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RESEARCH ARTICLE

Ancient wheat species are suitable to grain-only and grain plus herbage utilisations in marginal Mediterranean environments

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Abstract

Thanks to their low fertilization requirements and high consumer demand, ancient wheats and old durum wheat cultivars represent an attractive option for the marginal areas of Mediterranean environments no longer cultivated due to the low grain yields attainable using modern wheat cultivars. Dual-purpose utilization may increase their value in these cropping systems, but no information is available on the suitability of ancient wheat species to this type of utilization. To fill this gap, Khorasan, einkorn, and emmer wheats, clipped at the terminal spikelet stage or left unclipped, were compared in a two-year field trial. The grains were sown in the month of October, in Sardinia (41°N, 80 m asl), Italy, on low-fertility soils and with low-medium fertilization rates. Einkorn cultivars produced the highest biomass yield (2–3 t ha^{-1}), reflecting the longer time to the onset of the terminal spikelet stage (119–138 days). After clipping, all species recovered their ability to intercept radiation to the levels of the unclipped crops, but clipping lowered their radiation use-efficiency. Grain yield was not penalized by clipping: the increase in the harvest index compensated for the decrease in biomass. Here we show for the first time that ancient wheat species are suitable for dual-purpose utilization (herbage plus grain in the same season) rendering them valuable for marginal areas; this was because the early sowing adopted for dual-purpose utilization allowed them to take full advantage of their lateness in terms of herbage yield, and to bring flowering forward (i.e. make it earlier) so that a satisfactory grain yield was obtained, even under severe water stress. Dual-purpose utilization of ancient wheats increases the sustainability of mixed cropping systems, by making herbage available to animals in a critical period, without decreasing the grain yield attainable after grazing in the same season.

Keywords Dual purpose · *T.monococcum* · *T. dicoccum* · Khorasan wheat · Marginal areas · Resource use · Ancient wheats

1 Introduction

The low grain yields attainable with modern wheat cultivars in marginal areas with low soil fertility levels is one of the reasons behind the decrease in the area devoted to durum wheat observed in Italy in the last two decades (from 1.664 million ha in 2000 to 1.433 million ha in 2016, ISTAT). One solution proposed to deal with abandoned agricultural systems and marginal areas is the diversification of cropping systems (Desclaux et al. 2008). Although cropping systems involving modern durum wheat cultivars stand to provide farmers with the greatest financial return in relation to fertile areas, low-fertility areas can also be of significant value when farmed using old durum wheat cultivars and ancient wheat species, such as einkorn (*Triticum monococcum L.* ssp. *monococcum)*, emmer (*T. turgidum* ssp. *dicoccum* (Shrank) Thell), and ‘Khorasan’ wheat (*T. turgidum ssp. turanicum*) (Giunta et al. 2019; Fhatolahi et al., 2020).

The cultivation of old durum wheat cultivars and ancient wheat species offers two specific advantages. First, they have low fertilization requirements (Fhatolahi et al., 2020; Vaghar and Ehsanzadeh, 2018) related to their low yield potentials and high susceptibility to lodging. Second, the relative economic return associated with these crops is greater than that of modern cultivars thanks to the high prices their products have been able to fetch in recent years as a consequence of their increased demand, arising from the growing consumer interest towards traditional products perceived as healthier, more

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sustainable and contributing towards biodiversity sustainability (Desclaux et al. 2007).

Grain yields between 2.6 and 3.5 t ha^{-1} associated with good quality have been reported for emmer grown in Southern Italy (De Vita et al. 2006) and einkorn grown in Central Italy (Vallega 1992), but these species, together with Khorasan wheat, are usually less productive than bread and durum wheat (Stagnari et al. 2008; Vallega 1992).

Giunta et al. (2017b) demonstrated that old durum wheats are also suitable to dual-purpose utilization (herbage plus grain in the same season), which represents an attractive option to farmers as it presents the possibility of increasing economic returns by applying mixed farming systems typical of Mediterranean environments. Herbage can be grazed by animals, or mowed ('clipped') and wrapped in forage bales (haylage). On the one hand, grazing/haylage contributes to reducing the incidence of lodging (Christiansen et al., 1989) in old and ancient wheats (Giunta et al., 2017b); on the other, it helps to fill the gap in the seasonal supply of herbage to animals (Kelman and Dove 2009) during the most critical period (high animal demands due to lactation + low forage availability due to low temperatures).

Breeding has led modern wheat cultivars towards a common phenology well suited to high inputs and grain-only production. The lateness of old durum wheat cultivars and ancient wheat species contributes to making them suitable to dual-purpose utilization, because it is generally associated with high final leaf numbers (Giunta et al. 2015; Giunta et al. 2017a).

Grazing/clipping, usually carried out at the onset of stem elongation to avoid damaging the shoot apex (Giunta et al. 2015), affects the capture and use of radiation and water – two processes associated with each other due to their common dependence on leaf area development. Species differences in leaf area development and recovery after grazing/clipping are expected to result in varying levels of grain yield reduction as a consequence of their reduced leaf area. Leaf area governs growth by affecting i) the radiation interception capacity and the photosynthetic rate, and ii) water utilization due to its direct effect upon transpiration and the transpiration/evaporation ratio. The efficiency in the use of these resources, i.e. the amount of biomass produced per unit of water transpired (transpiration efficiency) and per unit of radiation intercepted by the crop (radiation use efficiency), are also physiologically associated (Sadras et al. 2016). Einkorn and emmer are two ancient species frequently studied in relation to their gene reservoir (Jaradat, 2019, and papers cited therein) and their agronomic and qualitative traits (De Vita et al. 2006; Longin et al. 2016; Stagnari et al. 2008; Vallega 1992), but much less so in relation to their ability to capture and use water and radiation at the crop level (Wang et al. 2017).

The suitability of three ancient wheat species – Khorasan, einkorn, and emmer – to both grain-only and dual-purpose utilization was evaluated in a cropping system characterized by low soil fertility and low-medium fertilization rates in a typical Mediterranean environment, and analysed in terms of resource use and capture, i.e. based on a framework that allows for an interpretation of the mechanisms through which leaf area development and removal influence grain yield. The old durum wheat cultivar Senatore Cappelli was also included in the experiment as a control species because it is suited to the same marginal environments.

2 Materials and methods

2.1 Experimental design

Two field trials were conducted in Sardinia, Italy, (Ottava, 41°N, 80 m above sea level) in the 2016/17 ('2016') and 2017/18 ('2017') seasons. The soil at this site consists of a sandy clay-loam over limestone (Xerochrepts). According to long-term data (past 60 years), the climate in Ottava is typically Mediterranean, with an annual rainfall of 552 ± 128 mm (mean ± standard deviation), mainly concentrated between October and April.

