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Critical nitrogen dilution curve and dry matter production parameters for several Mediterranean vegetables

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ABSTRACT

Inadequate nitrogen fertilizing practices lead to low nitrogen uptake efficiency (NUE), which increases water NO_3^- pollution, as well as N_2O emissions to the atmosphere. In order to increase the NUE and decrease the N losses as NO_3^- and N_2O from the soil-plant system, accurate data about optimum crop N concentrations and dry matter production throughout the growing season are still needed for many vegetables typically grown under Mediterranean climate. For this reason, several N fertilization trials were set up for globe artichoke, carrot, cauliflower, chard, chinese cabbage, early potato, leek, lettuce, onion, red cabbage, romanesco, and spinach, under the semiarid Mediterranean conditions of the Valencian Community (Eastern Spain) during several years. The fresh and dry matter weight (W), as well as the nitrogen concentration in the dry matter (%N) in both the marketable and non-marketable crop parts, was measured between 3 and 7 times throughout their respective growing seasons. The a and b coefficients of the average N dilution curve ($\%N = a\, W^{-b}$), for which all %N and W data were used, and the critical N dilution curve ($\%N_c = a\, W_c^{-b}$), for which only the minimum %N for maximum W data were used if available, in addition to the dry/fresh yield matter ratio (*DM*) and the harvest index (*HI*), were calculated for all these crops. No significant differences were observed between the average and critical N dilution curve coefficients in this work. Interestingly, the coefficients of both N dilution curves differed from the ones found in the literature with the exception of those obtained for similar cultivars, e.g., early potatoes, and under similar climatic conditions, i.e., Mediterranean. Besides, there were neither differences of *DM* and *HI* among the several N fertilization treatments. Therefore, due to the absence of changes in the N dilution curve and dry matter production coefficients for the different N supplies, all these parameters were estimated on the basis of the whole dataset, i.e., regardless of the N input. The use of the critical nitrogen dilution curve coefficients and dry matter production parameters presented in this work should contribute to better fit the N fertilizer additions to N demands of these vegetables under Mediterranean conditions, mainly, by their use through simulation models. Therefore, the NUE in horticulture should increase and the N losses as NO_3^- to inland and sea waters in these environments, and as N_2O to the atmosphere should decrease.

1. Introduction

Horticultural crops require large nitrogen fertilizer amounts, which range between 40 and 350 kg N ha^{-1} (Generalitat Valenciana Ordre 10, 2018). Additionally, due to brief growing seasons, usual harvest before crop senescence, shallow rooting depths, and imbalance between N uptake and assimilation rates (Cardenas-Navarro et al., 1999), the cultivation of vegetables is characterized, in general, by low N use efficiency (Benincasa et al., 2011; Widowati et al., 2011). As a consequence, large quantities of nitrogen are lost from the soil-plant system in horticulture, thus rising environmental concerns due to the pollution of inland and sea waters by NO_3^-, and the release to the atmosphere of large amounts of greenhouse and stratospheric ozone-depleting gasses, primarily N_2O, and secondarily NH_3 (Oenema et al., 2011; Cameron et al., 2013).

To reduce the environmental issues brought about by the N losses from the soil-plant system, first of all, an accurate knowledge about the N demand (N_{dmd}) of each crop, including their variation along the

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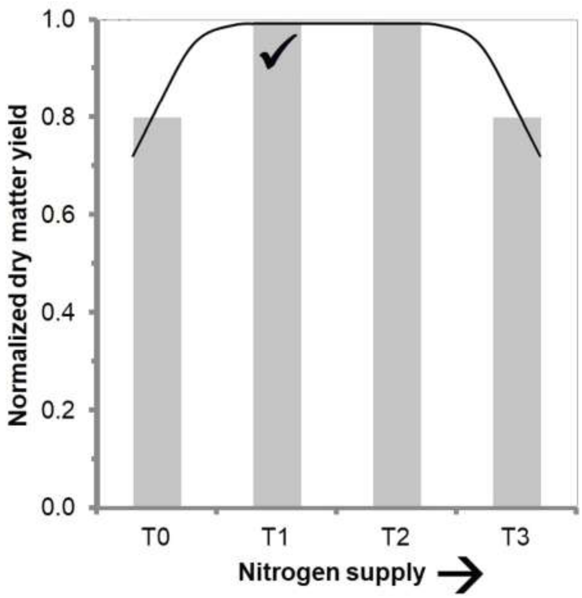

Fig. 1. Normalized dry matter yield evolution as a function of nitrogen supply following a linear-plateau model (solid line), where the rising, tableau and decreasing stretches of the normalized *DMY* against the N input are shown, in addition to the expected normalized *DMY* of four N fertilization treatments of increasing nitrogen supply in the order T0 < T1 < T2 < T3 (bars). The adequate N treatment for maximum N uptake efficiency is highlighted with a check mark.

growing season is needed. In its simplest, the N_{dmd} can be assessed from the nitrogen concentration in the dry matter (%*N*) and the dry matter per unit surface (*W*) through:

$$N_{dmd} = f_W W \%N/100 \tag{1}$$

where f_W is the cumulated fraction of dry matter throughout the growing season, which ranges from almost 0 at the growing onset, to 1 at harvest, and can be modelled by a sigmoid-type function (Yin et al., 2003). The %*N* evolves along the growing season according to a negative power function (Eq. (2)) because, as plant development progresses, i) the plant supportive and storage organs, which are low in N, grow more than the photosynthetic and meristematic ones, which are high in N (Greenwood et al., 1990), and ii) the leaf N concentration increases in the well-illuminated canopy outside at the expense of the poorly-illuminated canopy inside (Ciampitti et al., 2021):

$$\%N = aW^{-b} \tag{2}$$

Then, replacing the N dilution curve given by Eq. (2) in Eq. (1), the following equation can be obtained:

$$N_{dmd} = 0.01 f_W a W^{1-b} \tag{3}$$

Besides, replacing *W* in Eq. (3) by its value given by:

$$W = DMY/HI \tag{4}$$

where *DMY* is the dry matter yield per unit surface, and *HI* is the harvest index, and furthermore, replacing *DMY* by its value given by:

$$DMY = DMFY \tag{5}$$

where *DM* is the dry/fresh yield matter ratio and *FY* is the fresh yield, the following equation is eventually reached:

$$N_{dmd} = 0.01 f_W a (FYDM/HI)^{1-b} \tag{6}$$

where the *a* coefficient represents the plant nitrogen concentration when crop dry biomass per unit surface is 1 t ha^{-1}, and the *b* coefficient is the logarithmic steepness of the crop N concentration decrease as crop dry biomass increases or, what it is the same, the ratio of N concentration in the dry biomass to the whole dry biomass (Plénet and Lemaire, 2000). The values that both coefficients take, depend on crop genetics as well as on environmental factors (Greenwood et al., 1990) and, therefore, it will be useful to have reliable estimations of these parameters for every crop and environment. Nowadays, however, there is still scarce information about the N dilution curve and production parameters for many horticultural crops (Chen et al., 2021). There is even less data for vegetable crops typical to Mediterranean and related semi-arid climates, with high insolation and temperature and low water availability, specifically during summer, which stress vegetables and may affect their N dilution curve coefficients (Bélanger et al., 2001; Errecart et al., 2014), and dry matter production parameters (Katroschan et al., 2014; Wakchaure et al., 2021).

