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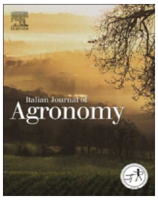

Full Length Article

Late summer sowing positively affects yield of lowland buckwheat in Northeastern Italy

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ABSTRACT

There is a growing demand for Italian buckwheat production. However, Italian buckwheat is still largely cultivated in upland regions and little is known about its cultivation outside traditional growing areas. In a two-year experiment the commercial buckwheat cultivar “Lileja” was sown on three different sowing dates (May, July, August) at two plant densities (250 and 350 seeds m^{-2}) within a split-plot design with four replicates. The objective of the study was to investigate the effect of planting date and seed rate on buckwheat yield and growth parameters. Despite a significant year effect, late summer sowing was stable between years in terms of yield, resistance to lodging and harvest index. Results from the growth analysis suggest that many growth parameters of buckwheat were affected by sowing date, with a slower biomass accumulation recorded in 2017. The findings illustrate the potential use of buckwheat as a cash crop in the lowland areas of northern Italy, when sown in August at a seed rate of 250 seeds m^{-2}.

Introduction

Common buckwheat (*Fagopyrum esculentum* Moench.) is a dicotiledonous annual species of the family *Polygonaceae*. Buckwheat achenes fall within the cereal grains category because of similar utilization and flour extraction, yet the crop is more properly classified as a pseudocereal (Mir et al., 2018). Buckwheat is currently grown across a large area of Central and Southeast Asia (Arduini et al., 2016; Chauhan et al., 2010). Outside of Asia, buckwheat cultivation is mainly localized in temperate areas of Europe (Arduini et al., 2016; Jacquemart et al., 2012), with about 2.2 million hectares harvested in 2022 according to the FAOSTAT database (Faostat, 2022).

Common buckwheat needs at least 6 °C to germinate and has no frost tolerance (Farooq et al., 2016). Vegetative growth requires air temperature in the range of 17–19 °C (Marshall and Pomeranz, 1982). During flowering the temperature should not exceed 19° and similar values are preferred in the seed formation phase (Podolska, 2016). Indeed, pollen vitality and seed set impaired if air temperatures exceed 18–22 °C (Podolska, 2016; Slawinska and Obendorf, 2001). In Italy these conditions are present in mountain areas, where buckwheat is traditionally sown from June-July, and harvested in August–September (Arduini and Mariotti, 2018). In contrast, the Mediterranean regions are characterized by a greater variety of temperature conditions during the growing season. Moreover, the year-to-year variability in rainfall, with nil or limited irrigation, could exacerbate heat stress caused by temperatures above 30 °C that are common in July and August in Mediterranean lowlands (Farooq et al., 2016). Other limitations have also been attributed to the indeterminate growth habit of most cultivated varieties and to a high degree of seed shattering (Marshall and Pomeranz, 1982). Therefore, common buckwheat cultivation faces several challenges, including a lodging-prone behaviour due to its narrow stem and difficulties in determining harvest time, that compromise yield stability (Jacquemart et al., 2012).

Buckwheat has the potential to be an important spring/summer cash crop due to its short growth cycle (80–110 days), ability to grow well in marginal areas, high competition with weeds and little to no need for inputs (Ikanovic et al., 2013; Loch and Lazányi, 2010). In addition, its high market value makes it commercially viable for farmers (Giménez-Bastida et al., 2015).

Common buckwheat is considered a short-day plant. In Japan three groups have been established: autumn (high photoperiod responsive), summer (weak photoperiod responsive) and intermediate ecotypes. Fruit ripening time seems more suitable for ecotype differentiation than flowering time, with different mechanisms tentatively regulating the

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timing of both stages (Takeshima et al., 2022). These new findings may be relevant to extending the growth area and fine-tuning the growth period, to maximize adoption of common buckwheat in Southern Europe.

To date, low and unstable yields represent a strong limitation to wider cultivation in non-traditional cropping areas across Europe, where the agricultural landscape is characterized by intensive large-scale crop production and where market prices greatly determine crop rotations. Nevertheless, buckwheat has received new interest worldwide in recent decades, due to evidence regarding the beneficial properties of its grain, including reduced starch digestibility with the consequent lowering of glycemic indices (Skrabanja et al., 2001; Biacs et al., 2002), a well-balanced amino acid composition, and a source of dietary fiber and minerals. Buckwheat achenes are rich in rutin (quercetin-3-rutinoside), a polyphenol with proven benefits on the cardiovascular system (Brunori et al., 2009; Gonçalves et al., 2024). Buckwheat is also the primary gluten-free alternative to wheat, making it a basic ingredient in gluten-free foods which attracts strong attention by specialty food firms in Central Europe and in Italy (Brunori et al., 2018). Additionally, sprouts and microgreens, i.e. tender greens made from true or cotyledonary leaves (Galieni et al., 2020), produced from common buckwheat are gaining increasing popularity because of their unique nutritional profile and excellent balance of nutraceuticals (Johnson et al., 2024). Moreover, buckwheat is being increasingly considered as a companion crop in arable cropping systems for the provision of biological pest control, weed suppression and support of pollinators (Virili et al., 2024).

Buckwheat utilization by the specialty food industry is quite large in Southern Europe, partly owing to marketing efforts to capture new health-conscious customers. Nonetheless, domestic acreage and production are largely insufficient, and imported grains are currently dominant (approx. 65 % of the used grains in Italy).

Buckwheat adoption in Mediterranean areas would be beneficial, but in 2022 less than 1000 ha in Southern Europe were assigned to the crop (FAOSTAT), mainly in the mountain areas. Common buckwheat is present in Italy as a subsistence/traditional grain crop in Alpine and Apennine valleys, or less frequently in lowland areas as a cover crop or as a replacement of a failed summer crop.

The increasing demand for buckwheat domestic production requires additional efforts to favour buckwheat adoption outside of traditional areas, such as lowland plains in which larger agricultural surfaces and mechanization are available.