Four species of the genus *Triticum* were compared: einkorn (*T. monococcum* ssp. *monococcum,* cultivar Monlis and cultivar Norberto), emmer (*T. turgidum* ssp. *dicoccum* Schubler, cultivar Giovanni Paolo and cultivar Padre Pio), durum wheat (*T. turgidum* L. ssp. *durum* Desf., cultivar Senatore Cappelli), and Khorasan wheat (*T. turgidum* ssp. *turanicum*). The two emmer cultivars Giovanni Paolo and Padre Pio are modern emmer cultivars that were selected from the progenies of crosses between cultivated emmer and durum wheat with the aim of obtaining new emmer genotypes with improved agronomic and qualitative traits while preserving the functional properties of the landraces (De Vita et al., 2006). Giovanni Paolo was registered in the Italian Register of cultivars (emmer section) in 2008 and Padre Pio in 2016. The einkorn cultivars were extracted from local landraces and registered (einkorn section) in 2006 (Monlis) and 2017 (Norberto). The old durum wheat cultivar Senatore Cappelli (from here on 'Cappelli'), was selected from the North-African landrace Jean Retifah in 1914; it was the most diffusely cultivated cultivar in Italy in the first half of the twentieth century. It was included in the experiment as a control species (relative to the ancient species) since the same low-input cropping systems used for ancient species are generally applied to Cappelli cultivation, and because it is suited to the same marginal environments. Moreover, it has already been proven to be suited to dual-purpose utilization (Giunta et al., 2017b). All cultivars are classified as intermediate with regard to habitus, i.e. exposure to cold enhances but is not essential for their reproductive development (Connor et al., 2011).

Two adjacent fields were used in the two years. They were selected from the less fertile fields of the experimental farm.

They are characterized by the presence of an underlying layer of limestone at a depth of about 0.4–0.5 m, 45 kg ha^{-1} of mineral nitrogen, a soil organic matter content of 1.4 ± 0.3% a total $CaCO_3$ content of 40 ± 4.4%, and 8.4 ± 0.5 ppm available phosphorus.

Fields were prepared by chisel-ploughing to a depth of 0.25 m, followed by surface cultivation. Sowing was performed on October 25, 2016, in the first season and on October 26, 2017, in the second season at a rate of 200 germinable seeds per m^2. In both seasons, the preceding crop was faba bean. Plots consisted of 6 rows 8.4 m long, with a between row distance of 0.15 m, for a total area of 10 m^2.

At sowing, nitrogen and phosphorous were applied as ammonium bi-phosphate at the rate of 36 kg ha^{-1} of N and 92 kg ha^{-1} of P_2O_5. A second N application was made after clipping with 26 kg of N ha^{-1} in the form of ammonium nitrate. Weeds, pests, and diseases were chemically controlled.

Clipping was carried out using a lawn mower immediately after the detection of the terminal spikelet stage (‘clipped’ treatment), leaving an aboveground plant height that did not exceed 2 cm.

Treatments were arranged in a split-plot design with four replications. Cultivars were assigned to the main plots and the clipping treatment to the sub-plots.

2.2 Measurements and data analysis

Emergence, flag leaf appearance (DC39, Zadoks et al., 1974), anthesis (DC 61) and physiological maturity (DC 92) were recorded by periodical inspections of the plots when more than 50% of plants in the plot had reached that phenological stage. The onset of the terminal spikelet stage was ascertained by means of destructive sampling performed on five plants per plot every 3–4 days and defined as having occurred when more than 50% of the plants exhibited the terminal spikelet.

The number of leaves on the main stem was recorded on a set of five marked plants per plot every 3–4 days until the flag leaf had completely emerged.

In the first season, lodging incidence was assessed by visual evaluation of the proportion of lodged plants in each plot every 3–4 days from the beginning of March until May 16 and expressed as % of the plot area. In the second season, plots were completely lodged from the beginning of March.

Three biomass samplings were carried out at the stages: terminal spikelet, anthesis, and maturity; i.e. sampling occurred on different calendar dates according to the different rates of development of the cultivars compared.

Four 0.5 m linear meter samples per plot were hand-cut at ground level at each stage, for a total of 0.4 m^2. Anthesis and maturity samples were divided into stems+leaves (indicated as ‘stems’) and spikes, and the number of stem and spikes ascertained. All samples were oven-dried at 80 °C for 48 h before weighing.

Spikes from the maturity samples were threshed and grains of emmer and einkorn were de-hulled before weighing. Thousand grain weight and moisture content were determined. The harvest index was determined on the maturity samples and used to calculate the final biomass from the grain yield obtained on a plot basis with mechanical harvesting. Grain weight and grain yield were expressed at 0% humidity.

The fraction of intercepted photosynthetically active radiation was periodically measured from emergence until the plants’ flag leaves had turned yellow, for a total of 26 readings in the first season and 23 in the second. Measurements were made at noon using a portable probe (Sun-Scan Canopy Analysis System SS1-UM-1.05. Delta-T Devices Ltd., Burwell, Cambridge, UK) allowing the simultaneous measurement of photosynthetically active radiation above (using an external sensor) and below (using the probe) the canopy. An indirect estimate of the leaf area index was obtained with this same instrument. The probe was placed parallel to the soil surface at right angles to the row direction. It was positioned at ground level in the first samplings, but thereafter at an increasing height from the soil, in order to be always above any dead leaves.

Weather data (maximum and minimum temperature, rainfall, solar radiation, and air relative humidity) were recorded in meteorological stations located approx. 300 m from the fields.

The fraction of intercepted solar radiation was calculated as:

Fraction of intercepted solar radiation = $1\text{-}e^{(-K_{SOL}*\text{leaf area index})}$,

where K_{SOL} (extinction coefficient for solar radiation) was calculated, according to Stöckle and Kemanian (2013), as:

$$K_{SOL} = 0.62 * {K_{PAR}}^{0.86}$$

and the K_{PAR} (extinction coefficient for photosynthetically active radiation) of each plot was calculated as:

K_{PAR} = −[LN(1-fraction of intercepted photosynthetically active radiation)] /leaf area index.

Cumulative intercepted solar radiation (MJ m^{-2}) was calculated as the sum of the daily values of intercepted radiation obtained by multiplying the daily fraction of intercepted solar radiation (obtained by linear interpolation of the measured data) by the daily values of solar radiation recorded at the meteorological station of the experimental station.

Weather data were used to calculate reference evapotranspiration for each season, crop evaporation, crop transpiration, and the soil water balance for each plot, according to the dual crop coefficient method under soil water stress conditions as proposed by Allen et al. (1998). The daily fraction of extractable water for the first 0–0.7 m soil layer was then calculated as (soil water content – soil water content at the permanent wilting point)/available soil water. The volumetric soil water content at the permanent wilting point was 14.8%, and the available soil water was 20.8%.

Daily fraction of intercepted solar radiation values and daily plant height data (obtained by linear interpolation of recorded data) were used to evaluate the effects of clipping and to partition evapotranspiration into evaporation and transpiration.

Radiation use efficiency (g MJ^{-1}) was calculated as the ratios between biomass and cumulative intercepted solar radiation, whereas transpiration efficiency (g m^{-2} mm^{-1}) was calculated as the ratio between biomass and water transpired, between emergence and clipping, and between emergence and anthesis.

After assessing the homogeneity of variances by means of the Bartlett Test, a combined analysis of variance (ANOVA) was performed superimposing the year as main plot on the original design. The resulting split-split-plot design is an extension of the split-plot design, usually adopted to accommodate a third factor (Gomez and Gomez, 1984). Year was the whole plot factor (A), cultivar was the sub plot factor (B), and clipping treatment the sub-sub plot factor (C). Error (a) (Block x A) was used to test the significance of A; error (b) (Block x B(A)) was used to test A and A x B; error (c) (Block x C x (A X B)) was used to test C, A x C, B x C and A x B x C. Statistical analysis were conducted using the R software (R Core Team, 2014), package 'agricolae', ssp.plot procedure. Following a significant F test, means were compared through the least significant difference (LSD) test considering a 0.05 probability level, calculated using the appropriate standard errors of the mean and t values (Gomez and Gomez, 1998). The Pearson's correlation coefficient was calculated to evaluate the existence of any causal relationships between pair of traits.

