The effects of forage removal on biomass and grain yield of intermediate and spring triticales

THE EFFECTS OF FORAGE REMOVAL ON BIOMASS AND GRAIN YIELD OF INTERMEDIATE AND SPRING TRITICALES

Francesco Giunta[a], Rosella Motzo[a*], Adriana Virdis[b] and Agnese Cabigliera[a]

[a] Dipartimento di Agraria, Sez. Agronomia, Coltivazioni erbacee e Genetica, University of Sassari Via de Nicola 1, 07100 Sassari, Italy.
[b] Agris Sardegna, Dipartimento per la ricerca nelle produzioni vegetali, Viale Trieste 111, 09123 Cagliari, Italy.

*Corresponding author. Tel. +39079229330; fax:+39079229222. E-mail address: motzo@uniss.it

Abstract

The dual-purpose use of cereals can be a convenient management option if grain yield (GY) is not significantly reduced. The effects of clipping at the terminal spikelet stage on biomass and grain production of an intermediate ('Bienvenu') and a spring ('Oceania') triticale cultivar grown at two sowing rates (300 and 600 seeds per m^2) were analysed in five different Mediterranean environments with no additional N application following clipping in terms of the changes induced on radiation and water capture and use and biomass partitioning. Clipped crops were able to recover completely in terms of the fraction of radiation interception (FIPAR) before anthesis, but the period in which plants exhibited a smaller leaf area resulted in a severe reduction – from 20 to 26% depending on the environment- in the total amount of radiation intercepted (IPAR, MJ m^{-2}), and consequently, in biomass at anthesis (from 14 to 30%). Radiation use efficiency (RUE) between clipping and anthesis ranged from 0.89 to 1.42 g MJ^{-1}, and only contributed to the decrease in biomass when leaf nitrogen levels were reduced as a consequence of clipping. Evaporation increased (by 13 mm on average) and transpiration decreased (by 11 mm on average) following clipping, with contrasting but quantitatively small effects on evapotranspiration. Transpiration efficiency decreased by about 20% following clipping in most environments because clipping decreased biomass production more than evapotranspiration in environments that did not allow the triticale crops to reach leaf area index values greater than 3–4. GY varied from about 300 to 850 g m^{-2} and was only affected by clipping in the two environments with favourable post-anthesis conditions where unclipped crops showed a higher harvest index (HI, 0.38 unclipped vs 0.36 clipped crops on the average of the two environments). In the environments where a severe water stress (transpiration lower than 18% of reference evapotranspiration) following anthesis led to similar amounts of IPAR under the two treatment conditions, the lower biomass at anthesis of clipped crops lead to a higher HI and no reduction in GY. No interaction between clipping and

cultivar was observed for FIPAR. Cultivar differences derived from their different phenologies and were mainly expressed before clipping; the longer duration of the phase prior to clipping (from 0 to 18 days depending on the environment) resulted in the intermediate cultivar being superior in terms of winter forage production (193 vs 135 g m^{-2} on average). On the other hand, the intermediate cultivar was less advantageous in terms of GY (270 vs 357 g m^{-2}) in the environments presenting the most severe terminal water stress. Sowing rate was only relevant in the pre-clipping period when the higher sowing rate produced, on average, 40% more biomass than the lower sowing density. Dual-purpose triticale can be a convenient management option in Mediterranean environments subjected to severe terminal water stress because GY is not affected and a variable amount of winter forage may be obtained.

Keywords: triticale, dual purpose, radiation interception, radiation use efficiency, evapotranspiration, transpiration efficiency.

Abbreviations: GY, Grain Yield; FIPAR, Fraction of Intercepted Photosynthetically Active Radiation; IPAR, cumulated Photosynthetically Active intercepted radiation; RUE, radiation use efficiency; TE, Transpiration Efficiency.

1. Introduction

Dual-purpose use of cereals (in which the cereal is grazed by animals and harvested for grain in the same season) is common where livestock and cereal crops are managed in the same area. Triticale (*x Tricosecale* Wittmack) is one of the cereal species grown for dual-purpose use in Mediterranean environments. This type of utilisation is particularly interesting under Mediterranean conditions, because it guarantees a source of forage in a period when animal food requirements are high

(Royo et al., 1997) and crop growth rates are low (Harrison et al., 2011) with low or no reduction in grain production. It offers a wide range of varieties, from spring types, whose developmental rate responds to temperature and day length, to winter and intermediate types, which are also responsive to vernalisation. The phenological differences that exist among triticale cultivars, including different times to maximum leaf area index (LAI), different rates of dry matter accumulation (Royo and Blanco, 1999) and different growth habits (erect or prostrate), influence their aptitudes to dual purpose use.

Any change in grain yield (GY) following grazing/clipping can be viewed as the results of clipping affecting the ability of crops to capture radiation and water, and/or the ability to convert them into biomass (Bonachela et al., 1995a, b; Harrison et al., 2011b, c). A rapid and full recovery of photosynthetic activity after the removal of aboveground biomass is important for obtaining a good GY (Winter and Thompson, 1987). Given the same biomass, the GY of dual-purpose triticale can also be affected by the altered partitioning of biomass into grain and straw (Bonachela et al., 1995) because clipping affects dry matter accumulation in stems (Royo and Romagosa, 1996) and green area duration (i.e., amount of biomass produced after anthesis) (Winter and Thompson, 1987).

Most studies that have discussed the effects of grazing/clipping on the GY of small grain cereals have reported dissimilar results with regard to the environmental conditions, management or crop/cultivar (Harrison et al., 2011a and papers cited therein). As underpinned by Harrison et al. (2011a), those papers lacked an approach that could be broadly applied (i.e., an analysis based on a framework that allowed an interpretation of mechanisms by which leaf area removal affects yield). Harrison et al. (2011b, c) performed such an analysis on bread wheat to analyse the effects of different intensities and duration of grazing, thereby obtaining a useful dataset for modelling the effects of grazing on GY (Harrison et al., 2012). In this paper, we adopted a similar type of

analysis for triticale, based on the capture and use of resources. We focused our analysis on the most critical period for dual-purpose cereals, i.e., the period of leaf area recovery, from clipping to anthesis, and evaluated the interaction between clipping and phenology. The aim of this study was to analyse the effects of clipping on biomass and grain production of winter and spring triticales with regard to clipping-induced changes on the capture and use of radiation and water, as well as on biomass partitioning.

2. Materials and methods

2.1. Experimental design

Five field trials were conducted across two locations in Sardinia, Italy (Ottava, 41°N, 80 m asl, and Ussana, 39°N, 97 m asl) in the 2011–2012 and 2012–2013 seasons, representing a subset of the experiments used to analyse how dual-purpose use affects the phenology of triticales by Giunta et al. (2015). The soil at Ottava consisted of a sandy- clay-loam that was overlaid on limestone (Xerochrepts), with a soil water content of 31% on a volume basis at field capacity and of 13% at the wilting point. The soil at Ussana consisted of loam, with a soil water content of 33% on a volume basis at field capacity and of 17% at the wilting point. According to long-term data, the climate at both Ussana and Ottava is typically Mediterranean, although the two sites differ in rainfall and thermal regime. There is 19% less rainfall at Ussana than at Ottava, and the temperature range is wider because of the higher maximum and lower minimum temperatures that occur during the whole year (Table 1).

Table 1. Long-term weather data for the two sites and weather data for the emergence-anthesis (EM-ANT) and anthesis-maturity period (ANT-MAT) of the five experiments. VPD, Vapor Pressure Deficit, T, transpiration, ETo reference evapotranspiration.