The present study aims to assess the key factors which influence buckwheat growth in Friuli-Venezia Giulia, one of the Northeastern regions in Italy, where buckwheat cultivation is minor. The present study investigates the effect of sowing date and plant density on crop growth and biomass accumulation to assess (i) if prolonged periods with air temperatures > 30 °C represent a bottleneck for grain yields, and (ii) crop responses when buckwheat is planted around May 20th (15 h 07 m day-length), July 3rd (15 h 42 m day-length) and August 1st (14 h 51 m day-length). Little has been published to date (Salehi et al., 2017; Sobhani et al., 2012) on buckwheat crop ecology using a growth analysis approach. Therefore, from basic aboveground biomass and leaf area data the authors calculated growth analysis parameters (LAI, LAD, CGR, NAR) to pinpoint major limits to crop production in Mediterranean lowland agricultural areas.

Spring sowing was hypothesized to pose the greatest threat to buckwheat yield, as the crop could be subject to high and variable temperatures at flowering. Summer sowing was expected to be best suited for lowland areas, since the highest air temperatures are concentrated at the beginning of the growing season, favouring emergence and early growth, while more stable temperatures at flowering minimize risk of flower abortion and seed shattering in the latter phases of crop development.

Material and methods

Experimental site

The trial was carried out in 2017 and 2018 at the experimental farm of the University of Udine (46 03 N, 13 22 E, 91 m a.s.l) located in the Friuli-Venezia Giulia region, the easternmost region of Northern Italy. The experimental area was typically assigned to a temperate-humid climate (Cfa) according to the Köppen-Geiger classification, but currently it is more appropriately classified as Mediterranean North (MDN) according to the European Environment Agency. The long-term (1993–2013) annual average rainfall and air temperature of the area is of 1427 mm and of 13.2 °C, respectively. Compared to other NE Italy areas, rainfalls in Friuli-Venezia Giulia are characterized by high amounts and strong geographical gradients, with rainfall increasing from the sea to the pre-alpine areas (Ceschia et al., 1991). The weather conditions were recorded by a local meteorological station (ARPA FVG – OSMER) situated within the experimental farm. Fig. 1 shows the average daily rainfall and temperatures during the growing seasons in 2017 and 2018. The soil is a sandy-clay loam (Chromi-Skeletic Cambisoil, FAO, 1998) with 1.2 % organic C and 7.2 pH, superficial, well-drained and characterized by medium-low fertility. Buckwheat was sown after artichoke in 2017, while in 2018 the preceding crop was soybean.

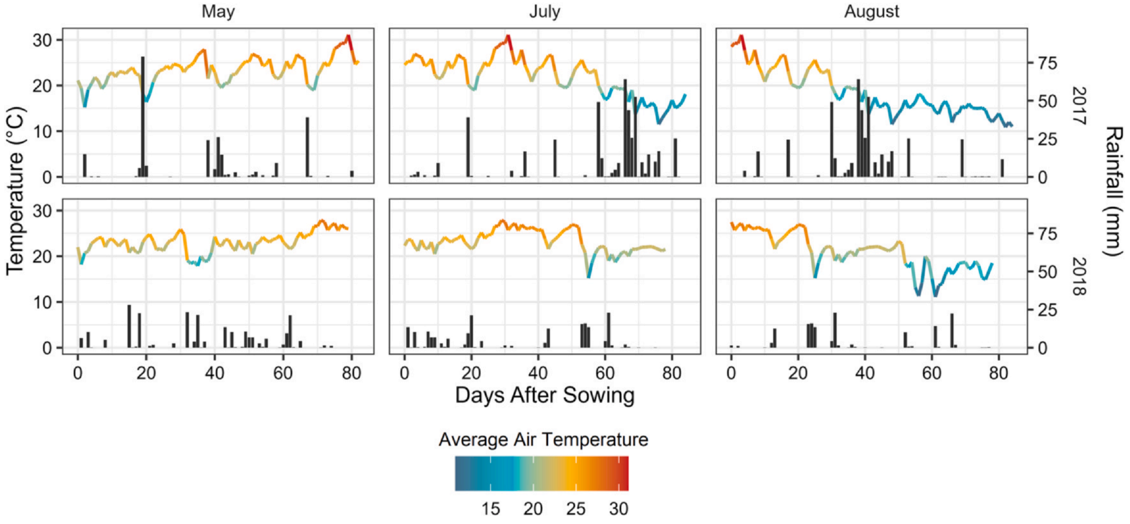


Fig. 1. Daily water supply, divided in rainfall (dark grey bars) and irrigation (light grey bars), and average temperature during the growing seasons of each sowing date in 2017 and 2018.

Experimental details

The early-maturing variety Lileja was chosen for the trial, as it is often selected by farmers and has been used in other field experiments (Arduini et al., 2016; Brunori et al., 2009; Ghiselli et al., 2016). The trial was arranged in a split plot design with four replicates. The main plots were assigned to the sowing date: T1 (18 May 2017, 21 May 2018), T2 (5 July 2017, 2 July 2018), T3 (2 August 2017, 1 August 2018). Subplots were assigned to seed rates: D1 (250 seeds m^2), D2 (350 seeds m^2). No fertilization was applied and sprinkler irrigation was provided within the first ten days after sowing (buckwheat emergence), at the beginning of flowering stage (between 30 and 40 days after sowing), between full and the end of flowering (between 40 and 60 days after sowing) and at achene ripening. Each plot was 10.8 m^2 (9 m × 1.2 m) and sowing was performed using a plot seeder with 8 rows spaced 15 cm apart, while the intra-row spacing was 3 cm. Prior to the T2 and T3 seed sowing, a black mulching film was added to maintain sufficient soil water and weed-free conditions from T1 seeding up to seeding of T2 and T3. Harvest was performed manually when around 75 % of achenes were ripe (BBCH: 86, Arduini et al., 2016) on 8 August 2017/18 for T1, on 27 September 2017–18 September 2018 for T2, and on 25 October 2017–18 October 2018 for T3.

Data collection

For each sowing date, 5 and 6 harvests (2017 and 2018) of aboveground biomass were performed throughout the growing season, from 0.21 m^2 quadrats. Harvests coincided with buckwheat phenological stages: third true leaf (BBCH:13 - 2018), blossoming (BBCH:50), full flowering (BBCH:65), late main stem flowering (BBCH:67), first green fruits (BBCH:70), and advanced fruit ripening (BBCH:86) (Arduini et al., 2016). On each sampling, number of plants, plant height, length and stem diameter, aboveground biomass and leaf area were recorded. Plants were oven-dried at 70 °C for 48 h, and the dry matter of stems, green and yellow leaves, flowers, green seeds and mature seeds were determined separately before combining into total aboveground dry biomass.