3 Results and discussion

Although the small set of cultivars within each species cannot adequately represent the variability existing within each of the four species compared – ancient wheats in particular (Jaradat, 2019) – we were interested in understanding whether their combinations of traits were suitable to dual-purpose utilization in low-input, marginal areas of a Mediterranean environment. In this regard, ancient wheats may exhibit noteworthy combinations of traits, derived from their adaptation to a wide range of 'low-input' environments and to variable growing seasons that distinguished their domestication (Jaradat 2019).

The environmental conditions under which this set of species was grown combined low soil fertility – a pre-requisite to consider ancient wheats and old cultivars as possible options (Giunta et al., 2019b) – and two seasons that were extreme and opposite in rainfall amount and distribution (Fig. 1).

Only 311 mm of rain fell in 2016, equivalent to just 40% the amount recorded for 2017. The probability of a seasonal rainfall lower than 311 mm – calculated from the normal distribution of rainfall at the same site over the past 60 years – is 7%, and the probability of a seasonal rainfall exceeding 785 mm is even lower, at just 2%. In 2016, the fraction of extractable water of the soil decreased rapidly from February 10, such that it was less than 25% during the anthesis of most cultivars. On the contrary, in 2017, the fraction of the soil's extractable water fell to a minimum of 47% for a short period coinciding with anthesis or the days preceding anthesis in all cultivars except for the two einkorn cultivars. With the exception of January, the mean monthly temperatures for the first five months after emergence were higher in 2016, with the greatest differences recorded in November (17.5 °C in 2016 vs 13.2 °C in 2017) and February (12.5 °C in 2016 vs 9.3 °C in 2017).

The set of species and cultivars compared performed very differently because of their profound genetic, morphological, and physiological differences, of which the phenological differences had the greatest impact. The key role of phenology for the dual-purpose use of cereals in this type of environment has been thoroughly discussed (Giunta et al., 2015, 2017a and 2017b).

Clipping was carried out once the terminal spikelet stage had been reached, because at this stage the apex starts to emerge from the soil surface and can be damaged by grazing (Giunta et al., 2015). The differences between cultivars in time to terminal spikelet appearance were large (Fig. 2). In both years, the earliest times of terminal spikelet onset were observed in Cappelli, Khorasan wheat, and Giovanni Paolo (59–72 days from sowing), and the latest in the two einkorn cultivars, Monlis and Norberto (119–138 days after sowing). Terminal spikelet appearance of the emmer cultivar Padre Pio was intermediate (92 days after sowing in both years). Coherent with this variation in time to terminal spikelet appearance, einkorn cultivars tillered more profusely (data not shown), and their leaf number at terminal spikelet stage was the highest, i.e. 10.7 on average, against 6.4 in Cappelli and Khorasan wheat, and 7.9 in the emmer cultivars. The higher number of tillers in the two einkorn cultivars derived from both their longer time to terminal spikelet and their higher rate of tillering, with maximum mean values of 7.2 tillers per leaf in 2016, and 5.9 tillers per leaf in 2017 in the cultivar Monlis, against minimum mean values of 0.14 tillers per leaf in the cultivar Khorasan in 2016, and 0.80 tillers per leaf in the cultivar Cappelli in 2017 (data not shown). This profuse tillering was the reason behind the high values obtained for the leaf area index and the fraction of intercepted radiation in einkorn cultivars at the terminal spikelet stage (Tab. 1), although genotypic differences in leaf area index and fraction of intercepted radiation were less than expected based on

Fig. 1 The experimental field in 2016 after the clipping treatment

tillering alone; this is because the einkorn cultivars were characterized by very small leaves (data not shown).

3.1 Biomass yield at clipping

The absence of abiotic stress up to the terminal spikelet stage– a common situation in this type of environment – allowed crops to acquire radiation and water without limitation, and led to similar biomass yields at clipping in the two seasons (1.6 t ha^{-1}). On average, the biomass yields of all cultivars were within the range of those quoted in the literature for dual-purpose cereals (Giunta et al. 2017 a and b; Tian et al. 2012), including those for emmer and einkorn – two species for which no data are available on dual-purpose utilization.

Einkorn cultivars produced the highest biomass at clipping in both seasons because the late onset of the terminal spikelet stage meant a longer growing period and double the radiation available in 2016 (928 MJ m^{-2} vs 446 MJ m^{-2} the latter being the average of the other four cultivars) and more than double in 2017 (1193 MJ m^{-2} vs 558 MJ m^{-2} again, the latter being the average of the other four cultivars). As a consequence, by terminal spikelet appearance, einkorn cultivars had cumulated the greatest amount of intercepted radiation, and evapotranspired the greatest amount of water (twice the amount of water used by the other species in 2017). Therefore, the variation in time to terminal spikelet was the main cause of the genotypic variation in biomass yield observed in the two seasons ($r = 0.83^{**}$, $n = 12$), and biomass yield was associated to the capture of water ($r = 0.66^{*}$ between biomass and transpiration) and radiation ($r = 0.58^{*}$ between biomass and cumulative intercepted solar radiation). A negative association was also found between leaf area index, and the proportion of evaporation over total evapotranspiration ($r = -0.77^{**}$, $n = 12$), i.e. the cultivars with the highest leaf area index and fraction of intercepted radiation lost a smaller proportion of water by evaporation. This result highlights the key role of leaf area development in determining the partition between the net radiation used for evaporation and for transpiration (Connor et al. 2011). Monlis was the least efficient cultivar in 2016, and Giovanni Paolo was the least efficient in 2017, whereas durum and Khorasan wheats exhibited the joint highest efficiencies in both years.

Thus, the genotypic variation in time to terminal spikelet appearance was so great that it cancelled out any other difference associated with the ability to capture radiation (e.g. number of leaves, number of tillers, growth habit), whereas the genotypic variability in water and radiation use efficiency were not relevant for biomass production by the terminal spikelet stage. This explains why cultivar x year interaction was not observed for biomass at clipping in spite of significant interaction for almost all the traits associated with capture and use of resources.

Similar results were reported by Giunta et al. (2017a) following the comparison of a spring and an intermediate triticale cultivar. It is worth mentioning that the lateness of einkorn cultivars responsible for their high biomass yield implied that the grazing period for these species could last until mid-February/the beginning of March (for an October sowing).

3.2 Clipping and leaf area recovery

Suitability to dual-purpose utilization can be evaluated by considering both the biomass and the grain yield, together with the extent of the reduction in grain yield brought about by grazing, since dual-purpose use can be a convenient management option if grain yield is not significantly reduced (Harrison et al. 2011). The most critical aspect in determining the impact of clipping on grain yield is the ability of crops to recover their leaf area and photosynthetic activity after clipping. In this experiment, clipping differentially affected the ability of crops to intercept radiation via its effects on phenology, plant height, and lodging incidence.

