

Inflorescence characteristics, seed composition, and allometric relationships predicting seed yields in the biomass crop *Cynara cardunculus*

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Abstract

Cynara (*Cynara cardunculus*) is a perennial C₃ herb that has its potential as bioenergy crop. This paper aims (a) to derive empirical relationships to predict cynara seed yield per head and per unit area, avoiding laborious extraction of seeds from the complex structure of its inflorescences; (b) to determine the head-weight distribution per unit area, the seed composition and the oil profile of cynara seeds; and (c) to estimate the range of cynara biomass, seed and oil yield in representative parts of Greece. We analyzed 16 field experiments, varying in crop age and environmental conditions in Greece. Seed yield per head (SY_{head}) can be accurately predicted as a linear function of dry head weight (H_w): SY_{head} = 0.429 · H_w - 2.9 (*r*² = 0.96; *n* = 617). Based on this relationship, we developed a simple two-parameter equation to predict seed yield per unit area (SY): SY = HN · (0.429 · μ - 2.9), where μ is the mean head weight (g head⁻¹) and HN is the total number of heads per unit area, respectively. The models were tested against current and published data (*n* = 180 for head-level; *n* = 35 for unit area-level models), and proved to be valid under diverse management and environmental conditions. Attainable cynara seed yields ranged from 190 to 480 g m⁻² yr⁻¹, on dry soils and on aquatic soils (shallow ground water level). This variation in seed yield was sufficiently explained by the analyses of head-weight distribution per unit area (small, medium and large heads) and variability of seed/head weight ratio at head level. Seed oil concentration (average: 23%) and crude protein concentration (average: 18.7%) were rather invariant across different seed sizes (range: 26–56 mg seed⁻¹) and growing environments.

Keywords: biomass production, cynara, harvest index, oil, protein, seed number, seed yield, yield prediction

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Introduction

Cynara cardunculus (commonly known as cynara) is a perennial C₃ herb prioritized as a new energy crop for Mediterranean areas because of its multiple uses and good yields even under harsh conditions. The crop can be used for solid biofuel production (Danalatos, 2008), as well as for biodiesel production, fiber production and forage production (Fernández *et al.*, 2006). *Cynara*'s

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perennial character, its large root system, and the winter–spring growth cycle (usually rainfed) are important advantages of the crop.

Four important variables determine whether it is feasible to include cynara into the current cropping systems: biomass yield, product quality, heating value and production cost. Studies in the Mediterranean region showed that cynara cultivation has an energy output:input ratio in the range of 15–30 (Danalatos, 2008; Angelini *et al.*, 2009; Mantineo *et al.*, 2009). This ratio is lower compared with C₄ perennials, viz. giant reed and miscanthus. However, particularly due to its lower resource input (e.g. propagated by seeds instead of rhizomes and growing without irrigation during

winter–spring), compared with summer C₄ perennials researchers inferred that cynara could be introduced in southern Europe for biomass production.

Cynara's biomass yield under rainfed conditions is usually reported at 15 t ha⁻¹ yr⁻¹ (Fernández *et al.*, 2005; Danalatos *et al.*, 2006, 2007; Raccuia & Melilli, 2007a; Angelini *et al.*, 2009) while dry biomass yields in excess of 30 t ha⁻¹ yr⁻¹ have been attained (Dalianis *et al.*, 1996; Archontoulis *et al.*, 2008). The average heating value of the cynara plant has been estimated at 15–17 MJ kg⁻¹ (Piscioneri *et al.*, 2000; Fernández *et al.*, 2006; Grammelis *et al.*, 2008; Angelini *et al.*, 2009). This energy content depends on the fraction of each plant component and its chemical composition and especially on the proportion of the oil rich seeds. Normally, the heating value per individual plant component is rather invariant contrary to the partitioning fractions (e.g. oil/seed and seed/biomass weight ratio) which largely depend on the environment × management interactions. Obviously detailed quantification of these seed-related fractions is essential in view of using the crop in the bioenergy sector.

C. cardunculus seed oil concentration ranges from 18.6% to 32.4% across different environments (Piscioneri *et al.*, 2000; Curt *et al.*, 2002). Regarding seed yield and seed/biomass ratio current information is rather scarce. To the best of our knowledge, rainfed cynara's seed yields range from 80 to 250 g m⁻² at planting densities of ≤ 2 plant m⁻² (Foti *et al.*, 1999; Piscioneri *et al.*, 2000; Raccuia & Melilli, 2007a; Ierna & Mauromicale, 2010). However, seed yield under appropriate management (e.g. higher plant densities; Raccuia & Melilli, 2007b) and high yielding environments is unknown.

The relatively few reports on seed yield might be attributed to the complex structure of cynara inflorescences. The basic type of inflorescence is the capitulum (head), which is organized in a (compound) corymb form. Within a plant or a unit area the heads of *C. cardunculus* are variable in terms of size, number, maturity and position on the plant. Within a head, seeds (achenes) are positioned at the base of the head (receptacle) surrounded by hairs (pappus) and bracts (erect spines), making seed extraction extremely laborious and time-consuming (Archontoulis *et al.*, 2010). Moreover, the seed/head weight ratio varies considerably across different head weights, thus cannot be easily addressed by a default value (Archontoulis *et al.*, 2009).

Quantitative (allometric) relations are commonly used to quantify the relation that exists between the growth rates of different plant components. Allometric relations have also been used to assess a crop's investment in reproductive growth, both in annual crop

species (e.g. in soybean, sunflower and maize; Vega *et al.*, 2000) and in perennial crop species (e.g. in *Lesquerella*; Ploschuk *et al.*, 2005).

Taking into account aforementioned difficulties in measuring seed yield, the primary objectives of this paper is to derive simple quantitative relationships, which can be used in practice to estimate seed yield per head and per unit area based on easily measurable inflorescence traits of cynara. In view of the lack of adequate information on attainable seed yield under varying management × environmental conditions, we also investigate the head-weight distribution per unit area, the seed composition and the oil profile of cynara seeds as a function of seed size, and the range of *C. cardunculus* biomass, seed and oil yield in representative parts of Greece.