Leaf area was measured with a photometric area-integrating meter (Model LI-3100, LI-COR Inc.). Lodging (i.e., the permanent displacement of a stem or part of a stem from a vertical posture) was calculated by dividing plant height and plant length, providing values which range from 0.1 (total lodging) to 1 (no lodging). At harvest, fresh yield and seed moisture were determined after threshing. Afterwards, the seeds were oven-dried at 30 °C for 72 h and weighed again.

Organic carbon (C) and total nitrogen (N) contents and corresponding C-to-N ratio were measured using a vario Micro Cube (Elementar GmbH, Langenselbold, Germany) elemental analyzer in triplicate aliquots of 2 ± 0.5 mg of each sample of buckwheat. Protein content in achenes was determined by multiplying the total nitrogen (N) value by 6.25. Rutin concentration in the achenes was determined through HPLC analysis, following the protocol proposed by Lukšič et al. (2016).

Growth analysis parameters

Crop aboveground biomass and leaf area were measured in repeated harvests. The growth analysis approach of populations and communities (Hunt, 1982) was used. The net gain in weight per unit leaf area, i.e. or *unit leaf rate* (ULR), also *net assimilation rate* (NAR) for its instantaneous value is:

$$\mathrm{NAR} = (1/L_A) * (\mathrm{d}W/\mathrm{d}T)$$

where L_A is the total leaf area of the crop. The estimation of mean ULR over a period of time is:

$${}_{1-2}\,\mathrm{NAR'} = [({}_{2}W - {}_{1}W)/({}_{2}T - {}_{1}T)] * [(\log_e {}_{2}L_A - \log_e {}_{1}L_A)/({}_{2}L_A - {}_{1}L_A)]$$

Accordingly, using P to represent the land area and assuming linearity between L and time, *leaf area index* (LAI) as an instantaneous value is:

$$\mathrm{LAI} = L_A/P$$

being the mean value for L between times 1 and 2:

$${}_{1-2}\,\mathrm{LAI'} = ({}_{1}\mathrm{L} + {}_{2}\mathrm{L})/2$$

If ${}_{1}\mathrm{W}$ and ${}_{2}\mathrm{W}$, the dry weights of crop harvested from equal areas, are expressed per unit quantity of P, then the *crop growth rate* (CGR) can be calculated as:

$${}_{1-2}\,\mathrm{CGR'} = ({}_{2}\mathrm{W} - {}_{1}\mathrm{W})/({}_{2}\mathrm{T} - {}_{1}\mathrm{T})$$

Finally, *leaf area duration* (LAD) that represent a measure of the whole opportunity for assimilation of the crop throughout the season, was derived graphically (Hunt, 1982):

$${}_{1-2}\,\mathrm{LAD'} = [({}_{1}\mathrm{L} + {}_{2}\mathrm{L}) * ({}_{2}T - {}_{1}T)/2$$

Data analysis

The effect of sowing date and density on buckwheat response variables was tested using a linear mixed effect model with the "lmer" function in the "lme4″ package (Bates et al., 2015) with the interaction between block and main plot in the random component (1| block: sowing date). The split plot design required inclusion of the sowing date, sowing density, year and year: block interaction as fixed explanatory variables in the model. The model was followed by an Analysis of Variance with the function "anova" in the "car" package (Fox et al., 2009). Models were validated with the "simulateResiduals" function in the "DHARMa" package which uses a Kolmogorov-Smirnov test to detect significant deviation and outliers (Hartig, 2018). A post-hoc Tukey test was then performed with the function "emmeans" in the package "emmeans" (Lenth, 2017). A Pearson correlation test was performed to verify whether the growth analysis parameters collected during the growing season were correlated with grain yield or other yield components (e.g., number of achenes per m^2). Growth parameters were expressed as the integral of the data points collected during the season to obtain a single value for each sowing date and year. This was done using the "cor" function within the "corrplot" package to produce the correlation matrix, followed by a significance test performed with the "cor.mtest", within the same package. Since the relationship between LAI, aboveground biomass, Crop Growth Rate (CGR), Net Assimilation Rate (NAR) and time was non-linear, GAMs (Generalized Additive Model) (Zuur et al., 2009) with Days After Sowing (DAS) as the nonlinear parameter were selected using the package "mgcv" in R. The GAMs allowed creation of smooth functions using additive base functions; in the present study, the cubic spline was selected as the smooth type with the "shrinkage" function (bs = "cs" in mgcv). A starting null model containing "year" as the fixed factor was tested against five other models containing sowing date and sowing density (Table 4) (Anderson and Burnham, 2002; Johnson and Omland, 2004). The six hypotheses for each response variable were compared based on the Akaike Information Criterion (AIC) value. The models were validated by checking distribution and homogeneity of residuals, as for the linear models. No post-hoc test was performed in this case. This decision is supported by Qian and Miltner (2018) who explain that for datasets with a small sample size or with large natural variability (such as in our case) p-values are also highly variable, leading to unstable tests. Moreover, mixed effects models fall under the umbrella of multilevel models, which inherently address the multilevel comparison problem as they perform partial pooling of the estimates towards a common mean (Gelman, 2006). All data analyses were performed using R Studio (version 4.3.3).

Results

Main growth stages

Planting dates for T1, T2 and T3 were consistently scheduled for the two years (Table 1). Crop emergence was observed after 6 ± 1 days after each planting in all the treatments. Full flowering, recorded following buckwheat phenological staging proposed by Arduini et al. (2016), occurred less than four weeks from sowing in all the treatments. Harvest, performed when plants reached 75 % senescence, occurred slightly later in 2017 compared to 2018 (12 and 11 weeks after seeding, respectively). The day lengths in Table 1 indicate that the cv. Lileja may be a neutral-day or facultative long-day plant.

