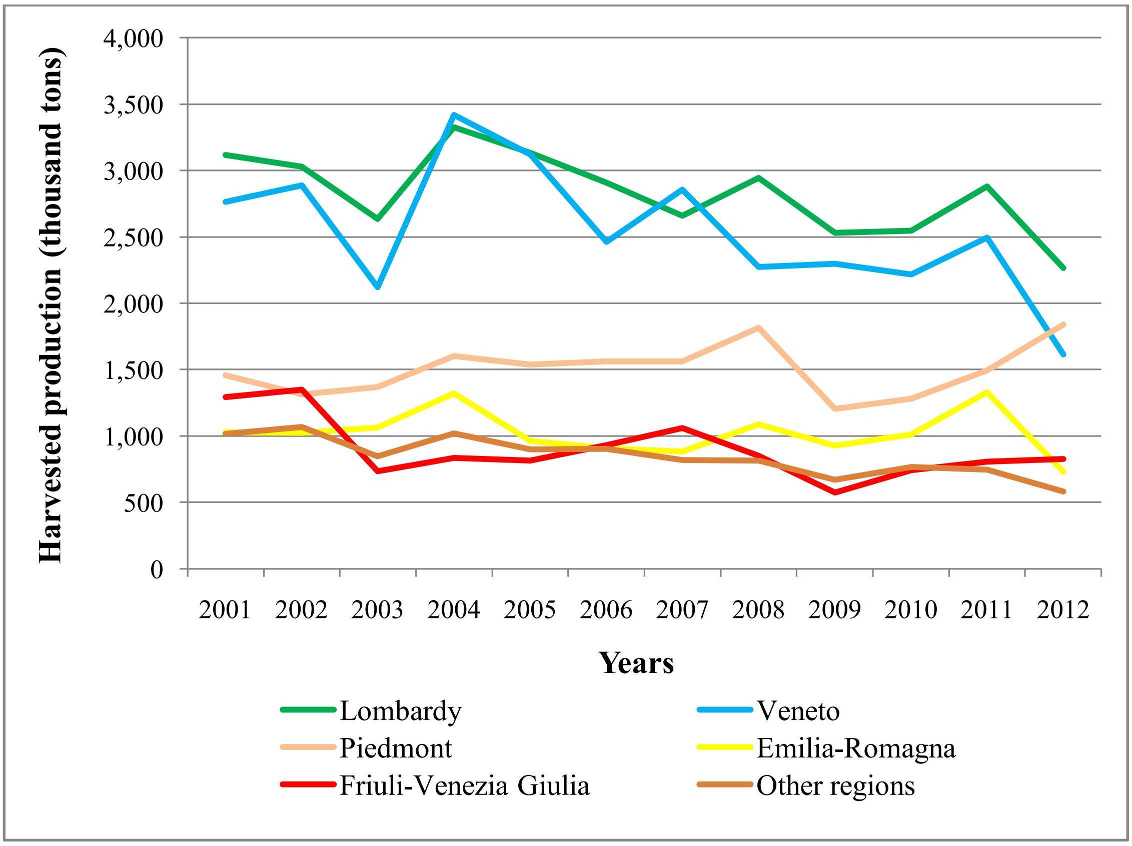

Figure 14. Trends in the regional maize production in Italy from 2001 to 2012 (source: ISTAT).

Regarding its use, most of the maize produced in Italy (about 90%) is used for animal feed as simple or compound feed (maize silage, mash silage and cobs, dry grain). Each year, 8% of available maize in Italy is used for the production of starch that is used by the food industry (production of sweets and drinks), for feed production of (corn gluten meal and feed) and in other industrial sectors (paper, chemical and pharmaceutical industries). A small fraction of the production is used for human consumption (as an ingredient in salads, corn flakes, popcorn, flour for polenta), the production of vegetable oil and for energy uses (production of ethanol and biogas) (USDA, 2012).

The maize germplasm in Italy is one of the most important in the world because it includes many varieties (hybrids and landraces). Initially, traditional varieties were cultivated, mainly for human consumption. The spread of hybrids dates back to the 1950s with the introduction of the U.S. varieties of *Zea mays* L. ssp. *dentata*, which were much more productive than the traditional ones. Thus, the traditional varieties were quickly replaced by hybrids (Leng et al., 1962; Brandolini et al., 2008).

One of the first research centers involved in the genetic improvement of maize in Italy was the Maize Section of Bergamo of the Istituto Sperimentale per la Cerealicoltura (currently the Unità di Ricerca per la Maiscoltura of the Consiglio per la Ricerca e la Sperimentazione in Agricoltura). As a result of hybridization techniques, maize it has spread in various areas thus becoming the first cereal for production (Sismondo, 2008). The old varieties of *Zea mays* L. ssp. *indurata* are still grown at higher altitudes and are used to produce flour for the polenta (Venturelli et al.,1990).

In the northern regions the best hybrids are those classified as FAO 600 and 700, while in Central Italy the medium-precocious hybrids (FAO classes 400 and 500) provide better results, due to the limitations on the use of irrigation.

Since several years, the Unità di Ricerca per la Maiscoltura of the Consiglio per la Ricerca e la Sperimentazione in Agricoltura (formerly Istituto Sperimentale per la Cerealicoltura) is involved in the national experimentation of maize hybrids marketed in Italy. Tests concern hybrids of different FAO classes and they are carried out every year for different sowing densities, for different levels of nitrogen fertilization, for different irrigation regimes and for different pesticide treatments.

1.2 CLIMATE CHANGE SCENARIOS AND MODELS

Climate change are due to the intrinsic variability of the climate system and external anthropogenic and environmental factors (see section 4.1 of this thesis). The impacts of anthropogenic climate change on the environment and society depend on the response of the Earth system to changes in atmospheric composition (in particular, the changes in the carbon dioxide concentration), but they also depend on the driving forces and the evolution of socio-economic conditions, technology, lifestyle and the policy which affect the behavior and activities of human society. Consequently, the system is very complex.

In order to understand better the processes and the complex interactions between the different components of the climate-environment-human activities system (Figure 15), various climatic scenarios were developed. These scenarios can be used to study the climate change impacts and test the effectiveness of related adaptation and mitigation strategies.

In research studies related to climate change, scenarios describe plausible trajectories of different aspects of the future that make it possible to assess the potential impacts of climate change on the different components of the climate system (e.g.,

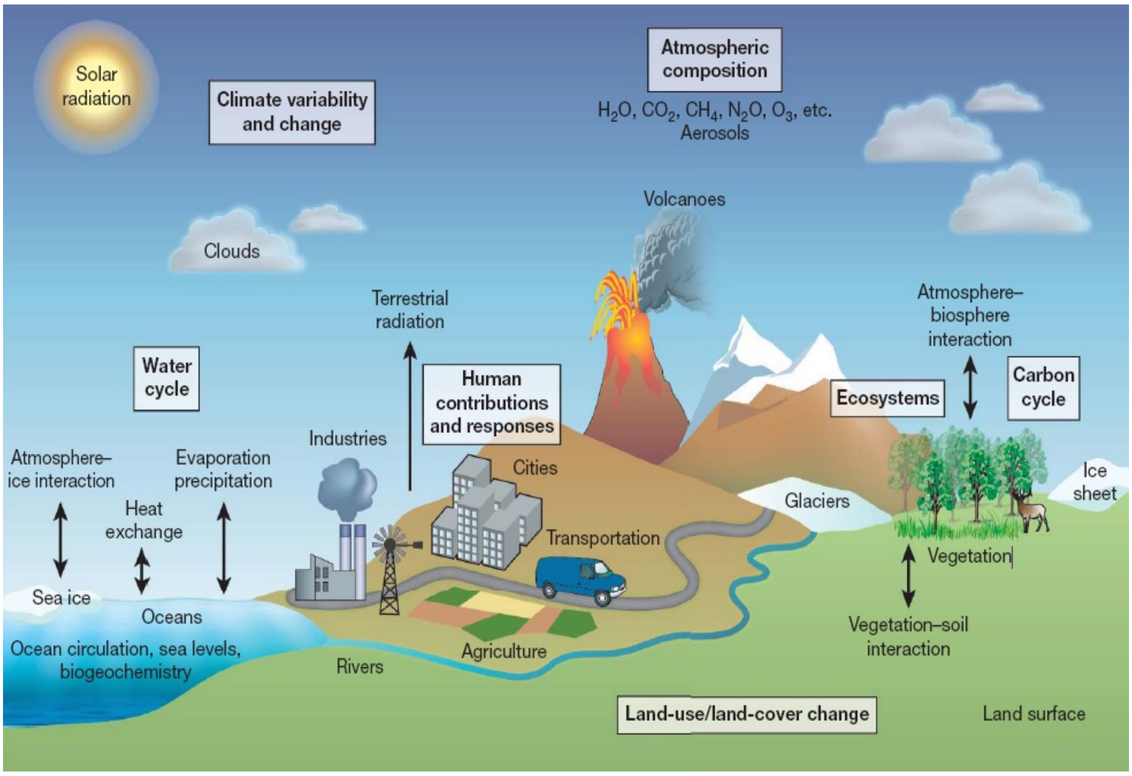

Figure 15. Major natural and anthropogenic processes and influences on the climate system addressed in scenarios (source: IPCC, 2007).

ecosystems, natural resources and economic activities). Scenarios represent many of the major driving forces, including processes, impacts (physical, ecological, and socio-economic), and potential responses that are important for informing climate change policy.

Research communities use the climatic scenarios for the following purposes:

I. to study and quantify the climate change impacts for decision making (e.g., the management of risks caused by natural disasters related to climate change (floods, droughts, fires, etc.));
II. to hand off information from one area of research to another (e.g., from research on energy systems and greenhouse gas (GHG) emissions to climate modeling).

The goal of working with scenarios is not to predict the future but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures. Table 9 presents a brief description of the different types of scenarios used in climate change research.

The Intergovernmental Panel on Climate Change (IPCC) has commissioned and approved several sets of scenarios for climate research over the past two decades. New scenarios are created periodically to reflect advances in research, new data, and to support the increasing sophistication of integrated assessment and climate models.

The IPCC in 2006 decided to encourage the research community to develop new scenarios. These new scenarios and research activities are an integral part of the 5th Assessment Report (2013/2014).

Following is a description of emissions scenarios, new climate change scenarios and the models used for research on climate change.

1.2.1 Emissions scenarios

The increase in greenhouse gas emissions and the consequent increase in the atmospheric concentration of these gases (particularly carbon dioxide) are responsible for the temperature increase in the post-industrial era (IPCC, 2013). The future evolution of greenhouse gas emissions is very uncertain because of the considerable complexity of the climate system.

Taking this into account, in order to improve the knowledges on climate change

Table 9. Types of scenarios in climate research and assessment (source: IPCC website, http://sedac.ipcc-data.org/ddc/ar5_scenario_process/scenario_background.html).

Type of scenario	**Description**
Emissions scenarios	Emissions scenarios describe future releases to the atmosphere of greenhouse gases, aerosols, and other pollutants and, along with information on land use and land cover, provide inputs to climate models. They are based on assumptions about driving forces such as patterns of economic, population growth, and technology development. In addition to their use as inputs to climate models, emissions scenarios are used in research on mitigation. They do not track "short-term" fluctuations such as business cycles or oil market price volatility but focus on long-term (e.g., decades) trends.
Climate scenarios	Climate scenarios are plausible representations of future climate conditions (temperature, precipitation, and other aspects of climate such as extreme events). They can be produced using a variety of approaches including analysis of observations, models, and other techniques such as extrapolation and expert judgment.
Environmental scenarios	These scenarios focus on changes in environmental conditions other than climate that may occur regardless of climate change. Such factors include water availability and quality at basin levels (including human uses), sea level rise incorporating geological and climate factors, characteristics of land cover and use, and local atmospheric and other conditions affecting air quality.
Vulnerability scenarios	Scenarios of demographic, economic, policy, cultural, and institutional characteristics are needed for evaluating the potential to be impacted by changes in climate as well for examining how future patterns of economic growth and social change affect vulnerability and the capacity to adapt. Many of the same socioeconomic factors that affect emissions also affect vulnerability and adaptive capacity and thus the underlying socioeconomic modeling must be coordinated.
Narratives	While some socioeconomic factors affecting emissions and vulnerability are modeled quantitatively, others (e.g., political, institutional, and cultural factors) are not effectively quantified. For this reason, qualitative narratives (also referred to in the literature as "storylines") are used to describe developments in these factors and how they could influence future forcing, vulnerability, and responses. Narratives can be used as the basis for quantitative scenarios. For example, the IPCC SRES scenarios were based on a set of four narratives that described a range of different development pathways for the world. Narratives can also facilitate coordination across spatial scales and substantive domains.

and their implications on the environment and human activities, the emissions scenarios (SRES[1], 2000) have been developed by IPCC in the 1990s.

The emissions scenarios, covering the entire 21st century, provide inputs for climate models and are widely used for the analysis of the climate change impacts and for the assessment of adaptation and mitigation strategies (IPCC, 2007, 2014b). In addition, these scenarios are used to study the effects of changes in socio-economic and political development on the global environment, with particular emphasis on the emissions of greenhouse gases into the atmosphere. Indeed, in addition to emissions of greenhouse gases and land use, the outputs of emissions scenarios include also drivers of change (e.g., demographic, socio-economic, technological, and political changes).

Emissions scenarios for climate change research are basically alternative images of the future. Therefore, each scenario provides a long-term perspective on future possibilities because it relates to the risks associated with climate change. The long-term perspective is necessary, taking into account the slow response of the climate system to changes in greenhouse gas concentrations.

The SRES emissions scenarios consider only the uncertainties related to known factors such as uncertainty about future socio-economic, political and technological conditions (Moss et al., 2010).

The scenarios are based on an extensive assessment of driving forces and emissions in the scenario literature, alternative modeling approaches, and an "open process"[2] involving many different modelling teams.

The emissions scenarios are divided into four narrative storylines (A1, A2, B1, and B2) that describe consistently the relationships between emission driving forces (different demographic, social, economic, technological, and environmental developments) and their evolution and add context for the scenario quantification (Figure 16). Each storyline include scenarios that represent different development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. All the scenarios based on the same storyline constitute a scenario "family".

Overall, forty emissions scenarios have been developed using different modeling

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[1] SRES-Special Report on Emission Scenarios, Working Group III-IPCC, 2000.

[2] The open process defined in the Special Report on Emissions Scenarios (SRES) Terms of Reference calls for the use of multiple models, seeking inputs from a wide community as well as making scenario results widely available for comments and review. These objectives were fulfilled by the SRES multi-model approach and the open SRES website.

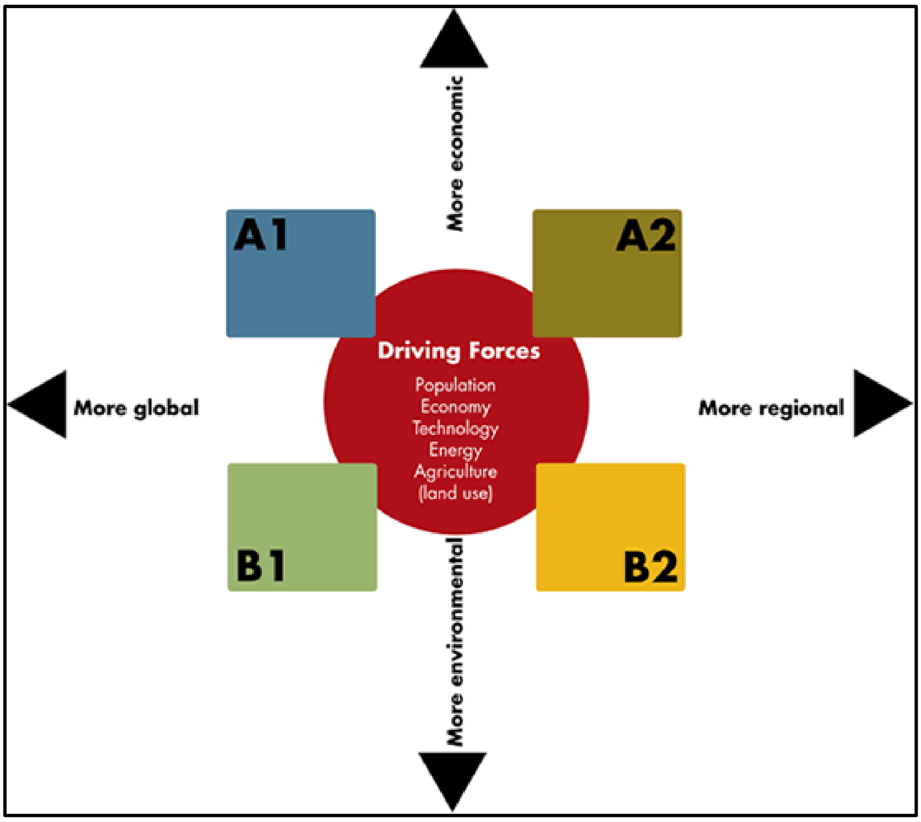

Figure 16. Schematic illustration of SRES emissions scenarios. Each storyline assumes a different direction for future developments, such that the four storylines differ in increasingly irreversible ways (source: BoM, 2003).

approaches. Each scenario has a menu of related driving forces: demographic changes, technological change and economic development, which would generate a range of outcomes when related to anthropogenic GHG emissions. These scenarios involve different development pathways that may influence GHG emissions as well as the sinks.

The set of scenarios consists of six scenario groups drawn from the four families (Figure 17): one group each in A2, B1, B2, and three groups within the A1 family, characterizing alternative developments of energy technologies: A1FI (fossil fuel intensive), A1B (balanced), and A1T (predominantly non-fossil fuel). Within each family and group of scenarios, some share “harmonized” assumptions on global population, gross world product, and final energy. These are marked as “HS” for harmonized scenarios. “OS” denotes scenarios that explore uncertainties in driving forces beyond those of the harmonized scenarios.

Main characteristics of the four storylines and scenario families are presented in Table 10.

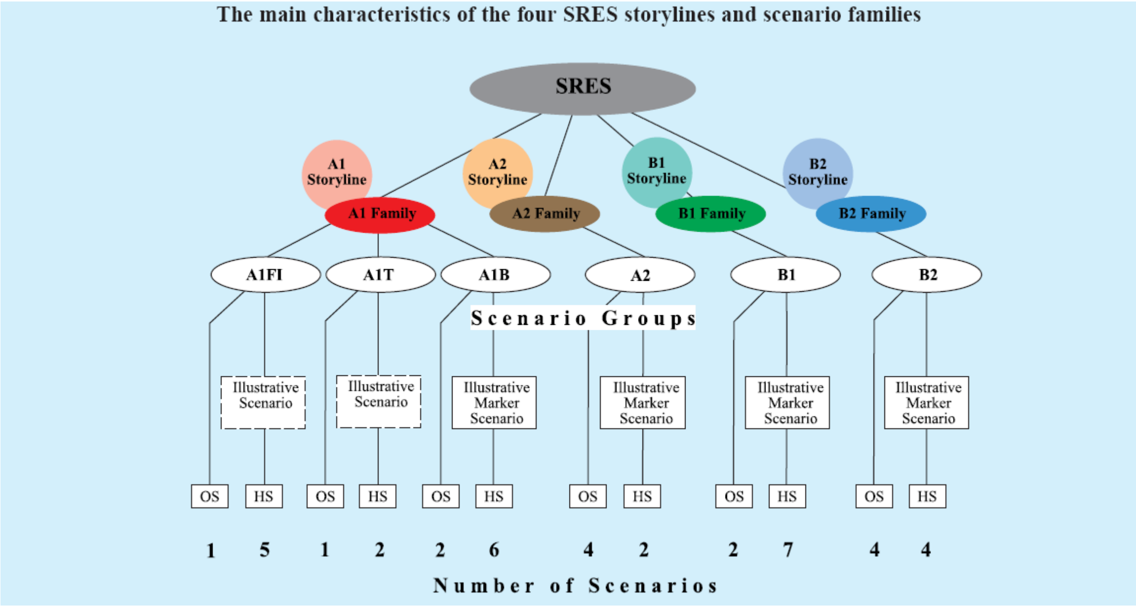

Figure 17. The main characteristics of the four SRES storylines and scenario families (source: SRES, 2000).

1.2.2 New climate change scenarios

The previous scenarios produced by the IPCC have proved very useful in the research on climate change. However, end users (including policy makers) have highlighted the need to develop new scenarios incorporating updated data on the recent historical emissions and to take account of new data relating to the economy, to environmental factors (e.g., land use and land cover change) and new technologies (van Vuuren and Riahi, 2008; Moss et al., 2010). In addition, the growing importance of assessment of the climate change impacts and adaptation strategies has revealed the need to use climate scenarios with a higher spatial and temporal resolution and with a better representation of extreme events.

The interest in the new scenarios has increased with the progress of research in the understanding of the climate system. This resulted in the the spread of increasingly complex climate models capable of simulating more processes, enabling the development of emissions scenarios extended beyond 2100 and with a greater level of detail (Moss et al., 2010).

The process used for the development of these new scenarios is substantially different from that used in the previous scenarios.

Previously, scenarios were developed and applied sequentially in a linear causal chain that extended from the socio-economic factors that influence greenhouse gas

Table 10. The main characteristics of the four SRES storylines and scenario families (source: SRES, 2000).

Storyline and scenario family	**Main characteristics**
A1	The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).
A2	The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
B1	The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
B2	The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

emissions to atmospheric and climate processes to impacts. The process included three steps (Figure 18). First, the production of socio-economic scenarios that give rise to alternative future greenhouse gas and aerosol emissions. Second, the evaluation of the effects of those emissions on the climate system. Finally, the assessment of the climate change implications, along with differing socio-economic futures and other environmental changes, on natural and human systems. Experience shows that this full,

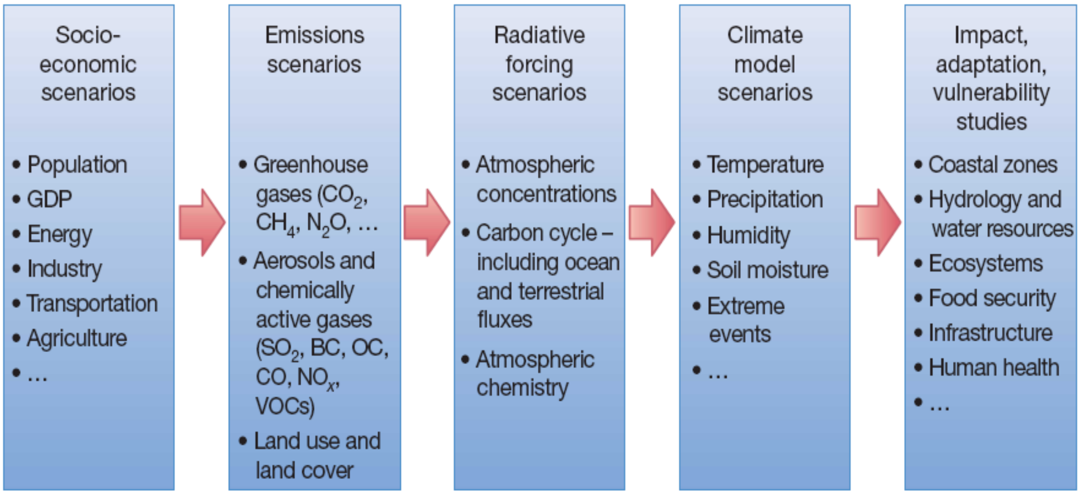

Figure 18. Sequential approach used for the development of the previous scenarios (source: Moss et al., 2010).

linear process takes about ten years.

In order to reduce the time interval between the development of emissions scenarios and the use of resulting climate scenarios in impact, adaptation, and vulnerability studies and in order to guarantee a better integration between socio-economic driving forces, changes in the climate system, and the vulnerability of natural and human systems, the climate change research communities have developed an alternative "parallel" approach (Figure 19).

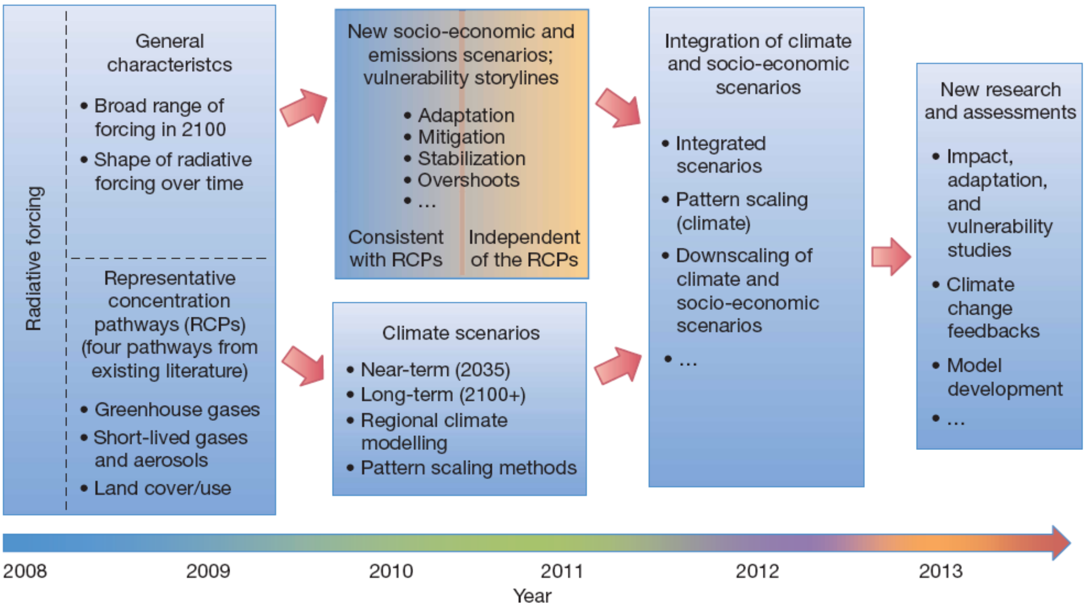

Figure 19. The parallel approach used for the development of the new scenarios (source: Moss et al., 2010).

In the new process now underway, emissions and socio-economic scenarios are developed in parallel, building on different trajectories of radiative forcing over time. Rather than starting with detailed socio-economic storylines to generate emissions and then climate scenarios, the new process begins with a limited number of alternative *pathways* (trajectories over time) of radiative forcing levels (or CO_2-equivalent concentrations) that are both *representative* of the emissions scenario literature and span a wide space of resulting greenhouse gas *concentrations* that lead to clearly distinguishable climate futures.

These radiative forcing trajectories were thus defined "Representative Concentration Pathways" (RCPs). The RCPs are not associated with unique socio-economic assumptions or emissions scenarios but can result from different combinations of economic, technological, demographic, policy, and institutional futures. In the preparatory phase, each RCP was simulated in an Integrated Assessment model to provide one internally consistent plausible pathway of emissions and land use change that leads to the specific radiative forcing target. The full set of RCPs spans the complete range of integrated assessment literature on emissions pathways and the radiative forcing targets are distinct enough to result in clearly different climate signals.

In the new process, scenario development proceeds in three main steps:

1. a preparatory phase for development of initial data on the major drivers of change in the physical atmosphere, including historical data and future scenarios of greenhouse gas emissions and land use change, to be used in subsequent climate and socio-economic modeling and research (from 2006 to 2010);
2. a 'parallel' phase in which climate and socio-economic scenarios are developed at the same time rather than sequentially and research community on new impacts, adaptation and vulnerability (IAV) establishes priorities for the evaluation and application of the scenarios (from 2009 to 2012);
3. an integration phase in which projections and research are brought together to form consistent sets of socio-economic, climate, and environmental scenarios and to apply them in IAV research (started in 2012 and continuing beyond).

During the parallel phase, climate modelers are conducting new climate model experiments to produce climate projections using the time series of emissions, concentrations and land use from the four RCPs. These model projections will be used to construct new climate scenarios for application in IAV and Integrated Assessment Models (IAM)[3] studies.

At the same time, the IAM and IAV communities are developing new socio-economic and emissions scenarios for use in analysis of impacts, adaptation, mitigation, and their implications for sustainable development. Some of these scenarios correspond to the RCPs, while others explore completely different levels of forcing and futures in response to evolving decision maker needs and research interests.

Since this work is done in parallel rather than sequentially, scenario development is shortened by the amount of time previously devoted to sequential development of emissions and then climate scenarios. For the various research communities involved in developing and applying these new scenarios, the novelty of the approach will also demand the building of new capacity for scenario research, assessment and interpretation.

Representative Concentration Pathways

Representative Concentration Pathways (RCPs) are new generation scenarios adopted by climate research communities. The RCPs were selected through a multi-step process involving several steps using an agreed set of selection criteria and an open review by modeling teams to facilitate climate research and assessment (Moss et al., 2008; van Vuuren et al., 2011a):

1. the RCPs should be based on scenarios published in the existing literature, developed independently by different modeling groups and, as a set, be ‘representative’ of the total literature, in terms of emissions and concentrations. At the same time, each of the RCPs should provide a plausible and internally consistent description of the future;
2. the RCPs should provide information on all components of radiative forcing that are needed as input for climate modeling and atmospheric chemistry modeling (emissions of greenhouse gases, air pollutants and land use). Moreover, they should make such information available in a geographically explicit way;

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[3] The IAM modeling community was organized in the Integrated Assessment Modeling Consortium (IACM).

3. the RCPs should have harmonized base year assumptions for emissions and land use and allow for a smooth transition between analyses of historical and future periods;
4. the RCPs should cover the time period up to 2100, but information also needs to be made available for the centuries thereafter.

Only 37 of the 324 scenarios published in the existing literature met the four selection criteria. In 2007 four RCP radiative forcing levels were chosen following an IPCC expert meeting (Moss et al., 2008).

Four RCPs were selected and defined by their total radiative forcing (cumulative measure of human emissions of GHGs from all sources expressed in W m^{-2}) pathway and level by 2100. These scenarios cover a wide range of future changes in radiative forcing (Moss et al., 2008; Moss et al., 2010). The RCPs were chosen to represent a broad range of climate outcomes, based on a literature review, and included one mitigation scenario leading to a very low forcing level (RCP2.6), two medium stabilization scenarios (RCP4.5 and RCP6) and one very high baseline emission scenario (RCP8.5). The name of each of the four RCPs scenarios refers to the radiative forcing target level for 2100. The main characteristics of the four RCPs scenarios are presented in Table 11.

The RCP2.6 is developed by the IMAGE modeling team of the Netherlands Environmental Assessment Agency. The emission pathway is representative for scenarios in the literature leading to very low greenhouse gas concentration levels. It is a so-called "peak" scenario: its radiative forcing level first reaches a value of about 3.1 W m^{-2} around mid-century, returning to 2.6 W m^{-2} by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially over time.

The RCP4.5 is developed by the MiniCAM modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Istitute (JGCRI). It is a stabilization scenario where total radiative forcing is stabilized before 2100 by employment of a range of technologies and strategies for reducing greenhouse gas emissions.

The RCP6 is developed by the AIM modeling team at the National Institute for Environmental Studies (NIES), Japan. It is a stabilization scenario where total radiative forcing is stabilized after 2100 without overshoot by employment of a range of

Table 11. Main characteristics of the four selected Representative Concentration Pathways (RCPs).

RCP scenario	Description	Integration Assessment Model	References
RCP2.6	Peak in radiative forcing at ~ 3 W m^{-2} (~490 ppm of CO_2 equivalents) before 2100 and decline.	IMAGE	van Vuuren et al., 2006 van Vuuren et al., 2007
RCP4.5	Stabilization without overshoot pathway to 4.5 W m^{-2} (~650 ppm of CO_2 equivalents) at stabilization after 2100.	GCAM (MiniCAM)	Smith and Wigley, 2006 Clarke et al., 2007 Wise et al., 2009
RCP6	Stabilization without overshoot pathway to 6 W m^{-2} (~850 ppm of CO_2 equivalents) at stabilization after 2100.	AIM	Fujino et al., 2006 Hijioka et al., 2008
RCP8.5	Rising radiative forcing pathway leading to 8.5 W m^{-2} (~1370 ppm of CO_2 equivalents) in 2100.	MESSAGE	Rao and Riahi, 2006 Riahi et al., 2007

technologies and strategies for reducing greenhouse gas emissions.

The RCP8.5 is developed by the MESSAGE modeling team and the IIASA Integrated Assessment Framework at the International Institute for Applies Systems Analysis (IIASA), Austria. The RCP8.5 is characterized by increasing greenhouse gas emissions over time representative for scenarios in the literature leading to high greenhouse gas concentration levels.

Figure 20 shows the trend of radiative forcing (expressed in W m^{-2}) for the four selected RCPs. The light grey area captures 98% of the range in previous IAM scenarios, and dark grey represents 90% of the range. The trend of emissions of the most important greenhouse gases (CO_2, CH_4, and N_2O) for various RCPs is shown in Figure 21.

While each single RCP is based on an internally consistent set of socio-economic assumptions, the four RCPs together cannot be treated as a set with consistent internal socio-economic logic. For example, RCP8.5 cannot be used as a no-climate-policy socio-economic reference scenario for the other RCPs because the socio-economic, technology, and biophysical assumptions of RCP8.5 scenario differ from

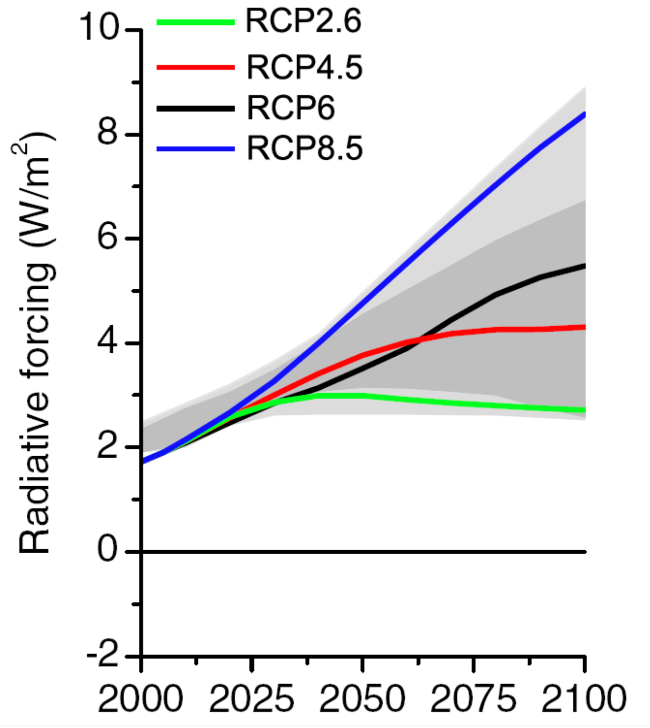


Figure 20. Trend in radiative forcing for the RCPs selected (source: van Vuuren et al., 2011a).

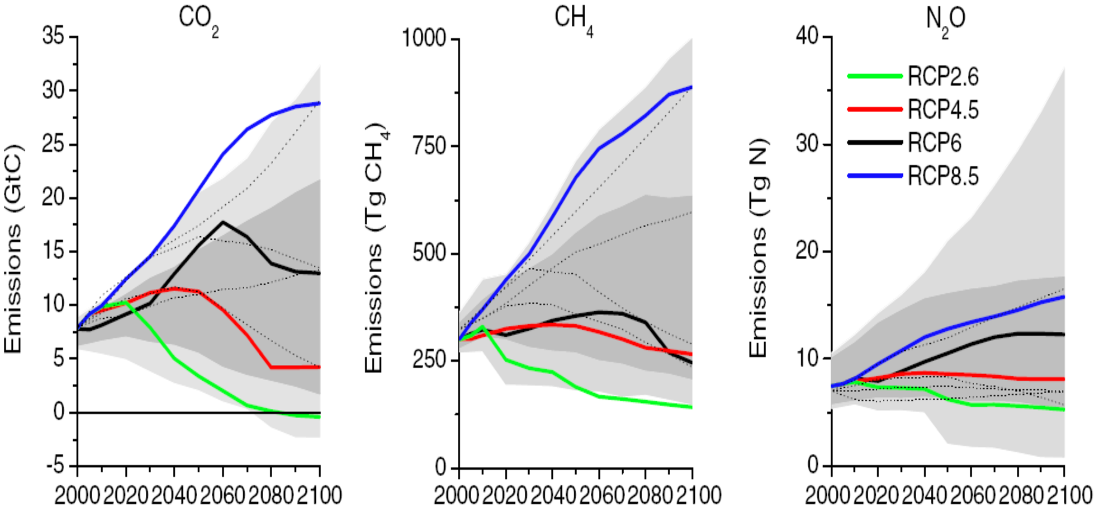


Figure 21. Emissions of main greenhouse gases across the RCPs (source: van Vuuren et al., 2011a).

those of the other RCPs.

Each RCP could result from different combinations of economic, technological, demographic, policy, and institutional futures. For example, the second-to-lowest RCP could be considered as a moderate mitigation scenario. However, it is also consistent with a baseline scenario that assumes a global development that focuses on technological improvements and a shift to service industries but does not aim to reduce greenhouse gas emissions as a goal in itself (similar to the B1 scenario of the SRES scenarios).

The RCPs scenarios are not forecasts or boundaries for potential emissions, land-use, or climate change. They are also not policy recommendations in that they were chosen for scientific purposes to represent the span of the radiative forcing literature at the time of their selection and thus facilitate the mapping of a broad climate space. They therefore do not represent specific futures with respect to climate policy action (or no action) or technological, economic, or political viability of specific future pathways or climates.

The RCP database, v. 2.0.5, (RCP, 2009) includes:

- historical atmospheric concentrations as well as concentrations for the RCPs (2005-2100) and their extension to 2300 (ECPs);
- historical emissions data (1850 - 2000) as well as emissions for the RCPs (2000-2100);
- historical aerosols data (1850 - 2000) for several species (e.g., sulfate (SO_4), ammonium nitrate (NH_4NO_3), and others);
- historical and RCP land-use projections and associated land-use transitions.

A wider range of possible future climates can be explored through RCPs scenarios, given that the radiative forcing levels extend beyond those considered by previously used global climate model projections. The main characteristics of the different scenario components of the RCPs are shown in Table 12. The RCP2.6 is a scenario with low mitigation. The RCP4.5 and RCP6 scenarios can be interpreted as intermediate and high-mitigation scenarios respectively. The RCP8.5 scenario, instead, corresponds to a high emission scenario.

Recent research shows that the RCPs scenarios are used as inputs for climate modeling (Hibbard et al., 2007; Taylor et al., 2012), for the assessment of climate change impacts (Kriegler et al., 2010; van Vuuren et al., 2011b) and represent an useful tool to study the possible adaptation and mitigation strategies to climate change.

The scenarios produced during the parallel phase will include both climate

Table 12. Main characteristics for each component of the RCPs scenarios (source: van Vuuren et al., 2011a).

Scenario component	**RCP2.6**	**RCP4.5**	**RCP6**	**RCP8.5**
Greenhouse gas emissions	Very low	Medium-low mitigation Very low baseline	Medium baseline; high mitigation	High baseline
Agricultural area	Medium for cropland and pasture	Very low for both cropland and pasture	Medium for cropland but very low for pasture (total low)	Medium for both cropland and pasture
Air pollution	Medium-low	Medium	Medium	Medium-high

model projections for each of the four RCPs forcings and also alternative socio-economic futures. Researchers wishing to use such scenarios for impacts, adaptation and vulnerability studies (as well as groups studying regional and local emissions mitigation) will need to have a means of establishing priorities for the scenarios to be evaluated.

Impacts, adaptation, vulnerability, and mitigation researchers working at the regional scale are commonly faced with the challenge of reconciling scenarios developed from global models with quite different, and often inconsistent, detailed scenarios developed locally. One approach is to develop regional narrative storylines that are consistent with the global storylines but also account for regional characteristics and processes. The advantage of developing regional storylines is that these can subsequently be used for quantifying regional scenarios that would not otherwise be available (or sufficiently reliable) from global scenarios based on IAMs. A crucial element of such exercises is stakeholder participation, which is required to ensure that regional scenarios and storylines are both credible and relevant for local needs. Some of these issues are explored in a recent review of regional storyline development (Rounsevell and Metzger, 2010).

Extended Concentration Pathways

The RCPs scenarios provide data until 2100. However, one of the objectives of the climate research communities is to study the long-term climate change impacts on the different components of the climate system. To such end, the projections of RCPs scenarios have been extended up to 2300. Only the concentration, emissions, and land-use data series were extended beyond 2100 because there is a high uncertainty on the long-term driving forces of emissions (socio-economic development, policy and technology). Thus the Extended Concentration Pathways (ECPs) were obtained (Meinshausen et al., 2011).

For each RCP scenario, an ECP scenario has been derived, using specific criteria (Table 13). The possibility of an additional peak and decline after 2100 for the RCP6 scenario with subsequent stabilization of radiative forcing at 4.5 W m^{-2} by 2250 has been discussed by the climate research community. Therefore, in addition to the four ECPs, another extension was introduced, referred to as SCP6to4.5.

Figure 22 shows the post-2100 extensions of CO_2 emissions and radiative forcing for each RCP scenario, so as to derive the different ECPs scenarios.

Table 13. Generic rules used for deriving Extended Concentration Pathways.

Parameter	**ECP scenario**	**Generic rules**
CO_2 and other well-mixed GHGs	ECP8.5	Follow stylized emission trajectory that leads to stabilization at 12 W m^{-2}.
	ECP6	Stabilize concentrations in 2150 (around 6.0 W m^{-2}).
	ECP4.5	Stabilize concentrations in 2150 (around 4.5 W m^{-2}).
	ECP3PD	Keep emissions constant at 2100 level.
	SCP6to4.5	Return radiative forcing of all gases from RCP6 to RCP4.5 levels by 2250.
Reactive gases	All ECPs	Keep constant at 2100 level.
	SCP6to4.5	Scale forcing of reactive gases with GHG forcing.
Land use	All ECPs	Keep constant at 2100 level.

1.2.3 General Circulation Models

In order to obtain long-term global climate projections on the basis of possible greenhouse gas emission scenarios, General Circulation Models (GCMs) are used. These models simulate the physical processes occurring in various components of the climate system (atmosphere, ocean, cryosphere, and land surface) in response to increasing concentrations of greenhouse gases.

An important goal of recent research on climate modeling is the development of Coupled Atmosphere-Ocean General Circulation Models (AOGCMs), which couple 3-D atmospheric GCMs with ocean GCMs, and sea-ice and land-surface components.

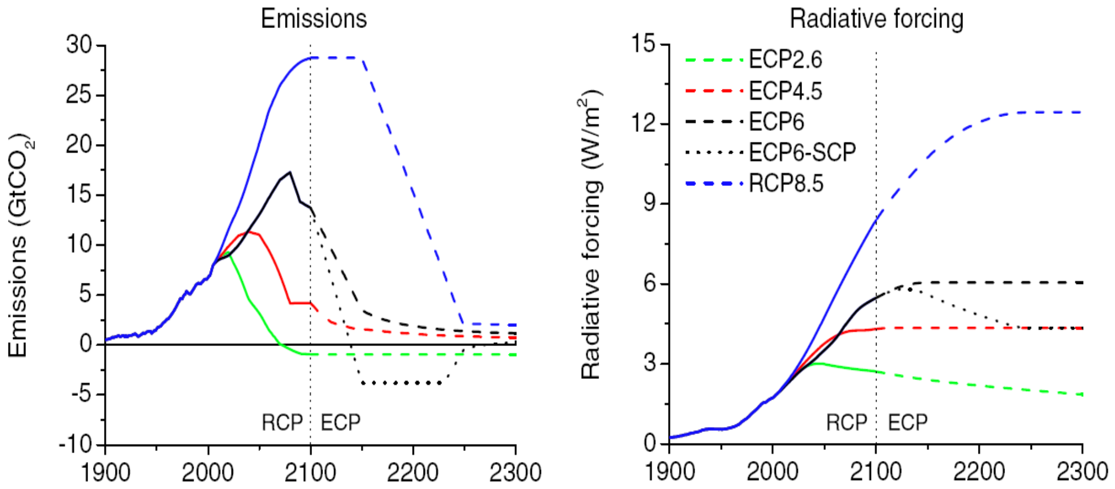


Figure 22. Extended projections for CO_2 emissions (left) and radiative forcing (right) for each Extended Concentration Pathways (source: van Vuuren et al., 2011a).

The equations are solved on a three-dimensional grid covering the entire planet (Figures 23-24). The horizontal resolution of grid cells has progressively increased from about 500 km to over 110 km, thanks to the increase of available computing power (IPCC, 2007). The number of vertical layers is between 10 and 20 for the atmosphere and up to 30 for the ocean. Despite progress in recent years, GCMs have a resolution too low for their use in the assessment of climate change impacts.

A source of uncertainty in the application of GCMs for the simulations based on future climate scenarios is the fact that different physical processes (e.g., processes related to the clouds and the storms) cannot be modeled correctly because they occur at smaller scales. Therefore, in order to make the numerical simulation possible, it is necessary to parameterize the effects of these processes in the short term and then consider the average of their known properties on a large scale. The representation of the various physical processes and feedbacks differs from one GCM to another.

The differences in the response are generally compatible with a wide range of projections on global warming. However, there is a high probability that the GCMs are representative of the range of uncertainty of regional climate projections (IPCC, 2007).

Table 14 shows a list of the GCMs currently most used by the research community on climate change.

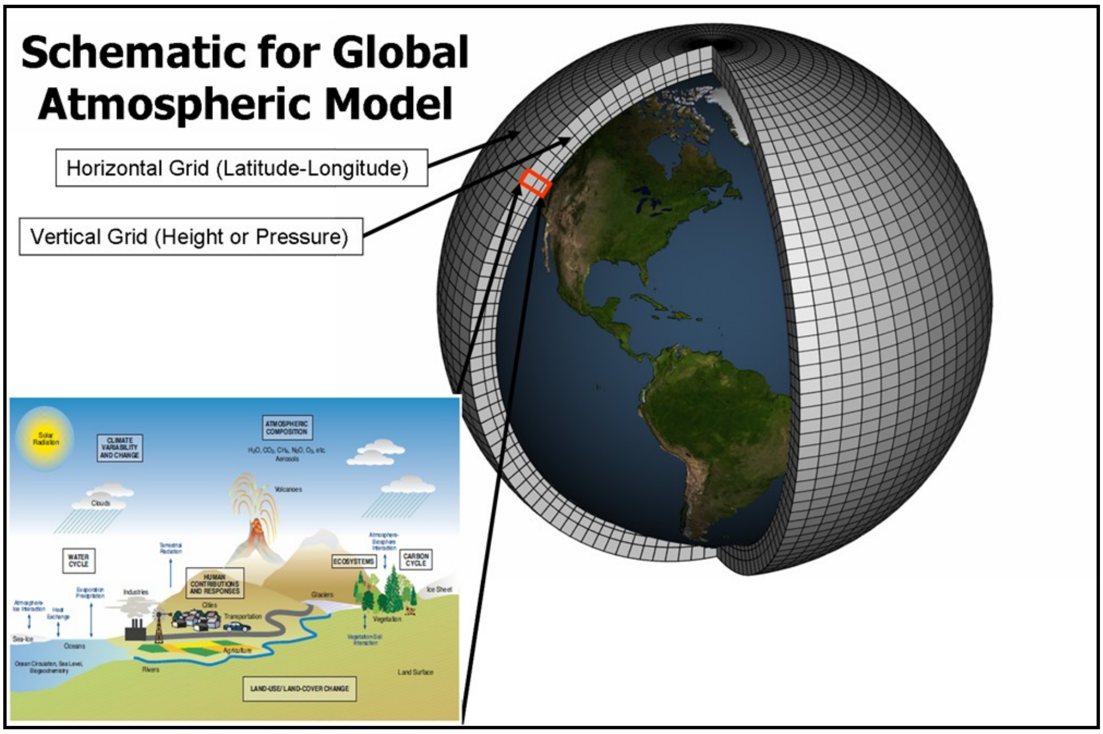


Figure 23. Scheme of Global Atmospheric Model (source: [http://alienspacescience news.files.wordpress.com/2013/07/schematic-for-global-atmospheric-model-earth-line-22-wow-data.png?w=600](http://alienspacesciencenews.files.wordpress.com/2013/07/schematic-for-global-atmospheric-model-earth-line-22-wow-data.png?w=600)).

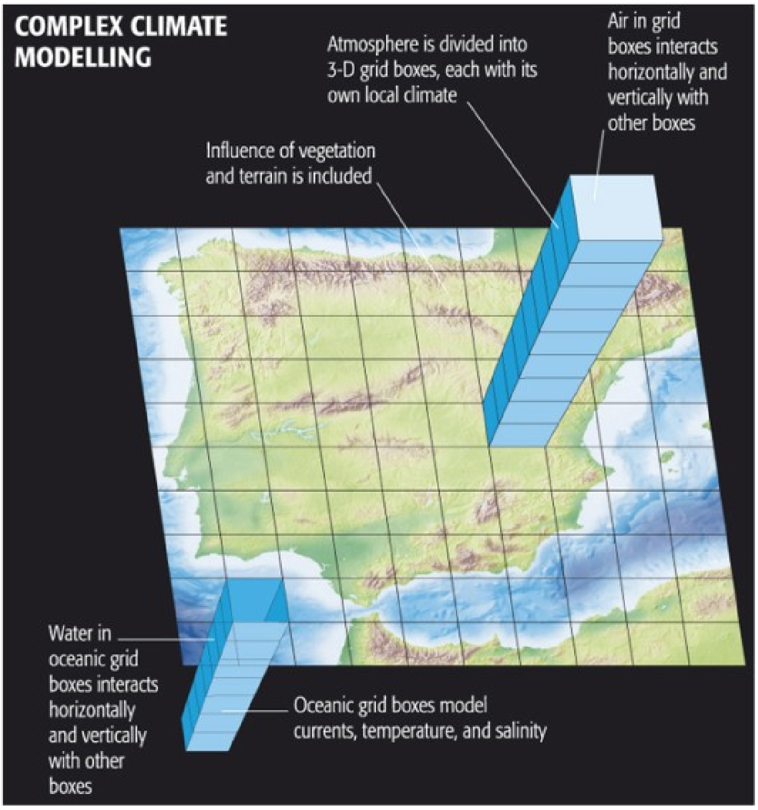


Figure 24. Three-dimensional grid of the General Circulation Models (source: https://www.e-education.psu.edu/meteo469/node/140).

Table 14. Some of the main General Circulation Models (GCMs) currently used for climate change studies.

GCM	**Atmospheric resolution (latitude x longitude)**	**Center**	**References**
HadCM3	2.5° X 3.75°	Met Office Hadley Centre (United Kingdom)	Gordon et al., 2000
MRI-CGCM_2.3.2	2.81° X 2.81°	Meteorological Research Institute (MRI, Japan)	Yukimoto et al., 2006
CNRM_CM3	2.81° X 2.81°	Centre National de Recherches Météorologiques (CNRM, France)	Salas-Mélia et al., 2005
CSIRO_Mk3.5	1.88° X 1.88°	Commonwealth Scientific and Industrial Research Organization (CSIRO, Australia)	Gordon et al., 2010
NCAR_CCSM3	1.41° X 1.41°	National Center for Atmospheric Research (NCAR, United States)	Collins et al., 2006
MIROC3.2-hires	1.125° X 1.125°	Center for Climate System Research, National Institute for Environmental Studies, Frontier Research Center for Global Change (CCSR, NIES, FRCGC, Japan)	Hasumi and Emori, 2004
GFDL_cm2.1	2.0° X 2.5°	Geophysical Fluid Dynamics Laboratory (GFDL, United States)	Delworth et al., 2006
ECHAM5	1.875° X 1.875°	Max Planck Institute for Meteorology (MPI, Germany)	Roeckner et al., 2003
FGOALS	2.8125° X 2.8125°	Institute of Atmospheric Physics (IAP, China)	Yongqiang et al., 2004
CMCC-CC	0.75° X 0.75°	Centro Euro-Mediterraneo per i Cambiamenti Climatici (CMCC, Italy)	Scoccimarro et al., 2011

1.2.4 Regional Climate Models

The projections of the GCMs cannot be used directly for assessing the impacts of climate change in agriculture at regional and local levels. In fact, their spatial resolution is very low than what is required for regional and local impact studies. In addition, in areas characterized by complex morphology, the local meteorological phenomena and physical processes can be very different from those at the regional scale as well as being highly variable within the same area. Therefore, local climate cannot be completely reproduced by GCMs, with resulting significant differences in the impact studies at different scales (BoM, 2003; Moriondo and Bindi, 2006).

To bring the outputs of GCMs at the scale required for impact assessments, downscaling techniques are used: dynamical downscaling and empirical/statistical downscaling. In particular, through the dynamical downscaling it is possible to simulate the processes both in large scale and sub-grid scale. Nesting techniques allow the transition from a low (GCM) to a higher resolution. In such a way it is possible to obtain Regional Climate Models (RCMs) that represent an intermediate level between the GCMs and field scales (Figure 25).

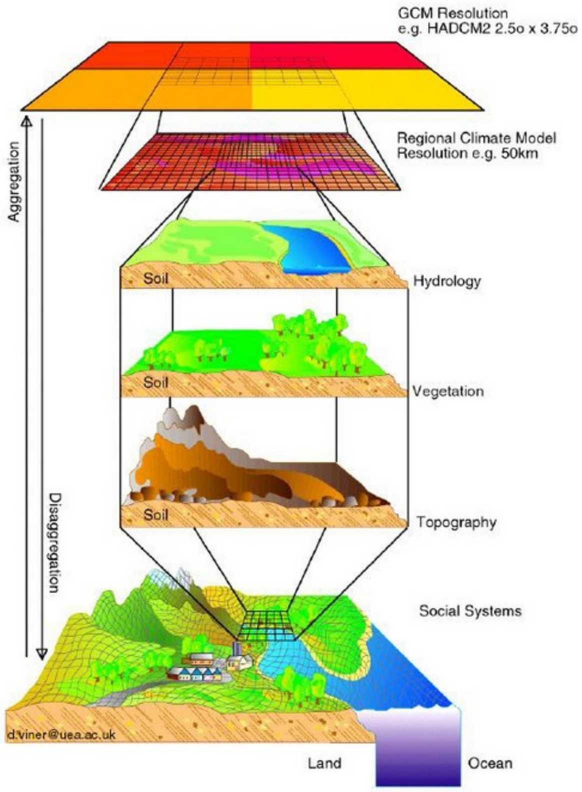


Figure 25. Application scheme of the dynamical downscaling (source: http://consulclima.co.uk/climate-modelling/downscaling-gcm-outputs).

The RCMs incorporate the local topography and land-atmosphere feedbacks, and represent the most mechanistic way for the simulation of variables and local climate fluxes (temperature, precipitation, solar radiation, relative humidity, wind, runoff, latent and sensible heat, soil moisture, etc.). In order to obtain high resolution climate data required as input to the models used for climate change impact studies (e.g., crop simulation models), the most common technique is to downscale the GCMs output (typical horizontal resolution between 100 and 200 km) in a data grid with higher resolution (usually between 10 and 25 kilometers using the dynamical downscaling applying the Regional Climate Models), or into the specific locations (e.g., weather stations) using statistical downscaling. However, the spatial resolution of the RCMs can still be low for the assessment of climate change impacts in morphologically complex areas (Moriondo and Bindi, 2005).

Usually, the necessary conditions needed to obtain a RCM are defined by the output of the GCM. Therefore, the reliability of the projections of the RCM depends on that of GCM under consideration. The computational and data storage resources required by dynamical downscaling are very high. Furthermore, the use of dynamical downscaling techniques requires a long time for data processing and involves high costs.

In recent years there has been a significant improvement of the RCMs. They are more and more widely used to produce climate change scenarios for the assessment of climate change impacts. Currently, numerous RCMs related to the CORDEX (Coordinated Regional Climate Downscaling Experiment) initiative are available at global level (Jacob et al., 2014). Regarding the European domain, several RCMs are available at two grid cell resolutions (12.5 and 50 km). Data of these RCMs integrate those of previous experiments as PRUDENCE (PRUDENCE, 2005) and ENSEMBLES (van der Linden and Mitchell, 2009) projects. With regard to Italy, an RCM (COSMO-CLM) with high cell resolution (8 km) is also available (Rockel et al., 2008). The availability of these RCMs not only enables the comparison between the outputs obtained using different RCMs with the same cell resolution and the analysis of uncertainties of the climate change impacts on agriculture, but also the uncertainty analysis of the simulation results due to the different climate data resolution (Olesen et al., 2007; Angulo et al., 2013; Zhao et al., 2015). However, the parameterizations of smaller scale processes are often based on observed data statistics, thereby limiting the general applicability of the RCMs.

1.3 CROP SIMULATION MODELS

The development, growth and productivity of crops are affected by many physical, chemical and biological processes that occur in the plant and the surrounding environment. Crop management practices (e.g., tillage techniques, fertilization, etc.) contribute to increase the complexity of cropping systems. As a result of this complexity, in many cases it is not possible to know the interactions between the different factors and the environment and their influence in determining the crop yield.

Since the 1960s there has been a widespread use of crop models in order to simulate the processes that regulate the development and growth of crops. The models are a mathematical representation of reality. However, this is a simplification of a real system because the models are not able to consider all the interactions between the processes of development and growth of crops and the surrounding environment.

A crop system model is defined as a combination of mathematical and logic equations that conceptually represent a simplified system of crop production (Ritchie et al., 1985).

The number of assumptions introduced in a model can be very high, particularly when there is little information on the cropping system and the interactions between the various processes (Hoogenboom, 2000; Wallach, 2006). Therefore, as reported by some authors (Porter et al., 2010), the commonly used crop models allow to simulate the processes that influence the growth of crops for a limited number of factors in limited conditions.

Crop simulation models can be used as tools for a variety of purposes: from business decision making and planning in crop management to scientific use for research purposes (Brouwer and van Ittersum, 2010; Ewert et al., 2011). In fact, crop models are useful tools to test the effect of different agronomic practices (e.g., different levels of nitrogen fertilization) in order to maximize the productivity of crops.

One of the most important applications of crop models is the estimation of crop yield on the basis of climatic and soil conditions and crop management (Hoogenboom, 2000). Therefore, they are tools increasingly used to study the impacts of climate change on growth, development and yield of crops and for the assessment of adaptation strategies at a scale that varies from field to regional scale (Parry et al., 2005; Rosenberg, 2010; White et al., 2011).

1.3.1 Classification of crop models

There are two categories of crop simulation models: mechanistic and empirical crop models. The difference between these two types of models is that a mechanistic model tries to explain the relationships between the modeled system and the explanatory variables. Instead, an empirical model is a direct description of the observed data and is generally defined through the analysis of the parameters of a multiple regression. Therefore, empirical models describe the behavior of the modeled system and demonstrate the existence of relationships between selected variables, but do not explain the mechanisms upon which these relationships are based (Donatelli, 1995).

The soil-plant-atmosphere system is complex. This does not allow the inclusion of all hierarchical levels in a single model. For this reason the crop models are typically a compromise between the mechanistic and empirical models (Sinclair and Seligman, 2000). In addition, they are generally dynamic models because they describe the evolution of the state variables in time (Wallach, 2006).

Another distinction is that between deterministic and stochastic crop models. The deterministic models make a prediction and the output is represented by a numerical value. Instead, the stochastic models contain random components in one or more of their parameters or variables. Therefore, they provide a distribution of probability of the output (Donatelli, 1995; Hoogenboom, 2000).

1.3.2 Main crop models

The first crop simulation models have been developed in Wageningen (The Netherlands) by de Wit and his collaborators in the 1960s, according to an approach based on different levels of production (de Wit and Goudriaan, 1974; Bouman et al., 1996). The first level is the potential production, which is the production obtainable in the absence of biotic and abiotic stress factors. Therefore, the factors that affect the potential production are temperature, solar radiation, the atmospheric concentration of carbon dioxide, the genetic characteristics of the crop and plant geometry. The second level is the production obtainable in the presence of limiting factors, such as water and nitrogen. Finally, the third level considers other inputs (e.g., other minerals different from nitrogen, pests, plant diseases and weeds). At this level, the crop models allow to simulate the soil-plant-atmosphere system in a comprehensive manner. The crop models at this level are few.

Among the representative models of the "School of de Wit" there are ELECROS (de Wit and Penning de Vries, 1970), BACROS (de Wit, 1978; Penning de Vries and van Laar, 1982), SUCROS (van Keulen et al., 1982) and WOFOST (Keulen and Wolf, 1986).

The 90's saw the development of crop models with greater mechanistic approach and more oriented on the agricultural components of the system, such as CERES (Crop Estimation through Resource and Environment Synthesis) (Ritchie and Otter, 1985; Jones and Kiniry, 1986), CROPGRO (Hoogenboom et al., 1992; Boote et al., 1997), CROPSYST (Stöckle and Donatelli, 1994) and APSIM (Agricultural Production System Simulator) (McCown et al., 1996).

The crop models included in APSIM and DSSAT-CSM (Decision Support System for Agrotechnology Transfer-Cropping System Model) (Jones et al., 2003; Hoogenboom et al., 2010) are among the most used at present. The CERES and CROPGRO crop models are based primarily on agronomic objectives, unlike the generic models, such as EPIC (Erosion Productivity Impact Calculator) (Williams et al., 1984), developed to consider the agro-environmental problems. In recent years generic and agro-environmental models that consider agricultural practices have been developed, such as the STICS model (Brisson et al., 2003).

Further progress in the modeling of cropping systems concerns the recent introduction of modularity. The modular structure allows to represent the processes related to climate, soil and crop growth into separate modules that represent the basic elements of the model. An example of modularity is represented by DSSAT-CSM which includes modules well defined for different crops (Jones et al., 2003). Another example is given by APSIM in which it is possible to assemble the modules in order to create models suitable to various environments (McCown et al., 1996).

In recent years the trend in the modeling of cropping systems is toward the association of crop growth simulation models with geographic information systems (GIS) (Resop et al., 2012). This approach allows: 1) the study of the effects of spatial variability of the model parameters on crop production, 2) the estimate of the impacts of future climate change on yields at the regional level, and 3) the assessment of the most effective adaptation strategies, in order to plan the future crop management. All over the world, the geospatial application of crop models is increasingly being used at different scales (Table 15). This association allows the crop simulation models (such as those included in DSSAT-CSM) to contribute to the economic and environmental

Table 15. Geospatial crop model applications at different scales in recent years (source: Resop et al., 2012).

Scale	Application	Resolution	References
Field	Precision farming	Vector	Irmak et al., 2001
	Precision farming	Vector	Thorp et al., 2007
	Climate change	45 m	Thorp et al., 2008
Subregional	Biofuel production	56 m	Zhang et al., 2010
	Crop yield constraints	100 m	Lobell and Ortiz-Monasterio, 2006
Regional	Climate change	Vector	Guo et al., 2010
	Climate change	50 km	Mearns et al., 2001
	Climate change	50 km	Tsvetsinskaya et al., 2003
	Regional calibration	50 km	Xiong et al., 2008
	Climate change	50 km	Tao et al., 2009
National	Spatial variability	Vector	Yun, 2003
	Spatial aggregation	10 km	Olesen et al., 2000
	Spatial variability	10 km	Priya and Shibasaki, 2001
	Climate change	50 km	Guereña et al., 2001
	Crop water stress	50 km	Challinor and Wheeler, 2008
Continental	Climate change	18 km	Jones and Thornton, 2003
	Climate change	18 km	Thornton et al., 2009
	Crop yield forecasting	25 km	de Wit et al, 2010
	Crop yield forecasting	50 km	de Wit et al., 2005
	Crop yield forecasting	50 km	de Wit and van Diepen, 2008
Global	Climate change	Vector	Parry et al., 2004
	Climate change	Vector	Lobell et al., 2008
	Climate change	11 km	Tan and Shibasaki, 2003
	Water use productivity	50 km	Liu et al., 2007
	Water use productivity	50 km	Liu, 2009

sustainability of agricultural systems because it allows to consider also the spatial variability of the growth and development processes of the crops (Sarkar, 2012).

The most widely used crop models for wheat and maize and their main characteristics are shown in Table 16.

Recently, some studies have been conducted to compare the performances of different crop models. The results obtained from Palosuo et al. (2011) show that DSSAT is one of the best performing crop models in the simulation of phenology and yield for winter wheat in Europe (Figure 26). Other crop models (such as STICS and CROPSYST) showed a tendency to underestimate or overestimate yields, probably due to the lower precision and accuracy of these models to different environment conditions (Palosuo et al., 2011).

Table 16. The main crop growth simulation models used for wheat and maize crops.

Software/Model	Type of model	Crops	Simulated processes	Notes	References
CSM-CERES-Wheat model implemented into DSSAT-CSM (Decision Support System for Agrotechnology Transfer - Cropping System Model) software	Dynamic mechanistic crop growth model	Wheat	Daily phenological development and crop growth	More specific details about CSM-CERES-Wheat model are given in the section 1.3.4 of this thesis	Ritchie and Otter, 1985 Hoogenboom et al., 2010
CSM-CERES-Maize model, implemented into DSSAT-CSM (Decision Support System for Agrotechnology Transfer - Cropping System Model) software	Dynamic mechanistic crop growth model	Maize	Daily phenological development and crop growth	More specific details about CSM-CERES-Wheat model are given in the section 1.3.4 of this thesis	Jones and Kiniry, 1986 Hoogenboom et al., 2010
CROPSYST (Cropping Systems Simulation Model)	Multiyear, multi-crop, daily time step crop growth simulation model	More than 20 different crops as well as grass (e.g., wheat, maize, barley, oat, rye, etc.), and trees	Daily phenological development and crop growth, water and nitrogen balance, salinity, and soil erosion by water	Include a link to GIS software and a weather generator	Stöckle et al., 2003
APSIM (Agricultural Production System sIMulator)	Dynamic mechanistic, daily time step crop growth model	More than 20 different crops as well as grass (e.g., wheat, maize, barley, sorghum, soybean, etc.) and trees	Dynamics of soil/plant-management interactions within a single crop or a cropping system		McCown et al., 1996
SIRIUS	Dynamic mechanistic crop growth model	Wheat	Daily phenological development and crop growth		Jamieson et al., 1998
STICS	Daily time step crop growth model	More than 20 different crops as well as grass (e.g., wheat, maize, barley, sorghum, soybean, etc.) and trees	Daily phenological development and crop growth		INRA, France Brisson et al., 2003
WOFOST	Mechanistic generic crop growth model	Wheat, grain maize, barley, rice, sugar beet, potato, field bean, soybean, Oilseed Rape, and Sunflower	Crop growth as biomass accumulation in combination with phenological development	Time step: one day	Boogard et al., 1998

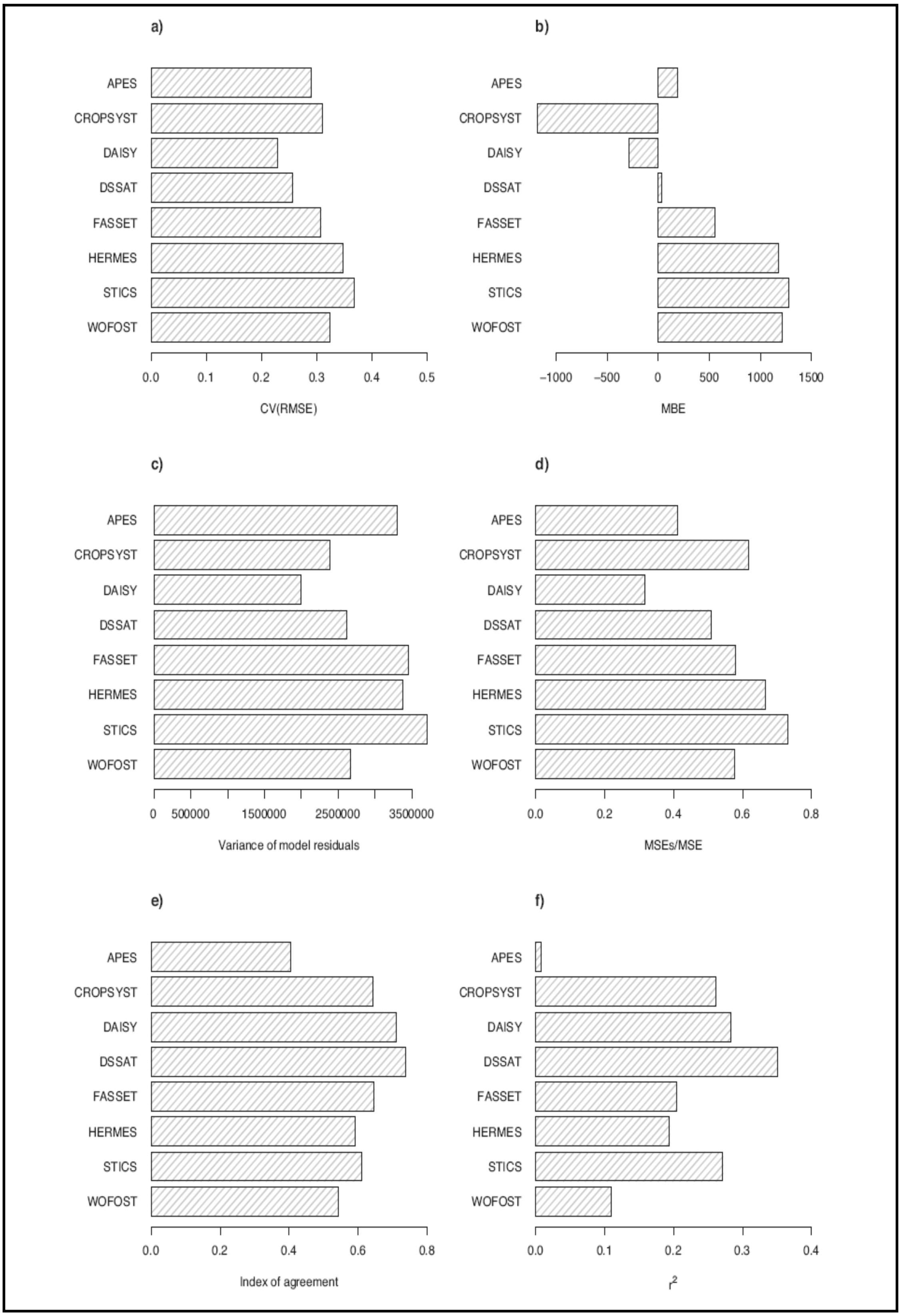


Figure 26. Graphical representation of statistics describing the performance of different crop models for grain yield of winter wheat in Europe (source: Palosuo et al., 2011).

1.3.3 Decision Support System for Agrotechnology Transfer - Cropping System Model (DSSAT-CSM)

The DSSAT-CSM (Decision Support System for Agrotechnology Transfer-Cropping System Model) (Jones et al., 2003; Hoogenboom et al., 2010) is a tool that allows the simulation of the growth and development of a given crop over time on a uniform surface of land under certain conditions of crop management (ordinary or assumed). In addition, this tool allows the simulation of the dynamics of water, carbon and nutrients that occur in soil and the effects of different agronomic practices on crop system. The DSSAT-CSM version 4.5 is process-oriented and dynamic and includes crop models that simulate the growth, development and yield of over 25 crops.

One of the main advantages of DSSAT-CSM is its modular structure (Porter et al., 1999; Jones et al., 2001; Hoogenboom et al., 2010). The modular structure of DSSAT-CSM is represented in Figure 27.

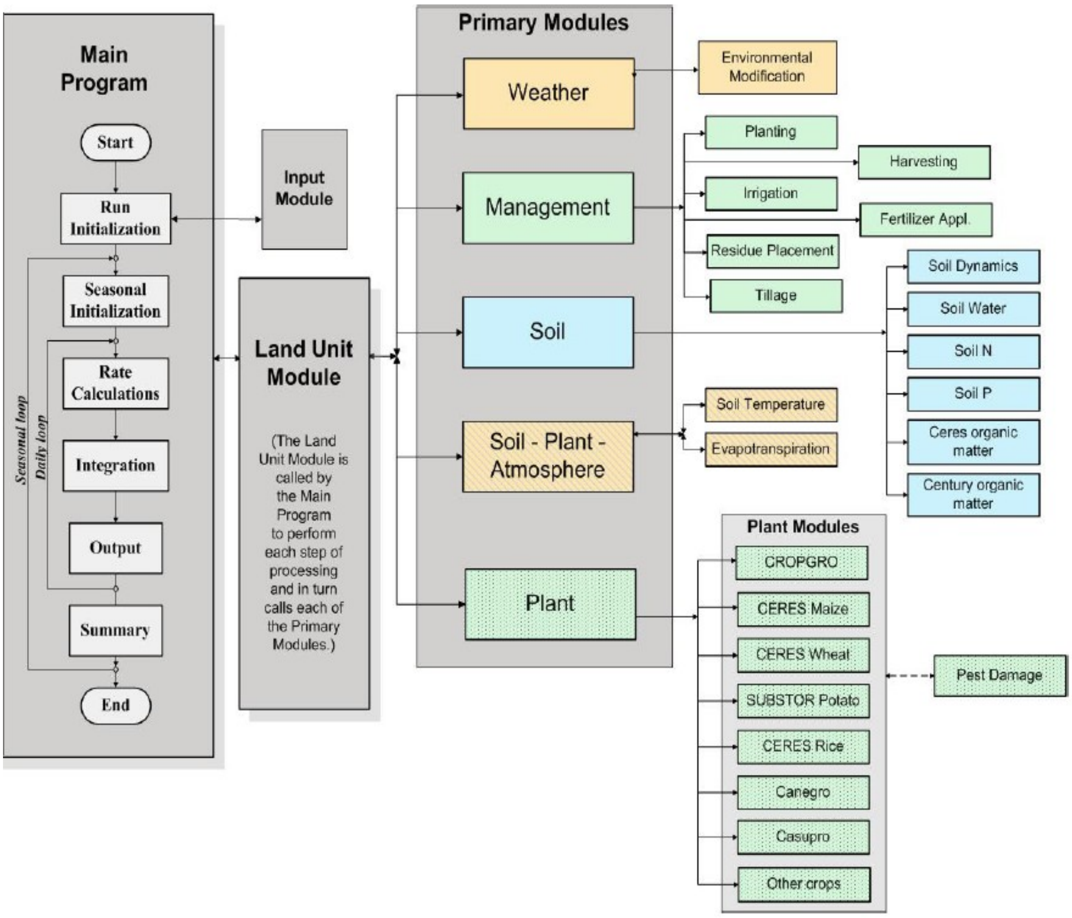


Figure 27. Overview of the components and modular structure of DSSAT-CSM (source: Hoogenboom et al., 2010).

It includes three main components:

- a main driver program, which controls the timing for each simulation;
- a land unit module, which manages all processes related to a land unit;
- the Primary modules (weather, soil, plant, soil-plant-atmosphere, and management), each of which simulates the processes within a land unit.

