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Maximising soybean productivity with late maturity groups in Mediterranean irrigated systems

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ABSTRACT

Context: The EU aims to improve plant protein production profitably and sustainably with a range of grain legumes suitable to different climatic conditions. Soybean (*Glycine max* Merrill) could be one important focus as the crop is adapted to diverse conditions and has the highest protein content per kg of grain. Under Mediterranean irrigated conditions, soybean presents a high-yielding potential, either as an annual single crop (SCS) or as part of a sequential double cropping system (DCS) following a winter crop. However, the lack of experimental data and knowledge in some southern areas like Spain, led to the use of rather early maturity groups (referring to experiences from more northern and eastern areas) that are underperforming in southern latitudes (i.e. < 42° N).
Objective: The aims were to (i) explore later soybean maturity groups than currently used for SCS and DCS and (ii) quantify the drivers of their performance under Mediterranean irrigated conditions.
Methods: A field experiment was carried out in NE Spain (2019, 2020 and 2021) in a split-plot design with four replications. In the main plots, SCS and DCS sowing dates were tested. In the sub-plots, 8–13 cultivars were tested per year covering MG from early 00 to late III. Five biomass sampling dates during soybean development were performed to fit a growth curve for every MG and sowing date. Grain yield, grain protein content, grains m^{-2}, thousand-grain weight, 1st pod height and biological N fixation were measured at physiological maturity.
Results: The growth curve asymptote showed the strongest correlation with the soybean grain yield ($r = 0.95$) and the number of grains m−2 ($r = 0.88$). Consistent higher yields for MG II and III (4476 and 5314 kg ha−1, respectively) were found in the SCS and DCS compared to earlier MG. Grain protein concentration was reduced in the later MG but in all cases exceeded 40 g 100 g^{-1}. In the DCS, a grain yield reduction of 25 % compared to SCS was observed, mainly caused by fewer grains m^{-2}. Biological N fixation was low (30 g 100 g^{-1}, on average), resulting from high residual soil N.
Conclusions: In the SCS, the use of later MG (II and III) increases soybean yields. However, further research exploring MG III or later would better define soybean potential in these systems. While the agronomic performance of late MG (II and III) in the DCS was promising, technical aspects such as later harvesting date (moisture, pod shattering, etc.) or a slight reduction in grain protein concentration (although still above 40 g 100 g^{-1}) should be considered.
Implications or significance: Our study proposes a shift towards the use of later soybean MG for Mediterranean irrigated cropping systems as a strategy to improve its competitiveness and, likely, farmer's adoption. This study highlights the potential to expand soybean production towards Mediterranean irrigated areas with a high yield potential.

1. Introduction

The European Union (EU) is largely dependent on plant protein imports, especially soybean (*Glycine max* Merrill), from areas such as the United States, Brazil and Argentina (Eurostat, 2022). In the last years, the EU started exploring ways to improve protein production in a profitable and sustainable way (European Commission, 2018), with legume crops being at the core of this strategy. Among them, soybean is

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one of the top candidates for protein production due to its high seed protein content (39–45 %) and perfect amino acid profile for feed (Gatel, 1994) and currently in expansion in central and northern Europe (Debaeke et al., 2022; Karges et al., 2022) Although most of the imported soybean (ca. 93 %) is devoted to feed production, food-grade soybean is gaining attention due to changing diet trends towards more plant-based food (Moller et al., 2019). This shift in dietary habits can also generate an opportunity for EU soybean growers, as the local production has a lower environmental footprint (Springmann et al., 2018) and ensures it is not genetically modified, currently a key requisite for European food-grade soybean (Eriksson et al., 2019). From the agronomic perspective, the EU Green Deal is promoting sustainable cropping systems with a larger share of grain legumes (European Commission, 2019). Introducing legumes in cropping systems brings certain benefits such as a sustainable nitrogen (N) input through biological fixation (Peoples et al., 2009), pest and disease break in cereal-dominated systems (Krupinsky et al., 2002), increased yield of the following crops (Preissel et al., 2015) and lower environmental impacts (Reckling et al., 2016). However, cultivars and management practices are often not adapted to the new cropping systems that are introduced to.

Soybean in particular is adapted to a broad range of temperatures and daylight length (Mourtzinis and Conley, 2017) and there is wide existing knowledge of its physiology and management from other areas (e.g. Cattelan and Dall'Agnol, 2018; Liu et al., 2008). While soybean production in Europe is expected to grow towards Northern latitudes due to climate change (Nendel et al., 2023), little attention is paid to the Mediterranean region where soybean is largely underexplored, especially in Spain. In that regard, Mediterranean regions present specific climate conditions that significantly differ from those in central Europe and the SW of France, with warmer temperatures enabling a longer cropping season and, especially, dry and hot summer (Metzger et al., 2012). However, when irrigated, Mediterranean cropping systems are characterized by highly-productive maize (*Zea mays* L.), as a single continuous crop or as a sequential double cropping system with a winter cereal (e.g. barley (*Hordeum vulgare* L.)-maize) (both grain crops) (Maresma et al., 2019; Martínez et al., 2017). Given the productivity of such systems, diversification with winter grain legumes (such as pea (*Pisum sativum* L.) or faba bean (*Vicia faba* L.)) is often not attractive for farmers due to poor performance compared to cereals. Soybean (especially if intended for food-grade) could be a suitable alternative for diversifying these systems, contributing to N use reduction as well as to increase protein production. In that regard, Simon-Miquel et al. (2023) studied the impact of introducing soybean at the crop, pre-crop and cropping system levels in a Mediterranean area of NE Spain. They concluded that despite a yield increase in the following maize, a three-year rotation with soybean competed poorly with high-yielding maize (ca. 16 t ha^{-1}) in a single cropping system in terms of energy and protein production. Nonetheless, a barley-soybean double cropping system led to a significant increase in protein production and a reduction in synthetic N use compared to the barley-maize double cropping system. A significant part of this reduction is due to soybean biological N capacity. While this process has been studied and quantified in several environments (Ciampitti and Salvagiotti, 2018; Salvagiotti et al., 2008), there is a lack of robust empirical data for soybean under Mediterranean conditions. In addition, introducing soybean in a maize-dominated cropping system should also decrease the demand for irrigation water, as soybean generally presents lower water needs than maize to achieve its yield potential (Suyker and Verma, 2009).

Under irrigated Mediterranean conditions, soybean could present a high yield potential (warm temperatures and water availability) but there is a lack of experimental data quantifying soybean production potential, and the drivers affecting this potential. In areas with large soybean production, models and decision tools for sowing date, maturity group (MG) selection or cultivar comparison have been developed. It is the case, for instance, of SoyStage (https://soystage.uark.edu/) in the US Midsouth (Santos et al., 2019) or Cronosoja (http://cronosoja.agro.uba.ar/), developed in Argentina (Severini et al., 2017). In Europe, similar approaches have begun at the research level and mainly for single cropping system conditions. It is the case, for instance, of the Simple Phenology Algorithm, developed in France to predict soybean phenology for a range of MG expanding from 000 to II (Schoving et al., 2020). In addition, under European conditions, the prohibition of GM-soybean use further stresses the need for local research. Therefore, the lack of information and commercial production leads to choices of MG and varieties based on experiences from more northern and eastern areas.

This situation can translate into the use of underperforming soybean maturity groups and cultivars. While simulation studies have been carried out covering the European Mediterranean area (Guilpart et al., 2022; Nendel et al., 2023), they reflect primarily soybean grown under single cropping systems (i.e. one crop per year, planted at the optimum sowing date). Nonetheless, in Mediterranean irrigated areas double cropping systems with soybean are feasible and highly competitive compared to the common barley-maize double cropping system (Simon-Miquel et al., 2023). Double cropping systems under Mediterranean –and most European areas– are understudied.