The N dilution curve can be developed, and the *a* and *b* parameters thus obtained, using %*N* and *W* data regardless of the crop available N. However, for maximizing the N uptake efficiency (NUE), defined as the ratio of crop N output to N input (Benincasa et al., 2011), critical %*N* and *W* values, i.e.,%N_c and W_c should be used instead. These critical N values are the minimum plant N concentrations that lead to maximum crop dry matter production (Ulrich, 1952; Lemaire and Salette, 1984). As it is shown in Fig. 1, yield and hence normalized dry matter yield can be modelled as a function of the N supply by means of a linear-plateau model. Therefore, an N supply treatment which features the maximum crop production from the minimum N extraction can be selected, i.e., the treatment highlighted with a check mark in Fig. 1.

Then, the N dilution curve relating %N_c to W_c, which is known as the critical N dilution curve can be developed (Lemaire, 2007), and the following negative power function:

$$\%N_c = a\,W_c^{-b} \tag{7}$$

is the most used, where the *a* and *b* coefficients have been mainly determined for field crops, among which wheat (Jeuffroy and Bouchard, 1999), corn (Plénet and Lemaire, 2000), rice (Sheehy et al., 1998;

Table 1
Characteristics of the nitrogen fertilization trials that were carried out to obtain the critical N dilution curve coefficients and dry matter production parameters.

Crop	Number of experimental plots	Number of seasons/plot	Number of N treatments/plot	Number of samplings/plot	Refs.
Artichoke	3	2	4	3	Khayyo et al. (2004)
Carrot	4	1	2	5–7	This work
Cauliflower	3	1	4	4	This work
Chard	1	1	4	6	This work
Chinese cabbage	3	1	3	4–5	This work
Early potato	3	1	2	4	Rodrigo (1995)
Leek	4	1	2	4–6	This work
Lettuce	1	1	4	8	This work
Onion	4	1	2–4	5–6	This work
Red cabbage	4	1	2	4	This work
Romanesco	1	1	4	4	This work
Spinach	1	3	4	4–6	This work
Total	**32**				

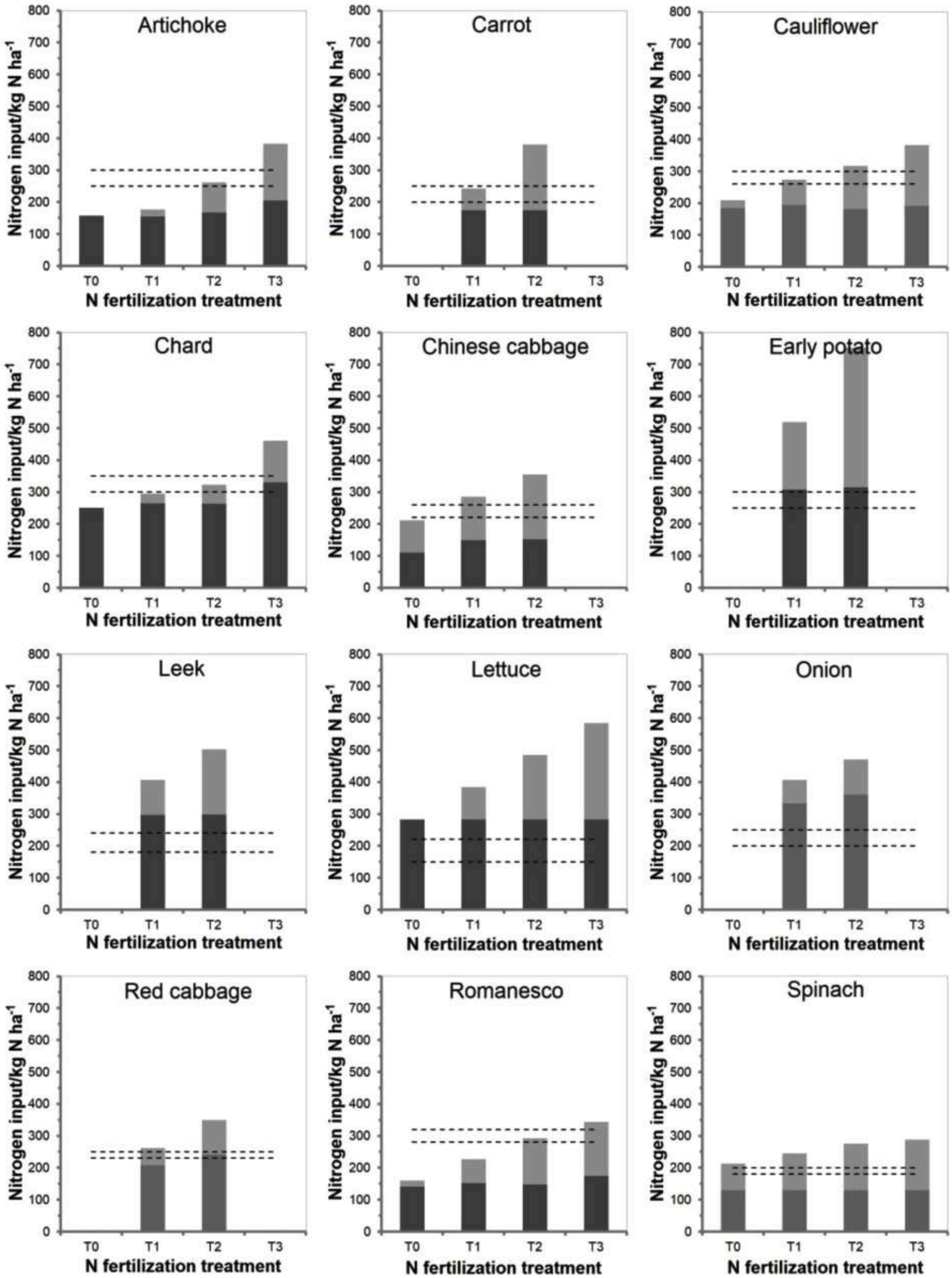

Fig. 2. Average nitrogen input as the sum of the soil mineral nitrogen before plantation (Nmin) in dark gray, plus the nitrogen rate from mineral fertilizers in light gray featuring the fertilization trials for each crop. The dashed lines represent the minimum and maximum N recommendations for each crop according to the Code of Good Agricultural Practices of the Valencian Community (Generalitat Valenciana Ordre 10, 2018).

Table 2
Mineral N fertilizer management information for the experimental trials: number of N fertilizer treatments (N), maximum, minimum, mean and standard deviation of the nitrogen applied by mineral fertilization in the experimental trials in comparison with the maximum input of nitrogen as established in the Code of Good Agricultural Practices of the Valencian Community (GAP), planting months and duration in days from plantation till harvest.