Site or environment	Period	Duration (d)	Maximum temperature (°C)	Minimum temperature (°C)	VPD (KPa)	Rainfall (mm)	ETo (mm d^{-1})	T/ETo
Ottava	Oct-May		17.2 ± *1.0*	8.8 ± *1.0*	0.76 ± *0.21*	473 ± *111*	2.5 ± *0.4*	
(58 years)	Apr-May		20.1 ± *1.4*	10.4 ± *1.3*	0.90 ± *0.28*	83 ± *46*	4.0 ± *0.5*	
Ussana	Oct-May		18.9 ± *1.1*	7.8 ± *0.7*	0.60 ± *0.11*	381 ± *123*	2.2 ± *0.3*	
(40 years)	Apr-May		22.4 ± *1.8*	9.6 ± *1.1*	0.83 ± *0.21*	72 ± *40*	3.6 ± *0.5*	
OTTOCT	EM-ANT	154	15.4	7.6	0.9	444	2.5	0.82
	ANT-MAT	101	20.3	11.1	1.2	148	4.6	0.38
OTTNOV	EM-ANT	143	15.5	7.7	0.9	185	2.7	0.56
	ANT-MAT	68	22.3	12.2	1.4	107	5.4	0.21
OTTJAN	EM-ANT	87	16.3	6.9	0.9	78	3.4	0.35
	ANT-MAT	61	25.0	14.7	1.7	80	6.0	0.28
USSDEC12	EM-ANT	107	16.7	3.9	0.6	187	2.5	0.53
	ANT-MAT	53	27.7	11.8	1.2	50	5.8	0.15
USSDEC13	EM-ANT	119	15.8	5.4	0.5	314	2.2	0.71
	ANT-MAT	54	24.2	11.8	0.9	18	4.8	0.18

Long-term data are means ± standard deviations

Two triticale cultivars with similar photoperiodic sensitivities but different vernalisation requirements were compared. Cultivar Oceania, which does not have a vernalisation requirement, can be classified as 'spring type' according to Loomis and Connor (1992), whereas cultivar Bienvenu, which has a quantitative response to low temperature, can be classified as 'intermediate type' according to the same authors. These plants were chosen among the most productive and well-adapted cultivars to the Mediterranean environment of Sardinia. During the 2011–2012 season, sowing was performed on 15 November 2011 and on 18 January 2012 at Ottava ('OTTNOV' and 'OTTJAN' environments), and on 28 December 2011 at Ussana ('USSDEC12'). During the 2012–2013 season, sowing was carried out on 9 October at Ottava ('OTTOCT') and on 19 December ('USSDEC13') at Ussana.

Two seed-rate treatments were compared in each of the environments: 300 seeds per m^2, the common sowing rate for triticale in this type of environment, and 600 seeds per m^2. Seed density

was calculated for each cultivar from thousand-grain weight and percentage of germination. Half of the plots were clipped at the terminal spikelet stage with a lawn mower ('clipped' treatment), so that their aboveground height did not exceed 2 cm. In each environment, a factorial combination of cultivar x clipping x sowing rate treatment was arranged in a randomised complete block design with four replications. Each plot was formed by eight 10 m long rows, separated from one another by 15 cm. The soil was dressed with 100 Kg ha^{-1} P_2O_5 and 100 Kg ha^{-1} N at sowing. All weeds, pests and diseases were chemically controlled.

2.2. Measurements

Emergence, booting, anthesis and physiological maturity were recorded by periodical inspections of the plots when more than 50% of plants in the plot had reached that phenological stage. The development of the apices of 5–10 main stems per plot was determined twice a week by destructive sampling to detect the stage of terminal spikelet, which corresponded to the end of terminal spikelet formation and was marked by the initiation of awns because of the elongation of the tip of the lemmas (Bonnett, 1936). The terminal spikelet stage was presumed to occur when it was exhibited by more than 50% of the plants sampled.

Plant height (from the soil surface to the tip of the last leaf) was recorded on 10 random plants per plot at clipping, booting and anthesis. On one or two sampling occasions between clipping and anthesis, depending on the length of the period, SPAD-502 readings were taken from the middle portion of the blades of 30 uppermost fully expanded leaves per plot. On the same blades, the following parameters were determined: leaf area with an electronic leaf area meter; dry weight after oven drying at 80°C; and leaf nitrogen percentage (Carbon/Hydrogen/Nitrogen Determinator 628 Series; LECO, St. Joseph, MI, USA). Using these data, leaf nitrogen level was expressed as g $leaf^{-1}$ and g m^{-2} leaf. Within each environment, clipping was performed in each 'cultivar by rate of sowing' treatment immediately after observation of the terminal spikelet stage. Before clipping, a

biomass sample of 0.60 or 0.72 m^2, depending on the environment, was hand-cut from all of the plots. In addition to the sampling at the terminal spikelet stage, dry matter production was evaluated on different occasions during the growing cycle on samples of 0.6 m^2 of uprooted plants, excluding the roots. All of the biomass samples were oven-dried at 80°C for 48 hours before weighing.

At physiological maturity, a sample of aboveground biomass of 0.72 m^2 was hand-cut from the internal rows, oven dried at 80°C for 48 hours, weighed and threshed. The harvest index (HI) was determined on these samples, and used to calculate the final biomass from the GY obtained on a plot basis with mechanical harvesting. In all of the environments and plots, the fraction of intercepted radiation (FIPAR) was measured on several occasions from emergence until the plants had yellow flag leaves. Measurements were made at noon with a tube solarimeter (Sun-Scan Canopy Analysis System SS1-UM-1.05. Delta-T Devices Ltd.; Cambridge, UK) allowing simultaneous measurements of photosynthetically active radiation above (using external sensor) and below (using a probe) the canopy. 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, and then subsequently positioned at increasing height from the soil in order to stay above the dead leaves. Indirect LAI measurements were obtained with this same instruments (Breda, 2003). Soil water content of the 0–0.7 m layer was measured periodically with a Time Domain Reflectometer (TDR, TRASE model 6050XI, Soil Moisture Equipment, Inc; Santa Barbara, CA, USA). Weather data (maximum and minimum temperatures, rainfall, solar radiation and air humidity) were recorded in meteorological stations located close to the fields.

2.3. Derived measures and data analysis

FIPAR was calculated as the ratio between the differences of incident and transmitted to incident radiation. Cumulative radiation interception (IPAR, MJ m^{-2}) was calculated as the sum of the daily

values of IPAR obtained by multiplying the daily FIPAR (obtained by linear interpolation of the measured data) by the daily values of solar radiation recorded at the meteorological station of each experimental station. Radiation Use Efficiency (RUE, g MJ^{-1}) between clipping and anthesis was calculated according to Sinclair and Muchow (1999) as the slope of the linear relationship between biomass and IPAR in that period. Accordingly, transpiration efficiency (TE, g m^{-2} mm^{-1}) was calculated as the slope of the linear relationship between biomass and amount of water transpired between clipping and anthesis. The R^2 of those relationships was always greater than 0.91 for RUE, and greater than 0.81 for TE.

Weather data were used to calculate reference evapotranspiration (ETo) for each environment, crop evaporation (E), crop transpiration (T) and soil water balance for each plot, according to the dual crop coefficient method under soil water stress conditions proposed by Allen et al. (1998). Daily FIPAR values and daily plant height data were used to take into account the effects of clipping and correctly partitioning ET into E and T. The basal crop coefficient K_{cb} of Allen et al. (1998) was considered equal to 0.15 for FIPAR values lower than 0.10. For FIPAR above 0.10, daily K_{cb} values were calculated from the linear relationship between FIPAR and Kc assuming that the tabular K_{cb} value of 1.1 for wheat (Allen et al., 1998) was reached when FIPAR was 0.98. These daily K_{cb} values were then adjusted for climatic conditions and plant height (Allen et al., 1998). The degree of water limitation was quantified for each environment both before and after anthesis through the ratio between the amount of water transpired (T) and the evapotranspirative demand of the atmosphere (ETo): the lower the ratio, the higher the water stress.

In four of the five environments TDR data were used to calibrate the soil water balance by adjusting the rooting depth (Figure 1).