Grain yield, yield components and lodging resistance

A significant interaction between sowing date and year was found for grain yield, percentage of green achenes and resistance to lodging (Table 2). Grain yield was generally lower in 2017 compared to 2018. The July sowing date (T2) was consistently conducive to high yields, while May (T1) sowing was associated with high variation across years. The same was found for harvest index (HI), T3 led to the highest HI values despite the significant differences between years (Table 3). Overall, 2017 was a poor season for buckwheat planted in May, as temperatures were consistently above the norm, with at least 3 days at $\geq 35\,^{\circ}$C and with a temperature maxima average of 29.9 °C. Consequently, from June to late July 2017, plants were largely exposed to temperature stress through the flowering and reproductive stages. In June and July of 2018, the temperature maxima also remained consistently above 30 °C, with an increase of 2–4 °C from early August to late September. The proportion of green seeds was also stable across years in T3, whereas the biggest differences between years were found

Table 1

Crop planting dates (T1, T2, T3) and major growth stages in the growing seasons of 2017 and 2018 in Udine. Day lengths (hours, in brackets) specific to the area were calculated using the solartopo website (http://www.solartopo.com/daylength.htm). CGDD indicates cumulative growing degree days, DAS indicates days after sowing.

		Sowing		Emergence			Full flowering			Harvest			
		Date	Hours	CGDD	DAS	Hours	CGDD	DAS	Hours	Date	CGDD	DAS	Hours
2017	T1	18/05/2017	(14:22)	101	6 ± 1	(14:36)	431.9	26 ± 1	(14:57)	08/08/2017	1527.1	82	(13:48)
	T2	05/07/2017	(14:52)	143.8	6 ± 1	(14:44)	435.5	27 ± 1	(14:04)	27/09/2017	1431.2	84	(11:31)
	T3	02/08/2017	(14:04)	159.6	6 ± 1	(13:46)	343.5	27 ± 1	(12:48)	25/10/2017	999.2	84	(10:01)
2018	T1	21/05/2018	(14:28)	120.2	6 ± 1	(14:43)	491.3	27 ± 1	(15:00)	08/08/2018	1456.3	79	(13:49)
	T2	02/07/2018	(14:55)	127.1	6 ± 1	(14:48)	498.4	26 ± 1	(14:18)	18/09/2018	1465.6	78	(11:55)
	T3	01/08/2018	(14:07)	153.2	6 ± 1	(13:49)	381	27 ± 1	(12:55)	18/10/2018	1082.8	78	(10:25)

Table 2

Effect of sowing date, sowing density and year on buckwheat grain yield, harvest index, percentage of green achenes, rutin content, protein %, plant length, stem diameter and resistance to lodging at final harvest. Numbers represent F-values. Effect was considered significant at the $P < 0.05$ level. * $0.01 < P < 0.05$; ** $0.0001 < P < 0.01$; *** $P < 0.0001$; "ns" = not significant.

	Yield (Mg ha^{-1})	Harvest Index	Green achenes %	Rutin (mg m^{-2})	Protein %	# achenes m^2	Plant length (cm)	Stem diameter (cm)	Resistance to lodging %
Year	9.41**	1.42 ns	3.52 ns	2.13 ns	0.50 ns	**15.63****	34.59***	13.91**	16.13**
Sowing Date	4.15*	103.5***	52.6***	1.58 ns	**5.65***	**4.55***	17.86**	7.74*	25.13*
Sowing Density	2.61 ns	1.71 ns	3.18 ns	**5.69***	0.14 ns	3.55 ns	**9.85****	**28.98*****	2.58 ns
Year: Sowing Date	**9.77****	**12.81*****	**22.35*****	0.16 ns	3.06 ns	2.32 ns	**11.11****	**28.46*****	**69.52*****
Year: Sowing Density	0.64 ns	1.40 ns	2.63 ns	0.0021 ns	0.18 ns	0.24 ns	1.22 ns	0.92 ns	1.19 ns
Sowing density: Sowing Date	0.12 ns	0.23 ns	1.27 ns	0.61 ns	0.65 ns	0.30 ns	0.33 ns	0.09 ns	1.55 ns
Year: block	1.25 ns	1.09 ns	1.33 ns	0.21 ns	0.94 ns	0.79 ns	0.79 ns	2.52 ns	1.46 ns
Year: Date: Density	0.28 ns	0.83 ns	1.41 ns	0.03 ns	1.03 ns	0.18 ns	0.04	0.28 ns	1.84 ns

Table 3

Significant differences in yield, harvest index, percentage of green seeds, resistance to lodging, plant length and stem diameter at final harvest between sowing dates (T1, T2, T3; see Table 1 for details) and years from the Tukey HSD post-hoc test in the two years of the trial. Effect was considered significant at the $P < 0.05$ level.

	Yield (Mg ha^{-1})	Harvest Index	Green achenes %	Plant length (cm)	Stem diameter (cm)	Resistance to lodging %
2017						
T1	0.763 ± 0.065 c	0.27 ± 0.01 c	6.089 ± 1.9 bc	84.0 ± 2.5 c	3.78 ± 0.1 cd	100 ± 0.0 a
T2	1.282 ± 0.094b	0.29 ± 0.01 c	8.106 ± 1.3 b	102.0 ± 2.8 b	5.03 ± 0.2 a	30.9 ± 2.4 e
T3	1.207 ± 0.152b	0.49 ± 0.1 a	0.269 ± 0.3 bc	72.3 ± 5.5 c	3.50 ± 0.2 d	63.3 ± 8.6 bc
2018						
T1	1.599 ± 0.138 ab	0.29 ± 0.02 c	2.789 ± 1.0 bc	117.5 ± 3.1 a	4.73 ± 0.2 ab	33.7 ± 0.9 de
T2	1.262 ± 0.030 b	0.22 ± 0.01 d	25.92 ± 3.5 a	108.9 ± 2.5 ab	4.11 ± 0.2 bcd	49.1 ± 3.7 cd
T3	1.705 ± 0.060 a	0.39 ± 0.01 b	0.00 ± 0.0 c	101.5 ± 3.1 b	4.34 ± 0.2 abc	66.0 ± 5.9 b

for T2 with 25 % of green seeds in 2018 compared to almost 10 % in 2017. Rutin content and protein concentration (%) in seeds were affected only by sowing density and sowing date, respectively (Table 2). Protein % in seeds was lowest in T1 (mean 12.1 % ± st. err. 0.26) compared to T2 (13.7 % ± 0.27) and T3 (13.4 % ± 0.28). Rutin content was higher at 250 seeds m^2 (60.0 mg m^{-2} ± 3.49) compared to 350 seeds m^2 (46.1 mg m^{-2} ± 3.58).