The main program controls the start and stop of the simulation, the initialization and the end of the crop season, and daily time loops. This allows each module to carry out the reading of inputs, the run Initialization, the rate calculations, the integration of state variables, and write daily outputs independently from the other modules.

Each Primary module is composed of two or more sub modules whose operation is the same as in the Primary modules, but the sub modules usually run only two or more phases of the loop (Table 17). The crop growth models of different crops are sub modules of the Plant module. It is possible to add new crop models by interfacing it with the Plant module. In this way the CSM-CERES-Wheat, CSM-CERES-Maize and other models have been incorporated into DSSAT-CSM.

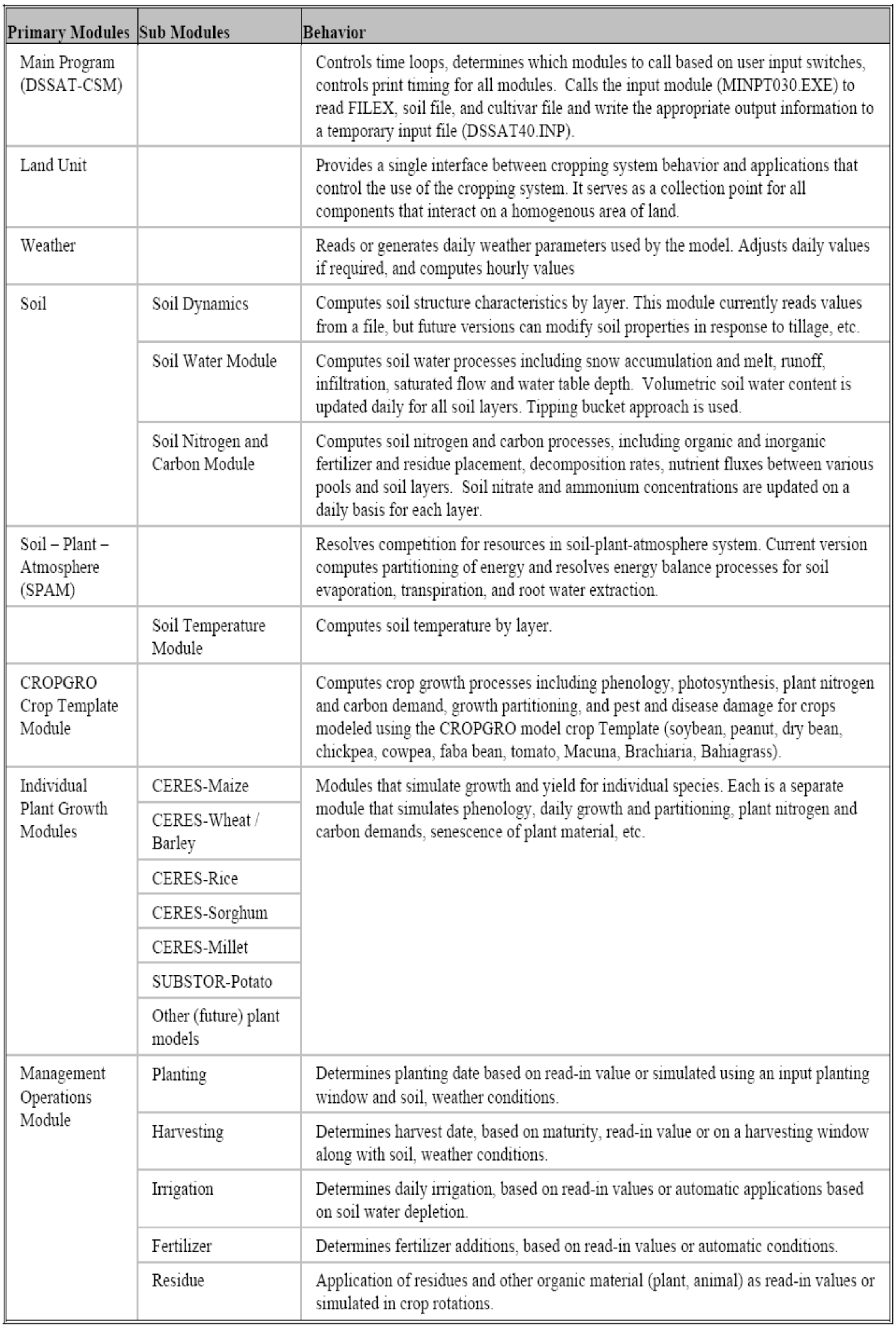
The new DSSAT-CSM version includes additional features (Hoogenboom et al., 2010).

New crop models (e.g., for sweet corn, cassava, and cotton) have been added into DSSAT-CSM.

Several new characteristics have been added to the CERES crop models for maize, millet and sorghum:

1. the creation of species and ecotype files;
2. the incorporation of several major pest damage types (leaf, stem, root and seed weight, leaf area index, seed numbers, and daily carbon assimilation rate and plant population);
3. the incorporation of a soil fertility factor to take into account the influence of soil nutrients (other than nitrogen) on daily plant growth rate;
4. the incorporation of a water-logging factor to consider the reduction of the photosynthesis and leaf expansion in the case of saturation of the soil within 2% for more than two days.

Table 17. Summary description of modules in the DSSAT-CSM (source: Hoogenboom et al., 2010).



Primary Modules	Sub Modules	Behavior
Main Program (DSSAT-CSM)		Controls time loops, determines which modules to call based on user input switches, controls print timing for all modules. Calls the input module (MINPT030.EXE) to read FILEX, soil file, and cultivar file and write the appropriate output information to a temporary input file (DSSAT40.INP).
Land Unit		Provides a single interface between cropping system behavior and applications that control the use of the cropping system. It serves as a collection point for all components that interact on a homogenous area of land.
Weather		Reads or generates daily weather parameters used by the model. Adjusts daily values if required, and computes hourly values
Soil	Soil Dynamics	Computes soil structure characteristics by layer. This module currently reads values from a file, but future versions can modify soil properties in response to tillage, etc.
	Soil Water Module	Computes soil water processes including snow accumulation and melt, runoff, infiltration, saturated flow and water table depth. Volumetric soil water content is updated daily for all soil layers. Tipping bucket approach is used.
	Soil Nitrogen and Carbon Module	Computes soil nitrogen and carbon processes, including organic and inorganic fertilizer and residue placement, decomposition rates, nutrient fluxes between various pools and soil layers. Soil nitrate and ammonium concentrations are updated on a daily basis for each layer.
Soil – Plant – Atmosphere (SPAM)		Resolves competition for resources in soil-plant-atmosphere system. Current version computes partitioning of energy and resolves energy balance processes for soil evaporation, transpiration, and root water extraction.
	Soil Temperature Module	Computes soil temperature by layer.
CROPGRO Crop Template Module		Computes crop growth processes including phenology, photosynthesis, plant nitrogen and carbon demand, growth partitioning, and pest and disease damage for crops modeled using the CROPGRO model crop Template (soybean, peanut, dry bean, chickpea, cowpea, faba bean, tomato, Macuna, Brachiaria, Bahiagrass).
Individual Plant Growth Modules	CERES-Maize	Modules that simulate growth and yield for individual species. Each is a separate module that simulates phenology, daily growth and partitioning, plant nitrogen and carbon demands, senescence of plant material, etc.
	CERES-Wheat / Barley	
	CERES-Rice	
	CERES-Sorghum	
	CERES-Millet	
	SUBSTOR-Potato	
	Other (future) plant models	
Management Operations Module	Planting	Determines planting date based on read-in value or simulated using an input planting window and soil, weather conditions.
	Harvesting	Determines harvest date, based on maturity, read-in value or on a harvesting window along with soil, weather conditions.
	Irrigation	Determines daily irrigation, based on read-in values or automatic applications based on soil water depletion.
	Fertilizer	Determines fertilizer additions, based on read-in values or automatic conditions.
	Residue	Application of residues and other organic material (plant, animal) as read-in values or simulated in crop rotations.

Another feature introduced in DSSAT-CSM regards the simulation of soil organic matter. In fact, the CENTURY-based soil carbon and nitrogen module has been added in a separate soil sub module into DSSAT-CSM (Hoogenboom et al., 2010). There exist three main differences between the CENTURY-based module and the CERES-based soil N module (default method in DSSAT-CSM) (Hoogenboom et al., 2010):

1. the CENTURY-based module subdivides the soil organic matter in three fractions (easily decomposable, recalcitrant, and almost inert), each of which is characterized by a variable C:N ratio and can mineralize or immobilize nutrients;
2. it has a residue layer on top of the soil;
3. the decomposition rate is texture dependent.

In this way, the CENTURY-based soil carbon and nitrogen module makes it possible to improve performance in low input agricultural systems and to simulate the sequestration of soil organic carbon for different crop rotations over long time periods.

1.3.4 CSM-CERES-Wheat and CSM-CERES-Maize models description

The CSM-CERES-Wheat and CSM-CERES-Maize crop simulation models are among the most widely used crop models to simulate processes upon which depend the growth, development and yield of wheat and maize. These models have been implemented in the DSSAT-CSM v.4.5 after the necessary changes for their integration into the modular structure of the DSSAT-CSM. For these two models, the crop cycle includes several stages that are similar for the two crops (Table 18).

Growth rate varies in relation to thermal time or growing degree-days (GDD), which is calculated on the basis of daily values of maximum and minimum temperature:

$$GDD = \frac{(T_{MAX} + T_{MIN})}{2} - T_b$$

where:

T_{MAX} = maximum daily temperature;

T_{MIN} = minimum daily temperature;

T_b = Base temperature (temperature below which crop development stops).

Table 18. Growth stages simulated by the CSM-CERES-Wheat and CSM-CERES-Maize crop models included in DSSAT-CSM, v.4.5.0.0 (source: Hoogenboom et al., 2010).

Wheat	Maize
Germination	Germination
Emergence	Emergence
	End of Juvenile
Terminal Spikelet	Floral Induction
End ear growth	
	75% Silking
Beginning grain fill	Beginning grain fill
Maturity	Maturity
Harvest	Harvest

The relationship between the average temperature and the number of GDD for the vegetative development varies with the species under consideration (Figure 28). The number of GDD required to change from a growing stage to another varies with the growing stage and allows estimating when a given growth stage is going to occur at a particular site (Acevedo et al., 2002). The GDD are defined as a user input through the genetic coefficients of the cultivar under consideration (Table 19), or are calculated internally based on the inputs and assumptions about the duration of the intermediate stages set by the user (Hoogenboom et al., 2010).

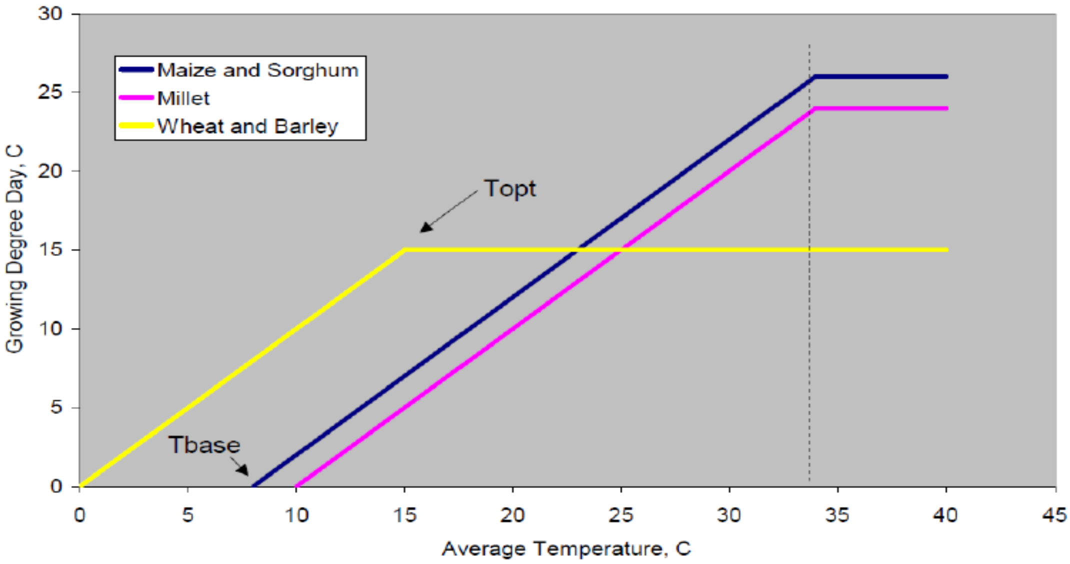


Figure 28. Growing Degree Days for Vegetative Development (source: Jones et al., 2007).

Table 19. Cultivar coefficients for the CSM-CERES-Wheat and CSM-CERES-Maize crop models (source: Hoogenboom et al., 2010).

Wheat	
P1D	Photoperiod sensitivity coefficient (% reduction/h near threshold)
P1V	Vernalization sensitivity coefficient (%/d of unfulfilled vernalization)
P5	Thermal time from the onset of linear fill to maturity (°C d)
G1	Kernel number per unit stem + spike weight at anthesis (#/g)
G2	Potential kernel growth rate (mg/(kernel d))
G3	Tiller death coefficient. Standard stem + spike weight when elongation ceases (g)
PHINT	Thermal time between the appareance of leaf tips (°C d)
Maize	
P1	Degree days (base 8°C) from emergence to end of juvenile phase
P2	Photoperiod sensitivity coefficient (0-1.0)
P5	Degree days (base 8°C) from silking to physiological maturity
G2	Potential kernel number
G3	Potential kernel growth rate (mg/(kernel d))
PHINT	Degree days required for a leaf tip to emerge (phyllochron interval) (°C d)

The number of GDD occuring on a calendar day is a function of a triangular or trapezoidal function defined by a base temperature, one or two optimum temperatures, and a maximum temperature above which development rate is reduced to zero.

Daylenght may affect the total number of leaves formed by altering the duration of the floral induction phase, and thus, floral initiation.

Daylenght sensitivity is an user input which varies with the cultivar under consideration. Currently the accumulation of GDD is determined only by temperature and, in some cases, by daylenght, while drought and nutrient stresses do not have any effect. During the vegetative development, emergence of new leaves is used to limit leaf area development until after a species-dependent number of leaves have appeared. Thereafter, vegetative branching can occur, and leaf area development depends on the availability of assimilates and specific leaf area. The daily GDD, and water and nitrogen stress modify the leaf area expansion.

Daily plant growth is computed by converting daily intercepted photosynthetically active radiation (PAR) into plant dry matter using a crop-specific radiation use efficiency parameter. Light interception is computed as a function of leaf area index (LAI), plant population, and row spacing.

In the CSM-CERES-Wheat and CSM-CERES-Maize crop models, the potential growth rate (PCARB, in g plant^{-1}) is directly proportional to the photosynthetically Active Radiation (PAR, in Mj m^{-1} d^{-1}), to the Radiation Use Efficiency (RUE, in g Dry Matter PAR^{-1}), to the Leaf Area Index (LAI) and to the CO_2 modification factor, while it is inversely proportional to Plant population (PLTOP, in plant m^{-2}) (Ritchie and Otter, 1985; Jones and Kiniry, 1986; Ritchie et al., 1998):

$$PCARB = \frac{RUE \cdot PAR}{PLTOP} \cdot \left(1 - e^{(-k \cdot LAI)}\right) \cdot CO_2$$

where: k = Light extinction factor (-0.85 for wheat, 0.65 for maize).

The amount of new dry matter available for daily growth may also be modified by the most limiting of water or nitrogen stress, and temperature, and vary with the atmospheric CO_2 concentration. The effect of the variation of CO_2 atmospheric concentration on photosynthesis is quantified by the CO_2 modification factor (Jones et al., 2007). The efficiency of photosynthesis increases with the increase of atmospheric CO_2 concentration, but to a variable extent with the species. In particular, with the increase of atmospheric CO_2 concentration, the model considers the greater photosynthetic efficiency of wheat (C3 plant) compared to maize (C4 plant) (Table 20).

Table 20. CO_2 modification factor for wheat and maize (source: Jones et al., 2007).

CO_2 (ppm)	**CO_2 modification factor**	
	Wheat	**Maize**
0	0	0
220	0.71	0.81
330	1	1
440	1.08	1.03
550	1.17	1.06
660	1.25	1.1
770	1.32	1.13
880	1.38	1.16
990	1.43	1.18

Above ground biomass has priority for carbohydrate, and at the end of each day, carbohydrate not used is allocated to roots. However, roots must receive a minimum fraction of the daily carbohydrate available for growth, and this fraction depends on the development stage. Leaf area is converted into new leaf weight using empirical functions.

Kernel numbers per plant are computed during flowering based on the cultivar's genetic potential, canopy weight, average rate of carbohydrate accumulation during flowering, and water, temperature and nitrogen stresses. Potential kernel number is a user-defined input for specific varieties. When the beginning of grain fill is reached, the model computes daily grain growth rate based on the potential kernel growth rate (mg / (kernel d)).

Temperature and assimilate availability modify the daily growth rate. The daily remobilization of a fraction of carbon from the vegetative to reproductive sinks is possible when the daily carbon pool is less than that required for growth. The growth of kernels occurs until the physiological maturity is reached, but stops if the plant resources are finished before this stage. Similarly, growth is terminated if the grain growth rate is reduced below a threshold value for several days (Ritchie and Otter, 1985; Jones and Kiniry, 1986; Ritchie et al., 1998).

The CSM-CERES-Wheat and CSM-CERES-Maize crop models included in DSSAT-CSM simulate all processes related to the growth and development of plants from seed to maturity at a daily time step. The input data required by the two crop models for the simulation of these processes include daily weather data, soil data (physicochemical properties of each layer), the characteristics of the cultivar (ecotype and cultivar coefficients) and crop management data (Hunt et al., 2001). The minimum inputs required to run the crop models simulation and outputs are as follows:

1. site weather data for the duration of the growing season;
2. site soil profile and soil surface data;
3. crop management data from the experiment.

However, for crop model calibration and evaluation it is necessary to have also the observed experimental data from the experiment (e.g. antheis date, maturity date, grain yield, etc). Table 21 shows the main inputs required by the CSM-CERES-Wheat and CSM-CERES-Maize crop models. The latitude is necessary for the calculation of day length.

Table 21. Minimum inputs required by the CSM-CERES-Wheat and CSM-CERES-Maize crop simulation models.

Input data	**Specific input**
Weather	Maximum temperature
	Minimum temperature
	Rainfall
	Solar radiation
Soil	Drainage coefficient
	Runoff coefficient
	First-stage evaporation
	Soil albedo
	Nitrogen and phosphorus contents for each layer
	Water-holding characteristics for each layer
	Rooting preference coefficients
	Saturated soil water content and initial soil water content for the first dayof simulation
Cultivar characteristics	Ecotype
	Genetic coefficients
Crop management data	Planting inputs (planting date, planting population, planting depth, row spacing)
	Fertilizer inputs (date and fertilization rate for each application)
	Date and amount of irrigation (only for irrigated crops)

The CSM-CERES-Wheat and CSM-CERES-Maize models can be used to simulate the processes of growth and development under different weather, soil and crop management techniques. The simulations can be performed for a single growing season or for different growing seasons. In the latter case, the two models can run simulations independently for each growing season (experiment mode) or considering the sequence of growing seasons (sequence mode). The sequence analysis tool included in DSSAT-CSM v.4.5 is useful to simulate crop rotations (Bowen et al., 1998). In addition, these models allow the estimation of the effects of abiotic and biotic stress factors (pests and plant diseases) on the processes of growth and/or development and, consequently, on the phenology and yield of crops.

The CSM-CERES-Wheat and CSM-CERES-Maize crop growth models allow to simulate different processes and parameters, the main of which are shown in Table 22.

In this work the simulations of anthesis and/or maturity date and grain yield were performed for each crop.

Table 22. Main processes and parameters that can be simulated using the CSM-CERES-Wheat and CSM-CERES-Maize crop models.

Process category	**Specific variable or process simulate by models**
Crop and soil status at main development stages	Date of each growth stage (day of year and days after planting (dap))
	Biomass (kg ha^{-1})
	Leaf area index (LAI) (m^{2} m^{-2})
	Leaf number produced on main axis
	Crop N (in kg/ha and %)
	Nitrogen and water stresses
	Evapotranspiration (mm)
	Rainfall (mm)
	Irrigation (mm)
	Soil water (mm)
Main growth and development variables	Anthesis date (dap)
	Physiological maturity (dap)
	Grain yield (dry weight) (kg ha^{-1})
	Grain number (grain m^{-2})
	Weight per grain (dry weight) (g)
	Grains per ear
	Maximum LAI (m^{2} m^{-2})
	Final leaf number
	Biomass at anthesis (kg ha^{-1})
	Biomass N at anthesis (kg N ha^{-1})
	Biomass at harvest (kg ha^{-1})
	Biomass N (kg N ha^{-1})
	Harvest index (kg kg^{-1})
Environmental and stress factors at different development stages	Maximum and minimum temperature (°C)
	Solar radiation (MJ m^{-2})
	Photoperiod (hours)
	Water stresses
	Nitrogen and phosphorus stresses
Other processes	Water balance
	Nitrogen balance
	Phosphorus balance
	Soil organic matter

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2. OBJECTIVES

The agricultural sector is very vulnerable to climate change and related impacts on growth and crops productivity. It is important to assess and quantify the individual and combined effects of the increase of carbon dioxide concentration, temperature rise and variation of rainfall, taking into consideration that agriculture too contributes in a significant way to atmospheric greenhouse emissions.

Given the socio-economic importance of the agricultural sector in guaranteeing food security in the coming decades, it becomes essential to evaluate the effectiveness of possible adaptation and mitigation strategies that may be undertaken in dealing with climate change. Thus, an accurate parameterization and evaluation of crops simulation models is necessary for the use of such models in subsequent applications (e.g. studies on climate change impacts on crop growth and productivity and evaluation of possible adaptation strategies to climate change).

The general objective of this research has been to evaluate the impacts of climate change on phenology and on the yield of the most important cereals (durum wheat, common wheat, and maize) at the Italian scale and to provide indications on the effectiveness of some possible adaptation strategies to climate change.

Through this approach it will be possible to provide an estimate of potential changes on the phenological development and productivity of the crops under consideration.

Specific objectives of this work are:

1. the parameterization of CSM-CERES-Wheat and CSM-CERES-Maize crop simulation models at the national level, in order to obtain a robust set of genetic coefficients for the most widespread cultivars of durum wheat, common wheat, and maize in Italy;
2. the assessment of climate change impacts on phenology (anthesis or maturity date) and grain yield for different cultivation areas of durum wheat, common wheat, and maize at the Italian national scale;
3. the evaluation of the effectiveness of some possible adaptation strategies aimed at reducing the negative impacts of climate change on phenology (anteshis or maturity date) and grain yield of the crops under consideration at the national scale. This will make it possible to provide useful information for farmers (autonomous adaptation), for policy makers and stakeholders (planned adaptation).

The objectives of this research are schematised in Figure 1.

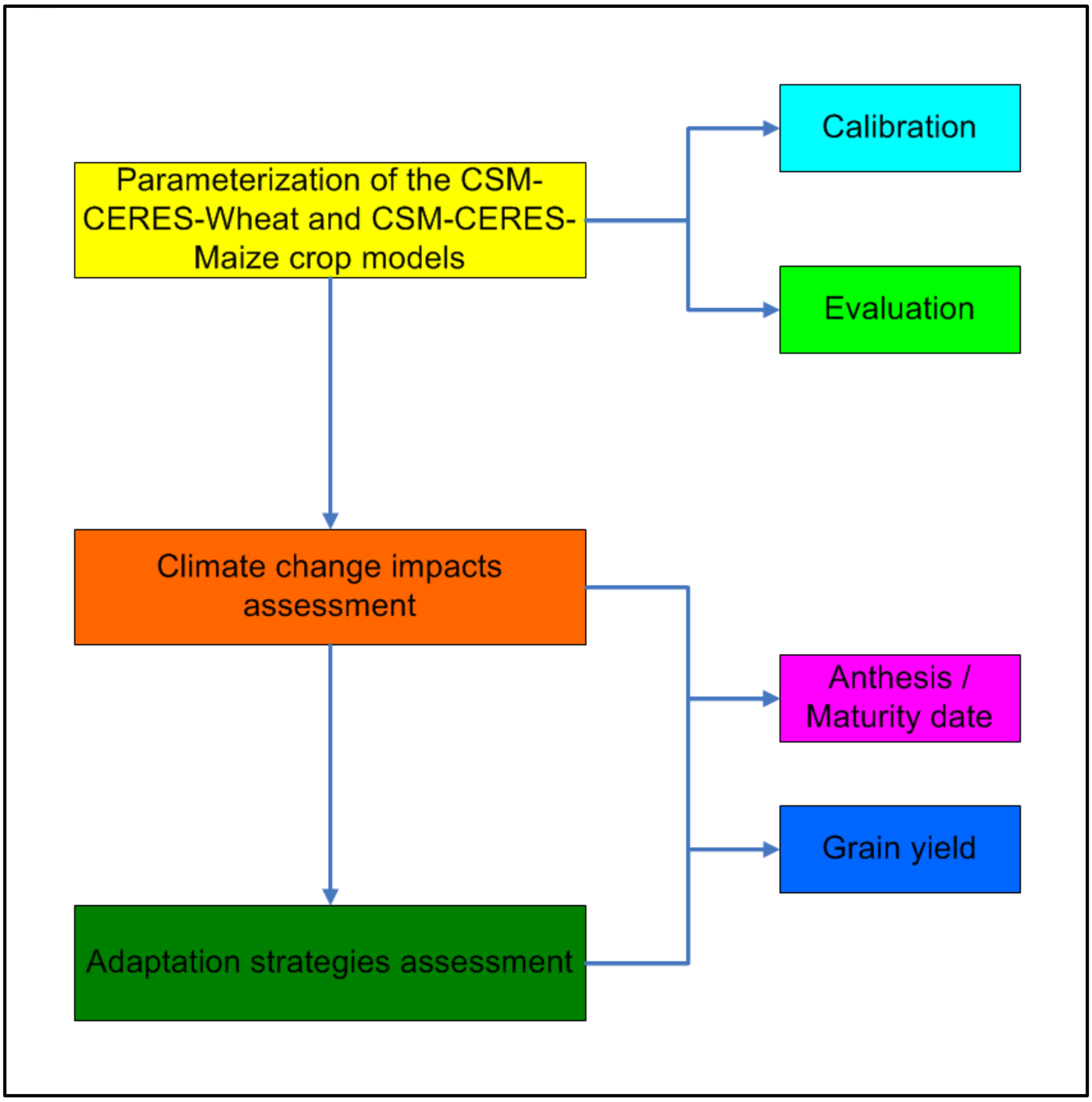


Figure 1. Specific objectives of the thesis.

3. PERFORMANCES OF CSM-CERES-WHEAT AND CSM-CERES-MAIZE MODELS TO PREDICT PHENOLOGY AND YIELD OF *TRITICUM DURUM* DESF., *TRITICUM AESTIVUM* L. AND *ZEA MAYS* L. AT ITALIAN SCALE

3.1 INTRODUCTION

Crop simulation models are dynamic models that make it possible to estimate the phenology and yield of a given crop depending on the climate and pedological characteristics and crop management techniques (Hoogenboom, 2000; Wallach, 2006). These tools are often used for several applications, such as the study of climate change impacts on phenology and yield and the assessment of potential adaptation strategies and mitigation, also on a regional scale (Resop et al., 2012). Therefore, an accurate parameterization of the crop models is necessary in order to achieve better results in further applications (e.g., the assessment of climate change impacts and adaptation strategies), especially at the regional and continental scales.

Recent studies have shown the disadvantages derived from use of these crop models at regional scale. First, in general the crop model calibration and evaluation are made at field scale considering a variable number of experimental sites (sometimes two only). In addition, the selected sites for model parameterization are often located in very different areas for climate, soil and crop management (e.g., fertilization, irrigation, etc.). A consequence of this is the high variability of the observed phenological and yield data in the different cultivation areas. Therefore, the application of these models at the regional scale involves errors in the prediction of yields (Ewert et al., 2011). Finally, in most cases the input data required by the crop model are available only at the field level (Faivre et al., 2004; Ewert et al., 2011).

Further aspects that influence the reliability of the parameterization are the quantity and quality of input data of the model. The availability of long-term phenological and yield observed data makes it possible to calibrate and evaluate the model with a greater number of crop years. In this way, good results were often obtained, in particular for phenological simulations (Timisina and Humphreys, 2006; Dettori et al., 2011).

A high quality of weather, soil and crop management measured input data is recommended for an optimal parameterization, but in general they are available at different levels of detail. In fact, the soil and climate data can be collected from several data sets also at regional level, but the crop management data are usually available at the field scale (Faivre et al., 2004; Maton et al., 2007; Mignolet et al., 2007; Godard et al., 2008; Leenhardt et al., 2010). The utilization of the low-data approaches to generate crop management data required for calibration and evaluation of the crop models on a regional scale has been demonstrated recently (Therond et al., 2011).

When the data are not available at the same level of detail, it is common to use interpolated data over grid with a variable cell-resolution or, for climate, data of the weather stations located at a certain distance from the experimental sites under consideration (Mereu et al., 2012). In this way a lower accuracy of the parameterization was obtained, with negative consequences for subsequent applications of the crop models (Angulo et al., 2013).

Finally, another possible source of error is the fact that the observed data on phenology and yield were often collected for an another purpose than the parameterization of the crop models (Žalud and Dubrovský, 2002; Mereu, 2010; Dettori et al., 2011).

In order to have an accurate crop model parameterization to be used in further applications at the regional or continental scale, an appropriate practice is to use observed data from experimental sites homogeneously distributed in the study area.

It is also important to study the behavior of a model in order to optimize the most important input parameters through the sensitivity analysis (Tarantola and Santelli, 2003). Sensitivity analysis is defined as "the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" (Saltelli et al., 2004). This tool allows to quantify the sensitivity of the model input parameters and identify the parameters that mostly influence the model outputs. Consequently, sensitivity analysis is very useful to understand and improve a model for future applications and it is used in different types of models, including crop simulation models (Lamboni et al., 2009).

There are two types of sensitivity analysis: local and global (Saltelli et al., 2008). Local sensitivity analysis allows us to study the effect of changes in model input parameters one at a time held keeping the other input parameter values constant. Conversely, global sensitivity analysis makes it possible to evaluate the sensitivity of the model to simultaneous changes of more model input parameters. Thus, the global sensitivity analysis requires a greater number of model simulations compared to the local sensitivity analysis (Varella et al., 2010).

Sensitivity analysis can be carried out through three approaches (Frey and Patil, 2002): 1) graphical; 2) mathematical; 3) statistical. The first approach is useful to view the sensitivity of the model input parameters through graphs. The graphical methods provide useful information for further evaluation and can integrate the results of the other methods. The mathematical methods enable to quantify the change in the model output by varying the inputs within their range of variation. This approach is useful to identify the most sensitive parameters in order to concentrate the efforts of the model calibration on such parameters. Finally, the statistical approach is based on the assumption that each input parameter has an associated probability distribution, and makes it possible to evaluate how the input variance affects the output distribution.

Crop simulation models (e.g. CSM-CERES-Wheat and CSM-CERES-Maize) are used to simulate the most important processes in the soil-plant-atmosphere continuum. These processes are affected by several parameters related to the soil, climate and crop management. Performances of the crop models are strongly influenced by the value of these parameters (Varella et al., 2010). Therefore, global sensitivity analysis is the most appropriate method because it allows a greater accuracy in the estimation of model input parameters considering their interactions. However, for crop model calibration, local sensitivity analysis is very useful to identify the more sensitive input parameters (Lamsal et al., 2012).

Although some studies on these crops have been conducted in Italy, they have nevertheless been carried out at the local scale, considering few experimental sites and/or a limited number of crop years (Pecetti and Hollington, 1997; Mereu, 2010; Ferrise et al., 2011; De Sanctis et al., 2012). Currently crop models parameterized at the local scale in Italy, have been used with good results for further studies conducted at the same scale, while their use for applications at different scales (e.g., parameterization at the local scale and climate change impacts assessment at the spatial scale) has not yet been observed. In such a context, this work contributes to the aim of ascertaining the reliability of crop simulation models for evaluations at the national scale.

The CSM-CERES-Wheat and CSM-CERES-Maize crop models implemented in the software package DSSAT-CSM ((Jones et al., 2003; Hoogenboom et al., 2010) are commonly used. Recent research shows that they have been used in many studies at different spatial scales, namely from the field scale to the continental scale (Tables 1-3).

Therefore, these crop models represent a useful tool for the simulation of processes that regulate the phenological development and productivity, particularly for durum wheat, common wheat and maize, which are the main Italian cereals.

Table 1. Some of the more recent studies based on CERES-Wheat and CSM-CERES-Wheat crop models for durum wheat.

Author	Object	Crop model	Location	Level of analysis	Variables
De Sanctis et al., 2012	Long-term no tillage increased soil organic carbon content of rain-fed cereal systems in a Mediterranean area.	CSM-CERES-Wheat	Italy (Marche)	Local	Yield and biomass
Dettori et al., 2011	Using CERES-Wheat to simulate durum wheat production and phenology in Southern Sardinia, Italy.	CERES-Wheat	Italy (Sardinia)	Local	Phenology and yield
Al-Bakri et al., 2010	Potential impact of climate change on rainfed agriculture of a semi-arid basin in Jordan.	CERES-Wheat	Jordan	Regional	Yield
Mereu, 2010	Climate Change Impact on Durum Wheat in Sardinia.	CERES-Wheat	Italy (Sardinia)	Local	Phenology and yield
Brassard et al., 2008	Assessment of the potential impacts of greenhouse gas climate change and changing ambient carbon dioxide (CO2) levels on wheat crop.	CERES-Wheat	Canada (Quebec)	Regional	Yield
Rezzoug et al., 2008	Application and evaluation of the DSSAT-wheat in the Tiaret region of Algeria.	CERES-Wheat	Algeria	Local	Phenology and yield
Iglesias, 2006	Use of DSSAT models for climate change impact assessment: Calibration and validation of CERES-Wheat and CERES-Maize in Spain.	CERES-Wheat	Spain	Local	Phenology and yield
Rinaldi, 2004	Water availability at sowing and nitrogen management of durum wheat: a seasonal analysis with the CERES-Wheat model.	CERES-Wheat	Italy (Apulia)	Local	Phenology and yield
Iglesias et al., 2000	Agricultural impacts of climate change in Spain: developing tools for a spatial analysis.	CERES-Wheat	Spain	National	Phenology and yield
Mavromatis and Jones, 1999	Evaluation of HadCM2 and Direct Use of Daily GCM Data in Impact Assessment Studies.	CERES-Wheat	France (central region of the country)	Regional	Phenology and yield
Pecetti and Hollington, 1997	Application of the CERES-Wheat simulation model to durum wheat in two diverse Mediterranean environments.	CERES-Wheat	Italy (Sicily) and Syria	Local	Phenology and yield

Table 2. Some of the more recent studies based on CERES-Wheat and CSM-CERES-Wheat crop models for common wheat.

Author	Object	Crop model	Location	Level of analysis	Variables
Bannayan and Rezaei, 2012	Future production of rainfed wheat in Iran (Khorasan province): climate change scenario analysis.	CSM-CERES-Wheat	Iran (Khorasan province)	Regional	Yield and biomass
Thaler et al., 2012	Impacts of climate change and alternative adaptation options on winter wheat yield and water productivity in a dry climate in Central Europe.	CERES-Wheat	Austria (Marchfeld region)	Local	Phenology and yield
Guo et al., 2010	Responses of crop yield and water use efficiency to climate change in the North China Plain.	CERES-Wheat	China (North China Plan)	Regional	Phenology and yield
Abeledo et al., 2008	Wheat productivity in the Mediterranean Ebro Valley: Analyzing the gap between attainable and potential yield with a simulation model.	CERES-Wheat	Spain	Local	Phenology, yield, and biomass
Langensiepen et al., 2008	Validating CERES-wheat under North-German environmental conditions.	CERES-Wheat	German	Local	Yield
Rezzoug et al., 2008	Application and evaluation of the DSSAT-wheat in the Tiaret region of Algeria.	CERES-Wheat	Algeria	Local	Phenology and yield
Singh et al., 2008	Evaluation of CERES-Wheat and CropSyst models for water-nitrogen interactions in wheat crop.	CERES-Wheat	India	Local	Yield and biomass
Bannayan et al., 2003	Application of the CERES-Wheat Model for Within-Season Prediction of Winter Wheat Yield in the United Kingdom.	CERES-Wheat	United Kingdom	Local	Phenology and yield
Weiss et al., 2003	Assessing winter wheat responses to climate change scenarios: a simulation study in the US Great Plains.	CERES-Wheat	U. S. A. (Nebraska)	Local	Phenology and yield
Ghaffari et al., 2001	Simulating winter wheat yields under temperate conditions: exploring different management scenarios.	CERES-Wheat	United Kingdom	Regional	Yield

Table 3. Some of the more recent studies based on CERES-Maize and CSM-CERES-Maize crop models for maize.

Author	**Object**	**Crop model**	**Location**	**Level of analysis**	**Variables**
De Sanctis et al., 2012	Long-term no tillage increased soil organic carbon content of rain-fed cereal systems in a Mediterranean area.	CSM-CERES-Maize	Italy (Marche)	Local	Yield and biomass
Mereu et al., 2012	Impact of climate change and adaptation strategies on crop production in Nigeria.	CERES-Maize	Nigeria	National	Yield
Salmerón et al., 2012	Effect of non-uniform sprinkler irrigation and plant density on simulated maize yield.	CERES-Maize	Spain	Local	Yield
Vučetić, 2011	Modelling of maize production in Croatia: present and future climate.	CSM-CERES-Maize	Croatia	Local	Phenology and yield
Guo et al., 2010	Responses of crop yield and water use efficiency to climate change in the North China Plain.	CERES-Maize	China (North China Plan)	Regional	Phenology and yield
Bannayan and Hoogenboom, 2009	Using pattern recognition for estimating cultivar coefficient of a crop simulation model.	CSM-CERES-Maize	U. S. A., Spain, Pakistan and Brazil	Local	Phenology, yield, and biomass
Braga et al., 2008	Crop model based decision support for maize (*Zea mays* L.) silage production in Portugal.	CERES-Maize	Portugal	Local	Phenology and biomass
Meza et al., 2008	Climate change impacts on irrigated maize in Mediterranean climates: Evaluation of double cropping as an emerging adaptation alternative.	CERES-Maize	Chile	Local	Yield
Quiring and Legates, 2008	Application of CERES-Maize for within-season prediction of rainfed corn yields in Delaware, USA.	CERES-Maize	U. S. A. (Delaware)	Regional	Yield
Soler et al., 2007	Application of the CSM-CERES-Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment.	CSM-CERES-Maize	Brazil	Local	Phenology and yield
Iglesias, 2006	Use of DSSAT models for climate change impact assessment: Calibration and validation of CERES-Wheat and CERES-Maize in Spain.	CERES-Maize	Spain	Local	Phenology and yield
López-Cedrón et al., 2005	Testing CERES-Maize versions to estimate maize production in a cool environment.	CERES-Maize	Spain (Galicia)	Local	Phenology, yield, and biomass
Kapetanaki and Rosenzweig, 1997	Impact of Climate Change on Maize Yield in Central and Northern Greece: A simulation study with CERES-Maize.	CERES-Maize	Greece	Local	Yield

3.2 OBJECTIVES

The main objective of this part of the work is the parameterization of the CSM-CERES-Wheat (for durum wheat and common wheat) and CSM-CERES-Maize (for maize) crop models on phenology and yield of the selected cultivars, considering data sets of experimental sites located in various areas of Italy with different conditions of climate, soil and crop management.

The specific objectives of the crop model parameterization for each crop are two:

1. the calibration of the crop model under the environmental conditions of different Italian experimental sites, in order to obtain the best combination of the genetic coefficients for the most used cultivars in Italy;
2. the evaluation of the crop model to test its ability to predict the observed data, considering others experimental sites than those used for model calibration;
3. the sensitivity analysis in order to quantify the outputs response of the CSM-CERES-Wheat and CSM-CERES-Maize crop models to changes in the model input parameters.

Through this approach it is possible to establish if the crop model is adequate or not for subsequent applications (e.g., assessment of the climate change impacts and the adaptation strategies to climate change at the Italian scale).

3.3 MATERIALS AND METHODS

In this work the CSM-CERES-Wheat e CSM-CERES-Maize crop simulation models were calibrated and evaluated at the Ialian scale. The parameterization of these crop models was performed considering the phenology (anthesis date for durum and common wheat and maturity date for maize) and grain yield using DSSAT-CSM v.4.5.0.0 (Hoogenboom et al., 2012).

The methodology proposed in this study is the same for each crop. The methodological scheme includes five steps (see also Figure 1):

I. selection of the cultivar;
II. collection of observed data for each experimental site located in Italy;
III. selection of the experimental sites to parameterize the crop models;
IV. loading data into DSSAT-CSM;
V. calibration and evaluation of the CSM-CERES-Wheat and CSM-CERES-Maize crop models at the national scale.

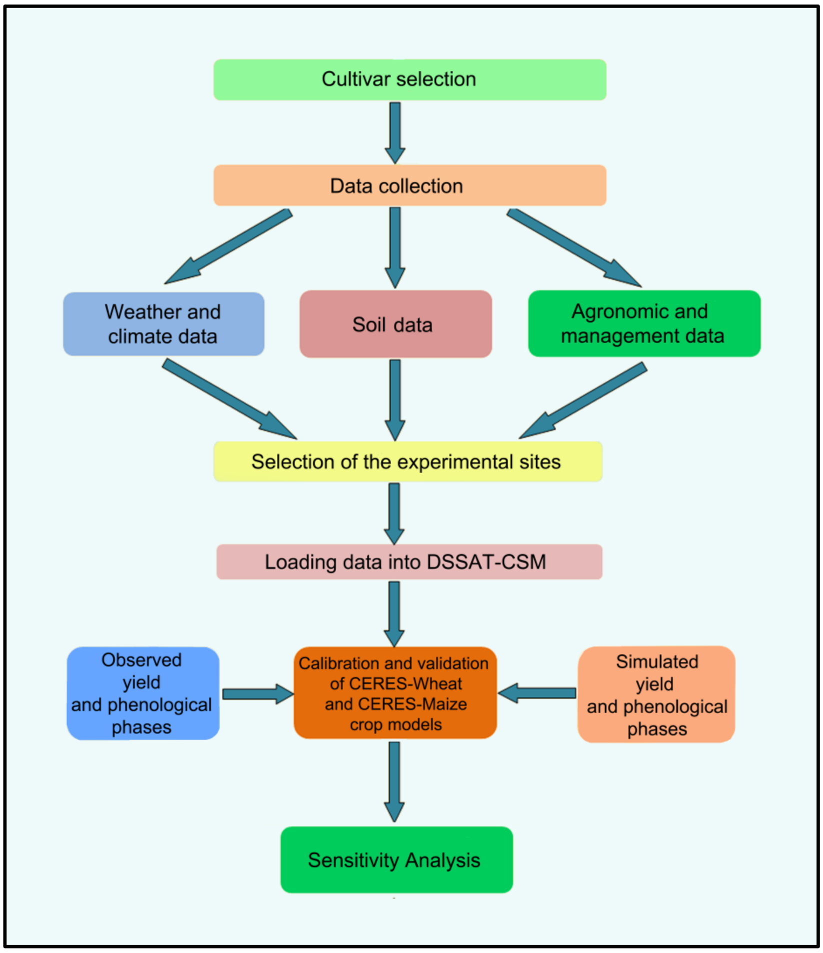


Figure 1. Methodological scheme for the calibration and evaluation of the CSM-CERES-Wheat and CSM-CERES-Maize crop models.

3.3.1 Cultivar selection

For this study one variety for each crop has been selected. For this purpose, the official data on annual production of certified seed in the 2006-2011 period were considered (INRAN-ENSE). The selected cultivars are Iride for durum wheat, Bologna for common wheat and Eleonora for maize. Following is a description of the reasons for their choice and their main characteristics.

Durum wheat

Iride has been selected because it is the second variety of durum wheat in Italy for the average production of certified seed in the period 2006-2011 and currently (2012) it is the first variety with over 25 thousand tons of certified seed (Table 4).

Iride has been released in 1996. For many years it was the best variety of durum wheat for grain yield in all cultivation areas in Italy. Iride is a variety of spring durum wheat characterized by a high production potential, due to the exceptional fertility of the ear, by its high adaptability to different areas of cultivation and its good resistance to cold, to lodging and to the main diseases. The precocious development and good tillering capacity make seeding possible from the third week of October in the northern area to the second half of December in the southern and insular areas.

Table 4. Production of certified seed in the period 2006-2011 for main cultivars of durum wheat in Italy (data provided by INRAN-ENSE).

Cultivar	**Certified seed (tons)**						**Average production (2006-2011) (tons)**
	2006	**2007**	**2008**	**2009**	**2010**	**2011**	
SIMETO	55,601.83	58,846.44	47,631.73	36,395.57	14,193.40	11,961.35	37,438.39
IRIDE	26,312.87	37,145.44	38,274.25	30,188.84	18,690.23	21,351.78	28,660.57
DUILIO	21,771.44	22,501.18	20,919.21	12,819.32	4,999.93	5,027.04	14,673.02
CLAUDIO	12,325.47	15,420.90	14,673.56	14,411.14	10,474.06	12,073.71	13,229.81
LEVANTE	7,363.61	13,904.39	13,877.16	12,356.13	8,429.59	8,196.89	10,687.96
SARAGOLLA	662.83	5,903.54	11,007.64	13,361.38	12,759.34	17,312.48	10,167.87
CICCIO	16,061.55	15,918.58	12,591.30	7,888.87	2,894.20	2,107.90	9,577.07

Common wheat

Bologna is the first cultivar of common wheat in Italy for the average production of certified seed in the period 2006-2011 and currently (2012) it is the first variety with over 17 thousand tons of certified seed (Table 5).

Released in 1999, Bologna is a variety of winter common wheat which is characterized by a high production stability and a considerable adaptability to all environments, mainly to the most fertile areas. The flours are of excellent quality. Bologna has a medium-late development cycle, with average resistance to cold and lodging, and it is resistant to main diseases.

These characteristics have enabled the rapid spread of this cultivar which has become one of the reference varieties in recent years. Bologna is actually the best variety of common wheat in Italy.

Table 5. Production of certified seed in the period 2006-2012 for main cultivars of common wheat in Italy (data provided by INRAN-ENSE).

Cultivar	**Certified seed (tons)**						**Average production (2006-2011) (tons)**
	2006	**2007**	**2008-**	**2009**	**2010**	**2011**	
BOLOGNA	9,142.79	10,931.80	13,134.22	14,135.78	19,222.83	21,188.13	15,064.38
AUBUSSON	11,028.80	13,157.21	18,388.05	15,521.68	12,047.84	10,220.77	12,633.63
PR22R58	3,993.10	6,059.78	6,369.58	6,429.49	7,525.58	8,128.60	6,949.24
MIETI	11,506.29	7,265.32	7,633.96	4,979.84	3,097.80	1,883.74	5,426.54
BLASCO	5,671.98	6,010.26	5,887.77	4,486.57	4,912.52	4,953.82	5,165.74

Maize

Eleonora is a hybrid of maize (FAO class 700) with an average production of certified seed in the 2006-2011 period among the highest. The quantity of certified seed has declined in recent years (about 726 tons in 2012) (INRAN-ENSE). Nevertheless, this variety has been chosen because it is the hybrid for which the greatest number of experimental observations in Italy is available. Besides it is a dual use hybrid (grain and silage).

Eleonora has been released in 1995. It has a high and stable productivity, especially in the most fertile cultivation areas. The high yield in fine and the high ear/plant ratio make it very suitable for silage production.

This variety reaches maturity in about 132 days. It has also a significant vegetative growth, a well developed root system and a high resistance to the main diseases (*Ostrinia nubilalis* and viruses).

3.3.2 Data collection

Available soil, climatic, agronomic and management data were collected at national level. The data used in this work and their sources are described below.

Soil data

For the experimental sites located in Sardinia, profile data measured in the test fields by the Agricultural Research Agency of Sardinia (AGRIS Sardegna) have been used. For all other experimental sites, the soil data in the field were not available. Therefore the data set ISRIC-WISE v.1.2 was used (Batjes, 2012). This is a database having a spatial resolution of 5x5 arcminutes, whit data derived from the Digital Soil Map of the World (DSMW). The latter was obtained from the WISE 3.1 database containing the data of 10,250 soil profiles worldwide (Batjes, 2008). The ISRIC-WISE database information used in this study is shown in Table 6.

The slope was obtained from the national slope map which was obtained from the ASTER Global Digital Elevation Model V2 (ASTER, 2011) having a cell-resolution

Table 6. Properties of soil derived from the database ISRIC-WISE v.1.2 and corresponding code.

Characteristic	Corresponding code in ISRIC-WISE v.1.2
Drainage	DRAIN
Clay (%)	CLPC
Silt (%)	STPC
Organic carbon (%)	TOTC
pH in water	PHAQ
Cation exchange capacity (cmol/kg)	ECEC
Total nitrogen (%)	TOTN
Bulk density (g/cm^3)	BULK

of 30 meters, released by the Ministry of Economy, Trade, and Industry of Japan (METI) and the United States National Aeronautics and Space Administration (NASA). The soil color was derived from the profiles data sheet of the same soil type. The fertility factor was assumed equal to 0.9 for all soil profiles. The runoff potential has been assumed according to the soil texture.

All other data were estimated using the "Calculate missing values" function of Soil Data module present in DSSAT-CSM.

Weather data

For parameterization of crop models at the national level, the national weather data database of ex Agricultural Ecology Central Department, actually Research unit for Climatology and Meteorology applied to Agriculture of the Agricultural Research Council (CRA-CMA, 2011), were used. Weather data from 2001 to 2012 were available, but for this study only the daily data from the 2001-2010 period were considered due to problems encountered in many weather stations in the two last years.

For the Sardinian experimental sites Ussana and Benatzu, the study used data of the weather station located in the experimental farm San Michele di Ussana, managed by the Agency for Agricultural Research of the Autonomous Region of Sardinia (AGRIS Sardegna). For this weather station the data were available from 2000 to 2010.

For the experimental sites located in Piedmont (Vigone, Alessandria, Cuneo, Castellazzo Bormida and Cigliano) the data of one of the nearest weather stations of the Regional Agency for Environmental Protection of Piedmont (ARPA Piemonte) were considered.

The weather variables considered are the maximum and minimum temperature, precipitation and solar radiation. Solar radiation data are not present for all weather stations. Therefore only the weather stations with availability of solar radiation data were considered.

In this study, only the crop years with a number of days with weather data missing less than or equal to fifty were considered. Missing weather data were reconstructed for each weather station and for each variable. Missing data for a single day, was reconstructed by calculating the average value of the previous and the following day. In the other cases, the equation of linear regression obtained with data for the same period of the nearest weather station was done. When a negative value for precipitation was obtained, a value of 0 mm was assumed.

Agronomic and crop management data

Phenology, yield and management data were collected by the National Network of Varietal comparison for durum wheat, common wheat, and maize database. These data were recorded from 2001 to 2010 in the "*Sperimentazione interregionale sui cereali*" project and were provided by the Experimental Institute for Cereal Research (Istituto Sperimentale per la Cerealicoltura). All data and information used in this study for each crop were obtained from special issues of the journal L'Informatore Agrario (http://www.informatoreagrario.it). Data for the Bologna cultivar are available since 2005. Several data were used for parameterization of the CSM-CERES-Maize model: trial data of nitrogen fertilization, trial data with different seeding densities, and trial data without differentiation of agronomic factors. Observed maturity date for maize was not available. Therefore the maturity of 132 days, indicated by the manufacturer of the seed of the Eleonora (Pioneer), was considered.

For durum and common wheat the experimental parcels area was 10 m^2. The dry seed method for seeding was used. The plant population at seeding was 450 plants m^{-2} for North and Centre areas and 350 plants m^{-2} for South-Peninsular, Sicily and Sardinia areas for durum wheat, and 450 plants m^{-2} for all common wheat areas.

For maize, each parcel consisted of four rows of 11 m including a transverse portion of 70-80 cm between the various parcels. The seeding density for the various trials were obtained with the manual thinning of the plants at the stage of 4th-5th leaf.

For other information the ordinary cultivation technique of each crop was considered. The initial conditions at planting date were considered. Weed control and diseases were not considered for all crops.

3.3.3 Selection of the experimental sites

In this study, only the crop years in which the number of days with missing weather data between sowing and harvesting is not higher than fifty were considered. In each area the experimental sites were selected between those whose distance from the nearest weather station does not exceed 30 km. Due to the high number of sites with available experimental observations, at least two sites for each area were selected (one for calibration and one for evaluation).

Durum wheat

Two sites in each area with at least two observations were considered. An exception is the Centre-Italy (Adriatic side) area in which only one site was considered. If more sites were located in the same area, those closest to a given weather station were selected.

Following these criteria fourteen experimental sites were selected (Table 7, Figure 2).

Table 7. Experimental sites selected for calibration and evaluation of the CSM-CERES-Wheat model at Italian scale for Iride cultivar.

Calibration				
Area	**Experimental site**	**Weather station**	**Distance (km)**	**Number of sample environments**
North	Cigliano	Candia*	12	2
Centre-Italy (Tyrrhenian side)	Roma	Roma Collegio Romano	8	5
Centre-Italy (Adriatic side)	Agugliano	Potenza Picena	27	5
South-Peninsular	Matera	Matera	1	5
Sicily	Santo Stefano Quisquina	Pietranera	14	7
	Caltagirone	Santo Pietro	13	6
Sardinia	Santa Lucia	Santa Lucia	1	7
Evaluation				
Area	**Experimental site**	**Weather station**	**Distance (km)**	**Number of sample environments**
North	Ceregnano	Rovigo	5	4
	Ostellato	Gualdo	18	3
Centre-Italy (Tyrrhenian side)	Viterbo	Caprarola	15	5
South-Peninsular	Gravina	Genzano di Lucania	13	2
Sicily	Castel di Judica	Libertinia	9	6
	Gela	Santo Pietro	23	4
Sardinia	Ussana	Ussana**	1	6

*ARPA Piemonte weather station

** AGRIS Sardegna weather station

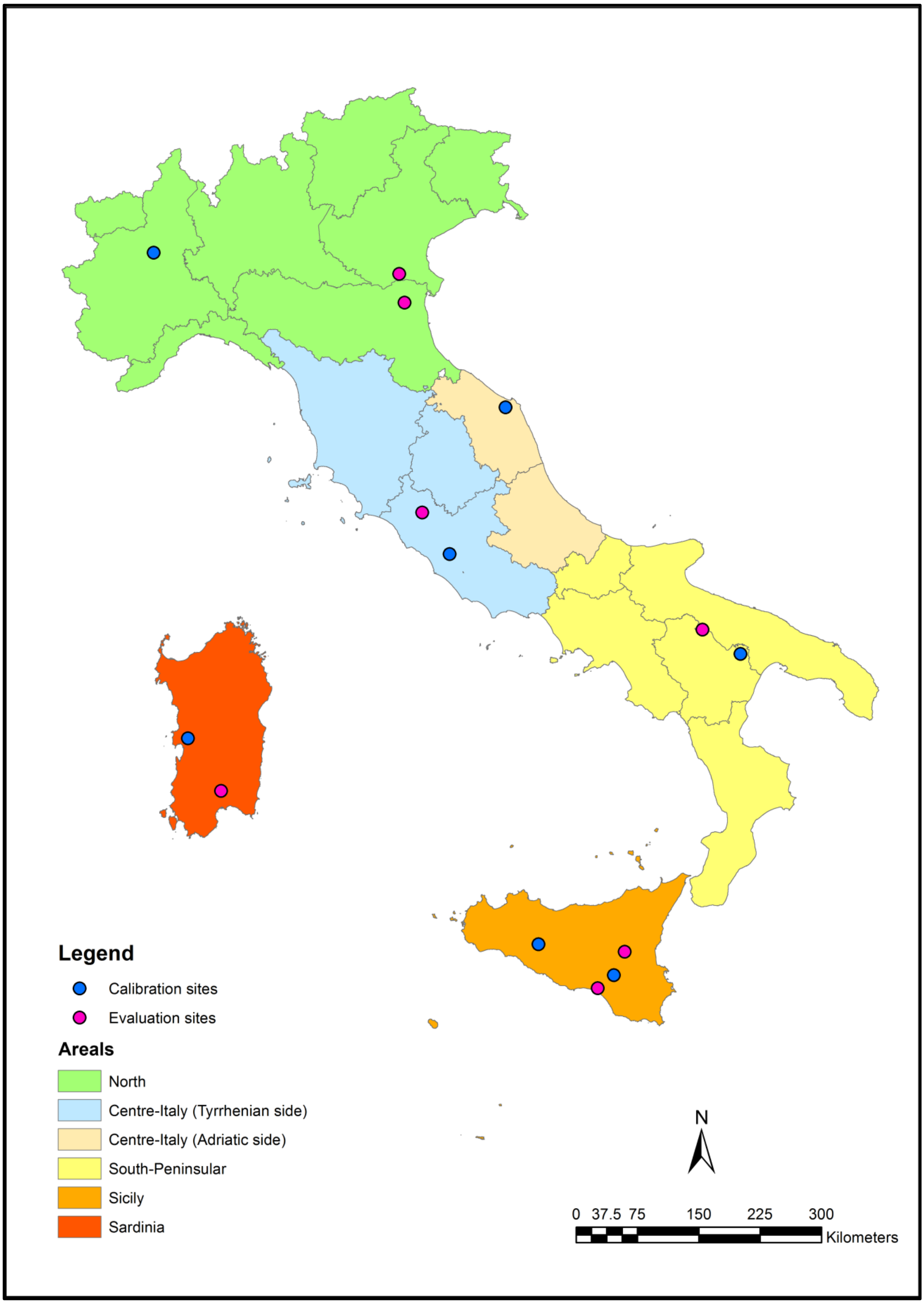


Figure 2. Experimental sites selected in different areas of Italy for calibration and evaluation of the CSM-CERES-Wheat crop model for Iride cultivar.

Common wheat

Since 2005, there are many experimental sites with observations for the Bologna cultivar, but their distribution is not uniform in different areas (fourteen sites in the North area, eleven in the Centre area, and six in the South-Islands area). Therefore at least two sites for area were considered (one for calibration and one for the evaluation). In each area the sites with the largest number of crop years were chosen. Centre area is an exception because many sites with a high number of crop years have problems.

Thus the study took into consideration more sites in the North area because in this area common wheat has widespread cultivation and there are more experimental sites.

Following these criteria twelve sites were selected (Table 8, Figure 3).

Table 8. Experimental sites selected for calibration and evaluation of the CSM-CERES-Wheat model at Italian scale for Bologna cultivar.

Calibration				
Area	**Experimental site**	**Weather station**	**Distance (km)**	**Number of sample environments**
North	Sant'Angelo Lodigiano	Montanaso Lombardo	10	5
	Ceregnano	Rovigo	5	2
	Malalbergo	Gualdo	16	2
Centre	Alba Adriatica	Monsampolo	13	1
South-Islands	Cammarata	Pietranera	17	5
	Caltagirone	Santo Pietro	13	3
Evaluation				
Area	**Experimental site**	**Weather station**	**Distance (km)**	**Number of sample environments**
North	Cigliano	Candia*	12	3
	Mogliano Veneto	Susegana	11	3
	Basiliano	Cividale del Friuli	25	3
Centre	San Piero a Grado	San Piero a Grado	2	3
South-Islands	Matera	Matera	1	5
	Santo Stefano Quisquina	Pietranera	14	3

*ARPA Piemonte weather station

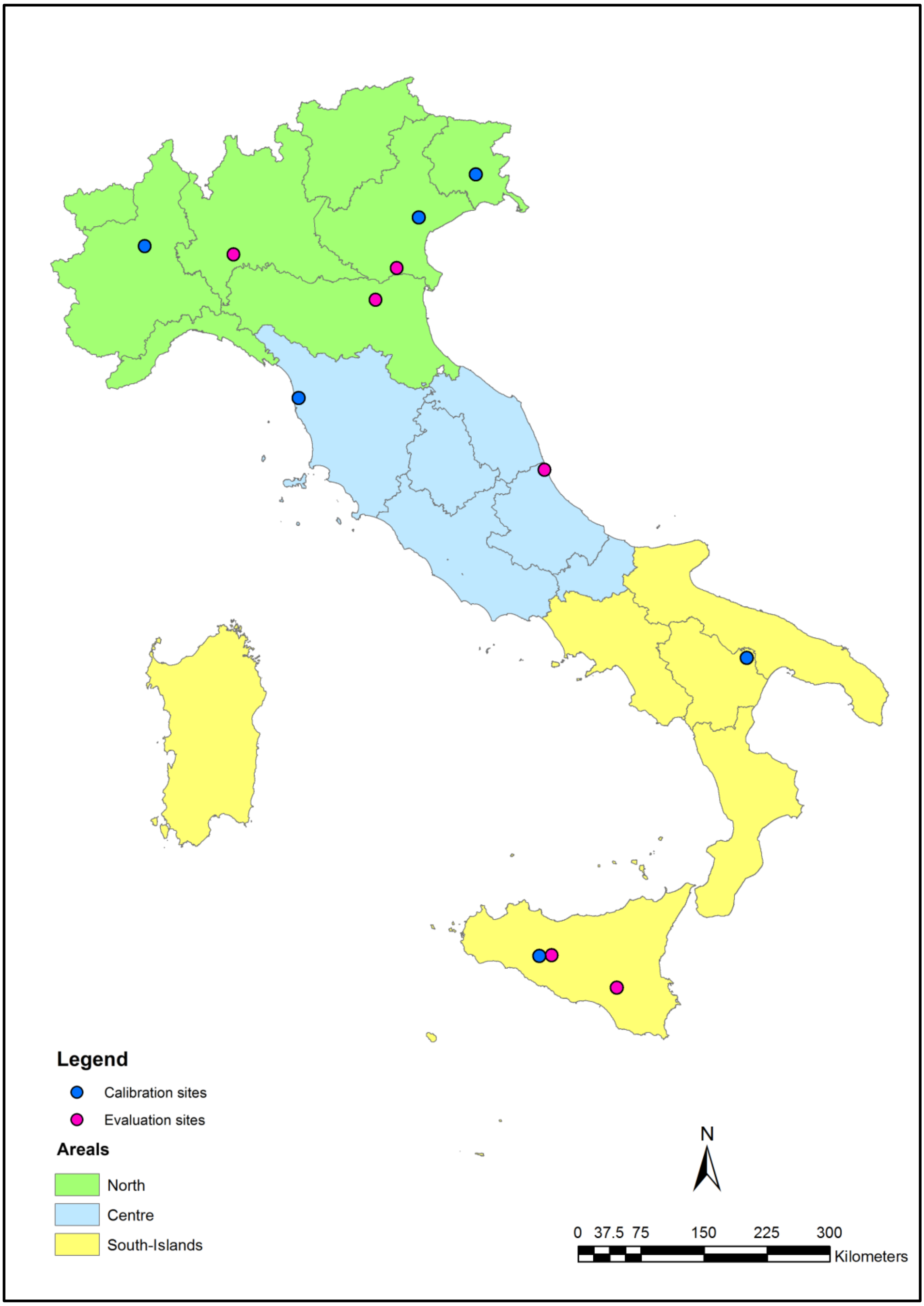


Figure 3. Experimental sites selected in different areas of Italy for calibration and evaluation of the CSM-CERES-Wheat model for Bologna cultivar.

Maize

Most experimental sites available for Eleonora are located in the North area because in Italy maize is grown mainly in this area. For many sites only one observation was available. Therefore more sites were selected with respect to durum wheat and common wheat.

Overall, fourteen experimental sites were selected for this study (Table 9, Figure 4).

Table 9. Experimental sites selected for calibration and evaluation of the CSM-CERES-Maize model at Italian scale for Eleonora cultivar.

Calibration				
Area	**Experimental site**	**Weather station**	**Distance (km)**	**Number of sample environments**
North	Vigone	Cumiana*	16	6
	Alessandria	Alessandria Lobbi*	10	1
	Caleppio di Settala	Montanaso Lombardo	14	1
	Villadose	Rovigo	4	1
	Codroipo	Fiume Veneto	27	1
	Latisana	Fiume Veneto	18	3
Evaluation				
Area	**Experimental site**	**Weather station**	**Distance (km)**	**Number of sample environments**
North	Cuneo	Fossano*	27	1
	Castellazzo Bormida	Basaluzzo*	13	1
	Cigliano	Candia*	12	1
	Sant'Angelo Lodigiano	Montanaso Lombardo	10	2
	Palazzolo dello Stella	Fiume Veneto	28	2
	Zoppola	Fiume Veneto	6	1
	Fiume Veneto	Fiume Veneto	3	1
	Ambrogio	Rovigo	16	2

* ARPA Piemonte weather station

Figure 4. Experimental sites selected in Italy for calibration and evaluation of the CSM-CERES-Maize model for Eleonora cultivar.

3.3.4 Loading data into DSSAT-CSM

After selecting experimental sites, we proceeded to load collected data in DSSAT-CSM. In this work the DSSAT-CSM v.4.5.0.0 (Hoogenboom et al., 2012) was used. For each crop the files with observed data (anthesis date and yield) were loaded, and the experimental files were created. The start simulations date was set on 15th August for durum wheat and common wheat, and on 1st January for maize. The volumes of water distributed with irrigation were not available for maize. Therefore, when required, automatic irrigation was set.

3.3.5 Calibration and evaluation of crop models

The minimum inputs required to run the CSM-CERES-Wheat and CSM-CERES-Maize crop models simulation and outputs are as follows:

1. site weather data for the duration of the growing season;
2. site soil profile and soil surface data;
3. crop management data from the experiment.

However, the observed experimental data from the experiment (e.g. anthesis date, maturity date, grain yield, etc.) are also necessary for crop model calibration and evaluation.

In this study the anthesis date (days after planting, dap) for phenology and grain yield (t ha^{-1}) were considered in order to parameterize the CSM-CERES-Wheat crop model and only grain yield for CSM-CERES-Maize crop model. The details of the calibration and evaluation for these crop models are described below.

CSM-CERES-Wheat model calibration

For the CSM-CERES-Wheat crop model calibration a new ecotype was created by default ecotype (DFAULT in file WHCER045.ECO) for durum wheat and another for common wheat. For both, durum wheat and common wheat, the ecotype coefficients P1 (duration of phase end juvenile to terminal spikelet (PVTU)), P2 (duration of phase terminal spikelet to end leaf growth (TU)), P3 (duration of phase end leaf growth to end spike growth (TU)) and P4 (duration of phase end spike growth to end grain fill lag (TU)) were modified, as indicated in the same file, depending on the value of the cultivar coefficient PHINT (interval between successive leaf tip appearances). The latter was set at 95 which is the value typical of the Mediterranean area for durum wheat and common wheat (Rezzoug, 2008). The values of the P1, P2, P3 and P4 ecotype coefficients have been optimized for durum wheat (400, 285, 190, and 200 respectively) and common wheat (375, 250, 200, and 300 respectively).

Seven cultivar coefficients are present in the CSM-CERES-Wheat crop model (Table 10). Recent studies have demonstrated the importance of photoperiod and vernalization in predicting the anthesis date for winter wheat in Europe (Herndl et al., 2008; He et al., 2012).

Table 10. Genetic coefficients used for parameterization of CSM-CERES-Wheat crop model for each cultivar and their description.

Genetic coefficient	**Description**
P1V	Days at optimum vernalizing temperature required to complete vernalization (days)
P1D	Percentage reduction in development rate in a photoperiod 10 hour shorter than the threshold relative to that at the threshold
P5	Grain filling (excluding lag) phase duration (degree days)
G1	Kernel number per unit canopy weight at anthesis (kernel numbers/g)
G2	Standard kernel size under optimum conditions (mg)
G3	Standard, non-stressed dry weight (total, including grain) of a single tiller at maturity (g)
PHINT	Interval between successive leaf tip appearances (degree days)

The P1V coefficient expresses the vernalization requirements of the wheat cultivars. The optimum temperature for vernalization is between 0 °C and 7 °C. The increase in temperature above 7 °C slows the vernalization process. It is assumed that 50 days of vernalization are sufficient to satisfy the vernalization requirements of all varieties, although the significant differences exist between cultivars.

The P1D coefficient reflects the sensitivity to photoperiod of the cultivars considered. Its value is normally between 20 and 100 depending on the cultivar. This coefficient is important because wheat is a long day plant, therefore decreases its development during short days.

For CSM-CERES-Wheat crop model calibration, the seven genetic coefficients were optimized considering the minimum difference between observed and simulated data. The genetic coefficients were optimized minimizing the error between simulated and measured values for phenology (anthesis date or maturity date) and yield. First, the genetic coefficients for phenology (P1V, P1D and P5) were calibrated. Then the coefficients relative to the grain yield (G1, G2, G3 and PHINT) were optimized.

CSM-CERES-Maize model calibration

For the CSM-CERES-Maize crop model calibration the default ecotype (IB0001 in file MZCER045.ECO) was considered.

Six cultivar coefficients are present in the CSM-CERES-Maize crop model (Table 11). First, the genetic coefficients for phenology (P1, P2 and P5) were calibrated. Then the coefficients relative to the grain yield (G2, G3 and PHINT) were optimized.

Table 11. Genetic coefficients used for parameterization of CSM-CERES-Maize crop model for each cultivar and their description.

Genetic coefficient	**Description**
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod (degree days)
P2	Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours) (days/hour)
P5	Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8°C) (degree days)
G2	Maximum possible number of kernels per plant (kernel numbers/plant)
G3	Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)
PHINT	Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances (degree days)

Crop models validation and evaluation

In existing literature, the terms "validation" and "evaluation" are often used like synonyms. In reality there is a substantial difference between the two terms (Thornley and France, 2007). The validation aimes at establishing if a model is adequate or not for a certain purpose. The model evaluation, instead, consists fundamentally in the comparison between simulated and observed values for the variables considered.

Modelers have often interest in knowing the way in which a crop model determines the crop responses (especially the crop growth, phenological development and productivity). Consequently, it is more appropriate to use the term "evaluation" (Wallach D., 2006).

There are several statistical indexes used to evaluate a model. The Pearson correlation coefficient (r) and the coefficient of determination (R^2) are the most commonly used. However, these statistical measures are not always related to the accuracy of the model. In addition, a high value or statistically significant R^2 may mislead because often this coefficient is unrelated to the dimension of the difference between observed and predicted values.

For this reason, other statistical indexes were also used in this study, so as to evaluate the performance of the crop models under different aspects.

The statistical indexes used in this work are described below.

3.3.6 Statistical analysis

In this study the performance of CSM-CERES-Wheat and CSM-CERES-Maize crop models were evaluated considering nine statistical indexes, mainly based on the calculation of the correlation and differences between simulated (E_i) and observed (M_i) values of anthesis or maturity date and yield for each crop.

The Pearson correlation coefficient (r) is a measure of the correlation existing between the measured and estimated data. It is defined as:

$$r = \frac{\sum_{i=1}^{n} (E_i - \bar{E})^2 (M_i - \bar{M})^2}{\sqrt{\sum_{i=1}^{n} (E_i - \bar{E})^2 (M_i - \bar{M})^2}}$$

The value of this coefficient is between -1 and +1 ($-1 \leq r \leq 1$). If $r = 1$ there exists a perfect positive linear relationship between estimated and observed values. A value of $r > 0.6$ indicates that there exists a strong positive correlation between simulated and observed data. In any case, a high value of r does not necessarily mean that the model is perfect.

The coefficient of determination (R^2) is the square of the correlation coefficient.

An important aspect is the evaluation of the model's accuracy. It is defined as the variation, expressed in the same unit as the data, between simulated and observed values

(Loague and Green, 1991). Three statistical indexes were used to evaluate the accuracy of crop models: the root mean square error (*RMSE*), the general standard deviation or relative root mean squared error (*GSD*), and the modeling efficiency index (*EF*).

The RMSE provides a measure of typical size of the errors produced by the model. It is defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i - M_i)^2}{n}}$$

where E_i and M_i represent the simulated and measured annual values of the year i, and n is the number of annual values. The optimum value of RMSE is equaling zero, which indicates perfect estimates.

The GSD is an index similar to RMSE but expressed as coefficient of variation. It is obtained by dividing the RMSE by the mean of the observed yield or anthesis date values ($\bar{M}$):

$$GSD = RMSE\,\frac{100}{\bar{M}} = \sqrt{\frac{\sum_{i=1}^{n}(E_i - M_i)^2}{n}}\,\frac{100}{\bar{M}}$$

The EF index is based on squared differences:

$$EF = 1 - \frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2}$$

When EF > 0 the model estimates are better predictors than average observed values. If EF = 1 the model estimates are perfect.

The tendency of the model to overestimate or underestimate the measured values was measured considering three statistics: the coefficient of residual mass (*CRM*), the mean bias error (*MBE*), and the mean absolute error (*MAE*). They are defined as follows:

$$CRM = 1 - \frac{\sum_{i=1}^{n} E_i}{\sum_{i=1}^{n} M_i}$$

$$MBE = \sum_{i=1}^{n} \frac{E_i - M_i}{n}$$

$$MAE = \sum_{i=1}^{n} \frac{|E_i - M_i|}{n}$$

The optimal value of CRM is equal to 0: positive or negative values indicate a tendency of the model to underestimate or overestimate the variable respectively (Xevi et al., 1996). A positive value of MBE indicates a tendency of the model to overestimate while a negative MBE indicates a tendency of the model to underestimate the variable. A value of MAE near or equal to zero represents the better match along the 1:1 comparison line of estimated and measured values (Rasse et al., 2000).

Finally, the Index of Agreement (d) was calculated. This is a standardized measure of the degree of model prediction error and varies between 0 and 1 (Willmott, 1981). It is defined as:

$$d = 1 - \frac{\sum_{i=1}^{n}(E_i - M_i)^2}{\sum_{i=1}^{n}(|E_i - \bar{M}| + |M_i - \bar{M}|)^2}$$

The optimal value of *d* is equal to 1 which is obtained if the simulated values are equal to observed values. In this case the model is perfect. Instead *d* = 0 when the model estimates are identical in all cases and equal to the average of the observed values.