The final plant height ranged from 60 to 80 cm for the einkorn cultivars, from 100 to 120 cm for the emmer cultivars, and from 160 to 170 cm for durum and Khorasan wheats. Fig. 3 In the latter two species, clipped plots were constantly and significantly shorter than unclipped ones by about 20 cm.

This effect of clipping on plant height was probably responsible for the halved lodging incidence observed in cultivars Cappelli and Khorasan wheat across the whole 2016 season. In this year, the lodging incidences were maximal (40–45%) in mid-May in the unclipped plots of cultivars Cappelli and Khorasan wheat, whereas emmer and einkorn never surpassed 10% of lodging at any point in either the clipped or unclipped plots. On the other hand, the exceptionally high rainfall in 2017 caused all the cultivars to exhibit complete lodging from March onwards. Lodging represents a serious limit to the production of high yields in old, tall cultivars and in ancient wheats. The reduced lodging observed in 2016 in Cappelli and Khorasan wheat following clipping

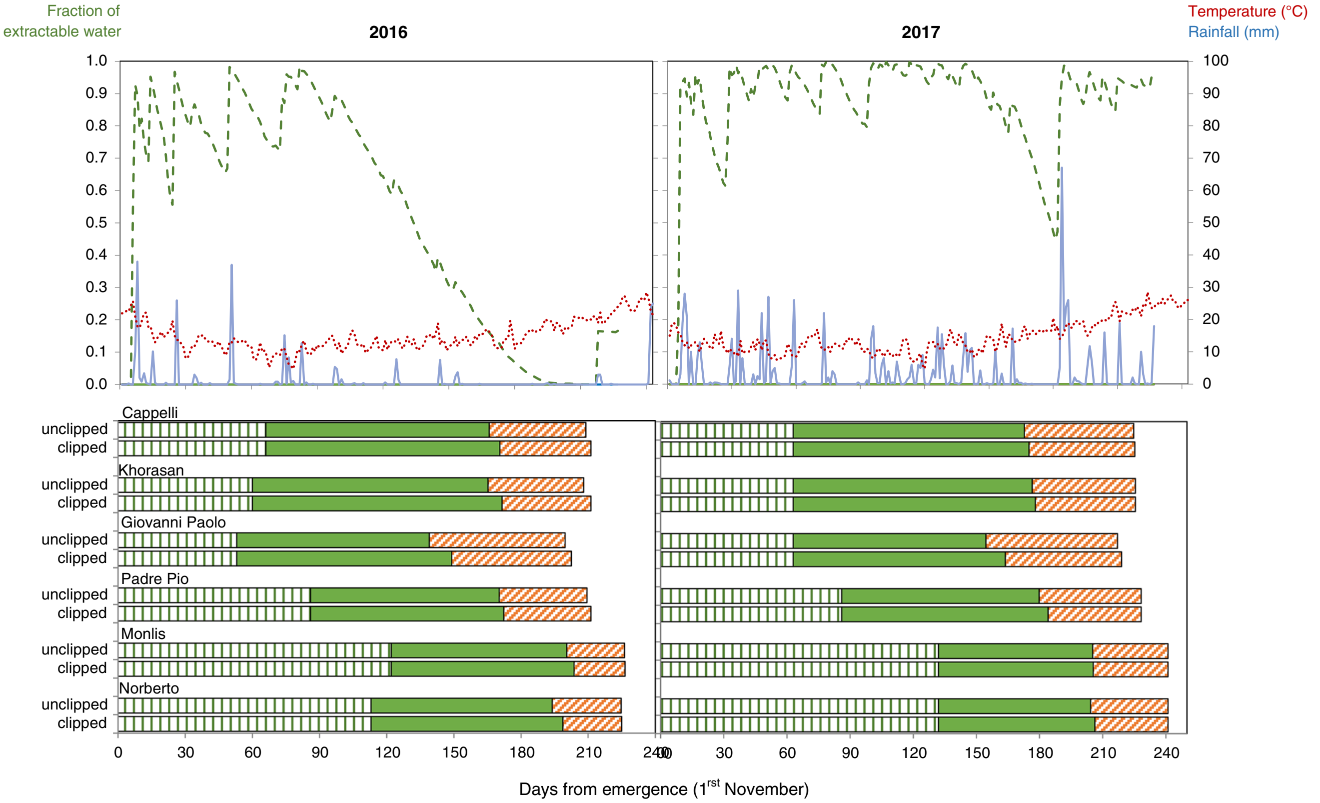

Fig. 2 Weather and phenology for 2016 (left side) and 2017 (right side) from emergence (November 1) to maturity. Upper panels: rainfall (blue solid lines), mean air temperature (dark orange punctuated line) and fraction of extractable water (green dashed line). Lower panels: time from emergence to terminal spikelet (bars filled with green vertical lines), time from terminal spikelet to anthesis (solid green bars), and from anthesis to maturity (bars filled with orange diagonal lines) for the clipped and unclipped treatments of the six cultivars

suggests that dual-purpose utilization could help minimize the reductions in grain yield brought about by lodging in species susceptible to this phenomenon (Berry et al. 2004). On the other hand, this advantage was strongly weather dependent, in accordance with Giunta et al. (2017b), and would most likely be lost in extremely rainy years, such as occurred in the 2017 season.

The occurrence of early and complete lodging in 2017 was responsible for the lower fraction of intercepted radiation recorded in this year (maximum values around 70–80%) compared with the previous year, when all cultivars showed maximal values for the fraction of intercepted radiation around 90% Fig. 4. Einkorn cultivars showed the lowest maximum fraction of intercepted radiations in 2017 (68–70%), but thanks to their lateness and to the late rainfall in this year, they were able to prolong the period of radiation interception by about one month in comparison with that achieved by the other species.

Clipping reduced the fraction of intercepted radiation to 15–50% of the unclipped treatment, depending on the cultivar and the season, but all cultivars were able to recover their ability to intercept radiation after clipping to the levels of the unclipped treatments well before anthesis in both years studied. This happened in spite of the large differences in the environmental conditions pertaining to the recovery period created by the different developmental rates. Specifically, the late terminal spikelet stage in einkorn cultivars in the 2016 season caused their terminal spikelet-anthesis period to occur in an almost totally dry period, with a fraction of extractable water that rapidly fell from 90 to 10%; similarly, in 2017 the late terminal spikelet stage again resulted in the plants being subjected to water stress, albeit temporary Fig. 2. We can hypothesise that einkorn cultivars were able to cope with this water stress in such a critical period thanks to a presumed vigorous root system that the late development of the terminal spikelet would have permitted the plants to develop. In fact, this late terminal spikelet stage was associated with a high number of leaves and tillers, and it is known that the development of leaves and root axes are integrated processes for both the main stem and tillers (Gregory, 1994); i.e. the number of roots axes is associated with the number of leaves and shoots. Moreover, a high root:shoot ratio has been reported for this species (Wang et al. 2017) which could have exerted a positive effect on their ability to recover leaf area under such severe water stress conditions.