Materials and methods

Experimental sites and treatments

The data used in this paper were taken from 16 diverse experiments conducted in eight sites representing a wide range of environments in Greece. Table 1 shows the geographic location and some soil characteristics of the eight sites. Table 2 provides details for each of the 16 experiments, including crop age, cycle length and sampling date. The experimental sites cover a wide range of soil types, fertility status, and ground water levels. The crop had been established in different years (2004–2008) providing plant samples from the first to the sixth growing cycle. Moreover, some crops were sown in spring (March 20 ± 1 week) and some in autumn (November 15 ± 1 week). Hence, the growing cycle length varied from 9 to 16 months (Table 2). Crops were kept free from weeds during the period of crop establishment by applying a presowing herbicide and by mechanical weeding during initial crop stages.

At some sites (*viz.* Palamas, Velestino, Kilkis and Ermitsi) the levels of irrigation and nitrogen fertilization were varied. Briefly, at Palamas (Karditsa) site, a 2 × 3 factorial experiment was carried out in which cynara was grown under (a) rainfed conditions (common farmer practice) with three N-application levels (0, 8 and 16 g N m⁻²); and (b) supplementary irrigation during BBCH 59–65 (2–3 irrigations; total 120–170 mm; Exp 5, 10 and 16) with the same N levels. The BBCH coding system (Archontoulis *et al.*, 2010) is used here to assess specific growth stages. At the Velestino site (Magnesia), two experiments were carried out; one was sown during 2004 with a plant arrangement of 100 × 50 cm (Exp 11, 12; Table 2) and one was established during 2008 with a plant arrangement of 75 × 25 cm (Exp 1). During the subsequent year, Exp 1 was divided into two

Table 1 Geographic location and some soil characteristics of the experimental fields

Location	Coordinates and altitude	Soil type and classification*	Ground water table†, organic matter (OM) and pH
Palamas	39°25' 49'' N 22°05' 09'' E Alt. 107.5 m a.s.l.	Loam Aquic Xerofluvent	Presence of shallow ground water OM = 1.0–1.6% at 0–50 cm pH = 8–8.2
Ermitsi	39°24' 49'' N 22°05' 03'' E Alt. 100 m a.s.l.	Loam Aquic Xerofluvent	Presence of shallow ground water OM = 1.2–1.8% at 0–50 cm pH = 7.9–8.1
Kalivakia	39°26' 19'' N 22°04' 51'' E Alt. 97 m a.s.l.	Loam Aquic Xerofluvent	Presence of shallow ground water OM = 1.1% at 0–50 cm pH = 8.2
Koskina	39°29' 08'' N 22°00' 24'' E Alt. 85 m a.s.l.	Loam Aquic Xerofluvent	Presence of shallow ground water OM = 1.4% at 0–30 cm pH = 8.1
Velesino	39°23' 55'' N 22°44' 36'' E Alt. 87 m a.s.l.	Clay Calcixerollic Xerochrept	No ground water table OM = 1.5–2.3% at 0–30 cm pH = 7.6–8.0
Elliniko	39°19' 53'' N 22°16' 45'' E Alt. 120 m a.s.l.	Clay Vertic Xerochrept	Presence of shallow ground water OM = 2.5% at 0–30 cm pH = 8.2
Fillo	39°24' 52'' N 22°11' 84'' E Alt. 107 m a.s.l.	Clay Vertic Xerochrept	Presence of shallow ground water OM = 2.0% at 0–30 cm pH = 8.2
Mataraga	39°24' 47'' N 22°03' 52'' E Alt. 102 m a.s.l.	Silty clay Aquic Vertic Xerofluvent	Presence of shallow ground water OM = 1.6% at 0–30 cm pH = 8.3
Kilkis	41°14' 39'' N 22°45' 56'' E Alt. 250 m a.s.l.	Sandy loam Typic Xerochrept	No ground water table OM = 1.0% at 0–30 cm pH = 6.8 (Slope relief)

All fields located in Thessaly Plain (central Greece), except for Kilkis.

*According to USDA (1975).

†Shallow means that ground water ranged from 250 to 600 cm below surface during May; for other cases (Velesino and Kilkis) ground water was deeper than 20 m below surface.

analogous experiments (Exp 8: irrigated with 138 mm during BBCH 53–63 and Exp 9: rainfed). Within each experiment 5N-rates were applied (0, 6, 12, 18 and 24 gN m⁻²). At Kilkis, the crop was grown under rainfed conditions and three N rates were applied (0, 8 and 16 gN m⁻²; Exp 7). At Ermitsi (Karditsa) site (second growth cycle) the field was fertilized with 0, 8, or 16 gN m⁻² and irrigated once during BBCH 60 with 55 mm (Exp 6). In all fertilized fields, N application took place during BBCH 51–55. The other fields (Exp 2, 3, 4, 13 and 15) comprised commercial crops, grown without additional irrigation and fertilizer inputs. The size of the specific experiments varied from 0.1 to 0.4 ha (individual plot size: 48–90 m²) and the commercial fields comprised an area of several hectares. Planting arrangement was 75 × 25 cm in all experiments except Exp 11 and 12. There were no pests or diseases in the experimental plots.

Sampling protocol and measurements

Plants were cut approximately 10 cm above ground level at BBCH 95–97 (total: $n = 201$ samples from 16 fields, Table 2). The sampling area was always 1 m². Every harvested sample was separated into stalks (stem and branches) and heads, and fractions were weighed fresh in the field. Plant height was measured as well (Table 2). Leaves were left out from our analysis since they were dry and usually fell off during sampling. The moisture content of the harvested plants was around 30%. The collected materials were put in a storage room to dry naturally. The moisture content in equilibrium with the storage environment was subtracted after assessing dryness of random subsamples by weighing in an oven at 70 °C until constant weight.

After drying, stalks were weighed again to determine the total stalk dry weight m⁻². Per sample the heads

Table 2 Summary of the experimental details and final plant height

Exp. # (symbol)	Location	Growing season	Cycle length* (month)	Year	Sampling date	Number of samples	Number of heads†	Plant height (cm)
<i>Parameterization datasets</i>								
1 (○)	Velestino	1st	9	2008	Aug 1	6	30	55
2 (○)	Kalivakia	1st	9	2009	Aug 20	6	18	131
3 (○)	Mataraga	1st	9	2009	Aug 20	5	16	76
4 (○)	Koskina	1st	9	2009	Aug 20	6	18	118
5‡ (□)	Palamas	2nd	16	2007	Aug 4	12	72	238
6 (□)	Ermitisi	2nd	16	2008	Aug 5	6	48	305
7 (□)	Kilkis	2nd	16	2008	Aug 8	9	48	114
8 (□)	Velestino	2nd	10	2009	Aug 2	30	90	208
9 (□)	Velestino	2nd	10	2009	Aug 1	30	86	206
10 (△)	Palamas	3rd	11	2008	Aug 4	24	128	234
11 (+)	Velestino	5th	10	2008	Aug 2	6	33	144
12 (×)	Velestino	6th	10	2009	Aug 1	6	30	194
Total						146	617	
<i>Validation datasets</i>								
13 (●)	Fillo	1st	9	2009	Aug 19	10	31	99
14 (▲)	Elliniko	2nd	16	2009	Aug 4	10	31	191
15 (■)	Ermitisi	3rd	11	2009	Aug 4	11	36	263
16 (◆)	Palamas	4th	11	2009	Aug 3	24	82	245
Total						55	180	

*From BBCH 10 to 95–97.