Crop	N	Mineral fertilizer doses (kg N ha^{-1})					Planting months	Crop duration (days)
		Max.	Min.	Mean	SD	Max. Input GAP		
Artichoke	6	240	0	74	81	300	Jul-Sep	234–317
Carrot	8	254	4	110	80	250	May-Jun	129–230
Cauliflower	14	200	0	91	63	300	Sep	152–158
Chard	4	130	0	55	56	350	Sep	42
Chinese cabbage	17	253	0	137	66	260	Oct-Jan	80–104
Early potato	6	586	150	325	156	300	Dec-Jan	126–138
Leek	6	266	84	167	73	240	Jul	175
Lettuce	4	301	0	151	129	220	Aug	50
Onion	10	136	72	95	28	250	Oct-Nov	112–154
Red cabbage	4	136	0	82	59	—	Aug	86–121
Romanesco	8	183	20	108	57	320	Sep	144–153
Spinach	12	198	54	126	47	200	Sep-Feb	41–83

Ata-Ul-Karim et al., 2017), and forage grasses (Fletcher and Chakwizira, 2012), stand out with over 58% of total published articles about critical N dilution curves in the Science Citation Index (Chen et al., 2021). Besides, in horticulture, the critical N dilution curve coefficients have been determined for several crops such as potato (Gómez et al., 2019 and references therein), tomato (Tei et al., 2002), lettuce (Tei et al., 2003) and broccoli (Conversa et al., 2019), and more sparsely for all the rest (Chen et al., 2021).

Similarly to the critical N dilution curve coefficients, both the *HI* and *DM* parameters have been thoroughly determined for field crops such as wheat (Zhang et al., 2008), corn (Liu et al., 2020), and rice (Ju et al., 2009). In horticulture, the *HI* and *DM* parameters have been determined also for potato (Vos, 1997), tomato (Ronga et al., 2019), and broccoli (Everaarts and De Willigen, 1999; Conversa et al., 2019). Besides, they have been determined for other important vegetables grown under Mediterranean conditions such as globe artichoke (Lombardo et al., 2020), carrot (Dezordi et al., 2015; Pereira et al., 2015), cauliflower (Idnani and Thuan, 2007; Riley and Vågen, 2003), onion (Wakchaure et al., 2021), romanesco (Riley and Vågen, 2003), and spinach (Biemond et al., 1996).

Therefore, because of the high variability in the crop N cumulative uptake and dry matter production due to environmental and management influences on crop gene expression, and because of the still scarce information about the critical N dilution curve coefficients and dry matter production parameters for vegetables grown under Mediterranean conditions, the generation of specific values for these parameters could improve the NUE of horticulture in this important production area.

Consequently, the objective of this work was to obtain the parameters of the critical N dilution curve and dry matter production of some typical vegetables grown under the semi-arid Mediterranean conditions characteristic of horticulture in the Valencian Community (Spain). The crops studied were: artichoke, carrot, cauliflower, chard, Chinese cabbage, early potato, leek, lettuce, onion, red cabbage, romanesco, and spinach.

2. Materials and methods

2.1. Study area, crops and N fertilization trials

Several nitrogen fertilization trials (Table 1) were carried out throughout various years in commercial horticultural plots of cooperating farmers from the Valencian Community (Eastern Spain) cultivated with crops that took account of 68% of vegetables production in this territory in 2018 (MAPA, 2019). They were first and second year globe artichoke (*Cynara cardunculus* L. var. *scolymus* L. (Fiori) cv. Blanca de Tudela), carrot (*Daucus carota* ssp. *sativus* cv. Maestro), cauliflower (*Brassica oleracea* var. *botrytis* subvar. *cauliflora* cv. Triomphant), chard (*Beta vulgaris* var. *cicla*), Chinese cabbage (*Brassica rapa* L. ssp. *pekinensis* cv. One-kilo, cv. Manoko, and cv. Asten), early potato (*Solanum tuberosum* L. cv. Edzina), leek (*Allium ampeloprasum* var. *porrum* cv. Tatum, and cv. Lincoln), lettuce (*Lactuca sativa* L. var. *butterhead* cv. Francesa), onion (*Allium cepa* L. cv. Bigger, and cv. Galaxia S), red cabbage (*Brassica oleracea* var. *capitata* f. *rubra* cv. Sombrero), romanesco (*Brassica oleracea* var. *botrytis* L., cv. Veronica), and spinach (*Spinacia oleracea* L.).

The soils in the trial plots are representative of the Valencian horticultural alluvial areas with textures from loam in the topsoil to clay loam at depth. The climate in these agricultural areas is characterized by being semiarid according to the Thornthwaite classification (de Paz et al., 2004), with mild winters and hot summers, and with a rainfall regime that intensifies in autumn and spring, with hardly any rain in summer, i.e., typically Mediterranean.

In the trials the effects of various nitrogen input rates on crop development and yield were tested (Fig. 2), whereas the other agricultural management practices, i.e., irrigation schedule, non-nitrogen fertilization, pesticide applications, etc., were those used by the farmers.

To calculate the nitrogen fertilizer rates for the N treatments, the soil mineral nitrogen content before plantation (Nmin in the 0–60 cm layer) was subtracted from the target N input. This way the total N input was made to linearly increase from deficit to well above the maximum crop N recommendations given by the Code of Good Agricultural Practices (GAP) of the Valencian Community (Generalitat Valenciana Ordre 10, 2018) (Fig. 2). In general, the maximum N rate applied through mineral fertilizer was 6% lower than the maximum recommended N in the GAP. For example, in the case of artichoke the N rate ranged from 0 to 240 kg N ha^{-1}, which contrasts with the maximum recommended N input of 300 kg N ha^{-1}; and in the case of spinach the N rate ranged from 54 to 198 kg N ha^{-1}, which contrasts with the maximum recommended N input of 200 kg N ha^{-1} (Table 2).

2.2. Crop samplings and laboratory determinations

Along the growing season of each crop, plants were sampled between 3 and 7 times, depending on the trial (Table 1), for the determination of the dry matter and N concentration in the plants. The aerial part of the plants was taken in full, sealed in plastic bags to avoid any water loss, and carried to the laboratory. There, when a marketable part could be differentiated in the plants, this was separated from the rest. The fresh matter from the marketable part and the rest was separately determined by weighing. Then, both parts were dried at 65 ºC in a Dry Big (J.P. Selecta S.A., Abrera, Barcelona, Spain) air-forced oven for at least 48 h until constant weight, and the dry matter determined by weighing. Next, each part was grounded to pass a 200 µm mesh sieve, homogenized and the N concentration determined using the Kjeldahl method to include nitrate (Dalal et al., 1984). For the *HI* and *DM* ratio estimations only the data from the harvest sampling was used and presented in this work