Soybean is a temperature and photoperiod-sensitive species. Temperature accelerates crop development and photoperiod modifies flowering induction (Garner and Allard, 1930; Yang et al., 2019), and pod setting and growth (Kantolic and Slafer, 2007). Soybean is a short-day plant species, meaning that floral induction occurs only when the day length is shorter than a certain threshold. The value of this threshold determines, in part, the MG of each cultivar, with cultivars in MG 000, 00 and 0 being fairly independent of photoperiod, while MG later than I will only be induced to flowering when exposed to shorter days (in summer) found in lower (nearer to the equator) latitudes (Yang et al., 2019). The former MG (earlier ones) are adequate for expanding soybean towards northern and colder European latitudes (Karges et al., 2022). However, two questions arise for the expansion towards the south. Firstly, higher temperatures than in central and northern Europe lead to a greater thermal time (growing degree days; GDD) and the southern latitude offers a less restricting photoperiod available for development. Therefore, exploring later maturity groups under these conditions could help maximize soybean yields. Secondly, the mild temperatures during winter and water availability (through irrigation) allow for a barley-soybean double cropping system (Simon-Miquel et al., 2023), which implies a significant delay in soybean sowing (from early May to early July). Such delay has been reported to cause yield reductions ranging from 18 to 45 % in areas such as the southern Pampas of Argentina (Calviño et al., 2003a) or the Southeast US (Morris et al., 2021). The drivers for the yield reduction are inevitably linked to a shorter growing period (Andrade et al., 2015) but can be minimized through management and adequate MG choice (Morris et al., 2021). While MG selection for double cropping has been extensively researched in N and S America (Andrade and Satorre, 2015; Salmerón et al., 2014), there is a knowledge gap for Mediterranean conditions on the behaviour of soybean MG under double cropping systems, a key aspect for the adoption of such cropping systems.

Our objectives were to (i) explore later soybean maturity groups than currently used for high-yielding irrigated cropping systems grown as a single or double crop and (ii) quantify soybean growth kinetics, N fixation and yield components as drivers for the performance under Mediterranean irrigated conditions. We hypothesize that later MG (II/III) than currently used (MG 00-I) would be able to exploit the long growing season under Mediterranean irrigated conditions, both in single and double cropping systems.

2. Materials and methods

2.1. Experimental site and design

Field experiments were carried out in the Lleida plain in north-eastern (NE) Spain in 2019, 2020 and 2021 (Table 1). Each year, the experiments were carried out on farmer's fields within a small distance among them (Table 1) The climate in the area is Mediterranean semiarid with an annual mean air temperature of 14.1 °C and a total precipitation of 384 mm distributed in autumn and spring months. Potential evapotranspiration is 1026 mm annually. Climate data was retrieved from the nearest weather station (5–7 km NE from the sites) owned by the Meteorological Service of Catalonia. In the latitude of the experimental sites, the annual photoperiod varies from 10.2 h (mid-December) to 16.3 h (late June). The soils were characterized each year before sowing and were classified as Xeric Pertocalcids (Soil Survey Staff, 2014). The soils were fine textured with a slightly basic pH (Table 1). Except in 2020 site, soil salinity was low. Calcium carbonate contents were moderate in 2019 and 2021 sites and high in the 2020 (Table 1). Soil organic C was higher in 2019 and 2021 sites compared to the 2020 and total N (Kjeldahl), available P (Olsen) and K (ammonium acetate) presented moderate to high levels in the three sites (Table 1).

The pre-crops were maize in all years and the soil was kept bare during winter. The field experiments were conducted in a split-plot design with four (2019 and 2020) and three (2021) replications. In the main plots, two sowing dates resembling a single-cropped soybean (SCS) and a double-cropped soybean (DCS) were tested. In the sub-plots, 8 cultivars were tested covering a maturity group range of 00 (2 cultivars), 0 (2 cultivars) and I (4 cultivars) every year (Table 2). According to the results observed in 2019, 2 cultivars of MG II were added in 2020. As well, an extra MG II cultivar and 2 MG III cultivars were added in 2021, making a total of 8, 10 and 13 cultivars in 2019, 2020 and 2021, respectively (Table 2). Plot size was 12 m^2.

2.2. Crop management

Soybean was inoculated with peat-based inoculum (HiStick® from BASF, *Bradyrhizobium japonicum)* at the recommended rate of 4 g kg^{-1} of seed in 2019 and 2021. In 2020, liquid-based inoculum (Lalfix DUO® from Lallemand, *Bradyrhizobium elkanii*) at the recommended rate of 3 g kg^{-1} seed was used. In all the cases, inoculation was done within 12–15 h before soybean sowing. Soil was prepared by a rototiller and soybean was planted on 15/5/2019, 20/5/2020, and 12/5/2021 in the SCS and on 28/6/2019, 7/7/2020, and 6/7/2021 in the DCS. The row width was 75 cm, and the sowing density was 45 seeds m^{-2}. The relatively high row width was chosen for technical reasons (using the farmers sowing machinery for maize) and because we did not detect differences in row width on grain yield in an earlier study (Simon-Miquel et al., 2023).

Table 1
Location and soil properties (0–30 cm) of the experimental sites in 2019, 2020 and 2021.

	2019	2020	2021
Location			
Latitude	41°39'11.1'' N	41°39'25.5''N	41°35'24.2''N
Longitude	0°45'01.8'' E	0°43'58.3''E	0°44'46.1''E
Altitude (m)	186	181	240
Soil characteristics (0-30 cm)			
pH (ext. 1:2.5 H_2O)	8.1	7.9	8.1
EC[*] (ext. 1:5 H_2O; dS m^{-1})	0.325	2.54	0.3
Organic C (g kg^{-1})	16.2	9.9	17.7
Calcium carbonate (g 100 g^{-1})	13	48	24
N (Kjeldahl) (g 100 g^{-1})	0.186	0.126	0.250
P (Olsen; mg kg^{-1})	24	23	30.5
K (ammonium acetate; mg kg^{-1})	246	343	184
Texture	Clay-loam	Clay	Clay-loam
Sand (g 100 g^{-1})	33	28	32
Silt (g 100 g^{-1})	34	28	34
clay (g 100 g^{-1})	33	44	34

[*] EC: Electric conductivity.

Table 2
Maturity group, name, breeder, and inscription country of the cultivars used in 2019, 2020 and 2021.

MG	Cultivar	Breeder	Country	2019	2020	2021
00	ES Mentor	Lidea France S.A.S	France	x	x	x
	RGT Siroca	RAGT	France	x	x	x
0	Pepita	ERSA[a]	Italy	x	x	x
	Primus	Semences Prograin	Austria	x	x	x
I	Avril	Asociados Don Mario S.A.	Italy	x	x	x
	ES Isidor	Lidea France S.A.S	France	x	x	x
	ES Pallador	Lidea France S.A.S	France	x	x	x
	Luna	IFVC[b]	Serbia	x	x	x
II	ES Creator	Lidea France S.A.S	France		x	x
	ES Inventor	Lidea France S.A.S	France		x	x
	RGT Symbala	RAGT Semences	France			x
III	Experimental I	Apsov	Italy			x
	Experimental II	Apsov	Italy			x

[a] ERSA: Agencia Regionale per lo Sviluppo Rurale.

[b] IFVC: Institute of field and vegetable crops.

Planting density was kept constant across cropping systems and cultivars to minimise sources of variability among treatments and avoid confounding effects. Weeds were controlled with a pre-emergence herbicide (Pendimethaline (688 g ha^{-1}) plus Clomazone (138 g ha^{-1})) and mechanical weeding when needed. The experimental fields were located in a surface irrigated area, where water flows down the field distributing it evenly through the cropped area. Irrigation events corresponded to 100–120 mm each, approximately. In the SCS, five (2019) and six (2020 and 2021) irrigation events were applied each year and four (2019) and five (2020 and 2021) were applied to the DCS. The number and date of irrigation events was decided according to crop needs and soil water status. Soybean fertilization was decided according to the pre-plant soil nutrient analyses. In the case of N, the pre-plant soil nitrate contents were, on average, 52 mg kg^{-1} in the 0–60 cm. Given the soybean potential for N fixation, no N fertilization was considered necessary. Similarly, the pre-plant soil contents of P and K, described in Table 1, were considered sufficient for a high-yielding soybean. Harvesting was performed whenever cultivars reached harvest maturity and adequate grain moisture level using a plot combine harvester.