3.3.7 Sensitivity analysis

A local sensitivity analysis was performed to study the effect of the variation of each cultivar genetic coefficient of the CSM-CERES-Wheat and CSM-CERES-Maize crop models on the variation of anthesis date (maturity date for maize) and grain yield of the three crops considered. The sensitivity analysis was performed considering only the experimental sites selected for model calibration. For this purpose, the mathematical and graphcal approaches were used. In particular, the sensitivity analysis of each crop model output was performed one at a time through a Sensitivity Index (SI). This index was calculated as follows (Deng et al., 2011):

$$SI = ((O_2 - O_1) / O_{avg}) / ((I_2 - I_1) / I_{avg})$$

where I_1, I_2, and I_{avg} are the maximum, minimum, and averages values of a specific input parameter, while O_1, O_2, and O_{avg} are the maximum, minimum, and averages values of the crop model output under consideration.

3.4 RESULTS

This section shows the results obtained in this study regarding the parameterization at the Italian scale of the CSM-CERES-Wheat and CSM-CERES-Maize crop models. In particular, results are presented for each selected cultivar (Iride for durum wheat, Bologna for common wheat, and Eleonora for maize), for a phenological stage (anthesis for durum and common wheat, and maturity for maize) and an index of production (grain yield). In addition, the final part shows sensitivity analysis results.

3.4.1 CSM-CERES-Wheat and CSM-CERES-Maize models calibration and evaluation

Firstly, the results of the crop model calibration of each cultivar using data sets collected for selected experimental sites are shown.

Secondly, the results of the crop model evaluation for each cultivar using data sets of other selected experimental sites are shown.

3.4.2 Durum wheat

In order to calibrate the CSM-CERES-Wheat crop model for Iride cultivar, the data from 2001 to 2010 of seven experimental sites (one for each distribution area) were used. The total number of sample environments considered is equal to twenty-three for anthesis and thirty-seven for grain yield. Four observations were excluded from the model calibration. In particular, the crop years 2003-2004 of the Roma experimental site and 2006-2007 of the Matera experimental site were not considered because of the excessive presence of weeds due to missed weeding during spring. The crop year 2007-2008 of the Roma site was excluded for the widespread presence of *Fusarium* sp. during crop cycle. Finally, the crop year 2000-2001 of the Santa Lucia experimental site was not considered for the excessive infection by *Puccinia recondita* Rob. ex desm. f.sp. *tritici*. The graphical and statistical results of model calibration for anthesis and grain yield were examined.

Calibration for Iride cultivar

The statistical results of the CSM-CERES-Wheat model calibration on anthesis date and yield for Iride cultivar are reported in Table 12.

The results obtained for anthesis model calibration indicate that the mean value

Table 12. Statistical results of the CSM-CERES-Wheat crop model calibration at the Italian scale on anthesis date (dap = days after planting) and grain yield (t ha^{-1}) for Iride cultivar.

		ANTHESIS DATE (dap)		**GRAIN YIELD (t ha^{-1})**	
		OBS	SIM	OBS	SIM
Mean	Mean	140	140	5.25	5.00
Standard deviation	SD	27.16	24.47	2.06	1.23
Minim value	Min	82	87	1.69	1.50
Maximum value	Max	192	191	10.12	7.54
Number of sample environments	N	23		37	
Pearson coefficient	r	0.94***		0.68***	
Coefficient of determination	R^2	0.89		0.46	
Root Mean Square Error	RMSE	8.88		1.53	
General Standard Deviation	GSD (%)	6		29	
Modeling Efficiency	EF	0.89		0.44	
Coefficient of Residual Mass	CRM	0.00		0.05	
Mean Bias Error	MBE	0.13		-0.25	
Mean Absolute Error	MAE	6.48		1.28	
Index of Agreement	d-Index	0.95		0.77	

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$; ns=not significant.

OBS=observed values; SIM=simulated values;

of the simulated data is equal to the corresponding mean value of the observed data.

This is probably due to the optimization of cultivar coefficients related to the vernalization (P1V = 5) and photoperiod (P1D = 65). On the contrary, the cultivar coefficient related to the grain filling duration does not affect the anthesis date and has a limited effect on grain yield (see also section 3.4.5 of this chapter). Therefore, the value of the P5 coefficient does not change (P5 = 450). The standard deviation for simulated values is lower than the standard deviation for the measured data.

The Pearson coefficient value (r = 0.94) is significant at $P \leq 0.001$. The high value of the coefficient of determination ($R^2 = 0.89$) indicates that the model explains 89% of the total variability. The correlation between simulated and observed data isrepresented in Figure 5. The equation of the linear regression shows a good correlation as shown by the values of the angular coefficient (b = 0.85) and intercept (a = 21.16).

The RMSE index value is low enough. Instead the value of the GSD index is very low (6%) and demonstrates a good ability of the model in predicting the anthesis date. The good predictive efficiency of the model is confirmed by the high value of EF index (0.89). The CRM index value (0.00) is equal to the optimal value and indicates

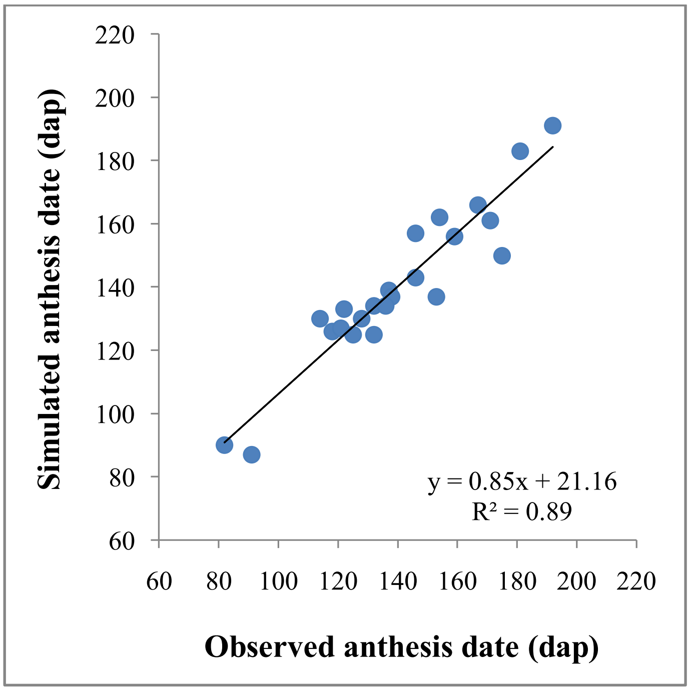


Figure 5. Calibration results of CSM-CERES-Wheat model on anthesis date (dap = days after planting) for Iride cultivar at the Italian scale. Correlation for simulated and observed yield values.

that the model is perfect to estimate anthesis date. The slight tendency of model to overestimate is shown by the values of the MBE (0.13 dap) and MAE (6.48 dap) indexes. Finally, the high value of the d-Index (0.95) confirms the good correlation between simulated and observed data.

The best combination of cultivar coefficients that affect the grain yield (G1 = 20, G2 = 35, G3 = 1.5) made it possible to minimize the difference between simulated and observed yield values. Regarding the PHINT coefficient, the typical value for durum wheat in the Mediterranean area (95) was considered. The statistical results show that the mean value for simulated yields is less than the mean value for observed yields for the period considered. In addition, the standard deviation value for simulated yields is lower than that of the observed yields. These results are due to the general tendency of the model to decrease the variability of simulated yields, as shown by the lower value of maximum simulated yield. In fact, the model does not take into account the effect of pests and plant diseases that normally have a negative impact on grain yield.

The Pearson coefficient value for yield is equal to 0.68 and is significant for $P \leq 0.001$. The coefficient of determination (R^2) explain only 46% of the total variability.

Figure 6 shows the correlation of values for the simulated and observed yields

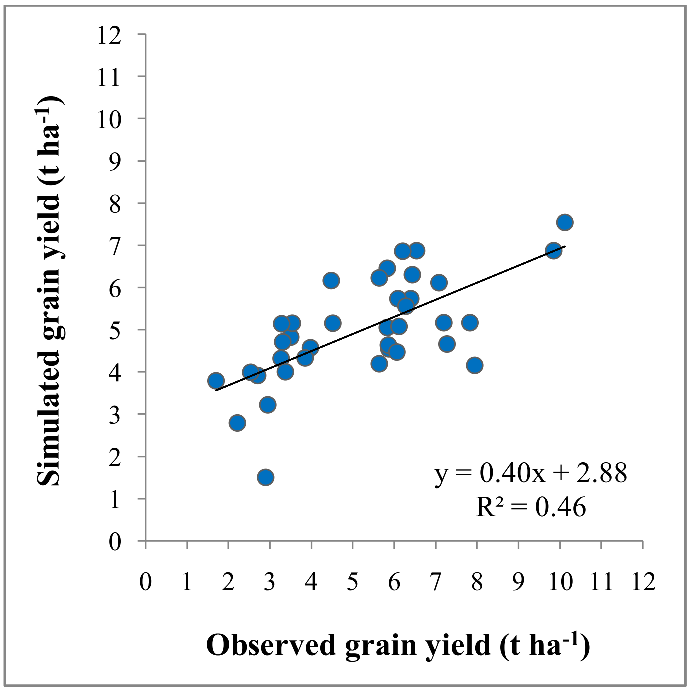


Figure 6. Calibration results of CSM-CERES-Wheat model on grain yield (t ha^{-1}) for Iride cultivar at the Italian scale. Correlation for simulated and observed yield values.

data. There exists a certain dispersion of data as shown by the parameters of the equation of linear regression (y = bx + a) (b = 0.40, a = 2.88).

Relatively to the indexes used to evaluate the accuracy of the model, based on differences between the simulated and measured data, a relatively low value of RMSE index (1.53 t ha^{-1}) was obtained. This demonstrates the good accuracy of the estimation of CSM-CERES-Wheat model, as confirmed by the GSD index value (29%). A further confirmation of the predictive efficiency of model is given by the EF index value (0.44). The value of CRM index (0.05), indicate the tendency of the model to underestimate yields. Similarly MBE (-0.25 t ha^{-1}) and MAE (1.28 t ha^{-1}) indexes confirm the predictive ability of the model and its tendency to underestimate. Finally, an acceptable value of the index of agreement between the simulated and observed data (d-index) (0.77) was obtained.

Evaluation for Iride cultivar

The evaluation of the CSM-CERES-Wheat crop model for Iride variety was performed using data from 2001 to 2010 of seven experimental sites located in different areas. Nineteen observations for anthesis and thirty for grain yield were used. Two observations (2004-2005 and 2008-2009) of Ussana experimental site were excluded from the analysis due to the infection by *Septoria tritici* Rob. ex Desm. The graphical and statistical results of model evaluation for anthesis and yield are shown below.

The results of CSM-CERES-Wheat model evaluation on anthesis date and yield for Iride cultivar are listed in Table 13.

Table 13. Statistical results of the CSM-CERES-Wheat crop model evaluation at the Italian scale on anthesis date (dap = days after planting) and grain yield (t ha^{-1}) for Iride cultivar.

		ANTHESIS DATE (dap)		**GRAIN YIELD (t ha^{-1})**	
		OBS	SIM	OBS	SIM
Mean	Mean	138	141	4.35	5.07
Standard deviation	SD	23.47	23.56	1.69	1.73
Minim value	Min	112	118	1.14	2.42
Maximum value	Max	192	184	7.92	9.03
Number of sample environments	N	19		30	
Pearson coefficient	r	0.95***		0.64***	
Coefficient of determination	R^2	0.91		0.41	
Root Mean Square Error	RMSE	7.73		1.59	
General Standard Deviation	GSD (%)	6		36	
Modeling Efficiency	EF	0.89		0.09	
Coefficient of Residual Mass	CRM	-0.02		-0.16	
Mean Bias Error	MBE	3.37		0.70	
Mean Absolute Error	MAE	6.63		1.29	
Index of Agreement	d-Index	0.97		0.77	

*$P \leq 0.05$; **$P \leq 0.01$; *** $P \leq 0.001$; ns=not significant.

OBS=observed values; SIM=simulated values.

The results of model evaluation for anthesis show a good correspondence between estimates and observed mean values. Standard deviation values too are very similar.

This correspondence is confirmed by the high value of the Pearson coefficient (r = 0.95) which is significant for $P \leq 0.001$. The high value of the coefficient of determination ($R^2 = 91\%$) indicates that the model explains 91% of the total variability. The correlation between simulated and observed values is good (b = 0.95, a = 3.69) and is shown in Figure 7.

The value of RMSE index is high enough, as in model calibration. However, the good accuracy and predictive capacity of the model is demonstrated by the very low

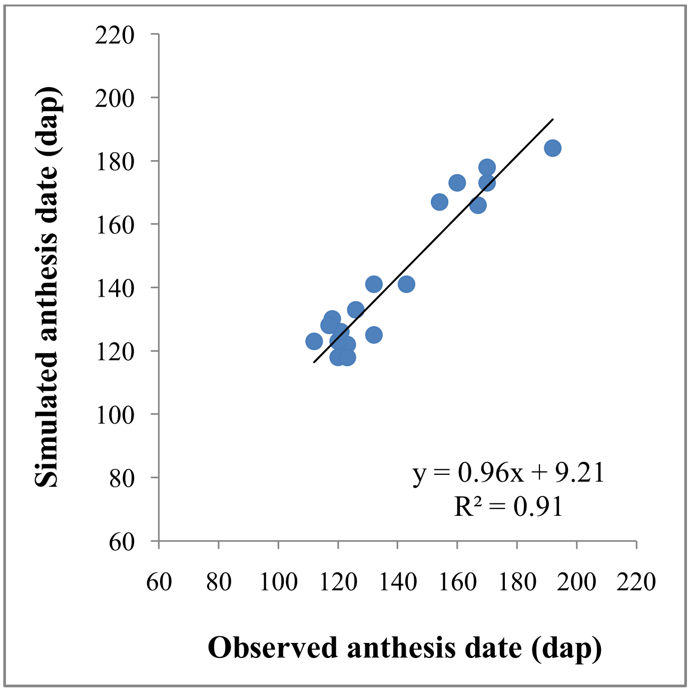


Figure 7. Evaluation results of CSM-CERES-Wheat model on anthesis date (dap = days after planting) for Iride cultivar at the Italian scale. Correlation for simulated and observed yield values.

value of GSD index (6%) and the high value of EF (0.89). The value of CRM index (-0.02) is almost equal to the optimal value and indicates a slight tendency of the model to overestimate. This tendency is confirmed by the value of MBE index (3.37 dap) and MAE index (6.63 dap). Finally, the high value of the d-Index (0.97) indicates a good agreement between simulated and observed data.

The results obtained for yields show the tendency of the model to overestimate the yield values. The mean value of simulated yields are higher than the mean value of observed yields for the period considered. The standard deviation value of estimated yields is a bit higher than the corresponding value for observed yields. These results are probably due to the particular characteristics of the soils for some experimental sites (e.g., Castel di Judica, Gela, and Gravina) that the model is not able to reproduce. As a consequence, the observed values of anthesis in these sites are lower than the simulated values. This results in lower values of the observed yields.

The Pearson coefficient value (r) is equal to 0.64 and is significant for $P \leq 0.001$. The coefficient of determination R^2 explains 41% of the total variability. The comparison between simulated and observed yields values is shown in Figure 8. The correlation between the data indicates a certain dispersion of the observed data as

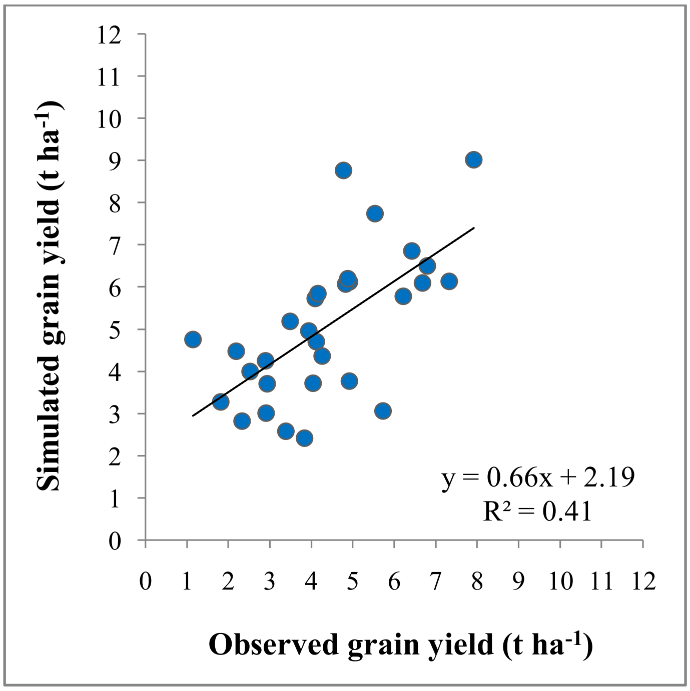


Figure 8. Evaluation results of CSM-CERES-Wheat model on grain yield (t ha^{-1}) for Iride cultivar at the Italian scale. Correlation for simulated and observed yield values.

confirmed by the parameters of the equation of linear regression (b = 0.66, a = 2.19).

Also for model evaluation for Iride cultivar, the RMSE index shows a relatively low value (1.59 t ha^{-1}). The good accuracy of the model in predicting the observed yields is confirmed by GSD index value (36%). Instead, the EF index has a very low but positive value (0.09). This indicates that the mean of simulated values are better predictors than the mean of observed values. The tendency of the model to overestimate is confirmed by the values of CRM (-0.16), MBE (0.70 t ha^{-1}) and MAE (1.29 t ha^{-1}) indexes. Finally, the d-Index value (0.77) shows a good agreement between simulated and observed yields.

3.4.3 Common wheat

For CSM-CERES-Wheat crop model calibration and evaluation for Bologna variety, the data collected from 2005 to 2010 for twelve experimental sites (eight in the Centre and North areas and four in South-Islands area) were used. The total number of years considered for the two variables studied is equal to eighteen for model calibration and twenty for model evaluation. The graphical and statistical results of the model calibration and evaluation for anthesis and yield are shown below.

Calibration for Bologna cultivar

The statistical results of the CSM-CERES-Wheat model calibration for anthesis date and yield are listed in Table 14.

Table 14. Statistical results of the CSM-CERES-Wheat crop model calibration at the Italian scale on anthesis date (dap = days after planting) and grain yield (t ha^{-1}) for Bologna cultivar.

		ANTHESIS DATE (dap)		**GRAIN YIELD (t ha^{-1})**	
		OBS	SIM	OBS	SIM
Mean	Mean	166	164	4.63	4.38
Standard deviation	SD	23.61	19.87	2.43	1.68
Minim value	Min	129	125	0.50	1.90
Maximum value	Max	203	191	8.23	7.02
Number of sample environments	N	18		18	
Pearson coefficient	r	0.95***		0.76***	
Coefficient of determination	R^2	0.91		0.57	
Root Mean Square Error	RMSE	7.51		1.57	
General Standard Deviation	GSD (%)	5		34	
Modeling Efficiency	EF	0.89		0.56	
Coefficient of Residual Mass	CRM	0.01		0.05	
Mean Bias Error	MBE	-1.78		-0.25	
Mean Absolute Error	MAE	6.44		1.30	
Index of Agreement	d-Index	0.97		0.83	

* $P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$; ns=not significant.

OBS=observed values; SIM=simulated values.

The cultivar coefficients related to genetic sensitivity to vernalization (P1V = 35) and photoperiod (P1D = 100) were optimized in order to calibrate the model for anthesis date. Regarding the P5 and PHINT coefficients, the same considerations for Iride cultivar have been made, so the same values (P5 = 450, PHINT = 95) were used. The results obtained for anthesis calibration show that the mean value of simulated data is lower compared to the corresponding mean value of measured data(164 vs. 166), with a lower standard deviation value for simulated data.

The value of Pearson coefficient is high (r = 0.95) and significant for $P \leq 0.001$. The coefficient of determination R^2 indicates that 91% of the total variability is explained by the model. The correlation between simulated and observed anthesis values is represented in Figure 9. The parameters of equation of the linear regression

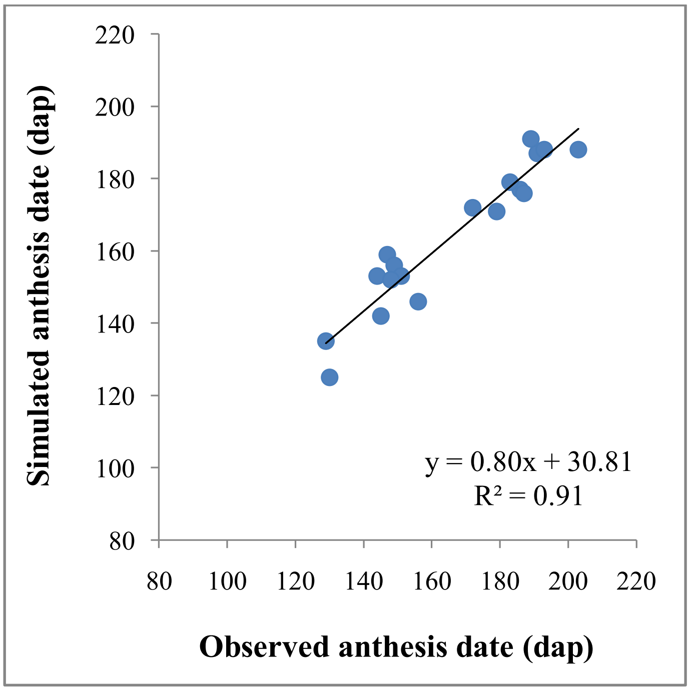


Figure 9. Calibration results of CSM-CERES-Wheat model on anthesis date (dap = days after planting) for Bologna cultivar at the Italian scale. Correlation for simulated and observed yield values.

between simulated and observed data (b = 0.80, a = 30.81) indicate a good correlation.

The RMSE index value is low enough. However, the good accuracy of model for anthesis is demonstrated by the very low value of GSD index (5%). A further confirmation of the predictive ability of model for phenological data is represented by the high value of EF index (0.89). A very low value of CRM index (0.01) was obtained. This indicates the reliability of simulations for anthesis with a slight tendency of the model to underestimate. This tendency is confirmed by the values of MBE (-1.78 dap) and MAE (6.44 dap) indexes. Finally, the high d-Index value (0.97) indicates a very good agreement between simulated and observed data.

The results obtained for grain yield show that the mean value for simulated yields is slightly lower compared to the corresponding mean value of observed yields. This was obtained through the optimization of the cultivar coefficients relative to the grain yield (G1 = 20, G2 = 30, G3 = 1.3). The value of standard deviation for simulated yields is lower than the standard deviation value of observed yields. So the model tends to reduce the variability of predicted yields.

The Pearson coefficient (r), which has a value of 0.76, is significant for $P \leq 0.001$ and the coefficient of determination (R^2) explains 57% of the total variability. The comparison between simulated and observed yields values is depicted in Figure 10, showing a certain dispersion of experimental data. This is confirmed by the slope value (b = 0.52) and intercept value (a = 1.96) of the equation of linear regression.

Regarding the indexes based on the differences between estimated and observed data, similarly to the Iride cultivar, a relatively low value of the RMSE index (1.57 t ha^{-1}) was obtained. This indicates the good accuracy of the CSM-CERES-Wheat model in predicting yields for Bologna variety. This is confirmed by the GSD index value (34%) and EF index value (0.56). The low tendency of the model to underestimate the yields and its predictive capacity are confirmed by the values of CRM (0.05), MBE (-0.25 t ha^{-1}), and MAE (1.30 t ha^{-1}) indexes. Finally, a satisfactory value of the index of agreement between simulated and observed data values (d-Index) was obtained.

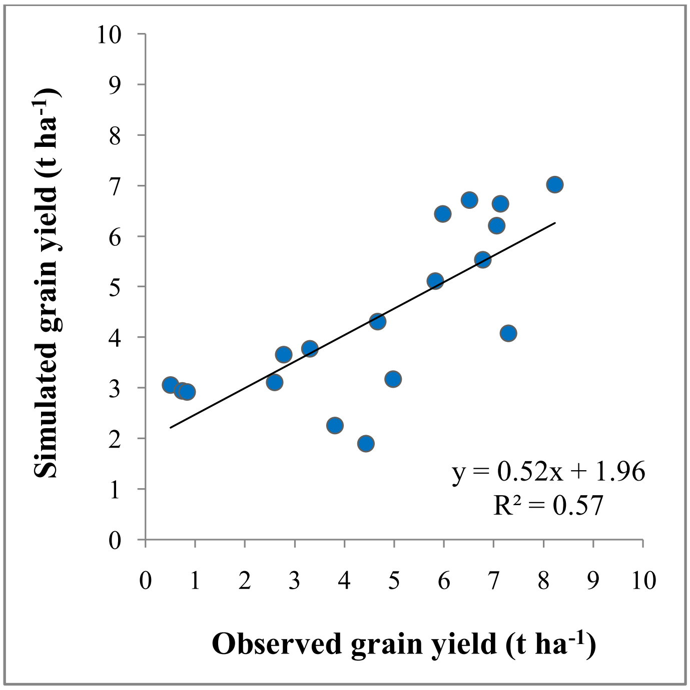


Figure 10. Calibration results of CSM-CERES-Wheat model on grain yield (t ha^{-1}) for Bologna cultivar at the Italian scale. Correlation for simulated and observed yield values.

Evaluation for Bologna cultivar

The results of CSM-CERES-Wheat model evaluation on anthesis date and grain yield for Bologna cultivar are shown in Table 15.

The statistical results for anthesis model evaluation indicate a good

Table 15. Statistical results of the CSM-CERES-Wheat crop model evaluation at the Italian scale on anthesis date (dap = days after planting) and grain yield (t ha^{-1}) for Bologna cultivar.

		ANTHESIS DATE (dap)		**GRAIN YIELD (t ha^{-1})**	
		OBS	SIM	OBS	SIM
Mean	Mean	177	178	5.19	4.62
Standard deviation	SD	22.63	23.05	2.25	1.63
Minim value	Min	94	102	1.65	1.09
Maximum value	Max	201	207	7.98	6.97
Number of sample environments	N	20		20	
Pearson coefficient	r	0.93***		0.66***	
Coefficient of determination	R^2	0.86		0.43	
Root Mean Square Error	RMSE	8.64		1.75	
General Standard Deviation	GSD (%)	5		34	
Modeling Efficiency	EF	0.85		0.36	
Coefficient of Residual Mass	CRM	-0.01		0.11	
Mean Bias Error	MBE	1.60		-0.57	
Mean Absolute Error	MAE	7.00		1.51	
Index of Agreement	d-Index	0.96		0.77	

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$; ns=not significant.
OBS=observed values; SIM=simulated values.

correspondence between mean values of simulated and observed data, with a little bit higher standard deviation value for simulated yields.

A high Pearson coefficient value (r = 0.93) was obtained and it is significant for $P \leq 0.001$. The coefficient of determination R^2, equal to 0.86, indicates that 86% of the total variability is explained by the model. The correlation between simulated and observed values is good (b = 0.94, a = 11.36) and is represented in Figure 11.

The value of RMSE index is low enough. However, the very low value of GSD index (5%) and the high value of EF index (0.85) confirm the good accuracy of the CSM-CERES-Wheat model for phenological data. The almost optimal CRM index value (-0.01) indicates a low tendency of the model to overestimate. The value of MBE index (1.60 dap) and MAE index (7.00 dap) confirm this tendency. Finally, the d-Index value (0.96) indicates a good agreement between simulated and observed phenological data.

The results for yields confirm the tendency of the model to underestimate the yield values. In fact, similarly to the model calibration, also for the model evaluation the

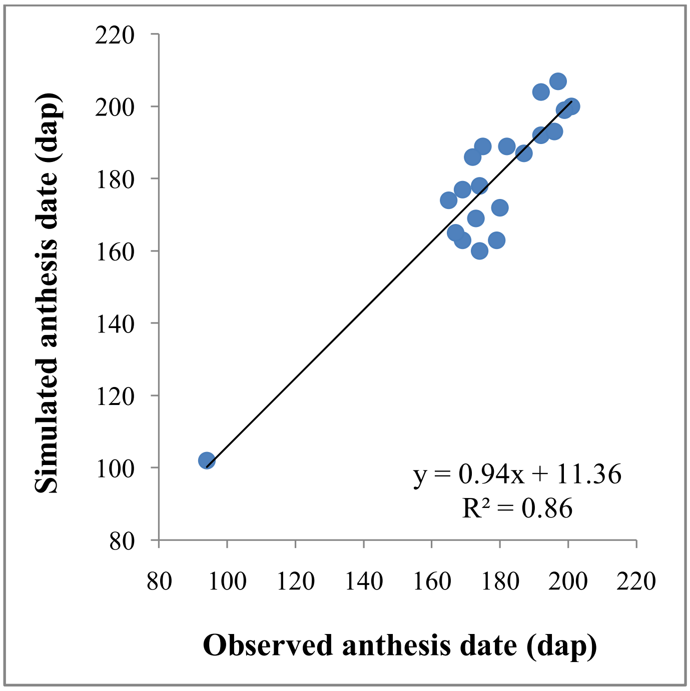


Figure 11. Evaluation results of CSM-CERES-Wheat model on anthesis date (dap = days after planting) for Bologna cultivar at the Italian scale. Correlation for simulated and observed yield values.

mean and standard deviation values obtained for simulated yields are lower than the corresponding values obtained for observed yields.

The Pearson coefficient obtained has a satisfactory value (r = 0.66) and is significant for $P \leq 0.001$. The coefficient of determination R^2 is equal to 0.43 and indicates that the model is able to explain 43% of the total variability. The comparison between simulated and observed values is shown in Figure 12. The parameters of the equation of linear regression (b = 0.48, a = 2.15) demonstrate that there exist a high dispersion of observed data along the 1:1 line.

A relatively low value of RMSE index (1.75 t ha^{-1}) was obtained. This demonstrates the good accuracy of CSM-CERES-Wheat model in predicting observed values.

This tendency is confirmed by the value of GSD index (34%) and EF index (0.36). The CRM index, equal to 0.11, confirms the tendency of the model to underestimate yields. Similarly, the values of MBE index (-0.57 t ha^{-1}) and MAE index (1.51 t ha^{-1}) confirm the predictive efficiency of the model and its tendency to underestimate yields.

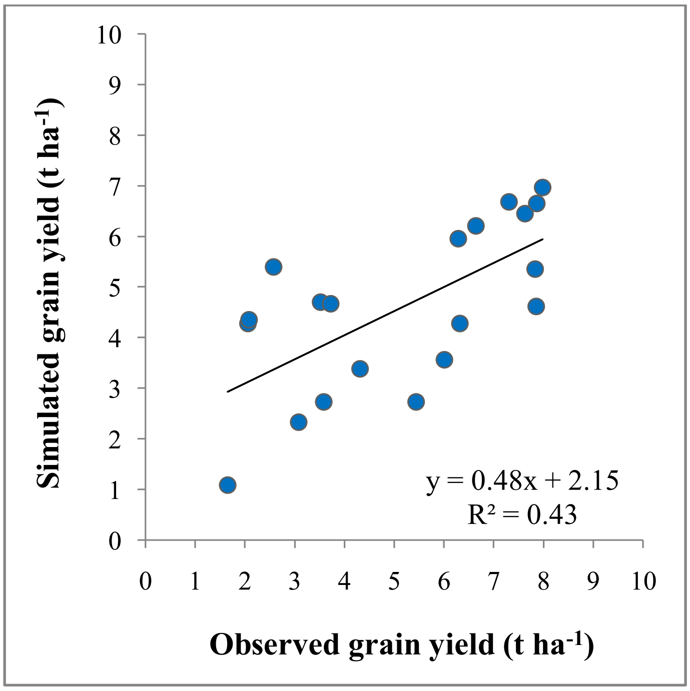


Figure 12. Evaluation results of CSM-CERES-Wheat model on grain yield (t ha^{-1}) for Bologna cultivar at the Italian scale. Correlation for simulated and observed yield values.

3.4.4 Maize

In order to parameterize the CSM-CERES-Maize crop model for Eleonora cultivar, the data of 2001-2010 period of fourteen experimental sites (six for calibration and eight for evaluation) located in the North area were considered. For Eleonora cultivar the anthesis data were not available. For all experimental sites and years the date of maturity specified by the manufacturer, which is equal to 132 dap, was considered. The total number of crop years considered for both variables is equal to thirteen for model calibration and eleven for model evaluation. The graphical and statistical results of the model calibration and evaluation for maturity date and grain yield are shown below.

Calibration for Eleonora cultivar

The calibrated genetic coefficients for Eleonora cultivar were 230 (P1), 0.55 (P2), 810 (P5), 907.9 (G2), 8 (G3), and 38.9 (PHINT). The statistical results of the CSM-CERES-Maize model calibration for maturity and yield are reported in Table 16.

The results for maturity do not include all indexes because the same observed data (132 dap) for all observations were used. Results show a perfect

Table 16. Statistical results of the CSM-CERES-Maize crop model calibration at the Italian scale on maturity date (dap = days after planting) and grain yield (t ha^{-1}) for Eleonora cultivar.

		MATURITY DATE (dap)		**GRAIN YIELD (t ha^{-1})**	
		OBS	SIM	OBS	SIM
Mean	Mean	–	132	11.49	11.82
Standard deviation	SD	–	8.92	2.13	1.64
Minim value	Min	–	112	6.86	8.32
Maximum value	Max	–	142	14.04	13.66
Number of sample environments	N	13		13	
Pearson coefficient	r	–		0.80***	
Coefficient of determination	R^2	–		0.63	
Root Mean Square Error	RMSE	–		1.29	
General Standard Deviation	GSD (%)	–		11	
Modeling Efficiency	EF	–		0.61	
Coefficient of Residual Mass	CRM	–		-0.03	
Mean Bias Error	MBE	–		0.34	
Mean Absolute Error	MAE	–		1.05	
Index of Agreement	d-Index	–		0.83	

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$; ns=not significant.

OBS=observed values; SIM=simulated values.

correspondence between the mean simulated value and typical maturity date value (132 dap) for Eleonora cultivar, with a standard deviation equal to about 9 dap. The simulated maturity date ranges from 112 to 142 dap.

The RMSE index value obtained is low enough. This demonstrates the good accuracy of the model in predicting phenological data. A further confirmation is represented by the low value of GSD index (6%). The good predictive capability of the model is demonstrated by the optimal value of CRM index (0.00) and the low value of MBE (0.15 dap) and MAE (0.62 dap).

The results obtained for grain yield show that the mean value of simulated yields is very similar to the corresponding mean value of observed yields, with a slight tendency of the model to overestimate. The standard deviation value for estimated yields is lower than the value of standard deviation for observed yields. This indicates the tendency of the model to reduce the variability of simulated values.

The Pearson coefficient is equal to 0.80 and is significant for $P \leq 0.001$. The coefficient of determination R^2 indicates that 63% of the total variability is explained by the model. The comparison between simulated and observed values is shown in Figure 13. The parameters of the equation of linear regression (b = 0.61, a = 4.81) indicate a high variability of the experimental data along the 1:1 line.

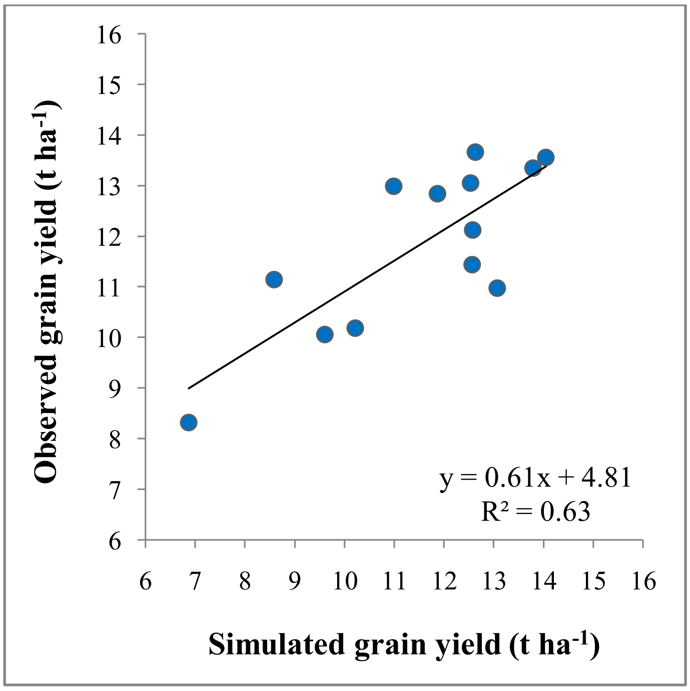


Figure 13. Calibration results of CSM-CERES-Maize model on grain yield (t ha^{-1}) for Eleonora cultivar at the Italian scale. Correlation for simulated and observed yield values.

Regarding to the accuracy indexes, a low value of RMSE index (1.29 t ha^{-1}) was obtained. The good accuracy of the model in predicting yields is confirmed by the values of GSD and EF indexes, which are equal respectively to 11% and 0.61. The low negative value of CRM index (-0.03) demonstrates the good predictive efficiency of the CSM-CERES-Maize model with a low tendency to overestimate. This tendency is confirmed by the low positive values of MBE (0.34 t ha^{-1}) and MAE (1.05 t ha^{-1}). Finally, a satisfactory value of d-Index (0.83) was obtained. This confirms a good agreement between simulated and observed yield values.

Evaluation for Eleonora cultivar

A list of the statistical results of the CSM-CERES-Maize model evaluation for maturity and yield is provided in Table 17.

For model evaluation too the results for maturity do not include all indexes. The

Table 17. Statistical results of the CSM-CERES-Maize crop model evaluation at the Italian scale on maturity date (dap = days after planting) and grain yield (t ha^{-1}) for Eleonora cultivar.

		MATURITY DATE (dap)		**GRAIN YIELD (t ha^{-1})**	
		OBS	SIM	OBS	SIM
Mean	Mean	–	133	10.38	11.24
Standard deviation	SD	–	7.31	1.84	1.50
Minim value	Min	–	123	7.29	8.88
Maximum value	Max	–	147	13.07	13.72
Number of sample environments	N	11		11	
Pearson coefficient	r	–		0.72**	
Coefficient of determination	R^2	–		0.52	
Root Mean Square Error	RMSE	–		1.50	
General Standard Deviation	GSD (%)	–		14	
Modeling Efficiency	EF	–		0.27	
Coefficient of Residual Mass	CRM	–		-0.08	
Mean Bias Error	MBE	–		0.86	
Mean Absolute Error	MAE	–		1.29	
Index of Agreement	d-Index	–		0.75	

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$; ns=not significant.

OBS=observed values; SIM=simulated values.

results show a slight tendency of the model to overestimate the maturity date (133 dap vs. a typical value of 132 dap), with a standard deviation of about 7 dap. The range of variation for simulated maturity date is between 123 and 147 dap.

The value of RMSE index is fairly low and the very low value of GSD index (5%) confirms the good accuracy of the model in predicting maturity. The value of CRM (-0.01), MBE (0.73 dap), and MAE (5.64 dap) are a further confirmation of the low tendency of the model to overestimate.

The results of model evaluation for yield show the tendency of the model to overestimate yields. In fact the mean value for simulated yields is higher than the corresponding mean value of measured yields. In addition, the standard deviation of simulated values is a little lower than the value of standard deviation for observed yields.

The Pearson coefficient (r = 0.72) is significant for $P \leq 0.01$. The coefficient of determination R^2 indicates that the model explains 52% of the total variability. Figure 14 shows the correlation between simulated and observed data. The high dispersion of experimental data along the 1:1 line is confirmed by the parameters of the equation of

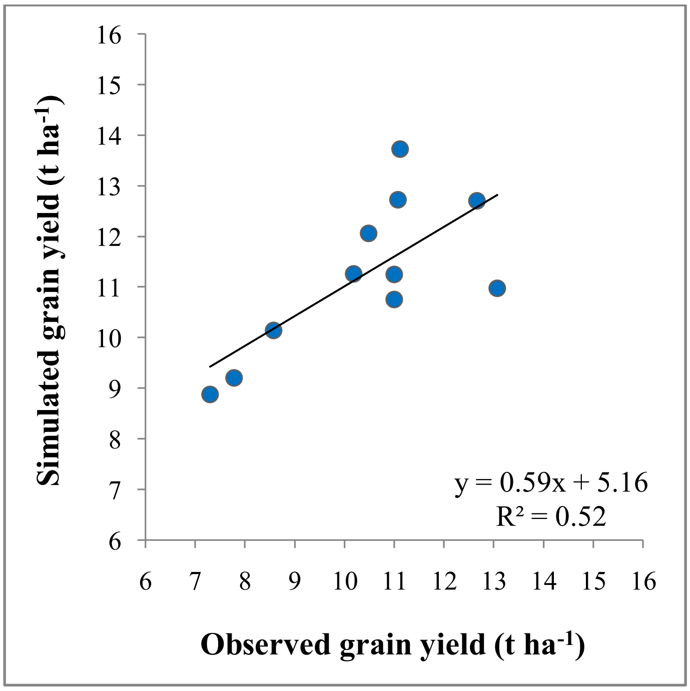


Figure 14. Evaluation results of CSM-CERES-Maize model on grain yield (t ha^{-1}) for Eleonora cultivar at the Italian scale. Correlation for simulated and observed yield values.

linear regression (b = 0.59, a = 5.16).

Regarding the model's accuracy, a relatively low value of RMSE index (1.50 t ha^{-1}) was obtained. The GSD index, with a value of 14%, confirms the efficiency of the model in predicting yield. The EF index shows a low value (0.27). However, its positive value indicates that the mean of simulated values are better predictors than the mean of the observations. The tendency of the model to overestimate the yields is confirmed by the negative value of CRM index (-0.08) and by the positive values of MBE (0.86 t ha^{-1}) and MAE (1.29 t ha^{-1}). Finally, the d-Index value obtained (0.75) indicates a good agreement between simulated and observed data.

3.4.5 Sensitivity analysis

Table 18 shows the results of the sensitivity analysis for durum wheat (Iride cultivar) and common wheat (Bologna cultivar) for the anthesis date and grain yield.

As it can be seen, the P1D cultivar coefficient of CSM-CERES-Wheat crop model is the most sensitive parameter for the anthesis date, especially for Iride cultivar (SI = 0.21). Regarding grain yield, the coefficients with the highest SI are G2 (0.65 for Iride and 0.19 for Bologna), followed by the G1 coefficient (0.60 and 0.18 for Iride and

Table 18. Sensitivity Index of CSM-CERES-Wheat crop model for anthesis date and grain yield of Iride and Bologna cultivars.

Cultivar coefficient	**Sensitivity Index**			
	Durum wheat (Iride cv.)		**Common wheat (Bologna cv.)**	
	Anthesis date	**Grain yield**	**Anthesis date**	**Grain yield**
P1V	0.06	0.05	0.02	0.01
P1D	0.21	0.24	0.06	0.24
P5	0.00	0.16	0.00	0.01
G1	0.00	0.60	0.00	0.18
G2	0.00	0.65	0.00	0.19
G3	0.00	0.04	0.00	0.02
PHINT	0.00	0.45	0.00	0.07

Bologna respectively). The sensitivity of the model to the grain yield is very low for the G3 coefficient (SI = 0.04 for Iride and SI = 0.02 for Bologna). Figures 15-16 show graphically the variation of the two variables studied consequent to the changes in each cultivar coefficient for the Iride and Bologna cultivars. The graphs confirm the results shown in Table 18. Regarding durum wheat, the anthesis date increases slightly (from 132 to 150 dap) with the increase of the P1V coefficient value from 0 to 100, while the change in P1D coefficient value in the same range involves a progressive increase of anthesis date (from 105 to 160 dap) (Figure 15). The P5 coefficient does not affect the anthesis date which remains constant at 135 dap. The grain yield increases significantly with the increase of the value of the G1 (from 0 to 5.5 t ha^{-1} for G1 = 30) and G2 (from 0 to 5.8 t ha^{-1} for G2 = 50) coefficients and it remains almost constant with the further increase of these coefficients. A progressive increase of grain yield is obtainable by increasing the value of the PHINT (up to 5.0 t ha^{-1} for PHINT = 100) and P1D (from 3.3 to 5.4 t ha^{-1} for P1D = 100) coefficients. Conversely, changes in the P1V, P5 and G3 coefficient values result in small variations of the grain yield of Iride cultivar.

The lower sensitivity of the CSM-CERES-Wheat model for the phenology of Bologna cultivar is confirmed by the graphs of Figure 16 which indicate an increase of anthesis date from 145 to 165 dap with an increase of the P1D coefficient value from 0 to 100. On the contrary, changes in the P1V coefficient values in the same range causes a negligible change in the anthesis date (from 162 to 167 dap), while its value remains

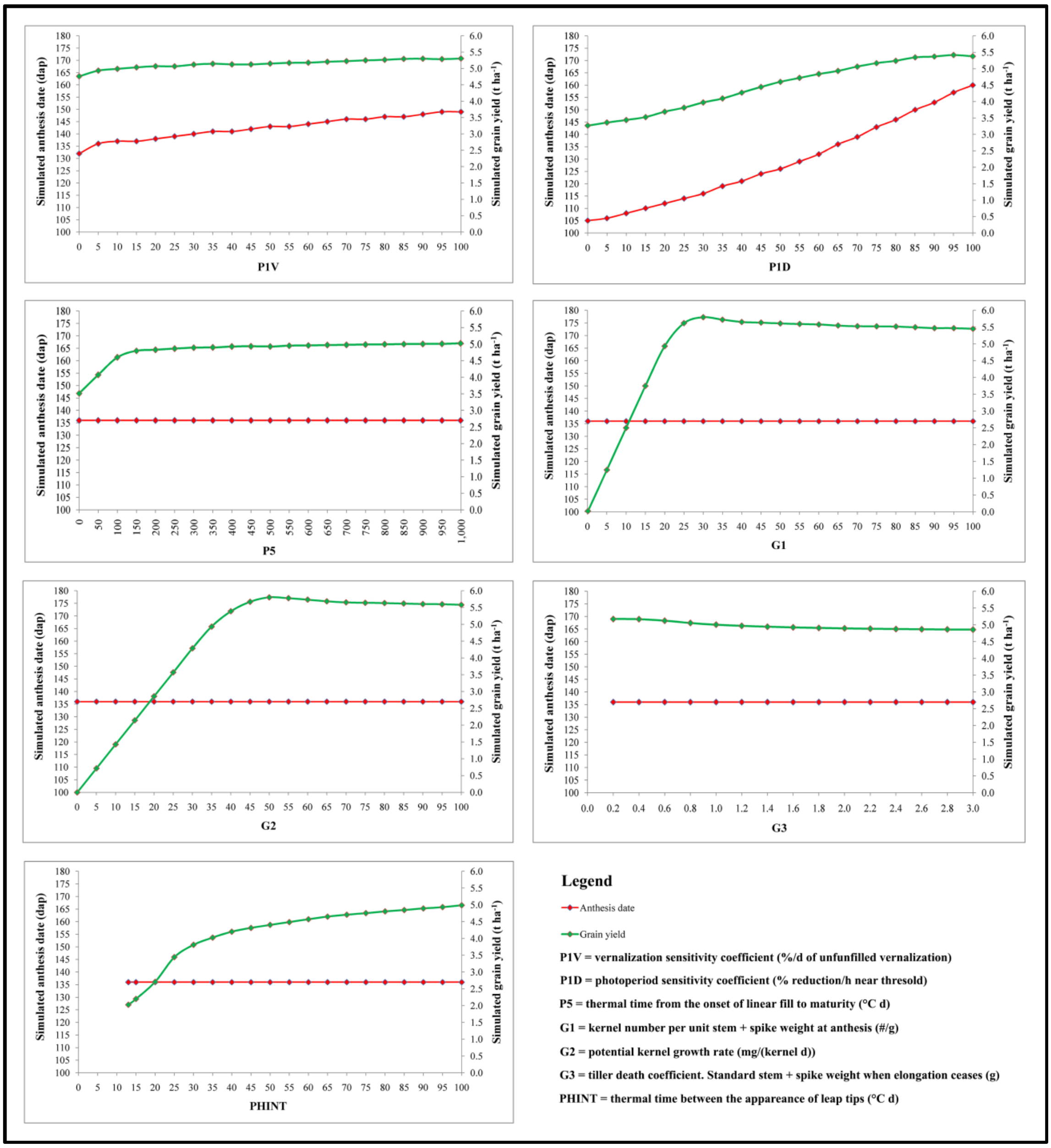


Figure 15. Trend of Sensitivity Index for the different cultivar coefficients of the CSM-CERES-Wheat model for anthesis date and grain yield of Iride cultivar.

constant (equal to 164 dap) by varying the P5 coefficient value. The grain yield increases from 3.0 to about 4.5 t ha^{-1} increasing the G1 and G2 coefficient values up to 30 and 45 respectively. A progressive increase of grain yield (from 3.3 to 5.5 t ha^{-1}) is obtained with an increase of the value of P1D coefficient from 0 to 95. Even the PHINT coefficient has a positive effect on grain yield but lower than the other coefficients (from 4.0 to 4.5 t ha^{-1} increasing the PHINT coefficient value from 15 to 100). The P1V, P5 and G3 coefficients have a negligible effect on grain yield.

Table 19 shows the results of sensitivity analysis of the CSM-CERES-Maize

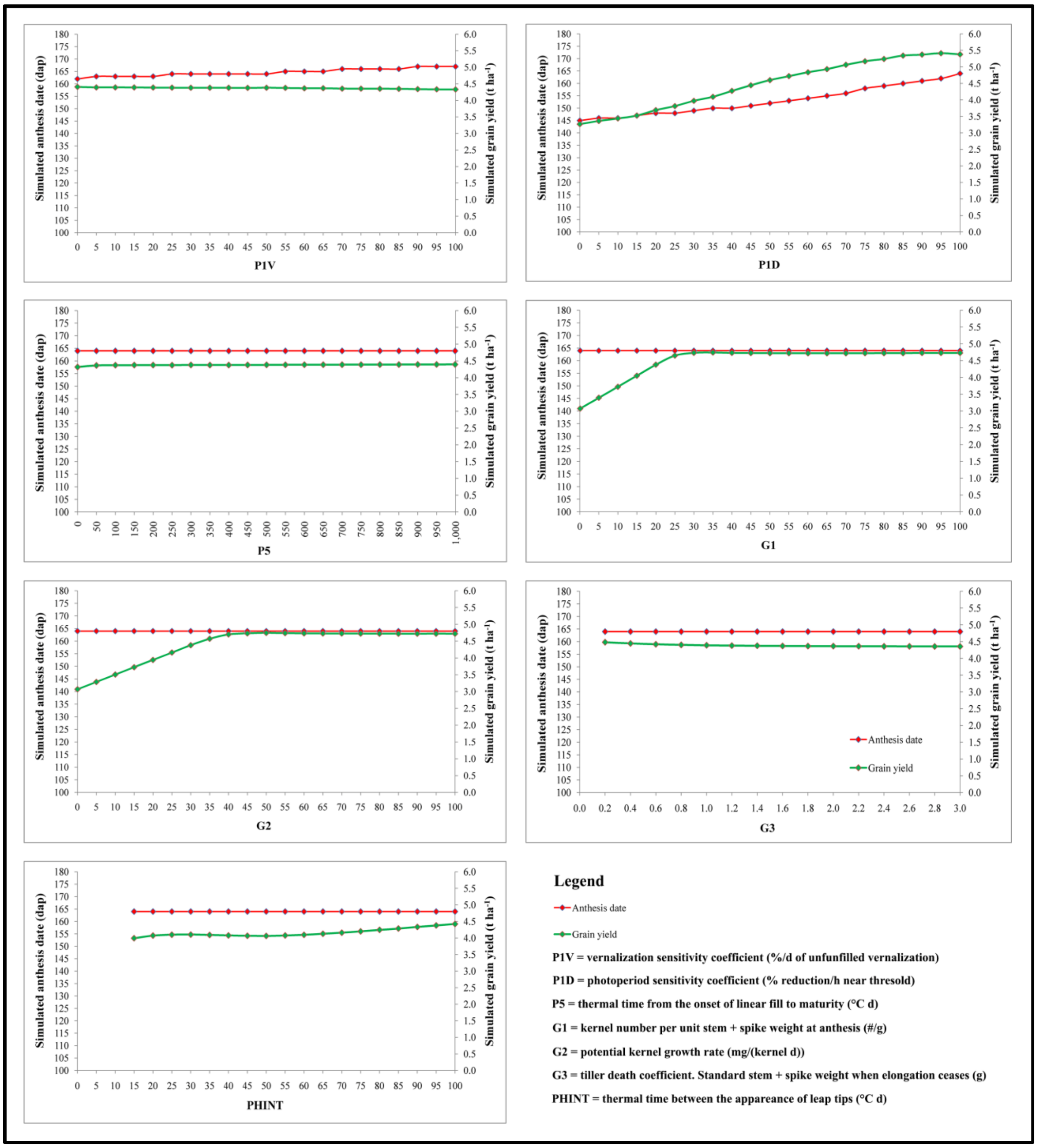


Figure 16. Trend of Sensitivity Index for the different cultivar coefficients of the CSM-CERES-Wheat model for anthesis date and grain yield of Bologna cultivar.

crop model for maturity date and grain yield of Eleonora cultivar. Regarding maturity date, the model has a high sensitivity to the P5 coefficient (SI = 0.41), followed by the P1 and PHINT coefficients (SI equal to 0.27 and 0.15 respectively). The Sensitivity Index of the P2 coefficient is very low (0.03). The most sensitive parameter on grain yield is P5 (SI = 1.38), followed by the G3 (SI = 0.92) and G2 (SI = 0.85) coefficients. The other coefficients have a minor influence on grain yield.

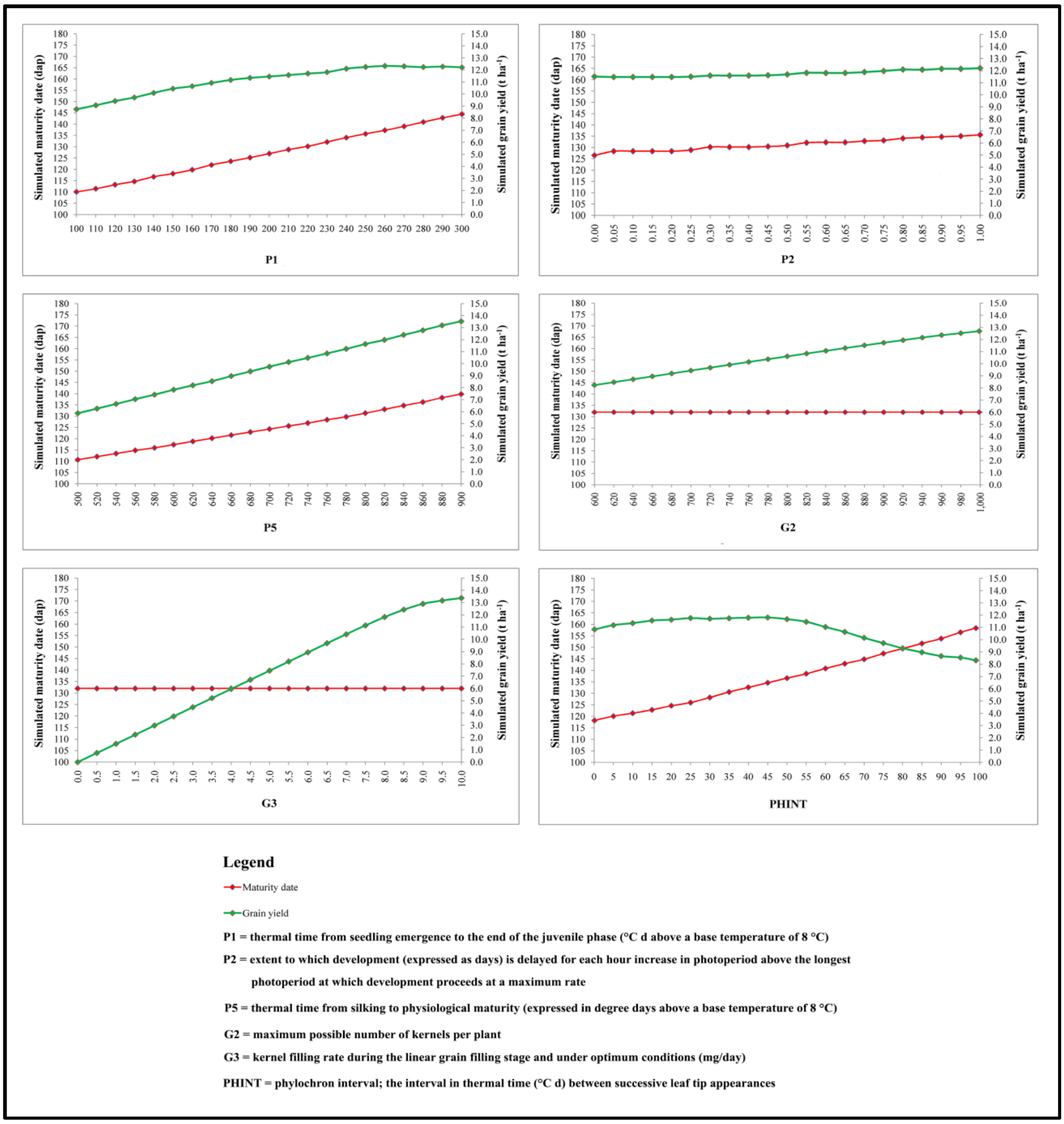
Changes in the maturity date and grain yield of Eleonora cultivar by varying the cultivar coefficient values of the CSM-CERES-Maize crop model are shown in Figure

Table 19. Sensitivity Index of CSM-CERES-Maize crop model for maturity date and grain yield of Eleonora cultivar.

Cultivar coefficient	**Sensitivity Index**	
	Maturity date	**Grain yield**
P1	0.27	0.32
P2	0.03	0.03
P5	0.41	1.38
G2	0.00	0.85
G3	0.00	0.92
PHINT	0.15	0.17

17. The sensitivity of the P5, P1 and PHINT coefficients on phenology is confirmed by the progressive increase of the maturity date (from 110 to 140 dap, from 110 to 145 dap and from 117 to 157 dap for the P5, P1 and PHINT coefficients respectively). Conversely, the P2 coefficient has a low influence on the maturity date (from 127 to 135 dap increasing this coefficient from 0 to 1).

P5 is the input model parameter with the highest sensitivity on grain yield causing an increase in yield from 6.0 to 13.5 t ha^{-1}. A constant increase of yield (from 0 to more than 13.0 t ha^{-1}) is due to the increase of the G3 coefficient from 0 to 10. The grain yield increases (from 8.0 to about 13.0 t ha^{-1}) in an almost linear way even with the increase of the G2 coefficient value (from 600 to 1,000). A lower sensitivity of the CSM-CERES-Maize crop model is associated to the P1 coefficient with an increase of grain yield from 8.5 t ha^{-1} (for P1 = 100) to 12.0 t ha^{-1} (for P1 = 300). The PHINT coefficient has a variable effect on yield. In fact, the grain yield increases from 11.0 to 12.0 t ha^{-1} with an increase of the value of the PHINT coefficient up to 45, while above this value the yield decreases progressively (up to about 8.0 t ha^{-1} for PHINT = 100). Finally, the change in the P2 coefficient value from 0 to 1 causes a negligible variation of the grain yield (from 11.5 to about 12.0 t ha^{-1}).



P1 = thermal time from seedling emergence to the end of the juvenile phase (°C d above a base temperature of 8 °C)

P2 = extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate

P5 = thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C)

G2 = maximum possible number of kernels per plant

G3 = kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day)

PHINT = phylochron interval; the interval in thermal time (°C d) between successive leaf tip appearances

Figure 17. Trend of Sensitivity Index for the different cultivar coefficients of the CSM-CERES-Maize model for maturity date and grain yield of Eleonora cultivar.

3.5 DISCUSSION

For purposes of parameterization of the CSM-CERES-Wheat and CSM-CERES-Maize crop models at the Italian scale, this study has used the experimental data obtained from the "*Sperimentazione interregionale sui cereali"* project.

In general, the predictive ability of the two models in relation to phenology and grain yield of the cultivars under consideration is good. Parameterization results present a good accuracy, as different climatic, soil and management characteristics have been considered, as opposed to recent studies conducted in Italy at the local scale on one or few experimental sites (Rinaldi, 2004; Mereu, 2010; Dettori et al., 2011; De Sanctis et al., 2012).

Overall, the cultivar genetic coefficients obtained in this work during the calibration of the CSM-CERES-Wheat and CSM-CERES-Maize crop models differ to those obtained in other studies on durum wheat, common wheat, and maize in the Mediterranean area (Iglesias, 2006; Abeledo et al., 2008; Braga et al., 2008; Rezzoug et al., 2008; Dettori et al., 2011; Vučetić, 2011; De Sanctis et al., 2012; Salmerón et al., 2012; Thaler et al., 2012). The differences are probably due to the different level of detail (national scale vs. field scale) at which the parameterization was performed, the different characteristics of the cultivars studied and the limited availability of the phenological and yield data in the selected experimental sites. However, the selection of experimental sites located in several Italian regions has made possible to take into account heterogeneous environments. This results in a more robust parameterization of the CSM-CERES-Wheat and CSM-CERES-Maize crop models. The cultivar coefficients related to photoperiod (P1D) and those related to kernel number per unit canopy weight at anthesis (G1) and the standard, non-stressed dry weight of a single tiller at maturity (G2) are the more sensitive coefficients of the CSM-CERES-Wheat model for anthesis date and grain yield, respectively for both the Iride and Bologna cultivars. Regarding the CSM-CERES-Maize model, the highest sensitivity of the model for maturity date is associated to the cultivar coefficient related to thermal time from silking to physiological maturity (P5). This coefficient, together with the maximum possible number of kernels per plant (G2) and the kernel filling rate during the linear grain filling stage and under optimum conditions (G3) are the more sensitive model input parameters for grain yield of the Eleonora cultivar.

Regarding durum wheat, the results of simulations for phenology (anthesis date) at the Italian scale, confirm the good performances of the CSM-CERES-Wheat crop model, despite a low tendency of the model to overestimate, as shown by the CRM (ranging from -0.02 to 0) and MBE (ranging from 0.13 to 3.37 dap) index values.

Regarding grain yield, there is a small contrast between the results obtained for calibration and evaluation of the model. In fact, the statistical analysis for model calibration shows a slight tendency of the model to underestimate the yield. On the other hand, for model evaluation, a low tendency to overestimate was observed, as confirmed by the various statistical indexes. This different tendency between model calibration and evaluation is probably due to the high variability in yields for Iride cultivar from North to South of Italy, to the particular characteristics of the soil that the model is unable to reproduce, and to the resulting water and nitrogen stresses simulated by the model in some sites and crop years where such stresses were not present in the actual experiment. The values for RMSE indexes (from 1.53 to 1.59 t ha^{-1}) and d-Index (0.77) in calibration and evaluation, confirm the ability of the CSM-CERES-Wheat model to predict grain yield at the national scale with a slight margin of error.

The obtained results are acceptable when compared with those obtained by Mereu (2010) for the Iride cultivar in Sardinia and with those obtained by several Authors for other durum wheat cultivars during recent studies conducted in the Mediterranean areas at the local scale (Iglesias, 2006; Rinaldi, 2004; Rezzoug et al., 2008; Mereu, 2010; Dettori et al., 2011; De Sanctis et al., 2012).

Based on these considerations, the CSM-CERES-Wheat crop model may be consider reliable in predicting with good accuracy the anthesis date and grain yield of Iride cultivar at the Italian scale.

Similarly, the performances of CSM-CERES-Wheat crop model for common wheat (Bologna variety) at the Italian scale are successful for anthesis date, although showing a slight difference in the predicting capacity of the model between calibration and evaluation, as shown by the index values of the CRM (ranging from -0.01 to 0.01) and MBE (ranging from 1.60 to -1.78 dap). This different trend is probably due to the fact that the model cannot reproduce the particular properties of the soil. Therefore, the model's accuracy in predicting the anthesis date is high.

Relatively to the grain yield, the tendency of the model to underestimate yields is confirmed, as demonstrated by the similar values of almost all indexes taken in consideration, in particular by the CRM (from 0.05 to 0.36) and by the MBE (from -0.25 to 0.57 dap) indexes. However, the results of simulations for the model calibration and evaluation show that the model is capable of predicting the grain yield on a national scale, albeit with an accuracy lower than anthesis, as confirmed by the index values of the RMSE (from 1.57 to 1.75 t ha^{-1}), GSD (from 29% to 36%) and d-Index (from 0.77 to 0.83).

The results obtained in this study for the Bologna cultivar at the Italian scale are similar to those obtained during recent studies in other Mediterranean areas at the local scale (Abeledo et al., 2008; Rezzoug et al., 2008; Thaler et al., 2012).

On the basis of such considerations and taking into account the high climate, soil and crop management variability from North to South, the CSM-CERES-Wheat crop model for Bologna cultivar at the Italian scale can be considered fairly accurate to estimate the anthesis date and grain yield for Bologna cultivar at the Italian scale.

Regarding maize, the performances of the CSM-CERES-Maize crop model for Eleonora cultivar at the Italian scale are successful for maturity date, taking into consideration the typical maturity date for a FAO class 700 hybrid (132 dap).

Regarding grain yield, the low tendency of the model to overestimate yields is confirmed, as demonstrated by the similar values of almost all statistical indexes. The index values of the RMSE (ranging from 1.29 to 1.50 t ha^{-1}), GSD (ranging from 11% to 14%) and d-Index (from 0.75 to 0.83) highlight the good accuracy of the model in predicting grain yield.

The results of the parameterization of the CSM-CERES-Maize crop model for grain yield of the Eleonora cultivar at the Italian scale are good when compared with those obtained by other Authors (Iglesias, 2006; Vučetić, 2011; Salmerón et al., 2012) in studies conducted recently in the Mediterranean basin at the local scale on different FAO class hybrids. The lower accuracy of the model in predicting yield at the Italian scale is due to the environmental hetorogeneity of the various experimental sites considered for parameterization.

Based on such considerations, the CSM-CERES-Maize crop model shows an acceptable accuracy also in predicting grain yield of the Eleonora cultivar.

In summary, the results of this study confirm that the CSM-CERES-Wheat and CSM-CERES-Maize crop models allow a simulation of the phenological development of cultivars under consideration with high accuracy. The ability of these models in predicting grain yield is quite good, although with a lower accuracy in relation to phenological development, particularly for durum wheat and common wheat.

3.6 CONCLUSIONS

The CSM-CERES-Wheat and CSM-CERES-Maize crop models have been evaluated in different areas of the world, but in most cases at the field scale considering one or few experimental sites. At the Italian level, these models have been calibrated and evaluated considering the most representative cultivars of the three most important cereals in Italy. The ability of both models to predict phenology (anthesis date or maturity date) and grain yield was tested. The study was carried out considering the datasets of more cropping seasons by heterogeneous environments located in various Italian regions.

Overall, the results confirm that the performances of the two models are good if applied in the environmental conditions of the Mediterranean area. Regarding the phenological data, the statistical results obtained in this study show the efficiency of the two crop models to predict the date of anthesis and maturity with a slight tendency to overestimate in the phase of model evaluation. Also for grain yield good results were obtained, but with differences between the various crops. The statistical analysis has revealed a tendency to overestimate for durum wheat and maize and to underestimate for common wheat. The results show that the trend highlighted in the model evaluation for common wheat and maize follows the one obtained in the model calibration, confirming the validity of the models in predicting crop yields for the Bologna and Eleonora cultivars. Instead, for durum wheat, the trend is reversed. This is probably due to the high variability of the yields, which was observed for Iride cultivar between the different cultivation areas and also between the different experimental sites.

The results obtained indicate that the parameterization of the CSM-CERES-Wheat and CSM-CERES-Maize crop models at the Italian scale are useful to predict phenology and yield of durum wheat, common wheat and maize in the Mediterranean area. However, an improvement of the calibration and evaluation of the models is possible in the area under consideration. The availability of long-term data sets and weather and soil data measured in the experimental sites are needed for further optimization of the genetic coefficients. In such a way a better parameterization of the crop models will be possible, resulting in an improvement of their ability to predict the phenology and grain yield of these crops and especially to perform a more detailed assessment of other aspects (e.g., soil carbon content, soil carbon and nitrogen dynamics, irrigation requirements for an optimal use of the water resources, etc.). This will enable obtaining more reliable results in subsequent applications of the CSM-

CERES-Wheat and CSM-CERES-Maize crop models (e.g. studies on climate change impacts and evaluation of potential adaptation strategies to offset negative effects of climate change on crops growth and productivity).

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4. ASSESSMENT OF CLIMATE CHANGE IMPACTS ON *TRITICUM DURUM* DESF., *TRITICUM AESTIVUM* L. AND *ZEA MAYS* L. AT THE ITALIAN SCALE USING A DIGITAL PLATFORM AND HIGH RESOLUTION CLIMATE DATA

4.1 INTRODUCTION

In recent decades there has been an increasing focus on climate change and related impacts (direct and indirect) on human activities and on socio-economic development. The situation becomes even more worrying when one considers future climate projections (IPCC, 2007, 2013). It is now scientifically proven that the increase in the atmospheric concentration of greenhouse gases (GHGs), particularly carbon dioxide (CO_2) is the main driver of climate change. In fact, this variation in the atmospheric composition determines not only the global warming of the climate system, but also a change in rainfall patterns (decrease in the number of rainfall events, increase of the intensity of the phenomena and increased frequency of extreme weather events) (IPCC, 2007, 2014a).

There are, however, several non climatic drivers (e.g., land use and land-cover changes, pollution, technological evolution, etc.) that may influence the responses of the climate system. In fact, such non climatic drivers do have effects (direct and/or indirect) on climate variables (e.g., reflected solar radiation).

One of the most common classifications of the impacts of climate change is that adopted by the Food and Agricultural Organization (FAO). According to this classification, such impacts can be of biophysical or economic type (Table 1).

An important aspect in the evaluation of the climate change impacts is represented by uncertainties, which in turn are derived mainly from the uncertainties of climate projections. Even the cell resolution of climate data influences the assessment of impacts: Regional Climate Models (RCMs) offer the possibility to obtain a more accurate estimate than the General Circulation Models (GCMs), as demonstrated by recent studies (Carbone et al., 2003; Tsvetsinskaya et al., 2003; Olesen et al., 2007). These considerations are of particular importance for the Euro-Mediterranean area, characterized by a significant variability of climatic conditions and which, in comparison to the rest of Europe, will be subject to a greater extent to the adverse impacts of climate change, as confirmed by recent research (IPCC, 2007, 2014b; Behrens et al., 2010; Ciscar et al., 2011; Iglesias et al., 2012).

Table 1. Classification of the impacts of climate change according to FAO.

Climate change impact category	**Impacts**
Biophysical impacts	- Sea level rise - Changes in ocean salinity - Physiological impacts on crops, pasture, forests and livestock (quantity and quality) - Changes in land, soil and water resources (quantity and quality) - Increased weed and pest - Changes in spatial and temporal distribution of impacts
Socio-economic impacts	- Decline in crop yields and production - Decrease of marginal Gross Domestic Product (GDP) from agriculture - Fluctuations in world market prices - Changes in geographical distribution of trade regimes - Increased number of people at risk of hunger and food insecurity - Migration and civil unrest

Recently, a large number of RCMs are available for different areas of the worldas part of CORDEX (Coordinated Regional Climate Downscaling Experiment) initiative (Jacob et al., 2014). Regarding Europe, several RCMs with a cell resolution equal to 12.5 and 50 km are available. The COSMO-CLM RCM at high cell resolution (8 km) is also available at Italian level (Rockel et al., 2008). The availability of climate data having different cell resolution allows to evaluate the uncertainty analysis of the simulation results associated with the different resolution of climate data and to evaluate which climate data resolution is better in order to obtain more reliable results (Angulo et al., 2013; Zhao et al., 2015).

4.1.1 The vulnerability of agriculture to climate change

The vulnerability of the agricultural sector to climate change and its impacts on both global and local scale is high. This vulnerability depends on the sensitivity of agriculture to changes in climate, the adaptive capacity of the system and the degree of exposure to climate hazards (IPCC, 2014a). Taking into account the high spatial variability of climate change, the vulnerability of agriculture to such changes varies greatly from one region to another.

The production of cultivated plants (particularly the irrigated crops) is very sensitive to local climatic conditions whose variability is the key factor of the variability of agricultural production (Petr, 1991; Fageria, 1992). Thus, the extent of climate change impacts in agriculture varies greatly in the different regions of the world (Parry et al., 2004; Nelson et al., 2009).

Considering climate projections for the coming decades, agricultural production will be significantly affected by climate change (increased atmospheric CO_2 concentration, temperature rise, changes in rainfall patterns, and alteration of the frequency of extreme events) with direct consequences (e.g., variation in the length of growth cycle and yield) and indirect consequences (e.g., variation of available water resources as well as variation of the distribution and extent of pest and plant diseases).

According to recent studies, the impacts of climate change on the yield of major crops (maize, wheat and rice) on a global scale in the coming decades will be negative, with a reduction in yield for 2050 ranging from -4% to -12% for maize, from -10% to -13% for wheat and from -9.5% to -12% for rice (Nelson et al., 2010). Regarding Europe, crop yields may vary in different ways from region to region. Iglesias et al. (2012) have estimated that in 2080 the average yield of maize, wheat and soybeans will increase in the Boreal region (from +41% to +54% with the A2 emission scenario and from +34% to +47% for B2 scenario), in the Alpine region (approximately +20% and from +20% to +23% with the A2 and B2 emission scenarios, respectively), in the Continental South region (from +26% to +33% with the A2 emission scenario and from +11% to +24% for B2 scenario), and in the Atlantic Central region (from +5% to +19% and from +6% to +17% under the A2 and B2 emission scenarios, respectively). On the other hand, yields will decrease in the Atlantic South region (from -10% to -26% with the A2 scenario and from -7% to -12% with the B2 scenario) and in the Mediterranean North region (from -8% to -22% and from 0% to -11% with the A2 and B2 scenarios respectively). Estimates for the Mediterranean South region have shown different changes in yield depending of the emission scenario, with a yield reduction (from -12% to -27%) with the A2 scenario and a small increase in yield (from +1% to +5%) with the B2 scenario.

On the basis of these considerations, probably there will be a reduction of food supply, with negative consequences on food security, particularly in poor countries (Fischer et al., 2005; IPCC, 2007, 2014a).

Therefore, it is necessary to have an accurate assessment of the impacts of climate change on crop productivity in order to identify the most effective adaptation strategies, so as to limit the negative effects of climate change on the agricultural sector and, consequently, on food safety.

In addition, agriculture is the main source of methane emissions (wetlands, rice paddies, livestock) and nitrous oxide (nitrogen fertilizers) (IPCC, 2007, 2014c).

For this reason, the agricultural sector is involved also in the adoption of mitigation strategies to climate change. The availability of resources and the willingness of policy makers will be key factors to address this issue that is becoming more and more important and currently of interest both at the global and local levels.