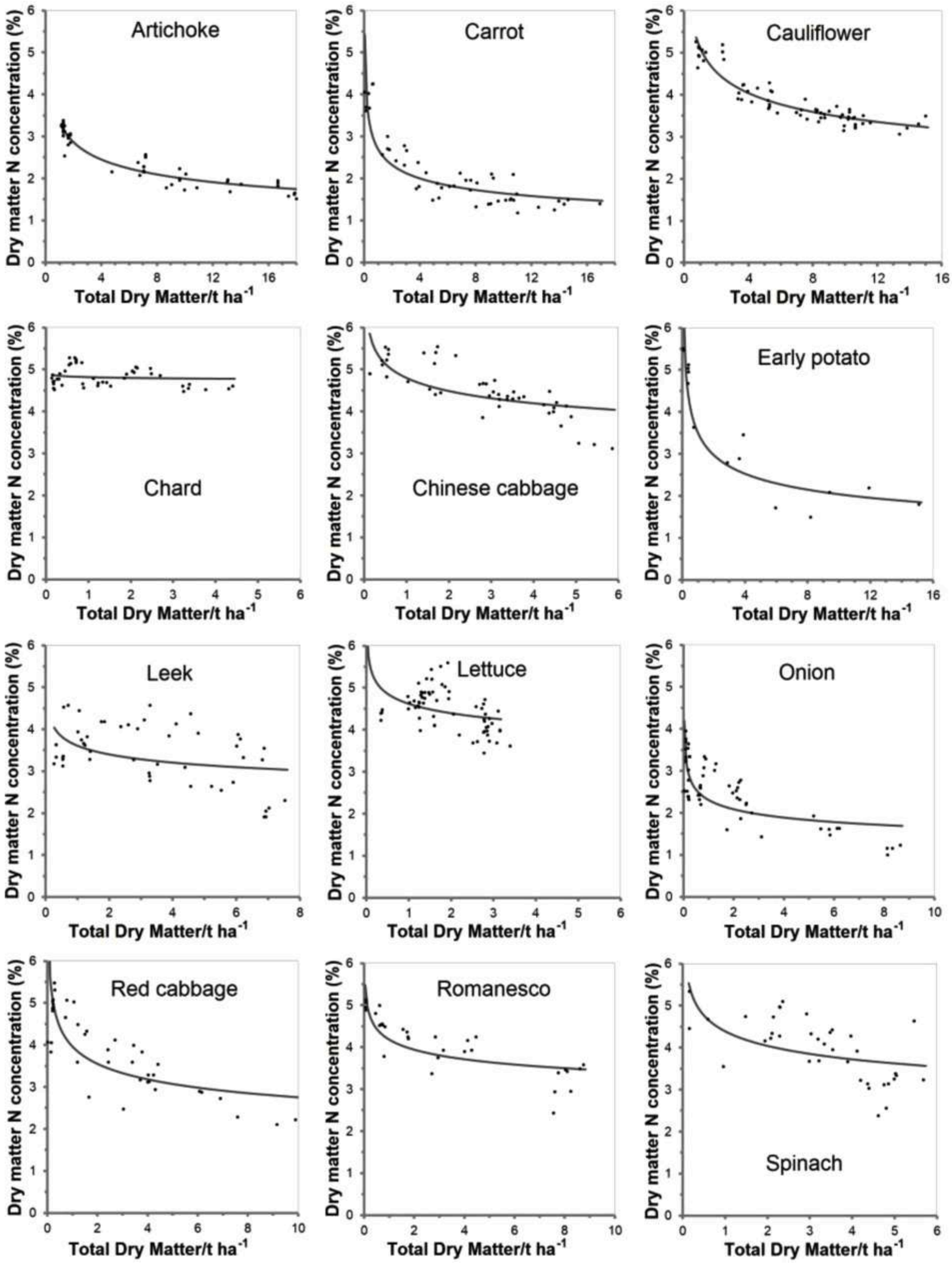

Fig. 3. Experimental nitrogen concentration in the dry matter against total dry matter and fitted average nitrogen dilution curve (Eq. (7)) for each of the crops studied in this work.

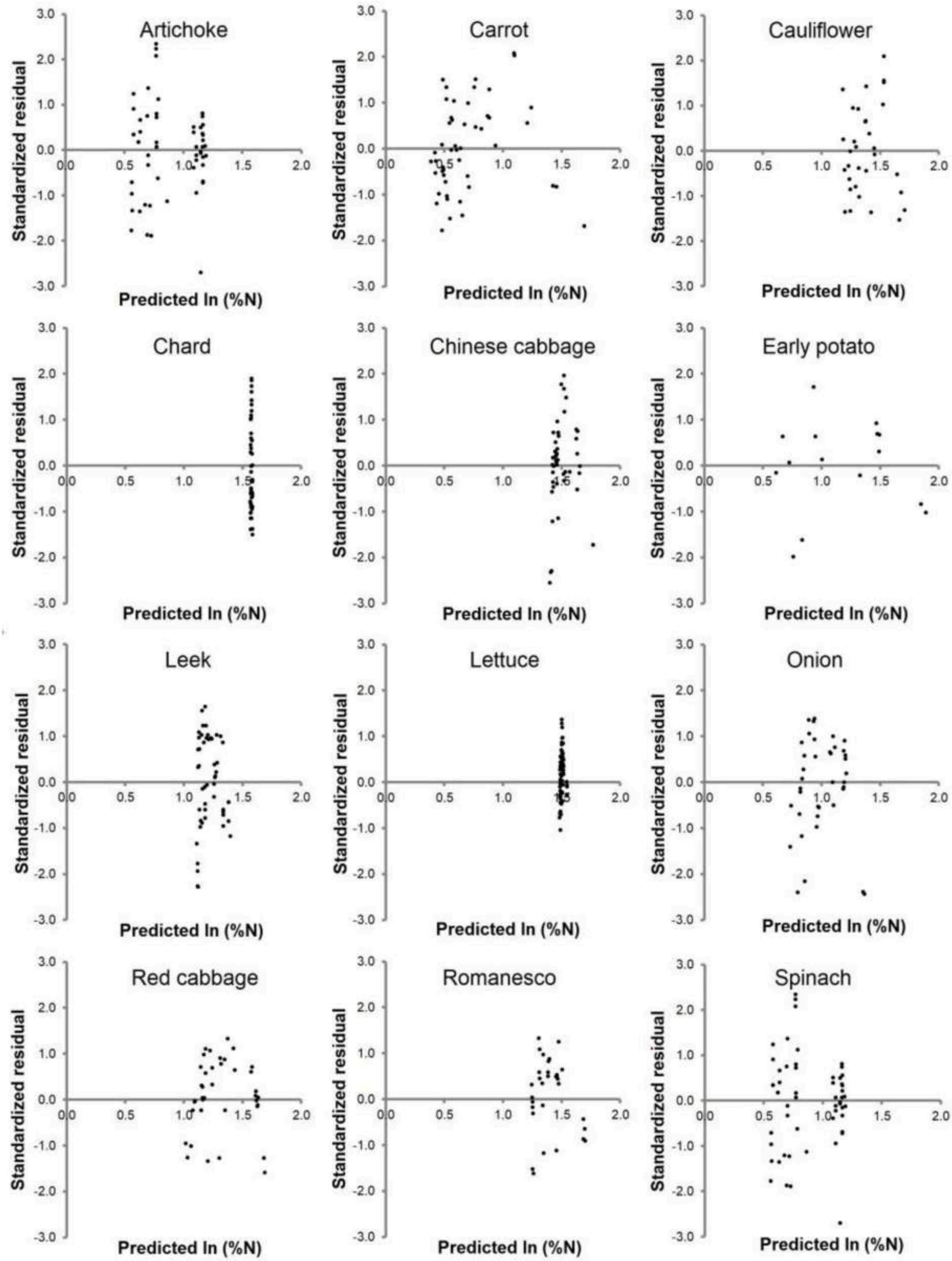

Fig. 4. Standardized residuals for the ln (%*N*) prediction against the predicted ln (%*N*) according to the fitted average nitrogen dilution curve for each of the crops studied in this work.

Specifically, the following equations, which are the reciprocals of Eqs. (4) and (5), were used in this regard for, respectively, the *HI* and the *DM* ratio calculations:

$$HI = DMY/W \quad (8)$$

$$DM = DMY/FY \quad (9)$$

Note that the plants' roots were not considered in this assessment.