†Refers to the heads that were used for seed separation and not to total heads per sample.

‡At six additional samples, the total head weight, the total head number and the total seed yield per sample were measured (see later, Table 5).

Table 3 List of terms and abbreviations

Symbol	Definition	Unit
Small	Head weight size class: <20 g head ⁻¹	–
Medium	Head weight size class: 20–40 g head ⁻¹	–
Large	Head weight size class: >40 g head ⁻¹	–
<i>HN</i>	Total number of seed-bearing heads per unit area	heads m ⁻²
<i>HW</i>	Total weight of seed-bearing heads per unit area	g m ⁻²
<i>H_w</i>	Single head weight	g head ⁻¹
<i>H_{base}</i>	Threshold <i>H_w</i> required for seed set	g head ⁻¹
<i>HI_{head}</i>	Seed/head weight ratio	g g ⁻¹
<i>SY_{head}</i>	Seed weight per head	g seed head ⁻¹
<i>SY</i>	Seed yield per unit area	g m ⁻²
<i>SN_{head}</i>	Seed number per head	seeds head ⁻¹
<i>SN</i>	Seed number per unit area	seeds m ⁻²
<i>SW</i>	Individual seed weight (<i>SY/SN</i> × 1000)	mg seed ⁻¹
<i>μ</i>	Mean head weight (<i>HW/HN</i>)	g head ⁻¹

were counted and weighed individually using an electronic balance (2-digits); the sum of the individual weights provided the total dry head weight m⁻². Total aerial dry biomass weight m⁻² was calculated as the sum of the weights of stalks and heads. Then, 3–8 heads

per sample (small: <20 g, medium: 20–40 g and large: >40 g; for abbreviations see Table 3) were randomly selected to manually separate the seed (*n* = 797 heads, Table 2). The diameters of the selected heads were accurately measured too. The extracted seeds per head

were counted and weighed. The quotient between seed weight and seed number expresses the individual seed weight (*SW*, Table 3).

Seed composition and oil profile

C. cardunculus fruit (called seed for simplicity) is an achene, formed by the embryo (also called true seed or kernel) and the pericarp (hull). Seed materials were forwarded to chemical laboratories soon after processing, to avoid any hydration of the stored grain as observed by Maccarone *et al.* (1999). Two sets of experiments were performed. In 2008, medium-sized seeds (30–40 mg seed⁻¹) were analyzed per location (Palamas, Ermitsi, Velestino and Kilkis). In 2009, seeds were graded into five weight classes (very small: <20 mg, small: 20–30, medium: 30–40, large: 40–50 and very large: >50 mg per seed) and analyzed for seed composition (oil, protein, cellulose, free fatty acids and ash). The concentrations (%) were expressed on dry weight basis, while total oil and protein content per seed (mg seed⁻¹) were calculated as *SW* multiplied by the concentration of each component. Seed protein concentration was approximated by the product of nitrogen concentration times (the default value of) 6.25, referred to as crude protein hereafter. Fatty acid composition of the extracted oil per group was also determined by gas chromatography. All data reported are expressed on dry-weight basis.

Data analysis

Seed parameters (weight and number) were first determined per head and subsequently converted into values per unit area. Two explanatory variables were initially assessed: (i) the weight of a single head and (ii) the diameter of a single head. Both variables are easily measurable inflorescence traits. Head weight is considered as an accurate measure while diameter as a fast and nondestructive measure. Among several methods/models in literature (e.g. Vega *et al.*, 2000), we selected the following two types of 'allometric' models (simple and biologically meaningful) to fit our data:

$$\text{Linear : } Y = a + bX$$

$$\text{Nonlinear : } Y = Y_{\max} \{ 2 / (1 + \exp(-c(X - X_{\text{base}}))) - 1 \},$$

where *Y* denotes the dependent variable; *X*, is the independent variable; *a* is a constant parameter; *b*, is the slope of the regression (allometric coefficient); *Y*_{max} is the asymptote of the dependent variable; *c* is the parameter determining the steepness of the curve for the nonlinear model; *X*_{base} is the intercept of the *X*-axis

denoting a threshold value. In order to fit our models, we used 12 datasets (parameterization sets: Exp 1–12, *n* = 617; Table 2). Model validations were conducted using four independent datasets (Exp 13–16, *n* = 180; Table 2).

Head-weight distribution

Per sample the heads were graded into three classes (small, medium and large; see Table 3) and frequency distribution histograms were produced per experiment. Statistical descriptors such as kurtosis (*k*), a measure of the 'peakedness' of the frequency distribution, skewness (*s*), a measure of the asymmetry of the probability distribution, mean head weight μ , and standard deviation σ , a measure of the variability in head weight, were calculated. The uniformity or the relative variability of the head-weight distribution per unit area was assessed by the coefficient of variation (CV, %), calculated as $\sigma/\mu \times 100$.

Thereafter, the 16 experiments were separated into three major groups. Group 1 comprises the first growth cycle experiments (Exp 1, 2, 3, 4 and 13; Table 2). Groups 2 and 3 refer to subsequent growth cycles experiments. Group 2 represents the experiments carried out on soils with no ground water (Exp 7, 8, 9, 11 and 12; Tables 1 and 2) and Group 3 refers to the experiments carried out on soils with shallow ground water levels (Exp 5, 6, 10, 14, 15 and 16; Table 2).