2.3. Data acquisition

Soybean phenology was registered using Fehr et al. (1971) scale throughout the growing season with an average frequency of three times a week. Aboveground biomass samplings were carried out when MG I cultivars reached stages V3, R1, R3, R6 and R8 and the sampling area was 0.5 m along the sowing row. At R8, besides total biomass, the following yield components were measured: pods m^{-2}, grains pod^{-1}, and thousand-grain weight (TGW). As well, the first pod height was also measured at R8. Grain N concentration was determined by dry combustion (model Truspec CN, LECO, St Joseph, MI, USA). To convert grain N content to crude protein concentration, the 6.25 factor was used (although controversial according to Mariotti et al., 2008) as it is the factor used by the industry to evaluate soybean suitability for food grade. Generally, the threshold for food-grade soybean in Spain is a minimum of 40 g 100 g^{-1} of crude protein, among other factors such as grain and hilum colour. Soybean N fixation was measured at the R3 (2019 and 2020) and R6 (2021) sampling dates using the ^{15}N natural abundance method (Unkovich et al., 2008) (Eq. (1)). A dicotyledonous weed (*Chenopodium album* L.) (2019) and buckwheat (*Fagopyrum esculentum* Moench) (2020 and 2021) were used as a non-N-fixing reference plant and were collected separately for each replication in order to minimize spatial variability.

$$Ndfa = \frac{\delta^{15}N \quad reference \quad plant - \delta^{15}N \quad of \quad legume}{\delta^{15}N \quad reference \quad plant - B} x100 \tag{1}$$

Where *Ndfa* is N derived from atmosphere (N biologically fixed), *$\delta^{15}N$ reference plant* and *$\delta^{15}N$ of legume* are the parts per thousand deviations relative to the nominated international standard atmospheric N_2 (0.3663 atom % ^{15}N) for the reference plant and the legume crop, respectively. *B* value is a constant to account for the within-plant fractionation of ^{14}N and ^{15}N between shoots and nodulated roots and was − 1.83 for soybean (Unkovich et al., 2008). The use of a tabulated *B* value is justified by the low levels of Ndfa found in this experiment. As stated in the cited manual, the impact of B value is relatively low (4–6 g 100 g^{-1}) in cases with low proportions of Ndfa (<40 g 100 g^{-1}).

2.4. Data analysis

Growth curves were adjusted to the aboveground biomass data (Y-axis) using the growing degree days accumulated as the X-axis. Given the photoperiod sensitivity of soybean, growing degree days (°C day) were calculated using the STICS soil-crop model algorithm for soybean development units (see ch. 2.3.3 in Brisson et al., 2008). Such algorithm is based on the mean air temperature and a correction factor for the photoperiod (Eq. (2))

$$GDD = udevair \quad x \quad RFPI \tag{2}$$

$$if \quad t_{air} \le td_{\min} \qquad udevair = 0$$

$$if \quad td_{\min} < t_{air} < td_{\max} \quad udevair = t_{air} - td_{\min}$$

$$if \quad t_{air} \ge td_{\max} \quad udevair = td_{\max} - td_{\min}$$

Where *GDD* are the growing degree days (°C day) summed from sowing to harvesting, *udevair (°C)* is the temperature effect calculated depending on the mean daily temperature and the minimum and maximum temperatures for development, t_{air} (°C) is the arithmetic mean between maximum and minimum daily temperature, td_{min} (°C) is the minimum temperature for GDD accumulation and td_{max} (°C) is the maximum threshold temperature for development. *RFPI* (dimensionless) is the factor that slows down development depending on the photoperiod and is calculated following Eq. (3).

$$if \quad phoi \le Phosat \quad RFPI = 1$$

$$if \quad Phosat < phoi < Phobase \quad RFPI = \frac{phoi - Phosat}{Phosat - Phobase} + 1 \tag{3}$$

$$if \quad phoi \ge Phobase \quad RFPI = 0$$

Where *phoi* is the daily photoperiod (h), *Phosat* (h) is the minimum photoperiod below which the photoperiod does not affect crop development, and *Phobase* (h) is the threshold photoperiod above which there is no crop development. The photoperiod effect is only applicable after the emergence of the crop which is estimated to be 9–14 days, according to the STICS germination algorithm (see ch. 2.2 in Brisson et al., 2008 for further explanation). The values of the parameters used for these calculations are described in Table 3.

The growth curves were fit using average values of each cultivar for each year, cropping system, and maturity group. A logistic function with three parameters was used (Eq. 4). Compared to other models, such as the four-parameter logistic and the three and four parameters Gompertz model, the selected one presented the lowest AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) values. In addition, this selection is supported by the broad use of this model in agricultural sciences, its parsimony and the fact that the parameters are associated with identifiable biological processes (Archontoulis and Miguez, 2015; Bodner et al., 2010).

Table 3
Parameter values used for growing degree days calculation.

Parameter	Value
Tdmin (°C)	5
Tdmax (°C)	25
Phosat (h)	15
Phobase (h)	18
RFPI range (dimensionless)	0.55-1

$$Y = \frac{Y_{asym}}{1 + \exp(-k(t - t_m)} \tag{4}$$

Where *Y* is the response variable (aboveground biomass (in kg ha^{-1}) accumulated at time *t*), Y_{asym} kg ha^{-1}) is the maximum biomass accumulation, *k* (GDD^{-1}) is the parameter that controls the steepness of the curve and t_m (GDD) is the inflection point (*t* at which the growth rate is maximum) (Archontoulis and Miguez, 2015). Once the curves were fit, the parameter estimates (Y_{asym}, t_m *and* *k*) were extracted for each curve (one for each year, cropping system and maturity group).

Statistical analyses and curve fitting were performed using JMP Pro 16 (SAS Institute Inc., 2019). The growth models were fitted using the *fit curve* platform from JMP Pro 16. The parameter estimates of each curve were subjected to an analysis of means. Analyses of variance (ANOVA) for the following variables were performed: grain yield, grain protein content, 1st pod height, grains m^{-2} (resulting from the multiplication of pods m^{-2} and grains pod^{-1}), TGW, N acquisition, Ndfa (proportion of N acquisition and magnitude), and N derived from soil (Ndfs). The cropping system was included as the main factor and the MG as a sub-factor. Independent ANOVA for each year was performed given the different number of maturity groups (and cultivars) included each year. The block effect was kept as a fixed factor. Honest Significant Difference (HSD) Tukey means separation test was performed for significant interactions and single effects ($p < 0.05$). Correlation analyses between the growth curves parameter estimates, phenology, and agronomic variables (grain yield, grain protein content, grains m^{-2}, TGW, 1st pod height and Ndfa (proportion of N acquisition and magnitude)) were performed.

3. Results

3.1. Climate

Precipitation during the soybean cropping season (May-October) was above the long-term average (201 mm) in 2019 and 2020 (273 and 217 mm, respectively) and below the long-term average in 2021 (126 mm). During the soybean growing season, the potential evapotranspiration is, on average, 4.9 times greater than the precipitation received, stressing the importance of irrigation water compared to precipitation. No remarkable differences were observed in the mean air temperature during the soybean growing season compared to the long-term average. Regarding extreme temperatures, 27, 20 and 14 days with maximum temperatures above 35 °C were registered in 2019, 2020 and 2021, respectively (Fig. 1). Such temperatures were registered mainly from late June to late July (Fig. 1). No cold spells were observed either year, defined as minimum temperatures below 5 °C during June-September (adapted from Nendel et al. (2023).