4.1.2 Climate change and crop growth

Among the various natural systems, agro-ecosystems are particularly sensitive to climate change with consequent positive or negative impacts on the different processes that occur in these systems (Figure 1).

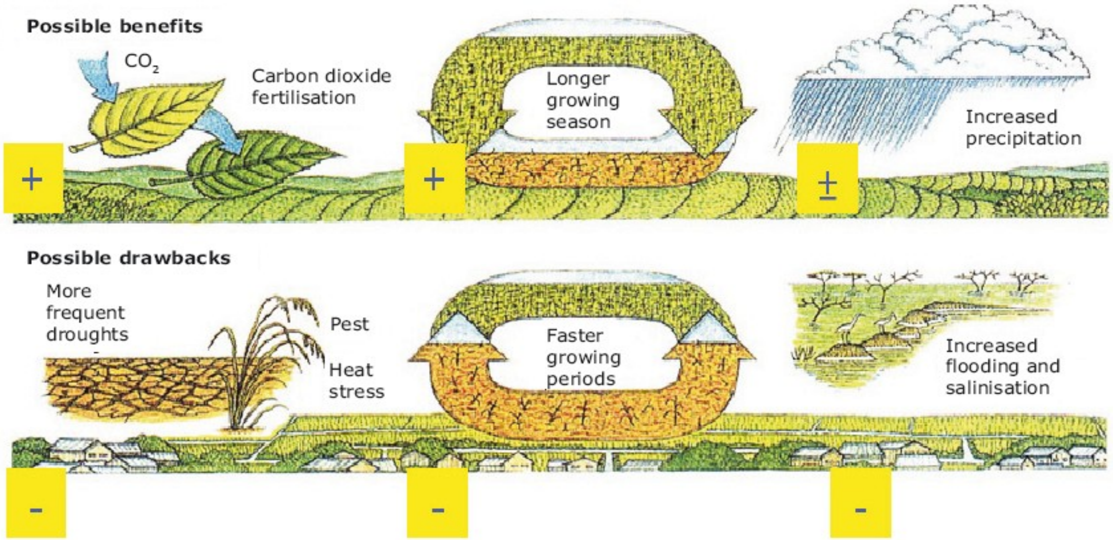

Figure 1. Agro-ecosystem processes and a changing climate (source: Bongaarts, 1994).

Therefore, in order to cope with the impacts of climate change in agriculture, it is essential to have a thorough understanding of the effects of climate change (individually and combined together) on the processes that directly or indirectly influence the development and productivity of crops.

Increase in the atmospheric concentration of carbon dioxide

The processes that regulate the growth and development of plants are directly favored by the increase of the atmospheric concentration of carbon dioxide (CO_2). Thus, the crop yield is positively influenced by the CO_2 fertilization effect. Recent studies show that in the absence of climate change and other stress conditions, many crops would respond positively to increased atmospheric CO_2 concentration due to the increase of the photosyntetic rate (Kimball et al., 2002; Long et al., 2004; Ainsworth and Long, 2005; Ainsworth and Rogers, 2007).

The crops that have a better response to elevated atmospheric CO_2 concentrations are C3 crops (wheat, rice, barley, soybean, etc.) due to their lower photosynthetic efficiency as compared to the C4 crops (maize, sugar cane, sorghum, millet, etc.) (Leakey, 2009). Several experiments carried out in the last decades have shown that the yields increase to a doubling of CO_2 concentration, particularly for C3 crops (+30% to +50%) (Kimball, 1983; Cure and Acock, 1986; Poorter, 1993; Fuhrer, 2003; Ainsworth and Long, 2005). The CO_2 fertilization effect on crop yield is greater in rainfed crops because the water-use efficiency and water absorption capacity are greater than in irrigated crops (Tubiello and Ewert, 2002; Nelson et al., 2009).

Other effects of increased atmospheric CO_2 concentration are the reduction of stomatal conductance and transpiration rate (Ainsworth and Rogers, 2007). Furthermore, elevated CO_2 usually determines a variation in plant tissues composition, with an increase in the concentration of non-structural carbohydrates and a reduction of protein content and mineral nutrients (Taub, 2010).

However, the positive effects of the atmospheric CO_2 enrichment may vary in the presence of other stress factors. For example, temperature increase and alteration of rainfall patterns may further increase crop response to high concentrations of CO_2 in the short term, while low nitrogen fertilization and increased frequency of extreme weather events (droughts, floods, etc.) can cause a reduction in yield (Kimball and Idso, 1983; Kimball et al., 2002; IPCC, 2007).

Increase in air temperature

Air temperature is one of the climatic variables with greater influence on the physiological processes related to crops development and growth. An increase in temperature usually results in an increase in the development rates of plants, but beyond a certain temperature threshold, the trend is reversed. Therefore, an increase in temperature during the growing season can have a significant impact on the productivity of agricultural systems (Battisti and Naylor, 2009).

The effect of temperature varies with latitude and elevation. In particular, at low latitudes and elevations, crops are more sensitive to high temperatures, thus an increase in temperature causes an increase of the length of the growing season, but it also creates additional water requirements and heat stress which in turn reduce the yields (up to -27% in 2080 with a temperature increase of 5.4 °C) (Ciscar et al., 2011).

Conversely, at high latitudes and elevations the limiting factor is represented by low temperatures. In these areas, the increase of temperatures will favor an increase in yields (up to 40-50% in 2080 with a temperature increase of 5.4 °C), as a result of a longer growing season, higher minimum winter temperatures and lower risk of frost damages (Behrens et al., 2010; Ciscar et al., 2011).

Therefore, temperature increase could be particularly useful for the spring-summer crops as it would allow to advance the date of sowing and to reach earlier physiological maturity (Lavalle et al., 2009; Olesen et al., 2012). Furthermore, it is possible to introduce cultivars with a longer growth cycle (for example, maize hybrids of the FAO 500, 600 or 700 classes, instead of the precocious hybrids of the FAO 300 or 400 classes). At low latitudes (for example, in Southern Europe), the temperature increase could lead to a reduction in yield for these crops (Audsley et al., 2006; Giannakopoulos et al., 2009; Saadi et al., 2014).

Instead, the autumn-winter cycle crops (e.g., wheat) could be affected by the milder winters that would lead to a shorter growth cycle. For example, recent studies on winter wheat (Moriondo et al., 2011) have shown that the temperature increase expected in the coming decades in the Euro-Mediterranean area will lead to a reduction in the time interval between the emergence and anthesis (on average -40.6 and -35 days for the A2 and B2 emissions scenarios respectively). Similarly, Saadi et al. (2014) have estimated a reduction of the average length of growing season of the winter wheat for 2050 (ranging from -3 to -41 days in the Euro-Mediterranean area and from -10 to -25 days in Italy) compared to 2000 under the A1B emission scenario. The result will be a probable reduction in yields and an increase in their variability (Audsley et al., 2006; Olesen et al., 2007; Giannakopoulos et al., 2009; Saadi et al., 2014). However, the increase of the temperature can allow winter crops to get closer to the optimum temperature for development, thus facilitating an increase in yields.

The effect of temperature increase on the yield varies with latitude: a temperature increase of 2 °C in the middle latitudes could increase wheat yield of 10%, while at low latitudes the yield may decrease almost to the same extent (IPCC, 2007, 2014a). The combined effect of temperature and atmospheric CO_2 concentration varies with the extent of warming and with the crop. It has been observed that in general for cereals a temperature rise of 1-2 °C with elevated CO_2 causes an increase in yield, but beyond this temperature threshold the positive effects of the high concentration of CO_2 on the yield are reduced (Rosenzweig and Tubiello, 1996; Streck, 2005).

The sensitivity to the temperature increase varies with the type of crop. For seed crops the temperature and the day length are important for reaching maturity. So, an increase in temperature reduces the length of the growing season with a potential negative impact on the yield (Peiris and McNicol, 1996). The perennial crops (for example, grapevine) are usually susceptible to spring frosts during flowering. Probably the temperature increase expected by future climate scenarios will not alter the risk of frost damage in warmer areas because the flowering date will occur earlier. On the other hand, warming up will probably result in a lower risk of early autumn frosts and an increase in water demand (Olesen et al., 2011).

Finally, the increase in temperature may cause the expansion and the northward shift of the cultivation areas of some species such as wheat, maize, sunflower, soybean, grapevine, olive trees, and energy crops, as shown by recent studies in Europe (Hildén et al., 2005; Maracchi et al., 2005; Schröter et al., 2005; Audsley et al., 2006; Olesen et al., 2007).

Changes in rainfall patterns

Rainfall indirectly influences various processes of crops growth and development. Therefore, agricultural production is strongly influenced by soil water availability. In areas where rainfall is not a limiting factor, there are the best conditions for crop growth and productivity (Lavalle et al., 2009). However, in the last decades, in many areas (especially at the lower latitudes) there has been a gradual decrease in annual precipitation, coupled with an increase of the irregularity of rainfall distribution in space and in time. The Mediterranean basin is an example. In the coming decades, this area, as compared to central and northern areas of Europe, will experience a decrease in rainfall and which rainfalls will be concentrated in autumn and winter to an increasing extent (IPCC, 2007, 2014b).

The decreased contribution of rainfall increases crop water stress (particularly for the spring-summer crops, like maize) due to increased water loss by evaporation and the decrease in soil moisture. Water stress is dangerous if it occurs during the most important phenological phases, particularly during flowering and grain filling in cereals (such as maize and wheat), with consequent loss of production. In addition, the increased losses of water by evapotranspiration lead to additional crop water requirements (Lavalle et al., 2009). This can result in an increase in irrigation water provision for the irrigated crops (e.g., maize) and the application of irrigation for rainfed crops (e.g., wheat).

An increase in rainfalls (expected at higher latitudes) allows crops to grow in the best conditions, notwithstanding the higher risk of nitrate leaching (Olesen et al., 2007). However, the increase in precipitation intensity is responsible for the increased frequency of extreme weather events (storms, floods, etc.), often with disastrous consequences on agricultural production.

Finally, the change in rainfall patterns together with rising temperatures, will lead to a change in the availability of water resources, with a general reduction expected for the Mediterranean basin (García-Ruiz et al., 2011).

Increased frequency of extreme weather events

Climate change (increase in air temperature, changes in rainfall patterns and increased climate variability) will probably cause the increase in frequency of extreme weather events in the coming decades (IPCC, 2007, 2013).

The expected increase of drought events and heat waves is due to the combined effect of rising temperatures and reduced rainfall (Meehl and Tebaldi, 2004; Schär et al., 2004). The predicted effects on agricultural systems are a decrease in average yield and an increase in its spatial and interannual variability (Jones et al., 2003; Trnka et al., 2004; Ciais et al., 2005; Eitzinger et al., 2009). A recent example is given by the extraordinary heat wave that occurred during 2003 in Europe, with significant yield reduction, particularly for irrigated crops with a spring-summer cycle, such as maize (van der Velde et al., 2012).

The Mediterranean basin area could be affected to a greater extent by the increased frequency of extreme weather events during phenological critical phases. For example, recent research shows that the increased frequency of heat stress and late frosts during anthesis, the increase in rainfall intensity and in the frequency and duration of drought events may reduce the yield of summer crops (e.g., sunflower) (Moriondo et al., 2011). The increase in precipitation can severely damage crops both directly (e.g., damages by root asphyxia, hail and floods) and indirectly (increased incidence of pest and plant diseases) (Rosenzweig et al., 2002a,b).

Perennial crops (e.g., grapevine and olive) are very sensitive to the increase in the frequency of extreme weather events, whose negative impacts on their productivity could last for several years.

Changes in distribution of weed and plant diseases

The development and spread of weed and plant diseases are closely dependent on crops and their geographical distribution. Thus, the shift of cultivation areas expected for some crops in the coming decades could lead to a significant change of the extent and distribution of weed and plant diseases.

In fact, temperature increase allows a greater number of reproductive cycles during the growing season of crops, favoring the proliferation of harmful insects and their introduction in areas where previously they were not present (Bale et al., 2002). Plant diseases are favored by higher temperatures as well, resulting in reduced production and increased consumption of pesticides (Salinari et al., 2006).

The increase in precipitation intensity and frequency of extreme weather events create conditions which are favorable to a higher incidence of pest and diseases (Rosenzweig et al., 2002a, b).

In contrast to plant diseases, weed species will be directly favored by the increase of atmospheric CO_2 concentration, with an increase in photosynthetic rate (higher in C3 species). This could alter the weed crops competition, favoring one or the other depending on the trend of climate change (Anderson et al., 2004).

Sea level rise and salinization

Another indirect effect of climate change is the rise in mean sea level, expected in the coming decades as a result of ice melting. Consequently the risk of coastal flooding will increase. Therefore, coastal agricultural regions could suffer serious flooding as well as soil and groundwater salinization (IPCC, 2014a,b). According to recent studies, the Mediterranean area is among those areas most at risk (Behrens et al., 2010).

4.1.3 Climate change impacts on Italian agriculture

Agriculture is one of the most important economic sectors of the European economy. Therefore, given the high sensitivity of agro-ecosystems to climate change, the assessment of their impacts on growth and productivity of crops is essential in order to evaluate the most effective adaptation strategies.

Recent research shows that the impacts of climate change on European agriculture will vary according to latitude, with a greater vulnerability of the southern areas (Table 2).

Table 2. Main benefits and disadvantages related to the climate change on European agriculture (source: IPCC, 2007, 2014b).

Area	Benefits	Disadvantages
Central and Northern Europe	- Introduction of new crops - Increase in yields - Expansion of the suitable areas for cultivation	- Increase in crop protection - Increase in risk of nitrate leaching - Acceleration of the organic matter decomposition
Southern Europe	- Introduction of new crops	- Decrease in yields - Increase in yield variability - Increase of the incidence of extreme weather events - Reduction of the suitable areas for traditional crops

The Italian agricultural sector, therefore, could be particularly affected by future climate change, particularly in the southern regions and the Islands in which the main limiting factor is the shortage of rainfall and their concentration during the winter. For this reason, irrigated high-income herbaceous crops (e.g., maize) are distributed mainly in the northern regions, while rainfed seed crops (e.g., durum wheat) prevail in the Southern Italy.

The higher yield decreases over the next decades are expected for spring crops (e.g., maize, sunflower, and soybean), while for autumn crops the impact on yields is more variable at the national scale. Recent research (Tubiello et al., 2000) shows that in the absence of adaptation, the cereal yield in Northern Italy (Emilia-Romagna) could decline by 5-15% for wheat and maize, more than 20% for barley and soybean and over

50% for sorghum. Instead, in the Southern Italy (Apulia) a higher reduction of the yield (30-50%) is expected for wheat and a lesser one (10-30%) for sorghum. However, a significant reduction in yield (over 40%) was obtained for sorghum also in Southern Italy (Ventrella et al., 2008). Mereu (2010), in a study conducted on durum wheat in four experimental sites located in Sardinia, has observed lower decreases in the average yield (2-6% by 2025 and 10-18% by 2075). Similarly, an increase in grain yield of durum wheat has been estimated by Carboni (2011) considering two experimental sites located in the same region (on average from +2% in 2025 to +13% in 2075).

The increase in frequency of extreme weather events (heat waves, droughts, floods) could severely damage the spring crops, with substantial reductions in yields even at a large scale. For example, during the extraordinary heat wave of summer 2003, the temperature has risen by more than 6 °C beyond the long-term average temperature, with serious effects on the maize yield in the Po Valley (up to -36%) (Eitzinger et al., 2009).

The expected increase in the frequency of heat waves and drought events in Italy, together with the increase in temperature will lead to the increase in evapotranspiration, and consequently result in greater irrigation water demand for irrigated crops. Therefore, considering the shortening of the crop cycle for the main crops, induced by the temperature increase (Moriondo and Bindi, 2007), changes in rainfall patterns will be crucial in determining future seasonal irrigation requirements of the crops (Figure 2).

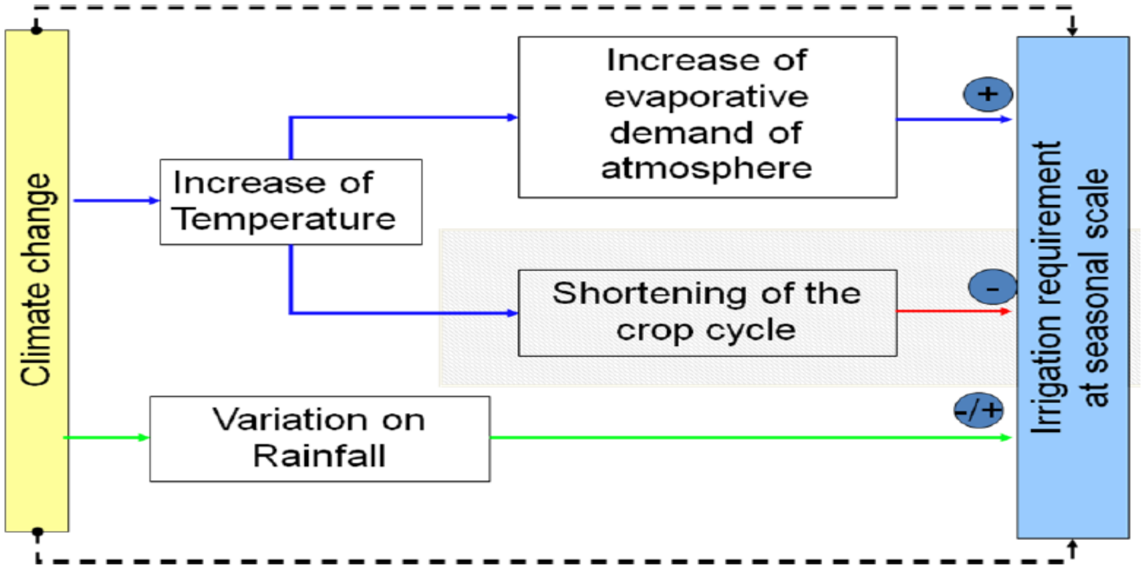

Figure 2. Links between climate change and crop irrigation requirement (source: Eitzinger et al., 2009).

Recent studies have shown an increase in irrigation requirements for the next decades, but to a different extent from north to south. In Northern Italy, the increase in irrigation requirements will be lower because the reduction of summer rainfall will be offset by the expected increase in spring precipitation (Gallo et al., 2012). Conversely, in Sardinia a higher irrigation water demand is expected on average (+5% for maize, +6% for grapevine, +10% for citrus, +11% for olive, and +14% for artichoke) (Mancosu, 2013). With regard to the change in cultivation areas, a northward shift is expected for suitable areas of durum wheat, for many horticultural crops (e.g., lettuce, fennel and cabbage) and for tree crops such as olive (Bindi et al., 1992; Eitzinger et al., 2009).

Finally, the expected increase in precipitation intensity and mean sea level rise may cause an increased risk of river and coastal floods and coastal salinization of agricultural land, resulting in further yield reduction (Behrens et al., 2010).

On the basis of such considerations and taking into account the fact that the durum wheat, common wheat and maize are the most important cereals in Italy (see section 1.1 of this thesis), the assessment of climate change impacts on phenology and productivity of these crops is essential in order to identify potential strategies for adaptation and mitigation to climate change. This will make it possible to optimally plan the priority actions in each cultivation area.

The use of crop simulation models such as DSSAT-CSM (Jones et al., 2003; Hoogenboom et al., 2010), is the most common approach for the assessment of impacts of climate change on the development and yield of crops. In fact, if the crop models implemented in this tool (e.g., CSM-CERES-Wheat and CSM-CERES-Maize) have been parameterized in a satisfactory manner, their predictive efficiency allows a fairly reliable estimate of the impacts of climate change both at the field and at the regional scale.

Table 3 shows some of the most recent studies regarding the assessment of the climate change impacts on wheat and maize in the world through the use of crop simulation models.

Table 3. Some of the more recent climate change impact studies for wheat and maize using crop simulation models (references to other studiescan be found in the text).

Author	**Object**	**Crop model**	**Location**	**Level of analysis**	**Variables**
Gonzáles-Zeas et al., 2012	Looking beyond the average agricultural impacts in defining adaptation needs in Europe.	CERES-Wheat CERES-Maize	Europe	Continental	Yield
Iglesias et al., 2012	A regional comparison of the effects of climate change on agricultural crops in Europe.	CERES-Wheat CERES-Maize	Europe	Continental	Phenology and yield
Mereu et al., 2012	Impact of climate change and adaptation strategies on crop production in Nigeria.	CERES-Maize	Nigeria	National	Yield
Thaler et al., 2012	Impacts of climate change and alternative adaptation options on winter wheat yield and water productivity in a dry climate in Central Europe.	CERES-Wheat	Austria (Marchfeld region)	Local	Phenology and yield
Moriondo et al., 2011	Climate change impact assessment: the role of climate extremes in crop yield simulation.	CropSyst	Mediterranean basin (Greece, Italy, Portugal, Spain, Balkans, France)	Sub-continental	Phenology and yield
Al-Bakri et al., 2010	Potential impact of climate change on rainfed agriculture of a semi-arid basin in Jordan.	CERES-Wheat	Jordan	Regional	Yield
Guo et al., 2010	Responses of crop yield and water use efficiency to climate change in the North China Plain.	CERES-Wheat CERES-Maize	China (North China Plan)	Regional	Phenology and yield
Mereu, 2010	Climate Change Impact on Durum Wheat in Sardinia.	CERES-Wheat	Italy (Sardinia, four exprimental sites)	Local	Phenology and yield
Giannakopoulos et al., 2009	Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming.	CropSyst	Mediterranean basin (Morocco, Algeria, Tunisia, Lybia, Egypt, Jordan, Turkey, Greece, Serbia, Italy, France, Spain, Portugal)	Sub-continental	Yield
Semenov, 2009	Impacts of climate change on wheat in England and Wales.	Sirius	England and Wales	Regional	Phenology and yield
Brassard et al., 2008	Impacts of climate change and CO_2 increase on agricultural production and adaptation options for Southern Québec, Canada.	CERES-Wheat CERES-Maize	Canada (Quebec)	Regional	Yield
Meza et al., 2008	Climate change impacts on irrigated maize in Mediterranean climates: Evaluation of double cropping as an emerging adaptation alternative.	CERES-Wheat CERES-Maize	Chile	Local	Yield
Mínguez et al., 2007	First-order impacts on winter and summer crops assessed with various high-resolution climate models in the Iberian Peninsula.	CERES-Wheat CERES-Maize	Iberian Peninsula	Regional	Yield
Tubiello et al., 2000	Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian locations.	CropSyst	Italy (Modena and Foggia)	Local	Phenology and yield

4.2 OBJECTIVES

The assessment of the impacts of climate change on phenology and yield of durum wheat, common wheat and maize in Italy is the objective of this section of the thesis. To this end, the CSM-CERES-Wheat and CSM-CERES-Maize crop models parameterized at the Italian scale (see section 3 of this thesis) have been used.

The specific objectives of the impact study are as follows:

1. to test the reliability of the CSM-CERES-Wheat and CSM-CERES-Maize crop models parameterized with field measurements in predicting yields at spatial scale using the climate change scenarios under consideration;
2. the study of the climate change impacts on phenology (maturity date) and grain yield of crops under consideration at the Italian scale, for each area under cultivation;
3. the analysis of the effect of different spatial resolution of climate data on the assessment of climate change impacts on maturity date and grain yield of the three crops.

This approach makes it possible to study at the national scale the effects of spatial variability of environmental conditions (weather, soil, and crop management) on crop productivity, to estimate the potential impacts of future climate change on phenology and yield of the considered crops, and to understand if the use of high resolution climate data is useful to obtain more reliable results.

4.3 MATERIALS AND METHODS

The CSM-CERES-Wheat and CSM-CERES-Maize crop models implemented in the Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM), described in the sections 1.3.3 and 1.3.4 of this thesis (Jones et al., 2003; Hoogenboom et al., 2010), have been used for climate change impact assessment on phenology and grain yield of the crops under consideration. In this work, the DSSAT-CSM v.4.5.0.0 was used (Hoogenboom et al., 2012).

The methodological scheme used in the assessment of the impacts of climate change on phenology and yield of durum wheat, common wheat and maize in Italy is shown in Figure 3. For each crop, the analysis was performed for the cultivars (Iride for durum wheat, Bologna for common wheat, and Eleonora for maize) and different cultivation areas, which have been considered for the parameterization of the CSM-CERES-Wheat and CSM-CERES-Maize crop models at the Italian scale (Gallo et al., 2014). For maize, the same areas of the common wheat have been considered.

Finally, a statistical analysis was performed for each crop and period so as to establish if the different spatial resolution of climate data determines statistically significant differences between the annual mean values of maturity date and grain yield in each area under consideration.

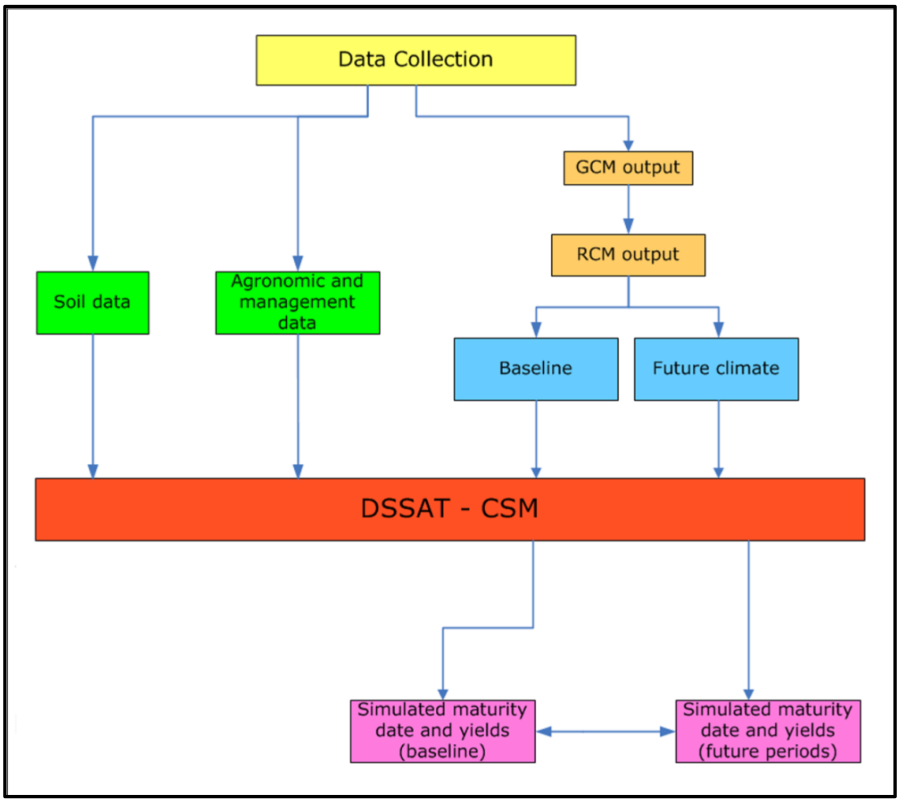

Figure 3. Methodological scheme of the climate change impact assessment.

4.3.1 Data collection

During the first phase, the required data for the study of impact have been collected. For each crop, the non-meteorological input data (soil data, characteristics of the cultivar and crop management data) were the same for each future period.

Soil data

The soil data used in this work have been obtained from the ISRIC-WISE v.1.2 raster data set, whose spatial resolution is equal to 5x5 arcminutes (Batjes, 2012). The data in this raster were derived by interpolation from the data of 10,250 soil profiles around the world (Batjes, 2008).

The global raster has been clipped for Italy and its resolution has been increased to 8 km, so as to ensure a perfect overlap of this raster with those of the RCP4.5 and RCP8.5 climate change scenarios used in this study.

Climate data

In this work, weather data of the RCP4.5 (Smith and Wigley, 2006; Clarke et al., 2007; Wise et al., 2009) and RCP8.5 (Rao and Riahi, 2006; Riahi et al., 2007) climate scenarios have been used to assess the climate change impacts on phenology and yield of the three crops under consideration (see also section 1.2.2 of this thesis).

The Regional Climate Model (RCM) that will be used to evaluate the climate change impacts is the COSMO-CLM model, with a cell resolution of 8 km and whose climate data were generated from the global model CMCC-MED through dynamic downscaling (Rockel et al., 2008; Gualdi et al., 2012). The COSMO-CLM model was run under the RCP4.5 and RCP8.5 climate change scenarios for the period 1976-2095. For each climate scenario, the daily data of the following variables were used:

1) minimum temperature measured at 2 meters from the surface;
2) maximum temperature measured at 2 meters from the surface;
3) total precipitation amount;
4) averaged surface net downward shortwave.

Tables 4 and 5 show the average annual values of minimum and maximum temperature and total precipitation with the RCP4.5 and RCP8.5 climate scenarios for the baseline period (1976-2005) and for future periods (2006-2035, 2036-2065 and 2066-2095) in each area for durum wheat, common wheat and maize respectively.

Table 4. Average annual values of minimum and maximum temperature and total precipitation for baseline and future periods with the RCP4.5 and RCP8.5 climate scenarios for each area of durum wheat in Italy.

Area	**Variable**	**Baseline (1990)**	**RCP4.5**			**RCP8.5**		
			2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	Tmax (°C)	14.4	15.6	16.8	17.6	17.2	17.2	19.9
	Tmin (°C)	7.3	8.4	9.5	10.3	8.7	9.9	12.3
	Tot. prec. (mm)	960.4	896.1	898.0	900.9	1012.4	922.1	838.2
Centre-Italy (Tyrrhenian side)	Tmax (°C)	16.2	17.3	18.5	19.3	18.9	18.9	21.5
	Tmin (°C)	8.1	9.1	10.2	11.0	9.5	10.7	13.0
	Tot. prec. (mm)	757.9	732.1	705.2	726.7	767.7	745.7	674.0
Centre-Italy (Adriatic side)	Tmax (°C)	15.1	16.2	17.3	18.2	17.8	17.8	20.3
	Tmin (°C)	7.6	8.6	9.7	10.5	8.9	10.2	12.5
	Tot. prec. (mm)	744.5	713.4	680.0	695.1	719.1	676.8	610.4
South-Peninsular	Tmax (°C)	17.1	18.2	19.3	20.2	19.8	19.8	22.3
	Tmin (°C)	9.0	10.0	11.1	11.9	10.3	11.6	13.8
	Tot. prec. (mm)	646.3	609.0	565.6	563.2	596.6	550.2	506.1
Sicily	Tmax (°C)	18.8	19.8	20.9	21.7	21.5	21.5	23.8
	Tmin (°C)	10.2	11.2	12.2	12.9	11.5	12.7	14.9
	Tot. prec. (mm)	474.3	475.5	428.2	391.1	447.5	382.3	359.5
Sardinia	Tmax (°C)	17.8	19.0	20.1	20.7	20.5	20.5	23.0
	Tmin (°C)	9.6	10.7	11.7	12.3	10.9	12.2	14.4
	Tot. prec. (mm)	527.9	511.6	480.3	487.7	526.0	487.8	417.0

Table 5. Average annual values of minimum and maximum temperature and total precipitation for baseline and future periods with the RCP4.5 and RCP8.5 climate scenarios for each area of common wheat and maize in Italy.

Area	**Variable**	**Baseline (1990)**	**RCP4.5**			**RCP8.5**		
			2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	Tmax (°C)	14.4	15.6	16.8	17.6	17.2	17.2	19.9
	Tmin (°C)	7.3	8.4	9.5	10.3	8.7	9.9	12.3
	Tot. prec. (mm)	960.4	896.1	898.0	900.9	1012.4	922.1	838.2
Centre	Tmax (°C)	15.9	17.0	18.2	18.9	18.6	18.6	21.2
	Tmin (°C)	7.9	8.9	10.0	10.8	9.3	10.5	12.8
	Tot. prec. (mm)	752.9	725.2	695.0	713.8	748.9	720.9	650.7
South-Islands	Tmax (°C)	17.7	18.9	20.0	20.8	20.5	20.5	22.9
	Tmin (°C)	9.5	10.6	11.6	12.3	10.8	12.1	14.3
	Tot. prec. (mm)	575.0	551.4	509.9	500.6	541.5	491.7	448.6

Agronomic and crop management data

For data related to the characteristics of the cultivar, ecotypes and genetic coefficients obtained during the parameterization of CSM-CERES-Wheat and CSM-CERES-Maize crop models at the Italian scale have been used (Gallo et al., 2014) (see Chapter 3 of this thesis).

For crop management data (in particular sowing details and fertilization regime), typical values representative of each cultivation area have been considered (Table 6). In particular, sowing dates and fertilization rates used in this study for each area were obtained by averaging the corresponding values observed from 2001 to 2010 in the different experimental sites by Istituto Sperimentale per la Cerealicoltura ("*Sperimentazione interregionale sui cereali*" project). All crop management data used in this work were obtained from the special issues of the journal L'Informatore Agrario. http://www.informatoreagrario.it). For maize these data were available only for the North area. For the Central and South-Islands areas, in the absence of experimental data, an early sowing date with respect to the North area has been considered. In fact, in these cultivation areas, maize is usually sown early, so as to allow early harvest and

Table 6. Characteristics related to the sowing and fertilization regimes of each crop in each area for climate change impacts assessment.

Crop	**Area**	**Sowing date**	**Total annual fertilization rates (kg ha^{-1})**		
			N	**P**	**K**
Durum wheat	North	5th November	160	84	94
	Centre-Italy (Tyrrhenian side)	11th December	164	87	88
	Centre-Italy (Adriatic side)	25th November	139	97	51
	South-Peninsular	2nd December	100	83	0
	Sicily	10th December	95	92	0
	Sardinia	15th December	98	74	0
Common wheat	North	2nd November	149	81	91
	Centre	28th November	161	89	51
	South-Islands	7th December	92	97	0
Maize	North	20th April	273	110	135
	Centre	1st April	273	110	135
	South-Islands	1st April	273	110	135

avoid drought events that could seriously compromise the production. Therefore, the sowing date of maize for these two areas was set at 1st April. Instead, with regard to the maize fertilization rates in the Centre and South-Islands areas, the same values used for the North area have been considered.

Ordinary tillages for each crop were considered given that there is not a substantial difference between different cultivation areas (Montemurro, 2008; Maggiore et al., 2008).

Irrigation was not considered for durum wheat and common wheat, as they are grown in dry conditions. On the other hand, as maize is usually an irrigated crop, in the absence of detailed data, automatic irrigation has been considered.

4.3.2 Climate change impact assessment

The method of assessment of the impacts of climate change used in this study is based on comparing the outputs from the multiple crop growth model runs with weather data from selected scenarios representing the present vs. changed climates.

The assessment has been performed at the level of area using the "seasonal analysis" run mode. To this end, a SNX file for each area and for each period has been created. The assessment was carried out through the use of a digital platform developed in R programming language by Trabucco (2014). This platform is based on DSSAT-CSM model computation with daily steps that allows the iterative simulation of crop processes and provides the output variables (e.g., anthesis date, yields, biomass, etc.) for every grid point within a study area. The digital platform uses netCDF (network Common Data Form) files as input and output data. For each output variable, the digital platform creates a netCDF file with the annual values and a netCDF file with the average value of thirty years for every grid point.

The analysis was carried out for the maturity date (for phenology) and grain yield, considering three future periods (2006-2035, 2036-2065, 2066-2095, centered at 2020, 2050 e 2080 respectively). Several simulations were carried out for each crop and climate scenario under consideration. Firstly, three simulations of 30 years were carried out with current CO_2 value (392.05 ppm). Then, the simulations were repeated considering future atmospheric CO_2 concentrations expected on the basis of the RCP4.5 and RCP8.5 climate change scenarios. In such a way, the indirect effect of the increase in CO_2 atmospheric concentration (related to changed weather conditions), as well as the direct effect (or CO_2-fertilization effect) and indirect effect of the increase of atmospheric CO_2 on the phenological development and on crop yield have been assessed.

A desktop PC with an Intel Core I7 processor and 16 Gb of RAM was used for the simulations. Overall, the digital platform has carried out 158,730 runs in about 3 hours for each simulation. The total hard disk space used by the outputs generated by the digital platform is about 66 Gb.

The netCDF output files relating to the average value of the maturity date and grain yield of each crop and for each future period and climate scenario have been processed through the Climate Data Operators (CDO) v.1.6.1 software (CDO, 2013) to obtain:

a) the netCDF file of the difference (in days) between the average maturity date of each future period and the average value of the baseline period;

b) the netCDF file of the percentage change in the average grain yield of each future period compared to the average yield of the baseline period.

The netCDF files obtained were processed with the CDO software and then with

ArcGIS Desktop v.10.2 software (ESRI, 2013). In particular, for the purposes of this study, areas with a slope greater than 30% were excluded from the analysis. For each period, the average absolute values of each output variable under consideration and the changes in the average values of the maturity date (in days) and grain yield (in percentage) have been extracted for each area.

The average absolute values of each output variable considered and the changes in the average values of the maturity date (in days) and grain yield (in percentage) for each area and period have been extracted.

4.3.3 Statistical analysis

In order to analyze how the spatial resolution of climate data affects the simulations results, the annual mean values of maturity date and grain yield obtained with climate data at high cell resolution (8 km) have been compared with those derived for Italy from the simulations performed for the Euro-Mediterranean basin using climate data with a cell resolution equal to 14 km as part of the GEMINA project (progetto GEMINA (MIUR/MATTM n. 232/2011)). The comparison was made considering the results of the impacts of climate change with future atmospheric CO_2 values under the RCP4.5 climate scenario, as currently these are the only results available at the European level.

Firstly, the annual output results at 14 km of cell resolution have been extracted for Italy for each crop using the ArcGIS Desktop v.10.2 software. Secondly, a Student's t-test was performed for each period to establish if the annual mean values of maturity date and grain yield for the two cell resolutions of climate data (8 and 14 km) are significantly different. The statistical analysis was performed for each cultivar and cultivation area. Finally, to evaluate the best cell-resolution for productivity simulation, simulated yields were compared with the grain yields observed between 2001 and 2010 in the experimental sites as part of the "*Sperimentazione interregionale sui cereali*" project. The observed average yield was compared with the average yields obtained from the simulations using the COSMO-CLM climate data, forced by ERA-Interim reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The comparison was made separately for each area. Regarding maize, the available experimental sites are located in the North area, with the exceptions of the Marciano della Chiana and Jesi experimental sites. Therefore, the comparison was made only in this area.

4.4 RESULTS

The results of the climate change impacts assessment on phenology and productivity of the three crops studied are presented in this section. More precisely, the results of impacts on maturity date and grain yield are shown for each crop and for different cultivation areas in Italy for the baseline period (1976-2005, centered at 1990) and future periods (2006-2035, 2036-2065 and 2066-2095, centered at 2020, 2050 and 2080 respectively) with the climate change scenarios under consideration (RCP4.5 and RCP8.5). In addition, with regard to the grain yield, the results of simulations with and without CO_2 are explained separately. Regarding maize, the results of impacts of climate change on irrigation requirements of this crop are also described. Finally, results of the statistical analysis are shown.

4.4.1 Durum wheat

Maturity date

Figure 4 shows the average maturity date (dap = days after planting) of durum wheat (Iride cultivar) in each Italian cultivation area for the baseline period (1990). The average maturity date values (dap) for the baseline and future periods for each area and climate scenario are shown in Table 7. Higher values of maturity date have

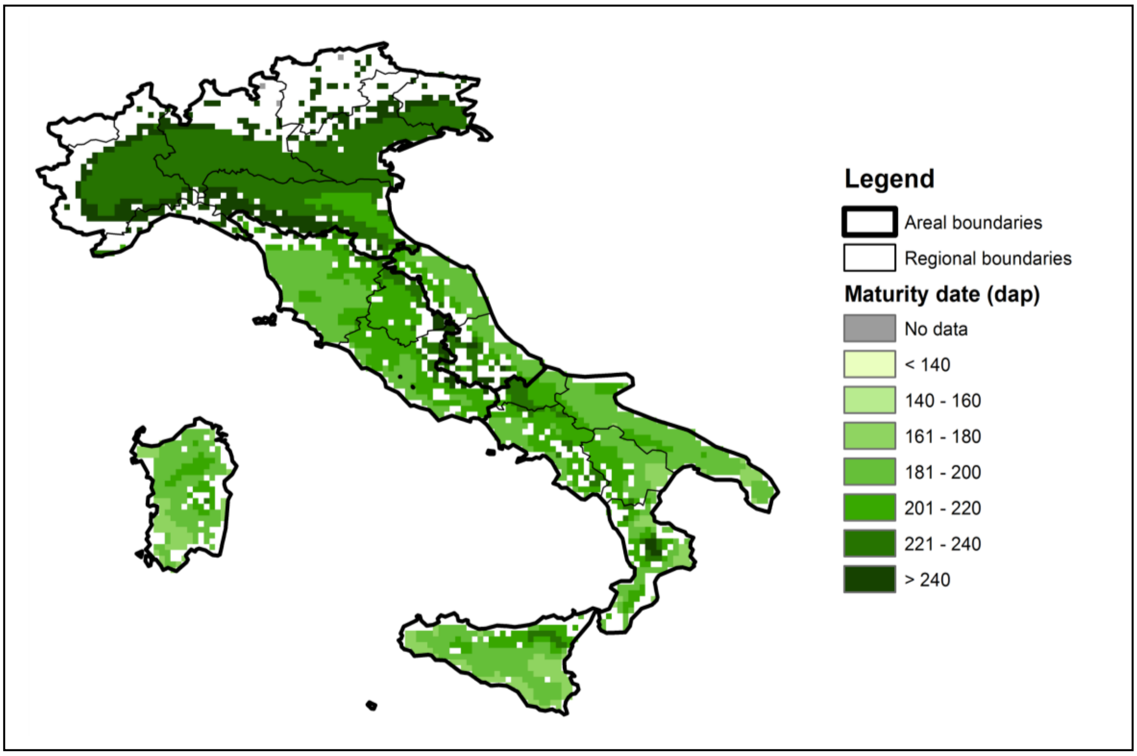

Figure 4. Average maturity date (dap = days after planting) for baseline period (1990) for the Iride cultivar in Italy.

Table 7. Average maturity date (dap) for baseline (1990) and future periods with the RCP4.5 and RCP8.5 climate scenarios for the Iride cultivar in Italy.

Area	**Baseline (1990)**	**RCP4.5**			**RCP8.5**		
		2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	236	229	220	216	226	218	203
Centre-Italy (Tyrrhenian side)	205	199	191	188	197	189	175
Centre-Italy (Adriatic side)	205	199	191	187	196	188	175
South-Peninsular	198	192	185	180	189	181	168
Sicily	189	182	175	170	179	170	158
Sardinia	189	181	174	171	179	171	159

been obtained for the North area (from 203 to 236 dap), while lower values have been simulated in the Sicily and Sardinia areas (from 158 to 189 dap). Changes in the average maturity date (days) from actual to future periods with each climate scenario in each area are shown in Table 8 and Figure 5.

In both scenarios under consideration, the results show a rising advance of the average maturity date for the Iride cultivar in each area and for each future period compared to the baseline period, more noticeable under the RCP8.5 scenario (ranging from -9 days in 2020 to -33 days in 2080) when compared to the RCP4.5 scenario (from -6 days in 2020 to -19 days in 2080). This is probably due to the fact that both climate

Table 8. Changes in average maturity date (days) from actual (1990) to future periods with the RCP4.5 and RCP8.5 climate scenarios for the Iride cultivar in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	-7	-16	-19	-9	-17	-33
Centre-Italy (Tyrrhenian side)	-6	-14	-18	-9	-16	-30
Centre-Italy (Adriatic side)	-7	-14	-18	-9	-18	-30
South-Peninsular	-6	-14	-18	-9	-17	-31
Sicily	-7	-14	-19	-10	-18	-31
Sardinia	-7	-15	-18	-10	-18	-30

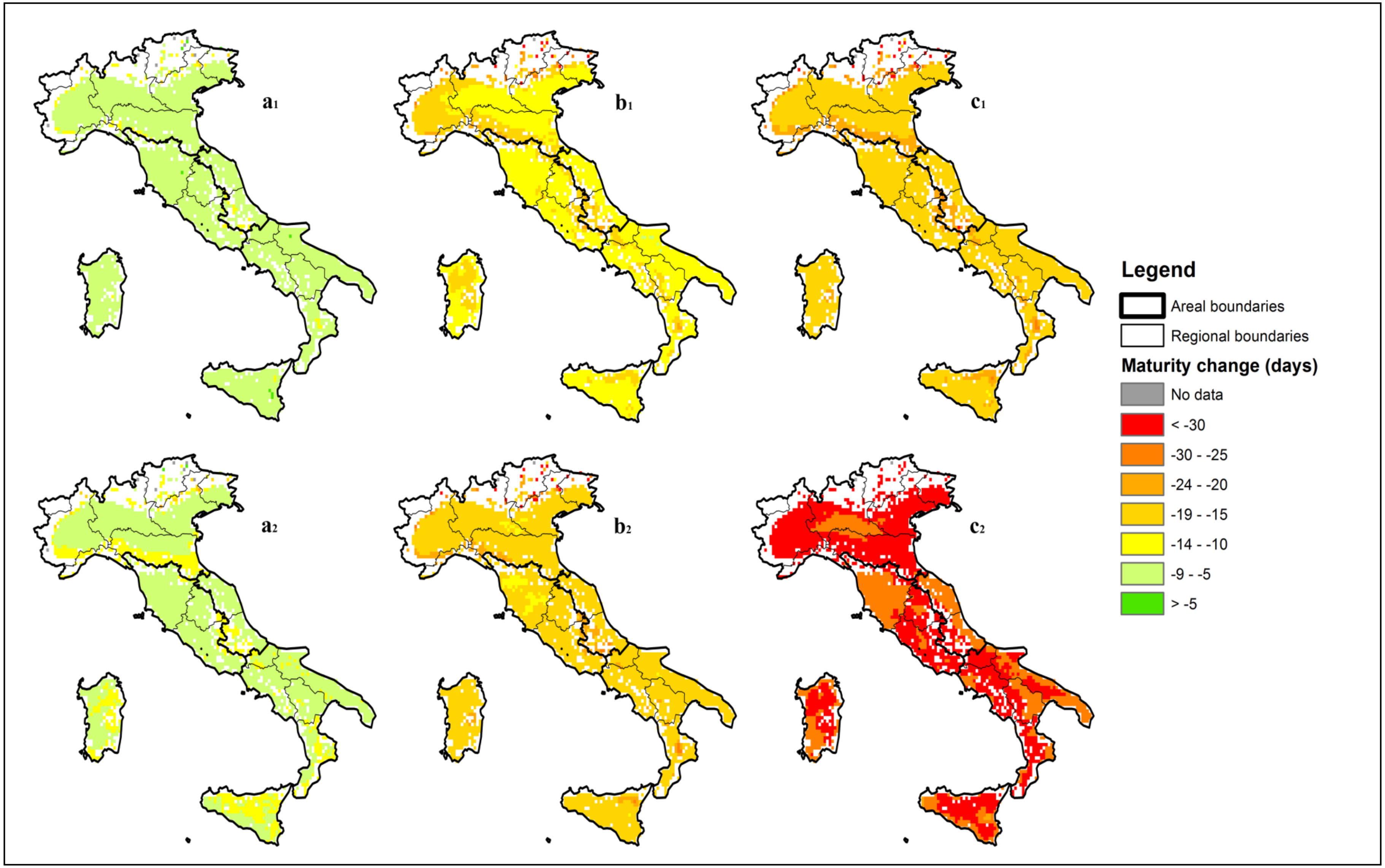

Figure 5. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios for the Iride cultivar in Italy.

scenarios project a progressive increase of the air temperature (greater under the RCP8.5 scenario) in all areas, as shown in Table 4. The advance of the maturity date indicates that the transition from a phenological stage to the next takes place more quickly, with a likely decrease in the accumulation of dry matter in the grain.

Grain yield

Figure 6 shows the actual average grain yield (kg ha^{-1}) simulated for Iride cultivar in Italy. The highest values were obtained for the Centre-Italy (Tyrrhenian side) area (about 6,100 kg ha^{-1}) and the lower ones for the Sicily area (about 4,600 kg ha^{-1}). Table 9 and Figures 7-8 show the results of climate change impacts on the variation in average grain yield in terms of percentage from actual to future periods with each climate scenario in each area with current and future CO_2 concentration values.

The results obtained without taking into account future increases in CO_2 concentration values show differences between the various areas. In fact, a progressive decrease in the average grain yield under both climate scenarios (particularly evident with the RCP8.5 scenario) was observed in the Sicily area (ranging from -1.9% in 2020

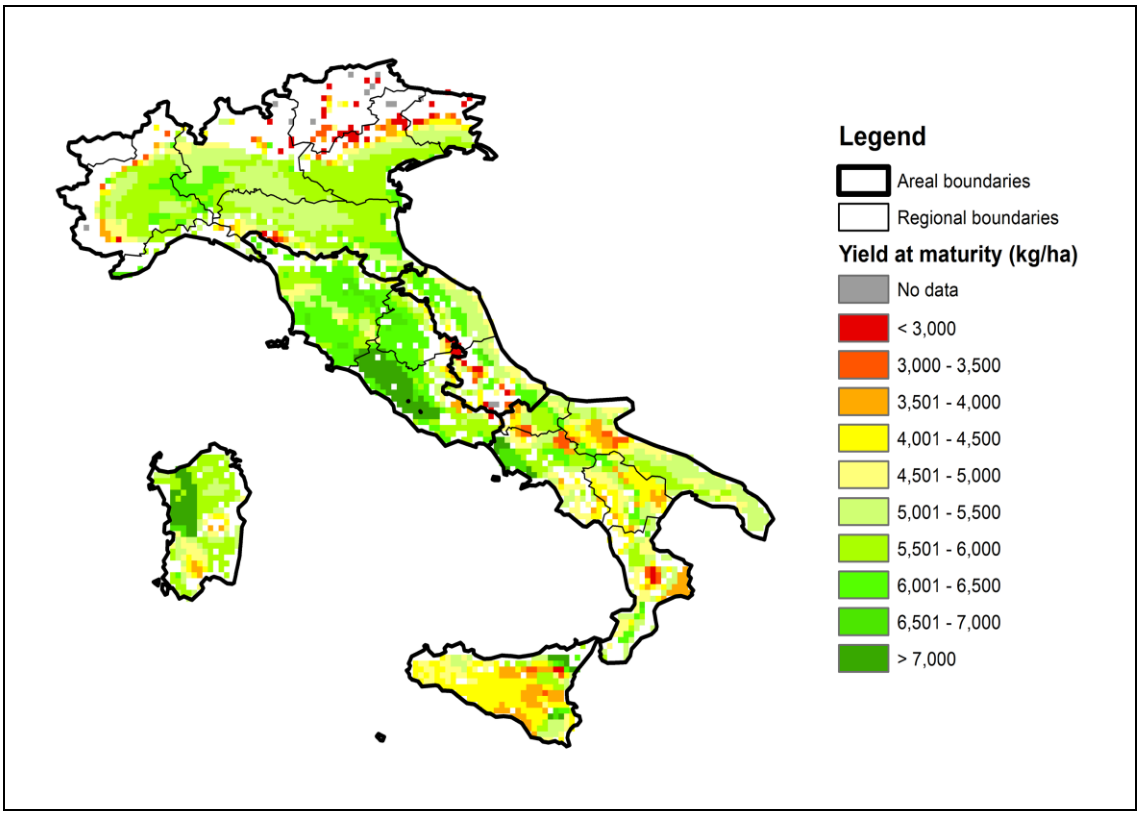

Figure 6. Average grain yield (kg ha^{-1}) for baseline period (1990) for the Iride cultivar in Italy.

Table 9. Changes in average grain yield (%) from actual (1990) to future periods with the RCP4.5 and RCP8.5 climate scenarios with current and future CO_2 concentrations for the Iride cultivar in Italy.

Area	**Future period**	**RCP4.5**		**RCP8.5**		**Mean yield change (%) considering CO_2 increases**
		Current CO_2	**Future CO_2**	**Current CO_2**	**Future CO_2**	
North	2020	+3.4	+5.0	+6.2	+8.3	**+6.7**
	2050	+6.8	+13.9	+9.7	+21.1	**+17.5**
	2080	+6.0	+16.2	-2.5	+21.8	**+19.0**
Centre-Italy (Tyrrhenian side)	2020	-1.2	+0.3	+2.2	+4.3	**+2.3**
	2050	-0.8	+6.2	-0.1	+11.0	**+8.6**
	2080	-3.3	+6.5	-13.7	+8.2	**+7.4**
Centre-Italy (Adriatic side)	2020	+3.8	+5.5	+11.8	+14.3	**+9.9**
	2050	+5.6	+13.5	+12.4	+25.5	**+19.5**
	2080	+8.5	+19.8	+3.4	+31.1	**+25.5**
South-Peninsular	2020	-2.7	-1.1	+2.6	+4.7	**+1.8**
	2050	-0.4	+6.6	-0.6	+10.4	**+8.5**
	2080	-0.8	+9.0	-9.4	+13.6	**+11.3**
Sicily	2020	-1.9	-0.3	-2.9	-0.8	**-0.6**
	2050	-9.2	-2.6	-11.9	-1.5	**-2.1**
	2080	-10.7	-1.3	-24.5	-2.8	**-2.1**
Sardinia	2020	-5.6	-4.1	-4.0	-2.1	**-3.1**
	2050	-8.4	-2.1	-8.9	+0.9	**-0.6**
	2080	-8.8	-0.1	-19.3	+0.5	**+0.2**

to -10.7% in 2080 under the RCP4.5 scenario and from -2.9% in 2020 to -24.5% under the RCP8.5 scenario) and in the Sardinia area (from -5.6% in 2020 to -8.8% in 2080 and from -4.0% in 2020 to -19.3% in 2080 under the RCP4.5 and RCP8.5 climate scenario respectively). This is probably due to both the lower accumulation of dry matter, caused by the shortening of the growth cycle induced by the increase in temperature, and the change in the rainfall pattern. In fact, both climate scenarios project a decrease in mean annual rainfall from 2020 to 2080, of greater magnitude with the RCP8.5 scenario,

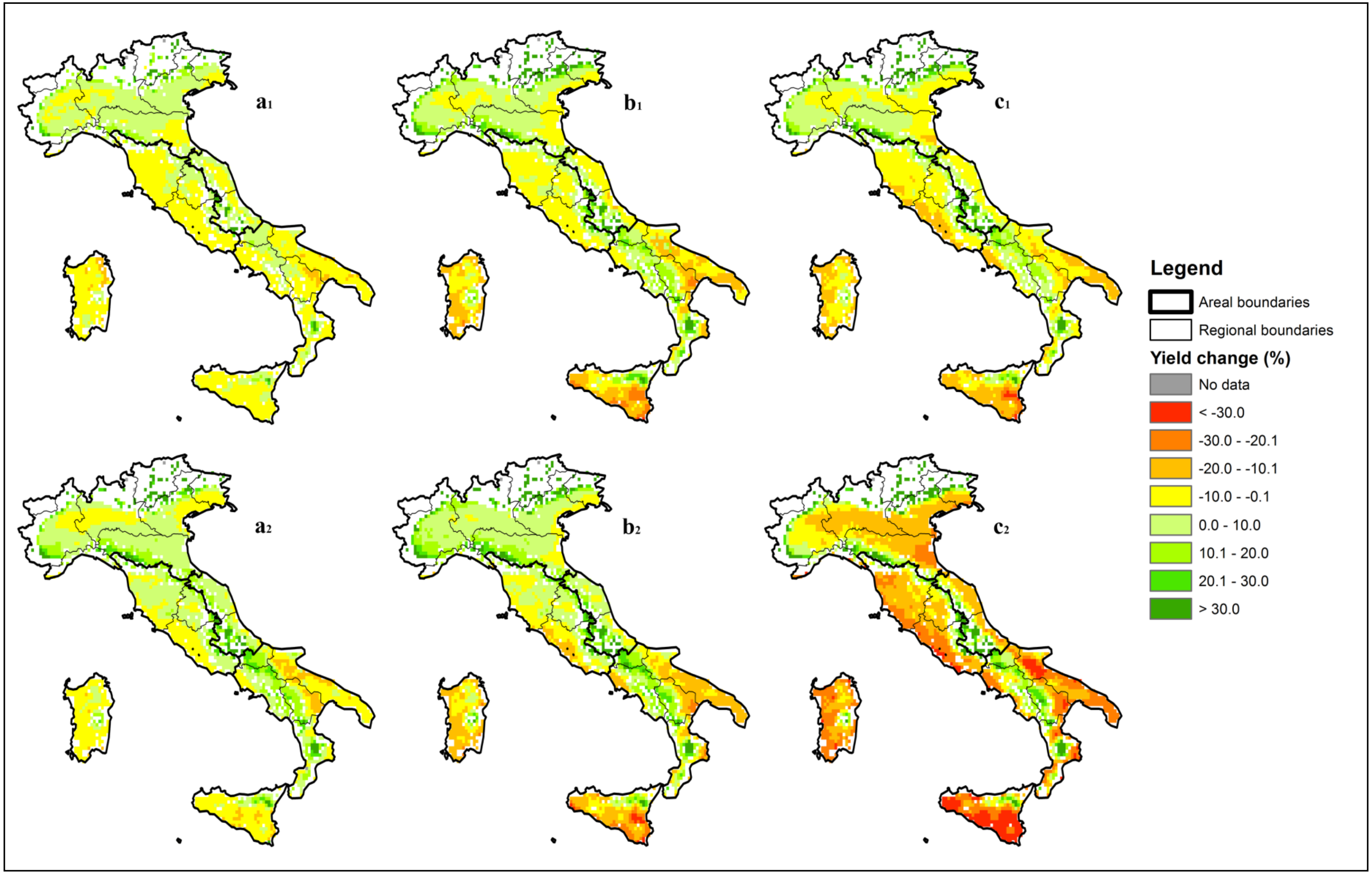

Figure 7. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with current CO_2 concentrations for the Iride cultivar in Italy.

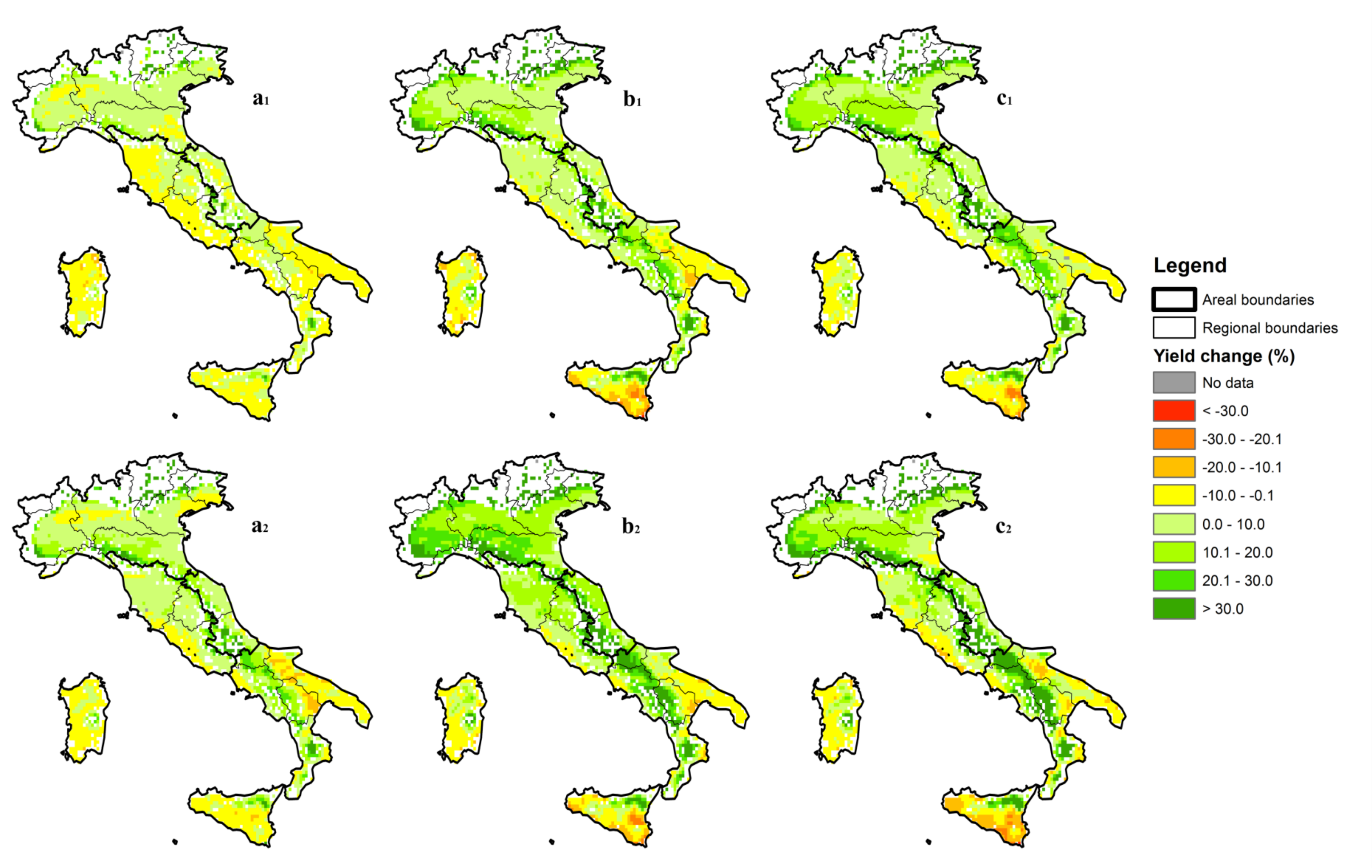

Figure 8. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (b_1, b_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with future CO_2 concentrations for the Iride cultivar in Italy.

especially in Siciliy (see Table 4).

A slight decrease in the average grain yield was estimated with the RCP4.5 scenario for the Centre-Italy (Tyrrhenian side) area (ranging from -1.2% in 2020 to -3.3% in 2080) and for the South-Peninsular area (from -2.7% in 2020 to -0.8% in 2080). On the other hand, a reverse trend was estimated under the RCP8.5 scenario in these two areas with an increase in the average yield in 2020 (+2.2% and +2.6% respectively) and a decrease in 2080 (-13.7% and -9.4%, respectively). This is probably due to a significant reduction of the average annual precipitation in both the areas compared to the baseline period

A different trend between the two climate scenarios was also observed for the North and Centre-Italy (Adriatic side) areas. In fact, an increase in the average grain yield was estimated under the RCP4.5 scenario for both the North area (ranging from +3.4% in 2020 to +6.0% in 2080) and the Centre-Italy (Adriatic side) area (from +3.8% in 2020 to +8.5% in 2080). On the other hand, the trend of the change in the average yield is reversed under the RCP8.5 scenario in the North area (from +6.2% in 2020 to -2.5% in 2080), while the impact of climate change on the average yield is positive in the Centre-Italy (Adriatic side) area (from +11.8% in 2020 to +3.4% in 2080). The positive impact of climate change on the average grain yield in these two areas is due to both the longer growth cycle (which allows a greater accumulation of dry weight in the grain) and the average rainfall during the crop development cycle, which are particularly high especially in the North area.

The results obtained with the simulations carried out considering the projected increases in CO_2 concentrations for future periods show an overall increase in the average grain yield in the North, Central and South-Peninsular areas and a small decrease or no change in the Sicily and Sardinia areas (Tables 9-10). This means that in the first areas the direct effect of CO_2 concentration is greater than the negative impact on yield due to the indirect CO_2 effect, especially in 2080 when the projections estimate an increase in CO_2 concentration ranging from 519 to 536 ppm and from 647 to 890 ppm under the RCP4.5 and RCP8.5 climate scenarios respectively.

The greatest increases in average yield were obtained for the Centre-Italy (Adriatic side) area (ranging from +5.5% in 2020 to +19.8% in 2080 under the RCP4.5 scenario and from +14.3% in 2020 to +31.1% in 2080 under the RCP8.5 scenario) and for the North area (from +5.0% in 2020 to +16.2% in 2080 under the RCP4.5 scenario and from +8.3% to +21.8% in 2080 under the RCP8.5 scenario). Hence, the direct effect

Table 10. Average grain yield (t ha^{-1}) for baseline (1990) and future periods with the RCP4.5 and RCP8.5 climate scenarios with current and future CO$_2$ concentrations for the Iride cultivar in Italy.

Area	**Period**	**RCP4.5**		**RCP8.5**	
		Current CO$_2$	**Future CO$_2$**	**Current CO$_2$**	**Future CO$_2$**
North	1990	5.2			
	2020	5.4	5.5	5.6	5.7
	2050	5.6	6.0	5.8	6.4
	2080	5.6	6.1	5.1	6.4
Centre-Italy (Tyrrhenian side)	1990	6.1			
	2020	6.0	6.1	6.2	6.4
	2050	6.0	6.5	6.1	6.8
	2080	5.9	6.5	5.3	6.6
Centre-Italy (Adriatic side)	1990	5.1			
	2020	5.3	5.3	5.7	5.8
	2050	5.4	5.8	5.7	6.4
	2080	5.5	6.1	5.2	6.6
South-Peninsular	1990	5.0			
	2020	4.9	5.0	5.1	5.3
	2050	5.0	5.3	5.0	5.5
	2080	5.0	5.5	4.5	5.7
Sicily	1990	4.6			
	2020	4.5	4.6	4.4	4.5
	2050	4.2	4.5	4.0	4.5
	2080	4.1	4.5	3.5	4.4
Sardinia	1990	5.8			
	2020	5.5	5.6	5.6	5.7
	2050	5.3	5.7	5.3	5.9
	2080	5.3	5.8	4.7	5.8

of CO_2 concentration is expressed with an average increase in the average yield from +9.9% in 2020 to +25.5% in 2080 in the Centre-Italy (Adriatic side) area and from +6.7% in 2020 to +19.0% in 2080 in the North area. A minor positive impact of climate change on the average yield was also estimated for the South-Peninsular area (from -1.1% in 2020 to +9.0% in 2080 with the RCP4.5 scenario and from +4.7% in 2020 to +13.6% in 2080 with the RCP8.5 scenario) and for the Centre-Italy (Tyrrhenian side) area (from +0.3% in 2020 to +6.5% in 2080 under the RCP4.5 scenario and from +4.3% in 2020 to +8.2% in 2080 under the RCP8.5 scenario).

Regarding to the Sardinia area, the indirect CO_2 effect was almost completely offset by the direct effect of CO_2 concentration resulting in an average increase in average yield ranging from -4.1% in 2020 to -0.1% in 2080 under the RCP4.5 scenario and from -2.1% in 2020 to +0.5% in 2080 under the RCP8.5 scenario.

On the other hand, a small decrease in the average grain yield was estimated in the Sicily area, both under the RCP4.5 scenario (ranging from -0.3% in 2020 to -1.3% in 2080) and the RCP8.5 scenario (from -0.8% in 2020 to -2.8% in 2080).

4.4.2 Common wheat

Maturity date

The actual average maturity date (dap) of common wheat (Bologna cultivar) in Italy is shown in Figure 9, while the average absolute values of the maturity date (dap) in each area for baseline and future periods under the RCP4.5 and RCP8.5 climate scenarios are shown in Table 11. Similarly to the durum wheat (Iride cultivar), also for common wheat (Bologna cultivar) the highest values of average maturity date were estimated for the North area (from 227 to 250 dap), followed by the Centre (from 201 to 224 dap) and South-Islands (from 185 to 207 dap) areas. Figure 10 and Table 12 show the changes in the average maturity date (days) from actual to future periods under each climate scenario in each area in Italy.

The results obtained show that, with respect to the baseline period, an advance of the average maturity date of similar magnitude was estimated in the various areas in 2020 (from -5 to -7 days) and in 2050 (from -11 to -13 days), while a different change in average maturity date was obtained in 2080 for the two climate scenarios considered (from -14 days with RCP4.5 scenario to -24 days with RCP8.5 scenario). This is probably due to the projected increase of air temperature in all the areas (from +1.0 °C to +2.8 °C in 2020 and from +2.8 °C to +5.4 °C in 2080 with the RCP4.5 and RCP8.5

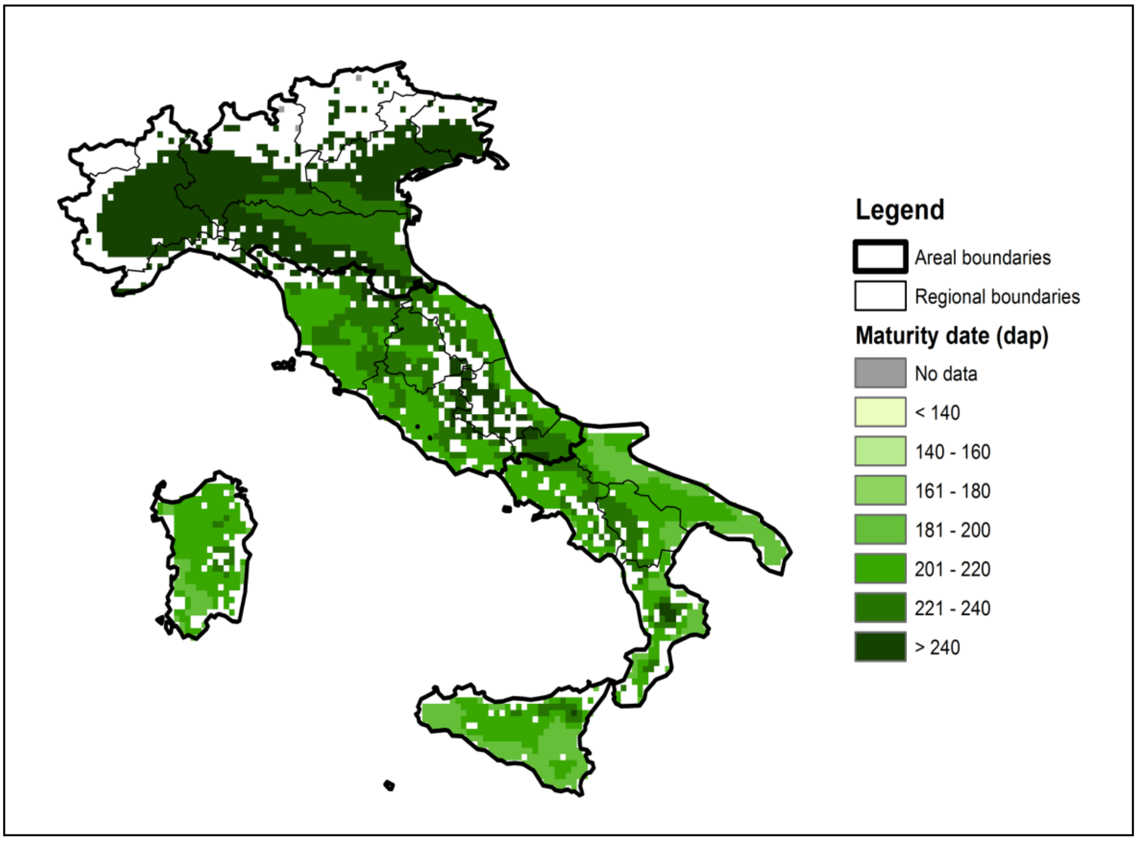

Figure 9. Average maturity date (dap = days after planting) for baseline period (1990) for the Bologna cultivar in Italy.

Table 11. Average maturity date (dap) for baseline (1990) and future periods with the RCP4.5 and RCP8.5 climate scenarios for the Bologna cultivar in Italy.

Area	**Baseline (1990)**	**RCP4.5**			**RCP8.5**		
		2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	250	245	238	236	244	237	227
Centre	224	219	212	210	218	211	201
South-Islands	207	201	195	193	200	193	185

Table 12. Changes in average maturity date (days) from actual (1990) to future periods with the RCP4.5 and RCP8.5 climate scenarios for the Bologna cultivar in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	-5	-12	-14	-6	-13	-24
Centre	-5	-12	-14	-7	-13	-23
South-Islands	-5	-11	-14	-7	-13	-22

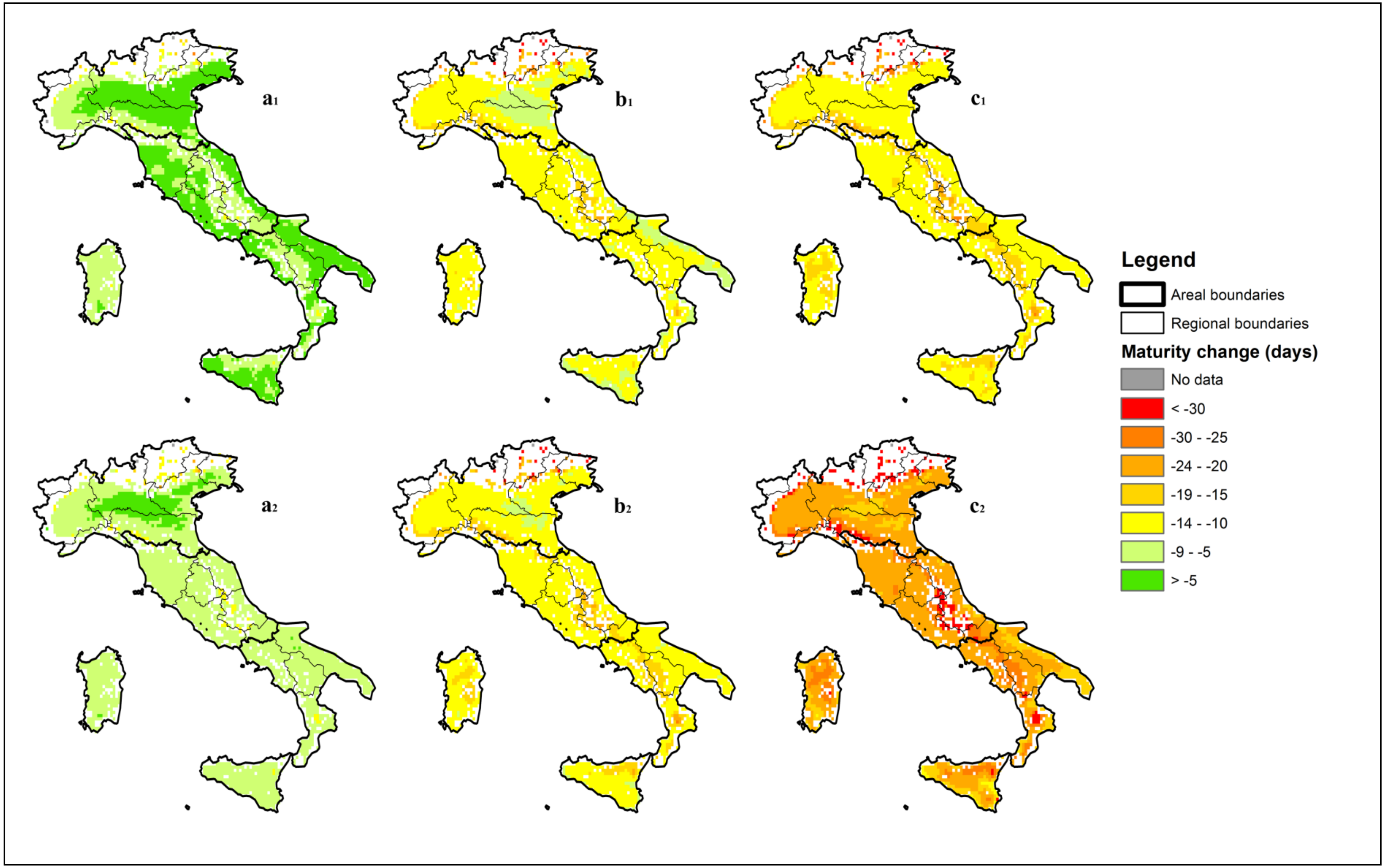

Figure 10. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios for the Bologna cultivar in Italy.

scenarios respectively), as shown in Table 5. The acceleration of the crop growth cycle implies a lower dry matter accumulation in the grain, with negative consequences on the yield.