Statistics

Analyses of variance were performed using GENSTAT software (12th Edition). At head-level, linear regression with groups (given the accumulated analysis of variance table) was performed to examine whether regression slopes and intercepts differed significantly among different experiments. Nonlinear model parameters were derived from nonlinear least-square regression in GENSTAT. The model's goodness of fit was assessed graphically (measured vs. predicted, residual plots) and by calculating *r*², *bias* and *rRMSE* (relative root mean square error), as follows:

$$\text{Bias} = \frac{1}{n} \sum_{i=1}^n (O_i - P_i)$$

$$\text{rRMSE} = \frac{1}{\bar{O}} \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - P_i)^2},$$

where *P*_{*i*} and *O*_{*i*} are the predicted and observed values, respectively, \bar{O} is the observed mean value and *n* is the number of observations. The *bias* measures the average

difference between observed and predicted data. The rRMSE measures the relative difference between observed and predicted data, while a model's fit improves as rRMSE approaches zero. Seed and oil composition parameters across five seed sizes were assessed following one-way analysis of variance. Similarly, the parameters of the head-weight distribution per group were also subjected to one-way ANOVA.

Weather conditions

Thessaly Plain (central Greece) is characterized by a typical Mediterranean climate with hot, dry summers and cool, humid winters. A 30-year Thessaly climatic average (1974–2006; data from Hellenic National Meteorological Service) reports mean annual precipitation of 568 mm (172, 113, 70 and 211 mm during winter, spring, summer and autumn periods, respectively) and a mean daily air temperature of 16.0 °C (7.5, 20.1, 25.3 and 11.1 °C during winter, spring, summer and autumn periods, respectively). The major part of *cynara's* growth cycle takes place in winter and spring, during which usually no irrigation is applied. The total

amounts of effective precipitation at the experimental fields of Thessaly (period: October–July) were 449, 378 and 709 mm for the 2007, 2008 and 2009 seasons, respectively. For Kilkis (2008) the precipitation was 401 mm. Temperature did not fluctuate much from its climatic mean values.

Results

Seed yield

Figure 1 illustrates the relationships between seed yield per head (SY_{head}), seed number per head (SN_{head}), seed/head weight ratio (HI_{head}) and individual seed weight (SW) as a function of head weight (H_w , Table 3).

SY_{head} ranged from 0 to 41 g head⁻¹ and H_w ranged from 2.5 to 100 g (Fig. 1a). SY_{head} showed a linear relationship with H_w for each treatment × experiment combination included in the study ($n = 146$ sets; Table 2). Regression analyses showed that lines ran almost parallel, and the intercepts were very similar. Thus, treatments within each experiment were grouped and 12 regression lines were constructed (Table 4). This analysis showed

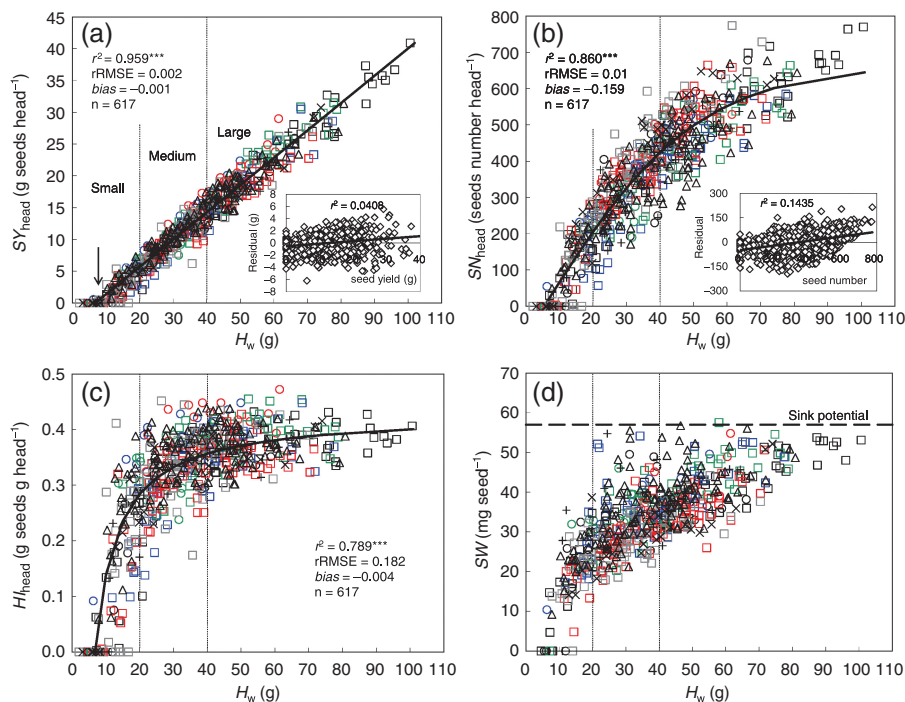


Fig. 1 (a) Seed weight per head (SY_{head}), (b) seed number per head (SN_{head}), (c) seed/head weight ratio (HI_{head}) and (d) individual seed weight (SW) as a function of head weight (H_w). Different symbols indicate material collected from different environments (Exp 1–12; Table 2). Fitted equations (solid bold lines) and parameters are provided in the text. Y-variable residuals are shown in the insets. Vertical broken lines indicate three classes of different head weights (small, medium, large; Table 3). Horizontal broken line (panel d) indicates seed sink potential. Arrow (panel a) indicates the threshold head weight required for seed set (H_{base}). *** indicates significant at $P < 0.001$; *bias* and *rRMSE* definitions are provided in the text.

Table 4 Parameters (standard error in parenthesis) of the linear regression ($Y = a + bX$) between seed yield per head and two explanatory variables for 12 independent sets

Exp.	Variable 1: head weight (g)			Variable 2: head diameter (cm)			<i>n</i>
	<i>b</i>	<i>a</i>	<i>r</i> ²	<i>b</i>	<i>a</i>	<i>r</i> ²	
1	0.432 (0.01)	-3.091 (0.54)	0.97	3.90 (0.30)	-11.44 (1.75)	0.86	30
2	0.408 (0.03)	-1.952 (0.87)	0.93	3.02 (0.36)	-7.27 (2.11)	0.81	18
3	0.469 (0.02)	-2.384 (0.57)	0.98	5.33 (0.59)	-17.66 (3.31)	0.85	16
4	0.446 (0.03)	-1.314 (1.33)	0.93	3.50 (0.58)	-6.34 (3.96)	0.70	18
5	0.425 (0.01)	-3.003 (0.38)	0.98	5.09 (0.19)	-17.46 (1.30)	0.92	72
6	0.448 (0.01)	-3.165 (0.73)	0.95	4.70 (0.36)	-15.06 (2.52)	0.79	48
7	0.448 (0.02)	-4.161 (0.63)	0.95	6.49 (0.50)	-29.29 (3.26)	0.79	48
8	0.412 (0.01)	-3.007 (0.32)	0.96	4.64 (0.20)	-15.74 (1.18)	0.86	90
9	0.443 (0.01)	-3.453 (0.38)	0.94	4.78 (0.32)	-16.06 (1.69)	0.72	86
10	0.410 (0.01)	-1.933 (0.34)	0.95	4.85 (0.21)	-17.45 (1.35)	0.81	128
11	0.431 (0.01)	-3.185 (0.54)	0.97	3.63 (0.36)	-9.24 (2.18)	0.77	33
12	0.424 (0.01)	-2.777 (0.44)	0.98	4.28 (0.39)	-13.12 (2.30)	0.82	30

All regressions were significant at $P < 0.0001$.