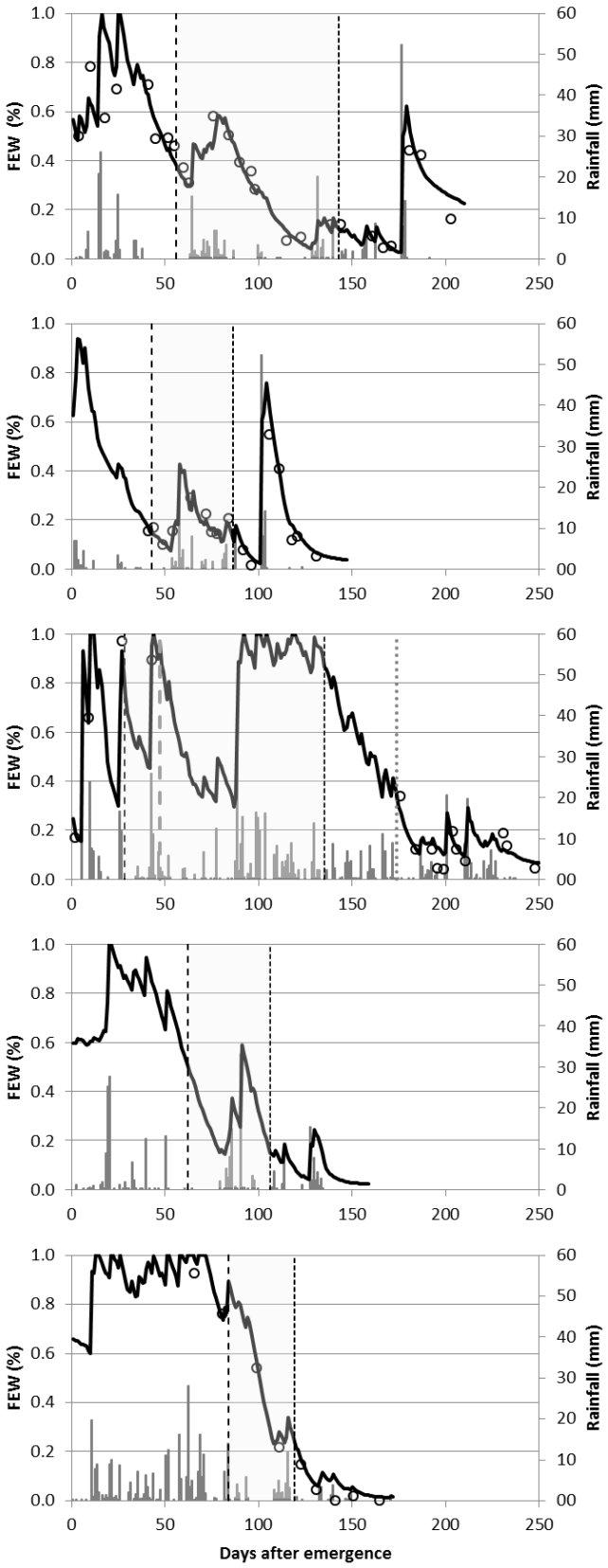

Fig. 1 Pattern of the fraction of extractable water (FEW) from emergence to maturity calculated through the soil water balance (black line) and TDR data (empty points). The grey bars represent daily rainfall, and the grey area represents the period from clipping to anthesis in the five environments (OTTOCT, OTTNOV, OTTJAN, USSDEC12 and USSDEC13 from the top to the bottom).

Analysis of variance (ANOVA) was performed separately for each environment. Only the main effects were reported because the interactions were generally not significant. When reported, means across all of the environments were compared using the Wilcoxon signed-rank non-parametric test. The significance of difference between cultivars or clipping treatments in RUE and TE was assessed according to Gomez and Gomez (1984). The package 'R' (R Core Team, 2014) was used for the statistical analysis.

3. Results

3.1. Weather

According to the long-term averages, the three Ottava environments showed higher minimum temperatures than the two Ussana environments (Table 1). The latter were also characterised by higher water stress (i.e., lower T/ETo after anthesis) compared with Ottava. USSDEC12 was the environment with the highest maximum temperatures and vapour pressure deficit (VPD) after anthesis, which contributed to creation of the most stressful anthesis-maturity period as indicated by the lowest T/ETo ratio.

3.2. From emergence to clipping

The main morphological differences between cultivars in this period were the growth habits, which were prostrate for cultivar Bienvenu and erect for cultivar Oceania, as well as the leaf size, which was larger in cultivar Oceania (39.9±1.4 cm^2 vs 27.9±1.5 cm^2 of cultivar Bienvenu). Biomass at clipping ranged from less than 100 g m^{-2} at OTTOCT to more than 300 g m^{-2} observed for cultivar Bienvenu at USSDEC13 (Table 2). On average, cultivar Bienvenu produced more biomass in this period compared with cultivar Oceania (193±14 g m^{-2} *vs*. 135 ±14 g m^{-2}, P=0.01), although this difference was due to the superiority of the former in only two of the five environments tested.

Table 2. Biomass production, total amount of available radiation, duration and intercepted radiation (IPAR) for the emergence-clipping period, the two cultivars and the two sowing rates in the five environments. Values are means ± standard errors. P refers to the probability of cultivar and sowing rate effect according to the analysis of variance (ns, not significant)

Environment	*Cultivar*	Biomass	Available radiation	Duration	IPAR	*Sowing rate*	Biomass	Duration	IPAR
		g m^{-2}	MJ m^{-2}	days	MJ m^{-2}		g m^{-2}	days	MJ m^{-2}
OTTOCT	Bienvenu	92 ± *12*	391	47 ± *0.0*	139 ± *6*	*300*	68 ± *5*	38 ± *3.3*	95 ± *12*
	Oceania	74 ± *5*	263	29 ± *0.3*	78 ± *5*	*600*	95 ± *11*	37 ± *3.6*	117 ± *12*
	P	*ns*		*<0.001*	*<0.001*		*0.009*		*0.002*
OTTNOV	Bienvenu	194 ± *12*	473	65 ± *0.5*	216 ± *15*	*300*	127 ± *19*	56 ± *4.0*	162 ± *11*
	Oceania	121 ± *14*	330	47 ± *0.0*	159 ± *7*	*600*	188 ± *16*	56 ± *3.3*	213 ± *16*
	P	*<0.0001*		*<0.001*	*<0.001*		*<0.0001*		*<0.001*
OTTJAN	Bienvenu	125 ± *5*	678	46 ± *0.0*	146 ± *12*	*300*	109 ± *11*	43 ± *1.3*	116 ± *13*
	Oceania	115 ± *13*	560	40 ± *0.0*	130 ± *12*	*600*	128 ± *9*	43 ± *1.2*	153 ± *8*
	P	*ns*		*<0.001*	*ns*		*ns*		*0.001*
USSDEC12	Bienvenu	252 ± *22*	570	62 ± *0.0*	183 ± *16*	*300*	218 ± *16*	62 ± *0.0*	187 ± *20*
	Oceania	250 ± *28*	570	62 ± *0.0*	228 ± *2*	*600*	306 ± *23*	62 ± *0.0*	222 ± *13*
	P	*ns*		*ns*	*ns*		*ns*		*ns*
USSDEC13	Bienvenu	303 ± *27*	688	77 ± *0.0*	316 ± *16*	*300*	204 ± *21*	69 ± *3.0*	247 ± *17*
	Oceania	193 ± *24*	486	61 ± *0.0*	229 ± *11*	*600*	304 ± *32*	70 ± *3.2*	308 ± *23*
	P	*<0.001*		*<0.001*	*<0.001*		*<0.001*		*0.002*

Differences in biomass accumulation were driven by IPAR, as shown by the unique relationship calculated for the two cultivars between biomass and IPAR (R^2=0.83***, n= 10) that indicated a common RUE of 1.1 ± 0.17 g MJ^{-1}. Therefore, the greater biomass of the cultivar Bienvenu was due to its greater IPAR, which resulted from a combination of a lower FIPAR compared with cultivar Oceania (Figure 2) but a longer duration of the emergence-clipping period. In fact, differences between cultivars in IPAR were associated with corresponding differences in the duration of the emergence-clipping period (R^2=0.86*, n=5).