Grain yield

The actual average grain yield (kg ha^{-1}) for Bologna cultivar in Italy is shown in Figure 11. The highest average yield was estimated in the North area (about 4,900 kg ha^{-1}), followed by the Centre and South-Islands areas (approximately 4,700 kg ha^{-1} and 3,700 kg ha^{-1} respectively). The impacts of climate change on the variation in the average grain yield (%) from baseline to the future periods in each area under the RCP4.5 and RCP8.5 climate scenarios with current and future CO$_2$ concentration values are shown in Table 13 and Figures 12-13.

The results of the simulations performed with current CO$_2$ concentration values show a decrease in the average grain yield in all areas (greater with the RCP8.5 scenario).

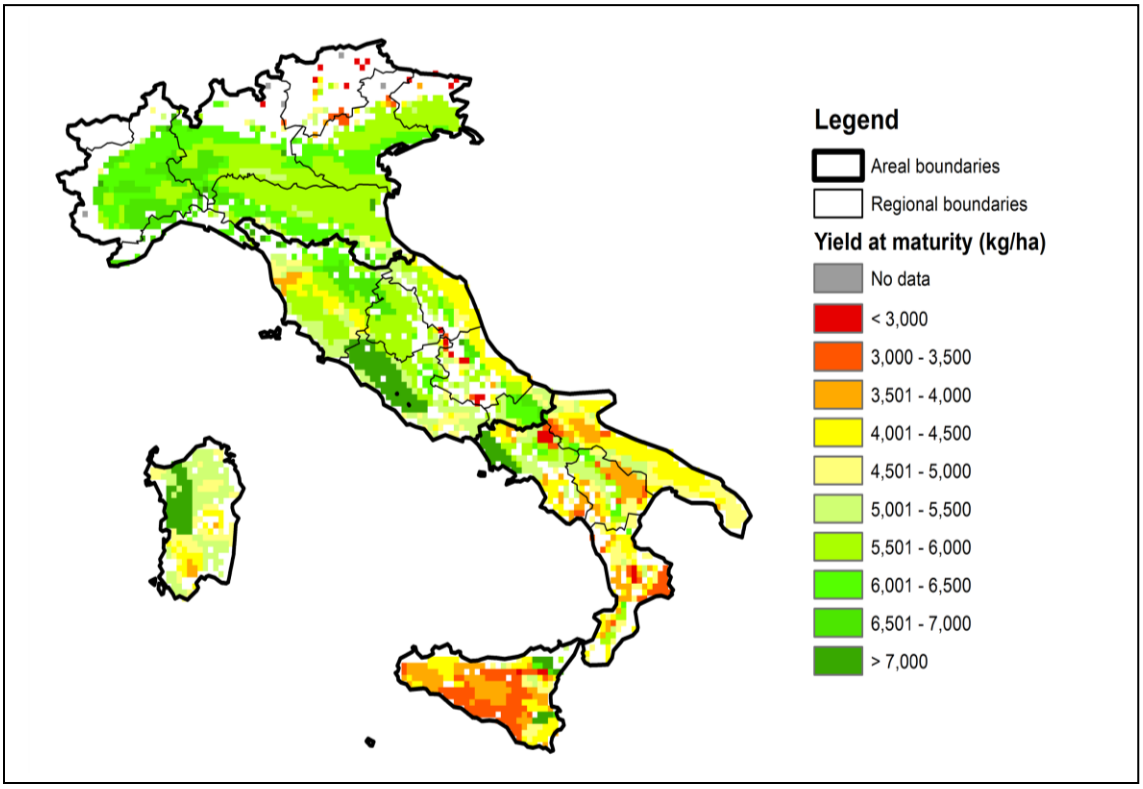

Figure 11. Average grain yield (kg ha^{-1}) for baseline period (1990) for the Bologna cultivar in Italy.

Table 13. Changes in average grain yield (%) from actual (1990) to future periods with the RCP4.5 and RCP8.5 climate scenarios with current and future CO_2 concentrations for the Bologna cultivar in Italy.

Area	**Future period**	**RCP4.5**		**RCP8.5**		**Mean yield change (%) considering CO_2 increases**
		Current CO_2	**Future CO_2**	**Current CO_2**	**Future CO_2**	
North	2020	-2.7	-1.2	+0.7	+3.0	**+0.9**
	2050	-0.5	+6.2	+0.2	+10.9	**+8.6**
	2080	-5.6	+3.5	-16.8	+2.1	**+2.8**
Centre	2020	-3.0	-1.5	+2.9	+4.9	**+1.7**
	2050	-3.3	+3.3	-2.3	+7.6	**+5.5**
	2080	-6.8	+1.8	-15.5	+3.0	**+2.4**
South-Islands	2020	-5.3	-3.9	-0.6	+1.4	**-1.3**
	2050	-3.0	+3.4	-4.6	+5.4	**+4.4**
	2080	-7.2	+1.4	-14.6	+4.2	**+2.8**

A decrease in the average yield (ranging from -2.7% in 2020 to -5.6% in 2080 under the RCP4.5 scenario) was estimated for the North area in particular, while a small increase in the average yield (+0.7%) in 2020, followed by quite a substantial decrease (-16.8%) in 2080 was obtained under the RCP8.5 scenario.

Similar results were obtained for the South-Islands area (ranging from -5.3% in 2020 to -7.2% in 2080 with the RCP4.5 scenario and from -0.6% in 2020 to -14.6% in 2080 under the RCP8.5 scenario).

A reduction of the average yield has been estimated for the Centre area (ranging from -3.0% in 2020 to -6.8% in 2080) under the RCP4.5 scenario, while a reversal trend (from +2.9% in 2020 to -15.5% in 2080) was obtained under the RCP8.5 scenario.

The negative impact of climate change on the average yield in the three areas in 2080 with the RCP8.5 scenario is due to both the significant advance of the average maturity date (from -22 to -24 days), resulting in a shorter crop growth cycle, and the change in rainfall pattern (see Table 5), which results in a decrease in average precipitations during the crop development cycle.

Taking into account the projected increases in CO_2 concentrations values for future periods, the simulation results show an overall increase in the average grain yield

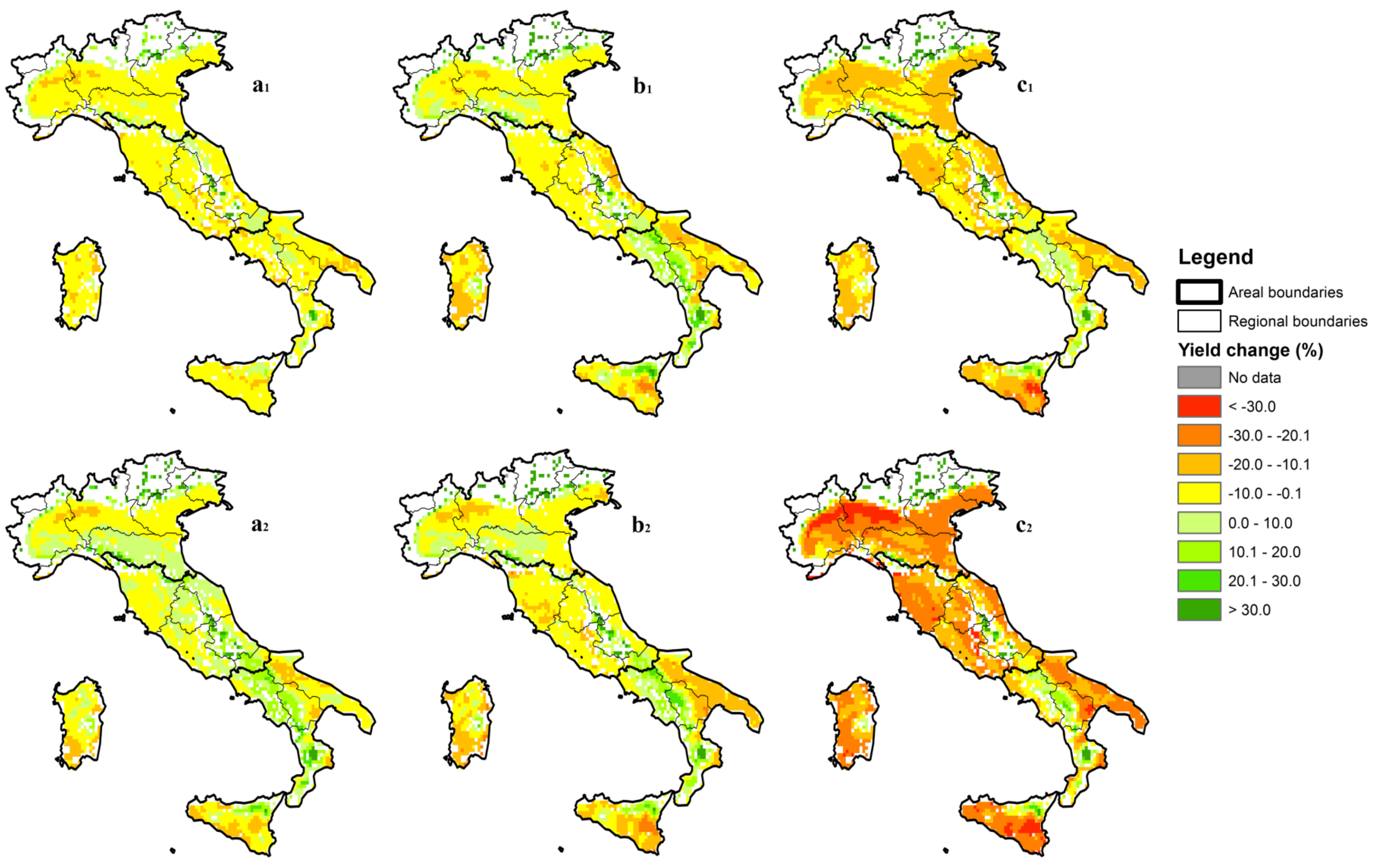

Figure 12. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with current CO_2 concentrations for the Bologna cultivar in Italy.

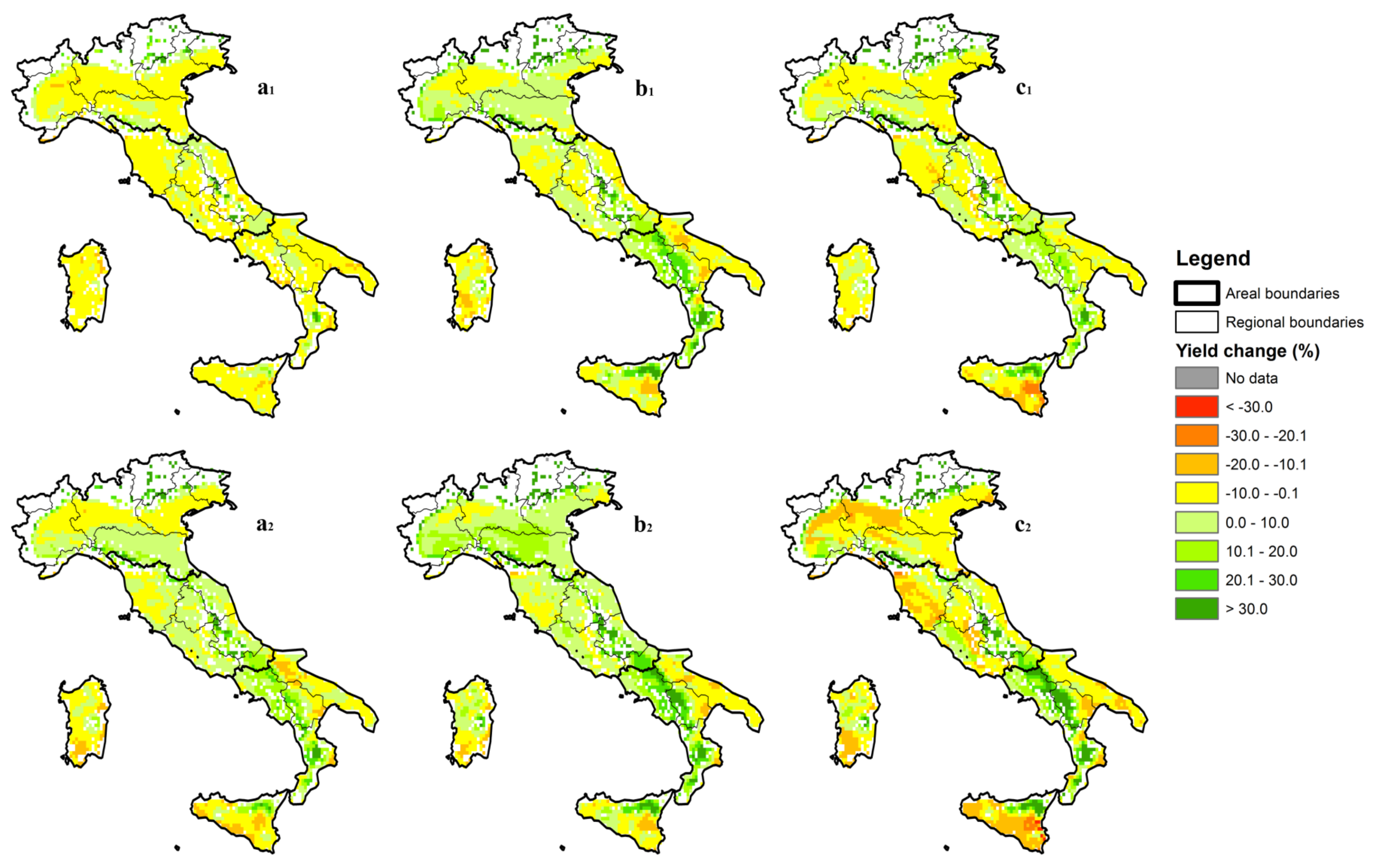

Figure 13. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with future CO_2 concentrations for the Bologna cultivar in Italy.

in all areas, with an increase in 2050 higher than in 2020 and an increase in 2080 lower than in 2050 (Tables 13-14).

Table 14. Average grain yield (t ha^{-1}) for baseline (1990) and future periods with the RCP4.5 and RCP8.5 climate scenarios with current and future CO$_2$ concentrations for Bologna cultivar in Italy.

Area	**Period**	**RCP4.5**		**RCP8.5**	
		Current CO$_2$	**Future CO$_2$**	**Current CO$_2$**	**Future CO$_2$**
North	1990	4.9			
	2020	4.8	4.9	4.9	5.1
	2050	4.9	5.2	4.9	5.5
	2080	4.6	5.1	4.1	5.0
Centre	1990	4.7			
	2020	4.6	4.6	4.8	4.9
	2050	4.5	4.9	4.6	5.1
	2080	4.4	4.8	4.0	4.8
South-Islands	1990	3.7			
	2020	3.5	3.6	3.7	3.8
	2050	3.6	3.8	3.5	3.9
	2080	3.4	3.8	3.2	3.9

Regarding the North area, the change in average yield undergoes a trend reversal (from -1.2% in 2020 to +3.5% in 2080) under the RCP4.5 scenario, while it changes from +3.0% in 2020 to +2.1% in 2080 under the RCP8.5 scenario.

Similar changes were obtained for the Centre area (from -1.5% in 2020 to +1.8% in 2080 and from +4.9% in 2020 to +3.0% in 2080 with RCP4.5 and RCP8.5 scenarios respectively).

On the contrary, the trends of the changes in the average yield obtained in the South-Islands area are different for the two climate scenarios when compared to the other areas (from -3.9% in 2020 to +1.4% in 2080 with the RCP4.5 scenario and from +1.4% in 2020 to +4.2% in 2080 under the RCP8.5 scenario).

Therefore, considering both climate scenarios, the direct effect of CO$_2$

concentration compensates the negative impact on yield due to the indirect CO_2 effect in all areas, with a mean change in average yield from 2020 to 2080 ranging from +0.9% to +2.8% in the North area, from +1.7% to +2.4% in the Centre area and from -1.3% to +2.8% in the South-Islands area.

4.4.3 Maize

Maturity date

Figure 14 shows the actual average maturity date of maize (Eleonora cultivar) in the various areas in Italy. The average maturity date values (dap) for baseline and future periods with both climate scenarios (RCP4.5 and RCP8.5) in each area are shown in Table 15. The highest values of average maturity date have been estimated for the Centre area (ranging from 125 to 174 dap), while the simulations for the North and South-Islands areas have provided lower values (from 115 to 159 dap and from 117 to 157 dap respectively). Figure 15 and Table 16 show the changes in average maturity date (days) from actual to future periods with RCP4.5 and RCP8.5 climate scenarios for the Eleonora cultivar in each area.

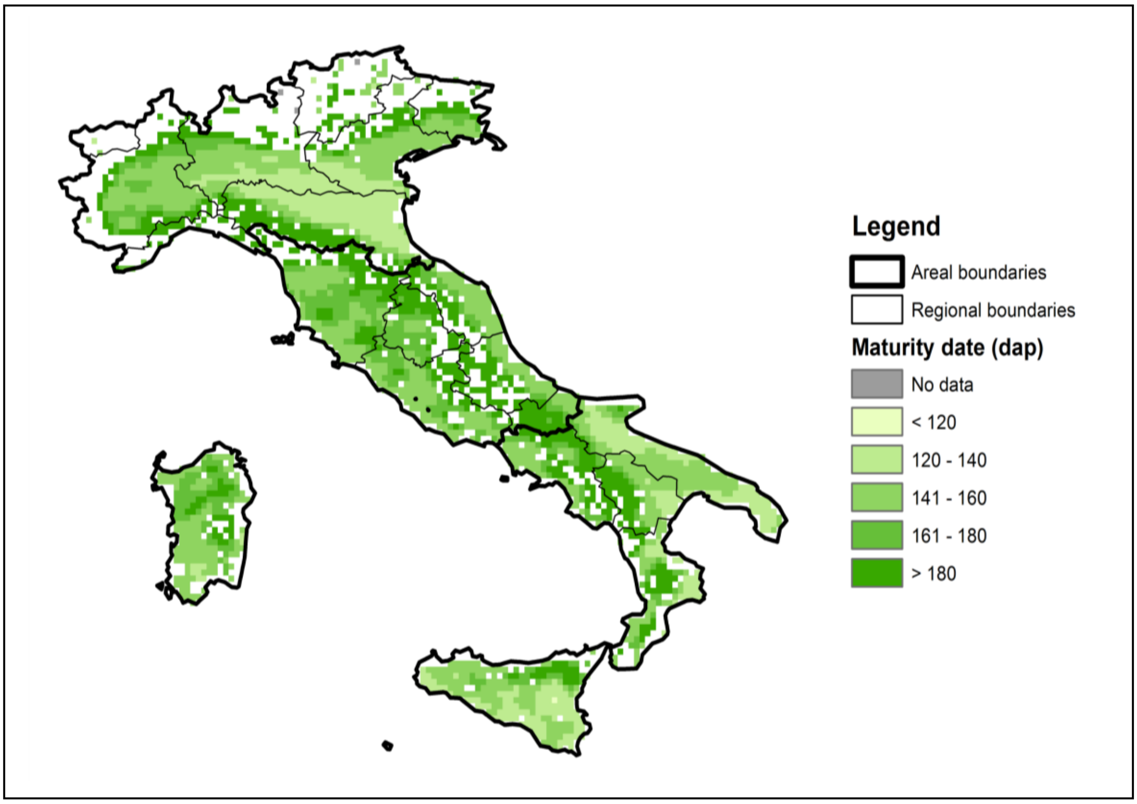

Figure 14. Average maturity date (dap = days after planting) for baseline period (1990) for the Eleonora cultivar in Italy.

Table 15. Average maturity date (dap) for baseline (1990) and future periods with the RCP4.5 and RCP8.5 climate scenarios for the Eleonora cultivar in Italy.

Area	**Baseline (1990)**	**RCP4.5**			**RCP8.5**		
		2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	159	147	135	130	148	134	115
Centre	174	160	146	142	161	146	125
South-Islands	157	145	134	129	144	133	117

Table 16. Changes in average maturity date (days) from actual (1990) to future periods with the RCP4.5 and RCP8.5 climate scenarios for the Eleonora cultivar in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	-12	-25	-29	-11	-25	-45
Centre	-14	-28	-32	-13	-28	-49
South-Islands	-12	-23	-28	-13	-25	-40

A progressive advance of the average maturity date compared to the baseline period was obtained in each area for each future period, with a similar change both in 2020 (from -12 to -14 days) and in 2050 (from -23 to -28 days) under both climate scenarios considered. Instead, a greater advance of the average maturity date was estimated for 2080 with the RCP8.5 scenario (from -40 days in the South-Islands area to -49 days in the Centre area) compared to the RCP4.5 scenario (from -28 days in the South-Islands area to -32 days in the Centre area). These results are probably due to the shortening of the crop growth cycle induced by the increase in air temperature projected in the three areas under the RCP4.5 and RCP8.5 climate scenarios (see Table 5).

Grain yield

Figure 16 shows the actual average grain yield (kg ha^{-1}) for the Eleonora cultivar in Italy. The highest values of average grain yield were obtained in the Centre and South-Islands areas (about 10,700 kg ha^{-1} in both), while an average yield of about 9,200 kg ha^{-1} was obtained in the North area. Changes in the average grain yield (%) from baseline to future periods under the RCP4.5 and RCP8.5 climate scenarios in each area with current and future CO_2 concentrations are shown in Table 17 and Figures 17-18.

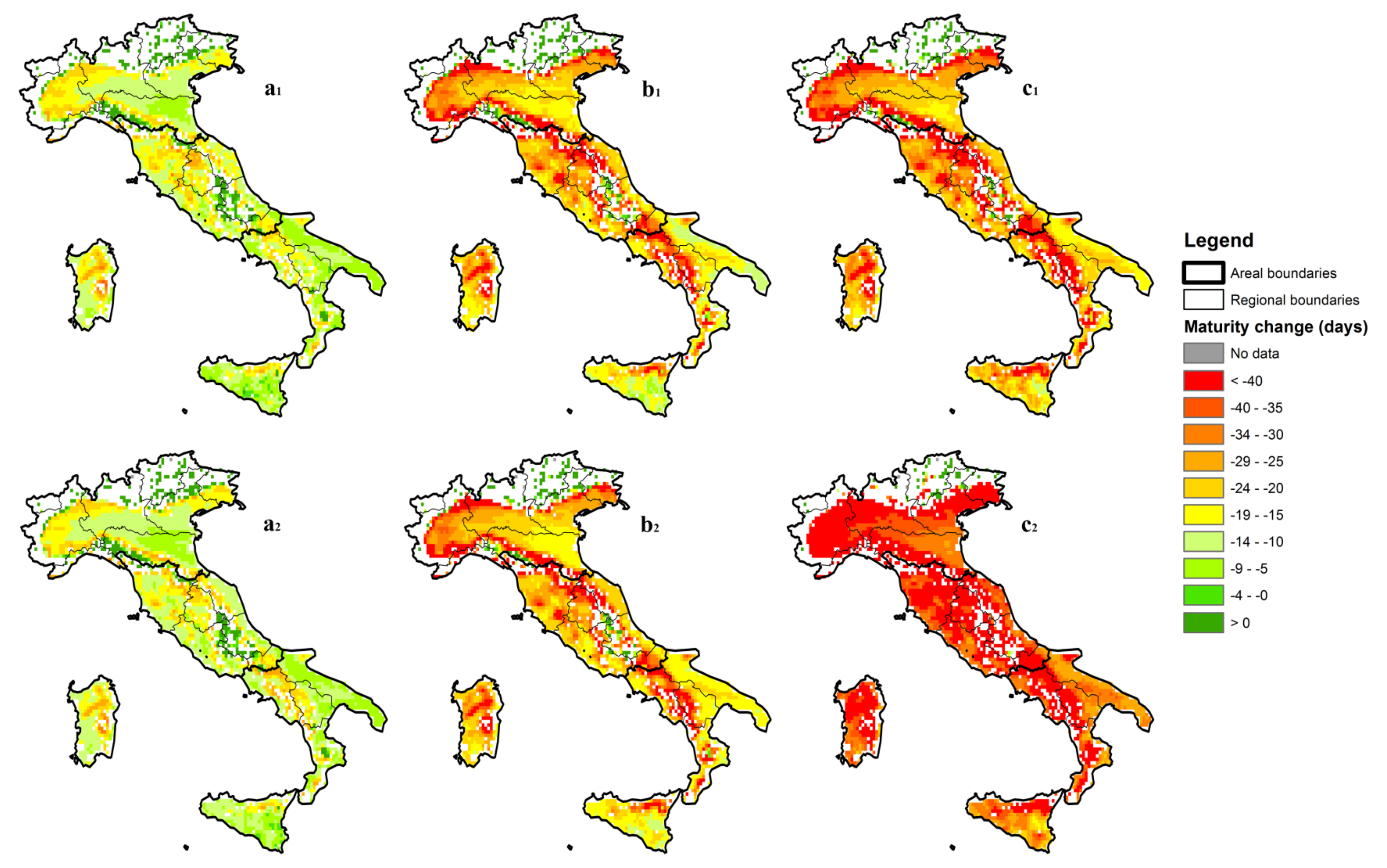

Figure 15. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios for the Eleonora cultivar in Italy.

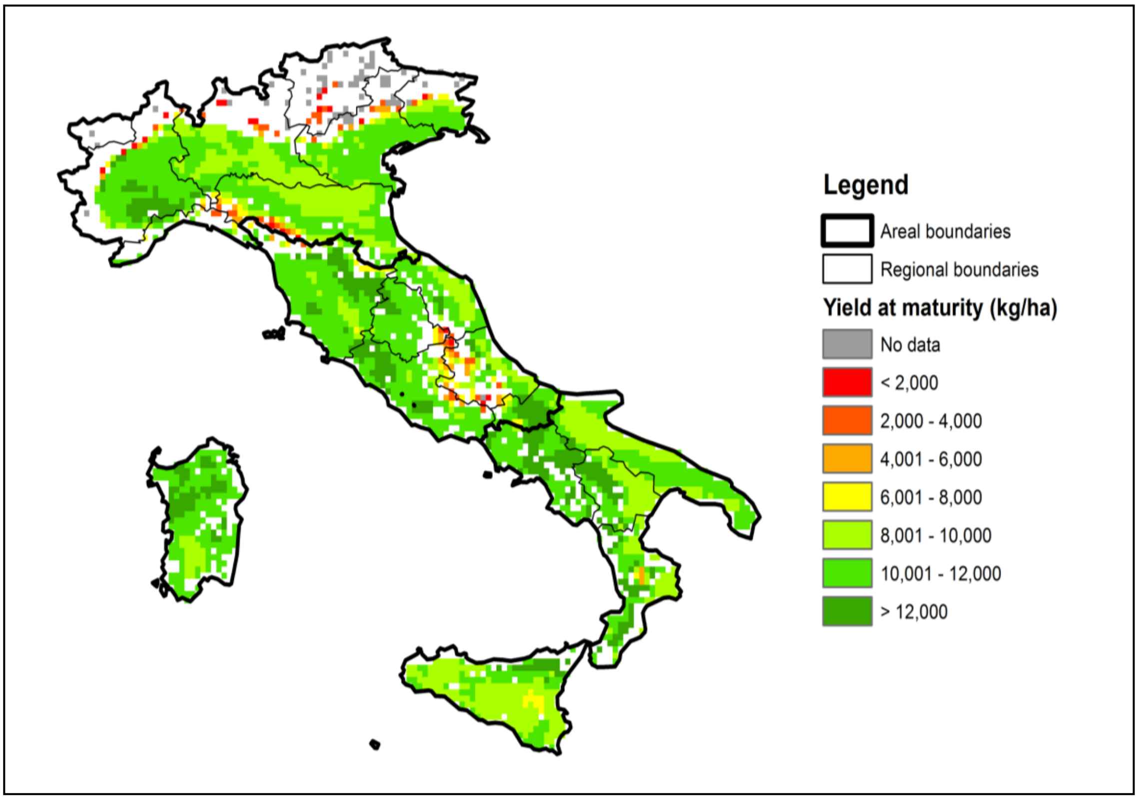

Figure 16. Average grain yield (kg ha^{-1}) for baseline period (1990) for the Eleonora cultivar in Italy.

With regard to the simulations performed with current CO_2 concentration, the results indicate a progressive decrease in the average yield in all areas with both climate scenarios, especially with the RCP8.5 scenario.

The main negative impacts of climate change on yield were obtained for the South-Islands area with a change in the average yield ranging from -8.8% in 2020 to -25.0% in 2080 under the RCP4.5 scenario and from -7.7% in 2020 to -47.5% in 2080 under the RCP8.5 scenario.

Similar changes were estimated for the North area between 2020 and 2080 (from -1.8% to -17.6% and from -0.6% to -43.3% with the RCP4.5 and RCP8.5 climate scenario respectively).

The Centre area is the one showing to a lesser extent the negative impact of climate change on the average grain yield with a change between 2020 and 2080 between -1.3% and -13.7% under the RCP4.5 scenario and between +0.2% and -37.1% under the RCP8.5 scenario.

Considering that the simulations were performed with the "Automatic irrigation when required" option, the probable causes of the negative impact of climate change on

Table 17. Changes in average grain yield (%) from actual (1990) to future periods with the RCP4.5 and RCP8.5 climate scenarios with current and future CO_2 concentrations for the Eleonora cultivar in Italy.

Area	**Future period**	**RCP4.5**		**RCP8.5**		**Mean yield change (%) considering CO_2 increases**
		Current CO_2	**Future CO_2**	**Current CO_2**	**Future CO_2**	
North	2020	-1.8	-1.5	-0.6	-0.1	**-0.8**
	2050	-12.1	-10.7	-12.2	-10.4	**-10.6**
	2080	-17.6	-15.8	-43.3	-41.2	**-28.5**
Centre	2020	-1.3	-1.0	+0.2	+0.7	**-0.2**
	2050	-9.3	-7.9	-11.0	-9.1	**-8.5**
	2080	-13.7	-11.8	-37.1	-34.7	**-23.3**
South-Islands	2020	-8.8	-8.5	-7.7	-7.3	**-7.9**
	2050	-17.4	-16.0	-21.5	-19.7	**-17.9**
	2080	-25.0	-23.2	-47.5	-45.4	**-34.3**

the average grain yield in the three areas are the increase in the average air temperature (see Table 5) and the increase in the frequency of droughts events. This is particularly evident in the South-Islands area where currently these factors, together with the low precipitations, have negative influence making maize cultivation difficult and not very widespread. In addition, the advance of the average maturity date and the consequent shortening of the crop growth cycle cause a diminished dry matter accumulation in the grain, resulting in decreased yield.

The results obtained with the simulations carried out considering the projected increases in atmospheric CO_2 concentrations for future periods confirm that the direct effect of future CO_2 concentrations on maize is very low in all areas (Tables 17-18).

The largest decreases in the average grain yield were observed for the South-Islands area (ranging from -8.5% to -23.2% under the RCP4.5 scenario and from -7.3% to -45.4% under the RCP8.5 scenario).

Similar changes have been estimated for the North area (from -1.5% to -15.8% and from -0.1% to -41.2% under the RCP4.5 and RCP8.5 scenarios respectively).

The Centre area has shown the lesser changes in average grain yield (from -1.0%

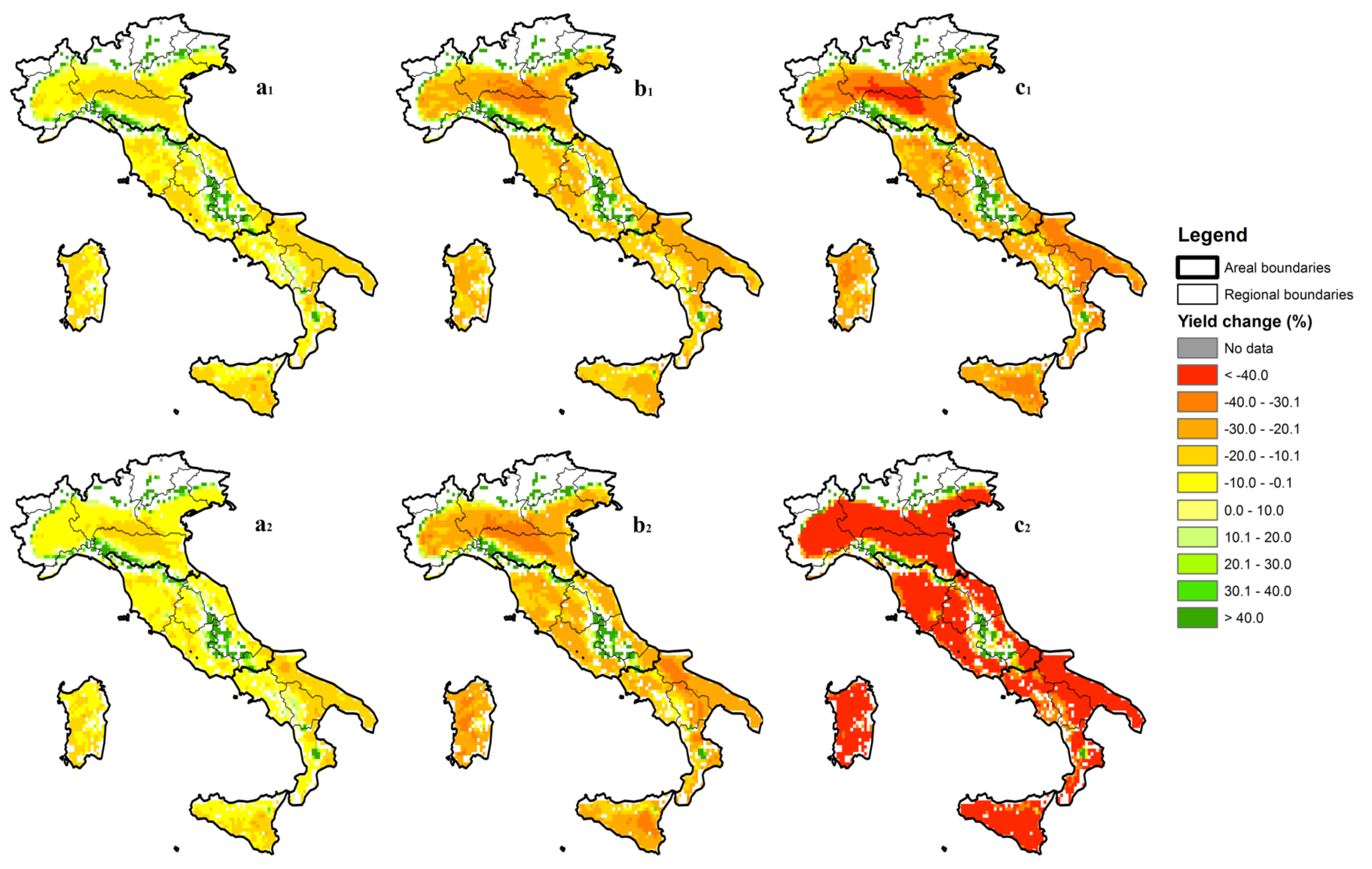

Figure 17. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with current CO_2 concentrations for the Eleonora cultivar in Italy.

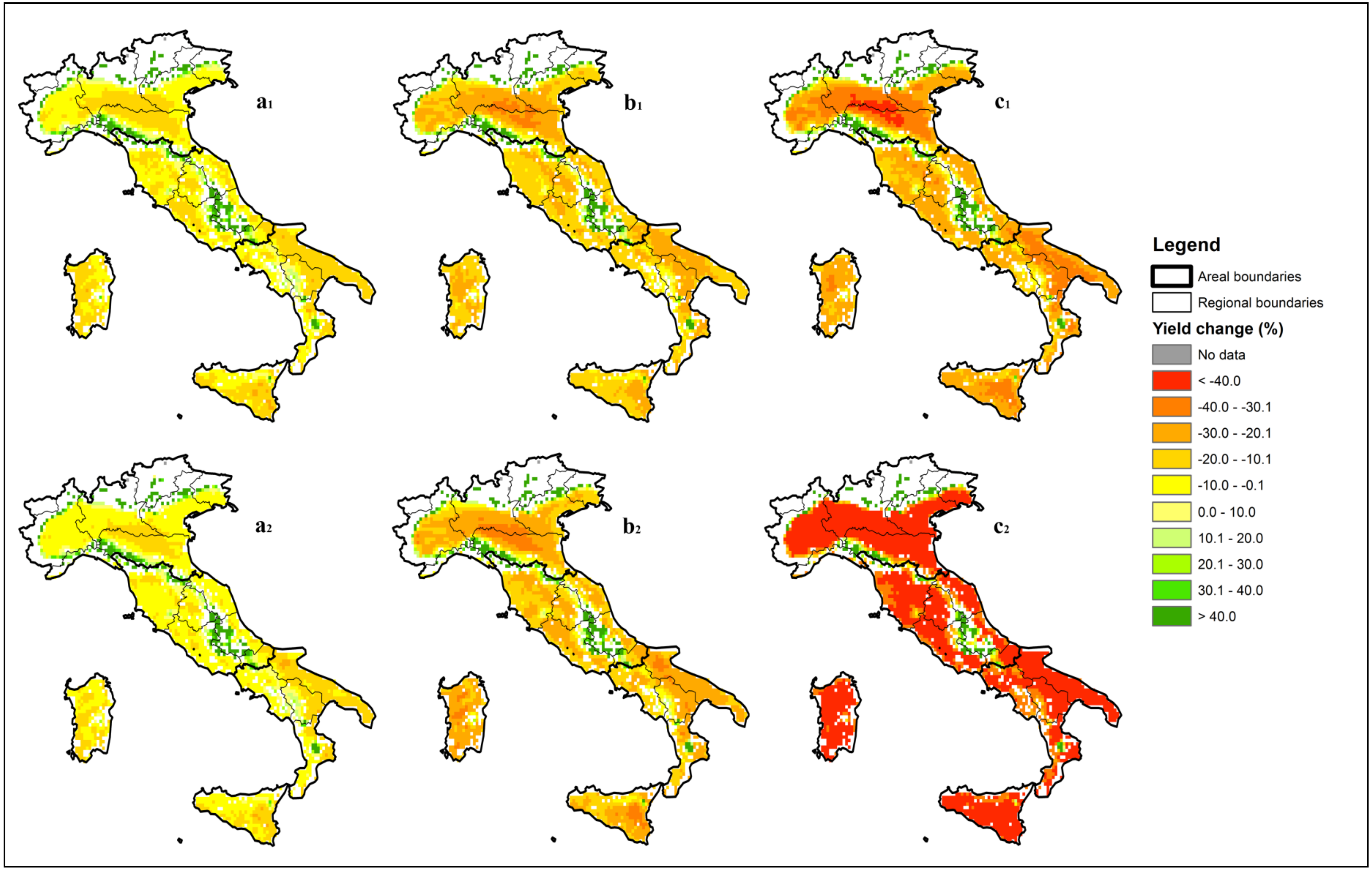

Figure 18. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with future CO_2 concentrations for the Eleonora cultivar in Italy.

Table 18. Average grain yield (t ha^{-1}) for baseline (1990) and future periods with the RCP4.5 and RCP8.5 climate scenarios with current and future CO_2 concentrations for the Eleonora cultivar in Italy.

Area	**Period**	**RCP4.5**		**RCP8.5**	
		Current CO_2	**Future CO_2**	**Current CO_2**	**Future CO_2**
North	1990	9.2			
	2020	9.0	9.1	9.2	9.2
	2050	8.1	8.2	8.1	8.3
	2080	7.6	7.8	5.2	5.4
Centre	1990	10.7			
	2020	10.5	10.6	10.7	10.7
	2050	9.7	9.8	9.5	9.7
	2080	9.2	9.4	6.7	7.0
South-Islands	1990	10.7			
	2020	9.7	9.8	9.8	9.9
	2050	8.8	9.0	8.4	8.6
	2080	8.0	8.2	5.6	5.8

to -11.8% with the RCP4.5 scenario and from +0.7% to -34.7% with the RCP8.5 scenario).

Therefore, considering both climate scenarios, the direct effect of CO_2 concentration is minimal and does not compensate the negative impact on yield due to the indirect CO_2 effect in all areas, with a mean change in average yield from 2020 to 2080 ranging from -0.8% to -28.5% in the North area, from -0.2% to -23.3% in the Centre area and from -7.9% to -34.3% in the South-Islands area.

Irrigation requirements

The actual average seasonal irigation for the Eleonora cultivar at the Italian scale is shown in Figure 19. The highest values has been obtained for the South-Islands area (on average 490 mm), while the actual seasonal irrigation is less for the North area (268 mm).

Table 19 shows the average seasonal irrigation (mm) for the baseline period and

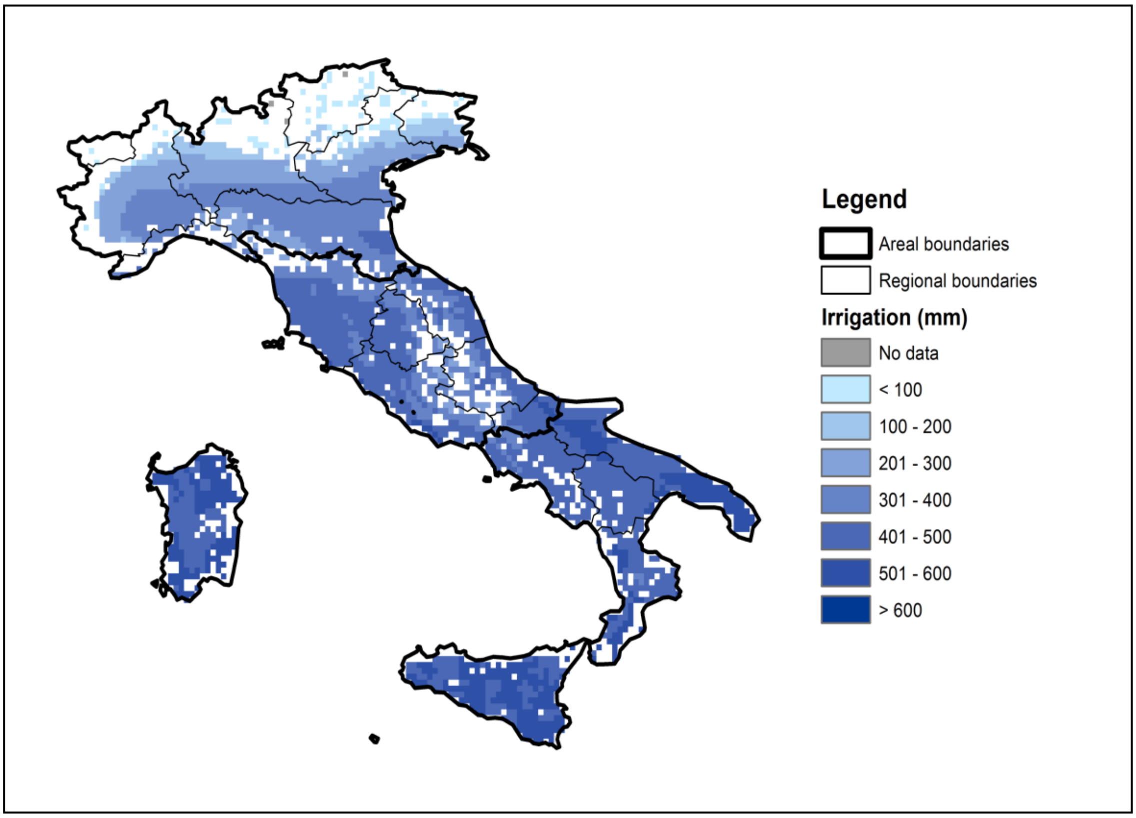

Figure 19. Average seasonal irrigation (mm) for baseline period (1990) for the Eleonora cultivar in Italy.

future periods under the RCP4.5 and RCP8.5 climate scenarios in Italy with current CO_2 concentration values. As it can be seen, the simulated seasonal irrigation with current CO_2 concentrations reaches the higher average values for the South-Islands area (ranging from 481 to 493 mm taking into account both climate scenarios), while the lowest irrigation requirements has been estimated for the North area (from 281 mm in 2020 to 383 mm in 2080 under the RCP8.5 scenario).

Table 19. Average seasonal irrigation (mm) for baseline (1990) and future periods with the RCP4.5 and RCP8.5 climate scenarios with actual CO_2 concentrations for the Eleonora cultivar in Italy.

Area	**Baseline (1990)**	**RCP4.5**			**RCP8.5**		
		2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	268	300	326	333	281	326	383
Centre	403	412	434	428	400	429	454
South-Islands	490	492	492	484	481	493	487

Similar values has been obtained with the simulations carried out considering the future CO_2 concentrations (from 466 to 491 mm in the South-Islands area and from 212 to 325 mm in the North area) (Table 20).

Table 20. Average seasonal irrigation (mm) for baseline (1990) and future periods with the RCP4.5 and RCP8.5 climate scenarios with future CO_2 concentrations for the Eleonora cultivar in Italy.

Area	**Baseline (1990)**	**RCP4.5**			**RCP8.5**		
		2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	268	299	321	325	212	250	310
Centre	403	411	428	419	391	416	433
South-Islands	490	491	486	475	480	484	466

Changes in average seasonal irrigation (%) from baseline to future periods under the two climate scenarios with actual and future CO_2 concentrations are shown in Table 21 and in Figures 20-21.

Results obtained with current CO_2 concentrations show a progressive increase in the average irrigation requirements in Northern Italy from 2020 to 2080 (from +12.2% to +24.3% and from +5.0% to +43.1% under the RCP4.5 and RCP8.5 scenarios respectively). A minor increase in the average sesonal irrigation has been estimated for the Centre area (up to +7.8% in 2050 with the RCP4.5 scenario and up to +12.8% in 2080 with the RCP8.5 scenario). Conversely, the estimates of irrigation requirements for the South-Islands area show an almost imperceptible change (from +0.5% to -1.1% and from -1.8% to +0.7% under the two climate scenarios).

With regard to the simulations performed with projected increases in CO_2 concentrations, the results show similar trends in the average irrigation with the RCP4.5 scenario in all areas (from +11.7% in 2020 to +21.3% in 2080 in Northern Italy, from +2.0% in 2020 to +6.3% in 2050 in the Centre area, and from +0.3% in 2020 to -2.9% in 2080 in Southern Italy and the Islands). A similar increase in average irrigation from 2020 to 2080 has been obtained under the RCP8.5 scenario in Central Italy (from +2.8% to +7.5%), while a reversal trend (from -20.8% in 2020 to +15.8% in 2080) has been estimated in the North area. A general decrease in the average irrigation (up to -4.8% in 2080) has been simulated for the South-Islands area.

Table 21. Changes in average seasonal irrigation (%) from actual (1990) to future periods with the RCP4.5 and RCP8.5 climate scenarios with current and future CO_2 concentrations for the Eleonora cultivar in Italy.

Area	**Future period**	**RCP4.5**		**RCP8.5**		**Mean yield change (%) considering CO_2 increases**
		Current CO_2	**Future CO_2**	**Current CO_2**	**Future CO_2**	
North	2020	+12.2	+11.7	+5.0	-20.8	**-4.6**
	2050	+21.8	+19.8	+21.9	-6.7	**+6.6**
	2080	+24.3	+21.3	+43.1	+15.8	**+18.6**
Centre	2020	+2.3	+2.0	-0.7	-2.8	**-0.4**
	2050	+7.8	+6.3	+6.4	+3.3	**+4.8**
	2080	+6.3	+4.1	+12.8	+7.5	**+5.8**
South-Islands	2020	+0.6	+0.3	-1.8	-2.0	**-0.9**
	2050	+0.5	-0.8	+0.7	-1.2	**-1.0**
	2080	-1.1	-2.9	-0.5	-4.8	**-3.9**

Therefore, taking into account both climate scenarios, the direct effect of CO_2 concentration offset the negative impact on irrigation requirements due to the indirect CO_2 effect in the South-Islands area, with an average change between -0.8% in 2020 and -3.9% in 2080, and in the other two areas in 2020 (-4.6% in Northern Italy and -0.4% in the Centre area). However, the direct effect of CO_2 concentration reduces the negative impact on irrigation in the North and Centre areas, but it is not enough to the its offset in 2050 and in 2080 (on average from +6.6% in 2050 to +18.6% in 2080 in Northern Italy and from +4.8% in 2050 to +5.8% in 2080 in the Centre area).

4.4.4 Statistical analysis

Tables 22-27 show the statistical results of the uncertainty analysis associated with different climate data resolution related to grain yield of durum wheat, common wheat and maize in each area.

In all comparisons, a statistically significant difference was obtained for the average maturity date estimated using climate data with a cell resolution equal to 8 and 14 km for each area and period for $P \leq 0.001$ ($P \leq 0.01$ for maize in the North area).

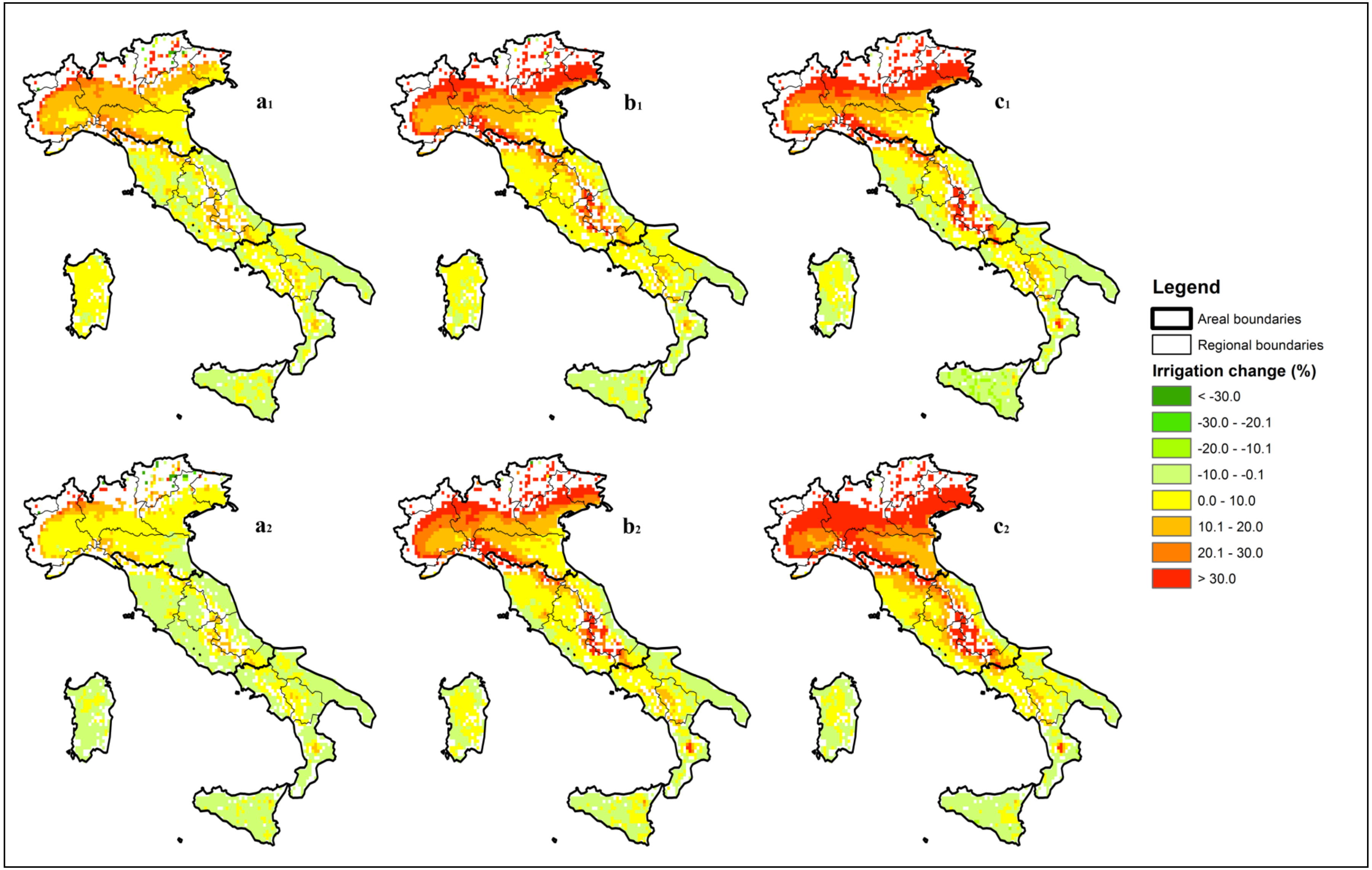

Figure 20. Changes in average seasonal irrigation (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with current CO_2 concentrations for the Eleonora cultivar in Italy.

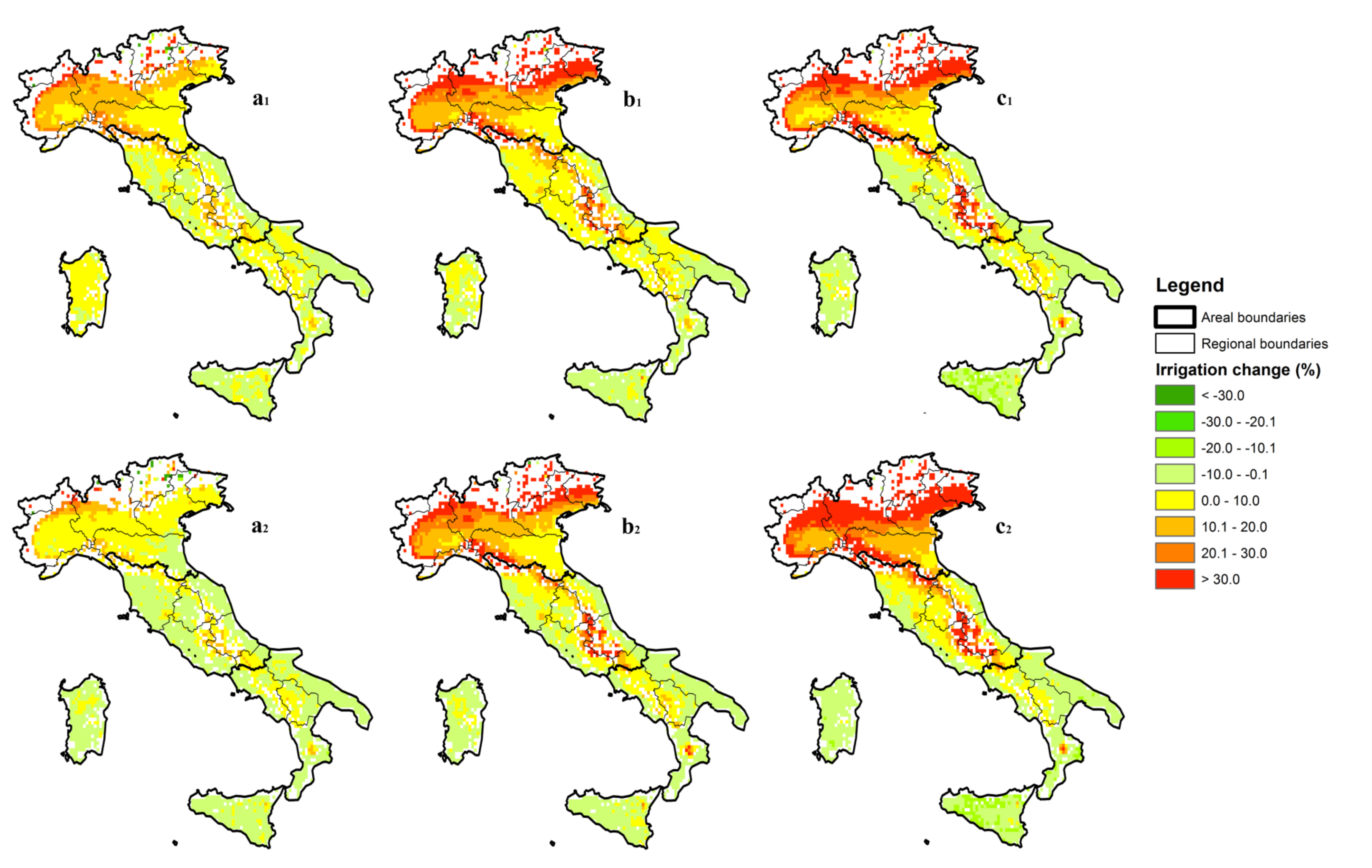

Figure 21. Changes in average seasonal irrigation (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with future CO_2 concentrations for the Eleonora cultivar in Italy.

Table 22. Results of Student's t-test for the annual average maturity date of the Iride cultivar derived from the simulations perfomed using two different spatial resolutions of climate data (values in days after planting).

Period	Area											
	North		Centre-Italy (Tyrrhenian side)		Centre-Italy (Adriatic side)		South-Peninsular		Sicily		Sardinia	
	8 km	14 km	8 km	14 km	8 km	14 km	8 km	14 km	8 km	14 km	8 km	14 km
1990	235***	219***	206***	220***	202***	223***	198***	213***	189***	204***	189***	212***
2020	228***	216***	199***	215***	197***	219***	192***	209***	182***	200***	181***	206***
2050	220***	211***	192***	208***	189***	212***	183***	203***	175***	194***	174***	200***
2080	217***	209***	188***	207***	186***	211***	180***	200***	169***	191***	171***	198***

*$P<0.05$; **$P<0.01$; ***$P<0.001$; ns=not significant.

Table 23. Results of Student's t-test for the annual average grain yield of the Iride cultivar derived from the simulations perfomed using two different spatial resolutions of climate data (values in t ha^{-1}).

Period	Area											
	North		Centre-Italy (Tyrrhenian side)		Centre-Italy (Adriatic side)		South-Peninsular		Sicily		Sardinia	
	8 km	14 km	8 km	14 km	8 km	14 km	8 km	14 km	8 km	14 km	8 km	14 km
1990	5.3***	3.9***	6.1***	5.0***	5.1***	3.8***	5.0***	4.5***	4.6***	3.8***	5.8***	5.3***
2020	5.5***	4.3***	6.1***	5.1***	5.4***	4.1***	5.0***	4.4***	4.6***	3.7***	5.6***	4.9***
2050	6.0***	4.8***	6.4***	5.4***	5.8***	4.5***	5.3***	4.8***	4.5***	3.9***	5.7***	5.0***
					6.1***	4.6***	5.5***	4.9***	4.5***	3.6***	5.8***	5.0***

*$P<0.05$; **$P<0.01$; ***$P<0.001$; ns=not significant.

Table 24. Results of Student's t-test for the annual average maturity date of the Bologna cultivar derived from the simulations perfomed using two different spatial resolutions of climate data (values in days after planting).

Period	**Area**					
	North		**Centre**		**South-Islands**	
	8 km	**14 km**	**8 km**	**14 km**	**8 km**	**14 km**
1990	249***	229***	224***	230***	206***	219***
2020	244***	226***	219***	225***	201***	214***
2050	238***	220***	212***	219***	195***	208***
2080	237***	218***	210***	217***	193***	205***

*P≤0.05; **P≤0.01; ***P≤0.001; ns=not significant.

Table 25. Results of Student's t-test for the annual average grain yield of the Bologna cultivar derived from the simulations perfomed using two different spatial resolutions of climate data (values in t ha^{-1}).

Period	**Area**					
	North		**Centre**		**South-Islands**	
	8 km	**14 km**	**8 km**	**14 km**	**8 km**	**14 km**
1990	4.9***	4.2***	4.7***	4.9***	3.7***	4.5***
2020	4.9***	4.4***	4.6***	4.9***	3.6***	4.3***
2050	5.2***	4.3***	4.9***	4.5***	3.8***	3.9***
2080	5.1***	4.3***	4.8***	4.7***	3.8***	3.9***

*P≤0.05; **P≤0.01; ***P≤0.001; ns=not significant.

Regarding durum wheat (Iride cultivar) the average maturity date estimated by the climate data at a cell resolution of 8 km is lower than the one derived from the simulations carried out using a coarser resolution (14 km) in almost all the areas, with a greater advance was estimated in Sardinia (from -23 days in 1990 to -27 days in 2080 under the RCP4.5 scenario) and in the Centre-Italy (Adriatic side) area (from -21 days in 1990 to -25 days in 2080). An exception is the North Italy with an average maturity date at a fine cell resolution greater than the cell resolution of 14 km (from +16 days in

1990 to +8 days in 2080) (Table 22). Similar results were obtained for common wheat (Bologna cultivar), with a crop cycle duration lower in the Centre (up to -7 days) and South-Islands (up to -13 days) and greater in the North area (up to +20 days) using a cell resolution of climate data of 8 km (Table 24). On the contrary, the simulations for maize (Eleonora cultivar) performed using a fine resolution resulted in an average maturity date greater than the one obtained using the climate data resolution of 14 km in all Italy (up to +7 days in 2080 in the North area, up to +21 days in 2050 in the Centre area and up to +23 days in 2020 in the Central-Southern Italy (Table 26). On the other hand, the effects of climate data resolution on the average maturity date vary with the period under consideration in the North area.

The average grain yield with the two climate data resolutions (8 and 14 km) was also statistically significant in different areas and periods, with the exception of maize for 1990 in Centre Italy where the average grain yield obtained was not statistically significant. Regarding durum wheat, a greater average grain yield was obtained in all the areas (from +1.0 to +1.5 t ha^{-1} in Central-Northern Italy and from +0.5 to +0.9 t ha^{-1} in Southern and Islands areas) using climate data at a cell resolution equal to 8 km (Table 23). On the contrary, the climate data resolution determines different effects on grain yield of Bologna cultivars depending on the area, with higher yield obtained with the finer resolution in North Italy (from +0.5 to +0.9 t ha^{-1}) and the coarser resolution in the South-Islands area (up to +0.8 t ha^{-1} in 1990) (Table 25). On the other hand, the effect of input data resolution changes depending on the period considered in the Centre area. Finally, the climate data at a cell resolution of 8 km results in a higher grain yield than the one obtained using the coarser resolution in almost all areas and periods for Eleonora cultivar (from +0.2 t ha^{-1} in 1990 to +2.4 t ha^{-1} in 2050 in South-Islands area) (Table 27).

Table 28 shows the average yield obtained using the COSMO-CLM climate data forced by ERA-Interim reanalysis with two resolutions (8 and 14 km) and the average grain yield observed in all experimental sites available between 2001 and 2010 for each crop and area. Regarding durum wheat (Iride cultivar), the finer cell resolution has provided the best results in the North (-0.2 t ha^{-1} compared to the observed grain yield), Centre-Italy (Adriatic side) (+0.3 t ha^{-1}), Sicily (-0.4 t ha^{-1}), and Sardinia (-0.7 t ha^{-1}) areas, while the best results were obtained using the cell resolution equal to 14 km in the Centre-Italy (Tyrrhenian side) and South-Peninsular areas (-0.1 t ha^{-1} and -0.2 t ha^{-1} respectively).

Table 26. Results of Student's t-test for the annual average maturity date of the Eleonora cultivar derived from the simulations perfomed using two different spatial resolutions of climate data (values in days after planting).

Period	**Area**					
	North		**Centre**		**South-Islands**	
	8 km	**14 km**	**8 km**	**14 km**	**8 km**	**14 km**
1990	160**	159**	174***	160***	157***	139***
2020	147***	141***	160***	139***	145***	122***
2050	135***	141***	146***	139***	134***	122***
2080	131***	124***	142***	122***	129***	110***

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$; ns=not significant.

Table 27. Results of Student's t-test for the annual average grain yield of the Eleonora cultivar derived from the simulations perfomed using two different spatial resolutions of climate data (values in t ha^{-1}).

Period	**Area**					
	North		**Centre**		**South-Islands**	
	8 km	**14 km**	**8 km**	**14 km**	**8 km**	**14 km**
1990	4.9***	4.2***	10.6ns	10.7ns	10.7***	10.5***
2020	9.1***	8.0***	10.5***	9.1***	9.8***	7.6***
2050	8.2***	7.0***	9.8***	7.8***	9.0***	6.6***
2080	7.8***	6.6***	9.4***	7.3***	8.2***	6.1***

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$; ns=not significant.

As for common wheat (Bologna cultivar), the two climatic data resolutions (8 and 14 km) made it possible to obtain similar results in the Centre and South-Islands areas. On the other hand, the average grain yield estimated using the cell resolution of 8 km differs to a lesser extent from the average value of the observed grain yield compared to the coarser resolution, even though the CSM-CERES-Wheat crop model underestimates the yield in both cases (-1.5 t ha^{-1} and -1.9 t ha^{-1} respectively). Conversely, better results have been obtained in Northern Italy using the finer resolution of climate input data

Table 28. Results of the comparison between the average values of the simulated grain yield (t ha^{-1}) obtained using the the COSMO-CLM climate data forced by ERA-Interim reanalysis to the cell resolutions of 8 and 14 km and the average value of observed grain yield of all the available experimental sites between 2001 and 2010 for each crop and area.

Durum wheat (Iride cultivar)			
Area	**Average grain yield (t ha^{-1})**		
	Observed	**Simulated (8 km)**	**Simulated (14 km)**
North	5.5	5.3	4.6
Centre-Italy (Tyrrhenian side)	4.9	5.6	4.8
Centre-Italy (Adriatic side)	4.8	5.1	3.8
South-Peninsular	3.8	4.8	4.0
Sicily	3.8	3.4	2.7
Sardinia	5.2	4.5	4.2
Common wheat (Bologna cultivar)			
Area	**Average grain yield (t ha^{-1})**		
	Observed	**Simulated (8 km)**	**Simulated (14 km)**
North	6.0	4.5	4.1
Centre	5.2	4.4	4.4
South-Peninsular	3.1	3.1	3.0
Maize (Eleonora cultivar)			
Area	**Average grain yield (t ha^{-1})**		
	Observed	**Simulated (8 km)**	**Simulated (14 km)**
North	11.1	8.0	7.2

(-1.5 t ha^{-1} vs. -1.9 t ha^{-1} using coarser resolution). Similar results were obtained for maize (Eleonora cultivar) with a minor underestimation of the average grain yield using climatic data at a resolution of 8 km (-3.1 t ha^{-1} versus -3.9 t ha^{-1} using climate data with a cell resolution of 14 km).

4.5 DISCUSSION

The methodological approach used in this study for the assessment of the climate change impacts on phenology and yield of durum wheat, common wheat and maize in Italy shows several advantageous aspects.

Firstly, the digital platform developed and applied in this study allows to perform the model simulations at spatial scale. This makes it possible to consider the variability of climate, soil and crop management features existing throughout the study area and not just in some experimental sites (as in the estimates made at the field scale). The performances of the digital platform are very good considering the high number of runs that it allows to perform automatically without user intervention once it has been started. The excellent performances provided by the digital platform in this study are also linked to the remarkable performances of the computer used for the simulations.

Secondly, the analysis has been performed at the national level using the ecotypes and genetic coefficients that have been used are those obtained with the parameterization of the CSM-CERES-Wheat and CSM-CERES-Maize crop models at the Italian scale (Gallo et al., 2014). In fact, these coefficients were calibrated and evaluated for each crop considering experimental sites with very heterogeneous and variable characteristics of climate, soil and crop management from North to South. Consequently, the parameterization is more robust than the one obtained by several Authors at the local or regional scale considering a very small number of experimental sites. The parameterization of crop models at the national scale makes it possible to obtain more reliable results for subsequent applications based on these models (e.g., the study of the impacts of climate change and the assessment of the potential adaptation strategies to climate change).

Thirdly, the large availability of information related to crop management (sowing dates, fertilization rates, etc.) for numerous experimental sites provided by the Istituto Sperimentale per la Cerealicoltura ("*Sperimentazione interregionale sui cereali"* project) has allowed to consider the typical agronomic techniques in every cultivation area. Therefore, the analysis of the results at the area level is the best approach to assess the impacts of climate change at the Italian scale. An exception is represented by maize for which the availability of such information is limited to the North area. In addition, in the absence of information related to irrigation of maize, the model's option "Automatic irrigation when required" has been used. Therefore, the potential impacts of climate change were evaluated for this crop, particularly for the Centre and South-

Islands areas.

In this study the impacts of climate change on maturity date and grain yield of durum wheat, common wheat and maize have been assessed under the RCP4.5 and RCP8.5 climate change scenarios. In particular, regarding grain yield, both the indirect effect and the combined (direct and indirect) effect of the increase of atmospheric CO_2 concentration have been evaluated.

Regarding phenology, the results show an advance of the average maturity date for all crops (especially under the RCP8.5 scenario). Maize (Eleonora cultivar) is the crop that has shown the greatest change, particularly in the Centre area (up to -49 days in 2080 with the RCP8.5 scenario). The durum wheat (Iride cultivar) and common wheat (Bologna cultivar) have shown fairly homogeneous and lower changes in maturity date in each future period and in each area compared to maize. The likely cause of the advance of the maturity date is represented by the increase in air temperature projected in the various areas for each future period compared to the baseline period under both climate scenarios, RCP4.5 and RCP8.5 (see Tables 4-5). Furthermore, the differences in average maturity date changes from actual to the future periods for each crop between the RCP4.5 and RCP8.5 scenarios are evident only in 2080, when the temperature increase projected in each area under the two scenarios is significantly different (higher under the RCP8.5 scenario).

The results relative to the grain yield with current CO_2 concentration, for common wheat and maize, show that the indirect effect of the atmospheric CO_2 concentration (related to changes in weather conditions) is generally negative in all areas and under both the RCP4.5 and RCP8.5 climate scenarios. The largest percentage decreases in yield were obtained under the RCP8.5 scenario in 2080 (up to -47.5% in the South-Islands area for maize and up to -16.8% in the North area for common wheat). The significant shortening of the crop growth cycle due to the increase in air temperature and the decrease in rainfall (above all in 2080 under the RCP8.5 scenario) are the probable causes of the negative impacts of climate change on grain yield of these crops. The differences between the two climate scenarios for 2020 and 2050 are less obvious than for 2080 in each area, as observed also for the changes in the average maturity date. In this case the differences in the various areas are mainly due to the characteristics of soil and agronomic crop management that play an important role on the development and growth of crops. On the other hand, the indirect effect of atmospheric CO_2 concentration on the change in grain yield for durum wheat varies with the area. In fact, it is positive in the North area (from +6.8% with the RCP4.5 scenario to +9.7% with the RCP8.5 scenario in 2020) and in the Centre-Italy (Adriatic side) area (from +8.5% in 2080 under the RCP4.5 scenario toto +12.4% in 2050 under the RCP8.5 scenario). This is caused by the greater accumulation of dry matter in the grain due to both the longer growing season and to the increased rainfall projected for the coming decades, especially in the North area. On the contrary, the impact of climate change with current CO_2 concentrations are generally negative in other areas, particularly in the Sicily and Sardinia areas (up to -10.7% and -8.8% and up to -24.5% and -19.3% in 2080 under the RCP4.5 and RCP8.5 climate scenarios respectively).

With regard to the change in grain yield for durum wheat (C3 crop) and considering the future values of atmospheric CO_2 concentration with the two scenarios under consideration, a general increase in the average grain yield (greater with RCP8.5 scenario) was obtained in Central-Northern Italy and in Southern-Peninsular Italy, with an average increase ranging from +1.8% in 2020 and +25.5% in 2080. The largest average increases were obtained in the Centre-Italy (Adriatic side) area (from +9.9% in 2020 to +25.5% in 2080) and in the North area (from +6.7% in 2020 to +19.0% in 2080). In contrast, the average impact of the increase in atmospheric CO_2 concentration is nearly zero or slightly negative in Sicily (from -0.6% in 2020 to -2.1% in 2080) and Sardinia (from -3.1% in 2020 to +0.2% in 2080). Therefore, in almost all the areas the direct CO_2 effect is greater than the negative impact due to the indirect CO_2 effect (especially in 2080 under the highest atmospheric CO_2 concentrations). Two exceptions are represented by the Sardinia area (in which the direct CO_2 effect offsets almost completely the indirect CO_2 effect) and by the Sicily area (in which, despite the CO_2 fertilization effect, a slight reduction in the average grain yield has been estimated).

The results of the simulations performed with future CO_2 concentrations for common wheat (C3 crop) show an average increase of the average grain yield with the two scenarios considered ranging from +0.9% and +1.7% in 2020 and from +2.4% and +2.8% in 2080 for the North and Centre areas respectively. On the contrary, a trend reversal occurs in the South-Islands area: from a decrease in the average grain yield of -1.3% in 2020 to an increase of +2.8% in 2080.

On the other hand, the results obtained for maize (C4 crop) show that the direct CO_2 effect is very low in all areas and under both climate scenarios (RCP4.5 and RCP8.5). Thus, the CO_2 fertilization effect does not compensate the indirect CO_2 effect. Considering both CO_2 effects (direct and indirect), the average impact on grain yield with the two scenarios under consideration is negative and increases between 2020 (from -0.2% in the Centre area to -7.9% in the South-Islands area) and 2080 (from -23.3% in the Centre area to -34.3% in the South-Islands area). Contrarily, the direct effect of atmospheric CO_2 concentration for durum wheat and common wheat (C3 crops) results in an overall positive impact on the change in grain yield, particularly with the RCP8.5 scenario (which projects the highest values of atmospheric CO_2 concentration in the coming decades).

The results of the climate change impacts on the irrigation requirements of maize (Eleonora cultivar) indicate an increase of irrigation from North to South Italy considering both the current and future atmospheric CO_2 concentrations. In particular, an increase of irrigation requirements is expected from 2020 to 2080 in the North area under both the RCP4.5 and RCP8.5 climate scenarios and in the Centre area with the RCP4.5 scenario. On the other hand, the irrigation requirements could decrease between 2020 and 2080 under the RCP4.5 scenario in the South-Islands area, while a reversal tendency is expected under the RCP8.5 scenario, with a decrease of irrigation requirements in 2080 compared to the baseline period under both scenarios under consideration. This is probably due to the increase in average precipitation during the spring in the South of Italy.