In 2017, cultivars Khorasan and Padre Pio showed the slowest leaf area recovery rates. As a consequence, the clipped plots intercepted 214 and 184 MJ m^{-2} less radiation than their

Table 1 Clipping sampling. Biomass yield, capture and efficiency in the use of water and radiation and related traits. Results of the ANOVA. Cultivar means sharing the same letter within each season do not differ significantly from one another (LSD Test at $P \leq 0.05$)

	Clipped biomass ($t\ ha^{-1}$)	Leaves emerged (n°)	Leaf Area Index	Fraction of intercepted radiation (%)	Cumulated intercepted radiation ($MJ\ m^{-2}$)	Radiation use-efficiency ($g\ MJ^{-1}$)	Cumulated evapo-transpiration (mm)	Cumulated transpiration (mm)	Transpiration efficiency ($g\ m^{-2}\ mm^{-1}$)
Year (Y)	ns	*	*	**	**	*	ns	**	*
Cultivar (C)	***	***	**	***	***	ns	***	***	*
Y x C	ns	*	**	***	***	*	*	**	ns
2016									
Cappelli	1.43 cd	5.9 f	2.27 be	0.86 a	216 c	0.69 be	106 c	46 bc	3.2 ce
Khorasan	1.37 cd	6.7 ef	2.34 be	0.81 a	182 cd	0.78 ad	98 cd	39 cd	3.7 bd
G.Paolo	0.92 de	6.5 ef	1.81 cf	0.66 bc	133 de	0.69 be	87 de	28 df	3.1 ce
Padre Pio	1.42 cd	7.9 cd	3.10 b	0.87 a	284 b	0.51 de	108 c	41 c	3.8 bd
Monlis	1.49 cd	11.6 a	2.77 bd	0.81 ab	424 a	0.36 e	185 a	91 a	1.5 e
Norberto	2.72 a	9.1 bc	4.63 a	0.89 a	415 a	0.64 ce	168 b	87 a	3.0 ce
2017									
Cappelli	1.13 de	5.9 f	1.20 df	0.59 cd	124 e	0.89 ac	82 e	22 ef	4.9 ac
Khorasan	1.05 de	6.0 f	0.77 f	0.45 e	95 e	1.11 a	82 e	18 f	5.7 a
G.Paolo	0.66 e	7.6 de	0.95 f	0.53 de	131 de	0.45 de	82 e	24 ef	2.4 de
Padre Pio	1.88 bc	9.4 b	3.10 bc	0.90 a	186 cd	0.99 ac	108 c	34 ce	5.3 ab
Monlis	2.47 ab	11.3 a	1.36 df	0.55 ce	231 c	1.05 ab	179 ab	55 b	4.4 ad
Norberto	2.55 ab	11.1 a	1.06 ef	0.51 de	232 c	1.11 a	179 ab	55 b	4.7 ac

respective unclipped plots during the recovery period, compared with 38–82 MJ m^{-2} calculated for the other cultivars. In 2016, the decrease in interception following clipping ranged from about 80 MJ m^{-2}, in Giovanni Paolo and Monlis, to 115 MJ m^{-2} in Cappelli and Khorasan wheat, and 155 and 178 MJ m^{-2}, in Norberto and Padre Pio, respectively.

Across the two seasons, the number of leaves emerged after clipping correlated with the final leaf number ($r = 0.60^*$, $n = 12$) in agreement with the findings reported by Jamieson et al. (2007), and ranged between 5.4 and 8.3 for all the cultivars, with the exception of the emmer species, that produced the lowest number of leaves after clipping (3–5.3). A high number of leaves emerging after clipping might have contributed to the rapid recovery of leaf area, as already discussed in relation to Cappelli and triticale (Giunta et al., 2017a and 2017b). A high final leaf number is a desirable trait under dual-purpose systems because it implies a high number of leaves and tillers at the terminal spikelet stage, i.e. high biomass production, and a high number of leaves left to emerge after terminal spikelet, meaning a good recovery capacity following grazing (Giunta et al., 2015; Giunta et al., 2017).

3.3 Anthesis

Anthesis is a critical period for the establishment of grain yield. This is due to its susceptibility to environmental stresses and to its critical role in the determination of grain number (Fischer 2011). In the case of dual-purpose utilization, the biomass accumulated by anthesis is expected to decrease as a consequence of the defoliation carried on by the terminal spikelet stage and of the consequent reduced amount of radiation intercepted. Therefore, the biomass produced by anthesis quantifies the magnitude of the negative consequences of clipping on the ability of crops to capture and use resources.

Clipping delayed anthesis by an average of 6 days in 2016 and an average of 3 days in 2017, but a larger delay (10 days in 2016 and 9 days in 2017) was observed in the emmer cultivar Giovanni Paolo compared with the other cultivars (Fig. 2). The mean anthesis date was April 26 in 2016 and May 4 in 2017. The earliest anthesis was observed in the emmer cultivar Giovanni Paolo, and the latest in the einkorn cultivar Monlis.

Old durum wheat cultivars, such as Cappelli, are later than modern cultivars (Motzo and Giunta 2007), and in Mediterranean environments they generally flower in the first week of May, which is outside the optimal window (which is the month of April), at least when sown in November–December (the most common sowing window for grain crops). Sowing crops earlier than usual is common practice with dual-purpose cereals as it improves crop establishment and enhances early vigour due to warmer autumn temperatures (Harrison et al., 2011). The early sowing (October) adopted anticipated the anthesis of the durum wheat