Details per experiment are provided in Table 2.

n, number of individuals per set.

that slopes did not differ significantly across environments ($P = 0.123$). Accordingly, data from all experiments were pooled ($n = 617$). Within this complete dataset, we further examined possible differences in slope between head weight classes (small, medium and large). Three regression lines were constructed and step-wise regression analysis revealed that SY_{head} vs. H_w relationship remained unchanged for the different head weight classes ($P = 0.075$; Fig. 1a). Hence, SY_{head} could be described adequately by a single, simple linear regression model ($r^2 = 0.96$; Fig. 1a):

$$SY_{\text{head}} = 0.4293(\pm 0.003)H_w - 2.9048(\pm 0.144), \quad (1)$$

where SY_{head} is the seed yield per head and H_w is the single head weight. Values in parenthesis represent \pm standard error of the regression estimates. SY_{head} becomes zero when $H_w = 6.76$ g. The value of 6.76 g thus indicates the threshold head weight, required for seed set (hereafter H_{base}). Thus, Eqn (1) is applicable to $H_w \geq 6.76$ g. The slope of the regression (viz. 0.4293) is an allometric coefficient that expresses the fraction of head growth above the threshold allocated to seeds.

Equation (1) was validated by using four independent data sets (Exp 13–16, Table 2). Graphical visualization of its performance is depicted in Fig. 2. Statistical criteria revealed that the model performed well ($r^2 = 0.89$ – 0.97 ; $r\text{RMSE} = 0.12$ – 0.19 ; $\text{bias} = -0.35$ to 0.68 g; Fig. 3) and was therefore accurate enough for further use. Consequently, Eqn (1) was applied to every head present in a sample, thus upscaling individual head weights to seed yield per unit area level (SY ,

g m^{-2}) as indicated below:

$$SY = \frac{\sum_{i=1}^n (0.4293H_{wi} - 2.9048)}{A_s}, \quad (2)$$

where A_s refers to the size of the sample area (m^2). Equation (2) was used in our study to derive seed yields per treatment. This procedure implies separate weighing of all heads (n parameters) included in a sample. To obtain a more convenient procedure for determining seed yield, Eqn (2) can be simply rewritten also as:

$$SY = HN(0.4293\mu - 2.9048), \quad (2a)$$

or

$$SY = 0.4293HW - 2.9048HN, \quad (2b)$$

where μ is the mean head weight, HN and HW ($= \mu \times HN$) are the total number and weight of all seed-bearing heads per unit area, respectively (Table 3). Equation (2a) or (2b) simply shows that SY increases with an increase of HW , whereas the term $2.9048 \cdot HN$ accounts for the cumulative threshold head weights required for seed set. Equation (2a) and (2b) illustrates a two-parameter model, comprising a much faster and easier way to calculate total seed yield per unit area. For such a purpose, barren heads (≤ 6.76 g head⁻¹) should be excluded in the calculation.

Five independent data sets (Table 5) were used to evaluate the ability of Eqn (2b) to predict total seed yields (Fig. 3). Equation (2b) performed very well for data from Exp 5 ($\mu = 33$ g m⁻²; $r\text{RMSE} = 0.07$; Fig. 3) and for the published data from Piscioneri *et al.* (2000),