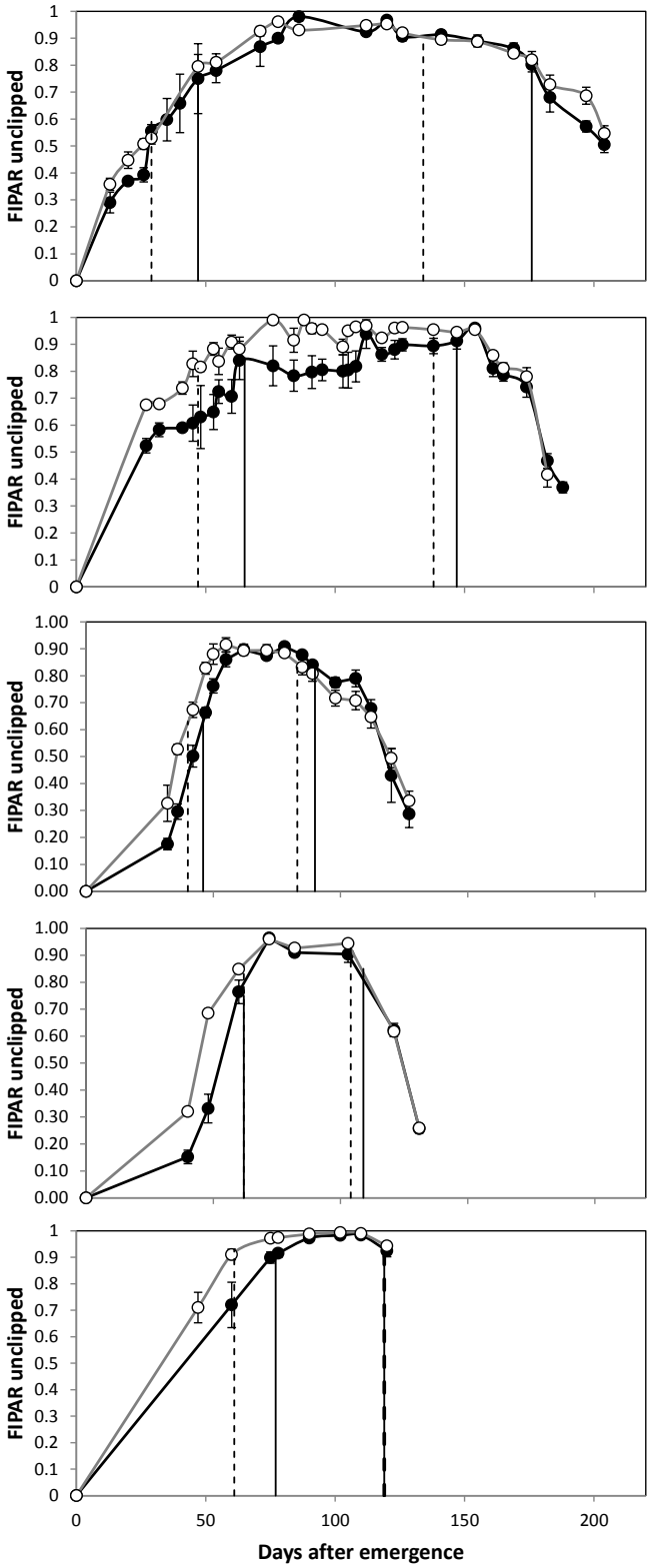

Figure 2. FIPAR patterns for the unclipped treatments in the period emergence-maturity for cultivar Bienvenu (closed symbols) and Oceania (open symbols) in the five environments (OTTOCT, OTTNOV, OTTJAN, USSDEC12 and USSDEC13 from the top to the bottom). Vertical lines, clipping and anthesis (dotted lines cultivar Oceania).

It can be concluded that any difference in biomass between cultivars was driven by their phenology, which, in turn, resulted in a different availability of radiation (Table 2), and was not due to a difference in ability to capture radiation because of their different growth habits or leaf sizes. The higher sowing density produced, on average, 40% more biomass than the lower sowing density, and the difference was significant in three of the five environments (Table 2). A greater IPAR was the reason for the superiority of the '600' treatment over the '300' one.

3.3. From clipping to anthesis

ANOVA did not show any significant 'clipping x cultivar' interaction for the traits analysed. The lack of any interaction is also shown in Figure 3 where, in spite of their different habitus and phenology, both cultivars showed the same pattern of recovery in FIPAR after clipping. Therefore, cultivar and clipping effects were analysed separately. Figure 3 also shows that FIPAR recovery was almost complete, ranging from a minimum of 90% to 100% despite the short period available in some of the environments. On average, clipped crops intercepted less radiation than unclipped ones for 44% of the clipping-anthesis period. Both cultivars had an erect growth habit between clipping and anthesis, but cultivar differences in single leaf area were still large. In this period, cultivar Oceania had a leaf area of 31.9±1.7 cm^2, whereas the area of a Bienvenu leaf was 22.6±1.3 cm2 on average. On average, no difference was detected between the spring (834 g m^{-2}) and **intermediate** cultivar (906 g m^{-2}) in the biomass produced between clipping and anthesis. This result masked the interaction between cultivars and environments, because cultivar Bienvenu produced more biomass than cultivar Oceania at OTTJAN and OTTOCT, but the opposite was true at OTTNOV and USSDEC13 (Table 3).

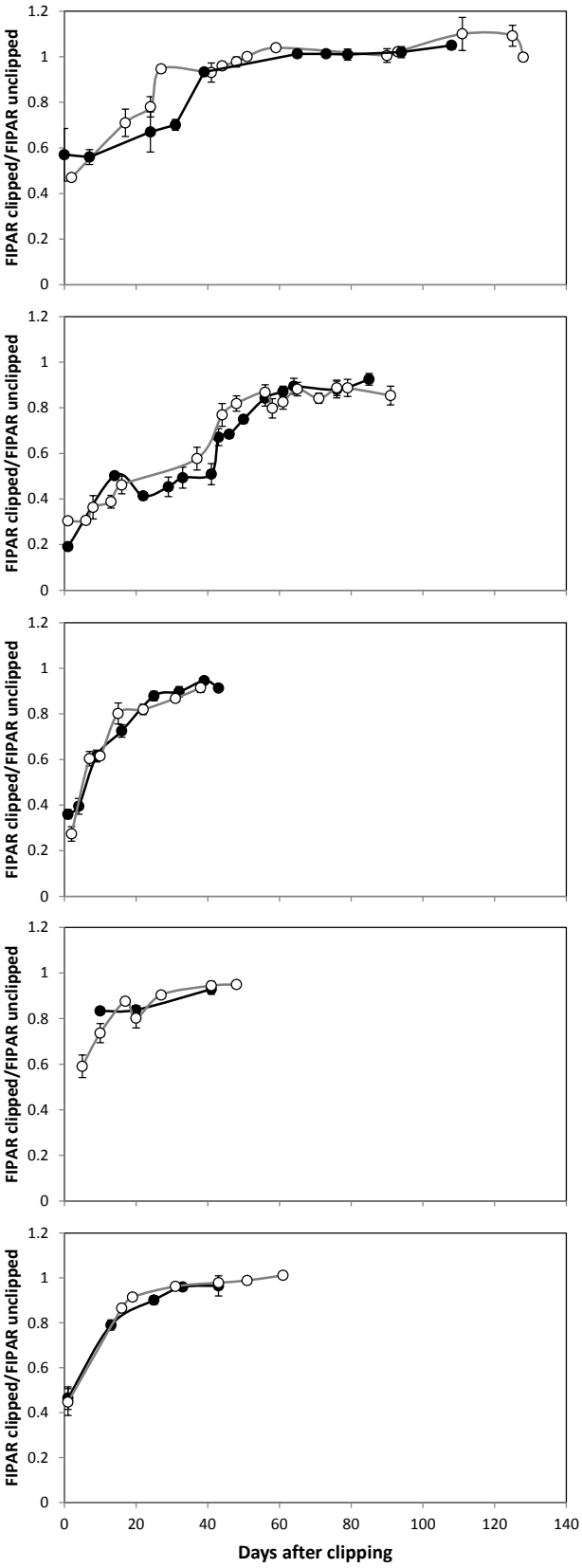

Figure 3. Recovery of FIPAR in the period clipping-anthesis for cultivars Bienvenu (closed symbols) and Oceania (open symbols) in the five environments (OTTOCT, OTTNOV, OTTJAN, USSDEC12 and USSDEC13 from the top to the bottom).