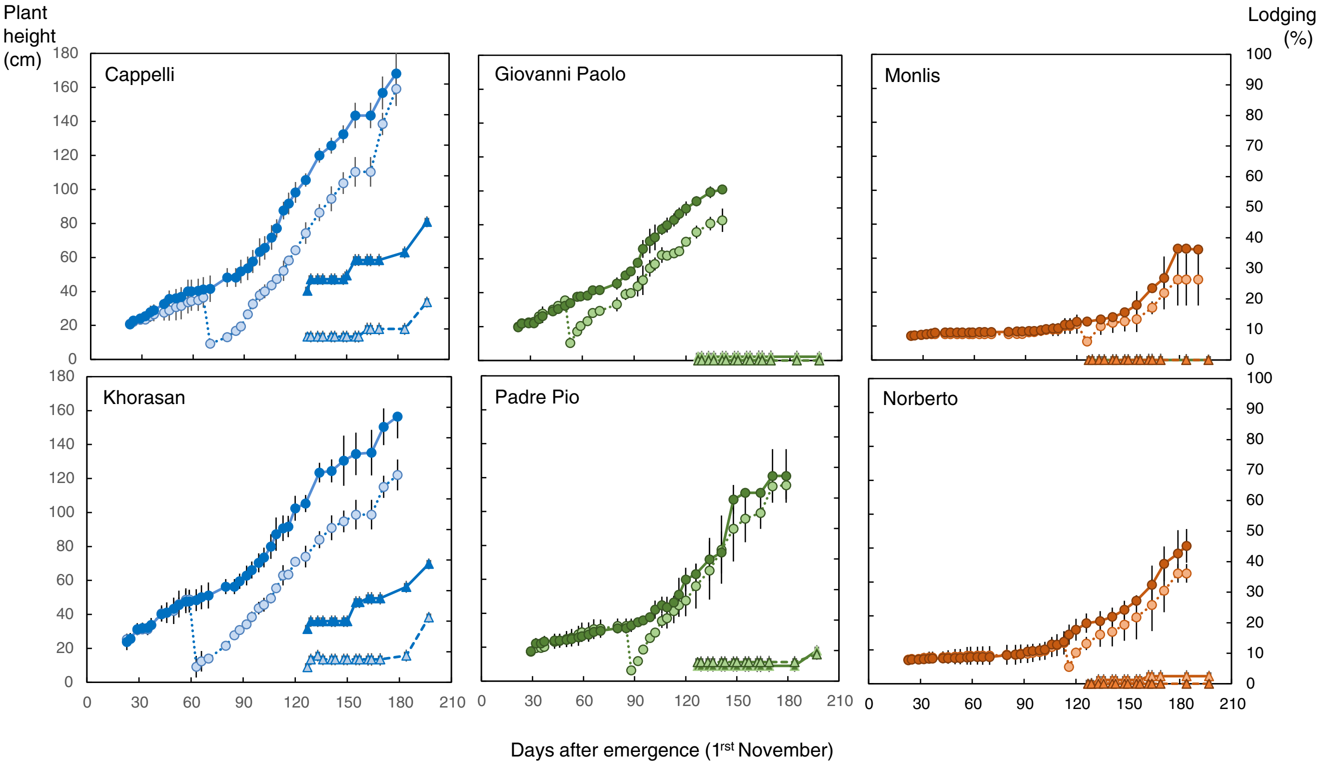

Fig. 3 Plant height (circles) and lodging incidence (triangles) in 2016 for the six cultivars and the clipped (dark coloured symbols), and unclipped treatments (light coloured symbols). Durum and Khorasan wheats in blue, emmer cultivars in green and einkorn cultivars in orange. Data are means ± standard errors

Cappelli to the month of April, despite the delay induced by clipping, as also shown by Giunta et al. (2017b) for this cultivar. The emmer cultivar Padre Pio had a similar phenology to durum and Khorasan wheats, and flowered in April or the first days of May in spite of the delay in anthesis caused by clipping. On the other hand, the extreme earliness of the other emmer cultivar, Giovanni Paolo, benefited from the largest delay (9–10 days) in anthesis induced by clipping, that moved this delicate phenophase to a period with a lower risk of late frosts. The remarkable late flowering of the two einkorn cultivars used in this experiment was in line with that observed by others (Vallega, 1992) and can be attributed to their high cold requirements. Their anthesis was even later following clipping, in spite of the October sowing, and resulted in grain filling taking place in the month of June, characterized by a long-term average rainfall (past 60 years, same location) of 18 ± 18 mm (mean ± standard deviation), but that was uncharacteristically rainy in the two seasons considered here (56 mm in 2016 and 37 mm in 2017), a situation that reduced the negative effects of the late anthesis.

The delay in anthesis partly compensated for the lower radiation interception after clipping by guaranteeing supplemental days of interception in a period with high incident solar radiation, such that a minimal reduction in radiation interception was associated with clipping (an average of 6% considering all cultivars), and Giovanni Paolo, the cultivar with the greatest delay in anthesis intercepted more radiation in the clipped than in the unclipped treatment (Table 2). Similar results were obtained for transpiration.

In spite of this almost unaffected capacity to capture resources, clipping caused an overall reduction in the amount of biomass produced by anthesis affecting both radiation use-efficiency (−21% on average) and transpiration efficiency (−25% on average).

Cultivars reacted differently to clipping, as highlighted by the significant cultivar x clipping interaction whereas no significant year x cultivar x clipping interaction was found. The cultivars displaying the greatest % reduction in total biomass were Giovanni Paolo (−43%) and Khorasan wheat (−39%). By contrast, Monlis did not show any reduction in biomass due to clipping. This was partly because it was the only cultivar (together with Padre Pio), whose efficiencies were not affected by clipping. When the cultivars were considered individually, the genotypic variation in the reduction in radiation use efficiency following clipping strongly correlated with the reduction in transpiration efficiency ($r = 0.99^{***}$, $n = 6$). This was due to the strong relationship between radiation and transpiration efficiency, as discussed by Sadras et al. (2016). This result contrasts with those by Harrison et al. (2011), and by Giunta et al. (2017a and b) who attributed the reduced biomass of cultivar Cappelli and triticale following clipping to a hampered capture of

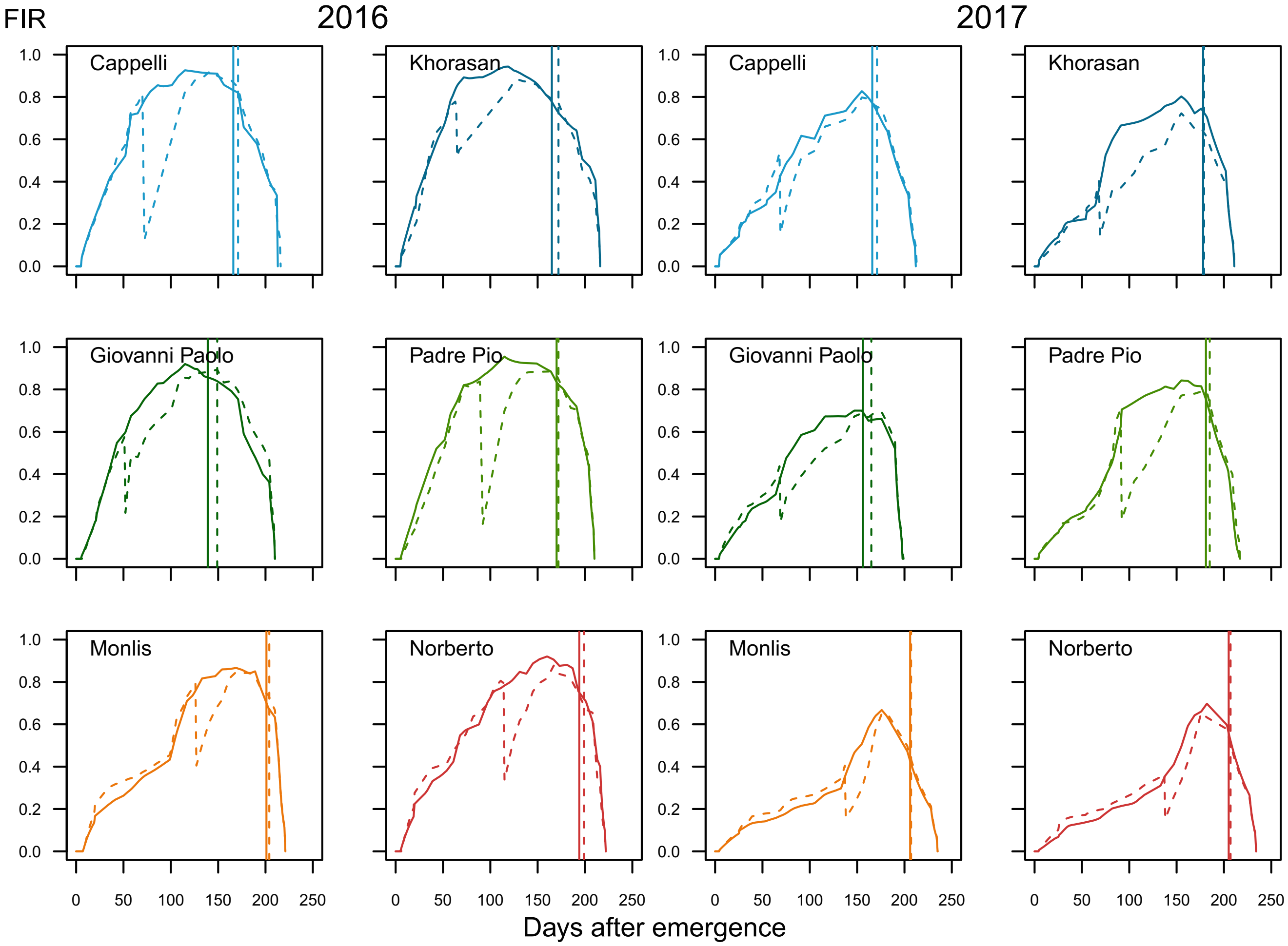

Fig. 4 Fraction of intercepted radiation (FIR) vs days after emergence for unclipped (solid curves) and clipped treatments (dashed curves) for the six cultivars in 2016 (left side) and 2017 (right side). Anthesis date; unclipped, solid vertical line; clipped dashed vertical line