3.2. Soybean biomass accumulation

Growth models showed differential soybean biomass accumulation kinetics within cropping systems and maturity groups. For each year, biomass accumulation models were plotted for the earliest (00) and the latest maturity group (I, II and III in 2019, 2020 and 2021, respectively) along with the pod development phenological stages (R3 to R6, Fig. 2). In the DCS, asymptotes (Y_{asym}) presented lower values than their SCS counterparts, except for MG 00 in 2019. In all the cases, the MG 00

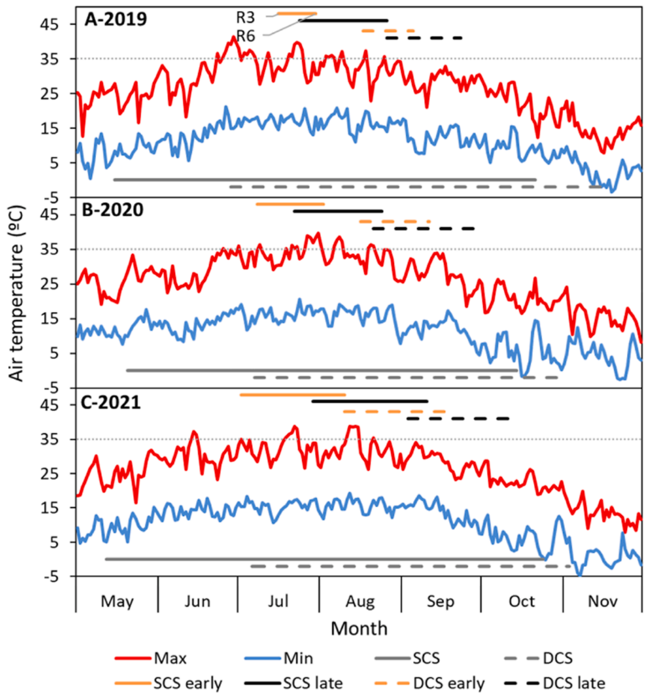


Fig. 1. Minimum and maximum air temperatures during soybean cropping season in 2019 (A), 2020 (B) and 2021 (C). Grey lines at the bottom indicate the cropping season for single-cropped soybean (SCS, solid) and double-cropped soybean (DCS, dashed). Black and orange lines at the top indicate phenological reproductive stages R3 to R6 for the earliest (MG 00) and latest MG (MG I, II and III in 2019, 2020 and 2021, respectively) in each cropping system according to the legend.

asymptote in the SCS (SCS early) fell at a similar level than the latest MG (DCS late) in the DCS (Fig. 2). Exceptionally, in 2019, the earliest cultivar in the SCS and both MG in the DCS presented the same asymptote. In 2019, the lowest asymptote was found in the MG 0 in the DCS (Table 4). Except in 2019, which presented overall lower asymptotes and k values (5660 kg ha^{-1} and 4.9E-03 GDD^{-1}, respectively), later MG presented significantly greater asymptotes in both cropping systems compared to earlier MG (Table 4). The non-represented curves all showed asymptotes within the extremes represented in Fig. 2 (Table 4).

k values were, on average, lower in 2019 (4.90E-03) than in 2020 and 2021 (6.33E-03 and 6.7E-03, respectively, Table 4). However, within each year, no significant differences were found between cropping systems or MG. The inflection point (t_m) was at 937, 773 and 963 GDD in 2019, 2020 and 2021, respectively, with the SCS presenting a trend towards earlier inflection points (although only significant in 2020, Table 4). Although not statistically significant, later MG presented a consistent trend towards later inflection points (except in 2019 DCS),

Table 4

Parameter estimates for the soybean growth curves (Y_{asym}: asymptote; k: parameter controlling the steepness of the curve; t_m: inflection point). *Indicates significant differences with the yearly average at $p < 0.05$ according to the analysis of means (CS, cropping system (SCS: single-cropped soybean; DCS: double-cropped soybean); MG, maturity group).

Year	CS	MG	Y_{asym} (kg ha^{-1})		k (GDD^{-1})	T_m (GDD)	
2019	SCS	00	4972		5.03E-03	825	
		0	6326		5.04E-03	865	
		I	7677	*	4.74E-03	927	
	DCS	00	4817		4.97E-03	1044	
		0	4472	*	6.03E-03	940	
		I	4757	*	4.79E-03	1037	
Average			**5660**		**4.90E-03**	**937**	
2020	SCS	00	8907		7.11E-03	669	
		0	9305		7.70E-03	673	
		I	9854		7.06E-03	657	*
		II	12,459	*	5.34E-03	763	
	DCS	00	6319	*	7.57E-03	910	
		0	6793	*	5.60E-03	932	
		I	8043		6.46E-03	990	*
		II	8744		6.79E-03	1026	*
Average			**8773**		**6.33E-03**	**773**	
2021	SCS	00	8376		8.47E-03	743	
		0	9728		8.76E-03	746	
		I	10,903		8.63E-03	801	
		II	11,391		7.52E-03	840	
		III	14,477	*	5.64E-03	951	
	DCS	00	5964	*	5.60E-03	898	
		0	7857		6.97E-03	1000	
		I	8553		5.73E-03	960	
		II	8241		9.11E-03	1016	
		III	9507		5.36E-03	1041	
Average			**9656**		**6.30E-03**	**869.95**	

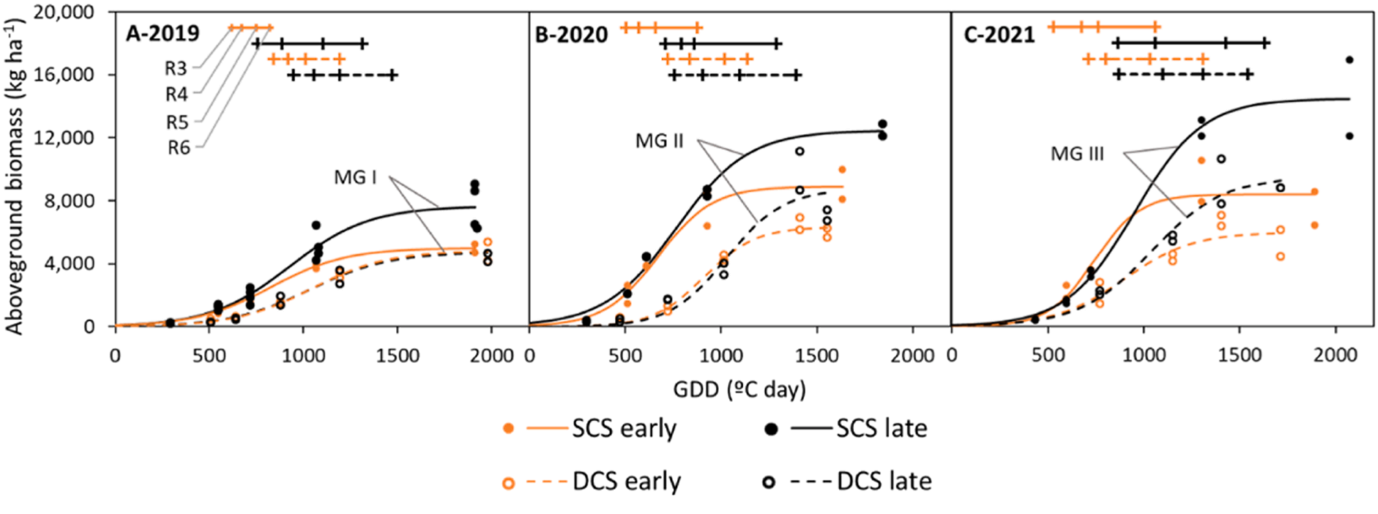


Fig. 2. Soybean biomass accumulation curves in 2019 (A), 2020 (B) and 2021 (C). Solid lines indicate single-cropped soybean (SCS) and dashed lines indicate double-cropped soybean (DCS). Only the earliest (00) (early, in orange) and the latest (late, in black) maturity groups (I, II and III in 2019, 2020 and 2021, respectively) were plotted. Straight lines at the top indicate phenology stages from R3 to R6 as detailed in subFig. A for the early SCS (solid orange line). Dots refer to average biomass observation (means for cultivar within each cropping system) for SCS (full dots) and DCS (empty dots).

with differences ranging between 94 and 143 GDD compared to MG 00 (Table 4).