Table 3. Biomass production, total amount of available radiation, duration, intercepted radiation (IPAR) and radiation use efficiency (RUE), transpiration (T) and evaporation (E), for the clipping-anthesis period and the two cultivars in the five environments. Values are means ± standard errors. P refers to the probability of cultivar effect according to analysis of variance (ns, not significant)

Environment	Cultivar	Biomass	Available radiation	Duration	IPAR	RUE	T	E	Transpiration efficiency
		g m^{-2}	MJ m^{-2}	days	MJ m^{-2}	g MJ^{-1}	mm	mm	g m^{-2} mm^{-1}
OTTOCT	Bienvenu	1290 ± *35*	1185	127 ± *1.4*	1018 ± *15*	1.26 ± *0.08*	311 ± *11*	36 ± *5*	4.1 ± *0.2*
	Oceania	998 ± *45*	791	106 ± *0.8*	680 ± *6*	1.42 ± *0.04*	222 ± *9*	29 ± *2*	4.3 ± *0.2*
	P	*<0.001*		*<0.001*	*<0.001*	*ns*	*<0.001*	*ns*	*ns*
OTTNOV	Bienvenu	793 ± *78*	1287	83 ± *1.4*	848 ± *58*	0.95 ± *0.04*	111 ± *9*	35 ± *10*	6.7 ± *0.5*
	Oceania	991 ± *60*	1148	91 ± *0.3*	949 ± *35*	1.08 ± *0.08*	128 ± *10*	17 ± *8*	7.4 ± *0.7*
	P	*0.0020*		*<0.001*	*<0.001*	*ns*	*<0.001*	*<0.001*	*ns*
OTTJAN	Bienvenu	775 ± *11*	1207	44 ± *0.0*	668 ± *10*	1.17 ± *0.05*	93 ± *7*	14 ± *3*	8.2 ± *0.4*
	Oceania	689 ± *11*	1169	43 ± *0.0*	632 ± *14*	1.07 ± *0.06*	65 ± *4*	11 ± *2*	10.0 ± *0.6*
	P	*0.0160*		*ns*	*ns*	*ns*	*<0.001*	*<0.001*	*0.0160*
USSDEC12	Bienvenu	716 ± *28*	859	47 ± *0.0*	665 ± *13*	1.06 ± *0.05*	109 ± *1*	9 ± *2*	6.5 ± *0.5*
	Oceania	738 ± *44*	761	42 ± *0.0*	605 ± *58*	1.11 ± *0.14*	109 ± *5*	7 ± *2*	6.7 ± *0.3*
	P	*ns*		*<0.001*	*0.0120*	*ns*	*ns*	*0.0230*	*ns*
USSDEC13	Bienvenu	628 ± *33*	720	42 ± *0.0*	639 ± *10*	1.00 ± *0.08*	116 ± *3*	7 ± *3*	5.4 ± *0.5*
	Oceania	924 ± *39*	916	58 ± *0.0*	844 ± *5*	1.07 ± *0.06*	165 ± *3*	10 ± *4*	5.6 ± *0.4*
	P	*<0.001*		*<0.001*	*<0.001*	*ns*	*<0.001*	*0.0100*	*ns*

RUE was not the underlying reason for this interaction because no difference in RUE was observed between the two cultivars in the five environments. Thus, the observed differences in biomass between cultivars must have derived from the corresponding differences in IPAR, as demonstrated by the analysis of regression (R^2=0.86*, n=5). Figure 2 highlights that cultivar differences in IPAR were not derived from different abilities to intercept radiation in any of the environments, except in relation to OTTNOV. In this case, the higher FIPAR of cultivar Oceania compensated for the less radiation available, thereby resulting in a greater IPAR compared with cultivar Bienvenu. The higher FIPAR of cultivar Oceania of the OTTNOV environment was derived from the sensibly higher LAI of this cultivar (Figure 4), which reached a maximum of more than 6, compared with approximately 5 in the cultivar Bienvenu.

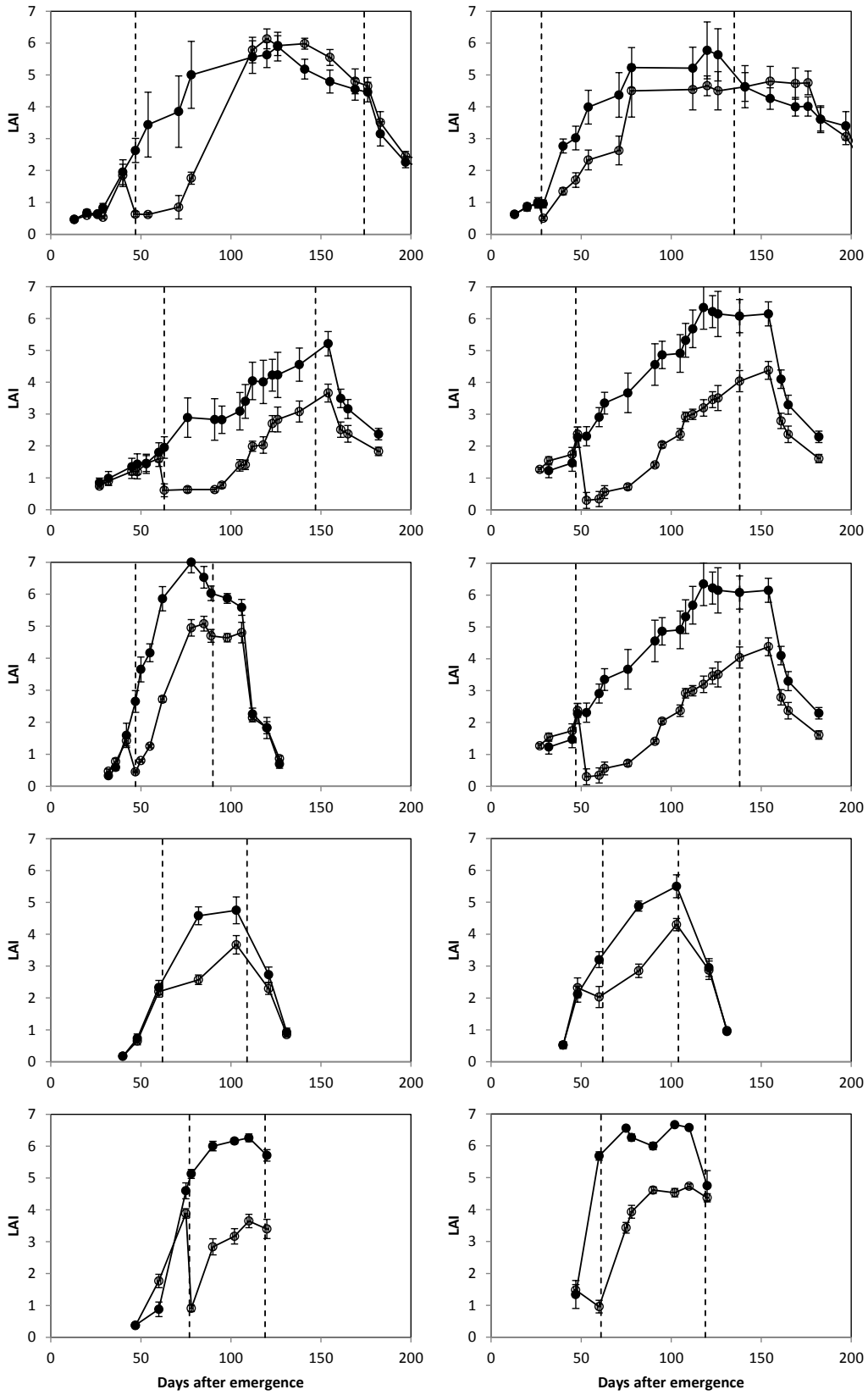

Figure 4. LAI pattern during the growing cycle for cultivar Bienvenu (on the left) and Oceania (on the right) in the five environments (OTTOCT, OTTNOV, OTTJAN, USSDEC12 and USSDEC13 from the top to the bottom). Closed symbols, unclipped treatment; empty symbols, clipped treatment. Vertical lines, clipping and anthesis.