resources at similar levels of efficiency in their use. Nitrogen nutrition is critical for determining the involvement of radiation use-efficiency (Sinclair and Horie 1989). In the case of the 2016 season, this suggests a possible effect of clipping on radiation use-efficiency, despite the application of the second nitrogen fertilization just after clipping, due to a decreased leaf nitrogen content mediated by the early and remarkable water stress characterizing this season. In the case of 2017, the radiation use-efficiency, already penalized by the total lodging of the crops (Berry et al., 2004), may have been further hampered by the presumably high level of nitrogen leaching resulting from the abundant rainfall. Of course, clipped crops are more dependent on soil nitrogen availability than unclipped ones, because they cannot translocate the nitrogen assimilated before clipping during leaf area recovery. The lower transpiration efficiency by anthesis following clipping, being calculated on transpiration, was not a consequence of the small increase in the proportion of water lost by evaporation over total evapotranspiration (data not shown). Instead, it derived from the leaf area index being lower than 4 after clipping, which was more limiting for biomass production than for evapotranspiration (Giunta et al. 2017a).

Monlis was the only cultivar to react to clipping by a significantly increasing tiller number (by 36%), and this contributes to explaining why its total biomass was less affected by clipping than the that of the other cultivars. Monlis and Padre Pio were also the only cultivars for which the dry matter allocated to spikes m^{-2} – a trait associated with grain number determination (Fischer 2011) – was not affected by clipping.

3.4 Grain yield

In contrast with anthesis data, the cultivar x clipping interactions of the traits recorded at harvest were not generally significant, as revealed by ANOVA; hence only the main effect of clipping, and the significant cultivar x year interactions are presented and discussed (Table 3).

Table 2 Anthesis sampling

	Total biomass (t ha^{-1})		Spike biomass (t ha^{-1})		Stems per unit surface (n m^{-2})		Cumulated intercepted radiation (MJ m^{-2})		Radiation use-efficiency (g MJ^{-1})		Cumulated transpiration (mm)		Transpiration efficiency (g m^{-2} mm^{-1})	
Year (Y)	*		ns		*		**		**		ns		***	
Cultivar (C)	**		***		***		***		***		***		***	
Y x C	**		***		***		***		**		ns		**	
Clipping (Cl)	***		**		***		**		***		**		***	
Cl x Y	***		ns		***		ns		**		ns		**	
C x Cl	***		*		***		*		***		*		***	
C x Cl x Y	ns		ns		ns		ns		ns		ns		ns	
	Unclipped	Clipped	Unclipped	Clipped	Unclipped	Clipped	Unclipped	Clipped	Unclipped	Clipped	Unclipped	Clipped	Unclipped	Clipped
Mean	*16.3*	*12.0*	*1.9*	*1.6*	*566*	*585*	*1260*	*1181*	*1.35*	*1.06*	*218*	*210*	*7.6*	*5.7*
Cappelli	19.3	14.4	1.7	1.5	360	329	1241	1202	1.56	1.20	224	218	8.7	6.6
Khorasan	19.1	11.6	2.0	1.4	299	221	1304	1182	1.49	1.03	230	217	8.3	5.4
Giovanni Paolo	14.3	8.2	1.8	1.4	464	446	812	850	1.75	0.96	160	163	9.0	5.0
Padre Pio	16.4	14.1	2.2	2.3	635	568	1397	1199	1.18	1.22	245	220	6.8	6.5
Monlis	12.9	13.4	2.0	2.1	835	1138	1384	1319	0.99	1.11	212	215	6.1	6.3
Norberto	15.6	10.0	1.8	1.2	803	809	1422	1334	1.11	0.82	237	226	6.5	4.4
$LSD_{0.05}$	*2.0*		*0.3*		*108*		*114*		*0.21*		*15*		*1.0*	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Mean	*15.2*	*13.1*	*1.7*	*1.9*	*579*	*570*	*1433*	*994*	*1.11*	*1.31*	*215*	*212*	*7.1*	*6.2*
Cappelli	19.1	15.2	1.6	1.6	352	339	1341	1120	1.43	1.36	221	221	8.6	6.9
Khorasan	14.4	17.1	1.2	2.3	271	254	1391	1081	1.04	1.56	229	217	6.3	7.8
Giovanni Paolo	13.3	9.3	1.5	1.7	399	520	919	727	1.47	1.28	168	154	8.1	6.0
Padre Pio	15.8	14.7	2.0	2.5	594	603	1423	1177	1.11	1.28	225	237	7.0	6.3
Monlis	14.6	11.5	2.3	1.7	975	975	1742	902	0.84	1.28	212	216	6.9	5.3
Norberto	14.1	10.7	1.5	1.4	881	732	1786	957	0.78	1.11	235	226	5.9	4.7
$LSD_{0.05}$	*2.1*		-		*109*		-		*0.24*		-		*1.1*	

Total biomass, capture, and efficiency in the use of water and radiation and related traits. Results of the ANOVA (ns, not significant; *, significant at $P \leq 0.05$; **, significant at $P \leq 0.01$; ***, significant at $P \leq 0.001$;). Cultivar × treatment and cultivar × year means and LSD ($P \leq 0.05$) for the comparison of means

Grain yield was not reduced by clipping because the reduction in biomass following clipping was associated with an increased harvest index, suggesting that clipped crops were disadvantaged to a lesser extent than unclipped crops by the severe water stress during grain filling. According to Winter and Musik (1991), the threshold level of terminal drought below which grain yield is not negatively affected by clipping corresponds with a transpiration / reference evapotranspiration value of 0.18. In this experiment, the mean transpiration / reference evapotranspiration was 0.007 for 2016, and 0.008 for 2017, values well below this threshold.

The lack of any reduction in grain yield after clipping was expected assuming the reduction to be proportional to the attainable grain yield level (Harrison et al. 2011), and irrelevant for grain yield levels around 1.85 t ha^{-1} (Giunta et al., 2017b). Adding the data from this experiment to those presented by Giunta and colleagues (Fig. 5) produced an updated grain yield threshold value below which clipping has a positive effect on cereal grain yields, 1.80 t ha^{-1}.