Table 3
Estimates of the average N dilution curve coefficients for the crops studied in this work along with their 95% confidence intervals, and the root mean square error (RMSE). The values of these parameters found by other authors are given for comparison, and when several data are available, the minimum and maximum are written between brackets, whereas when only one datum so is, it has been written along with the 95% confidence interval if provided.

Crop	This work			Other authors'		
	a	b	RMSE	a	b	Refs.
Artichoke 1st & 2nd	3.3 ± 0.1	0.23 ± 0.02	0.17	3.27	0.27	Carpintero et al. (2006)
Carrot	2.7 ± 0.2	0.21 ± 0.03	0.48	2.63	0.22	Shlevin et al. (2018)
Cauliflower	5.4 ± 0.3	0.19 ± 0.03	0.24	4.84 ± 0.14	0.09 ± 0.02	Kage et al. (2002)
Chard	4.82 ± 0.07	0.005 ± 0.014	0.23	–	–	–
Chinese cabbage	4.8 ± 0.2	0.10 ± 0.03	0.45	–	–	–
Early potato	3.5 ± 0.4	0.23 ± 0.06	0.58	[2.99, 6.74]	[0.25, 0.58]	Gomez et al. (2019) and references therein
Leek	3.6 ± 0.3	0.09 ± 0.06	0.66	–	–	–
Lettuce	4.6 ± 0.2	0.07 ± 0.05	0.46	[3.65, 3.79]	[0.12, 0.29]	Conversa and Elia (2019), Tei et al. (2003)
Onion	2.5 ± 0.2	0.11 ± 0.04	0.53	–	–	–
Red cabbage	4.0 ± 0.2	0.16 ± 0.04	0.60	5.1 ± 0.5	0.33 ± 0.03	Ekbladh and Witter (2010)[A]
Romanesco	4.2 ± 0.2	0.09 ± 0.02	0.40	5.8 ± 0.9	0.46 ± 0.09	Riley and Vågen (2003)
Spinach	4.4 ± 0.4	0.12 ± 0.07	0.63	4.11	0.24	Giménez et al. (2019)

[A] White cabbage

2.3. Data analyses

First, the a and b coefficients of the average N dilution curve for each crop were assessed by including the $\%N$ and W data from all the N treatments. Specifically, Eq. (2) was linearized to give:

$$\ln(\%N) = \ln a - b \ln W \tag{10}$$

and simple ordinary least squares regression (OLSR) of ln ($\%N$) against ln W data was carried out. This linearized model should better fulfilled the assumptions for regression and thus the mean a and b coefficients plus their 95% confidence intervals should be more reliably obtained for each crop.

Second, the a and b coefficients of the critical N dilution curve for each crop were assessed by including only the $\%N$ and W data from the optimum N treatments, i.e.,$\%N_c$ and W_c, following Justes et al. (1994). Accordingly, the $\%N_c$ and W_c data were selected from the N fertilization treatment that significantly gave the highest normalized *DMY* with the least N as pointed out in Fig. 1, where the normalized *DMY* is the ratio of *DMY* to maximum *DMY* in each particular trial (Schultz et al., 2018). By using the normalized *DMY*, different experimental datasets could be adequately gathered as recommended (Fernandez et al., 2021), thus avoiding the effects of cultivar, soil, water quality, and other potentially-confounding environmental and management factors different from nitrogen input. The use of normalized yields in this regard is similar to what is done when, e.g., the effects of soil salinity on crops are assessed (Maas and Hoffmann, 1977), or crop water production functions are developed (Saseendran et al., 2015).

To compare the normalized *DMY*, the *DM* ratio and *HI* among the N fertilization treatments, the ANOVA and the Tukey's Honest Significant Difference (HSD) were used.

Finally, the estimates of the a and b coefficients obtained from the average N dilution curve and from the critical N dilution curve were compared by using the Student's t-test for independent samples.

All estimates of mean values obtained in this work are expressed along with the 95% confidence interval.

3. Results and discussion

The data obtained in the N fertilization trials, i.e., soil Nmin at the onset of the cropping season, N applied through mineral fertilization, total plant-available mineral N, dry matter yield per unit surface as such and also normalized, *HI* and *DM* ratio, as well as crop N percent and dry matter weight per unit surface throughout the cropping season, can be found in de Paz et al. (2021).

3.1. Average N dilution curves

Fig. 3 shows the fit to the data of the average N dilution curves for the different crops. In general, the data are uniformly distributed throughout the W (Total Dry Matter) range as recommended (Fernandez et al., 2021). Furthermore, on the basis of a visual inspection of the plot of standardized residuals against predicted ln ($\%N$) (Fig. 4), no kind of systematic pattern can be found. The residuals appear evenly distributed over and below the x axis, and this detrended distribution does not seem to change as ln ($\%N$) increases. Therefore, since the requirements for the normality of the residuals and their homocedasticity can be accepted for the OLSR of ln ($\%N$) on ln W for all crops in general, the simple negative power function given by Eq. (7) can be considered to adequately fit the $\%N$ against W data and, moreover, the a and b coefficients obtained by OLSR of Eq. (10) can be considered as their best

Table 4
Summary of the ANOVAs for the normalized DMY, DM ratio and the HI value among the nitrogen fertilization treatments for each of the crops studied in this work.

Crop	Number of N treatments	Total degrees of freedom[A]	F values			p values[B]		
			Norm. DMY	DM	HI	Norm. DMY	DM	HI
Artichoke	4	49–59	5.507	0.308	1.045	**0.0026**	0.8197	0.3817
Carrot	2	14	0.255	0.736	0.012	0.6218	0.4066	0.9158
Cauliflower	4	54	2.062	1.513	0.402	0.1168	0.2223	0.7522
Chard	4	—	—	—	—	—	—	—
Chinese cabbage	3	42	1.443	0.644	0.545	0.2483	0.5304	0.5839
Early potato	2	9–19	2.006	0.017	0.005	0.1944	0.8996	0.9443
Leek	2	47	0.372	1.044	—	0.5448	0.3122	—
Lettuce	4	23	1.271	—	—	0.3113	—	—
Onion	2–4	31–47	1.227	2.098	1.750	0.2738	0.1542	0.1959
Red cabbage	2	15	7.504	0.452	0.584	**0.0160**	0.5122	0.4574
Romanesco	2–4	27	4.488	4.571	3.668	**0.0123**	**0.0114**	**0.0263**
Spinach	4	71	6.332	2.604	2.936	**0.0008**	0.0589	**0.0394**

[A] Total degrees of freedom may vary depending on the number of available data for each variable.
[B] Significant values at the 95% confidence level in bold.