Regarding the phenology, the pod filling period (R3-R6) started earlier in the SCS early MG than in the DCS (Fig. 2, straight lines at the top). Also, the pod-filling period was longer in the late maturity groups (I, II and III in 2019, 2020 and 2021, respectively) than in the earlier ones (MG 00) (Fig. 2).

3.3. *Agronomic performance*

Soybean grain yield was affected by the cropping system and maturity group simple effects in 2019 and 2020 and only by the maturity group in 2021 (Table 5). Regarding the maturity group effect, the latest MG tested each year (I in 2019, II in 2020 and III in 2021) showed the highest yields (Fig. 3A). In 2019, with overall lower yields, MG I was significantly higher than MG 00, but not than MG 0. In 2020, MG I and II presented the highest yields (4765 kg ha^{-1}, on average) compared to the earlier ones (3505 kg ha^{-1}, on average). In 2021, MG III presented the highest yield (5314 kg ha^{-1}), significantly higher than the other MG, except for MG I (4702 kg ha^{-1}) (Fig. 3A). A consistent reduction of soybean yields was observed in the DCS compared to the SCS, with this effect being significant in 2019 and 2020 (32 % and 27 % yield reduction, respectively), but not in 2021 with a 16 % yield reduction (Fig. 3B).

Grain protein concentration was affected by the cropping system and the maturity group simple effects in 2020 and 2021 (Table 5) and followed the opposite trend of grain yield with values ranging from 41.7 to 48.5 g 100 g^{-1}. In 2019, no significant differences were observed, but a trend toward lower grain protein concentration in MG I compared to MG 00 and MG0 was identified (Fig. 3A). This trend was evident, and statistically significant in 2020 and 2021, except for MG II in 2020 (Fig. 3A). Regarding the cropping system effect on grain protein concentration (significant in 2020 and 2021), higher protein concentrations were obtained in the SCS (44.8 and 45.4 g 100^{-1} g in 2020 and 2021, respectively) compared to the DCS (42.7 and 44.1 g 100^{-1} g in 2020 and 2021, respectively) (Fig. 3B). In all cases, grain protein concentrations observed, albeit the described differences, exceeded the 40 g 100^{-1} g threshold for food grade soybean in Spain.

The number of grains m^{-2} was affected by the maturity group in all years (Table 5), with more grains m^{-2} in the late MG (Table 6). Qualitatively, 2019 was the year with fewer grains m^{-2} (1105 grains m^{-2}, on average) compared to 2020 and 2021 (on average, 1969 and 2088 grains m^{-2}, respectively). Although not significant, the number of grains m^{-2} in the SCS was higher than in the DCS by 217–424 grains m^{-2} (Table 6). The TGW was only affected by the maturity group in 2020, with greater grains in the MG 00 compared to MG I and II (Table 6). The cropping system did not affect the TGW. The height of the first pod was affected by the MG and cropping system simple effects. Regarding the former one, later MG presented a higher insertion point of the first pod (Table 6). In 2019, all MG presented the first pod below 8 cm. In 2020 and 2021, first pod insertion was generally higher with late MG presenting values above 12 cm (2020) and 14 cm (2021) (Table 6). The SCS led to higher first pod insertion compared to DCS, with differences of 2.3, 6.9 and 2.4 cm found in 2019, 2020 and 2021, respectively (Table 6).

Overall, biological N fixation in the experiments was low (below 30 g 100 g^{-1} in most cases, Table 7) and was affected by the cropping system in 2019 and by the cropping system and MG interaction in 2020 (Table 5). In 2019, the proportion of Ndfa was higher in the SCS than in the DCS (Table 7). In 2020, a lower Ndfa proportion was found in the earlier MG compared to MG II in the SCS and all MG in the DCS (Table 7). In 2021, no significant differences were found in the Ndfa proportion regarding the cropping system and MG. Values of δ 15 N for the soybean and the reference plants can be found in Table S1.

Biomass at Ndfa measurement was not significantly affected by the cropping system (Table 5), presenting average values of 1800, 4096 and 10,112 kg ha^{-1} in 2019, 2020 and 2021 (Fig. 4A). The greater amount of biomass accumulated in 2021 was due to the later sampling date (R6 stage) compared to the other years (R3 stage). The amount of Ndfa was affected by the cropping system in 2019 and 2020 (Table 5). In 2019, higher Ndfa values were found in SCS than in the DCS (18 vs. 7 kg ha^{-1}, respectively), whereas in 2020 the opposite situation was observed with 9 and 72 kg ha^{-1}, respectively (Fig. 4A). In 2021, the difference between cropping systems was not significant. The amount of Ndfs was affected by the cropping system in 2019, with a greater value in the DCS (Fig. 4A). Biomass accumulation was affected by the MG in 2021 (Table 5), with the later MG presenting larger biomass accumulated (Fig. 4B). As explained above, the larger biomass in 2021 was due to a later sampling date. The amount of Ndfa was, on average, 11 kg N ha^{-1} in 2019. In 2020, the amount of Ndfa was greater in MG II than in MG 0 (60 and 38 kg N ha^{-1}, respectively), with MG 00 and I presenting intermediate values. In 2021, no significant differences between MG were detected. However, as in 2020, a trend towards greater Ndfa in the later MG was observed (Fig. 4B). The amount of Ndfs was affected by the MG only in 2020, with more Ndfs in MG 00 and I than in MG II (Fig. 4B).

3.4. *Linking soybean growth and agronomic performance*

The parameter estimates characterizing the growth curves were correlated with the soybean phenology and agronomic performance (Fig. 5; Fig. S1). The asymptote showed the strongest correlations with

Table 5

Effects (p values) of cropping system, maturity group and their interaction for soybean grain yield, grain protein content, grains m^{-2}, thousand-grain weight (TGW), 1st pod height, proportion of N derived from atmosphere (Proportion Ndfa), aboveground biomass at Ndfa measure, and amount of Nitrogen derived from atmosphere (Ndfa) and soil (Ndfs) for the three experimental years (2019, 2020 and 2021). **Bold** p-values indicate $p < 0.05$.

Year	Factor	Grain yield	Grain protein content	grains m^{-2}	TGW	1st pod height	Proportion Ndfa	Biomass at Ndfa measure	Ndfa	Ndfs
2019	Cropping system (CS)	**0.013**	0.766	0.096	0.096	**0.008**	**0.016**	0.120	**0.016**	**0.016**
	Maturity Group (MG)	**< .001**	0.098	**0.003**	0.678	**0.028**	0.083	0.189	0.083	0.076
	CS x MG	0.383	0.976	0.705	0.696	0.392	0.753	0.620	0.753	0.330
2020	Cropping system (CS)	**0.009**	**< .001**	0.179	0.472	**0.005**	**0.003**	0.530	**0.009**	0.129
	Maturity Group (MG)	**< .001**	**< .001**	**< .001**	**< .001**	**0.049**	**< .001**	0.348	**0.036**	**0.026**
	CS x MG	0.343	0.470	0.715	0.553	0.643	**0.002**	0.381	0.146	0.054
2021	Cropping system (CS)	0.135	**0.026**	0.139	0.616	**0.032**	0.319	0.190	0.250	0.909
	Maturity Group (MG)	**< .001**	**< .001**	**0.003**	0.176	**< .001**	0.496	**0.013**	0.344	0.186
	CS x MG	0.956	0.292	0.796	0.402	0.349	0.786	0.640	0.617	0.203