What differed between cultivars was the amount of radiation available as a consequence of a combination of different clipping-anthesis period durations and the different 'positioning' of these time periods within the year, particularly in the earliest sowing period in OTTOCT. In this environment, 1185 MJ m^{-2} were available to cultivar Bienvenu across 127 days and only 791 MJ m^{-2} were available to cultivar Oceania across 106 days. Therefore, a strong relationship was calculated between the difference between the two cultivars in IPAR and in the duration of the clipping-anthesis period (R^2 = 0.99***, n=5). As in the previous emergence-clipping period, the different amount of biomass produced and IPAR by the spring and intermediate cultivars was a consequence of the different availability of radiation derived from their different phenology.

E represented 6–24% of ET, with the highest proportion in OTTNOV due to the high frequency of rainfall immediately after clipping. Differences between cultivars in T were particularly marked in those environments where the greatest differences in duration of the clipping-anthesis period were observed. Therefore a positive relationship was calculated between cultivar differences in T and cultivar differences in the duration of the clipping-anthesis period (R^2 = 0.90*, n = 5) and in IPAR (R^2 = 0.94**, n=5). Clipping reduced the biomass produced between clipping and anthesis compared with the unclipped treatment across all of the environments, with the exception of OTTOCT (Table 4). In this environment, the longer clipping-anthesis period duration combined with the rapid and complete recovery of radiation interception (Figure 3) translated into a higher IPAR for the clipped treatment than the IPAR for the unclipped one. The very low biomass at clipping in the OTTOCT environment (Table 2) probably contributed to this pattern of interception recovery. In all of the other environments, the lower biomass of the clipped plots was derived from a lower IPAR, although the RUE was also lower in the clipped treatments in two of the environments (OTTNOV and OTTOCT).

Table 4. Biomass production, duration, radiation intercepted (IPAR) and radiation use efficiency (RUE), transpiration (T), evaporation (E) and transpiration efficiency (TE) for the clipping-anthesis period and the two clipping treatments in the five environments. Values are means ± standard errors. P refers to the probability of clipping effect according to analysis of variance (ns, not significant)

Environment	Clipping treatment	Biomass	Duration	IPAR	RUE	T	E	Transpiration efficiency
		g m^{-2}	days	MJ m^{-2}	g MJ^{-1}	mm	mm	g m^{-2} mm^{-1}
OTTOCT	Unclipped	1191 ± *41*	112 ± *2.5*	813 ± *19*	1.42 ± *0.04*	274 ± *29*	27 ± *1*	4.3 ± *0.1*
	Clipped	1084 ± *35*	119 ± *3.1*	864 ± *9*	1.16 ± *0.07*	259 ± *25*	38 ± *4*	3.8 ± *0.2*
	P	*ns*	*<0.001*	*0.0060*	*0.0020*	*<0.001*	*0.0020*	*ns*
OTTNOV	Unclipped	1081 ± *80*	84 ± *1.8*	1033 ± *32*	1.06 ± *0.05*	134 ± *7*	12 ± *6*	7.5 ± *0.5*
	Clipped	732 ± *61*	90 ± *0.6*	780 ± *40*	0.89 ± *0.05*	104 ± *6*	40 ± *6*	5.8 ± *0.7*
	P	*<0.001*	*ns*	*<0.001*	*0.0120*	*<0.001*	*<0.001*	*0.0500*
OTTJAN	Unclipped	848 ± *8*	43 ± *0.1*	744 ± *18*	1.11 ± *0.06*	88 ± *10*	8 ± *1*	8.6 ± *0.5*
	Clipped	621 ± *8*	43 ± *0.1*	553 ± *16*	1.13 ± *0.05*	70 ± *7*	17 ± *2*	8.3 ± *0.7*
	P	*<0.001*	*ns*	*<0.001*	*ns*	*<0.001*	*<0.001*	*ns*
USSDEC12	Unclipped	850 ± *32*	46 ± *0.7*	720 ± *16*	1.14 ± *0.09*	106 ± *3*	5 ± *1*	7.7 ± *0.6*
	Clipped	638 ± *31*	45 ± *0.7*	579 ± *22*	1.03 ± *0.09*	113 ± *3*	11 ± *1*	5.1 ± *0.5*
	P	*<0.001*	*ns*	*<0.001*	*ns*	*<0.001*	*<0.001*	*0.004*
USSDEC13	Unclipped	839 ± *39*	49 ± *2.1*	787 ± *2*	1.07 ± *0.08*	141 ± *12*	4 ± *1*	6.1 ± *0.4*
	Clipped	620 ± *55*	46 ± *2.3*	624 ± *24*	0.95 ± *0.05*	140 ± *17*	14 ± *1*	4.6 ± *0.3*
	P	*<0.001*	*ns*	*<0.001*	*ns*	*ns*	*<0.001*	*0.008*

In these environments, the lower RUE of the clipped treatments was associated with a lower leaf nitrogen content and SPAD index (Table 5).

Table 5. Leaf nitrogen status and SPAD Index for the clipping-anthesis period and the two clipping treatments in the two environments where RUE was affected by clipping. Values are means ± standard errors. P refers to the probability of a clipping effect according to analysis of variance (ns, not significant).

Environment	Clipping treatment	Days after emergence	Leaf nitrogen			SPAD
			(%)	(mg $leaf^{-1}$)	(g m^{-2} leaf)	
OTTOCT	Unclipped	82	3.94 ± *0.06*	7.94 ± *0.66*	2.20 ± *0.08*	46 ± 0.5
OTTOCT	Clipped	82	3.86 ± *0.07*	6.98 ± *1.41*	2.16 ± *0.09*	45 ± 0.5
	P		*ns*	*<0.001*	*ns*	*0.04*
	Unclipped	112	4.22 ± *0.11*	7.95 ± *1.14*	2.71 ± *0.11*	49 ± *0.3*
	Clipped	112	4.32 ± *0.13*	6.54 ± *1.61*	2.56 ± *0.14*	47 ± *0.3*
	P		*0.03*	*0.01*	*ns*	*0.01*
OTTNOV	Unclipped	109	3.15 ± *0.09*	4.79 ± *0.65*	2.12 ± *0.17*	42 ± *0.4*
OTTNOV	Clipped	109	2.80 ± *0.04*	3.70 ± *0.50*	1.97 ± *0.02*	39 ± *0.4*
	P		*<0.001*	*<0.001*	*0.02*	*<0.001*

It is likely that the longer duration of the clipping-anthesis period in these environments, coupled with the lack of any fertilisation following clipping, compromised the recovery of an adequate leaf

nitrogen status after clipping. As expected, clipping increased the amount of water lost by evaporation from the soil surface and decreased the amount of water transpired in all Ottava environments. Clipping negatively affected TE in three environments because of the notable decrease in biomass production induced by clipping, with the T of the clipped treatments being lower or similar to that of the unclipped treatment. In the three environments where this greater effect of clipping on biomass production than on T was observed, the maximum LAI of the clipped treatments was around 4 compared with the higher maximum values observed in the other two environments (Figure 4). No interaction between clipping and sowing rate was detected by ANOVA, meaning a similar pattern and entity of leaf area recovery occurred at the two sowing rates. The effect of sowing rate on the biomass produced and water used between clipping and anthesis were negligible or absent given a maximum difference between sowing rate treatments of 0.5 LAI units (data not shown).