Comparison with other impact studies, using the IPCC SRES scenarios, would have only an indicative value. In addition, different sets of GCMs and RCMs are usually considered in other studies. For example, this study has considered only one GCM and two climate scenarios (RCP4.5 and RCP8.5) at the spatial scale, while Mereu (2010) and Carboni (2011) have considered three GCMs and various climate change scenarios at the local scale. Therefore, the changes in anthesis date obtained by Mereu (2010) and Carboni (2011) for Iride (from -2 days in 2025 to -15 days in 2075) and Simeto (from -3 days in 2025 to -8 days in 2075) cultivars, could have only an indicative value when compared with the results obtained in this study for changes in maturity date for Iride in Sardinia (from -7 days in 2020 to -30 days in 2080). The calculation of the average values of each pixel on a regional scale is probably the main cause of these differences. Saadi et al. (2014) have estimated an overall decrease in the average length of crop season for winter wheat in 2050 compared to 2000 under the A1B emission scenario, ranging from -3 to -41 days in the Euro-Mediteranean area and from -10 to -25 days in Italy, thus very similar to the reduction of average maturity date obtained in this work for durum wheat in 2050 under the RCP4.5 (from -14 to -16 days) and RCP8.5 (from -16 to -18 days) climate scenarios.

Regarding the impacts of climate change on grain yield, the results obtained in this study for durum wheat (Iride cultivar) with current CO_2 concentration for the Sardinia area (from -5.6% in 2020 to -8.8% in 2080 with the RCP4.5 scenario and from -4.0% in 2020 to -19.3% in 2080 with the RCP8.5 scenario) are different when compared with those obtained by Mereu (2010) for the Iride cultivar (from +2-4% for 2025 to +10-16% for 2075) and by Carboni (2011) for the Simeto cultivar (on average from +2% in 2025 to +13% in 2075). On the other hand, considering the future values of the atmospheric CO_2 concentration, Mereu (2010) has obtained average increases of grain yield ranging from +7% in 2025 to +21% in 2075 for the Iride cultivar, while a small change (on average from -3.1% in 2020 to +0.2% in 2080 considering the two scenarios) has been estimated in this work. This difference in results is mainly due to the different scale at which the analysis was conducted, considering that in this study, undertaken at the Italian scale, the heterogeneous characteristics of climate, soil and crop management were considered in each area, in contrast to the studies carried out in Italy at the local scale on a small number of experimental sites (Tubiello et al., 2000; Mereu, 2010).

Tubiello et al. (2000) have estimated a mean reduction in grain yield without adaptation between -5% and -15% for wheat and maize in North Italy (Emilia-Romagna) and between -30% and -50% for wheat in the Apulia region. These reductions are due to the shorter length of the growth cycle of these crops (advance of the maturity of 2-4 weeks compared to baseline period) induced by the increase in air temperature.

Thaler et al. (2012), in a study conducted in Austria with three GCMs, have obtained increases in yield for winter wheat (up to +18% until 2050), while for maize they estimated yield changes of more than +10% under conditions of low climate sensitivity and a general decrease of yield (even < -16%) under conditions of high climate sensitivity.

Iglesias et al. (2012), in a study conducted at the European scale, have simulated a change in the average grain yield of wheat, maize and soybeans in 2080 ranging from -8% to -22%, and from 0% to -11% under the A2 and B2 emission scenarios, respectively, in the Mediterranean North region and from -12% to -27% for A2 scenario and from +1% to + 5% for B2 scenario in the Mediterranean South region. These results are very similar to those obtained in this work for common wheat in the various areas and for durum wheat in the South-Peninsular, Sicily and Sardinia areas. Nevertheless, there exist differences for durum wheat in Central and Northern areas for which the results obtained in this study indicate an overall positive impact of climate change on average grain yield for 2080.

The results obtained in this study relative to the changes in grain yield for 2050 with the RCP4.5 and RCP8.5 climate scenarios for durum wheat are in contrast with those obtained by Saadi et al. (2014) who have estimated relative yield losses up to 30% for winter wheat under rainfed conditions with the A1B emission scenario in Italy, especially in Sicily and Apulia. On the contrary, the results of this work indicate a general increase in average grain yield in Central-Northern and South-Peninsular Italy and a negligible variation of the average grain yield in Sicily and Sardinia. On the contrary, the relative yield losses estimated by Saadi et al. (2014) for winter wheat under mild deficit irrigation do not exceed 15%. Therefore, the application of irrigation could be a useful adaptation strategy to limit the impact of climate change on grain yield of durum wheat, particularly in Southern Italy and the Islands.

A general increase in average yield of wheat was also obtained from Moriondo et al. (2011) in a study conducted in the Euro-Mediterranean area under conditions of heat stress (from +11.4% to +48.9% under the A2 scenario and from +7.3% to +25.9% under the B2 scenario).

Finally, the results of this work indicate a greater negative impact on the average grain yield for maize in all areas for 2080 with both the RCP4.5 and RCP8.5 scenarios when compared to that obtained by Iglesias et al. (2012) for the two Mediterranean regions.

In general, it can be said that the direct effect of increase in atmospheric CO_2 on average grain yield is positive, especially for C3 crops, and that its magnitude is related to the increase in photosynthetic rate (from +30% to +50% with a doubling of CO_2 concentration), as confirmed by numerous studies (Kimball, 1983; Cure and Acock, 1986; Poorter, 1993; Fuhrer, 2003; Ainsworth and Long, 2005). Furthermore, the greater values of water-use efficiency and water absorption capacity of rainfed crops (e.g., durum wheat and common wheat) result in a greater direct effect of the CO_2 concentration for these crops compared to irrigated crops (e.g., maize) (Tubiello and Ewert, 2002; Nelson et al., 2009).

The significant reduction of grain yield expected for maize in the North area for 2080 under the RCP8.5 scenario (-41.2%) is due to the high increase in air temperature (see Table 5) and to an increase in the frequency of heat waves and drought events that determine a significant reduction of the growth cycle length of this crop and a consequent lower accumulation of dry matter in the grain (Eitzenger et al., 2009).

A further consequence is the increase in irrigation requirements for irrigated crops (e.g., maize), as confirmed by Gallo et al. (2012) and Mancosu (2013) in Emilia-Romagna and Sardinia respectively.

Based on these considerations, the cost of production for irrigated crops such as maize could rise considerably as a result of climate change, while the economic convenience of the cultivation for rainfed crops (e.g., durum wheat and common wheat) could increase, assuming the potential positive impact of climate change on grain yield of these crops.

Overall, the average values of simulated maturity date and grain yield for the three main Italian cereals using climate data at the cell resolution equal to 8 and 14 km are significantly different in different areas and periods. Taking into account the fact that the soil type does not change in a consistent manner varying the cell resolution from 8 to 14 km, this study confirms that the use of climate data with higher resolution allows to obtain average values of grain yield closer than those observed in almost all areas, but with a different range of variation from one area to another. An exception is presented by the average yield obtained for the Iride cultivar with a cell resolution of 14 km in the Centre-Italy (Tyrrhenian side) and in the South-Peninsular areas. This could be due to the fact that different experimental sites are located in areas where the average yield simulated by CSM-CERES-Wheat model with the finer climate data is significantly higher when compared with the one estimated with the coarser resolution. However, it is not possible to separate the effects of climate and soil input data on the final result, as the digital platform requires input data with the same cell resolution. These factors should be taken into account for a more reliable assessment of the impacts of climate change on phenological development and productivity of crops under consideration.

4.6 CONCLUSIONS

This study has enabled an accurate assessment of the climate change impacts on phenology and yield of the main Italian cereals using a digital platform and climate input data with a higher cell resolution when compared to the other Regional Climate Models available for Europe.

The results obtained in this work indicate that the length of the development cycle of main cereals cultivated in Italy may be shortened, especially for maize. With regard to productivity, the yield of maize in Italy could decrease significantly in the coming decades. Conversely, wheat could benefit from climate change, especially durum wheat in Central-Northern and Southern-Peninsular Italy. The yield of common wheat could increase slightly (particularly in 2050).

The implications on crop productivity and on the Italian agricultural economy might be considerable if the projections of climate change indicated by the RCP4.5 and RCP8.5 climate scenarios will become reality. Such considerations are valid in particular for maize, particularly in the North area where this crop is most widespread for both human and animal feeding.

The digital platform combined with high resolution climate data is a useful tool for the evaluation of climate change impacts at the Italian scale if compared with the analysis performed for wheat and maize by other Authors in studies conducted in Italy and in the Euro-Mediterranean area at the at the local scale using different emission scenarios. The higher spatial resolution of the climate and soil data, the use of more GCMs, RCMs and climate change scenarios (to perform the uncertainty analysis), the availability of bias-corrected climate data and the performing of the analysis only on the areas actually suitable for each crop, would enable to obtain results with a greater level of accuracy. However, cultivated areas change over the years due to crop rotations and other factors (e.g., desertification, soil loss for urbanization, etc.). Under these conditions, it could also be possible to increase the level of detail of the analysis (from the area level to regional or provincial level), so as to provide more precise information for subsequent applications (for example, the assessment of the potential adaptation strategies to climate change).

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5. COMPARISON OF SEVERAL ADAPTATION STRATEGIES TO REDUCE CLIMATE CHANGE IMPACTS ON *TRITICUM DURUM* DESF., *TRITICUM AESTIVUM* L. AND *ZEA MAYS* L. AT ITALIAN SCALE

5.1 INTRODUCTION

The impacts of climate change projected for the coming decades vary with the location and time depending on many factors such as non-climate stressors (e.g., soil fertility, irrigation, fertilizers, socio-economic and political factors, etc.) and the extent of adaptation and mitigation (IPCC, 2014a).

The agricultural sector is particularly sensitive to climate change, which may have impacts on growth and productivity of crops that vary from one region to another (see section 4.1 of this thesis). In addition, agriculture contributes to emissions of greenhouse gases (GHGs), particularly of methane (CH_4) and nitrous oxide (N_2O). The emissions of these GHGs have increased in recent decades, especially N_2O emissions (about +20% compared to pre-industrial era), because of the growth of the agricultural sector and the consequent increased use of nitrogen fertilizers (IPCC, 2013).

Considering the population growth expected in the future, agricultural production must increase in order to meet the growing demand for food. Therefore, an increase in the emissions of CH_4 and N_2O it is expected in the coming decades, resulting in a probable negative impact on agricultural production.

However, it is possible to reduce the negative impacts of climate change on growth and yield of crops. In addition, several opportunities can be created by climate change.

For these reasons, the agricultural sector is involved in the adoption of two types of strategies:

1. adaptation strategies to climate change;
2. climate change mitigation strategies.

The goal of adaptation strategies is to minimize the negative effects of climate change, while mitigation strategies are the measures aimed at the progressive reduction of emissions or at greater sinking of greenhouse gases. Since recent decades, many countries and organizations are involved in the adoption of these two types of strategies. However, the speed with which climate change is occurring is high and the expected impacts are inevitable in the coming decades, particularly in the agricultural sector. The high complexity of the climate system leads to longer response times of the system to climate change, whose negative effects cannot be completely removed only with the adoption of mitigation strategies. Therefore, in order to deal in the best possible way with the problem of climate change impacts, adaptation and mitigation strategies should be complementary (IPCC, 2007, 2014a).

Such need is confirmed by the United Nations Framework Convention on Climate Change (UNFCCC, 1992), which in Article 4.1b states that countries are "committed to formulate and implement national and, where appropriate, regional programs containing measures to mitigate climate change and measures to facilitate adequate adaptation to climate change". The promotion of adaptation and the implementation of adaptation strategies to climate change by committed parties are also established in Article 10 of the Kyoto Protocol (UNFCCC, 1998).

Following is a description of the two types of strategies adoptable in the agricultural sector and their interactions in response to climate change.

5.1.1 Adaptation strategies

The emissions of greenhouse gases in recent decades (particularly carbon dioxide) are the main cause of the ongoing climate change and those expected by the end of the century. In order to reduce the negative impacts and take advantage of potential positive effects of climate change in agriculture, the best approach is the adoption of the most effective adaptation strategies (Howden et al., 2007). The importance and the need for adaptation to climate change in various sectors is recognized by most countries and organizations (IPCC, 2007, 2014a).

Adaptation refers to all actions and measures that can be put in place at local or regional scale to reduce the vulnerability to climate change of natural and human systems or to exploit new opportunities that may arise as a result of climate change (Burton, 1996; Smit et al., 2000).

The Fifth Assessment Report of the IPCC defines *vulnerability* as: "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (IPCC, 2014a,b). As reported in recent studies (e.g., Kates, 2000), the vulnerability of an agricultural system can be defined as a function of three components of the system, that are exposure to climate hazards (E), its intrinsic sensitivity to that exposure (S), and its adaptive capacity (AC):

$$\text{Vulnerability} = f(\text{E, S, AC})$$

Therefore, the vulnerability of a system cannot be directly measured or observed, but it can be estimated under different climates even keeping the adaptive capacity unvaried (Patt et al., 2009). However, the socio-economic changes expected for the coming decades could modify the adaptive capacity of systems (Tubiello and Rosenzweig, 2008).

The *adaptive capacity* is defined as "the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC, 20014a,b). Therefore, the adaptive capacity of a system is not easily measurable, unlike the actual adaptation responses that can be measured and evaluated with a monetary approach (e.g., cost-benefit analysis) or a non-monetary one (Tubiello and Rosenzweig, 2008).

There are different types of adaptation, depending to the criterion taken into consideration.

A first distinction is that between the autonomous and planned adaptations. The IPCC (2001a) defines the *autonomous adaptation* as "adaptation that does not constitute a conscious response to climatic stimuli but is triggered by ecological changes in natural systems and by market or welfare changes in human systems". Instead, the Fifth IPCC Report (2014a,b) defines the *autonomous adaptation* as the "adaptation in response to experienced climate and its effects, without planning explicity or consciously focused on addressing climate change". These are usually feasible strategies in the short-term and at a small-scale (e.g., farm scale) that can be implemented without the involvement of other sectors (e.g., politics). Instead, the *planned adaptation* is defined as "adaptation that is the result of a deliberate policy decision based on an awareness that conditions have changed or are about to change and that action is required to return to, maintain, or achieve a desired state". Therefore, planned adaptation refers to major structural interventions involving different sectors (e.g., policy, research, etc.) and that are feasible in the medium-long term (IPCC, 2001b).

Another distinction is that based on the players who are putting in place the adaptation strategies to climate change. *Private* adaptation includes all actions undertaken by individual private actors (e.g., individuals, enterprises, etc.), while *public* adaptation refers to the measures (e.g., public investments) undertaken by regional, national and international policies aimed at improving and/or facilitating the adaptative responses by private actors (single and organizations).

Finally, based on the timing when adaptation strategies are put in place, it is possible to distinguish between *anticipatory* (or proactive) and *reactive* (or responsive) adaptation, which are respectively defined as "adaptation that takes place before and after impacts of climate change are observed", (IPCC, 2001a). In some cases, anticipatory adaptation can be more effective and economic than reactive adaptation (as in the case of protection from rivers or coastal floods).

Agro-ecosystems are highly vulnerable to climate change. Therefore, adaptation in agriculture is very important for socio-economic development and food security. The IPCC (2001a) defines agricultural adaptation as "the adjustment in agricultural systems in response to actual or expected climatic stimuli or their effects, to moderate harm or exploits beneficial opportunities".

Adaptation, both in the short and the long term, can help reduce the vulnerability of agricultural systems to climate change. However, adaptive responses can vary significantly with the geographical area, as demonstrated by the recent research on agricultural adaptation in Europe (Olesen et al., 2011).

Adaptation is the norm in the agricultural sector. In fact, farmers always have to adapt to climate change on different time scales (from one week to one year and beyond), as well as to socio-economic changes (e.g., market conditions and reforms of agricultural policy). In the coming decades the adaptation capacity of farmers may not be enough to deal with the high rate at which the expected climate change will occur (Rosenzweig and Tubiello, 2007).

However, if the future climate change will be limited, farmers will be able to deal with adaptation easily and at a low cost, through the adoption of autonomous adaptation measures (e.g., changes in cultivars, sowing dates, and fertilization rates, use of the irrigation for rainfed crops, etc.). The efficiency of these strategies has already been demonstrated with the current climate even in the most vulnerable areas such as Southern Europe (Tubiello et al., 2000; Alexandrov et al., 2002; Ghaffari et al., 2002; Trnka et al. 2004; Minguez et al., 2007; Olesen et al., 2011; Ventrella et al., 2012).

On the other hand, adaptation strategies feasible in the long term (planned adaptation) are related to structural changes necessary to deal with the negative effects of climate change. Examples of planned adaptation are changes in land allocation and farming systems (also useful for stabilizing production), breeding of crop varieties, new land management techniques (useful for water conservation or increasing the irrigation use efficiency), etc. Obviously, planned adaptation strategies are more expensive than autonomous adaptation. However, some costs can be reduced by decreasing the implementation times (Stern, 2006).

Planned adaptation requires careful planning that takes place through several stages (Figure 1). The first phase of the adaptation plan is the assessment of climate change impacts and vulnerability of the agricultural system. Adaptation strategies are identified, and costs and responsibilities are evaluated. Finally, priority measures are chosen, before proceeding to the planning and implementation of the selected strategies. The plan should be regularly monitored and evaluated so as to take into account the socio-economic and technological development, as well as the progress of knowledge on climate change.

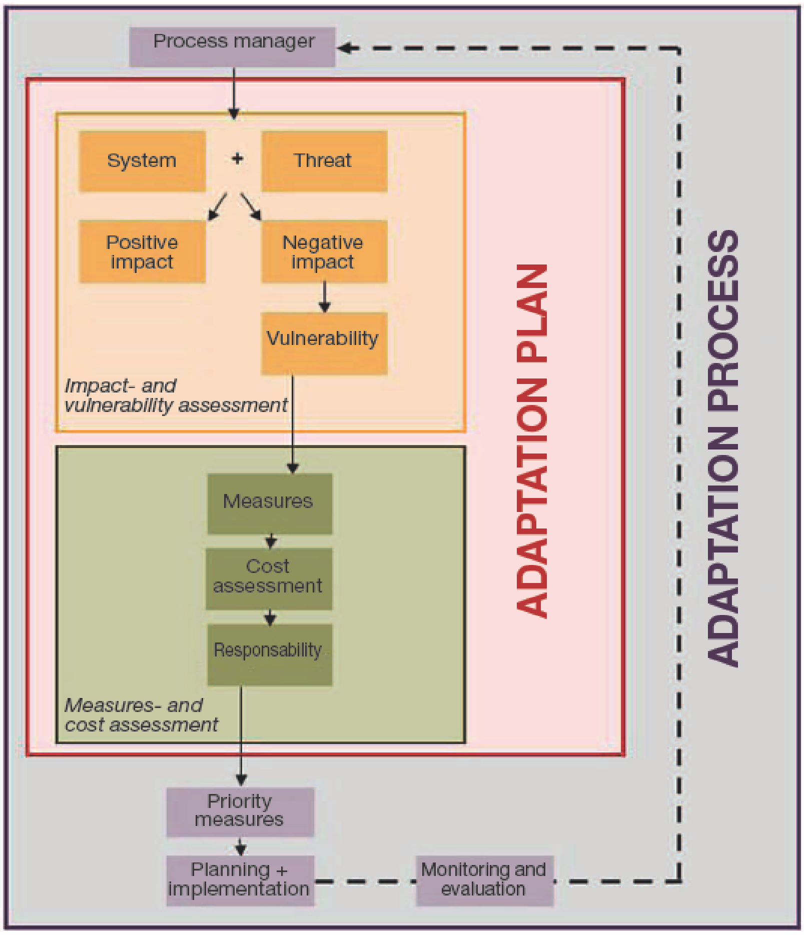

Figure 1. Climate adaptation process and plan (source: Marletto et al., 2012).

The implementation of adaptation strategies to climate change has a cost both for producers and consumers alike. This cost is related to changes in income and consumer prices at the enterprise and regional level respectively. Therefore, the availability of capital by companies could be a limiting factor in adapting to climate change (Easterling and Apps, 2005).

Adaptation strategies in agriculture are different and variable depending on the geographical area, the agricultural system and the climate change scenarios considered, with consequent variability of the adaptive responses of individual agricultural systems. For example, the adaptation strategies for cereals in autumn sowing (e.g., winter wheat and barley) are different from those for cereals in spring sowing (e.g., spring wheat and maize).

Adaptation strategies in the short term

For spring-sowing crops, the adaptation to climate change can be achieved with early sowing, which allows the prolongation of the crop growth cycle. In this way it is also possible to use long season cultivars (e.g., hybrids of FAO class 700 for maize), which allow an increase of potential yield in the absence of other stress factors (e.g., inadequate soil moisture, high risk of heat stress, etc.). In agricultural areas located at low latitudes (for example, in Southern Europe), such stress factors are usually present. Therefore, in order to reduce production losses related to water and thermal stress in conditions of climate change, it is necessary to carry out early sowing and use short-season varieties (Rosenzweig and Tubiello, 2007).

In order to survive, winter crops (e.g., winter wheat) must be sown when the temperatures are close to values favorable for vernalization. Therefore, a possible adaptation strategy for these crops (especially in southern areas) is the introduction of new cultivars with reduced needs for vernalization. Instead, in the northern areas, the use of longer-maturing varieties represents a valid adaptation strategy for winter crops, if the rainfall during the prolonged growing season is enough to sustain grain filling (Rosenzweig and Tubiello, 2007).

The optimization of crop management techniques could enable adaptation to climate change in the short term with good results.

For irrigated crops, irrigation optimization is an important adaptation strategy to cope with increased water loss by evapotranspiration expected in the coming decades, particularly in the southern latitudes. An example is given by the replacement of existing irrigation systems with more efficient ones as the localized irrigation method (e.g., drip irrigation or microsplinker irrigation). These methods of irrigation are already widely used in the southern areas for tree crops (e.g., grapevine, citrus, and olive) and for vegetable crops (e.g., tomato, lettuce, etc.) (Eitzinger et al., 2009). The decrease of water resources and the expected increase in irrigation demand (Gallo et al., 2012; Mancosu, 2013) will probably lead to the extension of their use (as well as to other irrigated crops) and to their growing spread in the northern areas.

For rainfed crops, a simple adaptation strategy is the introduction of irrigation that may result in positive effects on agricultural production. For example, the use of irrigation for the winter durum wheat in Italy in the South-Peninsular areas could increase grain yield and reduce its inter-annual variability from 40% to 10% (Ventrella et al., 2012). However, the reduced water availability, the rising cost of water and the competition with other sectors are factors that must be carefully considered (Iglesias et al., 2007; Rosenzweig and Tubiello, 2007).

The optimization of fertilization techniques can be a useful strategy for adapting to climate change, particularly at high latitudes (e.g., Northern Europe and Northern Italy), where increases in yield are expected over the next few decades, due to prolongation of the growth cycle (Olesen et al., 2011). However, the risk of nitrogen and phosphorus leaching in these areas may increase as a result of the expected increase in precipitation (Iglesias et al., 2007; Eitzinger et al., 2009; Olesen et al., 2011). A possible solution to reduce this risk is the adoption of fertigation, commonly used for tree and vegetable crops with high income (Eitzinger et al., 2009).

The adaptation of agricultural systems to climate change can also be achieved by improved tillage practices, which are important for the conservation of water in the soil and for the protection of soil from erosion by water and wind (Falloon and Betts, 2010). The adoption of water-conserving tillage techniques can be useful in hot and dry areas, especially for cereals (e.g., winter wheat, maize, and barley) and grapevine (Eitzinger et al., 2009; Olesen et al., 2011). Other tillage practices useful for the conservation of water in the soil are the tillages in the inter-rows and controlled grassing (for tree crops) and soil mulching with synthetic or vegetal material (e.g., residues of the previous crop) (Eitzinger et al., 2009).

Finally, the improvement of the effectiveness of pest, disease and weed management practices is an important strategy for climate change adaptation, particularly for cereals (wheat, maize, and barley) in the mid-high latitudes (Olesen et al., 2011). Therefore, monitoring services are of strategic importance for crop protection.

Adaptation strategies in the medium-long term

In agriculture, feasible medium-long term adaptation strategies are planned adaptation measures. Thus, they need to be planned at a high level by involving other sectors (e.g., policy, research, etc.) at the regional or national level.

An important measure of adaptation feasible in the medium-long term is the introduction of new genetically improved cultivars. Therefore, breeding programs are important for an effective adaptation, especially in the areas most vulnerable to climate change. In such a way it is possible to use new varieties, with higher and more stable yields, more resistant to pest, plant disease and weeds and suitable to changing climatic conditions (e.g., cultivars with lower requirements for vernalization for winter crops and varieties more resistant to water and thermal stress for spring crops). However, genetic varietal improvement occurs through a process that takes several years before the possible use of improved cultivars (Rosenzweig and Tubiello, 2007; Eitzinger et al., 2009). In Europe, the greatest benefits of the introduction of new cultivars are expected for spring barley and grain maize (Olesen et al., 2011).

The changes in farming systems and land use can be an effective strategy for adapting to climate change, given the expected northward shift of the cultivation areas of different crops (e.g., durum wheat, grapewine, olive, and cytrus) (Eitzinger et al., 2009; Bindi and Olesen, 2011). The reduction (up to 50%) of croplands and grassland areas expected in Europe in the coming decades (Rounsevell et al., 2005) could provide opportunities, such as the introduction of bioenergy crops (e.g., oilseed crops, starch crops, etc.) in substitution of crops for food production (Tuck et al., 2006).

The structural improvement of irrigation efficiency is another possibility in order to achieve agricultural adaptation to climate change in order to reduce water losses, especially in hot and dry areas (e.g., Southern Italy). This objective can be achieved with the construction of new dams or the adoption of de-salinization systems (Eitzinger et al., 2009). Furthermore, the use of new technologies for planning irrigation at the enterprise/regional level may allow increased water use efficiency. In this regard, the seasonal forecasting services for crop water requirements can be very useful, particularly for crops sensitive to water stress (Tomei et al., 2011). Another useful technology for irrigation planning at a regional scale is remote sensing which allows for better land cover classification (Spisni et al., 2011).

The increase in climate variability could result in greater yield losses than those estimated in mean conditions (Porter and Semenov, 2005). This causes greater difficulties for the adaptation of agriculture in conditions of greater climate variability. Adaptation strategies in these conditions may be different from those in mean climate change and include strategies aimed at increasing the resilience of production and income (e.g., changes in cropping rotations, better soil conservation, integrated pest management, etc.) (Rosenzweig and Tubiello, 2007; Reidsma and Ewert, 2008).

The success of planned adaptation in agriculture is linked to the effectiveness of the strategies put in place, many of which require an active role of policy, research and other sectors in order to increase the resilience of cropping systems. In this context, the conservation of biodiversity is important because it increases the adaptive capacity of the system to changing climatic conditions.

5.1.2 Mitigation strategies

The IPCC (2014c) defines mitigation as "an human intervention to reduce the sources or enhance the sinks of greenhouse gases".

The ongoing changes in climate and those expected for the next decades will have a negative impact on agriculture, whose production will have to increase in the coming decades so as to ensure food security. However, the agricultural sector is responsible for climate change as it is one of the main sources of emissions of greenhouse gases, particularly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2001b, 2014b).

According to recent estimates, the cumulative carbon emissions over the last century by management of land for food and feed production were about 150 Gt C, while carbon emissions from fossil fuels were about 300 Gt C (LULUCF, 2000). Currently, in European Union (EU-27) about 10% of the total global anthropogenic emissions of GHGs derive from agriculture (IPCC, 2014b). However, the agricultural contribution to anthropogenic emissions of GHGs varies depending on the greenhouse gas considered. In fact, the annual anthropogenic emissions of agricultural origin are limited for carbon dioxide (about 15% of the total), while they are higher for methane and nitrous oxide (about 50% and 60%, respectively) (FAO, 2003; U.S.-EPA, 2006). The major sources of agricultural emissions of carbon dioxide are the microbial decay and burning of soil organic matter and plant litter. Livestock and rice cultivation are the main sources of emissions of agricultural origin for methane, while nitrous oxide is emitted mainly through nitrogen fertilization and manure management. According to recent estimates, the absorptions of carbon dioxide by the forest and grassland soils (carbon dioxide sinks) totally offset the emissions of methane and nitrous oxide from agriculture in Europe (Schulze et al., 2010).

Due to the greater development of agriculture and the consequent expected increase in livestock production and nitrogen fertilizer use, a global increase of emissions of nitrous oxide (from +35% to +60%) and methane (about +60%) is expected up to 2030 (FAO, 2003). Conversely, compared to 2010, a marked decrease (from -25% to -40%) of the forest carbon sink is expected until 2030 in the European Union (IPCC, 2014b).

Considering that methane and, mainly, nitrous oxide have a Global Warming Potential (GWP) greater than carbon dioxide, the increased atmospheric emissions of these greenhouse gases could have a significant negative impact. Therefore, a possible solution for the mitigation of global anthropogenic emissions is the adoption of measures to modify and optimize the management of agricultural systems. However, the climate system responds slowly to such interventions, whose potential benefits could be observed only in the second half of the century (Milly et al., 2002; Tubiello and Fischer, 2007).

According to estimates by the IPCC, the global agricultural GHG mitigation potential by 2030 will be between 5,500 and 6,000 Gt CO_2-equivalent year^{-1}, the greater part of which (approximatively 89%) is due to the reduction of CO_2 emissions by soil, related to carbon sequestration. Recent studies (Smith et al., 2008) show that the total biophysical mitigation potential, estimated by 2030, taking into consideration all GHGs, varies widely from one country to another. This is particularly evident in Europe (Figure 2).

The mitigation of GHGs emissions from agriculture can be achieved through two approaches:

1. the sequestration of atmospheric carbon and its storage in the soil;
2. the reduction of GHGs emissions, through the adoption of practices that enable more efficient management of carbon and nitrogen flows in cropping systems.

The first approach is useful because agro-ecosystems have a high capacity to store carbon in the soil. Therefore, the adoption of crop management practices that increase carbon inputs in soil and reduce the rate of decay of soil organic matter, allows the removal of the atmospheric carbon. However, the effectiveness of this approach is

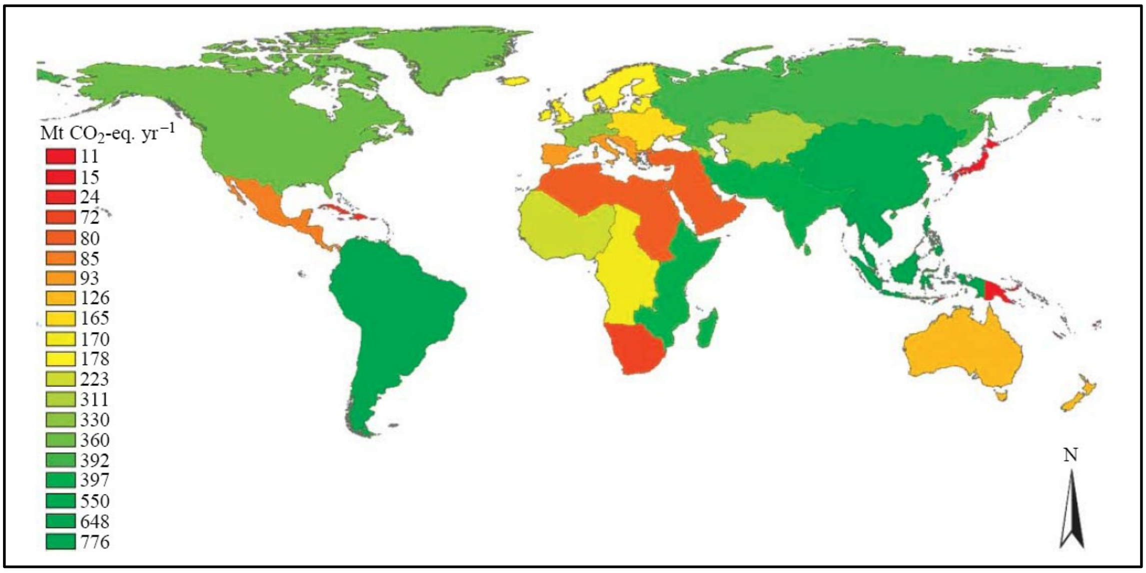

Figure 2. Total biophysical mitigation potentials (all practices, all GHGs: Mt CO_2-eq. yr^{-1}) for each region by 2030 (source: Smith et al., 2008).

limited in time (20-40 years), while the adoption of crop management techniques aimed at reducing carbon emissions can be effective for much longer (Rosenzweig and Tubiello, 2007). The net benefit varies according to the adopted management practice and the greenhouse gas taken in consideration: some emission reductions are temporary, others are indefinite.

Improvement of management practices and technological progress in agriculture offer various possibilities for reducing emissions of methane and nitrous oxide (Weiske et al., 2006). For example, it was estimated that improving energy efficiency could provide an additional global GHG mitigation potential of 770 Mt CO_2-eq. yr^{-1} by 2030, especially in Asia and Europe (Smith et al., 2008).

Some strategies that could be used for climate change mitigation in agriculture are described in Table 1.

5.1.3 Interactions between adaptation and mitigation strategies

The adoption of only a single type of strategy is not sufficient to deal with the unavoidable impacts of climate change expected in the coming decades. Therefore, it is essential to implement both strategies (adaptation and mitigation) to reduce and prevent the direct and indirect damages to agriculture due to climate change (IPCC, 2007, 2014a,c).

However, there are some substantial differences between mitigation and

Table 1. Strategies adoptable for the climate change mitigation in agriculture and relative benefits.

Mitigation strategies	**Examples**	**Benefits**
Optimization of agronomic practices	- Use of improved cultivars - Extension of crop rotation to perennial crops - Incorporation of crop residues.	- Increase in crop yields - Increase of carbon storage in the soil.
Adoption of less intensive cropping systems	- Rotations with legume crops	- Decrease of nitrogen fertilizers use
Improvement of the fertilizer-nitrogen use efficiency	- Improvement of the timing of the applications - Use of slow-release fertilizers or nitrification inhibitors - Avoiding applications with nitrogen fertilizers when possible	- Reduction of GHGs emissions by nitrogen fertilizers and manures
Reduction of tillages	- Minimum tillage - No-tillage	- Decrease in carbon emissions from soil (reduction of decomposition, run-off and soil erosion)
Optimization of water-use management	- Improvement in water irrigation management - Use of more efficient irrigation systems - Soil drainage in the wetlands	- Increase in crop yields - Reduction of nitrous oxide emissions
Improvement of rice cultivation management	- Drainage of wetland rice during the growing season - Keeping the soil in dry conditions in the off-rice season	- Reduction of methane emissions
Cultivation of marginal land for agricultural production	- Cultivation of bioenergy crops (e.g., wheat, maize, cellulosic crops, etc.)	- Decrease in atmospheric CO_2 concentration (production of liquid bio-fuels)
Improvement of livestock production	- Improvement of the feeding practices - Use of specific agents and dietary additives - Longer term management changes and animal breeding	- Reduction of methane emissions
Optimization of animal manures management	- Improvement of handling and storage of animal manures - Better management of organic fertilizers	- Reduction of methane and nitrous oxide emissions

adaptation.

First, mitigation and adaptation are two solutions with different objectives. In fact, adaptation is a temporary solution because its aim is to reduce the existing or expected damage resulting from climate change, whereas mitigation can be considered as a type of "permanent" solution in the fight against anthropogenic emissions of greenhouse gases.

The two types of strategies also differ in their effectiveness over time (Wilbanks, 2005; Füssel and Klein, 2006; Tubiello and Fischer, 2007): the effectiveness of adaptation strategies in reducing the damage is immediate, while the effects of mitigation strategies will only be visible in the future and with a greater level of uncertainty.

Another difference between adaptation and mitigation concerns the spatial scale at which they exert their effects. In fact mitigation strategies provide advantages at a "global" scale. Conversely, the benefits arising from the adoption of adaptation strategies can be "local" (in the case of autonomous adaptation) or at the "regional" scale (in the case of planned adaptation) (IPCC 2001a; Bosello et al., 2009).

The agricultural sector contributes significantly to greenhouse gases emissions into the atmosphere, so it is responsible for climate change and its impacts on growth and yield of crops which are expected to occur in the coming decades. Therefore, farmers, policy makers and other stakeholders will necessarily have to act in a synergistic way with regards to adaptation strategies (to cope with the ongoing climate change) and mitigation strategies (to prevent damages associated with climate change expected in the coming decades).

The mitigation and adaptation strategies can interact reciprocally. In some cases, adaptation measures may reduce the potential for mitigation of the affected land. An example is represented by northwards shifting of the cultivation areas of some crops (e.g., durum wheat) and by the replacement of these crops with other. This may cause a decrease of the soil organic carbon and, therefore, the potential for mitigation. In other cases, adaptation and mitigation interact in a synergistic way. For example, the increase in fertilization and irrigation under climate change conditions could increase the carbon sequestration capacity of these soils, especially in the semi-arid regions such as sub-Saharan Africa (Solomon et al., 2000). Reduced tillage and no-tillage result in the reduction of run-off and soil erosion and at the same time reduce fossil-fuel use (Khaledian et al., 2010; Soane et al., 2012). Finally, the incorporation of crop residues and manure in the soil and the better management of crop rotations improve the soil water holding capacity, contributing both to adaptation and mitigation (Smith and Olesen, 2010).

The interactions between adaptation and mitigation strategies could be reinforced further in the coming decades due to increased climate variability. For example, various mitigation practices useful to improve the carbon sequestration in soil could increase biodiversity, the capacity of soils to hold moisture and protection from erosion. In this way, the crop systems may suffer less negative impacts related to the expected increase in the frequency of extreme weather events (e.g., drought and flood) (Rosenzweig and Tubiello, 2007).

However, the positive effect of these interactions is limited by the cost of implementation of strategies, by the high uncertainty of the effects of mitigation measures and by a series of obstacles (biological, physical, social, and political) that tend to reduce the potential for mitigation in the area considered (Smith et al., 2007; IPCC, 2014a).

It is in this context that dynamic crop simulation models (refer to section 1.3 of this thesis) can represent a valuable tool to test the effectiveness of possible agronomic adaptation strategies under different climate change scenarios at both the local and regional scale.

5.2. OBJECTIVES

The general objective of this part of the thesis is the study and assessment of the effectiveness of some possible adaptation strategies in order to reduce the negative impacts of climate change on phenology and yield of main Italian cereals (durum wheat, common wheat and maize) at the spatial scale. To this end, the assessment was carried out for the different cultivation areas using the CSM-CERES-Wheat and CSM-CERES-Maize crop simulation models.

The specific objective of this work is the assessment of some adaptation strategies feasible in the short term on maturity date and grain yield of the crops considered at the Italian scale using the climate change scenarios considered for climate change impact assessment.

In this study it has been decided to analyze only some of the adaptation strategies feasible in the short term because they are of immediate implementation by farmers (autonomous adaptation).

This approach will make it possible to identify the most effective adaptation strategies in each area and the implementation of an adaptation plan at the national scale in order to contrast the negative impacts of climate change on growth and productivity of crops considered.

5.3 MATERIALS AND METHODS

In this work, the assessment of adaptation strategies was performed for the different cultivars (Iride, Bologna, and Eleonora for durum wheat, common wheat, and maize respectively) and for different cultivation areas.

To this end, the Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM) was used (see section 1.3.3 of this thesis) (Jones et al., 2003; Hoogenboom et al., 2010). More precisely, the CSM-CERES-Wheat and CSM-CERES-Maize crop models (see section 1.3.4 of this thesis) implemented in DSSAT-CSM v.4.5.0.0 were used (Hoogenboom et al., 2012).

The CSM-CERES-Wheat and CSM-CERES-Maize crop models parameterized at the Italian scale (see Chapter 3 of this thesis) (Gallo et al., 2014a) were used to assess the adaptation strategies. The study follows the same methodological scheme used for the assessment of the climate change impacts on phenology and grain yield of the three crops at the Italian scale (see section 4.3 of this thesis) (Gallo et al., 2014b). These models were used to test the effectiveness of different adaptation strategies, so as to provide to policy makers a valid support in decision making on how to cope with the impacts of climate change in agriculture. Therefore, several potential adaptation strategies feasible in the short time have been studied (Table 2).

Table 2. Adaptation strategies assessed in this work.

Adaptation strategies	**Description**
Shifting of sowing date	Advance of sowing date (-15 days)
	Advance of sowing date (-30 days)
	Delay of sowing date (+15 days)
Changes in fertilization regime	Increase in N, P and K fertilization rates (+20%)
	Incorporation of crop residues (5 t ha^{-1}) + ordinary inorganic fertilization*
Application of the irrigation	Automatic irrigation**

*Only for maize.

**Only for durum wheat and common wheat.

Regarding the shifting of sowing date, three adaptation strategies were studied for each crop: early sowing date (-15 and -30 days) and delay of sowing date (+15 days). The details of each of them regarding the sowing dates used for each crop in each area are shown in Table 3.

Table 3. Ordinary and modified sowing dates for each adaptation strategy relative to the shifting of sowing date for each crop and area.

Crop	**Area**	**Ordinary sowing date**	**Advanced sowing date**		**Delayed sowing date**
			-15 days	-30 days	+15 days
Durum wheat	North	5th November	21th October	06th October	20th November
	Centre-Italy (Tyrrhenian side)	11th December	26th November	11th November	26th December
	Centre-Italy (Adriatic side)	25th November	10th November	26th October	10th December
	South-Peninsular	2nd December	17th November	02nd November	17th December
	Sicily	10th December	25th November	10th November	25th December
	Sardinia	15th December	30th November	15th November	30th December
Common wheat	North	2nd November	18th October	03rd October	17th November
	Centre	28th November	13th November	29th October	13th December
	South-Islands	7th December	22nd November	07th November	22nd December
Maize	North	20th April	05th April	21st March	05th May
	Centre	1st April	17th March	02nd March	16th April
	South-Islands	1st April	17th March	02nd March	16th April

Two adaptation strategies linked to the change in fertilization regime were studied. One of these is the increase of the total annual fertilization rates of N, P and K (kg ha^{-1}) by 20% compared to the average fertilization rates in each area for the three crops considered (Table 4). As regards the nitrogen fertilization, all doses have been increased by 20%. Another adaptation strategy concerns the incorporation of crop residues (5 t ha^{-1}) of *Vicia villosa* Roth. (for maize). Incorporation of crop residues with the plowing has been hypothesized.

Another potential adaptation strategy studied is the application of irrigation. The effectiveness of the latter strategy has been evaluated only for durum wheat and common wheat, as maize is usually irrigated. These are strategies feasible in the short

Table 4. Total annual fertilization rates (kg ha^{-1}) increased by 20% for each crop and area.

Crop	**Area**	**Total annual fertilization rates (kg ha^{-1})**		
		N	**P**	**K**
Durum wheat	North	192	116	61
	Centre-Italy (Tyrrhenian side)	197	104	106
	Centre-Italy (Adriatic side)	167	116	61
	South-Peninsular	120	100	0
	Sicily	114	110	0
	Sardinia	118	89	0
Common wheat	North	179	97	109
	Centre	193	107	61
	South-Islands	110	116	0
Maize	North	327	132	162
	Centre	327	132	162
	South-Islands	327	132	162

time, and whose answers to climate change can be immediate. In this study, the "Automatic irrigation when required" option was used.

The simulations were performed for two climate scenarios (RCP4.5 and RCP8.5), through the digital platform (Trabucco, 2014) used for the assessment of climate change impacts on phenology and yield (see section 4.3 of this thesis). The analysis was carried out for the maturity date (for phenology) and grain yield, considering three future periods (2006-2035, 2036-2065, 2066-2095, centered at 2020, 2050 and 2080 respectively).

Simulations were performed using a desktop PC with an Intel Core I7 processor and 16 Gb of RAM. Overall, the digital platform has carried out about 14 million runs. The total hard disk space used by the outputs generated by the digital platform is about 212 Gb.

The Climate Data Operators v.1.6.1 software (CDO, 2013) was used for the post-processing of the netCDF output files. Areas with a slope greater than 30% were excluded using ArcGIS Desktop v.10.2 software (ESRI, 2013). In this work, the average absolute values of maturity date (in days after planting) and grain yield (in kg ha^{-1}) and the changes of these variables for each future period compared to baseline period have been extracted for all areas.

5.4 RESULTS

This section presents the results of the assessment of the adaptation strategies to climate change (climate change scenarios with adaptation) for durum wheat, common wheat and maize at the Italian scale.

For each crop and cultivation area, this study has evaluated the effects of the adaptation strategies on changes in maturity date and grain yield for each future period (2020, 2050 and 2080) compared to the baseline period (1990) under the RCP4.5 and RCP8.5 climate change scenarios. Results concerning changes in the average maturity date for adaptation strategies related to changes in fertilization regime are not shown as changes in the application of fertilizers and irrigation do not affect crop phenology. Finally, a graphical comparison of changes in maturity date (days) and grain yield (%) between adaptation strategies was carried out for each crop and area, taking separately into account the two climate change scenarios used.

5.4.1 Durum wheat

Shifting of sowing date

Results relative to the changes in sowing date (advance (-15 and -30 days) and delay (+15 days)) on maturity date and grain yield of Iride cultivar in Italy are described below.

Maturity date

Results of the advance of sowing date (-15 days) on changes in average maturity date (days) from actual to future periods for each climate scenario for Iride cultivar in Italy are shown in Figure 3.

Results show a decrease in the average maturity date in all areas, when compared to that of the baseline period under both climate scenarios for 2050 (ranging from -2 to -5 days with the RCP4.5 scenario and from -5 to -10 days with the RCP8.5 scenario) and 2080 (from -6 to -10 days and from -19 to -24 days under the RCP4.5 and RCP8.5 scenarios respectively), while a slight increase in the average maturity date was estimated for 2020 (from +2 to +6 days with the RCP4.5 scenario and up to +3 days with the RCP8.5 scenario). Thus, the average length of the growing season (from sowing to maturity), simulated with the advance of the sowing date of 15 days, increases when compared with the one simulated with the ordinary sowing date for each

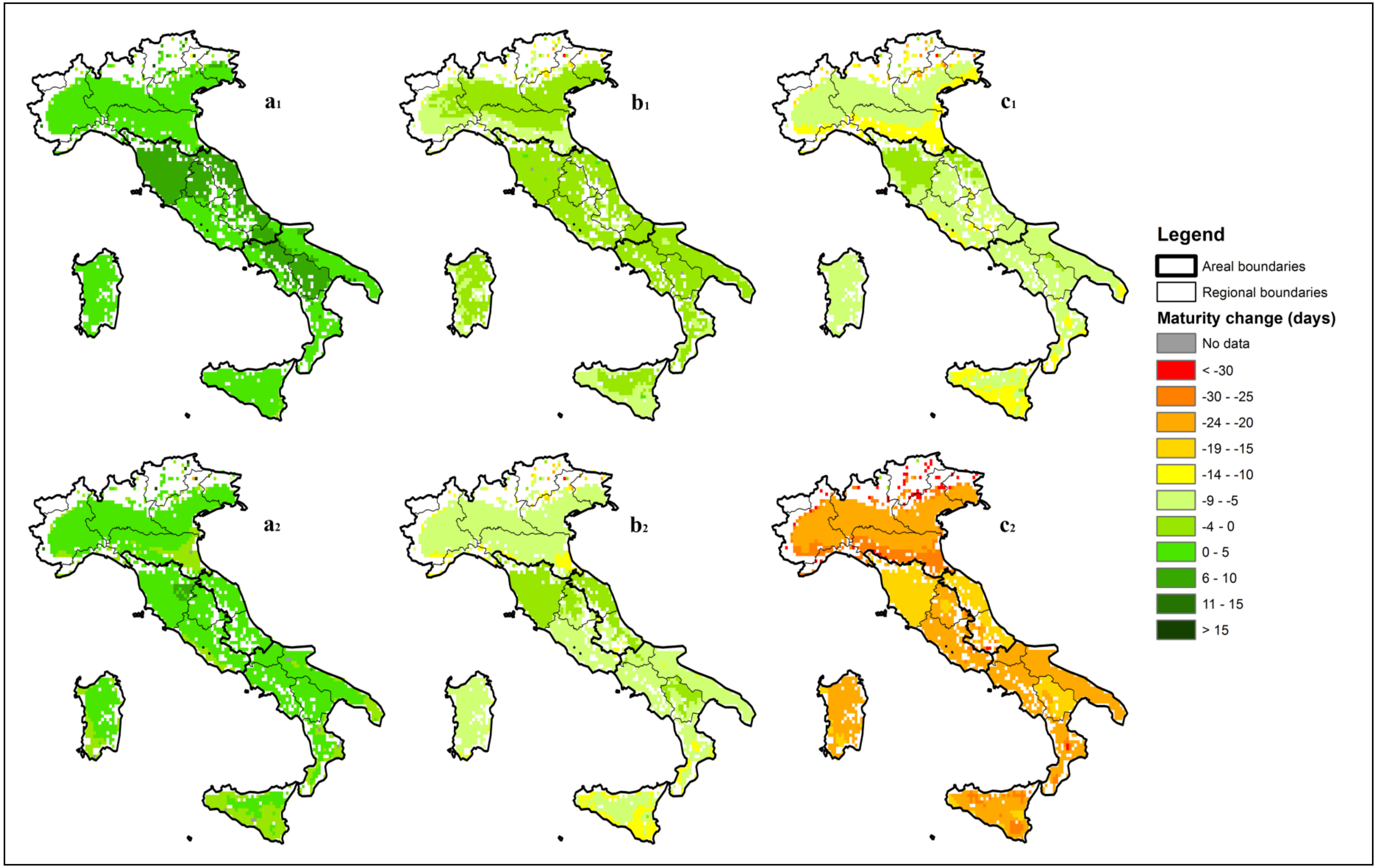

Figure 3. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-15 days)) for the Iride cultivar in Italy.

future period in all areas (ranging from +3 to +13 days with the RCP4.5 scenario and from +7 to +13 days with the RCP8.5 scenario) (Table 5).

Table 5. Changes in average maturity date (days) for each future periods and climate scenarios with adaptation (advance of sowing date (-15 days)) for the Iride cultivar compared with climate change impacts without adaptation in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	+10	+11	+3	+10	+10	+8
Centre-Italy (Tyrrhenian side)	+12	+12	+9	+12	+11	+10
Centre-Italy (Adriatic side)	+13	+12	+8	+13	+13	+11
South-Peninsular	+11	+11	+10	+11	+10	+9
Sicily	+9	+9	+9	+9	+9	+7
Sardinia	+11	+10	+10	+10	+10	+9

Simulations carried out with a 30 days advance of the sowing date predict a positive change in the average maturity date when compared to that of the baseline period. This is even greater than the advance of the sowing date by 15 days in all areas, in particular in 2020 (ranging from +6 to +18 days) and in 2050 (up to +10 days) taking into consideration both climate scenarios, as shown in Figure 4. On the other hand, the average maturity date in 2080, when compared with the baseline (particularly under the RCP8.5 scenario), is always lower in all areas, albeit to a lesser extent compared with the 15 days advance sowing. Overall, the advance of the sowing date of 30 days would allow an increase in the average maturity date in all periods between +10 and +19 days in the North area, between +16 and +25 days in Central-Southern Italy, and between +13 and +19 days in the Islands (Table 6).

Conversely, a greater reduction of the average maturity date compared to the baseline period was obtained in all areas with the the sowing date delayed by 15 days with respect to ordinary sowing date, especially in 2080 (ranging from -29 to -31 days and from -39 to -44 days under the RCP4.5 and RCP8.5 scenarios respectively) (Figure 5). Therefore, the average lenght of the crop cycle decreases in each future period under both climate scenarios (from -11 to -18 days in Central-Northern Italy and from -9 to -12 days in the South-Peninsular area and in the Islands) (Table 7).

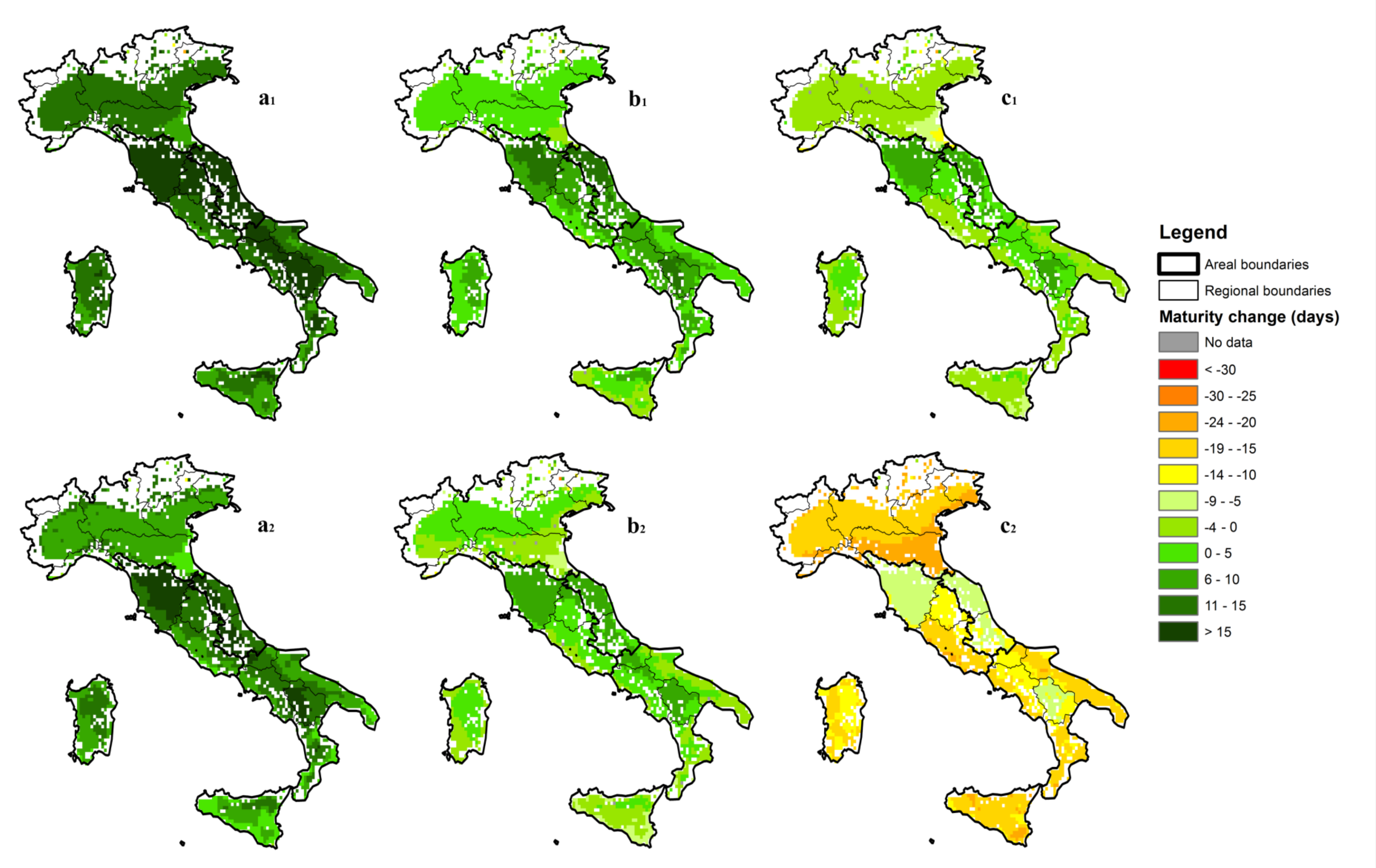

Figure 4. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-30 days)) for the Iride cultivar in Italy.

Table 6. Changes in average maturity date (days) for each future periods and climate scenarios with adaptation (advance of sowing date (-30 days)) for the Iride cultivar compared with climate change impacts without adaptation in Italy.

Area	RCP4.5			RCP8.5		
	2020	2050	2080	2020	2050	2080
North	+19	+19	+10	+18	+17	+13
Centre-Italy (Tyrrhenian side)	+22	+22	+18	+22	+21	+18
Centre-Italy (Adriatic side)	+25	+24	+19	+24	+24	+21
South-Peninsular	+20	+19	+18	+20	+19	+16
Sicily	+16	+15	+16	+16	+15	+13
Sardinia	+19	+19	+18	+19	+18	+15

Table 7. Changes in average maturity date (days) for each future periods and climate scenarios with adaptation (delay of sowing date (+15 days)) for the Iride cultivar compared with climate change impacts without adaptation in Italy.

Area	RCP4.5			RCP8.5		
	2020	2050	2080	2020	2050	2080
North	-13	-12	-18	-12	-12	-11
Centre-Italy (Tyrrhenian side)	-13	-12	-14	-13	-12	-11
Centre-Italy (Adriatic side)	-13	-13	-18	-13	-13	-12
South-Peninsular	-12	-12	-12	-12	-12	-10
Sicily	-11	-10	-9	-10	-10	-9
Sardinia	-12	-11	-10	-11	-11	-10

Grain yield

Figure 6 shows the changes in average grain yield (%) from the baseline period to future periods under the RCP4.5 and RCP8.5 climate scenarios for Iride cultivar in Italy with an advance of sowing date by 15 days. In general, this adaptation strategy increases the positive impact of climate change on grain yield in Centre-Italy (Adriatic side) and the South-Peninsular areas in all future periods and under both climate scenarios (on average +2.1% in 2020, +0.2% in 2080 and from +2.5% in 2020 to +0.3% in 2080 for the two areas respectively) (Table 8). Similar results were also obtained in

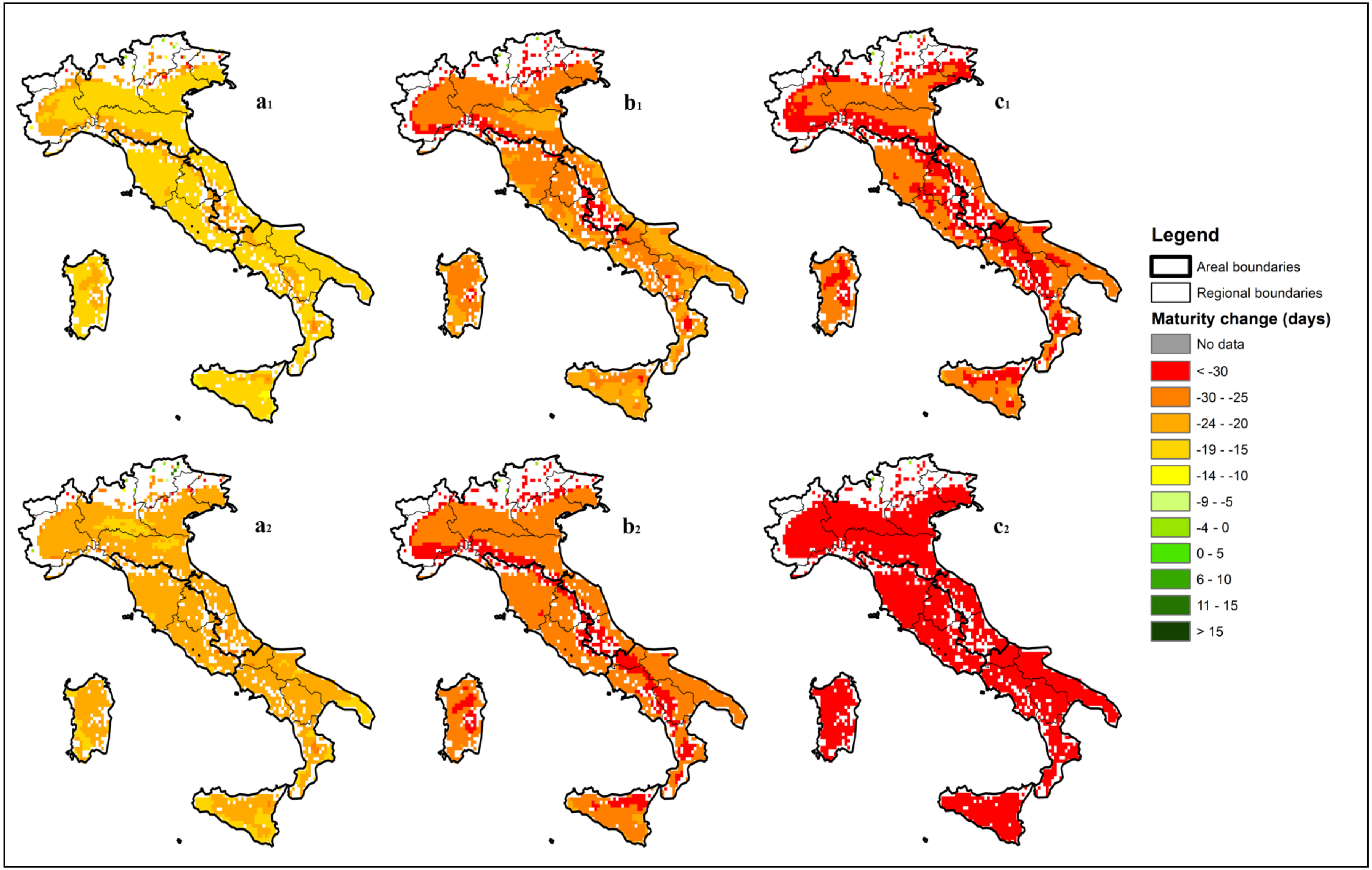

Figure 5. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (delayed sowing date (+15 days)) for the Iride cultivar in Italy.

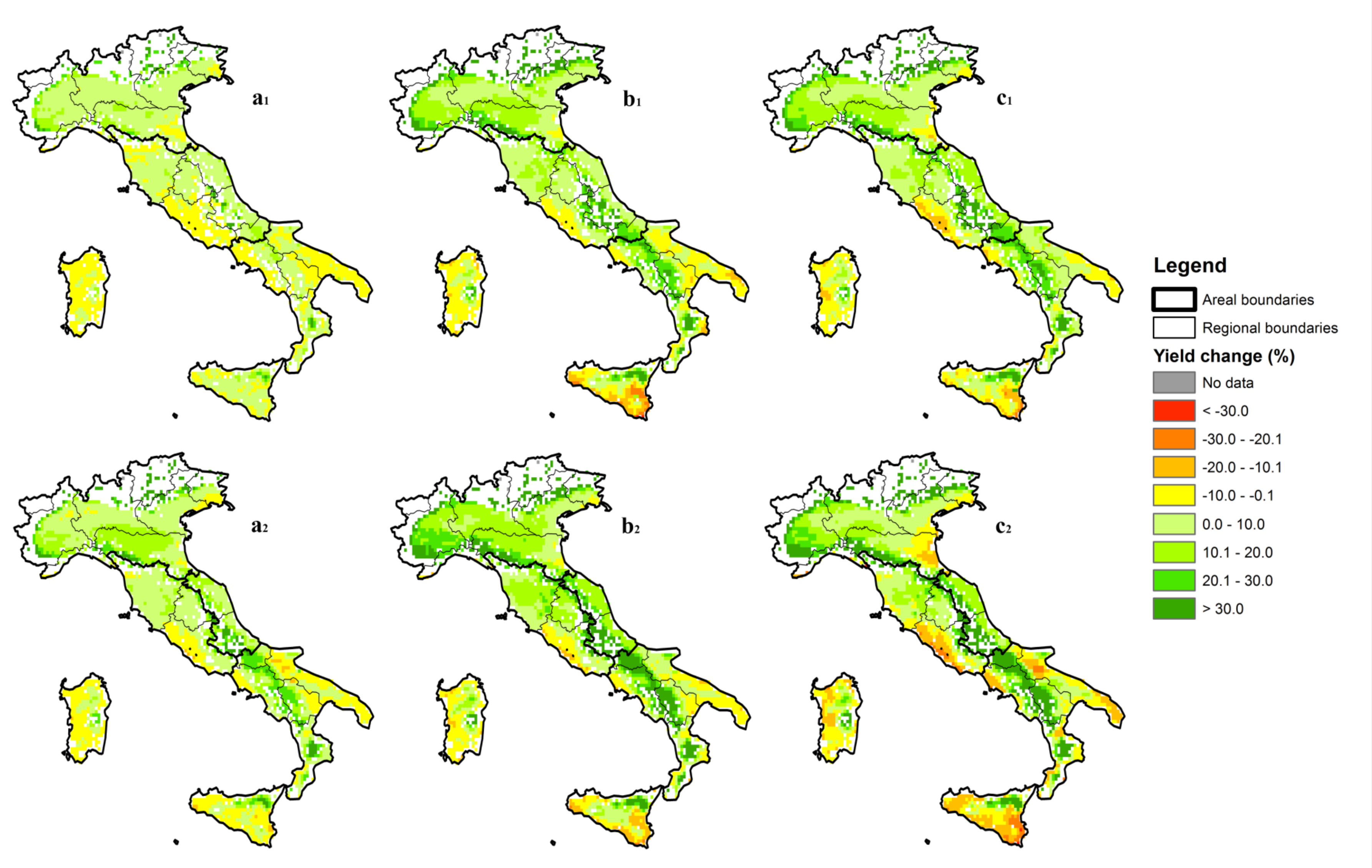

Figure 6. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-15 days)) for the Iride cultivar in Italy.

Table 8. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (advance of sowing date (-15 days)) for the Iride cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+2.1	+2.3	**+2.2**
	2050	+2.0	-1.5	**+0.3**
	2080	-0.8	-2.8	**-1.8**
Centre-Italy (Tyrrhenian side)	2020	+0.8	+0.3	**+0.6**
	2050	+0.7	-1.1	**-0.2**
	2080	-0.5	-2.0	**-1.3**
Centre-Italy (Adriatic side)	2020	+1.8	+2.4	**+2.1**
	2050	+3.6	+2.4	**+3.0**
	2080	+2.3	-2.0	**+0.2**
South-Peninsular	2020	+2.7	+2.2	**+2.5**
	2050	+1.4	+1.3	**+1.4**
	2080	+1.7	-1.1	**+0.3**
Sicily	2020	+3.1	+2.1	**+2.6**
	2050	+0.6	+2.6	**+1.6**
	2080	+2.5	-1.4	**+0.6**
Sardinia	2020	+1.5	+1.0	**+1.3**
	2050	+0.4	-0.5	**-0.1**
	2080	-0.8	-2.6	**-1.7**

the North and Centre-Italy (Tyrrhenian side) areas, where the advance of the sowing date by 15 days increases the positive impact of climate change on grain yield in 2020 (in mean +2.2% and +0.6% respectively), while it decreases slightly in 2080 (with a mean of -1.8% and -1.3% respectively in the two areas). In Sicily this adaptation strategy could make it possible to have an increase of the average grain yield in each future period if compared with the impacts of climate change without adaptation (on average from +2.6% in 2020 to +0.6% in 2080 considering the two climate scenarios). This could remove the negative impact of climate change on yield in 2020 (in both scenarios), in 2050 (with the RCP8.5 scenario) and in 2080 (under the RCP4.5

scenario). A slight positive effect on grain yield was also simulated in Sardinia, in particular in 2020 (on average +1.3% considering both climate scenarios), but not sufficient to compensate the negative impact of climate change in the various future periods (except 2050 under the RCP8.5 scenario). Results of the change in grain yield obtained with the advance of the sowing date by 15 days are probably due to the increase in the average length of the period between sowing and maturity in the various future periods and under the two climate scenarios as the grain yield is positively affected by the lengthening of growing season.

Figure 7 shows changes in the average grain yield of Iride cultivar, simulated with a 30 days advance of the sowing date in the three future periods with the RCP4.5 and RCP8.5 climate scenarios, compared with the baseline period in the various areas. The average grain yield increases also with this adaptation strategy with respect to the ordinary sowing date in all future periods in the Centre-Italy (Adriatic side) area, even if only slightly when compared to the advance of the sowing date by 15 days (ranging from +2.2% in 2020 to +1.7% in 2080 considering the two scenarios) (Table 9). Similar increases were obtained in 2020 in the North, South-Peninsular and Sicily areas (+1.2%, +1.8%, and +1.9% respectively), while a decrease in average grain yield was estimated in 2050 and 2080, particularly in the North area (on average -2.4% in 2050 and -12.9% in 2080) and in the Centre-Italy (Tyrrhenian side) area (on average -3.4% in 2050 and -6.8% in 2080). Finally, the advance of sowing date by 30 days increases the negative impact of climate change on average grain yield, compared with the early sowing date by 15 days in the Sardinia area (from -0.9% in 2020 to -8.7% in 2080 considering the two climate scenarios).

The delay of sowing date (+15 days) involves a general decrease in the average grain yield for Iride cultivar, compared with the baseline period for all future periods under both climate scenarios in all areas (Figure 8 and Table 10). As can be seen, the greatest reductions in average grain yield with respect to the impacts of climate change without adaptation were obtained in Sicily (on average ranging from -6.4% in 2020 to -4.1% in 2080 considering the two climate scenarios), while smaller reductions were obtained for the Centre-Italy (Tyrrhenian side) area (on average from -2.1% in 2020 to -1.3% in 2080). Despite these decreases, the change in average grain yield compared to the ordinary sowing date is anyway positive in Central-Northern and South-Peninsular Italy, particularly in 2050 and in 2080.

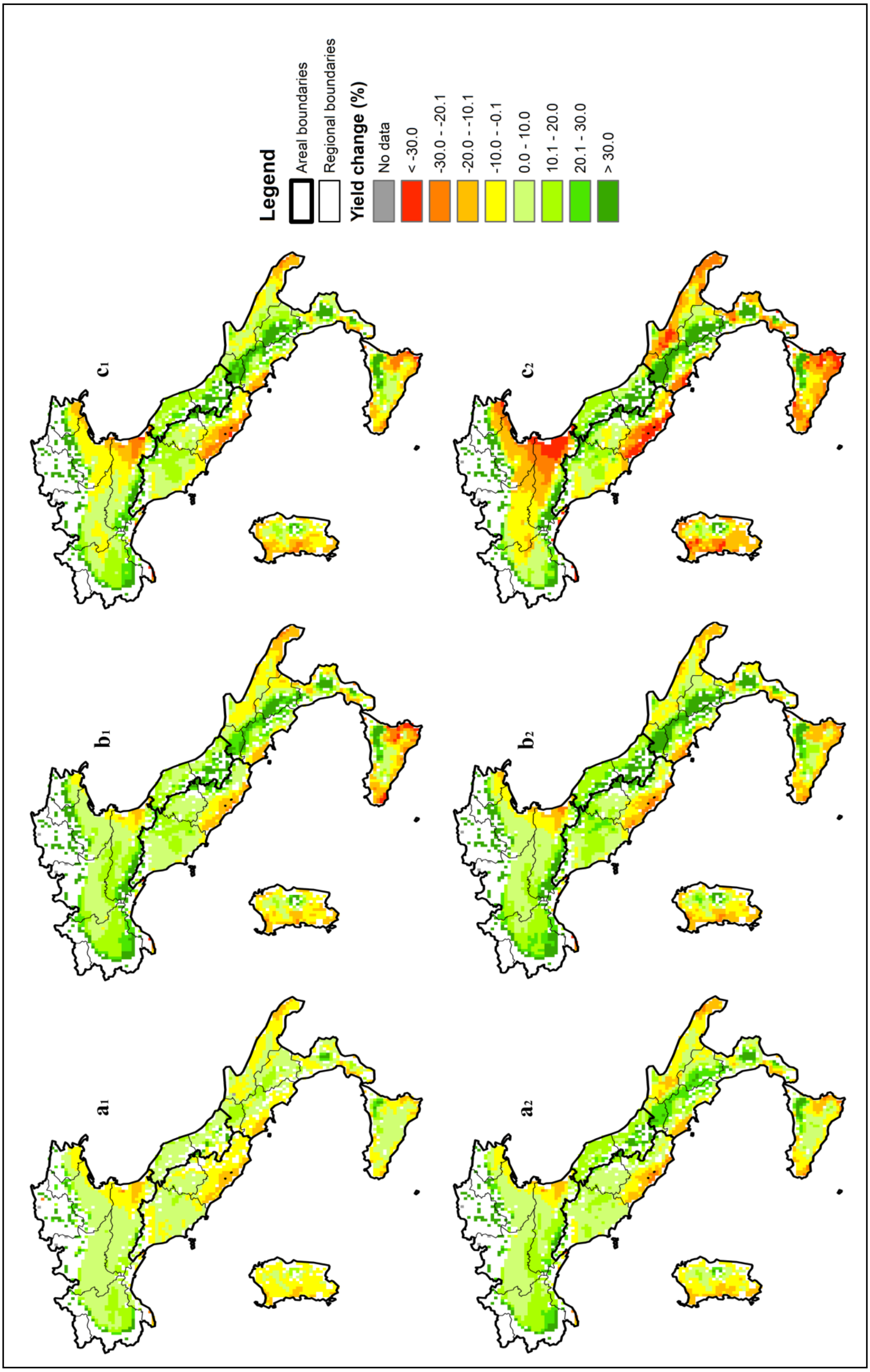

Figure 7. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-30 days)) for the Iride cultivar in Italy.

Table 9. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (advance of sowing date (-30 days)) for the Iride cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+0.9	+1.5	**+1.2**
	2050	+1.4	-6.2	**-2.4**
	2080	-7.6	-18.1	**-12.9**
Centre-Italy (Tyrrhenian side)	2020	-0.8	-1.7	**-1.3**
	2050	-1.4	-5.4	**-3.4**
	2080	-4.7	-8.9	**-6.8**
Centre-Italy (Adriatic side)	2020	+1.3	+3.1	**+2.2**
	2050	+5.9	+2.4	**+4.2**
	2080	+3.4	0.0	**+1.7**
South-Peninsular	2020	+2.3	+1.2	**+1.8**
	2050	0.0	-0.9	**-0.5**
	2080	-0.2	-8.6	**-4.4**
Sicily	2020	+2.2	+1.6	**+1.9**
	2050	-2.4	+1.1	**-0.7**
	2080	+0.3	-8.9	**-4.3**
Sardinia	2020	+0.1	-1.8	**-0.9**
	2050	-2.5	-5.2	**-3.9**
	2080	-5.5	-11.8	**-8.7**

Changes in fertilization regime

Following are the outcomes of the increase in N, P and K fertilization rates by 20% on grain yield of Iride cultivar at the Italian scale.