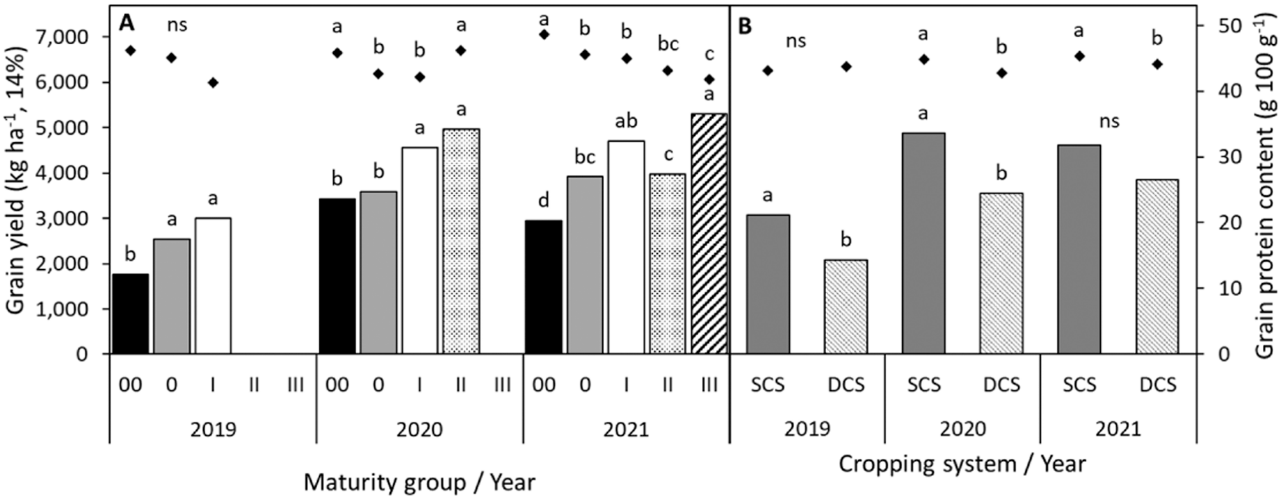


Fig. 3. Soybean grain yield (columns) and protein content (dots) for the three experimental years depending on the maturity group (A) and the cropping system (SCS: single-cropped soybean; DCS: double-cropped soybean) (B). Different letters within each variable and year indicate significant differences at $p < 0.05$.

Table 6

Number of grains m^{-2}, thousand-grain weight (TGW) and 1st pod height depending on the cropping system (SCS: single-cropped soybean; DCS; double-cropped soybean) and maturity group simple effects for the three experimental years (2019, 2020 and 2021). Different letters within each variable and year indicate significant differences at $p < 0.05$. ns: not significant.

Year	Maturity group	grains m^{-2}		TGW (g)		1st pod height (cm)	
2019	00	874	b	209	ns	5.8	b
	0	1129	ab	218		5.9	b
	I	1311	a	208		7.8	a
2020	00	1468	b	218	a	9.6	b
	0	2010	ab	203	ab	11.1	ab
	I	2344	a	185	b	12.3	a
	II	2052	a	193	b	12.5	a
2021	00	1538	c	198	ns	6.7	b
	0	2150	ab	183		8.0	b
	I	2437	a	193		9.2	b
	II	1958	bc	209		9.9	b
	III	2357	ab	204		14.7	a
	Cropping system						
2019	SCS	1265	ns	206	ns	7.9	a
	DCS	1048		216		5.6	b
2020	SCS	2168	ns	198	ns	15.0	a
	DCS	1920		195		8.1	b
2021	SCS	2326	ns	196	ns	10.8	a
	DCS	1901		199		8.4	b

Table 7

Proportion of N derived from atmosphere (Ndfa) depending on the cropping system and maturity group interaction in 2019, 2020 and 2021. Brackets indicate soybean phenological stage at the Ndfa measure. Different letters within each column indicate significant differences at $p < 0.05$.

Cropping system	Maturity group	Proportion Ndfa (g 100 g^{-1})				
		2019 (R3)		2020 (R3)		2021 (R6)
SCS	00	30.0		7.9	b	15.7
	0	23.9		16.0	b	25.8
	I	31.0		9.8	b	26.3
	II			47.7	a	23.3
	III					31.8
	Average	28.3	a	20.4		24.6
DCS	00	12.9		55.0	a	6.0
	0	3.4		47.8	a	3.8
	I	17.2		57.4	a	12.8
	II			61.0	a	11.0
	III					12.2
	Average	11.2	b	55.3		9.2

soybean agronomic performance. Soybean grain yield and the number of grains m^{-2} were positively correlated with the asymptote ($r = 0.95$ and 0.88, respectively) (Fig. 5). The 1st pod height and the amount of Ndfa were also positively correlated with the asymptote ($r = 0.86$ and 0.56, respectively) (Fig. 5). Phenology did not show any correlation with the asymptote. The k parameter showed similar positive correlations as the asymptote, although weaker. It was positively correlated with the number of grains m^{-2} and the amount of Ndfa, but not with the soybean phenology (Fig. 5). The third curve parameter, the inflection point, was positively correlated with the phenology of the crop (Fig. 5), with the correlation coefficient decreasing from R3 to R6, indicating that the maximum growth point is closely linked with the beginning of the reproductive stages (Fig. 5). The inflection point was negatively correlated with the 1st pod height (Fig. 5). The TGW and the grain protein content were not significantly correlated with any of the parameters. The former was negatively correlated with the grain yield and the number of grains m^{-2} (Fig. S1), while the latter showed a negative correlation with phenology stages R4, R5 and R6 (Fig. S1).

4. Discussion

Soybean expansion towards the Southern European (Mediterranean) latitudes has been largely underexplored (especially below 42° N and warm areas such as the bottom of the Ebro Valley) often leading to the use of underperforming MG, more adequate for temperate conditions. In this work, we aimed to identify the best-performing MG for a high-yielding environment, such as the irrigated Mediterranean cropping systems, and quantify the drivers for this performance. Our first hypothesis was that later MG than currently used (MG 00-I) might be able to better exploit the potential of the area and lead to higher yields. Indeed, our results showed consistently higher yields for later MG such as MG II (4476 kg ha^{-1}, on average) and III (5314 kg ha^{-1}) compared to 2715 and 4090 kg ha^{-1} in the MG 00 and I, respectively (values averaged across years and cropping systems). Similar results were reported in the South of France (latitude 43° N), where MG I and II were identified as the highest yielding ones, with a larger number of pods and grains m^{-2} as the responsible driver for the increased yields (Schoving et al., 2022). The hypothesis that later MG can be suitable under our Mediterranean conditions is further supported by the delineation of MG across the US reported by Mourtzinis and Conley (2017). For a similar latitude than in our study (41° N), they identify MG between III and IV as the best adapted for a SCS. While the areas at the same latitude in the US have lower annual mean air temperatures (i.e. 11 °C) than in our case (i.e. 14 °C), the mean temperatures during the soybean growing season are