Plant length and diameter were affected by the interaction between sowing date and year (Table 2), with July sowing producing longer but more robust plants at harvest in 2017, while May sowing resulted in the highest values for length and stem diameter in 2018 (Table 3). Sowing density was also a significant factor for both length and diameter (Table 2), resulting in larger (4.56 cm ± 0.1) and longer (101.7 cm ± 1.8) plants at the 250 plants m^{-2} density, compared to 350 plants m^{-2} (3.94 cm ± 0.1 diameter; 93.7 cm ± 1.9 length).

Lodging resistance was also variable between years for T1 and T2. No lodging was recorded for T1 in 2017, although a significantly lower value (about 33 %) was recorded in 2018. Again, T3 showed stable values at around 60 % lodging resistance. Mean comparisons for grain yield, harvest index, lodging resistance and the percentage of green seeds can be found in Table 3. It is worth noting that higher lodging seemed independent from stem diameter, but the lowest resistance to lodging was observed at the highest plant lengths.

The number of achenes per square meter was affected both by sowing date and year (Table 2), but no interaction was detected. July sowing (T2) produced the highest number of achenes per m^2 (58,136 achenes m^{-2} ± 3469.9), while sowing in May produced the lowest number of seeds (44,081 achenes m^{-2} ± 4812.7). No differences were found between the first two sowing dates and the latest sowing (August, 53,221 achenes m^{-2} ± 3310.7). Seed production per m^2 was almost double in 2018 (62,184 achenes m^{-2} ± 2149.7) compared to 2017 (39,980 achenes m^{-2} ± 2829.7).

Buckwheat growth analysis

A significant ($P < 0.05$) positive correlation was observed between buckwheat achene number and Leaf Area Duration (LAD) ($p = 0.03$). Buckwheat yield was significantly correlated only with achene number ($P = 0.048$). Total above-ground biomass (AGDM) was significantly ($P < 0.05$) and positively correlated with Crop Growth Rate (CGR) ($P = 0.0015$), LAD ($P = 0.0012$), Leaf Weight Ratio ($P = 0.019$) and Relative Growth Rate (R) ($P = 0.0026$).

The addition of the sowing date greatly improved the model fit for all the tested response variables in the growth analysis (Table 4). The LAI model obtained the best fit with the addition of sowing date, while the interaction between sowing date and year greatly improved the model fit of the other response variables. The NAR model benefitted from the addition of sowing density, although the factor was not significant.

The accumulation of aboveground biomass developed differently between years and sowing dates, showing no correlation with grain yield data. Aboveground dry biomass accumulation was just barely (2017) or exponential (2018) up to 50 DAS, then decreased in the last two weeks (Fig. 2A). Differences in AGDM between sowing dates were less apparent in 2017 compared to 2018. In 2017 peak AGDM just below 400 g m^{-2} was observed at 70 DAS for May and August sowing, while in the July sowing the peak was registered at around 550 g m^{-2}. In 2018 values were almost two-fold, with May and July registering peak values above 800 g m^{-2}, while AGDM values in the August sowing plateaued around 700 g m^{-2} (Fig. 2A).

Leaf Area Index trends were in line with aboveground biomass accumulation. In 2017 LAI peaks were achieved at 30–40 DAS for the three planting dates: maximum LAI values around 2 were measured for T2, while a maximum LAI of 1.2 was observed for the May and August sowing dates. In 2018, the July planting date (T2) led to a delay in maximizing LAI close to 60 DAS, relative to the other two dates (Fig. 2D).

Among the growth indices, the net assimilation rate (NAR) measures the net gain in weight per unit leaf area, i.e. the average rate of assimilation (Hunt, 1982). In the 2017 season, NAR peaked at 8–10 g m^{-2} day^{-1} after 55–60 DAS, with negative values from 70–75 DAS for two out of three dates. On the other hand, in 2018 NAR values were positive up to 70 DAS and topped earlier. A final increase in NAR was observed in T1 of 2017 and, to a lesser degree, T3 of 2018. Furthermore, NAR values in T1 of 2017 never went below 0, contrary to all other sowing dates in the two years (Fig. 2C).

The CGR trends, calculated with reference to the whole biomass, were dramatically different between years (Fig. 2B). Environmental conditions in 2017 were conducive to maximum CGR of around 10 g m^{-2} day^{-1}, that were measured slightly later (around 60 DAS) for T1, relative to the other sowing dates. In all of the cases, negative CGR values were obtained after 70 DAS. In 2018 maximum CGR values at or above 20 g m^{-2} day^{-1} were obtained around 30–55 DAS and negative CGR values were registered just before 60 DAS in T3, whereas CGR in T2 and T1 became negative after 70 days similarly to 2017.

Distinct trends were observed in both years for green achenes (CGRg) and mature (CGRm) achenes biomass. In line with biomass accumulation and yield data, in 2017 we obtained CGRg top values (20–45 g m^{-2} day^{-1}) that apparently increased with the delay in sowing dates (Fig. 3). The CGRg peaks anticipated CGRm ones by approximately three weeks, reaching negative values after 40 DAS. Similarly, top CGRm values (40–100 g m^{-2} day^{-1}) increased from T1 to T3 dates and became negative after 62–65 DAS. Albeit at much higher levels, in 2018 CGRg and CGRm trends were consistent with those obtained in 2017. However, for the T1 date we observed higher CGRm values than total CGR. Finally, CGRm developed negative values after 63–70 DAS. Total biomass CGR and CGRm trends were rather complex in both seasons, particularly at the T3 date (Fig. 3).