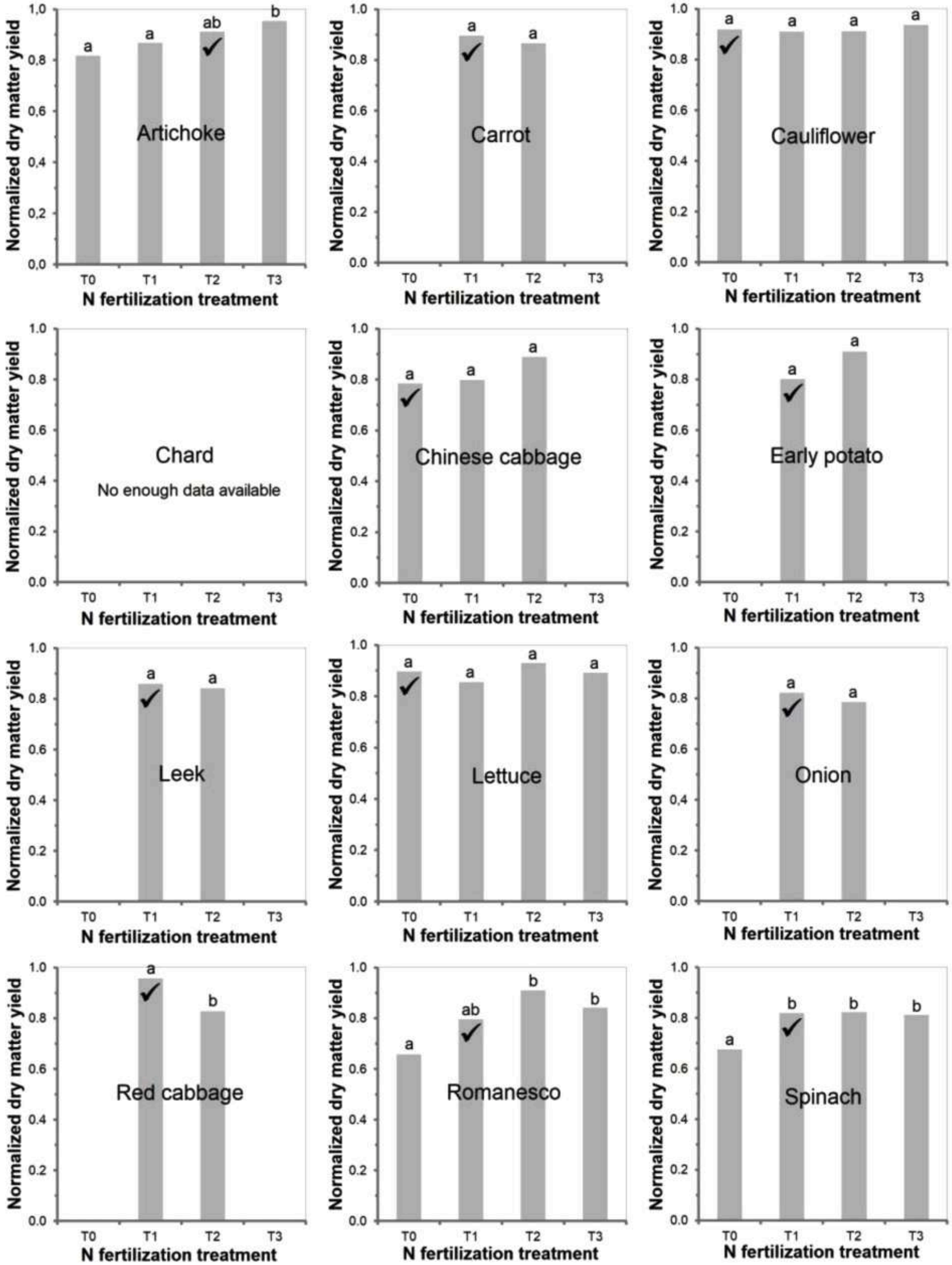

Fig. 5. Mean normalized dry matter yield in the different nitrogen fertilization treatments arranged from highest to lowest nitrogen supply in the order T0 < T1 < T2 < T3, for each of the crops studied in this work. Different letters within the same crop denote significant differences at the 95% confidence level according to the Student's *t*-test when only two N treatments are compared, and to the Tukey's honest significance difference test when more than two N treatments are compared. The treatments that were selected for the critical N dilution curve development are highlighted with a check mark.

Table 5
Estimates of the critical N dilution curve coefficients for the crops studied in this work along with their 95% confidence intervals, and the p values of the Student's *t*-test for the comparison of the critical N dilution curve coefficients with the average N dilution curve ones.

Crop	Normalized DMY differences between N treatments?	Coefficients' estimates		p values	
		a	b	a	b
Artichoke 1st & 2nd	YES	3.4 ± 0.2	0.23 ± 0.03	0.620	0.802
Carrot	NOT	2.6 ± 0.2	0.22 ± 0.05	0.780	0.750
Cauliflower	NOT	5.3 ± 0.6	0.21 ± 0.06	0.633	0.598
Chard	—	—	—	—	—
Chinese cabbage	NOT	4.7 ± 0.3	0.11 ± 0.05	0.381	0.512
Early potato	NOT	3.7 ± 0.7	0.20 ± 0.10	0.593	0.533
Leek	NOT	3.5 ± 0.4	0.10 ± 0.09	0.800	0.732
Lettuce	NOT	4.3 ± 0.2	0.06 ± 0.05	0.327	0.938
Onion	NOT	2.4 ± 0.2	0.12 ± 0.06	0.484	0.671
Red cabbage	YES	3.8 ± 0.3	0.16 ± 0.06	0.434	0.961
Romanesco	YES	4.2 ± 0.2	0.09 ± 0.04	0.666	0.857
Spinach	YES	4.1 ± 0.5	0.13 ± 0.09	0.335	0.839

unbiased estimators. In this regard other more complex mathematical functions are used for the N dilution curve modeling, e.g., Rahn et al. (2010). However, according to the results in this work, such more complex mathematical functions would not be necessary, at least for the crops studied in this work.

In Table 3 the estimates of the *a* and *b* coefficients of the average N dilution curve are presented along with the corresponding root mean squared errors (RMSE) for the prediction of %*N* by means of Eq. (7). In the case of artichoke, though this was a two-year crop both the *a* and *b* coefficients did not significantly change from one year to the next (*p* values of 0.55 and 0.89, respectively) (Table 3). Therefore, a joint average N dilution curve using the two growing cycles is thus presented for artichoke.

The average N dilution curve coefficients ranged between 0.23 and 0.01 (*b*), and between 2.5 and 5.4 (*a*), with RMSE values for the fit between observed and predicted %*N* with Eq. (2) between 0.17 and 0.66% (Table 3).

In general, the estimates for the *a* and *b* coefficients in this work differ from those obtained by other authors (Table 3) except when the cultivars and climate under which they were grown are similar to those in this work. For instance, the *a* and *b* coefficients estimated in this work for potato are in the lower stretch of the range found in the literature, where the cultivars known as "Spunta", "Bellini" and "Asterix" lay (Gomez et al., 2019 and references therein). These cultivars are from the very early to medium early kind according to the European Cultivated Potato Database (2021). Therefore, they are similar to the cv. Edzina analyzed in this work, which is classified as medium early. Moreover, the data that could be found in other studies are from trials under Mediterranean climate. That is, similar earliness and climate seem to lead to closer *a* and *b* coefficients.