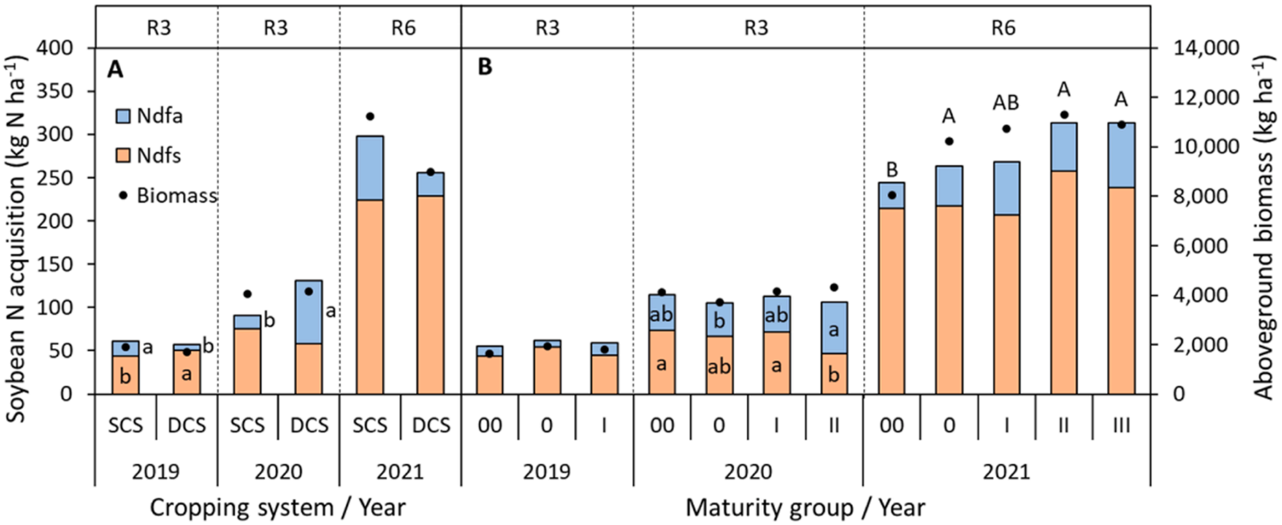
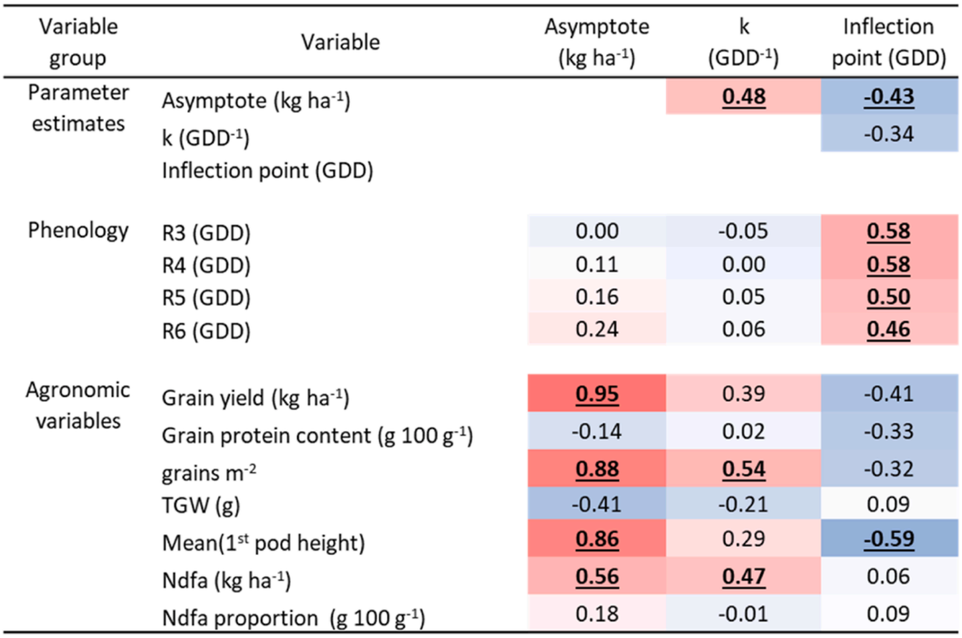


Fig. 4. Above-ground biomass (dot series), nitrogen derived from atmosphere (Ndfa) and nitrogen derived from soil (Ndfs) (column series) depending on the cropping system (A) and the maturity group (B) in 2019, 2020 and 2021. Within each subfigure and year, uppercase and lowercase letters indicate significant differences at $p < 0.05$ for the biomass and N acquisition source (Ndfa and Ndfs), respectively. Measurements were performed at the R3 phenological stage in 2019 and 2020 and at R6 in 2021, as stated in the boxes above the figure.



Variable group	Variable	Asymptote (kg ha^{-1})	k (GDD^{-1})	Inflection point (GDD)
Parameter estimates	Asymptote (kg ha^{-1})		**0.48**	**-0.43**
	k (GDD^{-1})			-0.34
	Inflection point (GDD)			
Phenology	R3 (GDD)	0.00	-0.05	**0.58**
	R4 (GDD)	0.11	0.00	**0.58**
	R5 (GDD)	0.16	0.05	**0.50**
	R6 (GDD)	0.24	0.06	**0.46**
Agronomic variables	Grain yield (kg ha^{-1})	**0.95**	0.39	-0.41
	Grain protein content (g 100 g^{-1})	-0.14	0.02	-0.33
	grains m^{-2}	**0.88**	**0.54**	-0.32
	TGW (g)	-0.41	-0.21	0.09
	Mean(1st pod height)	**0.86**	0.29	**-0.59**
	Ndfa (kg ha^{-1})	**0.56**	**0.47**	0.06
	Ndfa proportion (g 100 g^{-1})	0.18	-0.01	0.09

Fig. 5. Correlation coefficients for the growth curves parameter estimates with soybean phenology and agronomic variables. Y_{asym}: asymptote; k: parameter controlling the steepness of the curve; t_m: inflection point. The colour scale indicates the level of correlation, with red values indicating a correlation coefficient close to 1 and blue ones indicating a correlation coefficient close to − 1. Bold and underlined coefficients indicate a significant correlation at $p < 0.05$. Correlation analyses are displayed in Fig. S1. n = 24.

close to the ones in our sites/Ebro valley. For instance, the mean air temperature at our experimental sites during the May-October period is 20.1 °C and the temperatures for the same period in Springfield (Illinois, 39° N), Cleveland (Ohio, 41° N) and Iowa City (Iowa, 41° N) are 20.2, 19.3 and 19.1 °C, respectively. Therefore, given the similarity in photoperiod and mean air temperatures during soybean development it is reasonable to assume that the same MG III, tested in our study, and even IV (although not tested, to our knowledge), would be better suited for a SCS under the conditions of our study and potentially other Southern European sites. The use of MG III in Southern Europe was previously proposed by Nendel et al. (2023) in an *ex-ante* simulation study (without having a data set for MG III for model calibration) under climate change conditions with an RCP 4.5 scenario for the years 2040–2069. Our results are the first that support this assumption with field data and identified that MG III could already be suitable under current climatic conditions. These findings need to be backed up by further testing across contrasting sites and years. Nonetheless, our results provide a soybean dataset for singular conditions within the continent in order to further develop prediction tools at the research level (e.g. Schoving et al., 2020), or decision support systems for farmers similar to those in soybean-production areas (Santos et al., 2019; Severini et al., 2017).

In the later MG, i.e. MG III, the reproductive period was induced later in the season (Fig. 2), due to the higher photoperiod sensitivity (Yang et al., 2019), allowing for a longer vegetative period and thus greater biomass accumulation before and during the reproductive phases (Kantolic and Slafer, 2007). A direct consequence of this situation is a greater capacity for light interception (Board and Hall, 1984; Salmerón et al., 2015) and greater capacity for bearing pods (Calviño et al., 2003b). In fact, our results show that the yield increase observed from MG 00 to the latest MG tested each year is directly linked with the greater biomass accumulated, leading to an increased number of grains m^{-2} (Fig. 5; Fig. S1). These results are in line with Carciochi et al. (2019), who reported that grain number accounted for 53 % of yield variability whereas TGW accounted for 11 % of it (and not significantly in all cases) across 9 site-year combinations (with 1344 data points) in the US and Canada. In the present study, no significant relationship was found between soybean grain yield and TGW either.

Under double cropping conditions, we observed a reduction in total biomass accumulation due to the later sowing date and thus shorter growing period (Andrade et al., 2015). Along with this, we observed a delayed inflection point in the growth curves, which might indicate a flowering induction with already less biomass than in the SCS. Less vegetative biomass can be linked with poorer soybean light interception (Purcell et al., 2002; Salmerón et al., 2015) and increased chances for weeds to thrive (Jha et al., 2017). In that regard, the use of narrower rows in DCS (instead of the 75 cm) could increase light interception and thus reduce yield penalty compared to SCS (Ball et al., 2000). In the present study, yield reduction of 25 % (16–32 % range) was observed in the DCS compared to the SCS. These findings are in agreement with the results reported by Andrade and Satorre (2015), who reported an average yield reduction of 25 % (ranging from 10 to 40 %) in double-cropped soybean for 11 sites in the Argentinean Pampas. The yield penalty was caused by a decreased number of grains m^{-2} (from 1919 to 1623 grains m^{-2} on average across years and MG), resulting from a shorter growing period as previously reported by Calviño et al. (2003b) in Argentina and Egli and Zhen-wen (1991) in the US and China.