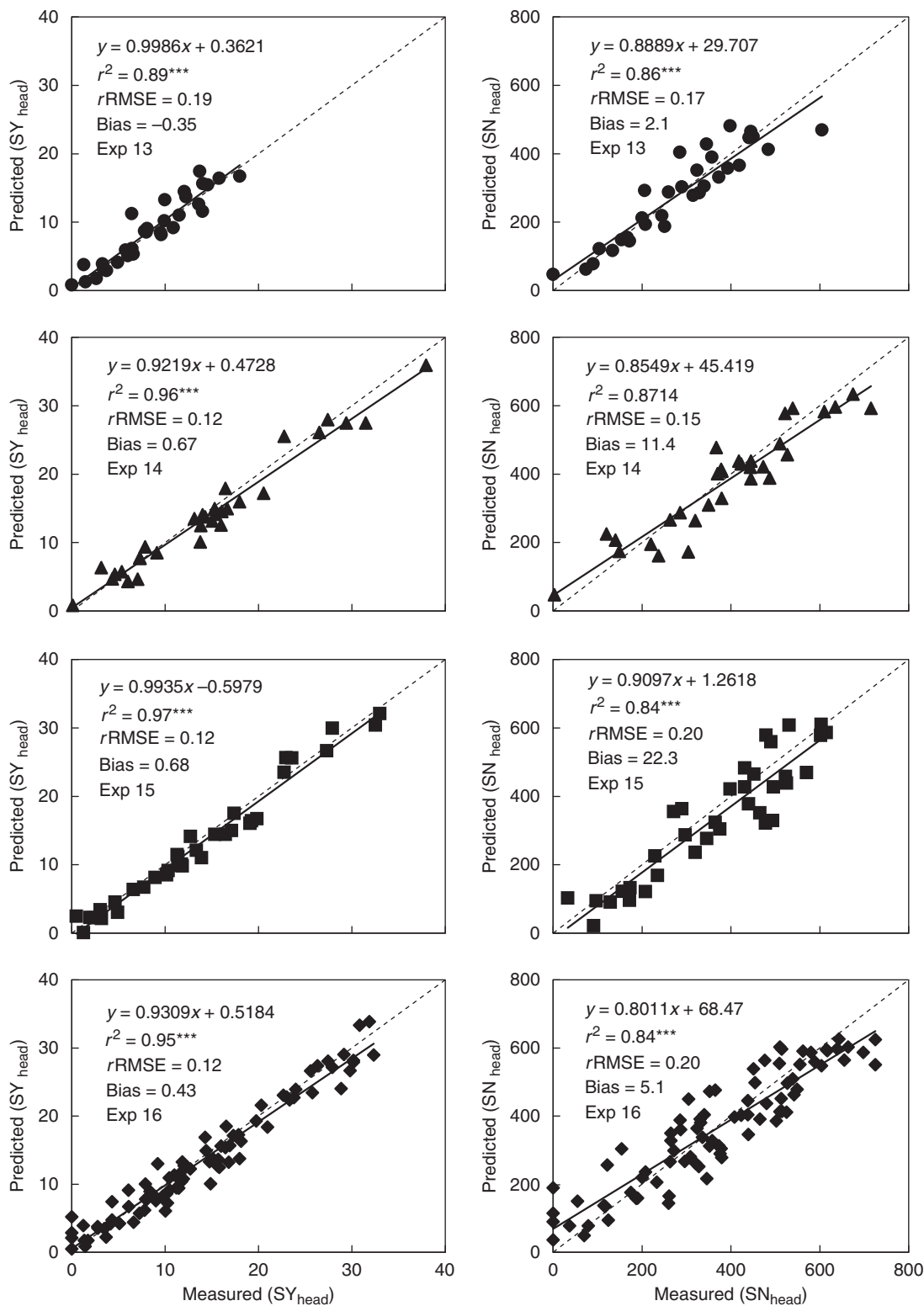


Fig. 2 Predicted versus measured seed yield per head (SY_{head} , left panels) using Eqn (1) and seed number per head (SN_{head} , right panels) using Eq. (3). Four independent datasets (Exp 13–16; 1st, 2nd, 3rd and 4th growing cycle; Table 2) were used to evaluate Eq. (1) and (3) goodness of fit at head-level. Diagonal broken lines are 1:1. Statistics as in Fig. 1.

Raccuia & Melilli (2007a) and Ierna & Mauromicale (2010) ($\mu = 18 \text{ g m}^{-2}$; $\text{rRMSE} = 0.24$; Fig. 3). Data from Foti *et al.* (1999) were not predicted well (Fig. 3), most probably due to a low μ ($= 12 \text{ g head}^{-1}$), which led us to suspect that non seed-bearing heads ($\leq 6.76 \text{ g}$) were included in the sample. However, the general trend across all datasets ($n = 35$) indicated a good agreement between predicted and measured seed yield ($r^2 = 93\%$; $\text{bias} = 14 \text{ g m}^{-2}$; $\text{rRMSE} = 0.23$; $n = 35$; Fig. 3). Predictions using Eqn (2b) would be further improved, if information on number of barren heads ($\leq 6.76 \text{ g}$) per sample was known for the published data sets.

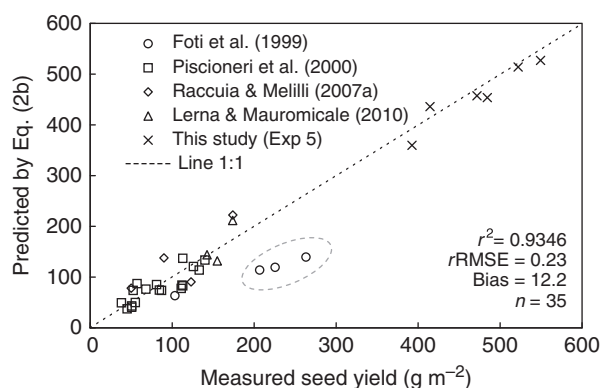


Fig. 3 Seed yield of *Cynara cardunculus* predicted by Eqn (2b) versus measured seed yield. Details on the validation datasets are provided in Table 5. Statistical indices refer to all data ($n = 35$). The three encircled points are outliers, resulting from the low mean head weight ($\mu = 13 \text{ g head}^{-1}$).

Seed number

Across the 12 experiments, seed number per head (SN_{head}) showed a nonlinear relationship with H_w (Fig. 1b). We described this relationship using the following nonlinear model ($r^2 = 0.86$; $n = 617$):

$$SN_{\text{head}} = 665.2(\pm 16.9) \times \left(\frac{2}{1 + \exp(-0.0436(\pm 0.002)(H_w - 5.422(\pm 0.526)))} - 1 \right). \quad (3)$$

Values in parenthesis represent \pm standard error of the estimates. Equation (3) estimated the threshold head weight for seed set at $5.4 \pm 0.53 \text{ g head}^{-1}$, which is (not surprisingly) close to the threshold estimated based on seed yield by Eqn (1). To avoid any misunderstandings, we propose that Eqn (3) should be applied to heads $\geq 6.76 \text{ g}$, similar to the seed yield model. The maximum seed number per head was most often 650–680 (Fig. 1b).

The nonlinear model can also be parameterized separately for specific experiments. To test whether Eqn (3) was valid for material collected from different experiments (Exp 1–12; Table 2), Eqn (3) (with three parameters) was compared with the experiment-specific model (12 experiments \times 3 parameters = 36 estimates). Predictions were assessed using the adjusted r^2 in order to account also for the degrees of freedom (slightly higher prediction is counterbalanced by a loss of degrees of freedom). The experiment-specific model improved predictions only slightly, from $r^2_{\text{adj}} = 0.860$ to $r^2_{\text{adj}} = 0.884$, meaning that the combined three-parameter model was adequate enough for further use.

Table 5 Validation datasets used to test the performance of Eqn (2b) at unit area level

Set	Year*	Genotype(s)†	Density	μ	n	Source‡
1	1994	Bianco avorio	1.2 pl m^{-2}	13.0	4	Foti <i>et al.</i> (1999)
	1995	Gigante di Lucca				
2	1995	9 genotypes (see reference)	1 pl m^{-2}	19.2	18	Piscioneri <i>et al.</i> (2000)
	1996					
3	1999	Bianco avorio	2 pl m^{-2}	17.7	4	Raccuia & Melilli (2007a)
	2000	Cardo di Nizza				
4	1999	Cardo gigante	1.3 pl m^{-2}	15.0	3	Ierna & Mauromicale (2010)
	2000	di Romagna				
	2001					
5	2007	Bianco avorio	5 pl m^{-2}	32.1	6	This study (Exp 5)§

*Observation year.

†All genotypes belong to the botanical variety *C. cardunculus* L. var. *altilis* DC.

‡Literature data on total head weight, number and seed yield were recorded from tables or read from figures and refer to mean values. Presence or absence of nonseed-bearing heads ($< 6.76 \text{ g}$) in the sample is unknown. Experiments were carried out on clay soils (without ground water).

§Barren heads were excluded.

n , number of data per set; μ , mean head weight per set.