3.4. GY and HI

The OTTOCT environment is omitted from this section because the very low temperatures around the anthesis of cultivar Oceania caused an almost complete sterility of the spike and compromised GY production. The **intermediate** cultivar Bienvenu produced a greater GY than the spring cultivar Oceania at OTTJAN (Table 6), whereas cultivar Oceania was more productive at USSDEC12, the most stressful environment in the post-anthesis period in terms of both T/ETo (0.15) and maximum temperatures (28 °C) (Table 1). In the case of Bienvenu, the greater GY at OTTJAN was derived from its greater biomass at maturity, despite its lower HI. In contrast, at USSDEC12, cultivar Oceania showed a greater GY derived from a combination of both a greater biomass and a greater HI. It is likely that the earlier anthesis of cultivar Oceania represented a great advantage in this environment, characterised by severe water stress in the post-anthesis period, resulting in its

higher HI. Cultivar ranking in biomass was not altered when the biomass clipped at terminal spikelet was added to the final biomass.

Table 6. Grain yield (GY) and HI, biomass at anthesis and at maturity (with and without the forage removed with clipping), and IPAR after anthesis for the two cultivars in the five environments. Values are means ± standard errors. P refers to the probability of cultivar effect according to the ANOVA (ns, not significant)

Environment	Cultivar	GY	Biomass at maturity	HI	Total biomass (clipped included)	Biomass at anthesis	IPAR after anthesis
		g m^{-2}	g m^{-2}		g m^{-2}	g m^{-2}	MJ m^{-2}
OTTNOV	Bienvenu	734 ± 80	2038 ± 212	0.36 ± 0.01	2116 ± 186	1009 ± 113	715 ± *37*
	Oceania	731 ± 83	2009 ± 242	0.37 ± 0.02	2060 ± 233	1111 ± 171	816 ± *32*
	P	*ns*	*ns*	*ns*	*ns*	*ns*	*<0.001*
OTTJAN	Bienvenu	764 ± 55	1972 ± 123	0.37 ± 0.01	2051 ± 86	895 ± 78	697 ± *20*
	Oceania	678 ± 42	1759 ± 90	0.39 ± 0.01	1852 ± 70	801 ± 56	745 ± *28*
	P	*0.004*	*<0.001*	*0.043*	*0.005*	*0.015*	*ns*
USSDEC12	Bienvenu	270 ± 5	1173 ± 72	0.24 ± 0.01	1350 ± 39	952 ± 54	361 ± *11*
	Oceania	357 ± 10	1296 ± 65	0.28 ± 0.01	1536 ± 36	952 ± 55	459 ± *7*
	P	*<0.001*	*0.015*	*0.004*	*0.002*	*ns*	*<0.001*
USSDEC13	Bienvenu	581 ± 34	1912 ± 131	0.30 ± 0.01	2039 ± 70	968 ± 78	612 ± *12*
	Oceania	597 ± 42	2132 ± 41	0.30 ± 0.01	2201 ± 30	1060 ± 68	696 ± *19*
	P	*ns*	*0.013*	*ns*	*ns*	*ns*	*<0.001*

Clipping negatively affected biomass at both anthesis and maturity in all of the environments, although no effect of clipping on biomass at maturity was detected in the two Ussana environments if the clipped forage was added to the final biomass (Table 7). Despite the generally remarkable effect of clipping on final biomass, GY was only reduced by clipping at OTTJAN and OTTNOV (i.e., environments where there was lower water stress post-anthesis) (Table 1), which was accompanied by a higher HI. In fact, these were the only environments where the unclipped treatments intercepted more radiation and produced more biomass post-anthesis compared with the clipped ones (data not shown). In contrast, the lower biomass of the clipped treatments was advantageous in the two environments – USSDEC12 and USSDEC13 – with the most severe water stress occurring after anthesis (T/ETo<0.18). In these conditions, clipped treatments intercepted the same amount of radiation and produced the same amount of biomass compared with

unclipped ones after anthesis, and thus compensated for their lower biomass at maturity with a higher HI.

Table 7. Grain yield (GY) and HI, biomass at anthesis and at maturity (with and without the forage removed with clipping), and IPAR after anthesis for the two clipping treatments in the five environments. Values are means ± standard errors. P refers to the probability of clipping effect according to the ANOVA (ns, not significant)

Environment	Clipping treatment	GY	Biomass at maturity	HI	Total biomass (clipped included)	Biomass at anthesis	IPAR after anthesis
		g m^{-2}	g m^{-2}		g m^{-2}	g m^{-2}	MJ m^{-2}
OTTNOV	Unclipped	849 ± 26	2323 ± 113	0.37 ± 0.01	2376 ± 112	1267 ± 116	862 ± *37*
	Clipped	589 ± 15	1656 ± 97	0.36 ± 0.02	1803 ± 125	883 ± 56	666 ± *32*
	P	*<0.001*	*<0.001*	*ns*	*<0.001*	*<0.001*	*<0.001*
OTTJAN	Unclipped	787 ± 29	2029 ± 105	0.39 ± 0.01	2043 ± 124	950 ± 49	749 ± *20*
	Clipped	624 ± 9	1699 ± 38	0.37 ± 0.00	1844 ± 52	739 ± 21	690 ± *28*
	P	*<0.001*	*<0.001*	*0.005*	*0.001*	*<0.001*	*0.041*
USSDEC12	Unclipped	323 ± 33	1328 ± 67	0.25 ± 0.02	1387 ± 85	1036 ± 10	398 ± *11*
	Clipped	311 ± 24	1172 ± 59	0.27 ± 0.01	1407 ± 80	890 ± 9	412 ± *7*
	P	*ns*	*<0.001*	*0.040*	*ns*	*<0.001*	*ns*
USSDEC13	Unclipped	622 ± 28	2110 ± 52	0.29 ± 0.01	2108 ± 52	1110 ± 18	664 ± *12*
	Clipped	533 ± 8	1812 ± 148	0.31 ± 0.01	2082 ± 115	858 ± 40	610 ± *19*
	P	*ns*	*0.005*	*ns*	*ns*	*<0.001*	*ns*

No sowing rate effect on GY was observed, as a result of the opposite direction of the differences in biomass at maturity and HI (Table 8). Biomass production was penalized by the higher sowing rate in the environment with the highest water stress in post-anthesis. No effect of sowing rate was observed on the biomass at anthesis.

Table 8. Grain yield (GY) and HI, biomass at anthesis and at maturity (with and without the forage removed with clipping), and IPAR after anthesis for the two sowing rate treatments in the five environments. Values are means ± standard errors. P refers to the probability of clipping effect according to the ANOVA (ns, not significant)

Environment	Clipping treatment	GY	Biomass at maturity	HI	Total biomass (clipped included)	Biomass at anthesis	IPAR after anthesis
		g m^{-2}	g m^{-2}		g m^{-2}	g m^{-2}	MJ m^{-2}
OTTNOV	300	710 ± 42	1870 ± 106	0.38 ± 0.01	1909 ± 112	1024 ± 74	776 ± 40
	600	756 ± 46	2189 ± 119	0.34 ± 0.01	2273 ± 117	1091 ± 102	767 ± 34
	P	*ns*	*<0.001*	*0.003*	*<0.001*	*ns*	*ns*
OTTJAN	300	708 ± 26	1847 ± 65	0.38 ± 0.01	1926 ± 75	874 ± 41	696 ± 22
	600	708 ± 27	1892 ± 71	0.37 ± 0.01	1967 ± 68	819 ± 36	745 ± 25
	P	*ns*	*<0.001*	*ns*	*ns*	*ns*	*ns*
USSDEC12	300	315 ± 16	1306 ± 41	0.25 ± 0.01	1423 ± 34	966 ± 32	405 ± 16
	600	318 ± 15	1161 ± 44	0.28 ± 0.01	1283 ± 82	936 ± 36	409 ± 20
	P	*ns*	*0.002*	*0.020*	*ns*	*ns*	*ns*
USSDEC13	300	609 ± 42	2005 ± 102	0.31 ± 0.01	2090 ± 83	987 ± 46	647 ± 17
	600	562 ± 32	1976 ± 95	0.29 ± 0.01	2105 ± 82	1026 ± 80	638 ± 21
	P	*ns*	*ns*	*0.050*	*ns*	*ns*	*ns*

4. Discussion

Clipping was used in place of grazing because, the type or rate of defoliation has generally only minor effects on GY of dual-purpose cereal crops (Harrison et al. (2011) and papers cited therein), and clipping is highly comparable with the grazing of sheep (Francia et al., 2006; Dann et al., 1983). The wide variation in environmental conditions and in the length of the growing season created by the interaction of cultivar, year and the large range in sowing dates, generated very different LAI patterns. This allowed to better understand the impact of clipping on the processes of LAI recovery and on the capture and use of radiation and water, as well as on biomass partitioning.