Table 4
Model comparison outputs for each response variable in the Generalized Additive Models (GAM). The model with the lowest AIC value (in bold) was chosen as the best model to fit the data. Date indicates the sowing date, density the sowing density. LAI stands for Leaf Area Index, CGR for Crop Growth Rate, NAR for Net Assimilation Rate.

	Fixed components	Aboveground biomass (g m^{-2})	LAI	CGR (g m^{-2} day^{-1})	NAR (g m^{-2} day^{-1})
Model 1	**year**	3792.4	498.7	2195.1	2091.9
Model 2	**year + date**	3782.5	**498.0**	2177.1	2083.1
Model 3	**year: date**	**3761.1**	498.9	**2172.3**	2079.5
Model 4	**year: date + density**	3761.4	499.0	2173.9	**2077.3**
Model 5	**year: date + year: density**	3763.2	500.6	2175.9	2078.8
Model 6	**year: date:density**	3769.7	507.5	2183.8	2086.4

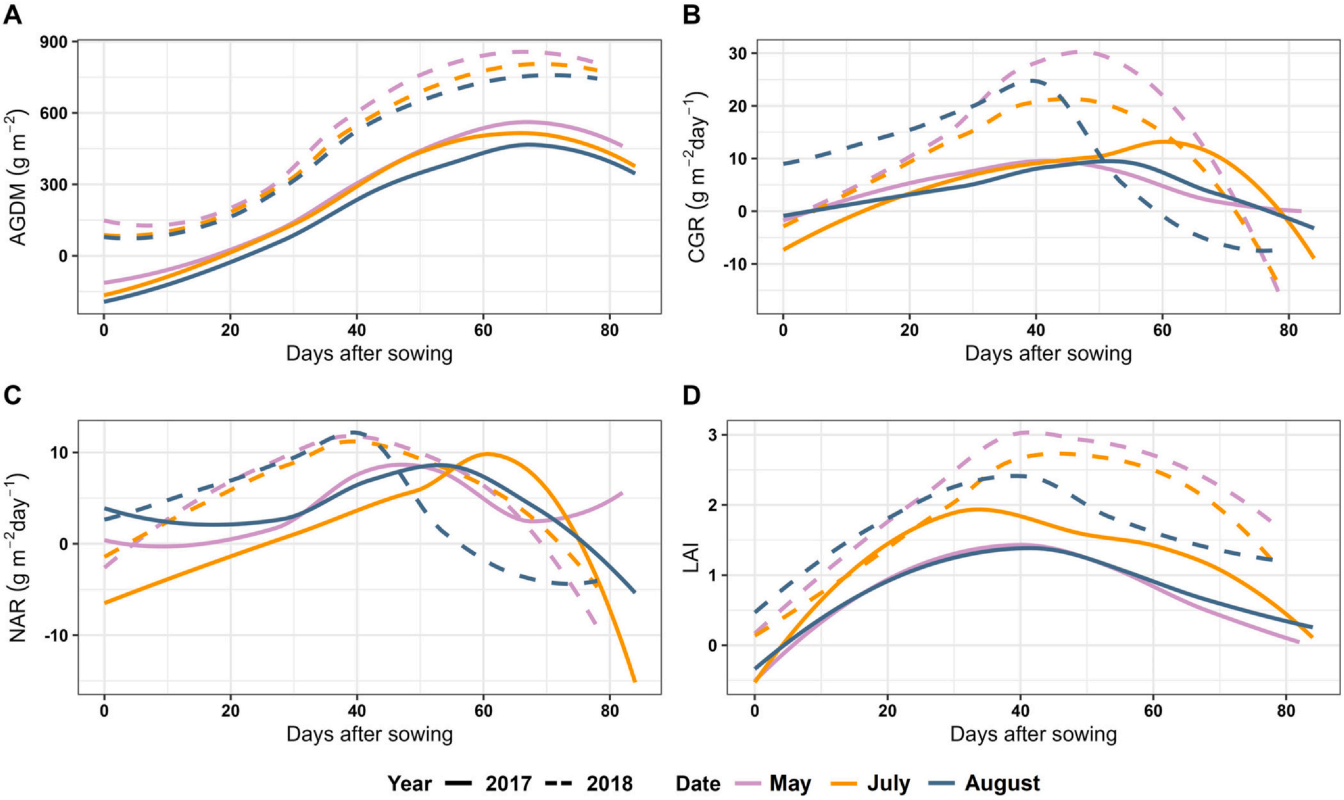
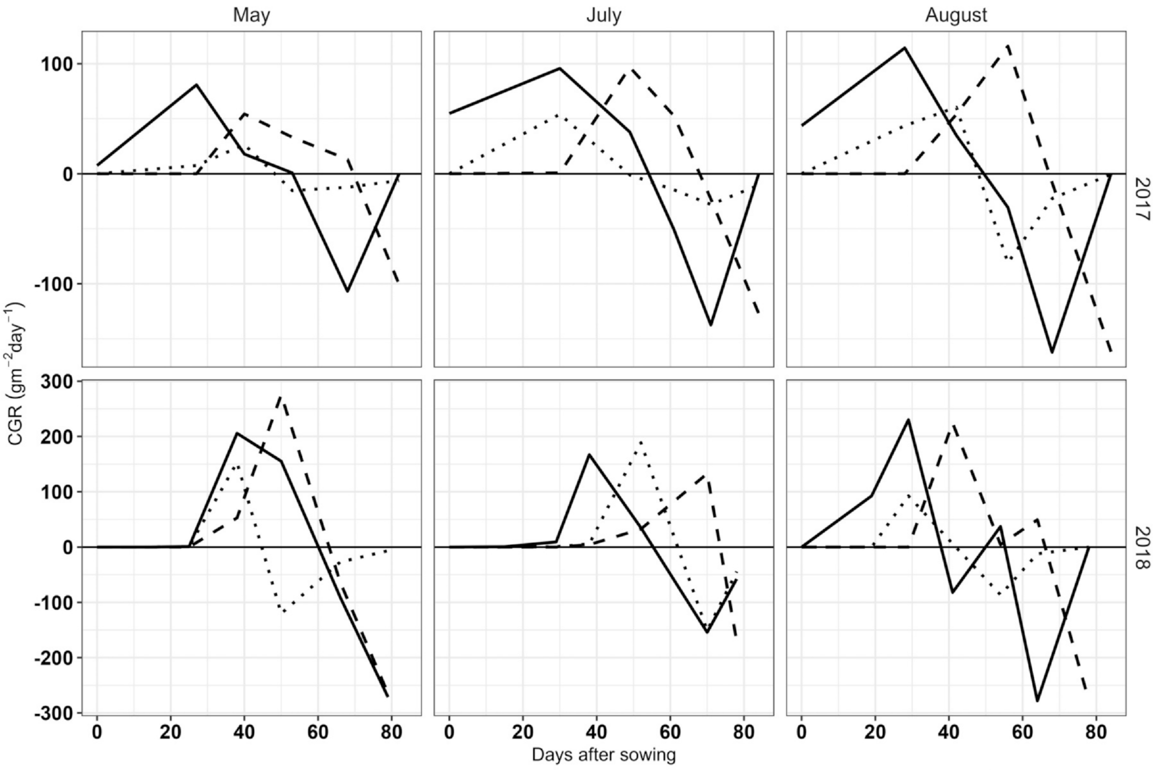