Equation (3) fitted the data well if H_w ranged from 6 to 75 g, and slightly underestimated seed number at very large head weights (>75 g; Fig. 1b inset). However, this is of low importance, since such large heads are rare, even under optimum conditions. We also tested other non-linear models such as negative exponential and rectangular hyperbola, to see whether this underestimation would disappear. The r^2 values, residual plots, and biases were similar for all model types. Therefore, we continued our analysis using Eqn (3) because its parameters have a clear biological meaning.

The higher scattering of the seed number data compared with seed weight data, caused slightly lower prediction ability of Eqn (3). Similar to Eqn (1), Eqn (3) was also evaluated with four independent datasets (Exp 13–16; Table 2) and statistics showed that predictions were good ($r^2 \approx 0.85$; rRMSE ≈ 0.18 ; bias ≈ 10 ; Fig. 2). Consequently, model (3) was applied to every seed-bearing head present in a sample, thus upscaling individual head weight to seed number per unit area level (SN, seeds m^{-2}) as indicated below:

$$SN = \frac{\sum_{i=1}^n \left(665.2 \left(\frac{2}{1 + \exp(-0.0436(H_{wi} - 5.422))} - 1 \right) \right)}{A_s} \quad (4)$$

The calculated seed number m^{-2} ranged from a minimum of 1764 to a maximum of 20 566 seeds m^{-2} .

Seed harvest index and individual seed weight

Figure 1c depicts the relationship between the seed/head weight ratio HI_{head} ($g g^{-1}$) and H_w . This relationship was described from Eqn (1) by dividing both parts with H_w , as follows:

$$HI_{head} = 0.4293 - \frac{2.9048}{H_w} \quad (5)$$

Equation (5) implies that HI_{head} increases with increasing H_w . The mean HI_{head} per head class was: 0.18, 0.33 and 0.39 $g g^{-1}$ for small, medium and large heads, respectively. The low determination coefficient of Eqn (5) ($r^2 = 0.79$; Fig. 1c) is due to the large data scatter caused by the combined random error of SY_{head} and H_w .

Figure 1d shows that the individual seed weight (SW, calculated as SY_{head}/SN_{head}) varied considerably across different H_w . It ranged from about 10 to a maximum value of 57 $mg seed^{-1}$ (data mean: 33.4 $mg seed^{-1}$). This upper threshold value gives an indication of the potential sink capacity of *C. cardunculus* seed under Greek conditions (Fig. 1d).

Head diameter and head surface area as predictors

Head samples collected from different environments, although having similar weights, showed differences in

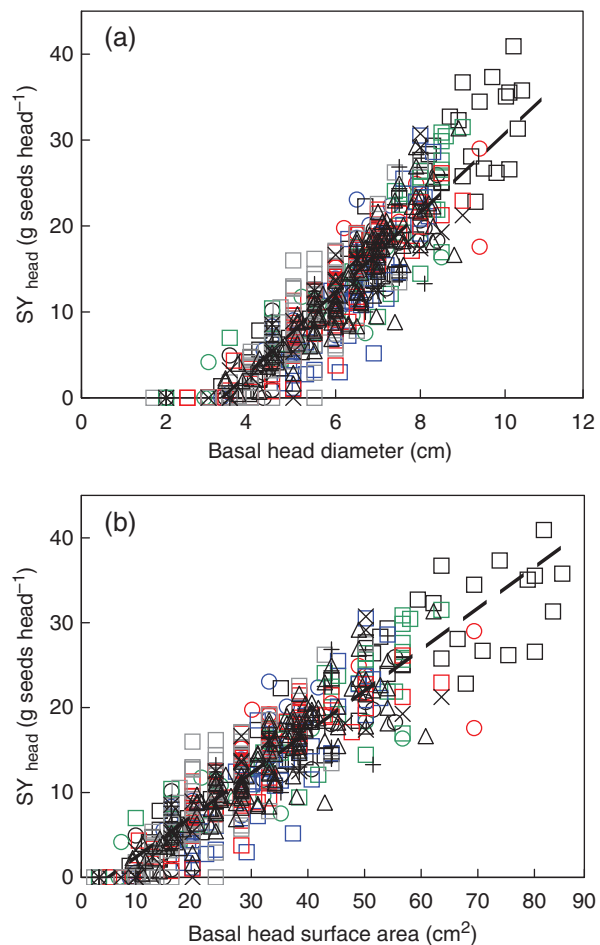


Fig. 4 (a) Seed weight per head (SY_{head}) as a function of head diameter and (b) of head surface area. Different symbols indicate material collected from different environments (Exp 1–12; Table 2). Broken bold lines indicate linear regressions.

shape (ovate to globular). Small, medium and large heads had diameters of 2–5, 3–7 and 4–10 cm, respectively (Fig. 4a). Contrary to H_w , the head diameter (nondestructive method) did not strongly correlate with SY_{head} (see r^2 in Table 4) and SN_{head} (data not shown). Figure 4a illustrates the relationship between SY_{head} and head diameter, while Table 4 presents the regression slopes and the constant values for the 12 experiments (parameterization datasets). Slopes of the regressions were significantly different ($P < 0.01$) among the 12 sets, thus our hypothesis on using head diameter as an appropriate means to estimate seed yield was rejected. We also examined the head surface area as the predictor (Fig. 4b) but regression slopes were still significantly different among environments. Our analysis indicated that neither head diameter nor surface area should be used as predictors for SY and SN .

Head-weight distribution

C. cardunculus is an indeterminate crop species and forms many heads of various weights. Small, medium

and large head-weight frequency distributions as well as statistical descriptors per experiment are illustrated in Fig. 5. The analyses indicated that the head distributions, the total number of heads, and the mean head