Furthermore, it is interesting to note that the scattering of %*N* against *W* data for green leaf crops like chard and lettuce remarkably depart from the others'. And moreover for lettuce, a reciprocal N dilution curve, i.e., one with a negative *b* coefficient, might be fitted to the points. The scattering of %*N* against *W* data observed for chard and lettuce is reflected in the estimates obtained for the *b* coefficients of their respective N dilution curves, which are closer than any other to zero. In this regard, note that they are 0.005 ± 0.014 for chard and 0.07 ± 0.05 for lettuce with p-values of the null hypothesis test ($b = 0$) of the *b* coefficient of, respectively, 0.5 and 0.003. In these green leaf crops the chlorophyll content keeps almost constant throughout the growing season with high N concentrations until their harvest in green (Fig. 3). For lettuce this is in accordance with Fontes et al. (1997), who reported average %*N* values going from 4.3 to 3.8% in a greenhouse trial, but disagrees with Tei et al. (2003), who reported average %*N* values going from almost 5 to below 3% in a spring-summer trial, i.e., similar to this (Table 2), but under humid subtropical climate. Such difference with Tei et al. (2003) suggests a more powerful N dilution under a more humid climate, and hence the potential interest of having climate-specific critical N dilution curves, which was the aim of the present work for Mediterranean climate. In comparison to the green leaf crops, others such as artichoke, carrot or potato, which develop big low-in-nitrogen organs and, moreover, are harvested when the plants start to wither, have nitrogen concentrations at harvest clearly below the ones they have at the growing season onset, featuring values of the *b* parameter around 0.2.

All these observations point towards the strong dependency the *a* and *b* coefficients have on cultivar, climate and management and, therefore, the need to know their values when these factors are known to significantly change with respect to the standards. Besides, note that there were vegetables for which no specific data could be found for comparison, e.g. chard, onion, and red cabbage (Table 3). Interestingly, the *a* and *b* coefficients for these three crops change significantly from one vegetable to the other and, furthermore, are away from the standard values of, respectively, 5.7 and 0.5, featuring C3 crops in general (Greenwood et al., 1990). Such differences among the vegetables and with the C3 standard, point towards the importance of having crop-specific critical N dilution curves. In this regard, this work aims at contributing specific estimates for the *a* and *b* coefficients of a good deal of horticultural crops, which can be advantageously used by practitioners instead of the generic *a* and *b* values for C3 crops, especially under Mediterranean climate.

3.2. Normalized dry matter yield differences among the N treatments

According to the ANOVAs (Table 4), there were significant differences of normalized *DMY* among the different N fertilization treatments for some crops. The results of the pairwise comparisons in accordance to the Tukey's HSD supported what was observed in the ANOVAs (Fig. 5).

The differences of normalized *DMY* were significant at the 95% confidence level for artichoke, red cabbage, romanesco and spinach (Fig. 5). Conversely, for carrot, cauliflower, Chinese cabbage, early potato, leek, lettuce and onion, significant differences were not found at the 95% confidence level among the N treatments. For chard no enough information was available for the normalized *DMY* comparison among the N treatments.

For artichoke, romanesco and spinach, the N treatments went through both the rising and tableau stretches of the curve of normalized *DMY* against nitrogen supply (Fig. 5). In comparison, Riley and Vågen (2003) also observed a continuous increase of romanesco total fresh yield from 150 to 250 kg N ha^{-1}, which is an N supply range very similar to the one from T0 (150 kg N ha^{-1}) to T2 (300 kg N ha^{-1}) through which romanesco normalized *DMY* significantly increased in this work. Since an optimum N supply was found for artichoke, romanesco and spinach then, for these crops, a maximum efficiency treatment could be identified and selected for the subsequent development of their critical N dilution curves.

For red cabbage, the N treatments crossed, conversely, part of the tableau and lowering stretches of the curve of normalized *DMY* against *N* supply, and although a maximum efficiency treatment could not be rigorously identified, the treatment of highest normalized *DMY* was chosen as the most adequate surrogate for the development of the critical N dilution curve (Fig. 5).

For the other six crops (carrot, cauliflower, Chinese cabbage, early

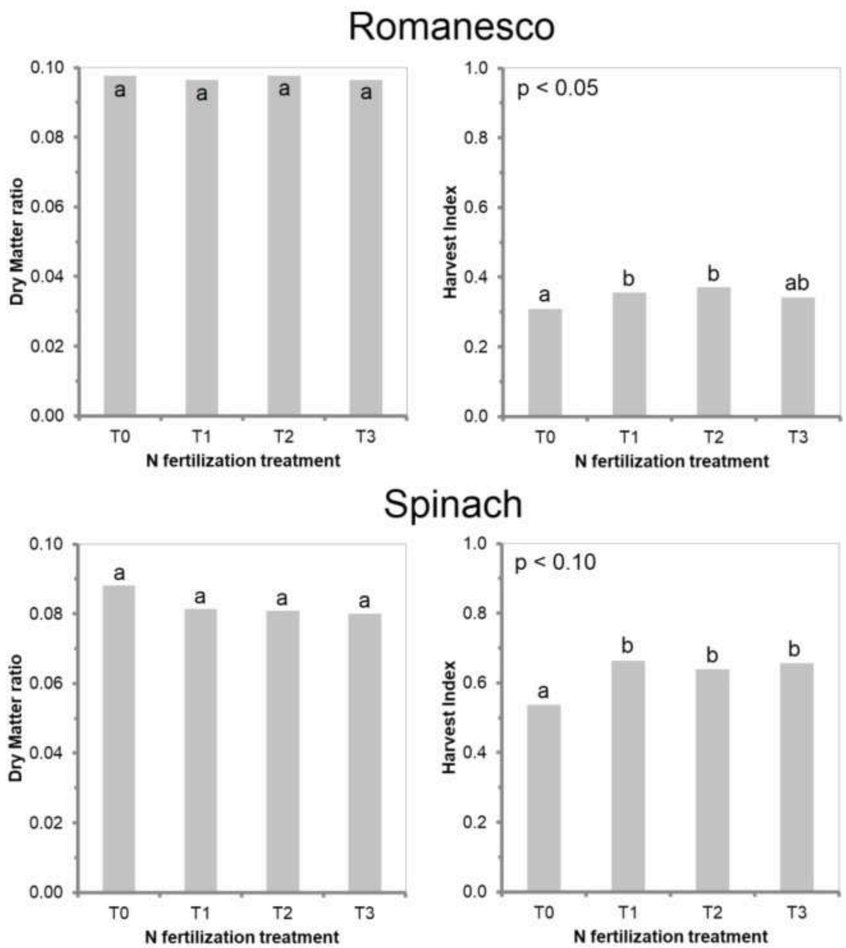

Fig. 6. Mean *DM* ratio and *HI* values in the different nitrogen fertilization treatments arranged from highest to lowest nitrogen supply in the order T0 < T1 < T2 < T3, for romanesco and spinach. Different letters within the same crop denote significant differences at the 95% confidence level, except for *HI* and spinach, in which it is 90%, according to the Tukey's honest significance difference test.

potato, leek, lettuce and onion), all the N treatments could be considered to be within the plateau stretch of the curve of normalized *DMY* against *N* supply. In comparison, Riley and Vågen (2003) did not either found cauliflower total fresh yield differences from 150 to 250 kg N ha^{-1}, which almost matches the two N lowermost treatments in this work, i.e., T0 (200 kg N ha^{-1}) and T1 (250 kg N ha^{-1}). Therefore, even though for carrot, cauliflower, Chinese cabbage, early potato, leek, lettuce and onion, a maximum efficiency treatment could neither be rigorously identified, the treatment with the lowest N supply was chosen as the best option for the ensuing critical N dilution curve development.