Fig. 2. Predicted A) Aboveground dry biomass (AGDM); B) Crop Growth Rate (CGR); C) Net Assimilation Rate (NAR); and D) Leaf Area Index (LAI) throughout the growing seasons of 2017 and 2018 for each sowing date.



solid = total achenes; dashed = ripe achenes; dotted = green achenes

Fig. 3. Buckwheat CGR divided in its total (solid line), mature achenes (dashed line) and green achenes (dotted line) components.

Discussion

The present study investigated the effect of sowing date and seeding density on the growth and yield of common buckwheat in the lowlands of Friuli-Venezia Giulia (NE Italy). Late summer sowing was hypothesized to be the most favourable to buckwheat, because high temperatures are normally present at the beginning of the cropping season, limiting flower abortion and empty seeds later in the cropping cycle.

To the best of the authors' knowledge, the field results obtained in the present study on buckwheat growth and yield formation processes are among the few across lowland Mediterranean environments. Although rainfall in Friuli-Venezia Giulia is above-average ($>$ 1400 mm year^{-1}) compared to other Italian regions, most of the region's rainfall occurs during the fall and spring. Additionally, it is frequent to have dry summer months in the plain areas (Ceschia et al., 1991), which allows extension of the findings of the present study to other lowland plains in the North of Italy. In the present trial, buckwheat yields and crop development processes were heavily influenced by the growing season, albeit in a different manner with reference to planting dates (Petris et al., 2021). Considering the collected data, summer sowing seems to produce the most stable yields from both a quantitative and qualitative standpoint when sown at 250 plants m^{-2}. Brunori et al. (2006) recommend the assumption of 50 mg/day of rutin; the average rutin content in the present study was 60 mg m^{-2}, found in 155 g of achenes m^{-2} (around a serving and half). Kalinová and Dadáková (2013) also found that a plant density of 200 plants m^{-2} produced the highest rutin content in common buckwheat compared to stands of 400 plants m^{-2}. Although July sowing appeared to produce better yields compared to August sowing, it also showed greater variability between years and no significant differences between the two summer sowing dates were found regarding protein concentration and rutin content in the achenes. Flower production in buckwheat greatly exceeds seed set (Quinet et al., 2004), therefore optimal reproductive development from flower initiation up to achene maturity is critical for grain yield determination (Mariotti et al., 2016). In a two-year field experiment on buckwheat in central Italy two varieties (Bamby and Lileja) were sown at three dates (early spring, late spring, late summer) in rainfed and irrigated conditions (Mariotti et al., 2016). In line with our results, the authors found that grain yield differed markedly in response to sowing time: top grain yields (2.24 Mg ha^{-1}) were achieved with early spring seeding, but dropped to 0.24 Mg ha^{-1} (rainfed) and 0.91 Mg ha^{-1} (irrigated) for late spring seeding. This result is consistent with ours, as late spring sowing in Tuscany occurred in the second half of May. Late summer sowing produced grain yields of around 1.5 Mg ha^{-1} (Mariotti et al., 2016), which is also comparable with our yields in T3 planting in 2018.

In substantially different climatic conditions, yield assessments of buckwheat varieties were performed in southern and central Italy, in a range from 480 to 1300 m above sea level (Brunori et al., 2005; Ghiselli et al., 2016): sowing occurred from early to late June and included the cv. Lileja. Due to the upland environment, the maximum temperature was consistently below 30 °C and grain yields of Lileja were around 1.57–1.67 Mg ha^{-1}. The common thread to obtaining acceptable grain yields seems to be temperature range and stability, as the lowest yields have been recorded in growing seasons characterized by rapidly fluctuating temperatures or low levels of precipitation (e.g., dryspells) (Domingos and Bilsborrow, 2021). Even in lowland areas more constant temperatures seem to favour buckwheat yields, despite being considerably higher compared to temperatures recorded in traditional growing areas. Koyama et al. (2019) also report that higher minimum daily air temperatures and longer light duration at the beginning of flowering stimulate flower production despite seed setting rate. This partly confirms our hypothesis that late summer sowing produces the highest grain yields due to less erratic temperature changes combined with a constant decrease in average temperatures by the time of flowering and achene formation. In the present study, the onset of flowering for T1 and T2 sowing fell within the longer photoperiod with higher air temperatures, whereas flowering in T3 started in late August when temperatures begin to steadily decrease and days shorten (Fig. 1 and Table 1). Unfavourable high temperatures and water stress have both been suggested as strong factors regulating seed set (Siracusa et al., 2017). Such conditions could have impacted more T2 reproductive stages and seed filling, as indicated by the high percentage of green seeds at harvest and final grain yields. Although July sowing produced more stable yields, significantly higher resistance to lodging and lower amounts of green achenes in T3 compared to T2 also need to be considered as important factors for the consideration of farmers when growing buckwheat in lowland areas.