Grain yield

Figure 9 shows the effect of the increase in N, P and K fertilization rates by 20% on changes in average grain yield (%) for each future periods under the RCP4.5 and RCP8.5 climate scenarios compared with the baseline period for Iride cultivar in Italy. Overall, this adaptation strategy involves an increase in the average grain yield with

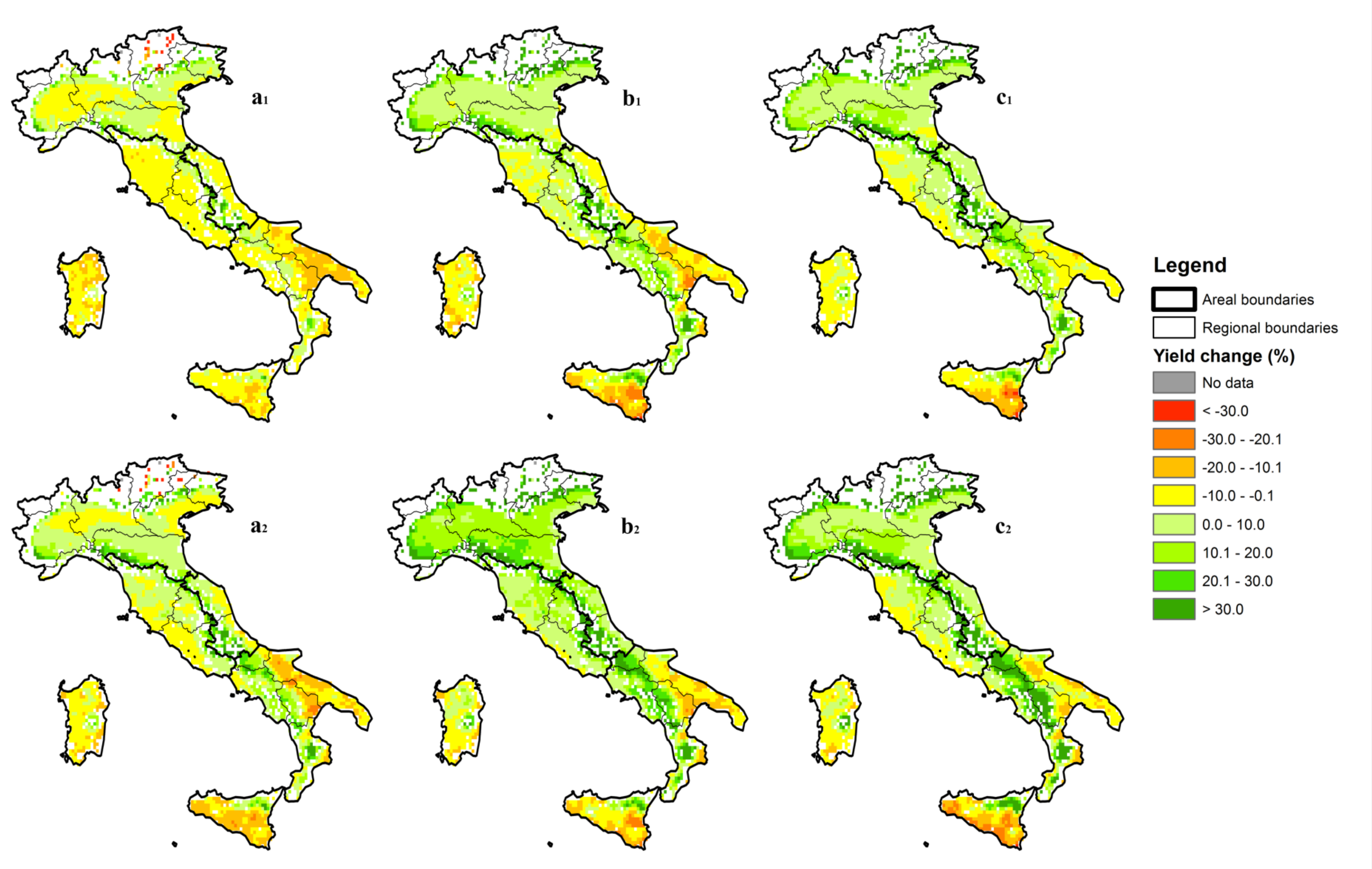

Figure 8. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (delayed sowing date (+15 days)) for the Iride cultivar in Italy.

Table 10. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (delay of sowing date (+15 days)) for the Iride cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	-3.1	-3.1	**-3.1**
	2050	-2.9	-2.4	**-2.7**
	2080	-3.3	-2.2	**-2.8**
Centre-Italy (Tyrrhenian side)	2020	-2.7	-1.4	**-2.1**
	2050	-2.9	-0.9	**-1.9**
	2080	-1.6	-1.0	**-1.3**
Centre-Italy (Adriatic side)	2020	-2.5	-2.5	**-2.5**
	2050	-4.8	-3.3	**-4.1**
	2080	-3.2	-5.2	**-4.2**
South-Peninsular	2020	-3.6	-3.8	**-3.7**
	2050	-4.0	-3.9	**-4.0**
	2080	-3.0	-2.4	**-2.7**
Sicily	2020	-5.6	-7.1	**-6.4**
	2050	-3.7	-3.3	**-3.5**
	2080	-5.0	-3.1	**-4.1**
Sardinia	2020	-3.6	-2.7	**-3.2**
	2050	-3.1	-1.8	**-2.5**
	2080	-1.8	-1.4	**-1.6**

respect to the impacts of climate change without adaptation in each future period under the two scenarios considered in all the Central-Southern areas, particularly in the Sicily area (on average ranging from +6.6% in 2020 to +6.0% in 2080), in the South-Peninsular area (from +5.6% in 2020 to +6.0% in 2080) and in the Centre-Italy (Adriatic side) area (from +4.7% in 2020 to +6.2% in 2080) (Table 11). Therefore, the adoption of this adaptation strategy could offset the negative impact of climate change on grain yield even in the Sicily and Sardinia areas, bringing about an increase in the average grain yield in each future period under both climate scenarios. On the other hand, the increase in fertilization rates by 20% does not affect the average grain yield in

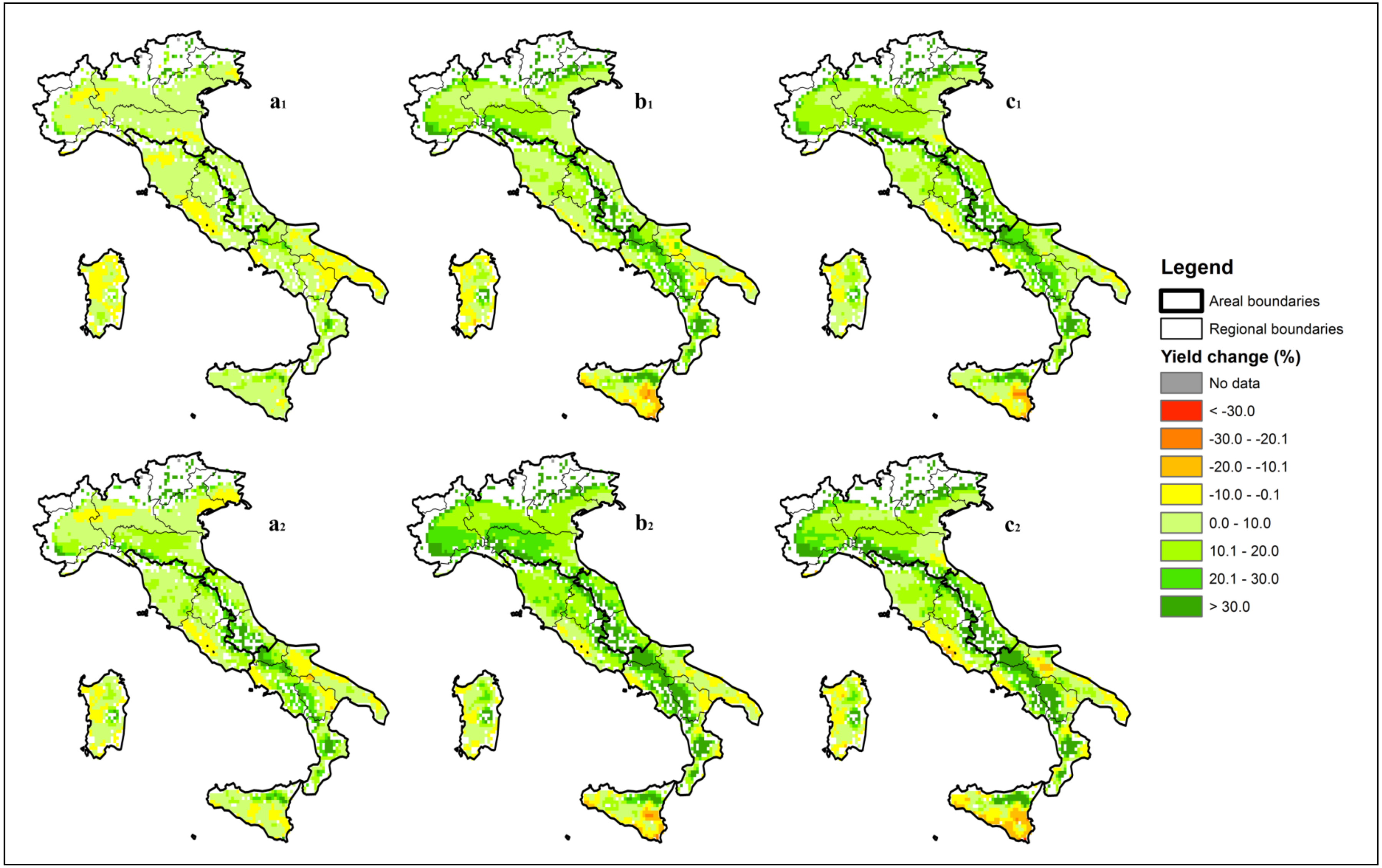

Figure 9. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (increase in N, P and K fertilization rates (+20%)) for the Iride cultivar in Italy.

Table 11. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (increase in N, P and K fertilization rates (+20%)) for the Iride cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+0.1	+0.1	**+0.1**
	2050	+0.8	+0.1	**+0.5**
	2080	+0.3	+0.9	**+0.6**
Centre-Italy (Tyrrhenian side)	2020	+3.8	+3.9	**+3.9**
	2050	+3.8	+4.6	**+4.2**
	2080	+4.1	+4.6	**+4.4**
Centre-Italy (Adriatic side)	2020	+4.7	+4.7	**+4.7**
	2050	+4.8	+6.0	**+5.4**
	2080	+6.0	+6.3	**+6.2**
South-Peninsular	2020	+5.6	+5.6	**+5.6**
	2050	+5.4	+5.9	**+5.7**
	2080	+6.1	+5.9	**+6.0**
Sicily	2020	+6.7	+6.5	**+6.6**
	2050	+5.9	+6.1	**+6.0**
	2080	+6.3	+5.7	**+6.0**
Sardinia	2020	+4.7	+4.8	**+4.8**
	2050	+4.4	+5.0	**+4.7**
	2080	+4.8	+4.6	**+4.7**

the North area (on average from +0.1% in 2020 to +0.6% in 2080 considering the two climate scenarios).

Application of the irrigation

Following are the outcomes of the simulations related to changes in grain yield for the three future periods under the RCP4.5 and RCP8.5 climate scenarios.

Grain yield

Figure 10 shows the effects of irrigation on changes in the average grain yield of

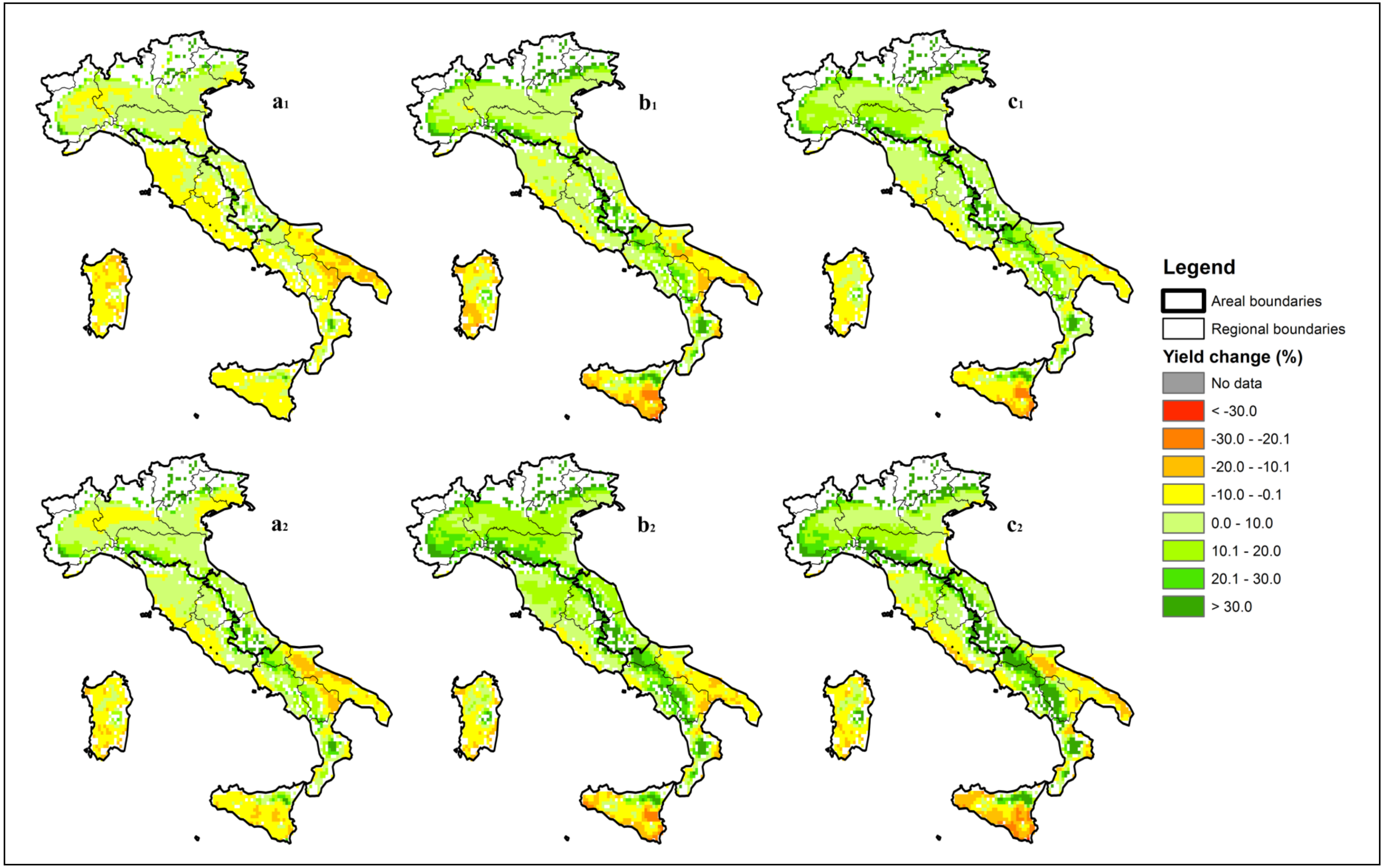

Figure 10. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (application of the irrigation) for the Iride cultivar in Italy.

Iride cultivar for each future period and climate scenario at the Italian scale. Overall, irrigation makes it possible to have an increase in the average grain yield compared to rainfed durum wheat in all areas for the three future periods under both climate scenarios (Table 12).

Table 12. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (application of the irrigation) for the Iride cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+7.9	+6.2	**+7.1**
	2050	+8.6	+3.4	**+6.0**
	2080	+5.4	+5.1	**+5.3**
Centre-Italy (Tyrrhenian side)	2020	+8.9	+7.3	**+8.1**
	2050	+11.1	+6.0	**+8.6**
	2080	+7.8	+8.5	**+8.2**
Centre-Italy (Adriatic side)	2020	+20.3	+18.1	**+19.2**
	2050	+25.9	+17.5	**+21.7**
	2080	+17.2	+17.9	**+17.6**
South-Peninsular	2020	+21.1	+18.7	**+19.9**
	2050	+21.3	+18.9	**+20.1**
	2080	+16.3	+15.8	**+16.1**
Sicily	2020	+27.6	+29.8	**+28.7**
	2050	+33.0	+32.5	**+32.8**
	2080	+29.7	+32.3	**+31.0**
Sardinia	2020	+13.2	+11.7	**+12.5**
	2050	+13.7	+10.5	**+12.1**
	2080	+9.9	+10.7	**+10.3**

The largest increases in average grain yield were estimated for 2020 and 2050 in the Sicily area (ranging from +27.6% in 2020 to +33.0% in 2050 with the RCP4.5 scenario and from +29.8% in 2020 to +32.5% in 2050 with the RCP8.5 scenario), in the Centre-Italy (Adriatic side) area (from +20.3% in 2020 to +25.9% in 2050 with the

RCP4.5 scenario and from +18.1% in 2020 to +17.5% in 2050 with the RCP8.5 scenario) and in the South-Peninsular area (about +21% and +19% under the RCP4.5 and RCP8.5 climate scenarios respectively). Increases in average grain yield were also obtained in the other areas, taking into consideration both climate scenarios (on average from +12.5% in 2020 to +10.3% in 2080 in Sardinia area, from +8.1% in 2020 to +8.6% in 2050 in the Centre-Italy (Tyrrhenian side) area, and from +7.1% in 2020 to +5.3% in 2080 in the North area). The smaller effectiveness of this adaptation strategy on grain yield in the North area is probably due to the greater rainfall during growing season compared with the other areas (see Table 4 of Chapter 4 of this thesis).

Comparison between adaptation strategies for durum wheat

Results obtained in each Italian area with the various adaptation strategies studied in this work for durum wheat (Iride cultivar) compared with climate change impacts without adaptation are summarized in Figures 11-12 for maturity date and in Figures 13-14 for grain yield.

5.4.2 Common wheat

Shifting of sowing date

The simulation results of adaptation strategies related to the advanced (-15 and -30 days) and delayed (+15 days) sowing date on the maturity date and grain yield for Bologna cultivar in Italy are described below.

Maturity date

Figure 15 shows the changes in average maturity date (days) from actual to future periods under the RCP4.5 and RCP8.5 climate scenarios obtained with the advance of sowing date (-15 days) for Bologna cultivar in each Italian area cultivation.

The results obtained indicate a general increase in the average maturity date with the two climate scenarios, especially in 2020 (ranging from +7 to +9 days) in all areas. The simulated average maturity date remains almost unchanged in 2050 compared with the baseline period under both scenarios (from +1 to +2 days) and in 2080 with the RCP4.5 scenario (from -1 to 0 days), while a decrease in all areas (from -9 to -10 days) is expected for 2080 with the RCP8.5 scenario. By comparing the results obtained in each future period with the advance of the sowing date by 15 days with those obtained

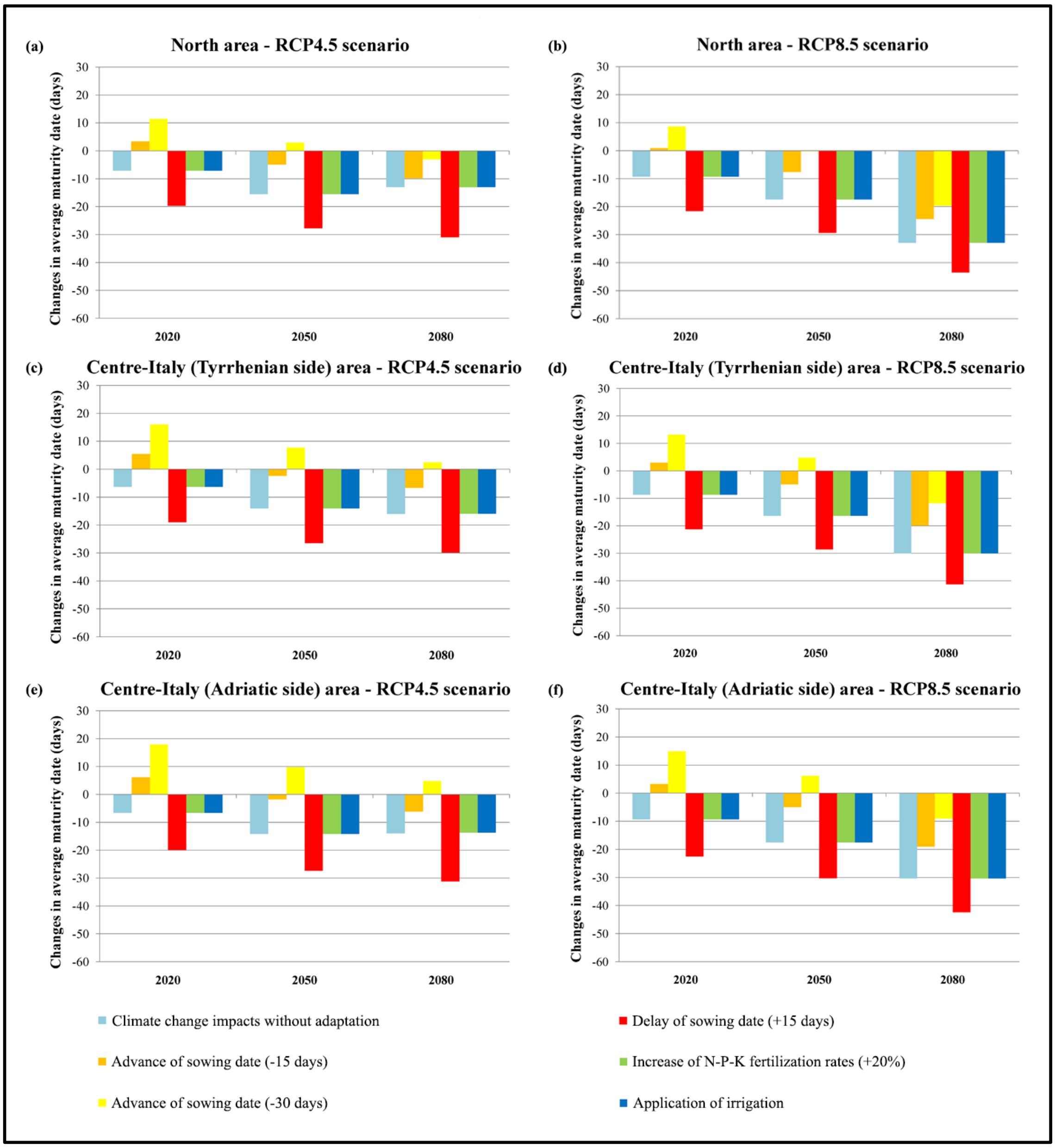

Figure 11. Effects of the adaptation strategies and climate change impacts without adaptation on changes in average maturity date (days) compared to baseline period in the Central-Northern Italy under the RCP4.5 (a, c and e) and RCP8.5 (b, d and f) climate scenarios for durum wheat (Iride cultivar).

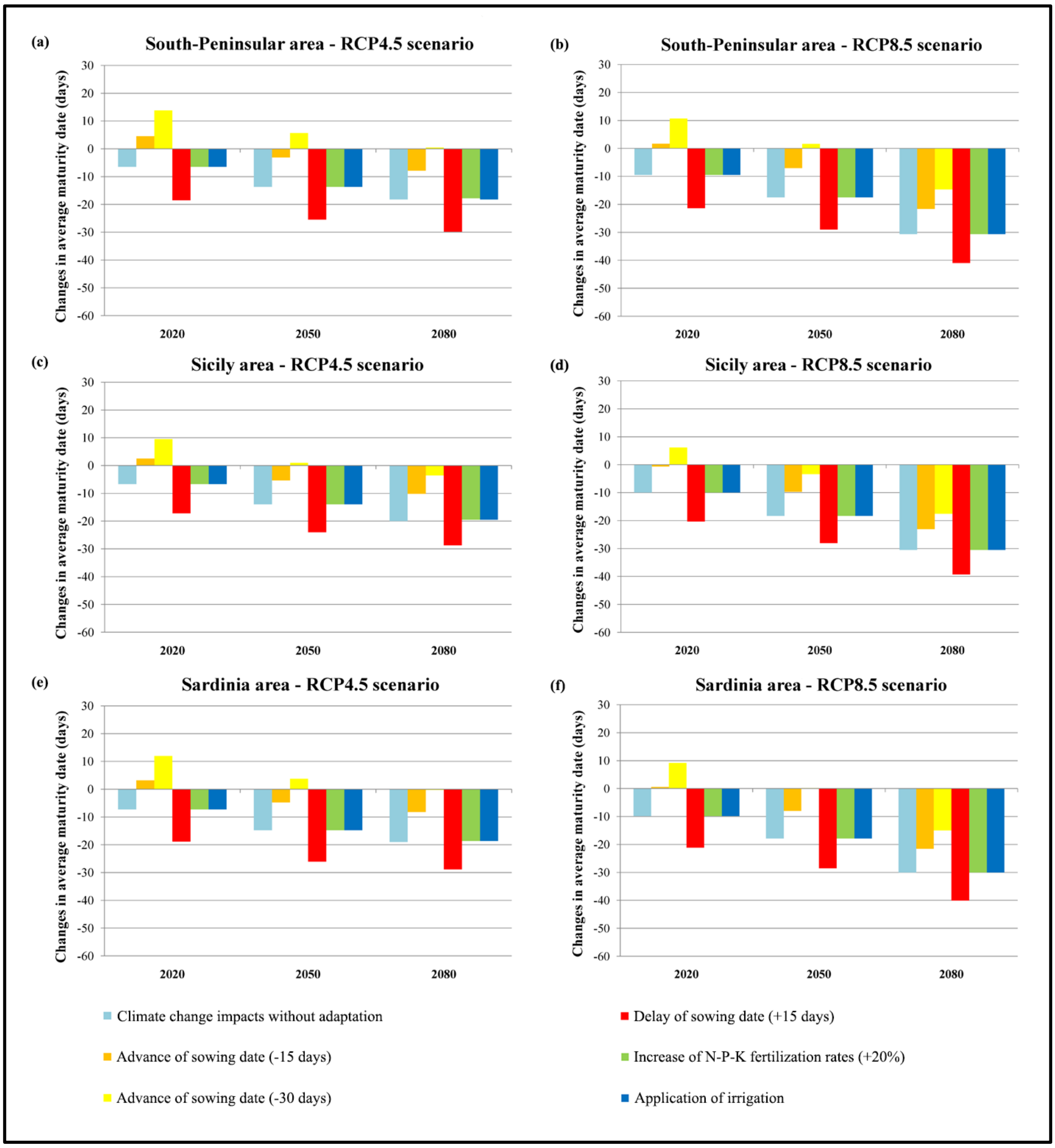

Figure 12. Effects of the adaptation strategies and climate change impacts without adaptation on changes in average maturity date (days) compared to baseline period in the South-Peninsular area and Islands under the RCP4.5 (a, c and e) and RCP8.5 (b, d and f) climate scenarios for durum wheat (Iride cultivar).

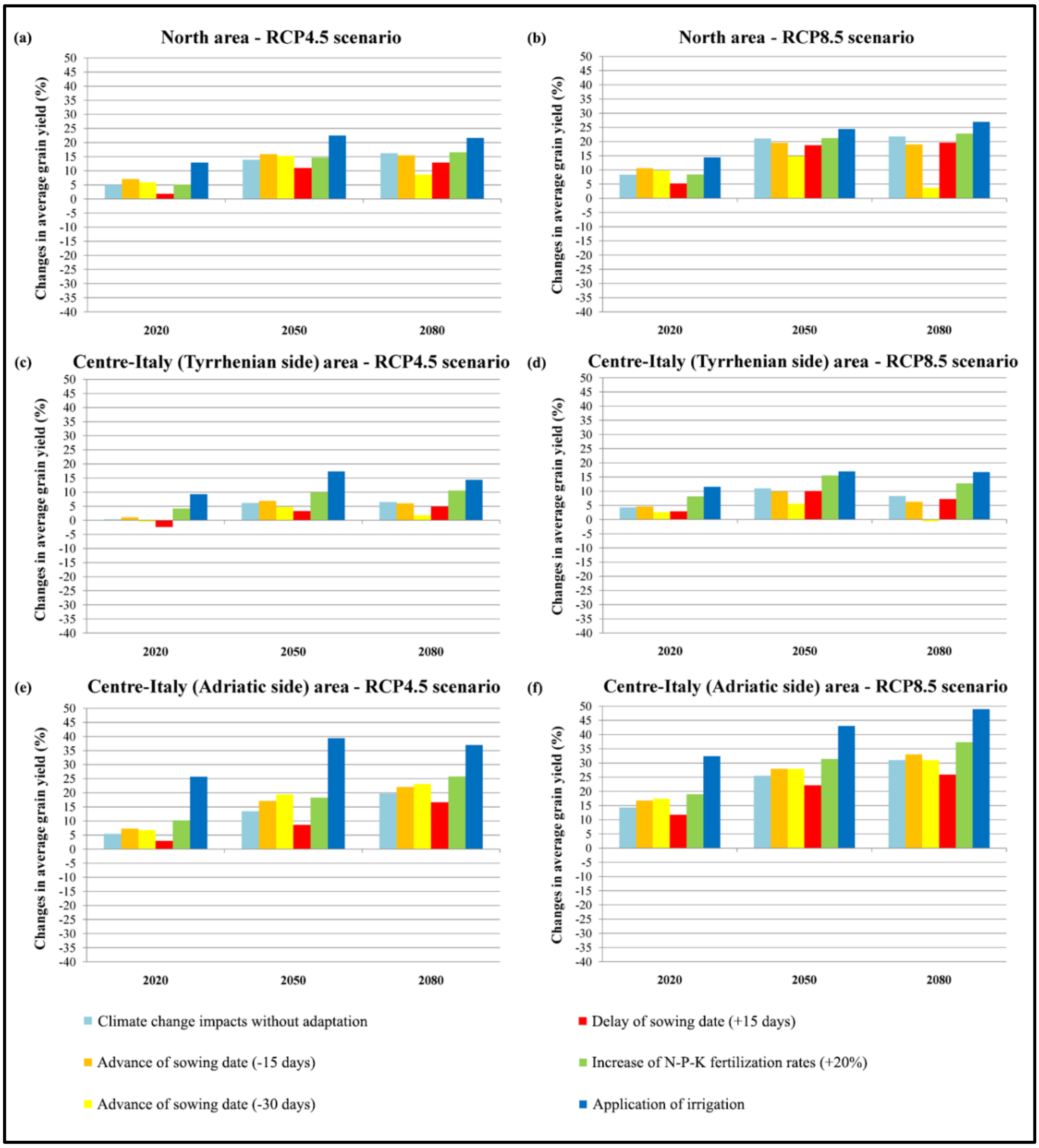

Figure 13. Effects of the adaptation strategies and climate change impacts without adaptation on changes in average grain yield (%) compared to baseline period in the Central-Northern Italy under the RCP4.5 (a, c and e) and RCP8.5 (b, d and f) climate scenarios for durum wheat (Iride cultivar).

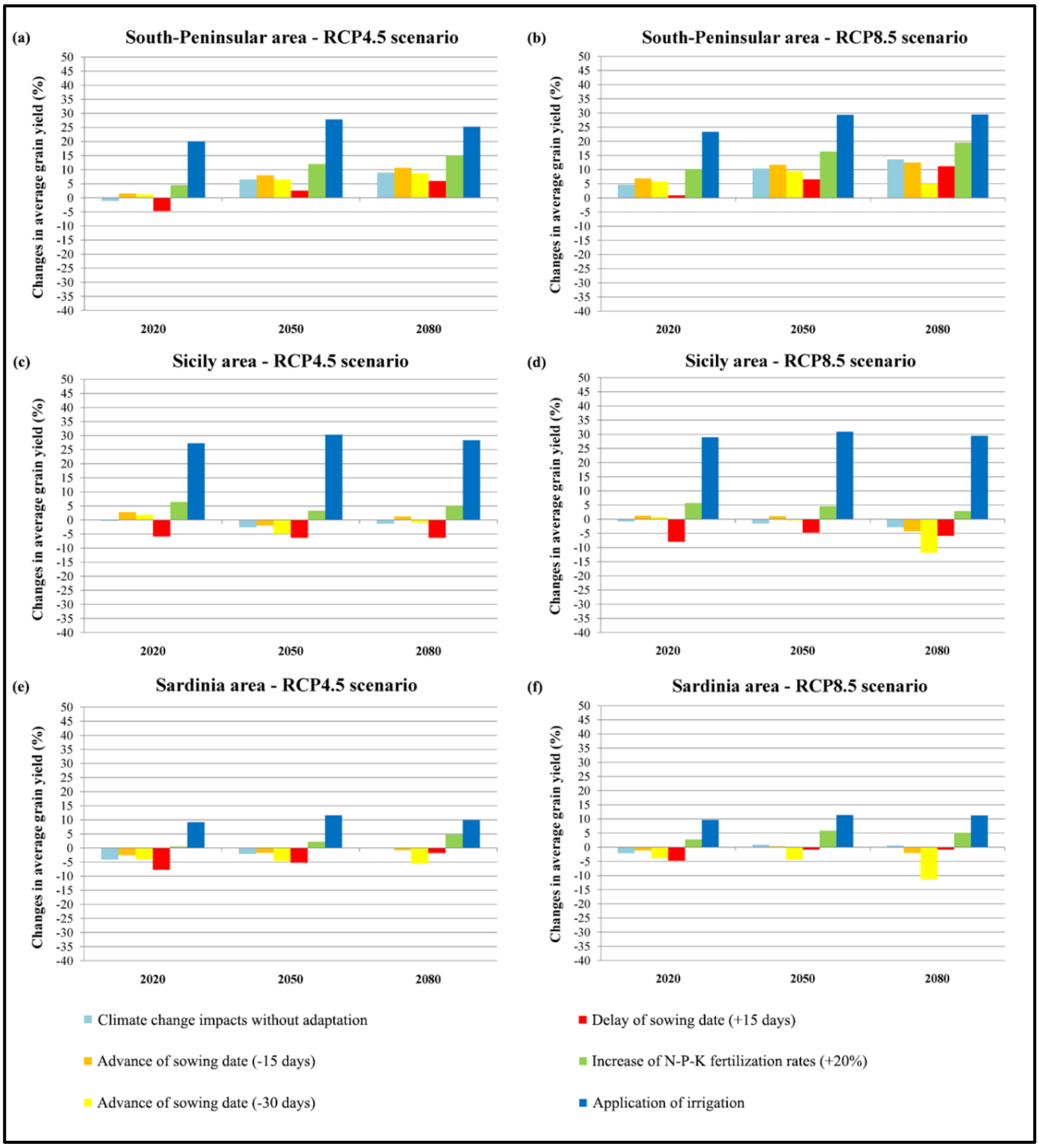

Figure 14. Effects of the adaptation strategies and climate change impacts without adaptation on changes in average grain yield (%) compared to baseline period in the South-Peninsular area and Islands under the RCP4.5 (a, c and e) and RCP8.5 (b, d and f) climate scenarios for durum wheat (Iride cultivar).

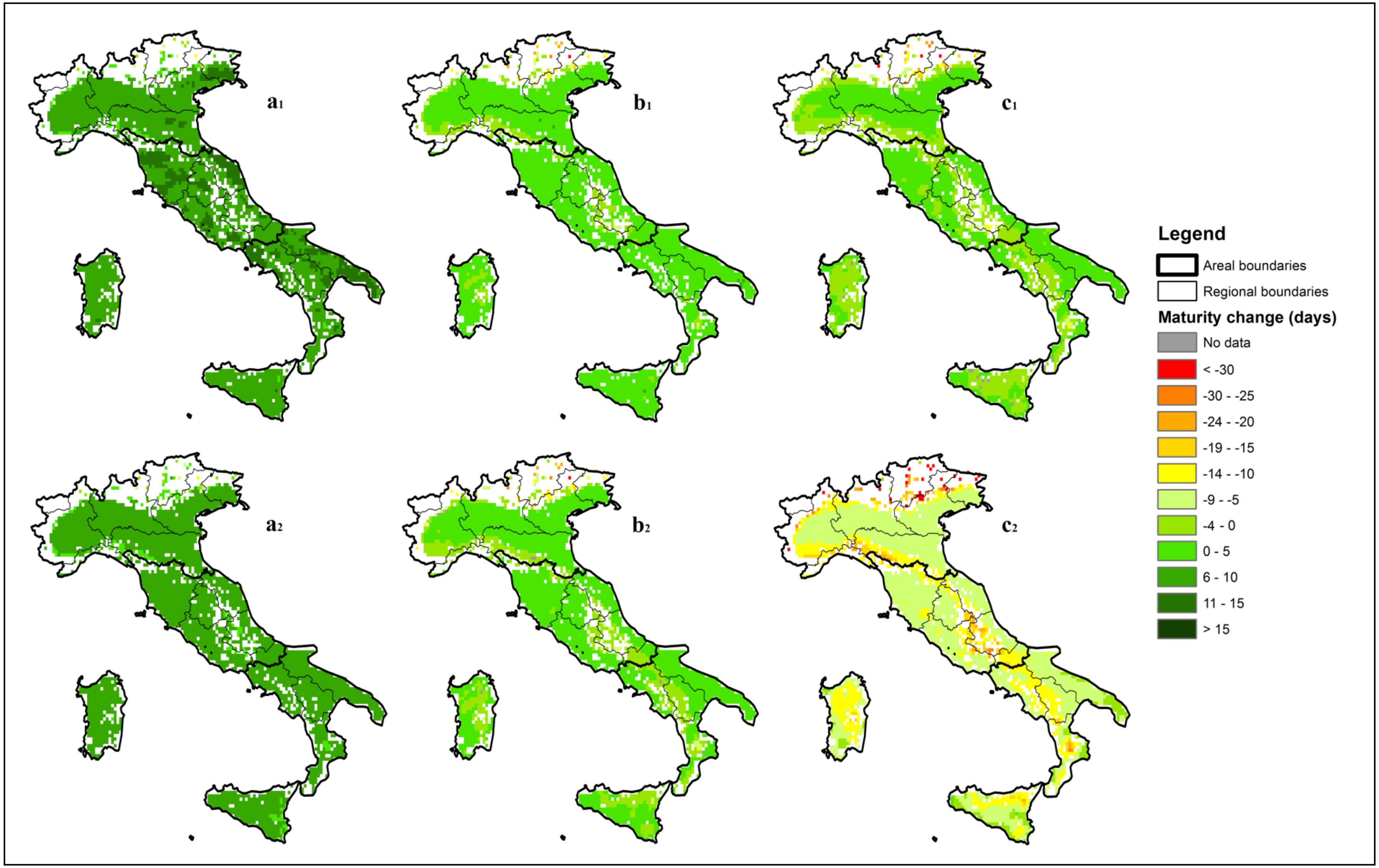

Figure 15. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-15 days)) for the Bologna cultivar in Italy.

in the same periods with climate change without adaptation, it is possible to observe a general increase in the average maturity date (from +13 to +15 days) in all areas (Table 13). Therefore, the adoption of this adaptation strategy could lead to a longer growth cycle of the Iride cultivar under both climate scenarios, with possible positive effects on grain yield.

Table 13. Changes in average maturity date (days) for each future periods and climate scenarios with adaptation (advance of sowing date (-15 days)) for the Bologna cultivar compared with climate change impacts without adaptation in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	+13	+14	+13	+13	+13	+13
Centre	+15	+14	+14	+14	+14	+14
South-Islands	+14	+14	+14	+14	+14	+13

An earlier average maturity date with respect to the baseline period was estimated with a 30 days advance of the sowing date in all areas (Figure 16). The largest increases were obtained in 2020 (ranging from +20 to +23 days with the RCP4.5 scenario and from +19 to +22 days with the RCP8.5 scenario) and 2050 (from +14 to +17 days and from +13 to +16 days under the RCP4.5 and RCP8.5 scenarios respectively). A minor increase in the average maturity date was obtained for 2080 (from +11 to +14 days with the RCP4.5 scenario and from +1 to +4 days with the RCP8.5 scenario). The greater changes in maturity date were obtained in the Centre area. Overall, with respect to the ordinary sowing date, a 30 days advance of the sowing date would allow a lengthening of the growing season, which would be higher than a 15 days advance of the sowing date in each future period under the two climate scenarios. This is particularly true in the Centre area (from +27 to +29 days) and South-Islands area (from +26 to +28 days) (Table 14).

Conversely, the simulations carried out by postponing the sowing date of 15 days with respect to the ordinary sowing date show a gradual decrease in the average maturity date of the same extent in all areas under the two scenarios considered for 2020 and 2050 (ranging from -19 to -21 and from -25 to -28 days respectively) (Figure 17). A further advance of the average maturity date was estimated in all areas for 2080, although of varying magnitude under the two climate scenarios (from -28 to -29 days

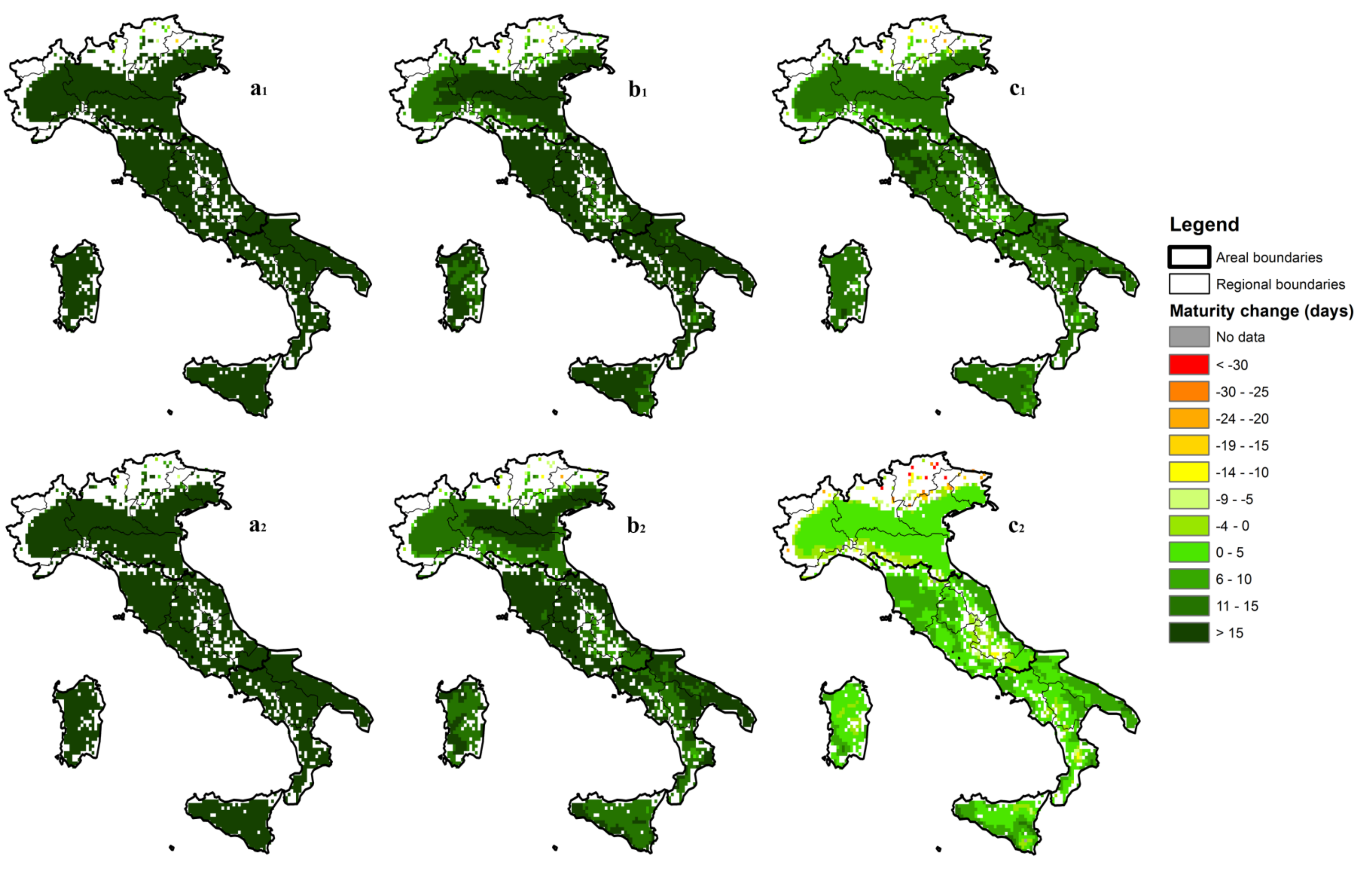

Figure 16. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-30 days)) for the Bologna cultivar in Italy.

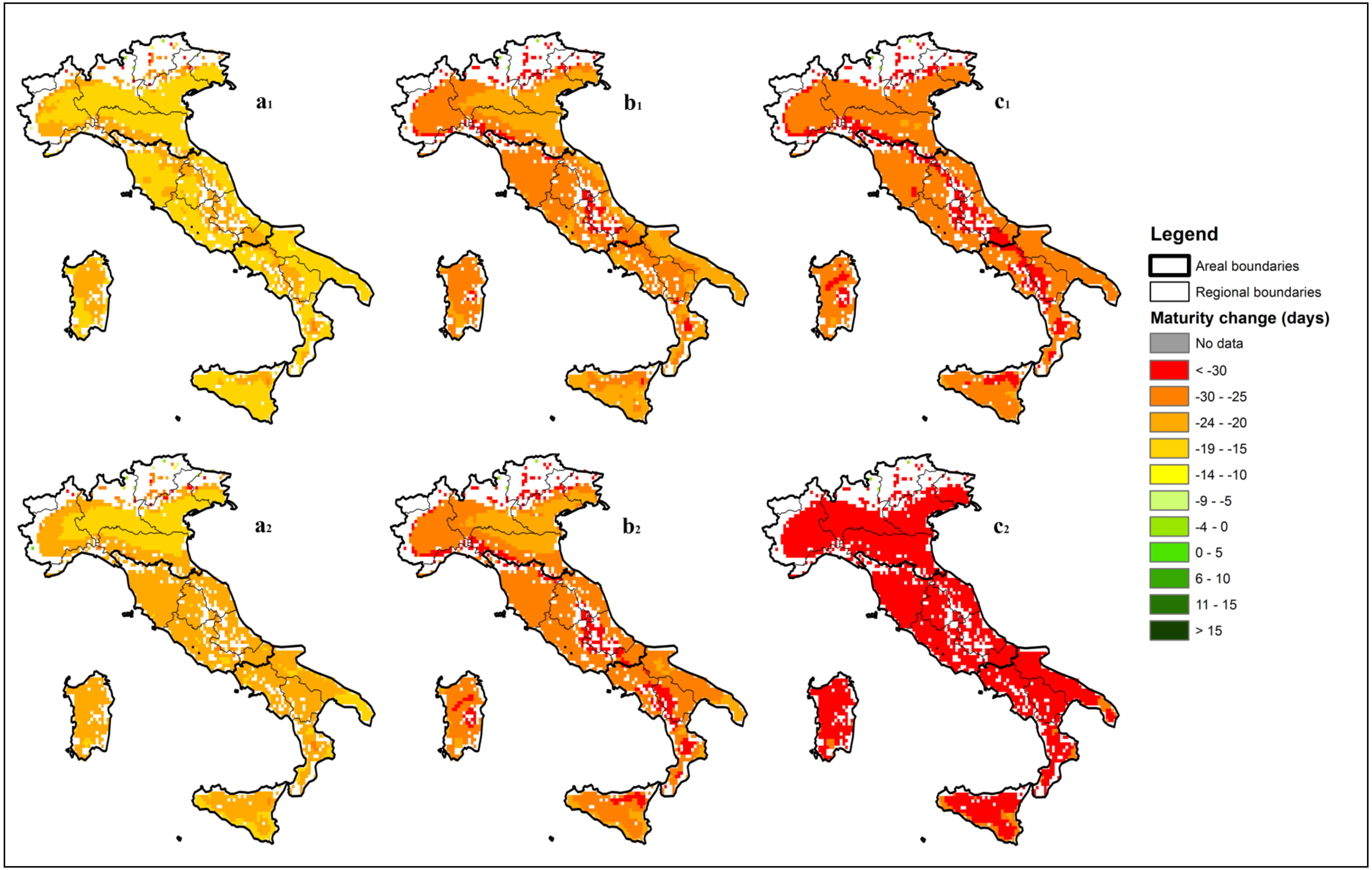

Figure 17. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (delayed sowing date (+15 days)) for the Bologna cultivar in Italy.

with the RCP4.5 scenario and from -36 to -38 days with the RCP8.5 scenario). Consequently, a decrease of the average length of the crop cycle (from -14 to -15 days) is expected for each future period and climate scenario in all areas with respect to the ordinary sowing date (Table 15).

Table 14. Changes in average maturity date (days) for each future periods and climate scenarios with adaptation (advance of sowing date (-30 days)) for the Bologna cultivar compared with climate change impacts without adaptation in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	+26	+26	+25	+25	+26	+24
Centre	+28	+29	+28	+28	+29	+27
South-Islands	+28	+28	+27	+28	+28	+26

Table 15. Changes in average maturity date (days) for each future periods and climate scenarios with adaptation (delay of sowing date (+15 days)) for the Bologna cultivar compared with climate change impacts without adaptation in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	-14	-14	-14	-14	-14	-14
Centre	-15	-15	-15	-15	-15	-14
South-Islands	-14	-14	-14	-14	-14	-14

Grain yield

Figure 18 shows the results of the changes in grain yield for the three future periods compared with the baseline period with the RCP4.5 and RCP8.5 scenarios with a 15 days advanced sowing date for the Bologna cultivar in Italy. In general, an increase in the average grain yield has been estimates, growing in each area from 2020 to 2050, then followed by a smaller increase in 2080. The greatest increases in grain yield are expected for the Centre area (from +10.2% in 2020 to +13.9% in 2050 with the RCP4.5 scenario and from +16.5% in 2020 to +18.8% in 2050 with the RCP8.5 scenario). Overall, this adaptation strategy increases the positive impacts of climate change on grain yield in each future period, when compared with the ordinary sowing date, in

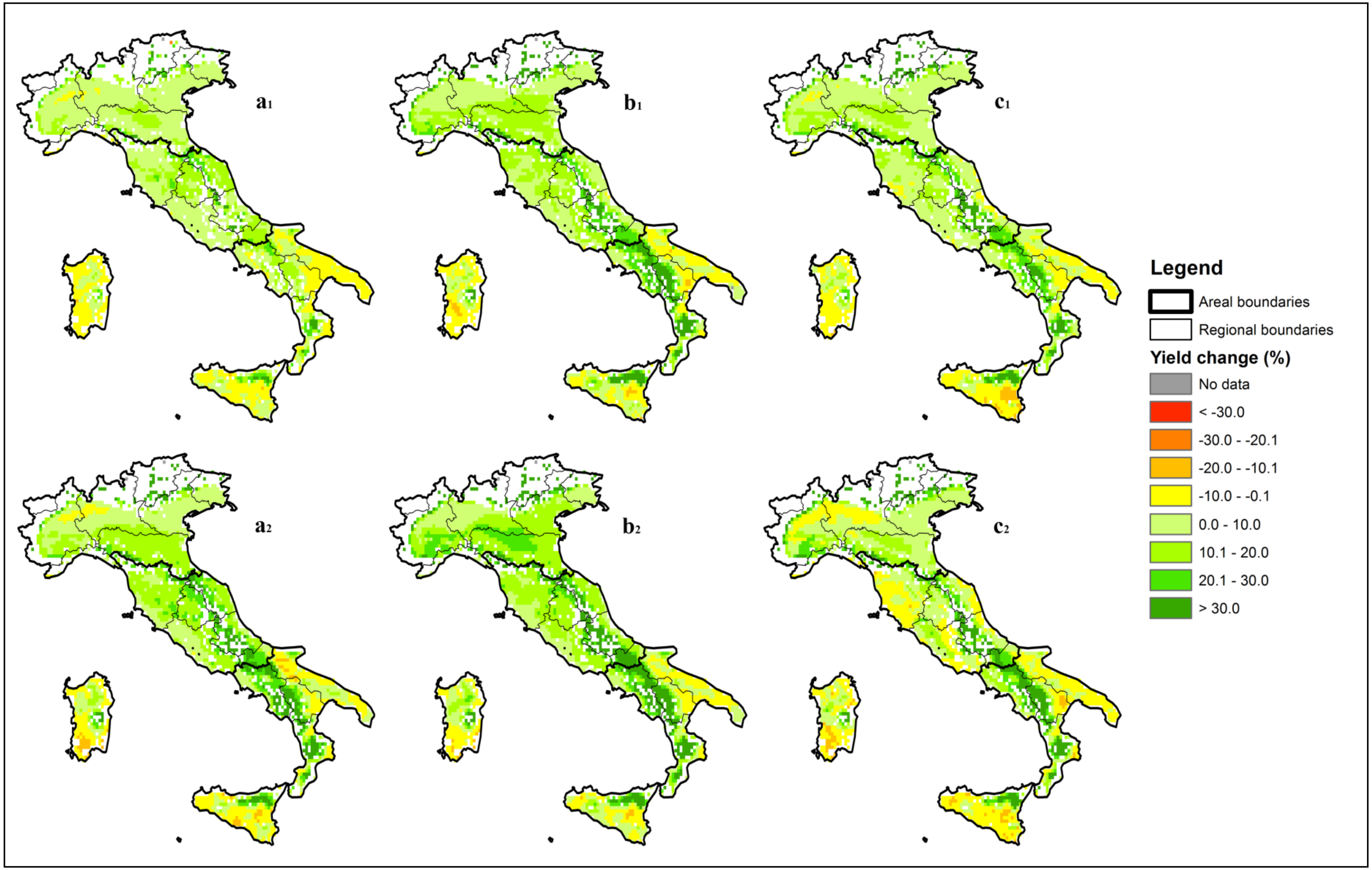

Figure 18. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-15 days)) for the Bologna cultivar in Italy.

particular in the Centre area (from +11.7% in 2020 to +9.7% in 2080 considering both the climate scenarios) and in the North area (on average from +8.4% in 2020 to +10.6% in 2080) (Table 16). Conversely, the effectiveness of this adaptation strategy on grain yield is less in the South-Islands area (from +6.1% in 2020 to +4.5% in 2080 considering the two climate scenarios).

Table 16. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (advance of sowing date (-15 days)) for the Bologna cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+8.8	+8.0	**+8.4**
	2050	+7.5	+7.6	**+7.6**
	2080	+8.8	+12.3	**+10.6**
Centre	2020	+11.7	+11.6	**+11.7**
	2050	+10.6	+11.2	**+10.9**
	2080	+10.9	+8.4	**+9.7**
South-Islands	2020	+6.2	+6.0	**+6.1**
	2050	+5.0	+5.1	**+5.1**
	2080	+4.8	+4.2	**+4.5**

The positive effect on grain yield increases with a 30 days advance of the sowing date when compared to the ordinary sowing date (Figure 19). The greatest increases in average grain yield were estimated for the Centre area (from +20.4% in 2020 to +24.4% in 2080 with the RCP4.5 scenario and from +26.0% in 2020 to +29.6% in 2050 with the RCP8.5 scenario). In the other two area the positive effects on grain yield are lower (from +12.2% in 2020 to +18.4% in 2080 and from +15.8% to +23.4% in 2050 under the RCP4.5 and RCP8.5 scenarios respectively in the North area and from +9.9% in 2020 to +14.1% in 2050 with the RCP4.5 scenario and from +14.0% in 2020 to +18.2% in 2050 with the RCP8.5 scenario). Table 17 shows the greater effectiveness of this adaptation strategy on grain yield of the Bologna cultivar compared to the advance of the sowing date by 15 days. The largest increases in grain yield compared to the impacts of climate change without adaptation were obtained for the

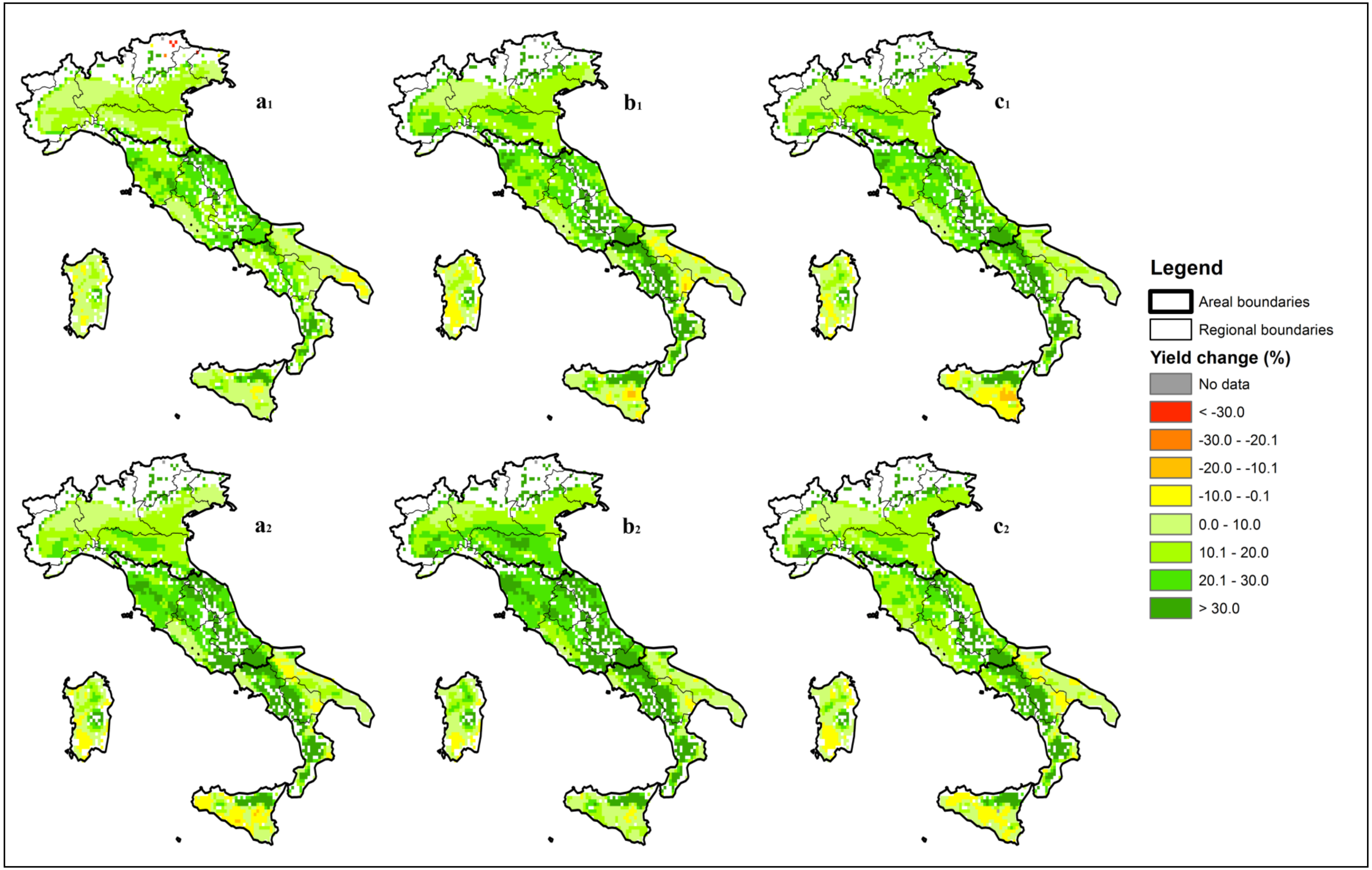

Figure 19. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-30 days)) for the Bologna cultivar in Italy.

Table 17. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (advance of sowing date (-30 days)) for the Bologna cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+13.4	+12.8	**+13.1**
	2050	+12.2	+12.5	**+12.4**
	2080	+14.9	+20.0	**+17.5**
Centre	2020	+21.8	+21.0	**+21.4**
	2050	+19.8	+22.0	**+20.9**
	2080	+22.6	+21.4	**+22.0**
South-Islands	2020	+13.8	+12.6	**+13.2**
	2050	+10.7	+12.9	**+11.8**
	2080	+12.3	+11.1	**+11.7**

Centre area (from +21.4% in 2020 to +22.0% in 2080 considering both climate scenarios), while smaller increases were estimated for the other two areas, especially in the South-Islands area (on average from +13.2% in 2020 to +11.7% in 2080).

Figure 20 shows the effects of a 15 days delay of the sowing date on the changes in grain yield of the Bologna cultivar for various future periods under the RCP4.5 and RCP8.5 scenarios compared to the baseline period. A general decrease in grain yield is expected in Central and Northern Italy, in particular in the North area in 2020 (ranging from -13.3% with the RCP4.5 scenario to -9.6% with the RCP8.5 scenario) and in 2080 (from -12.0% to 13.7% under the two climate scenarios respectively). Instead, in the South-Islands area a general decrease has been estimated in 2020 (-8.3% with the RCP4.5 scenario and -2.9% with the RCP8.5 scenario) and an almost imperceptible change in 2050 and in 2080, with a small increase (up to +1.7% in 2050) under the RCP8.5 scenario. Overall, this adaptation strategy reverses the positive impact of climate changes on grain yield for all future periods and both climate scenarios in the North area and also in the Centre and South-Islands areas in 2050 and in 2080 with the RCP4.5 scenario. The greatest reductions in grain yield compared to the impacts of climate change without adaptation considering the two climate scenarios have been obtained for the North area (from -12.3% in 2020 to -15.7% in 2080) (Table 18).

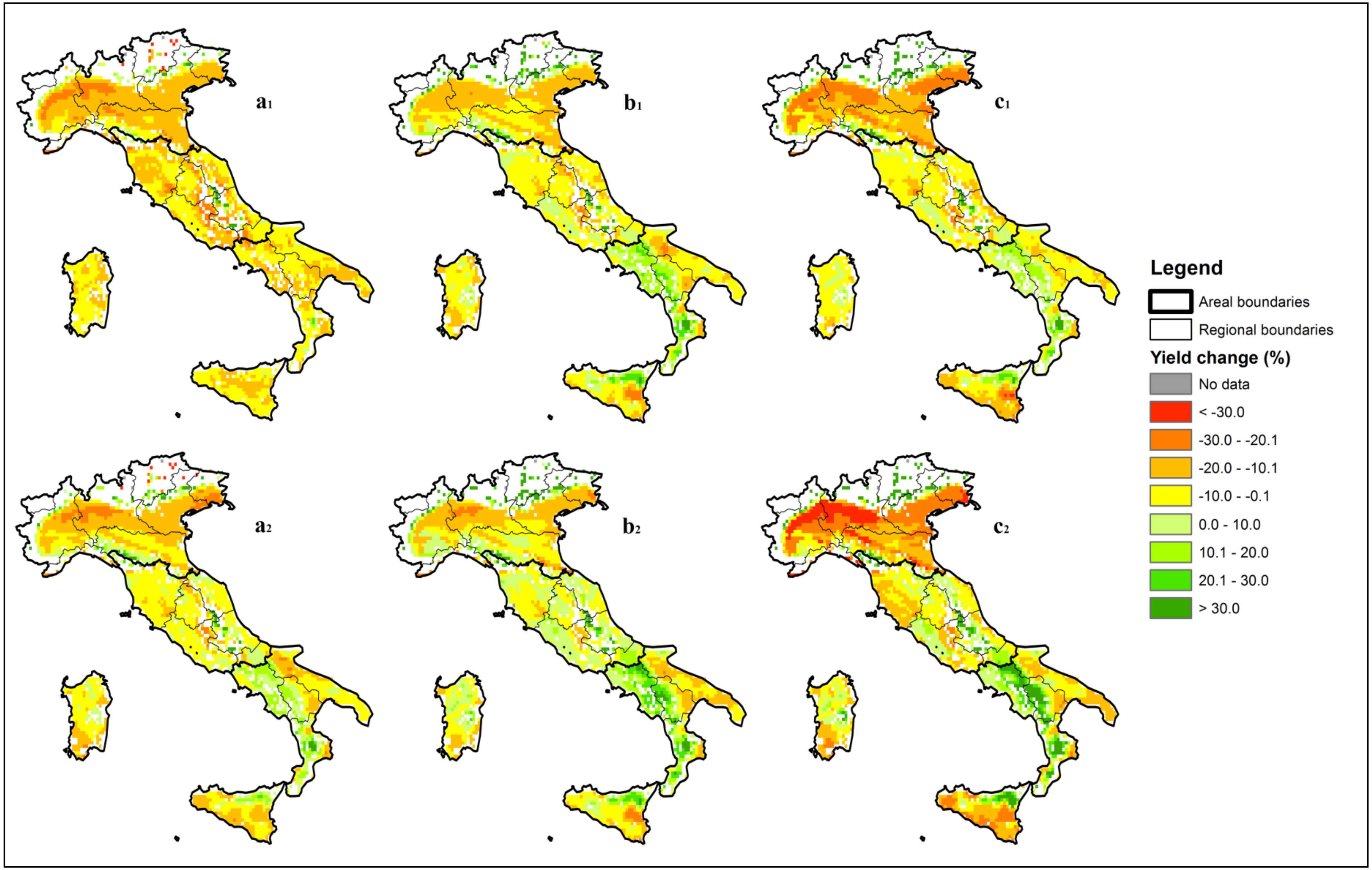

Figure 20. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (delayed sowing date (+15 days)) for the Bologna cultivar in Italy.

Table 18. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (delay of sowing date (+15 days)) for the Bologna cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	-12.1	-12.5	**-12.3**
	2050	-12.6	-15.6	**-14.1**
	2080	-15.5	-15.8	**-15.7**
Centre	2020	-7.8	-7.5	**-7.7**
	2050	-6.9	-5.2	**-6.1**
	2080	-5.2	-3.4	**-4.3**
South-Islands	2020	-4.4	-4.3	**-4.4**
	2050	-3.8	-3.7	**-3.8**
	2080	-2.9	-2.8	**-2.9**

Smaller decreases were estimated in the Centre area (from -7.7% in 2020 to -4.3% in 2080) and South-Islands area (from -4.4% in 2020 to -2.9% in 2080).

Changes in fertilization regime

Results relative to the increase in N, P and K fertilization rates by 20% on grain yield of the Bologna cultivar in Italy are described below.

Grain yield

Figure 21 shows the results of simulations, carried out with the increase in N, P and K fertilization rates by 20% on changes in average grain yield (%) from actual (1990) to future periods under the RCP4.5 and RCP8.5 climate scenarios for the Bologna cultivar in Italy. A general increase in grain yield was estimated in all areas, particularly in 2050 (ranging from +9.2% in the Centre area to +11.4% in the North area with the RCP4.5 scenario and from +12.2% in the South-Islands area to +16.7% in the North area with the RCP8.5 scenario). Smaller increases of grain yield were estimated for 2020 and 2080, mainly in the North area (from +3.4% to +8.0% in 2020 and from +8.9% to +7.6% in 2080 under the RCP4.5 and RCP8.5 scenarios respectively). The comparison of the results obtained in each future period with the two climate scenarios

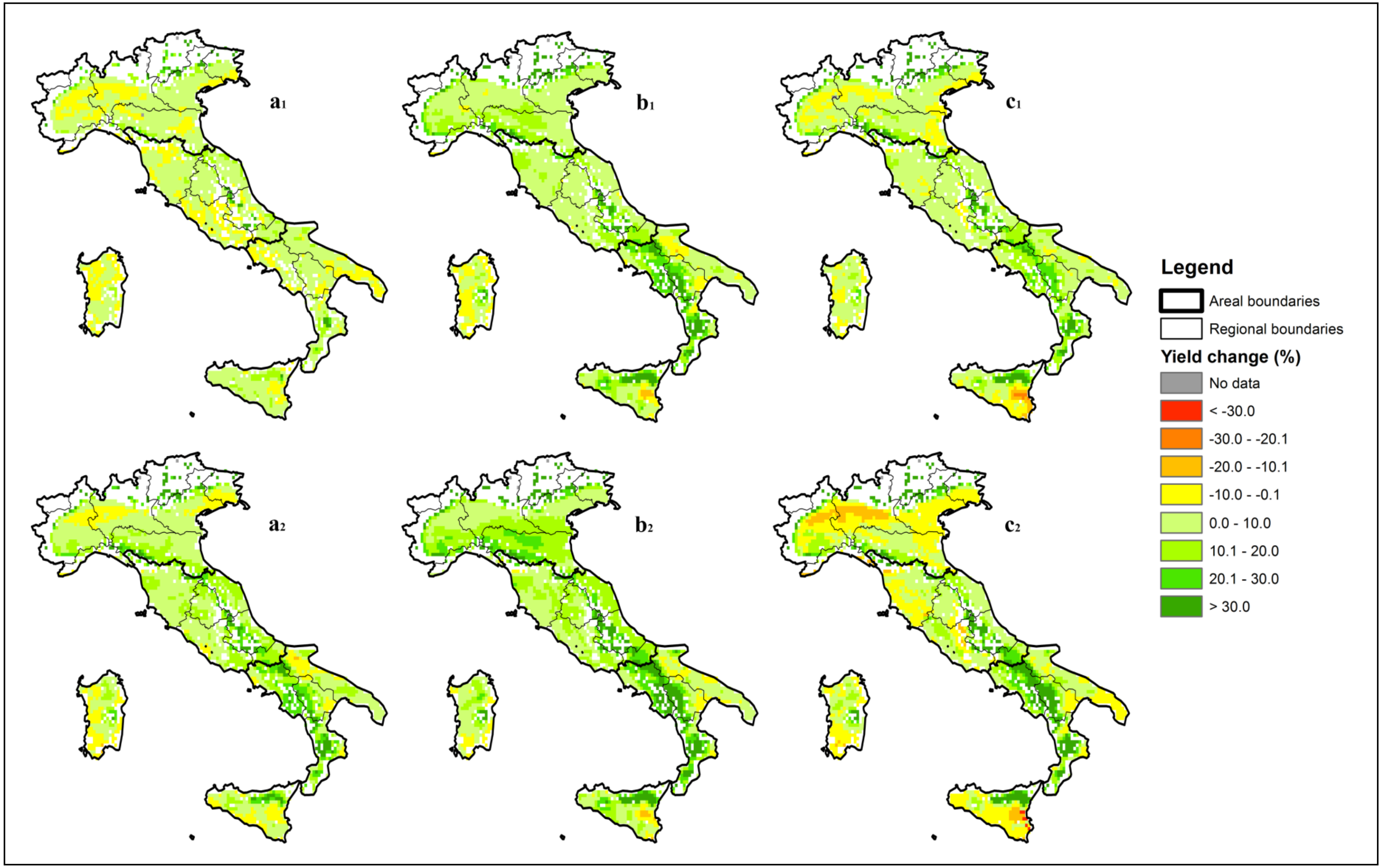

Figure 21. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (increase in N, P and K fertilization rates (+20%)) for the Bologna cultivar in Italy.

without adaptation highlight the effectiveness of this adaptation strategy on grain yield in all areas (Table 19). Therefore, the increase in N, P and K fertilization rates by 20% reverses the negative impact of climate change on yield in 2020 and improves the positive impact on yield in 2050 and in 2080 under both climate scenarios, especially in the Centre and South-Islands areas (on average from +6.3% to +6.7%).

Table 19. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (increase in N, P and K fertilization rates (+20%)) for the Bologna cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+4.6	+5.0	**+4.8**
	2050	+5.2	+5.8	**+5.5**
	2080	+5.4	+5.5	**+5.5**
Centre	2020	+5.2	+5.8	**+5.5**
	2050	+5.9	+6.6	**+6.3**
	2080	+6.2	+6.5	**+6.4**
South-Islands	2020	+6.3	+6.5	**+6.4**
	2050	+6.6	+6.8	**+6.7**
	2080	+6.6	+6.6	**+6.6**

Application of the irrigation

Results of changes in average grain yield resulting from the application of irrigation with RCP4.5 and RCP8.5 climate scenarios for the Bologna cultivar in Italy are described as follow.

Grain yield

The simulations carried out with the application of irrigation show a general increase in the average grain yield in all future periods, with respect to the baseline period under the two climate scenarios considered (Figure 22). The largest increases in yield were obtained for the South-Islands area (ranging from +26.2% in 2020 to +34.9% in 2050 with the RCP4.5 scenario and from +30.4% in 2020 to +37.2% in 2080 with the RCP8.5 scenario). Increases in grain yield of minor magnitude were estimated in the

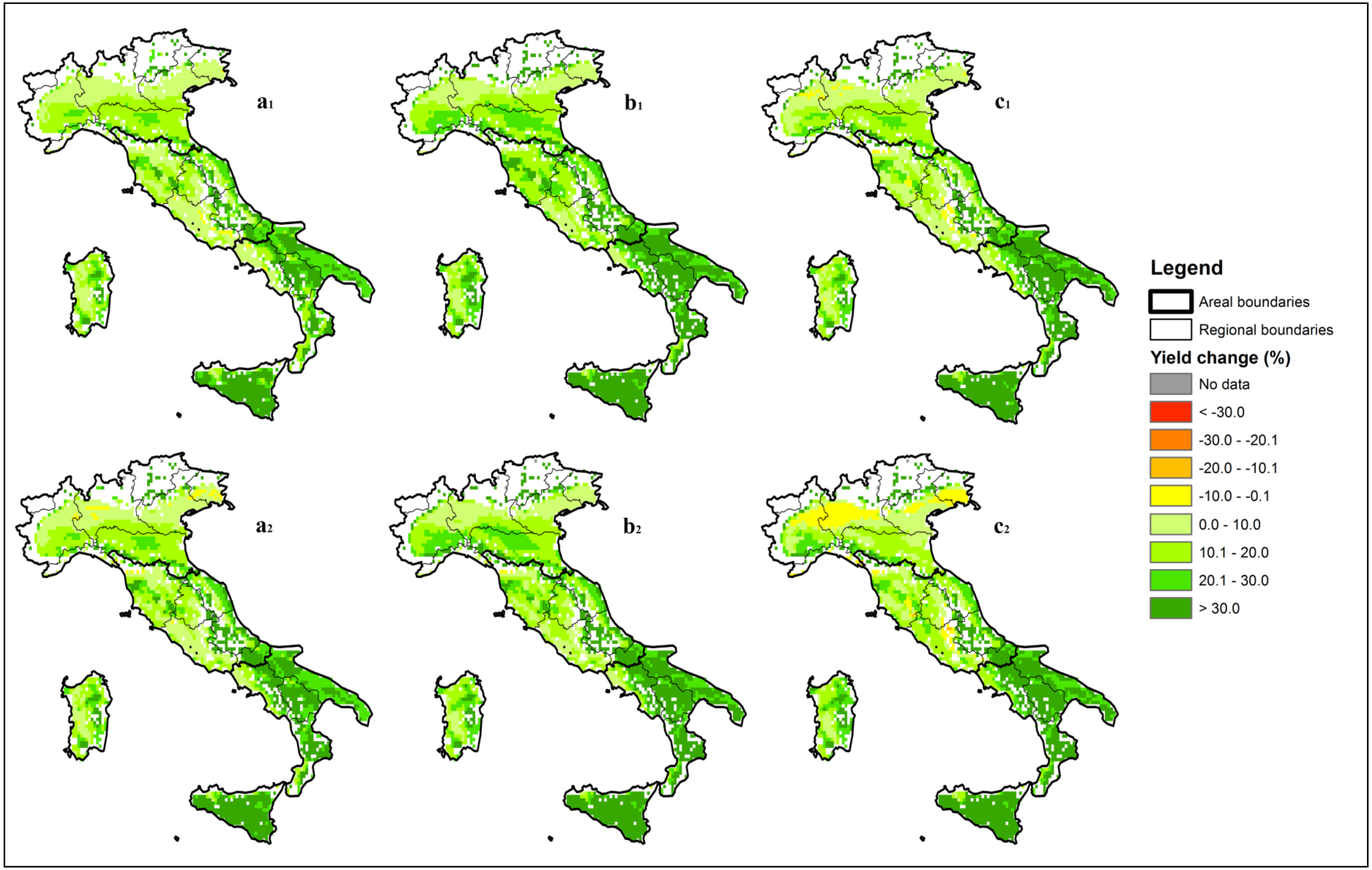

Figure 22. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (application of the irrigation) for the Bologna cultivar in Italy.