In our study, we did not find a significant interaction between the MG and the cropping system (p-value >0.3), suggesting that the different maturity groups behave similarly between the SCS and the DCS but with a lower magnitude in the latter. In that regard, Salmerón et al. (2014) recommended replace MG IV-V by MG III-IV for double cropping systems in the US Midsouth (30–36° N) to attain the highest yields in both situations. Instead, Morris et al. (2021) in the US Southeast (35–36° N) found that using earlier MG in DCS (MG IV-VI instead of MG V-VII recommended in the SCS) was only necessary in low-yielding environments, whereas in high-yielding ones MG performance (MG IV-VI) was similar across cropping systems (low- and high-yielding environments were based on yield trends from previous field experiments). Our results point out to the use of later MG the DCS, instead of the MG 00 used in the small surface under barley-soybean double cropping system. However, MG II and III tend to be harvested later in the season thus complicating the combine harvester tasks and compromising the yield (more biomass, more difficulty in drying out). To some extent, DCS harvest conditions resemble the soybean harvest conditions in central and northern Europe, with increased rainfall risk, pod shattering and difficult trafficability due to wet soils, as pointed out by Nendel et al. (2023), and difficulties to sow the subsequent crops timely to take up the residual N. Therefore, the use of late MG (i.e. MG II and III) in DCS should be further studied before recommending it, ideally under on-farm conditions that would allow a better evaluation of the limitations described.

Also related to the soybean crop harvest is the height of the first pod insertion. In our study, we found a positive correlation of this variable with the total amount of biomass accumulated (the asymptote in the growth curves, Fig. 5). Generally, larger amounts of biomass, and so higher first pod insertion, were found in the SCS and the later MG. This finding is in line with Kang et al. (2017), who reported higher first pod insertion in earlier planted soybean in Korea. The absolute values for the first pod height are relevant for preventing yield losses during harvest. In that regard, the cited study estimated a 3–14 % yield loss when the combine header level is at 15 cm aboveground. While lowering the header below 15 cm is possible, it increases the risks for stones and debris pick up by the combine. This problem can be partly overcome with a flexible cutter bar at the combine that adjusts to different soil conditions (with a low cutter bar setting). In our study, the first pod height was below 15 cm, thus stressing the need to assess cultivars and management practices that could increase it. Reducing row width has been reported to increase soybean first pod height, especially in double-cropped soybean (Vlachostergios et al., 2021). However, previous research in the area reported no benefits in terms of yield for narrower row widths (Simon-Miquel et al., 2023). Finally, it is worth mentioning that while some management practices can slightly modify it, genetics (at the cultivar level rather than MG level) is often regarded as a much stronger driver for the first pod height (Kuzbakova et al., 2022).

An increase in soybean yield is often followed by a decrease in grain protein content due to the N dilution effect (Greenwood et al., 1991; Karges et al., 2022; Rogers et al., 2015). Indeed, in the present study, we observed a grain protein concentration reduction from earlier to later MG (Fig. 3), though only significant in 2020 and 2021. Such decreases correspond to an approximate protein concentration loss of 0.21 g 100 g^{-1} per every 100 kg ha^{-1} of yield increase. This value is in line with the 0.2 g 100 g^{-1} in protein loss per every 100 kg ha^{-1} yield increase reported in Nebraska (US) for 75 soybean lines (Chung et al., 2003). Between cropping systems, the SCS presented higher grain protein concentrations than the DCS in 2020 and 2021 (1.65 g 100 g^{-1}, on average). Similarly, Salmerón et al. (2022) and Assefa et al. (2019) reported a reduction in seed protein concentration with later planting dates in a range of 40–45° N. Such reduction was more accentuated in meal protein rather than in total seed protein (Salmerón et al., 2022). Besides the dilution effect across MG and the reduction observed in the DCS, it is worth mentioning that in all cases the grain protein concentration was above 40 g 100 g^{-1}, considered the minimum required for food-grade soybean (at least, in Spain). Producing food-grade soybean can increase soybean gross margins, given the higher selling prices compared to feed-grade, and thus increase the farmer's willingness to produce it (Karges et al., 2022). Along with it, introducing soybean can increase the following cereal's yield and reduce N use at the cropping system level, especially under barley-soybean double cropping (Simon-Miquel et al., 2023). This reduction is especially patent during the year of the legume crop, as soybean N requirements are significantly lower than those of a cereal. Regarding the pre-crop effect, this can be divided into the N effect and the break crop effect (Chalk, 1998; Notz and Reckling, 2022). While it is reported that soybean has often a negative net N balance (N fixed < N exported) (Salvagiotti et al., 2008), the break crop effect can lead to significant yield increases.

Indeed, N fixation was generally low in our study, rarely exceeding the 30 g 100 g^{-1}, except in the DCS in 2020 (Table 7). These results are lower than the 50–60 g 100 g^{-1} of Ndfa reported from 637 data sets covering most soybean-growing regions around the world (Salvagiotti et al., 2008). Our results can be partially explained by the relatively high amounts of soil mineral N at the soybean sowing (on average, 52 mg kg^{-1} of N-NO_3-, 0–60 cm), which might have hindered soybean N fixation. In that regard, Herridge et al. (1990) concluded that initial high contents of soil mineral N can have a detrimental impact on biological N fixation. In their case, they observed values of Ndfa below 30 g 100 g^{-1} when the soil nitrate contents exceeded 260 kg N ha^{-1} (1.2 m depth). Later on, Tamagno et al. (2018) studied the effect of N fertilization on soybean N fixation across the US Midwest reaching similar conclusions, a reduction in the proportion of Ndfa as the N availability increased. Such values are not unusual in the area as a consequence of intensive maize production, especially in SCS, with high fertilization rates of up to 280 kg N ha^{-1} (Villar-Mir et al., 2002). Nitrogen fixation measurements in our study were performed at R3 in 2019 and 2020 and at R6 in 2021, thus observing a greater amount of Ndfa in 2021 (31 vs. 54 kg ha^{-1} on average at R3 and R6, respectively). These values are within the minimum and the 25 % quartile (0–72 kg ha^{-1}, n = 733) reported by Ciampitti and Salvagiotti (2018) in the US and Argentina, mainly. However, the cited study reported data from R6 to R8 stages, when most of the crop biomass is accumulated. Therefore, the total N fixed in our study at a later crop stage might have been slightly higher than the values measured. Further strategies such as inoculum and soybean genotypes response in specific environments could help increase nodulation and, thus, biological N fixation (Omari et al., 2022).

5. Conclusions

We found that later soybean maturity groups under Mediterranean irrigated conditions improved current yields. Both systems, SCS and DCS, showed increased soybean potential with later MG (especially MG II and III). In the SCS, the use of MG III opens a possibility to significantly increase yields beyond the current ones, while maintaining a high grain protein content that ensures the food grade. Such a combination is key in increasing soybean profitability and, likely, adoption by farmers. Further research exploring cultivars within MG III or later would help define a potential soybean yield for the studied conditions, especially under more severe climate change conditions. In the DCS, the use of later MG led, as well, to higher yields than the traditional MG 00 to MG I. However, technical aspects such as a later harvesting date (moisture, pod shattering, etc.) or a slight reduction in grain protein concentration (although still above 40 g 100 g^{-1}) should be investigated further. At the larger picture, we report results on the performance of later MG (III) in the EU and we show the potential to expand soybean towards Mediterranean irrigated cropping systems with a high yield potential.

CRediT authorship contribution statement

Moritz Reckling: Writing – review & editing, Supervision, Formal analysis. **Genís Simon-Miquel:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Plaza-Bonilla:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2024.109274.

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