Most of our crops were close to this value, with the exception of the two einkorn cultivars that, in 2017, were able to produce the same grain yield in clipped and unclipped plots in spite of an attainable yield well above the threshold (around 4 t ha^{-1}): a performance made possible only by the heavy and prolonged rainfall of this year, given the extreme lateness of these cultivars.

The lack of any effect of clipping on grain yield and of a genotype x clipping interaction means that the best species/cultivars for dual-purpose utilizations are also the best for grain-only, at least at the low grain yield levels characterizing the marginal areas of Mediterranean environments. The potential of einkorn wheats under the unusual rainfall pattern of 2017 was mainly associated with their ability to combine a good biomass yield and the greatest grain yield thanks to a particularly high number of grains m^{-2}. More than 12,000 grains m^{-2} were produced by the einkorn cultivars Monlis and Norberto, compared with an average of 5390, for the other four cultivars. The combination of the highest fruiting efficiencies and number of spikes per unit surface was the reason for the high numbers of grains m^{-2} of the einkorn cultivars in both 2016 and 2017. The high number of grains m^{-2} of these cultivars resulted in high grain yields despite its association with very low grain weights, partly deriving

Table 3 Maturity sampling. Grain yield and its components. Results of ANOVA (ns, not significant; *, significant at $P \leq 0.05$; **, significant at $P \leq 0.01$; ***, significant at $P \leq 0.001$). LSD ($P \leq 0.05$) for the comparison of year x cultivar means

	Grain yield (t ha^{-1})	Above ground biomass (t ha^{-1})	Harvest Index	Grain weight (mg)	Grains per unit surface (n m^{-2})	Spikes m^{-2} (n m^{-2})	Fruiting efficiency (n° of grains g spike^{-1})
Year (Y)	**	ns	**	ns	**	ns	***
Cultivar (C)	**	**	**	***	***	***	***
Y x C	**	***	ns	***	ns	ns	**
Clipping (Cl)	ns	***	*	ns	ns	ns	ns
Cl x Y	ns	***	ns	ns	ns	ns	ns
C x Cl	ns	ns	ns	ns	ns	ns	**
C x Cl x Y	ns	ns	ns	ns	ns	ns	ns
2016							
Cappelli	2.3	17.0	0.14	54.2	4293	238	28.6
Kamut	1.6	13.7	0.09	59.2	2838	177	22.4
Giovanni Paolo	2.2	13.5	0.16	51.4	4387	322	29.9
Padre Pio	2.7	15.9	0.17	47.3	5655	424	29.7
Monlis	2.2	12.7	0.19	18.2	12,032	898	53.3
Norberto	1.9	14.9	0.13	21.5	8870	679	66.1
2017							
Cappelli	2.2	12.8	0.13	42.6	5094	243	30.9
Kamut	2.6	15.1	0.18	47.7	5817	201	28.0
Giovanni Paolo	2.6	9.4	0.27	49.1	5311	313	34.9
Padre Pio	2.2	12.9	0.17	41.2	5339	327	20.8
Monlis	4.3	16.2	0.27	27.8	15,494	768	92.7
Norberto	3.8	15.8	0.24	30.9	12,374	646	91.7
$LSD_{0.05}$	***0.7***	***2.4***	***0.05***	***6.0***	***2042***	***91***	***15.5***

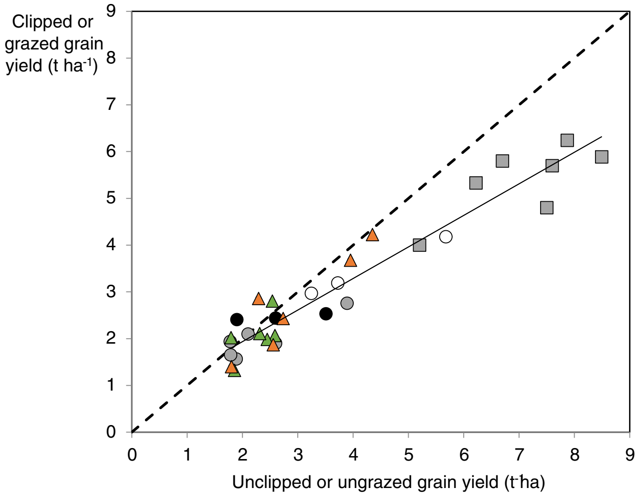

Fig. 5 Grain yield relationship of grazed/clipped and ungrazed/unclipped treatments for ancient and old wheats in this experiment (triangles, green symbols 2016; orange symbols 2017) and various cereals from other studies: empty circles, Cappelli in Giunta et al. (2017b); filled circles, tall bread wheat in Christiansen et al. (1989); grey circle, semi-dwarf bread wheat in Edwards et al. (2011), Zhu et al. (2004) and Frischke et al. (2015); grey squares, triticale in Giunta et al. (2017a) and Royo et al. (1999). $y = 0.675x + 0.5862$ $R^2 = 0.92$***

from the genetically low potential grain weight of einkorn (Castagna et al., 1995), partly originating from the negative relationship between yield components. Much of the einkorn cultivars' superiority was due to their lateness, which did not hamper their grain yield as a result of the abundant and prolonged rainfall in 2017. Giunta et al. (2017a) highlighted that the good winter forage production of the late semi-winter or intermediate triticales (with quantitative vernalization requirements) is generally associated with low grain yields because of their susceptibility to terminal water stress. On the other hand, the above-mentioned capacity of the einkorn cultivars to cope with drought, as demonstrated in 2016, permits us to hypothesise that they would be able to combine a good biomass yield with a grain yield comparable to the grain yields obtained by the other species, even under terminal drought and in spite of their lateness.

By contrast, the early drought of 2016 highlighted the scarce ability of Khorasan wheat to produce adequate grain yields under this kind of stress compared with the other cultivars. Its low grain yield (the lowest of all cultivars) was likely the result of its poor tillering capacity that was further impeded by the drought during stem elongation (Fig. 2), resulting in the lowest number of spikes m^{-2} and hence, as a consequence, in the lowest number of grains m^{-2} (Tab. 3) with respect to all the other cultivars. According to Blum and Pnuel, (1990), the main yield component responsible for grain yield reduction as a result of moisture stress during stem elongation is spike number per unit surface, which is affected by tiller survival rate.

4 Conclusions

The present study showed that species never previously considered for their suitability to dual-purpose utilization–emmer and einkorn – were in fact highly suited to it. This was because the early sowing adopted for dual-purpose utilization allowed the crops to take full advantage of their lateness in terms of biomass yield, and to bring flowering forward (i.e. making it earlier) so that a satisfactory grain yield was obtained even under severe water stress. The combination of the remarkable lateness and high fruiting efficiency found in the two einkorn cultivars is particularly interesting for the cropping system analysed here. Lateness guarantees high biomass yields, and the high fruiting efficiency, being unaffected by clipping, ensures a good sink and hence a potentially high grain yield even under dual-purpose utilization. On the other hand, a cropping system based on a combination of the ancient wheat species compared in this experiment could prolong the availability of herbage in the winter and still ensure a valuable grain yield.

Sustainability of mixed farming systems can be increased by the double-utilization of ancient wheats, as the herbage clipped or grazed by animals before terminal spikelet does not affect the grain yield attainable in the same season.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics approval not applicable.

Consent to participate not applicable.

Consent for publication not applicable.

Code availability not applicable.

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