Centre area (up to +23.3% in 2050 with the RCP4.5 scenario) and in the North area (up to +18.5% in 2050 under the RCP8.5 scenario). Comparing the results obtained for each future period and scenario with the impacts of climate change without adaptation, it can be seen that this strategy is very effective to increase grain yield in the South-Islands area (from +23.9% in 2020 to +26.5% in 2050 and 2080 under the RCP4.5 scenario and from +23.1% in 2020 to +28.8% in 2080 under the RCP8.5 scenario) (Table 20). On the other hand, irrigation is less effective in the North area, particularly in 2050 (+4.2% with the RCP4.5 scenario and 0.0% with the RCP8.5 scenario) and in 2080 (+2.6% and +0.5% under the RCP4.5 and RCP8.5 scenarios respectively). This is probably due to the higher rainfall predicted for the three future periods in this area, as compared to the other areas (see Table 5 of Chapter 4 of this thesis).

Table 20. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (application of the irrigation) for the Bologna cultivar compared with climate change impacts without adaptation in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	+4.7	+4.2	+2.6	+1.5	0.0	+0.5
Centre	+5.3	+9.4	+4.6	+2.3	+3.6	+8.9
South-Islands	+23.9	+26.5	+26.5	+23.1	+25.7	+28.8

Comparison between adaptation strategies for common wheat

For the purposes of an evaluation of the different adaptation strategies studied for common wheat (Bologna cultivar), the results related to the maturity date and grain yield for each area under the RCP4.5 and RCP8.5 climate scenarios, compared to climate change impacts without adaptation, are summarized in Figures 23 and 24.

5.4.3 Maize

Shifting of sowing date

Following is a description of results of adaptation strategies related to the change in sowing date (advance (-15 and -30 days) and delay (+15 days)) on the maturity date and grain yield of the Eleonora cultivar in Italy.

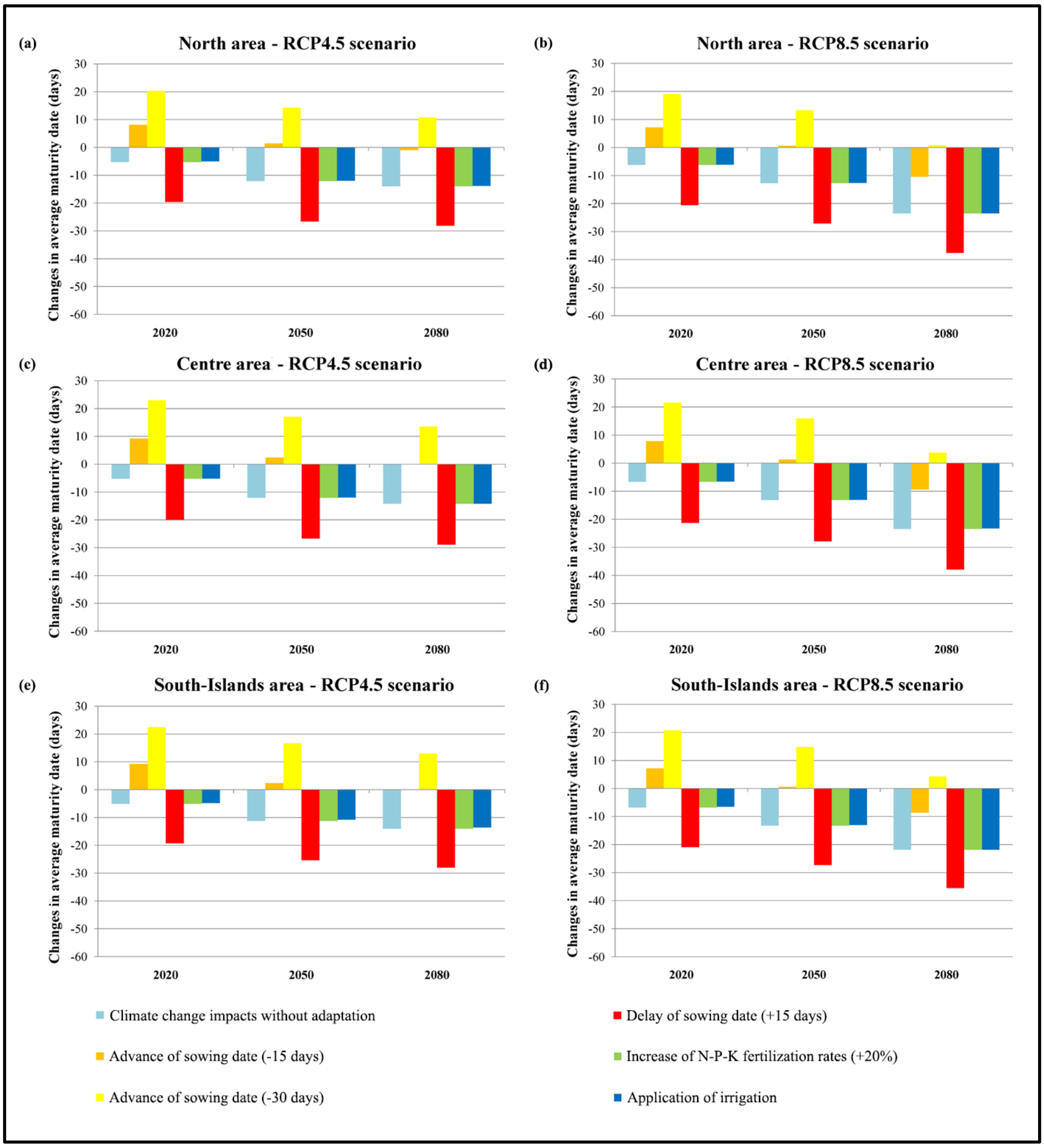

Figure 23. Effects of the adaptation strategies and climate change impacts without adaptation on changes in average maturity date (days) compared to baseline period in each area under the RCP4.5 (a, c and e) and RCP8.5 (b, d and f) climate scenarios for common wheat (Bologna cultivar).

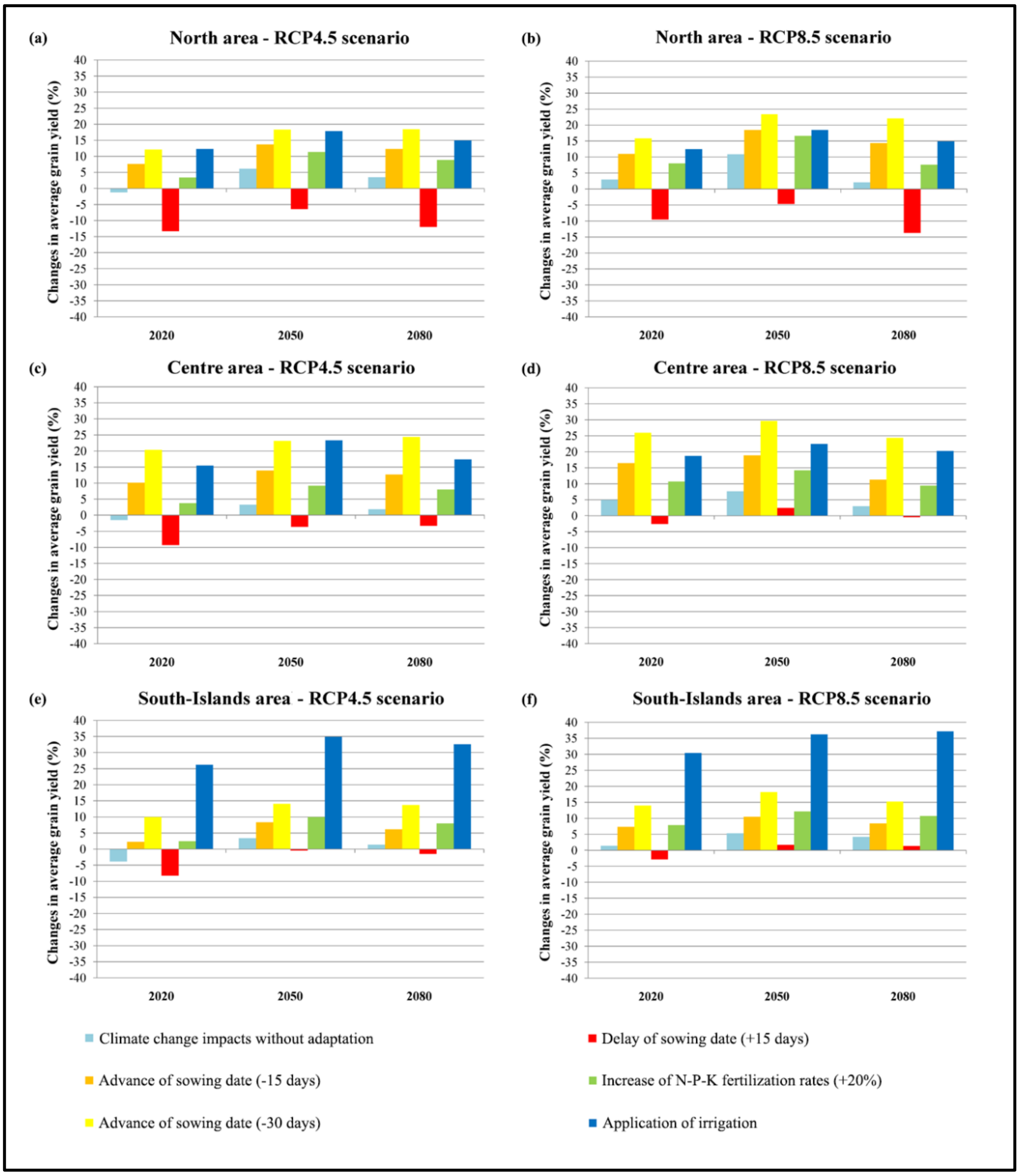

Figure 24. Effects of the adaptation strategies and climate change impacts without adaptation on changes in average grain yield (%) compared to baseline period in each area under the RCP4.5 (a, c and e) and RCP8.5 (b, d and f) climate scenarios for common wheat (Bologna cultivar).

Maturity date

Figure 25 shows the effects of the advance of sowing date (-15 days) on changes in average maturity date (days) from actual to future periods for each climate scenario for the Eleonora cultivar in Italy.

As can be seen, changes in the average maturity date compared to the baseline period are lower than those obtained with the ordinary sowing date for each future period under scenarios RCP4.5 and RCP8.5 in all areas. In addition, a similar variation in average maturity date was estimated under the two scenarios, namely in 2020 (ranging from -1 to -3 days with the RCP4.5 scenario and equal to -2 days with the RCP8.5 scenario) and in 2050 (from -11 to -17 days and from -13 to -16 days under the RCP4.5 and RCP8.5 scenarios respectively). These changes increase in each area from 2020 to 2080 (especially under the RCP8.5 scenario). This means that, with a 15 days advance of the sowing date, the average duration of the period between sowing and maturity is greater than thae one estimated with the ordinary sowing date for each future period, particularly in the Centre and South-Islands areas under both climate scenarios (ranging from +10 to +13 days with the RCP4.5 scenario and from +10 to +12 days with the RCP8.5 scenario) (Table 21).

Table 21. Changes in average maturity date (days) for each future periods and climate scenarios with adaptation (advance of sowing date (-15 days)) for the Eleonora cultivar compared with climate change impacts without adaptation in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	+9	+8	+9	+9	+9	+8
Centre	+12	+13	+10	+11	+12	+10
South-Islands	+11	+12	+11	+11	+11	+11

A further reduction of the average maturity date compared to the baseline period was estimated for all future period and scenarios in all the areas with an advance of the sowing date equal to 30 days with respect to the ordinary sowing date (Figure 26). The change in average maturity date becomes positive in 2020 (ranging from +9 days in the North area to +11 days in the Centre area under the two climate scenarios considered). Therefore, the average duration of the period between sowing and maturity increases in

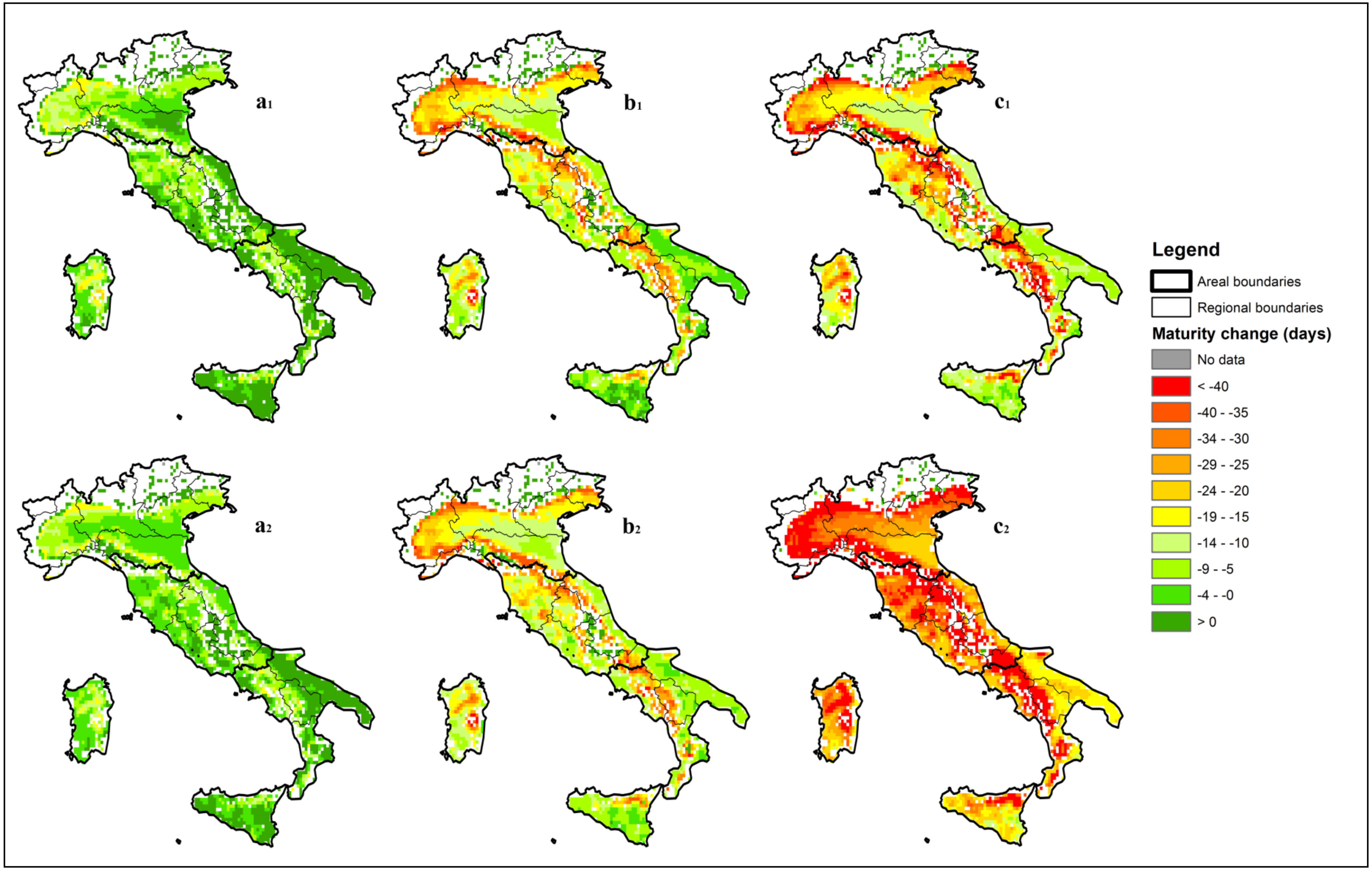

Figure 25. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-15 days)) for the Eleonora cultivar in Italy.

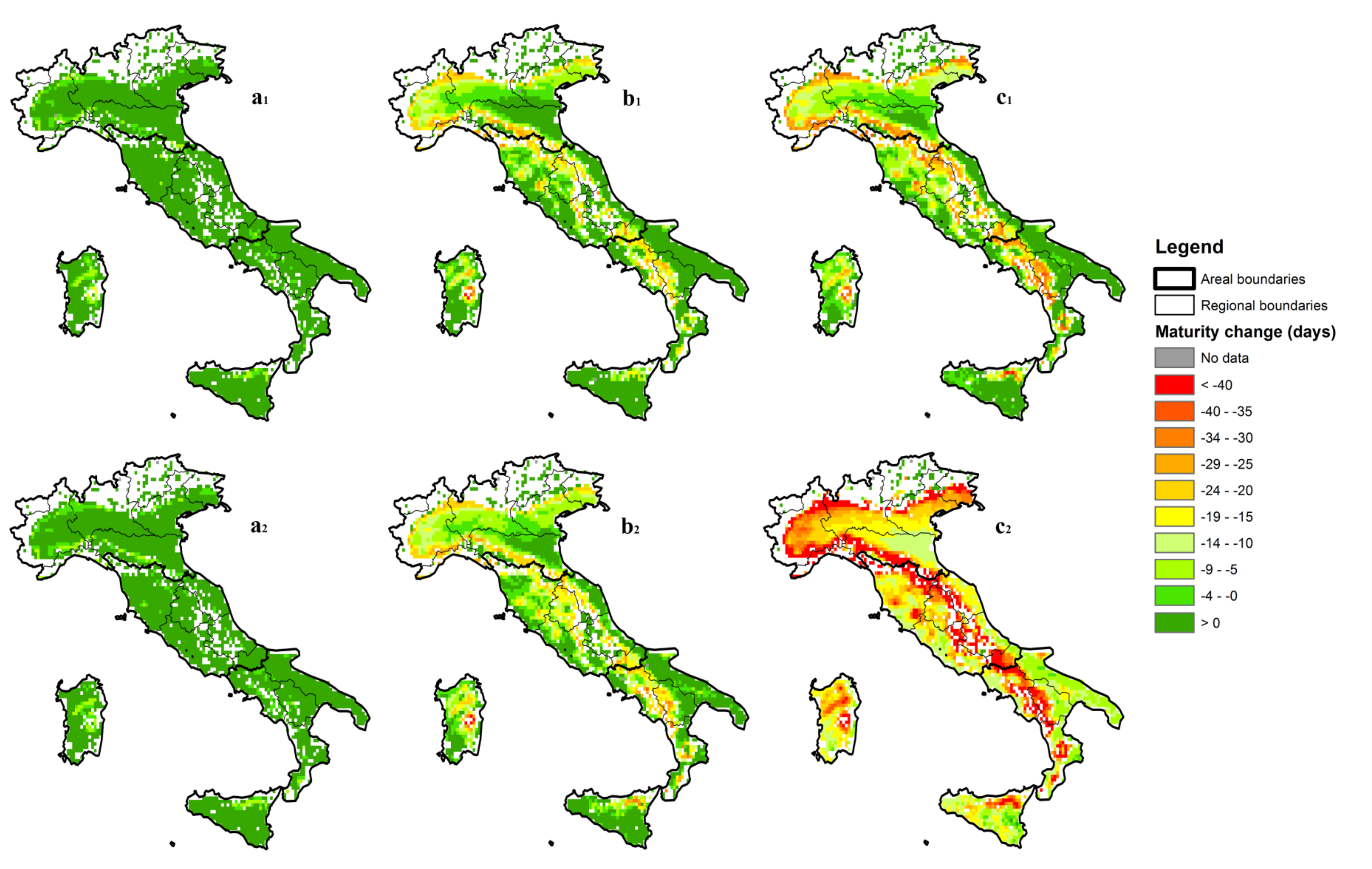

Figure 26. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-30 days)) for the Eleonora cultivar in Italy.

each future period and scenario, when compared to the early sowing date by 15 days (Table 22). Changes in average maturity date for the different periods are similar (ranging from +21 to +22 days in the North area, from +23 to +25 days in the Centre area, and from +21 to +24 days in South-Islands area).

Conversely, the delay of the sowing date by 15 days compared with the ordinary sowing date involves a greater advance of the average maturity date with respect to the baseline period in all the areas, especially in 2080 under the RCP8.5 scenario (ranging from -50 to -59 days) (Figure 27). As a result, the range of time between sowing and maturity decreases for all future period and scenarios (from -7 to -8 days for the North area and from -10 to -11 days for the Centre and South-Islands areas) (Table 23).

The differences in the changes in average maturity date obtained with the two climate scenarios reflect the different temperature projections for the coming decades (see Table 5 of Chapter 4 of this thesis) as the maturity is highly affected by temperature.

Table 22. Changes in average maturity date (days) for each future periods and climate scenarios with adaptation (advance of sowing date (-30 days)) for the Eleonora cultivar compared with climate change impacts without adaptation in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	+21	+21	+22	+21	+21	+21
Centre	+25	+25	+23	+24	+23	+23
South-Islands	+22	+24	+24	+22	+21	+21

Table 23. Changes in average maturity date (days) for each future periods and climate scenarios with adaptation (delay of sowing date (+15 days)) for the Eleonora cultivar compared with climate change impacts without adaptation in Italy.

Area	**RCP4.5**			**RCP8.5**		
	2020	**2050**	**2080**	**2020**	**2050**	**2080**
North	-7	-7	-8	-7	-7	-7
Centre	-10	-8	-10	-11	-11	-10
South-Islands	-11	-10	-9	-11	-11	-10

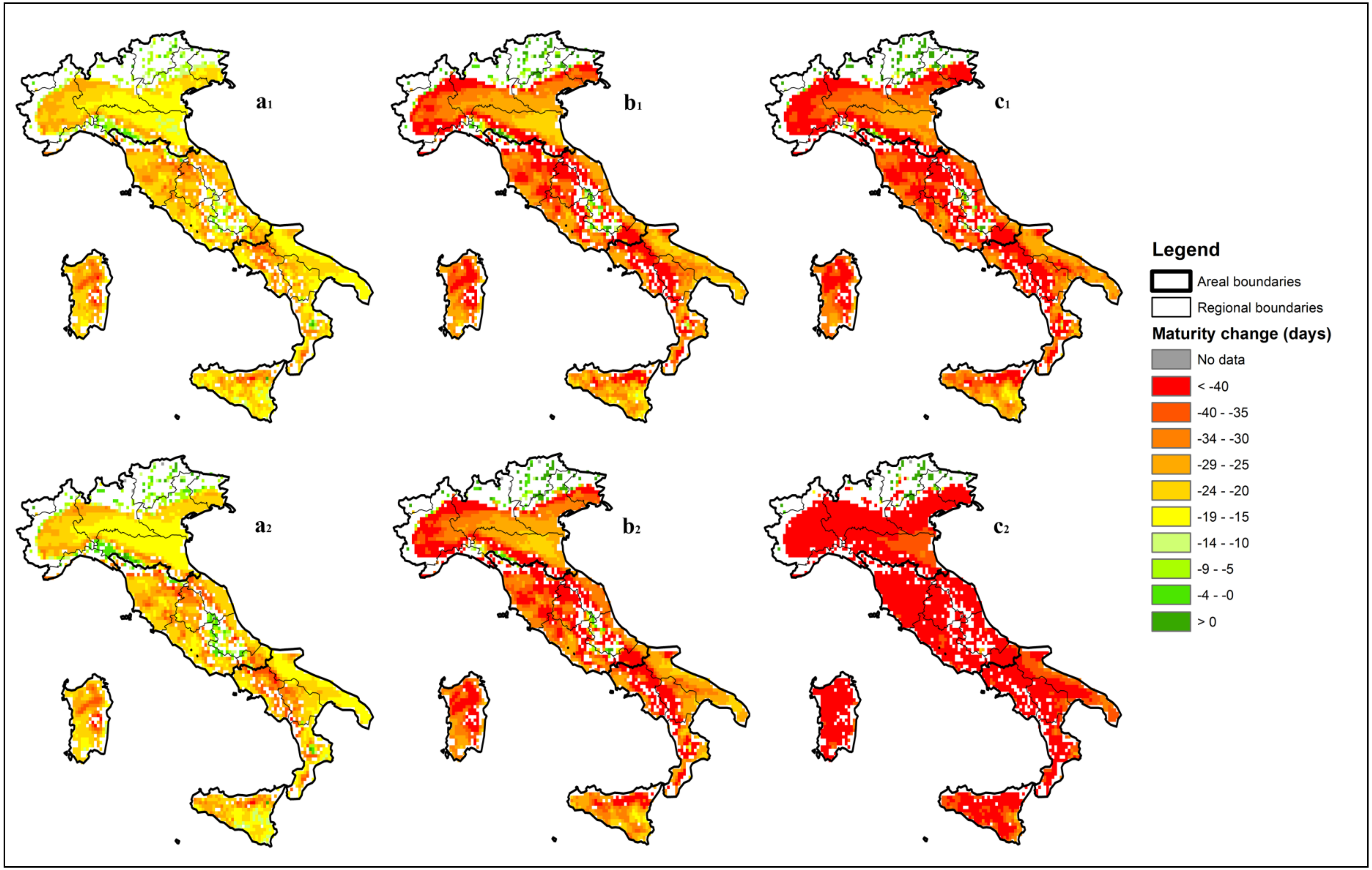

Figure 27. Changes in average maturity date (days) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (delayed sowing date (+15 days)) for the Eleonora cultivar in Italy.

Grain yield

Changes in average grain yield (%) from baseline period to the future periods under the projected future climate change conditions for Eleonora cultivar in each area with an advanced sowing date (-15 days) are shown in Figure 28. Overall, the advance of the sowing date by 15 days enables to cancel the negative impact of climate changes on grain yield only in 2020 in the North area (-0.1% with the RCP4.5 scenario and +0.2% with the RCP8.5 scenario) and in the Centre area (-0.5% and +1.1% under the RCP4.5 and RCP8.5 scenarios respectively), because of the longer duration of the crop cycle. Table 24 shows the changes in grain yield (%) compared to the ordinary sowing date in each area for all the future period and scenarios. On average, the greatest effects on the change in grain yield, with respect to the ordinary sowing date and considering the two climate scenarios, have been obtained for the North area (ranging from +0.9% in 2020 to +3.9% in 2080) and the South-Islands area (from +0.6% in 2020 to +3.1% in 2080). However, while under the RCP4.5 scenario an increase in the change in grain yield between 2020 and 2050 and a subsequent decrease between 2050 and 2080 has been estimated, the change in grain yield increases progressively from 2020 to 2080 under the RCP8.5 scenario. These trends reflect those of the growth cycle duration of the Eleonora cultivar in the different future periods under the two scenarios. In fact, a

Table 24. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (advance of sowing date (-15 days)) for the Eleonora cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+1.4	+0.3	**+0.9**
	2050	+3.9	+2.2	**+3.1**
	2080	+3.0	+4.7	**+3.9**
Centre	2020	+0.4	+0.4	**+0.4**
	2050	+1.8	+1.2	**+1.5**
	2080	-0.2	+1.6	**+0.7**
South-Islands	2020	+0.6	+0.5	**+0.6**
	2050	+1.5	+1.8	**+1.7**
	2080	+2.4	+3.7	**+3.1**

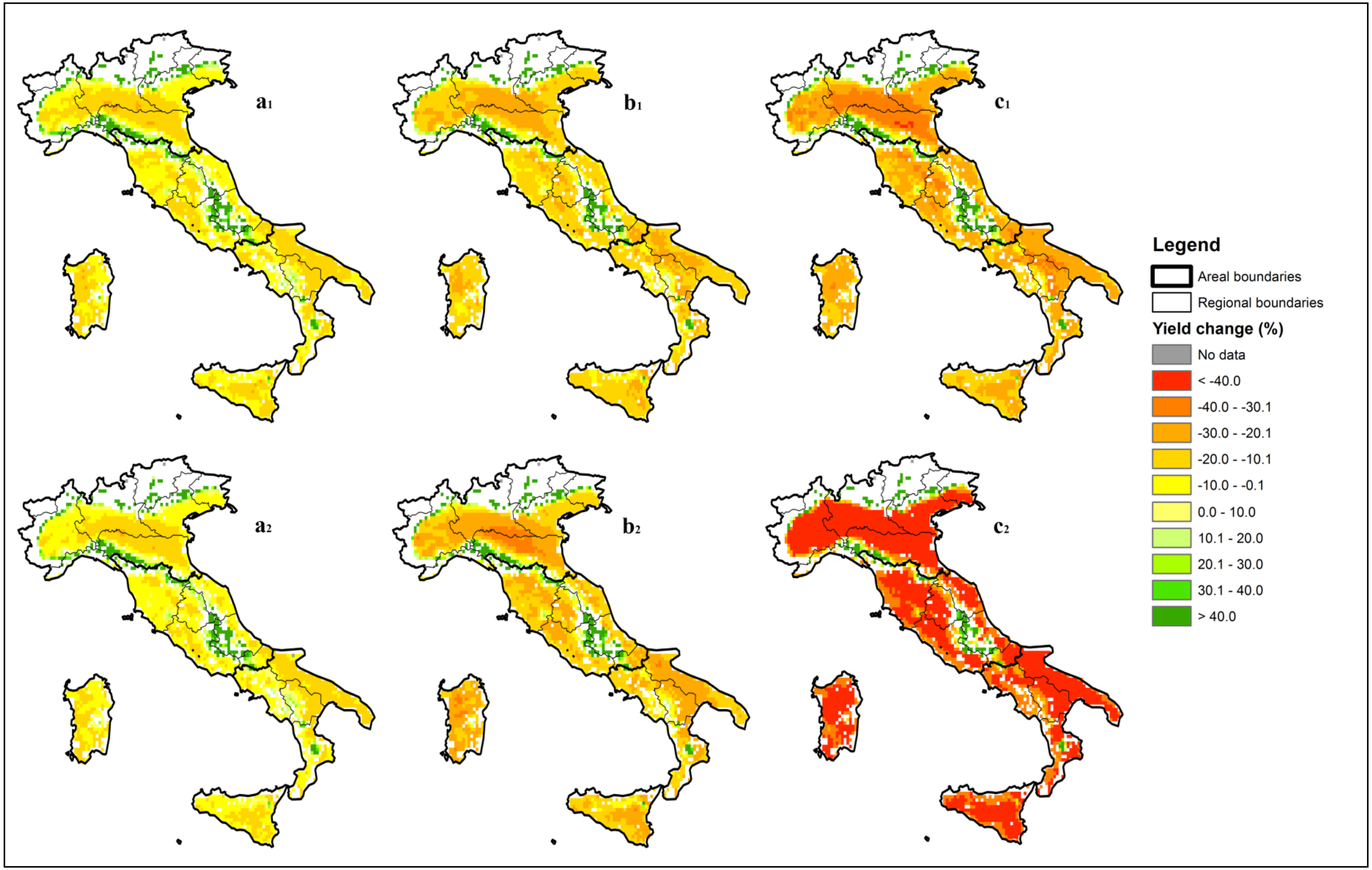

Figure 28. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-15 days)) for the Eleonora cultivar in Italy.

longer duration of the crop cycle has a positive effect on grain yield.

Figure 29 shows the effect of the advanced sowing date (-30 days) on the change in grain yield in the three future periods compared to the baseline period in the various areas with the RCP4.5 and RCP8.5 climate scenarios. Even with this adaptation strategy, the change in average grain yield compared to baseline period is almost canceled in 2020 in the Central-Northern Italy (from -0.7% in the Centre area to -1.5% in the North area with the RCP4.5 scenario and from -1.3% in the North area to +1.0% in the Centre area under the RCP8.5 scenario), while the strategy is not effective in all areas in 2050 and in 2080. However, as shown in the data of Table 25, the average reduction in grain yield for each future period, taking into consideration the two scenarios, is less than the one estimated with the advance of the sowing date of only 15 days in all the areas. The average effect of this strategy is greater in the North area (ranging from -0.6% in 2020 to +5.3% in 2080) and in the South-Islands area (from +0.3% in 2020 to +5.9% in 2080).

Table 25. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (advance of sowing date (-30 days)) for the Eleonora cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	0.0	-1.1	**-0.6**
	2050	+5.5	+1.6	**+3.6**
	2080	+3.4	+7.2	**+5.3**
Centre	2020	+0.3	+0.3	**+0.3**
	2050	+2.1	+0.4	**+1.3**
	2080	+0.8	+3.9	**+2.4**
South-Islands	2020	-0.2	+0.7	**+0.3**
	2050	+2.2	+1.5	**+1.9**
	2080	+4.4	+7.3	**+5.9**

Figure 30 shows the effect of delay of a 15 days delay of the sowing date on the change in average grain yield, compared to the baseline period in each area for the three future periods and under the two scenarios considered. As can be seen, this strategy is

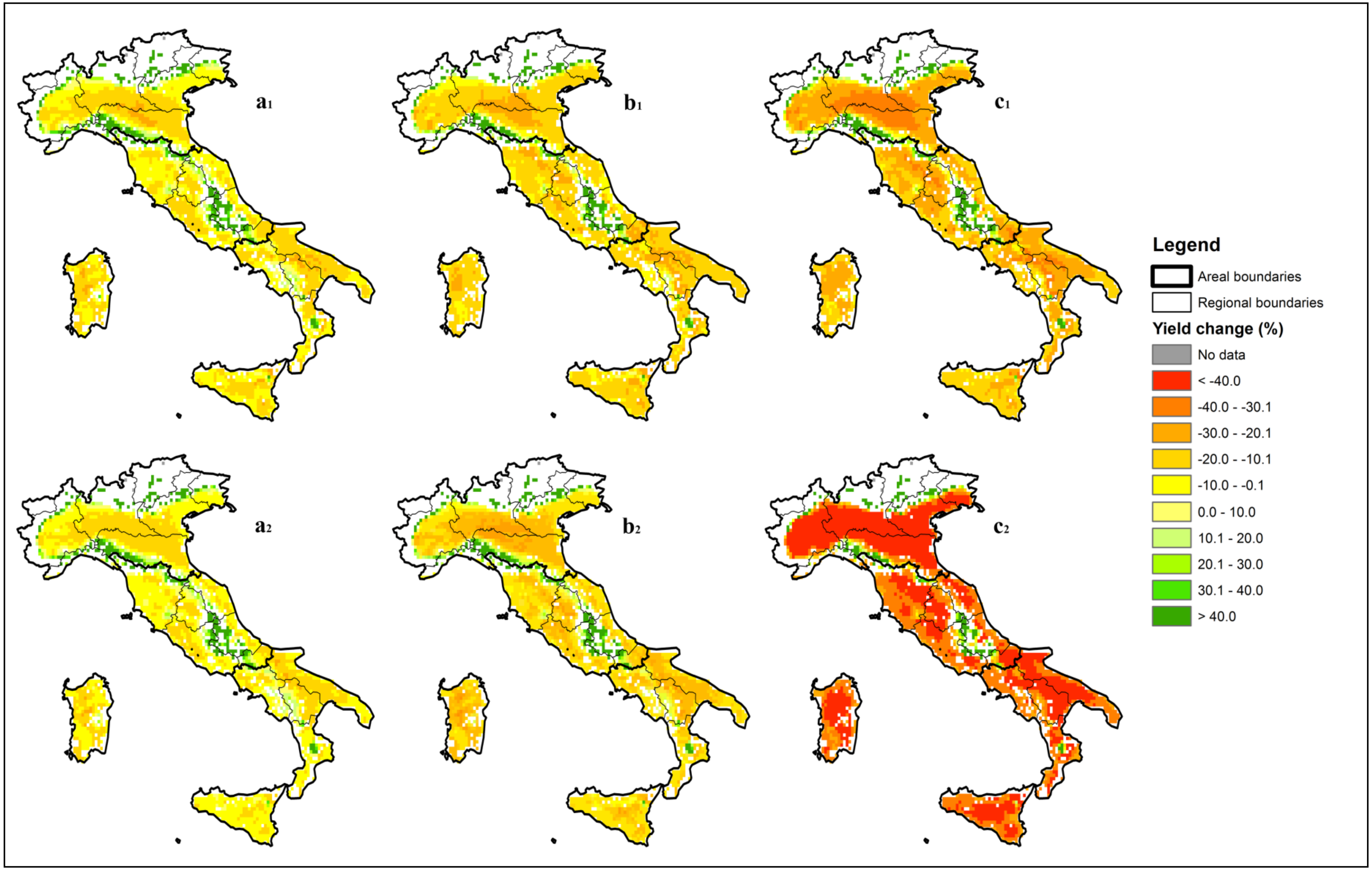

Figure 29. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (advanced sowing date (-30 days)) for the Eleonora cultivar in Italy.

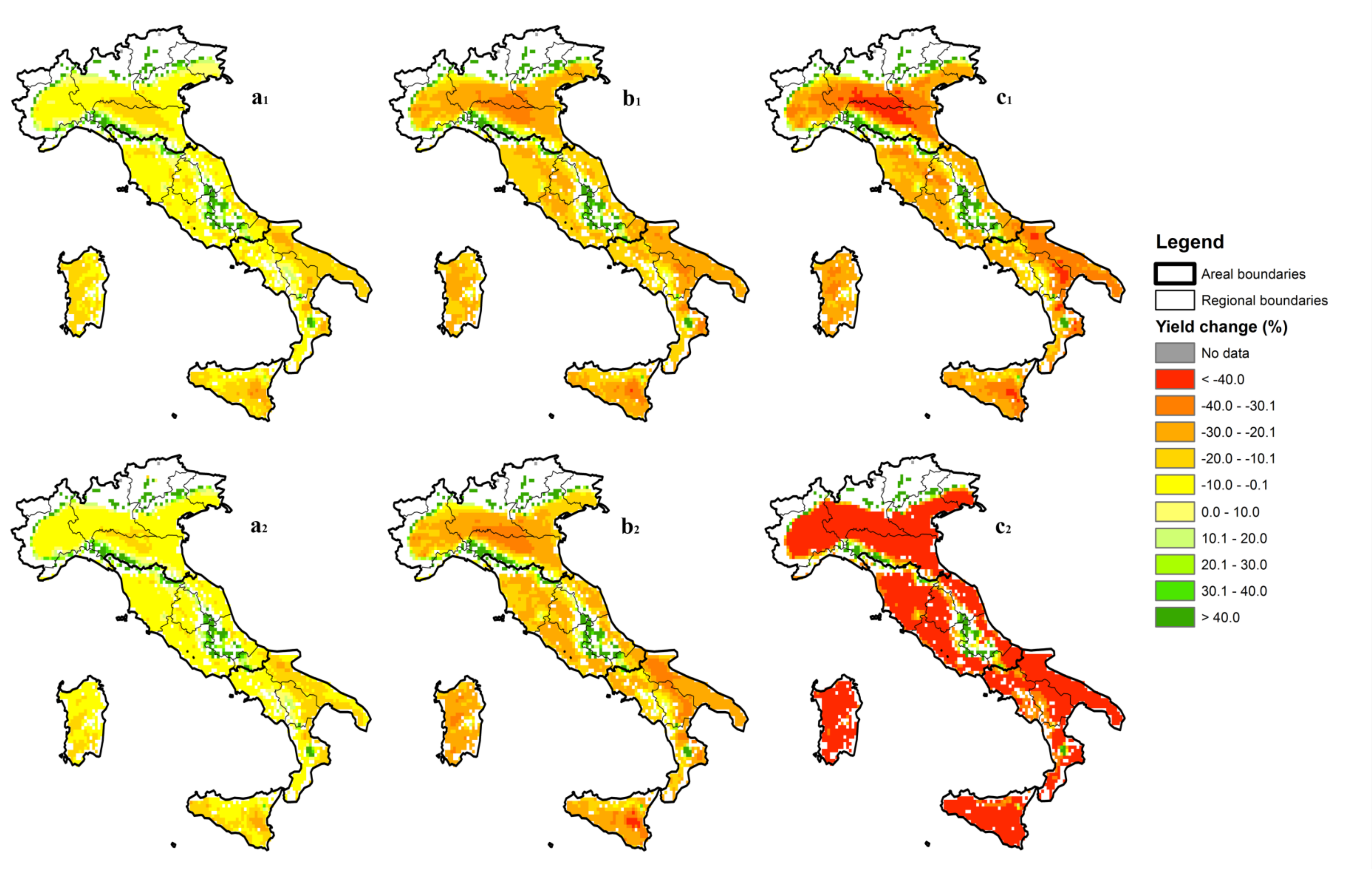

Figure 30. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (delayed sowing date (+15 days)) for the Eleonora cultivar in Italy.

effective only in 2020 in the North area (+0.4% with the RCP4.5 scenario and +0.7% with the RCP8.5 scenario) and in the Centre area (-1.6% and 0% under the RCP4.5 and RCP8.5 scenarios respectively) making possible to obtain a simulated average yield almost equal to the one estimated with the ordinary sowing date. On the other hand, this strategy entails a greater reduction in average yield in 2050 and in 2080, probably due to excessive shortening of the crop cycle, with consequent lower dry matter accumulation in grain. On average, considering the two scenarios, the delay of the sowing date by 15 days results in a negative effect on the change in average grain yield from 2020 to 2080 (ranging from +1.4% to -1.7% in the North area, from -0.6% to -2.3% in the Centre area, and from -0.7% to -3.1% in the South-Islands area) (Table 26).

Table 26. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (delay of sowing date (+15 days)) for the Eleonora cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+1.9	+0.9	**+1.4**
	2050	-0.4	-0.2	**-0.3**
	2080	-0.6	-2.7	**-1.7**
Centre	2020	-0.6	-0.6	**-0.6**
	2050	-1.8	-1.4	**-1.6**
	2080	-1.1	-3.5	**-2.3**
South-Islands	2020	-1.1	-0.3	**-0.7**
	2050	-3.4	-1.7	**-2.6**
	2080	-1.6	-4.5	**-3.1**

Changes in fertilization regime

Results of the adaptation strategies relative to the change in fertilization regime (increase in N, P and K fertilization rates by 20% and incorporation of the crop residues (5 t ha^{-1}) on the average grain yield of the Eleonora cultivar in Italy are described below. As the crop phenology is not affected by different applications of fertilizer, the results relative to changes in the average maturity date for these adaptation strategies are not described in this study.

Grain yield

Changes in average grain yield (%) from baseline period to future periods under the RCP4.5 and RCP8.5 climate scenarios for the Eleonora cultivar in each area with an increase in N, P and K fertilization rates (+20%) are shown in Figure 31. Based on the results obtained, this adaptation strategy shows its effectiveness particularly in 2020, resulting in a small increase in the average grain yield with respect to the baseline period in the North area (ranging from +1.6% with the RCP4.5 scenario to +3.2% with the RCP8.5 scenario) and in the Centre area (from +1.5% to +3.5% under the RCP4.5 and RCP8.5 scenarios respectively). On the other hand, the increase in fertilization rates by 20% leads to a reduction in the average yield slightly less than the one estimated with the ordinary inorganic fertilization in 2050 and 2080 in all the areas. Therefore, considering the two scenarios, the average effect of this adaptation strategy on the change in average grain yield decreases from 2020 to 2080 (from +3.2% to +0.8% in the North area, from +2.7% to +0.8% in the Centre area, and from +1.8% to +0.4% in the South-Island area) (Table 27).

Table 27. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (increase in N, P and K fertilization rates (+20%)) for the Eleonora cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+3.1	+3.3	**+3.2**
	2050	+1.6	+1.6	**+1.6**
	2080	+1.1	+0.4	**+0.8**
Centre	2020	+2.5	+2.9	**+2.7**
	2050	+1.7	+1.7	**+1.7**
	2080	+1.2	+0.4	**+0.8**
South-Islands	2020	+1.7	+1.8	**+1.8**
	2050	+1.0	+0.9	**+1.0**
	2080	+0.6	+0.2	**+0.4**

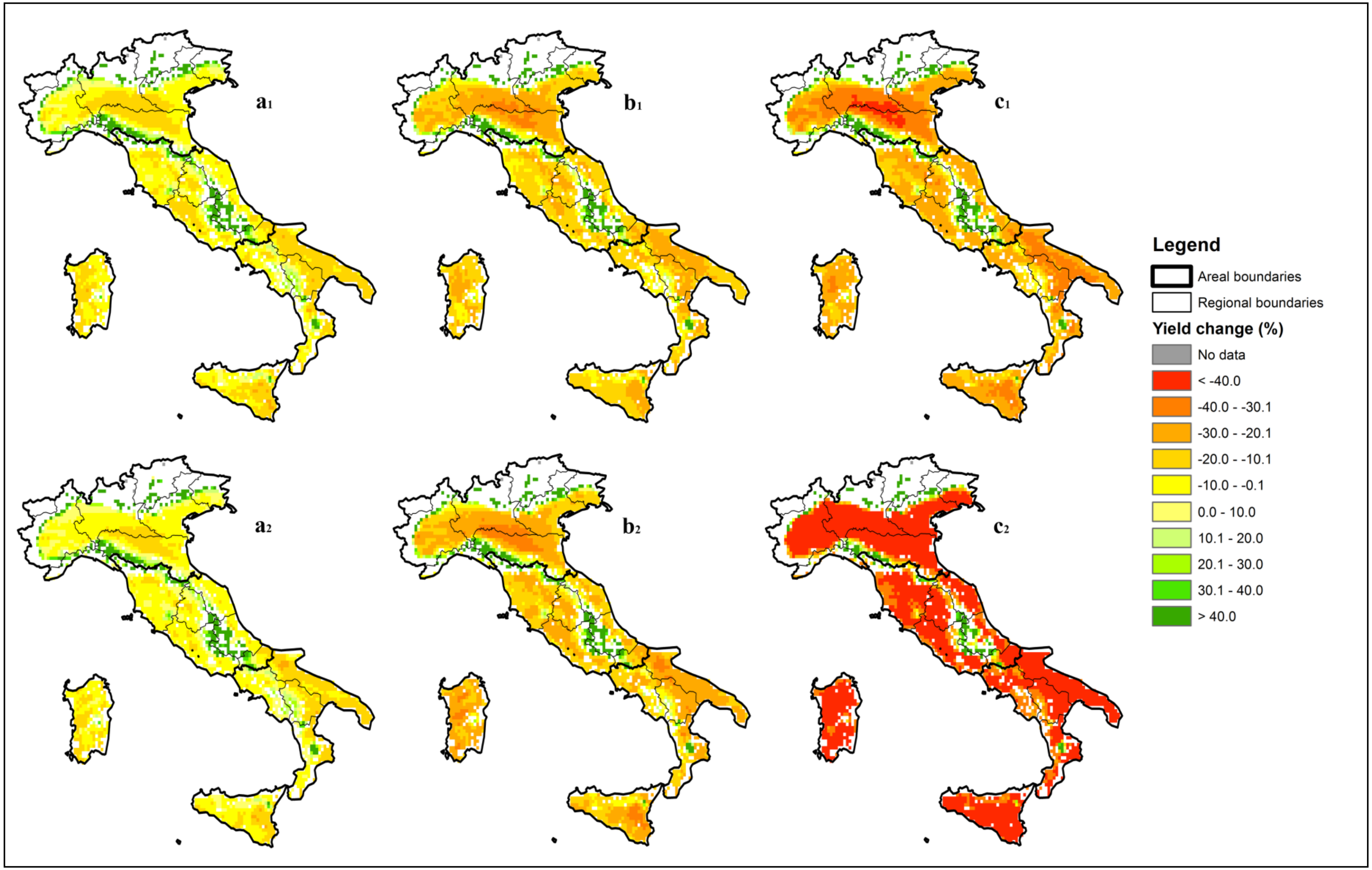

Figure 31. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (increase in N, P and K fertilization rates (+20%)) for the Eleonora cultivar in Italy.

The incorporation of crop residues of *Vicia villosa* Roth. (5 t ha^{-1}) leads to a positive effect on the grain yield, which is greater than the increase by 20% in N, P and K fertilization rates (Figure 32). In fact, an increase in the average grain yield compared to the baseline period under both climate scenarios was estimated with this adaptation strategy in 2020 in the North area (ranging from +4.9% with the RCP4.5 scenario to +6.4% with the RCP8.5 scenario) and in the Centre area (from +3.4% to +6.3% under the RCP4.5 and RCP8.5 scenarios, respectively). In addition, this strategy reduces the negative impact of climate change on average grain yield in 2050 and in 2080 in all the areas with respect to the ordinary inorganic fertilization. Taking into consideration both scenarios, the average effect of the incorporation of crop residues on the change in average grain yield, is positive in all the areas, although decreasing over time (from +6.5% in 2020 to +1.6% in 2080 in the North area, from +5.0% in 2020 to +1.4% in 2080 in the Centre area, and from +3.2% in 2020 to +0.6% in 2080 in the South-Islands area) (Table 28). This is probably due to the increased availability of nutrients (especially nitrogen and potassium) both during the sowing and between flowering and maturity (due to the mineralization of the organic matter contained in crop residues incorporated into the soil).

Table 28. Changes in average grain yield (%) for each future periods and climate scenarios with adaptation (organic amendment of soil with crop residues (5 t ha^{-1})) for the Eleonora cultivar compared with climate change impacts without adaptation in Italy.

Area	**Future period**	**RCP4.5**	**RCP8.5**	**Mean yield change (%)**
North	2020	+6.4	+6.5	**+6.5**
	2050	+3.3	+3.1	**+3.2**
	2080	+2.4	+0.8	**+1.6**
Centre	2020	+4.4	+5.6	**+5.0**
	2050	+2.9	+3.2	**+3.1**
	2080	+2.1	+0.7	**+1.4**
South-Islands	2020	+2.9	+3.5	**+3.2**
	2050	+1.5	+1.4	**+1.5**
	2080	+0.9	+0.3	**+0.6**

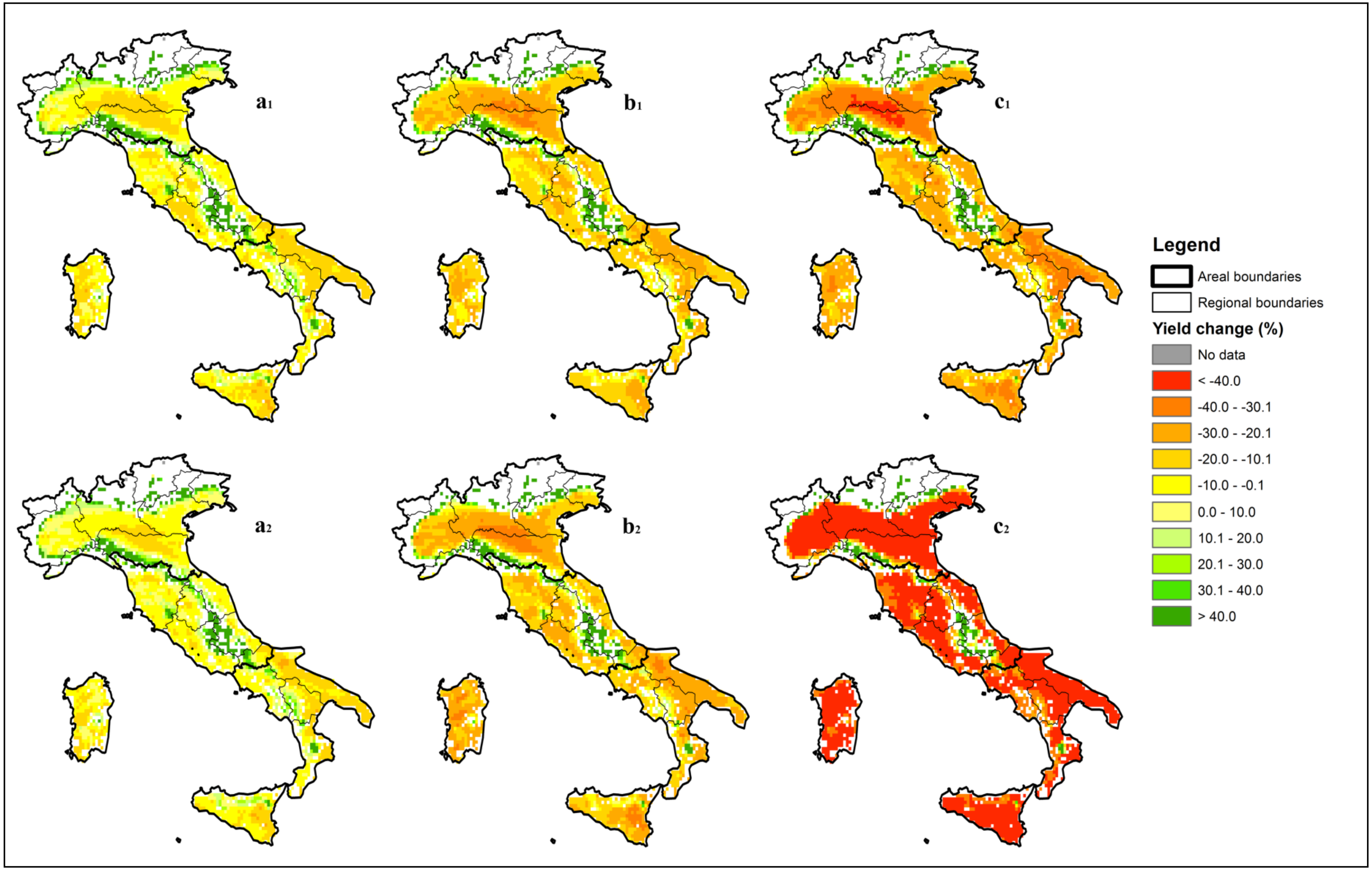

Figure 32. Changes in average grain yield (%) from actual (1990) to 2020 (a_1, a_2), 2050 (b_1, b_2) and 2080 (c_1, c_2) with the RCP4.5 (top) and RCP8.5 (bottom) climate scenarios with adaptation (organic amendment with crop residues (5 t ha^{-1}) for the Eleonora cultivar in Italy.

Comparison between adaptation strategies for maize

In order to compare the effectiveness of the various adaptation strategies assessed in this study in limiting the impacts of climate change on phenology and yield of maize (Eleonora cultivar), the results obtained for each area and climate scenario compared with impacts without adaptation are summarized in Figures 33 (for the maturity date) and 34 (for the grain yield).

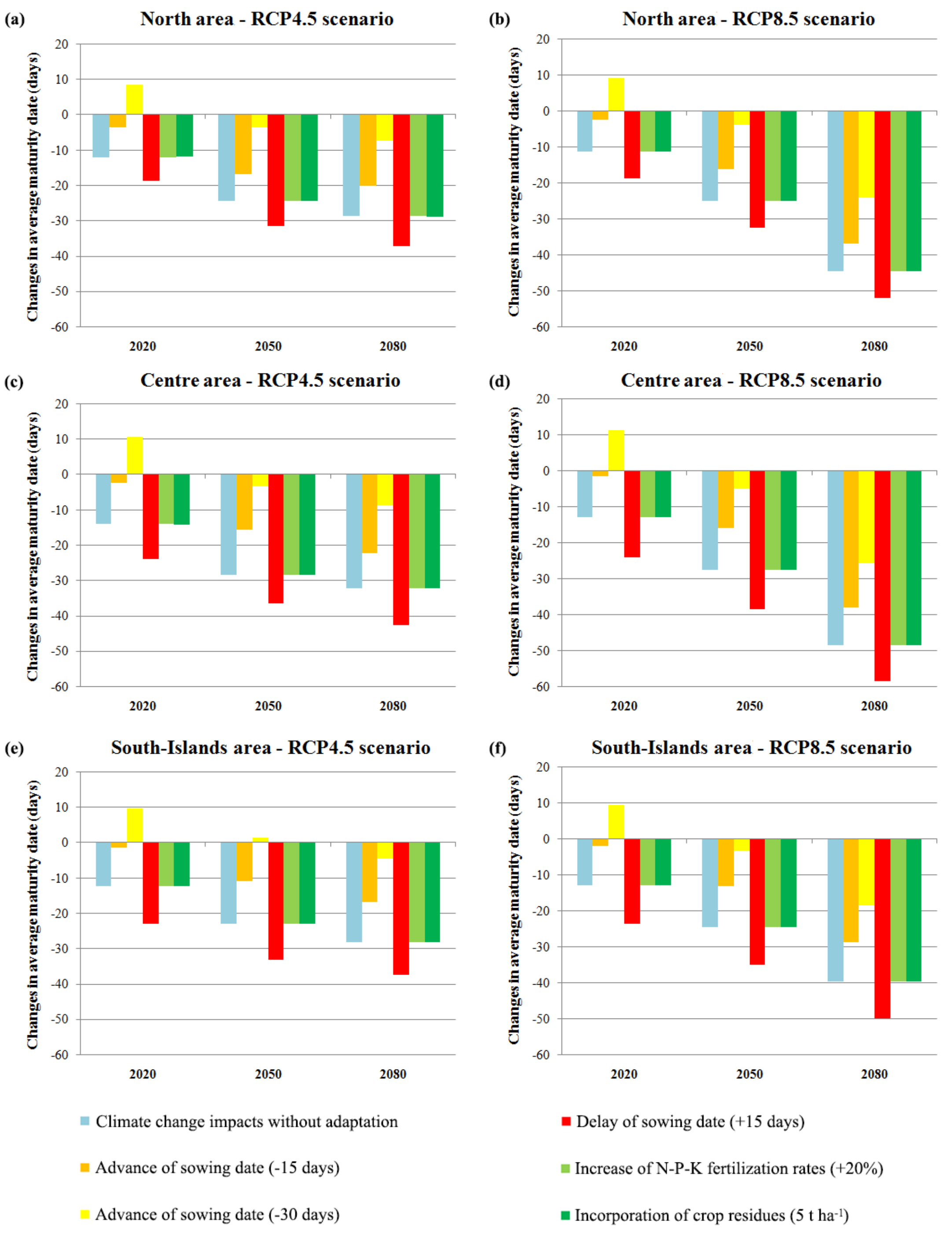

Figure 33. Effects of the adaptation strategies and climate change impacts without adaptation on changes in average maturity date (days) compared to baseline period in each area under the RCP4.5 (a, c and e) and RCP8.5 (b, d and f) climate scenarios for maize (Eleonora cultivar).

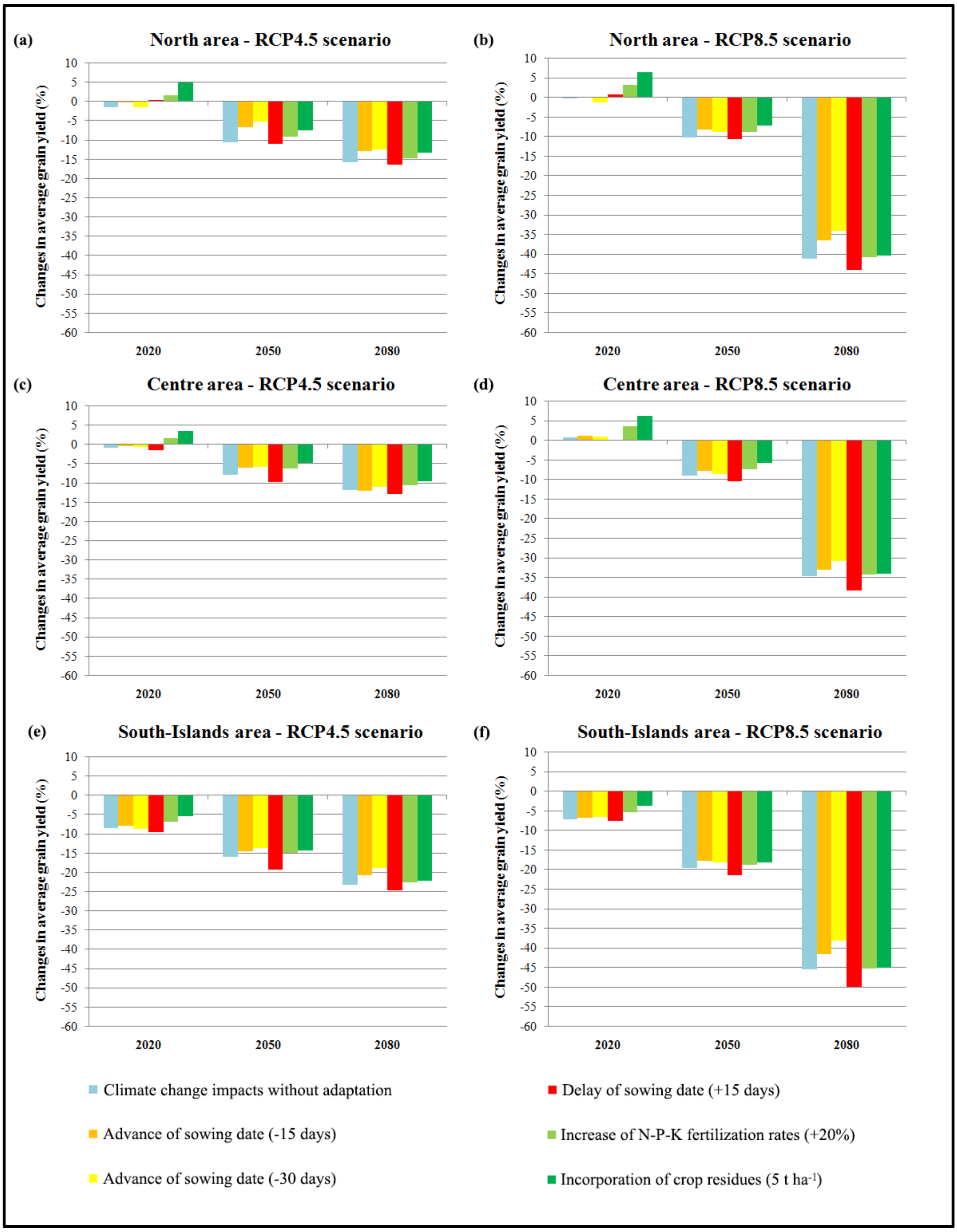

Figure 34. Effects of the adaptation strategies and climate change impacts without adaptation on changes in average grain yield (%) compared to baseline period in each area under the RCP4.5 (a, c and e) and RCP8.5 (b, d and f) climate scenarios for maize (Eleonora cultivar).

5.5 DISCUSSION

The durum wheat (*Triticum durum* Desf.), common wheat (*Triticum aestivum* L.), and maize (*Zea mays* L.) are the most widely cereals in Italy. Their importance is significant for both human and animal food. In the coming decades, the expected impacts of climate change on phenology and productivity of these crops differ depending on the crop and area under consideration (Gallo et al., 2014b). Therefore, the evaluation of the effectiveness of adaptation strategies to climate change is necessary in order to better plan the actions to limit the negative effects of climate change on the phenology and yield of these crops from local to national level.

This study has evaluated some adaptation strategies that can be implemented in the short term at the farm level, such as the shifting (advance and delay) of sowing date, the change in fertilization regime (increase in N, P and K fertilization rates (+20%) and incorporation of crop residues (5 t ha^{-1})), and the application of irrigation (only for the durum wheat and common wheat, given that maize is usually irrigated). The assessment of each adaptation strategy was carried out using the CSM-CERES-Wheat and CSM-CERES-Maize crop models implemented in DSSAT-CSM and parameterized at Italian scale (Gallo et al., 2014a). The simulations were performed for each crop and period, using the digital platform and climate data of the RCP4.5 and RCP8.5 scenarios used to assess the impacts of climate change on phenology and yield of the same crops (Gallo et al., 2014b).

Regarding phenology, the simulations carried out for the Iride cultivar indicate that the advance of sowing date (particularly the one equal to -30 days) is the most effective strategy because it results in an increase of the average maturity date with respect to the baseline period in all areas, unlike the climate change without adaptation. In particular, an earlier sowing (-30 days) produce a lengthening of the crop cycle in 2020 and in 2050 under the RCP4.5 scenario (ranging from +10 to +18 days in 2020 and from +1 to +10 days in 2050) which is greater when compared with the RCP8.5 scenario (from +6 to +15 days in 2020 and up to +6 days in 2050). On the contrary, the delay of sowing date (+15 days) is not an effective strategy because it causes a further reduction of the maturity date under both climate scenarios compared with a baseline period greater than the ordinary sowing date. Results of the advance of sowing date by 30 days for the Sardinia region (from +9 to +12 days in 2020, from 0 to +4 days in 2050 and from -15 to 0 days in 2080 with the two climate scenarios) are comparable to those obtained by Mereu (2010) for Iride cultivar considering four experimental sites and three GCMs (on average, from +14 to +23 days in 2025, from +10 to +19 days in 2050, and from +6 to +16 days in 2075).

The application of irrigation seems to be the most effective adaptation strategy for grain yield of Iride cultivar in all areas for each period and with both climate scenarios under consideration. The largest increases in grain yield compared to climate change without adaptation are expected in Central Italy (Adriatic side) (up to +39.4% in 2050 with the RCP4.5 scenario and up to +49.0% in 2080 under the RCP8.5 scenario) followed by Sicily (up to about +30% in 2050 and 2080 with the two scenarios under consideration) and the South-Peninsular area (up to +27.8% in 2050 and up to +29.4% in 2050 and 2080 under the RCP4.5 and RCP8.5 scenarios respectively). These results agree with those obtained by Ventrella et al. (2012) on durum wheat (Simeto cultivar) in the Capitanata region (Apulia) (increase in average grain yield equal to +38.8% compared to rainfed condition). The irrigation allows to increase grain yield of the Iride cultivar in other areas, albeit to a lesser extent. The effectiveness of this strategy is probably related to the fact that irrigation compensates for the decrease in rainfall during the grain filling expected in the coming decades. In fact, it is known that a water stress in this phase causes the formation of smaller kernels and the consequent reduction of the grain yield. The advance of sowing date has a slightly more positive effect on the average grain yield than climate change without adaptation in Central Italy (Adriatic side) (up to +5.9% in 2050 under the RCP4.5 scenario and up to +3.1% in 2020 under the RCP8.5 scenario with sowing advanced of 30 days), and in the South-Peninsular, Sicily and Northern areas in 2020 (on average +2.5%, +2.6%, and +2.2% respectively, considering the two climate scenarios). The effectiveness of this strategy decreases in the other periods, in particular in the North and in the Sardinia areas, where a decrease of average grain yield (on average up to -12.9% and -8.7% respectively considering the RCP4.5 and RCP8.5 scenarios) is expected in 2080 with the sowing advanced by 30 days.

These results differ from those obtained by Mereu (2010) for Iride cultivar (on average from +33.3% in 2025 to +43.8% in 2075 considering four experimental sites) and Carboni (2011) for Simeto cultivar (on average from +8.8% in 2025 to +14.9% in 2075 with a 40-days early sowing and from +0.7% in 2025 to +6.5% in 2075 with a 20-days early sowing considering two experimental sites) using three GCMs. Another useful adaptation strategy is the increase in N, P and K fertilization rates (+20%), which is effective in all areas of Central and Southern Italy, with increases in average grain yield up to +6.6% in 2020 in Sicily and up to +6.2% in 2080 in Central Italy (Adriatic side) considering both climate scenarios. Therefore, this strategy can be useful to compensate for the negative impacts of climate change on average grain yield in Sicily and Sardinia. Similar results were obtained by Ventrella et al. (2012) doubling the nitrogen fertilization rate, resulting in an average change in grain yield ranging from -13.7% to +16.0% compared to the baseline period. However, the increase in fertilization rates should be carefully evaluated for a greater environmental sustainability.

Regarding common wheat, the advanced sowing results in a lengthening of the growing season compared to the ordinary sowing date in all areas (ranging from +13 to +15 days and from +24 to +29 days with sowing advanced by 15 and 30 days respectively). Conversely, the growing season is shorter (up to -15 days) with planting delayed by 15 days. Therefore, the advance of sowing is an useful strategy to increase the average grain yield of Bologna cultivar in all areas and periods, particularly in Central Italy (up to +11.7% in 2020 considering the two scenarios) and in Northern Italy (up to +12.3% in 2080 under the RCP8.5 scenario). Even the application of irrigation is an effective adaptation strategy to improve yield of Bologna variety at national level. The largest increases in average grain yield are expected in the South-Islands area (up to +26.5% and +28.8% in 2080 under the RCP4.5 and RCP8.5 scenarios respectively), while the minor benefits derived by the irrigation are expected in the North area where the spring rainfall projected for the coming decades are greater than the Central-Southern Italy. The increase in N, P and K fertilization rates (+20%) has a similar positive effect on the average grain yield in all areas, particularly in Central and Southern Italy (up to about +6.5% in 2050 and 2080 considering the average of both the scenarios).

Similarly to the durum wheat and common wheat, the results of simulations for maize (Eleonora cultivar) indicate that the advance of sowing is effective because it results in an increase in the average maturity date in all areas under the two climate scenarios under consideration. In particular, the earlier sowing by 30 days involves an average lengthening of the crop cycle of about 10 days in 2020 compared to the baseline period, thus reversing the negative impact of climate change on maturity. This strategy is useful also in 2050 and in 2080, even though the average maturity date in each area decreases in comparison to the baseline period (up to -5 and -26 days respectively in Central Italy under the RCP8.5 scenario). A 15-days early sowing date is less effective than a 30-days early sowing, as it causes a lower positive change on the average maturity date. On the other hand, the delay of sowing date (+15 days) shortens the crop cycle of the Eleonora hybrid in each area and period (from -7 to -11 days considering both climate scenarios). Regarding grain yield, the adaptation strategies related to the change in the fertilization regime are the most effective, especially in the Central and Northern areas. The incorporation of the crop residues of *Vicia villosa* Roth. equal to 5 t ha^{-1} is the strategy that could bring major benefits, with an increase in the average grain yield in 2020 (up to about +6.5% under the RCP8.5 scenario vs. +3.5% expected with the increase in the fertilization rates by 20%). This confirms the importance of leguminous crops in crop rotation. The change in fertilizer regime is less effective in 2050 and 2080 in the South-Islands area, as it does not limit the negative impacts of climate change on grain yield of Eleonora cultivar. Different results could be obtained by the incorporation of crop residues of other species. In general, the early sowing date is not very effective because it cancels the negative effects of climate change on grain yield only in the North and Centre areas in 2020. However, this strategy results in a grain yield change which is lower than the variation of fertilization regime in 2080 under the RCP8.5 scenario. This is due to the greater length of the crop cycle compared to the ordinary sowing date.

In summary, irrigation is the most effective adaptation strategy to improve grain yield of durum and common wheat at national level. Therefore, considering that in many Italian areas the wheat producers pay the water connection without using the service, irrigation could be a valid strategy for these cereals to contrast climate change in coming decades. The advance of sowing date (especially -30 days) and the increase in fertilization rates by 20% would also allow an increase in grain yield compared to climate change without adaptation. Conversely, the incorporation of crop residues (5 t ha^{-1}) is the adaptation option that would allow to obtain most benefits regarding the grain yield of maize (Eleonora cultivar) in the short term (especially in Central and Northern Italy), while early sowing (especially -30 days) entails a greater reduction of the negative effects of climate change on grain yield in the mid-long term.

The differences between the results obtained in this study and those obtained recently by Mereu (2010), Carboni (2011) and Ventrella et al. (2012) are probably due to the different level of analysis (local vs. national scale) and to the greater heterogeneity of climate and soil characteristics considered in this study that have a considerable impact on the average values of maturity date and grain yield. Therefore, in order to increase the reliability of results, the evaluation of adaptation strategies should be carried out by considering only the areas under cultivation for each crop. Unfortunately, the data relating to the distribution of the cultivated areas for each cultivar are not available and, in any case, it would be subject to variation from one year to another due to crop rotation and other processes (e.g., the reduction of the cultivated areas as a result of the urbanization, desertification, etc.).

The main advantages of the method proposed here are related to the flexibility of use of the digital platform and the high resolution of the climate input data used to carry out the simulations. However, the analysis was performed considering only one RCM. Therefore, the results obtained in this work require a comparison with those resulting from works perfomed using climate data of more climate models. In addition, for an accurate assessment of adaptation strategies aiming their immediate implementation at farm level, the use of climate data at higher cell resolution is essential. However, the climate models currently available for Europe have a lower resolution than the one used in this study (Jacob et al., 2014). Finally, it is also important to evaluate the effects of the interaction of two or more adaptation strategies (e.g., advance of sowing date and irrigation for durum and common wheat) in order to further reduce the impacts of climate change on phenology and grain yield of crops under consideration.

5.6 CONCLUSIONS

This study provides detailed information on the possible response of the most important Italian cereals following the implementation at the local level of some adaptation strategies related to the change in crop management techniques currently in use in each area. The effects on phenology and grain yield of each crop were evaluated using the CSM-CERES-Wheat and CSM-CERES-Maize crop models calibrated and evaluated at the Italian scale and using high resolution climate data of the RCP4.5 and RCP8.5 scenarios.

The effectiveness of each adaptation strategy to climate change varies with the crop. In particular, the different results obtained for wheat and maize are due to the different photosynthetic efficiency and different growing season of these crops. Therefore, the response of the two crops to climatic conditions is different considering the same adaptation strategy. The transition from rainfed to irrigated conditions is the most effective strategy for durum wheat and common wheat given that it involves a significant increase in grain yield in all cultivation areas under both climate scenarios. Good results are expected with the advance of sowing date (especially -30 days) and the increase in fertilization rates by 20%. The grain maize (usually irrigated in Italy) could respond positively to the incorporation of crop residues in the short term (especially in the North and Centre areas). On the other hand, the effect of the advance of sowing date on phenology and grain yield of maize is lower than wheat and does not compensate the negative impacts of climate change expected in the coming decades.

To contrast in an effective way the impacts of climate change on crop development and yield, it is necessary to consider the high variability and the high level of uncertainty of climate projections. Therefore, a more detailed level of analysis (from national to regional or provincial level) and the utilization of climate projections from different climate models (possibly at high cell resolution) must be taken into account for a more reliable assessment of the effectiveness of adaptation strategies. However, the anthropogenic greenhouse gases emissions in the agricultural sector will likely increase in the coming decades because of climate change, so it is also necessary to adopt appropriate mitigation strategies. However, mitigation strategies exert their effects in the mid-long term with a high level of uncertainty and interact in a synergistic way with adaption strategies. This is a very important challenge for the scientific community if we consider that the changes in grain yield expected over the coming decades as a result of climate change will affect important crops for human food consumption and for animal feed. Through this approach, the scientific community will be able to provide elements of decision support for decision makers aimed at the implementation of the most effective adaptation and mitigation strategies against climate change in agriculture in the short-mid term, from local to national level.

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