3.3. Critical N dilution curves

In Table 5, the values of the *a* and *b* coefficients of the critical N dilution curves obtained by OLSR of Eq. (6) are shown. In the comparison of the critical and the average N dilution curves, significant differences in the *a* and *b* coefficients between one curve and the other were not observed at the 95% confidence level for any of the crops. Moreover, the *p* values of the Student's *t*-test for this comparison were between 0.34 and 0.96, which are very high. Accordingly, differences between the average and critical N dilution curves were far from being observed even though the statistical power was also high. This result may be a consequence of the scarce differences of normalized *DMY* between the N treatments. For example, in rice the critical and maximum N dilution curves have been found to be non-significantly different, whereas the critical and minimum so are (Ata-Ul-Karim et al., 2017). However, in this work, there were no differences between the critical and average N dilution curves for both the crops for which significant normalized *DMY* differences were not obtained among any N treatment (carrot, cauliflower, Chinese cabbage, early potato, leek, lettuce and onion), as well as for the crops for which significant normalized *DMY* differences were obtained between at least one treatment and the others (artichoke, romanesco, spinach and red cabbage). Therefore, it seems that from the critical N supply upwards the N dilution curve of the vegetables studied in this work barely changes as the N supply increases and, as a consequence, the same *a* and *b* coefficients would be adequate for critically- as well as for over-fertilized crops.

3.4. Dry matter production parameters

The ANOVAs for the *DM* ratio and *HI* among the N treatments for each crop are shown in Table 4. According to these results, there were only significant differences ($p < 0.05$) of *DM* ratio or *HI* among the N treatments for romanesco and spinach. For the *DM* ratio of these crops, however, the differences among the N treatments were not broad enough to show as statistically significant in the Tukey's HSD pairwise test at the 95% confidence level (Fig. 6). And for the *HI*, although the differences were sufficiently wide to be also observed in the Tukey's HSD pairwise test, at least at the 90% confidence level, they cannot be considered very relevant. To delve into this, note that in the case of romanesco, at the 95% confidence level, the *HI* increases from the T0 to the T1, then, it keeps the same from the T1 to the T2, and eventually decreases again, not being the differences significant between the T0 and T3. In the case of spinach, the difference of *HI* between the T0 and

Table 6
Estimates of the average dry matter ratio (DM) and harvest index (HI) for the crops studied in this work along with their 95% confidence intervals. The values of these parameters found by other authors are given for comparison, and when several data are available, the minimum and maximum are written between brackets, whereas when only one datum so is, it has been written along with the 95% confidence interval if provided.

Crop	This work			Other authors'		
	N	DM	HI	DM	HI	Refs.
Artichoke 1st & 2nd	60	0.148 ± 0.006	0.20 ± 0.01	[0.07, 0.16]	[0.08, 0.30]	Almela et al. (2006) Herrero (2004) Lombardo et al. (2020), Magnifico and Lattanzio (1976) Pomares et al. (2004)
Carrot	15	0.101 ± 0.008	0.69 ± 0.03	[0.06, 0.12]	[0.42, 0.84]	Dezordi et al. (2015) Pereira et al. (2015) Vahrmeijer et al. (20180
Cauliflower	70	0.065 ± 0.001	0.25 ± 0.01	[0.07, 0.08]	[0.30, 0.40]	Gondim et al. (2011) Idnani and Thuan (2007) Riley and Vågen (2003)
Chard	8	0.08 ± 0.01	1[a]	[0.04, 0.05]	[0.84, 0.86]	Miceli and Miceli (20140
Chinese cabbage	43	0.037 ± 0.001	0.47 ± 0.03	[0.09, 0.10]	–	Liu et al. (2016)
Early potato	22	0.22 ± 0.03	0.84 ± 0.02	[0.16, 0.27]	[0.84, 0.95]	Canet (1988) Vos (1997)
Leek	48	0.110 ± 0.007	1[a]	[0.08, 0.09]	[0.32, 0.53]	Biemond (1995) Dadali and Ozbek (2008)
Lettuce	1	0.036 ± 0.006	0.62 ± 0.10	[0.06, 0.07]	–	Canet (1988) Reinink (1993)
Onion	48	0.078 ± 0.003	0.979 ± 0.004	0.07	[0.93, 0.96]	Canet (1988) Wakchaure et al. (2021)
Red cabbage	16	0.073 ± 0.008	0.58 ± 0.04	[0.04, 0.10][b]	[0.35, 0.44][c]	Ashfaq et al. (2018) Vahrmeijer et al. (2018)
Romanesco	28	0.0968 ± 0.0003	0.35 ± 0.01	[0.09, 0.10]	[0.30, 0.35]	Riley and Vågen (2003)
Spinach	72	0.083 ± 0.002	0.61 ± 0.04	[0.06, 0.12]	[0.63, 0.76]	Biemond et al. (1996) Lokhande et al. (2014)

[a] The whole plant was considered as marketable.
[b] data from red and white cabbage.
[c] data from white cabbage.

all the other N treatments are only significant at the 90% confidence level (Fig. 6).

Since the nitrogen treatment did not affect the *DM* ratio or *HI* value obtained for each vegetable, all the data from the various N treatments was jointly used to estimate the mean *DM* ratio and *HI* value for each vegetable (Table 6).

The *DM* ratios and *HI* values determined in this work are, in general, very similar to the ones found by other authors. For the *DM* ratio, there are only four exceptions worth highlighting: chard, Chinese cabbage, leek and lettuce. In the case of chard and leek, the *DM* ratio found in this work is higher, whereas in the case of Chinese cabbage and lettuce, the *DM* ratio is lower. For the *HI*, there are three exceptions: cauliflower, chard, and leek. These divergences can be mainly caused by the use of specific cultivars, overall for chard and leek, or either cultural practices. Regarding this latter reason, the whole chard and leek plants were considered as marketable in the field by the local Valencian farmers with the consequence that no crop residues were left behind on the soil, but generated during the postharvest processing. This may be differently done in other horticultural zones, and also change throughout time as farmers become more and more aware of the high N content of vegetable leftovers and thus their potential N contribution to feed the next crop in the rotation.

4. Conclusions

The critical N dilution curve coefficients and dry matter production parameters of 12 vegetables grown under semi-arid Mediterranean climate in the Valencian Community (Eastern Spain), have been obtained. These parameters did not depend on the N supply within the N ranges studied in this work for any of the crops, even when significant differences of normalized dry matter yield did exist. Accordingly, for each vegetable the critical N dilution curve coefficients could be reliably estimated from the average N dilution curves, and the *DM* ratios and *HI* values so could from the joint N fertilization treatments. Therefore, the critical N dilution curve coefficients, in addition to the *DM* ratios and the *HI* values, which have been obtained in this work, are a valuable contribution for improving the N fertilization recommendations, as well as the N nutritional status monitoring, of these important Mediterranean horticultural crops. All these parameters can be used along with the different strategies available to farmers to optimize the N crop fertilizing of these specific vegetables, which are either simple systems such as the Nmin, or more complex ones such as simulation models. The use of all the parameters obtained in this work should support better fits between N fertilizer inputs and N crop demands, and hence simultaneously underpin high production and quality standards for vegetables, improved nitrogen uptake, and thus N use efficiency, and diminished N losses from the soil-plant system, either as NO_3^- to inland and sea waters, or as N_2O to the atmosphere.

CRediT authorship contribution statement

José Miguel de Paz: Conceptualization, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Carlos Ramos:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Fernando Visconti:** Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization.

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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