The present study employed the cultivar Lileja, as it is commonly utilized by farmers in the Friuli-Venezia Giulia region (personal communication) and has been previously used in other Italian studies on buckwheat (Arduini et al., 2016; Ghiselli et al., 2017; Mariotti et al., 2016). Like many agricultural crops, buckwheat has undergone varietal selection, and many accessions are available in different locations across Europe and Asia (Chauhan et al., 2010). Despite this, buckwheat cultivars are typically adapted to highland areas with temperate climates (Singh et al., 2020), which necessitates site-specific varietal selection outside of traditional growing areas and would greatly impact future studies on best agronomic practices for buckwheat.

The present study considered various growth indices in an effort to better understand how biomass accumulation during the growing season affected grain yield. Final aboveground dry biomass values of 2018 were comparable, around 900 g m^{-2}, with results of a growth analysis experiment by Salehi et al. (2017), in which buckwheat and fenugreek were tested in Iran. While AGDM values in the present study peaked at ~ 580 g m^{-2} in 2017. In response to sowing time and irrigation, Mariotti et al. (2016) presented five out of six cases in which forage dry weights were below 300 g m^{-2} at the green achene stage, while at the brown achene stage values were in the range of 300–600 g m^{-2}, with the highest values in the irrigated late spring sowing treatment. Although no significant relationship was detected between AGDM and grain yield, Mariotti et al. (2016) also obtained the lowest yields with late spring sowing despite recording higher leaf and stem biomass compared to late summer sowing. Gaberščik et al. (2002) found that buckwheat plants exposed to higher UV levels produced lower total aboveground biomass. The authors also found lower seed number at higher UV levels, which contrasts with our results since late summer sowing produced a higher number of seeds m^{-2} compared to May sowing. In relation to AGDM, specific leaf weight was also positively affected by UV levels, which was also found for other crops (Mark and Tevini, 1997).

The lack of literature on buckwheat growth parameters makes comparison with our study difficult for many variables aside from grain yield. The present study provides different growth analysis indices, which are rarely considered in buckwheat trials (Arduini et al., 2016; Salehi et al., 2017). Growth analysis studies require extensive labour and results are particularly difficult to interpret for crops with indeterminate growth such as buckwheat. For example, LAI is strongly correlated to AGDM, but provides different information about crop development (Gebbers et al., 2011; Li et al., 2015). Leaf Area Index is one of the most measured parameters in agricultural crops (Fang et al., 2019; Gebbers et al., 2011), but we were unable to find information about LAI values for buckwheat aside from those collected in our study. Buckwheat has few leaves and a pronounced indeterminate growth which makes it difficult to compare buckwheat LAI values to those of other common major crops such as corn or sunflower. The growth analysis data collected provide valuable information regarding the response of buckwheat to different temperature conditions in the lowlands of North-Eastern Italy.

Net assimilation rate values peaked at around 40 DAS in 2018 for all sowing dates, while marked differences were observed between sowing dates in 2017. Peaks in NAR were recorded at 45 and 55 DAS for T1 and T3, respectively, while T2 in 2017 peaked at around 60 DAS. As shown in Table 1, full flowering was recorded at around 26–27 DAS in all growing seasons. Koyama et al. (2019) reported that high NAR and crop growth rate at the late ripening stage did not contribute to yield increase. Thus, the sink capacity of buckwheat is decisive until the full flowering stage while high source ability at the late ripening stage contributes little to yield increase. Our results seem to be in line with this consideration, as NAR peaks around 15 days after the beginning of the full flowering period led to yields > 1 Mg ha^{-1}, except for T1 in 2017. Furthermore, during the 2017 T2 NAR peaked at around 60 DAS which would correspond to beginning of fruit ripening, but in contrast with the results obtained by other authors produced yields > 1Mg ha^{-1} (Sugimoto, 2004; Koyama et al., 2019). Nonetheless, weather conditions and heat stress may have contributed to the unexpected yields compared to NAR values. Higher and earlier peaks were observed in 2018, whereas in 2017 the slopes were not as pronounced and seemed to peak later in the season at fruit ripening. Trends in CGR were highly correlated to NAR, and similar to those recorded by Salehi et al. (2017). We note that the predicted NAR values seemed to best predict grain yields, whereas CGR trends were more cumbersome to interpret. Potapov et al. (2017) measured Net Photosynthetic Production (NPP), which represents the actual biomass produced by plants, in five different buckwheat varieties in Slovenia. The authors found that higher NPP values recorded during the seed formation phase led to less prolonged flowering, despite lower aboveground biomass accumulation during the vegetative phase. Although NAR determines how efficiently plants use available resources, NPP provides similar information as the two indices are both expressed as g m^{-2} day^{-1}. Potapov et al. (2017) found no significant yield differences between varieties despite NPP values which ranged between ~ 90 and ~ 250 g m^{-2} day^{-1} at seed formation.

Conclusions

The present findings support the hypothesis that delayed sowing of buckwheat in lowland plains of Northeastern Italy is favourable to buckwheat growth and yield. Late summer sowing produced the best and most stable results across the two experimental years, since environmental conditions were less variable compared to the previous sowing dates. Our results support the introduction of buckwheat as a summer cash crop to diversify the short rotations dominated by soybean, maize and winter cereals in the region. Although varietal selection of buckwheat is ongoing, there remains a lack of knowledge on the best cultivars to use in lowland Mediterranean areas, since many of the available cultivars are adapted to temperate climates. To the best of our knowledge, this is the first study of its kind in our area, furthermore the analysis of data on growth parameters also presents novel approaches which provide statistical strength to our findings. Growth analysis parameters require further research to better pinpoint the underlying dynamics contributing to buckwheat grain yield. Despite this, we found that NAR may be useful to predict grain yields when taken at the full bloom stage. Future studies may benefit from cultivar screening in lowland plains at different sowing dates to verify the effect of photoperiod and temperature ranges on different buckwheat varieties. This would greatly improve both researchers' and farmers' knowledge on the best buckwheat cultivars to use for food or as a cover crop, especially in cases in which a spring sowing fails or in fields where the production of high-input summer crops such as maize or soybean is not feasible.

CRediT authorship contribution statement

Alessandra Virili: Writing – review & editing, Writing – original draft, Data curation. **Raffaela Petris:** Writing – review & editing, Project administration, Methodology, Conceptualization. **Fabiano Miceli:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Data statement

Data will be made available upon request.

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.

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