Irrespective of the environment, of the short time available, and of their higher phyllochron (Giunta et al., 2015), clipped crops were able to make a complete recovery of radiation interception, in terms of FIPAR, before anthesis. This was partly due to the lack of clipping effects on the number of leaves left to emerge after anthesis (Giunta et al., 2015), given the strong

relationship between leaf number and LAI (Lawless et al., 2005). Nevertheless, the period with reduced leaf area following clipping was mirrored by a severe reduction in IPAR, and consequently, of biomass at anthesis. In some environments, the lower RUE between clipping and anthesis contributed to this lower biomass at anthesis, in contrast to the observations reported by Harrison et al. (2011c) on winter wheat. The lower RUE was probably due to the lower leaf nitrogen levels of clipped crops, consistent with what has been proposed by Lawlor (2001) and Hay and Porter (2006) on the base of the relationship between Rubisco and leaf nitrogen levels and the sensitivity of carbon assimilation rate to Rubisco under light saturated conditions. The impossibility of translocating the nitrogen assimilated before clipping during leaf area recovery likely makes clipped crops more dependent on soil nitrogen availability. It is worth mentioning that Harrison et al. (2011b) considered the RUE of the entire emergence-anthesis period, and that the soil nitrogen availability in their experiments was likely superior to ours. This indicates that a decrease in RUE can be avoided by a proper fertilisation. Hence, the lower nitrogen level of clipped crops could have reduced any positive effect of clipping on RUE, which could have eventually been derived from a better light distribution (Singer et al., 2007).

As expected, clipping caused an increase in E and a decrease in T in most environments in the recovery period, with contrasting but quantitatively small effects on ET, in accordance with the results reported by Harrison et al. (2011c) and Bonachela et al., (1992b). TE between clipping and anthesis decreased with clipping in most environments, signalling a greater impact of decreased leaf area on biomass production than on ET. The LAI lower than 4 observed in the clipped crops with a lower TE supports the suggestion made by Ritchie (1983) (i.e., that ET is nearly maximised at LAIs approaching 3, whereas absorbed radiation continues to increase with LAIs exceeding 4 to 5). That is why the two processes of ET and photosynthesis, although both largely governed by absorbed radiation, respond in quantitatively different ways to its availability. Therefore, it seems

that in our environments, the decrease in TE was not the result of an increase in E, as proposed by Harrison et al. (2011c), but rather, of the drastic reduction in leaf area and biomass production following clipping, according to Bonachela et al. (1995b).

The lower biomass at anthesis of clipped crops can sometimes result in a lower GY, depending on the environmental conditions after anthesis, as observed by Bonachela et al. (1995a). The direction of change in GY was the same as that in HI, which was mainly determined by the post-anthesis conditions (Harrison et al., 2011a). GY was not reduced by clipping when the drought after anthesis was severe enough to increase HI to increase in the clipped crops. Severe drought (T/ETo lower than 0.18), while reducing the average HI compared with environments with more favourable post-anthesis conditions, was more penalizing for the unclipped crops as a consequence of their larger LAI and biomass. Giunta et al., (1995) demonstrated that, in these same environments, LAI values at anthesis of around 5–6 cause faster depletion of soil water compared with values of around 3–4. The consequent levelling-off of differences in LAI between clipped and unclipped treatments lead to similar IPAR and biomass after anthesis, finally resulting in a greater HI of clipped crops and similar GYs. Thus, in contrast to what was proposed by Harrison et al. (2011c), the greater susceptibility to water stress of unclipped crops was not mediated by a lower RUE in this period, but rather by a decrease in IPAR. The entity of the observed reductions in GY in the environments with more favourable post-anthesis conditions (i.e., 21% at OTTJAN and 31% at OTTNOV) are of the same order of magnitude as those reported by Royo and Tribò, (1997) and Royo and Pares (1996) for triticales grown in Mediterranean environments.

In addition to current assimilation in the post-anthesis period, the variation in dry matter partitioning and in HI due to grazing could also result from a reduced amount of shoot dry matter available for retranslocation (Royo and Romagosa, 1996). We did not measure retranslocation, but

when we estimated it according to Santiveri et al. (2004) (data not shown), we found that, in our experiments, the contribution of retranslocation to GY was generally absent or very low. Therefore IPAR after anthesis confirms its key role in determining the effects of grazing on partitioning and on GY variation.

Our results demonstrated the net prevalence of developmental differences over morphological ones throughout the entire growing season in establishing cultivar differences in biomass production. In other words, the availability of radiation as determined by the duration of interception has a greater impact than the ability to capture radiation as determined by morphological traits. Cultivar differences in duration were clear before terminal spikelet and led to general superiority of the intermediate cultivar in terms of biomass production. Both winter forage yield and cultivar differences were highly variable in this period depending on the environment, as also observed by Bonachela et al. (1995). The duration of the subsequent clipping-anthesis period was not always greater in the intermediate cultivar, which was also a consequence of the 'convergence' phenomenon (Hay and Kirby, 1991). Therefore, the amount of IPAR and of biomass produced in this period was clearly not determined by the spring or intermediate habitus.

Morphological differences between cultivars in leaf size and growth habits were also irrelevant in determining their ability to recuperate IPAR after clipping. The relatively high sowing density adopted in this experiment might have contributed to this lack of difference, but usually morphological differences between spring and winter cultivars decline after clipping, in part because winter triticales display a higher tillering rate before terminal spikelet, but a higher tiller mortality than spring cultivars after terminal spikelet (Royo, 1997). The greater winter forage production of the intermediate cultivar was not related to GY reductions due to clipping, but the intermediate cultivar was penalised in terms of GY in the environments with the most severe

terminal water stress. The greater susceptibility of late flowering cultivars to terminal water stress is well documented in triticales and small grain cereals in general (Royo, 1996 and 1997). Sowing rate was only relevant in the pre-clipping period, when the higher rate translated into more biomass at clipping, in accordance with the results of Harrison et al. (2011a). The LAI of the lower rate was high enough to avoid any substantial advantage of the higher rate during the recovery period, but at the same time, it was not so high as to be detrimental after anthesis. Accordingly, Giunta and Motzo (2004) did not find any effect of sowing density (300 vs. 700 plants m^{-2}) on biomass or GY of triticales grown in the same type of Mediterranean environment.

5. Conclusions

Dual-purpose triticale can be a convenient management option in Mediterranean environments that are subjected to severe terminal water stress (T/ETo < 0.18), at least in the environments evaluated in this study. Under these conditions, GY is not affected, but a variable amount of winter forage may be obtained. The amount of IPAR was the main cause of the observed differences in biomass, whether due to cultivar, clipping or sowing rate. In addition, differences in GY were linked to the amount of IPAR after anthesis, regardless of biomass at anthesis. Clipping differentially affected biomass production and ET in environments that did not allow the triticale crops to reach LAI values greater than 3–4. The most important cultivar trait that should be taken into account for dual-purpose utilisation is phenology, as it influences both winter forage yield and GY. However, GY is affected by biomass partitioning more than by differences in leaf area recovery after clipping.

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