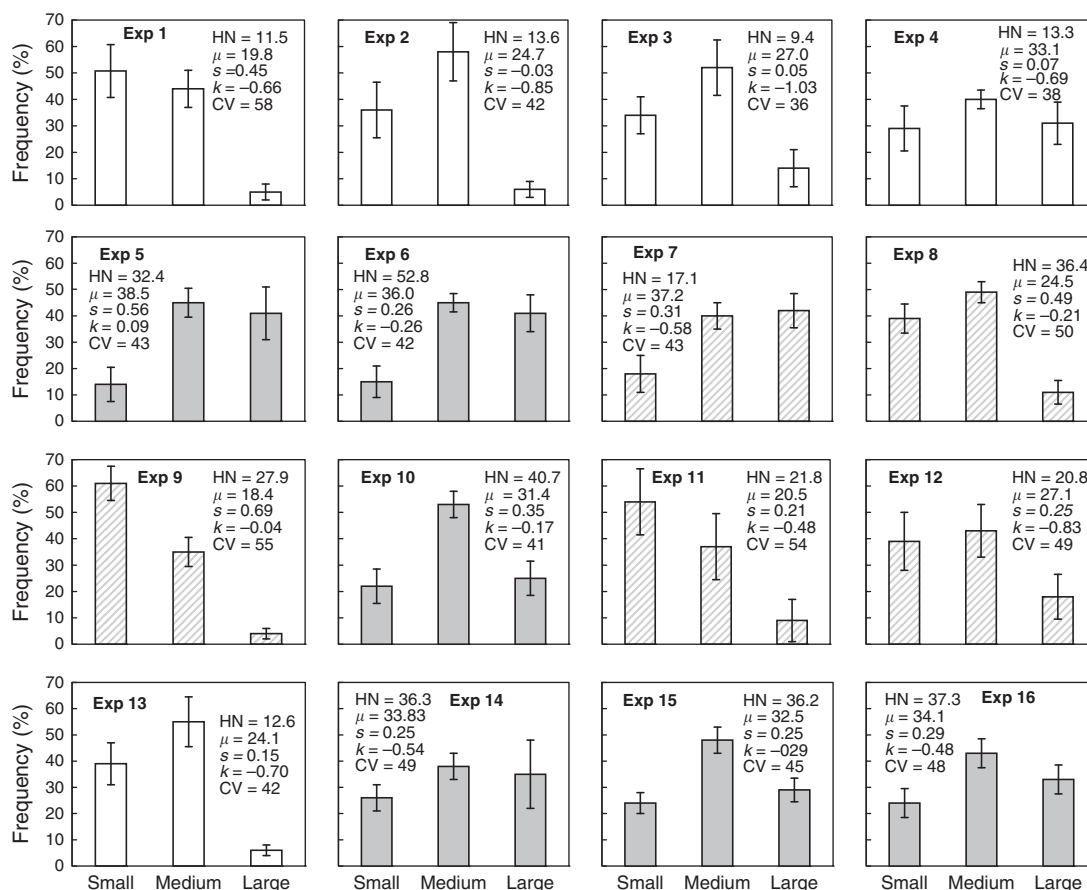


Fig. 5 Frequency distributions (\pm standard deviation) of *Cynara cardunculus* heads per m² (small, medium and large; Table 3) for 16 experiments carried out in Greece in 2007–2009. Open columns represent the 1st cropping cycle experiments. Partially and fully gray columns refer to experiments from 2nd to 6th growing cycle, for dry and aquatic soils, respectively. Details on the experiments are provided in Table 1 and 2. HN = total number of head per m², μ = mean head weight (g head⁻¹), s = skewness, k = kurtosis, CV = coefficient of variation, for other symbols see Table 3.

Table 6 Inflorescence characteristics of *Cynara cardunculus* during crop establishment cycle (Exp 1, 2, 3, 4 and 13: group 1) and during subsequent growing cycles on dry (Exp 7, 8, 9, 11 and 12: group 2) and on aquatic soils (Exp 5, 6, 10, 14, 15 and 16: group 3) in Greece in 2007–2009

Exp. Group	Number of heads per m ²								μ g head ⁻¹	CV %	k –	s –
	Total		Small		Medium		Large					
	#	%	#	%	#	%	#	%				
Group 1	12.1a	4.8a	38b	5.8a	50a	1.4a	12a	25.8a	43a	–0.8c	0.14a	
Group 2	24.8b	11.1a	42b	10.1ab	41a	3.6ab	17a	25.6a	50a	–0.4ab	0.39b	
Group 3	39.8c	8.1a	20a	18.5c	46a	13.2c	34b	34.5b	44a	–0.2a	0.34b	
Mean	25.6	8.0	33	11.5	46	6.1	21	28.6	46.0	–0.5	0.29	

Different letter within a column indicates significant difference at $P < 0.05$.

CV, coefficient of variation; k , kurtosis; s , skewness, for other symbols see Table 3.

weight varied significantly across 16 experiments, in contrast to coefficient of variation, kurtosis and skewness that varied only slightly.

In the present analysis, we classified the experiment-to-experiment variability into three major groups (Group 1: first cycle; Group 2 and Group 3 refer to subsequent cycles on dry and aquatic soil types, respectively; Table 6 and Fig. 5). Under the prevailing management conditions in Greece (note planting arrangement 75×25 cm), cynara produced about 12 heads m^{-2} during the establishment year. During subsequent years, the crop formed 25 and 40 heads m^{-2} on dry and on aquatic soils types, respectively ($P < 0.001$; Table 6).

Figure 5 depicts that the frequency distributions, and particularly the distributions of small and large heads were significantly affected across different sets of experiments ($P < 0.05$; Table 6). Nevertheless, the CV was unchanged for these sets of experiments ($CV = 46\%$; $P = 0.22$; Table 6). This is because on dry sites the distribution was: small 42%, medium 41% and large 17%, whereas on aquatic sites the distribution was: small 20%, medium 46% and large 34%. Hence, it can be inferred that beyond the first cycle, under conditions of high soil moisture availability (shallow ground water) an increased HN by some 35% (large heads by

72%) may be expected compared with conditions of moderate water stress (dry soils). This is expected since cynara – as all crops – performs much better on aquatic soils where high seed yields are expected (see later Fig. 6). Across different experiments the mean head weight, μ , was $\leq 40 \text{ g head}^{-1}$ (Fig. 5), indicating an upper threshold value.

Analysis of skewness and kurtosis showed that on average *C. cardunculus* head-weight distribution was platykurtic ($k = -0.48$) and positively skewed ($s = 0.29$; Table 6). On aquatic soil types this distribution tended to reach the normal distribution, since k and s shifted from -0.39 to -0.22 and from 0.41 to 0.34 , respectively (Table 6; Fig. 5).

Seed composition

Seed composition parameters for different SW classes are presented in Table 7. Oil concentration significantly increased with an increase in seed size from 17 to 26 mg seed^{-1} ($P = 0.016$), while in the range from 26 to 52 mg seed^{-1} , the oil concentration was rather constant at 22.9%. Calculating oil content per seed (mg oil seed^{-1}), a significant effect of seed size was detected ($P < 0.001$), throughout the range of seed weights stu-

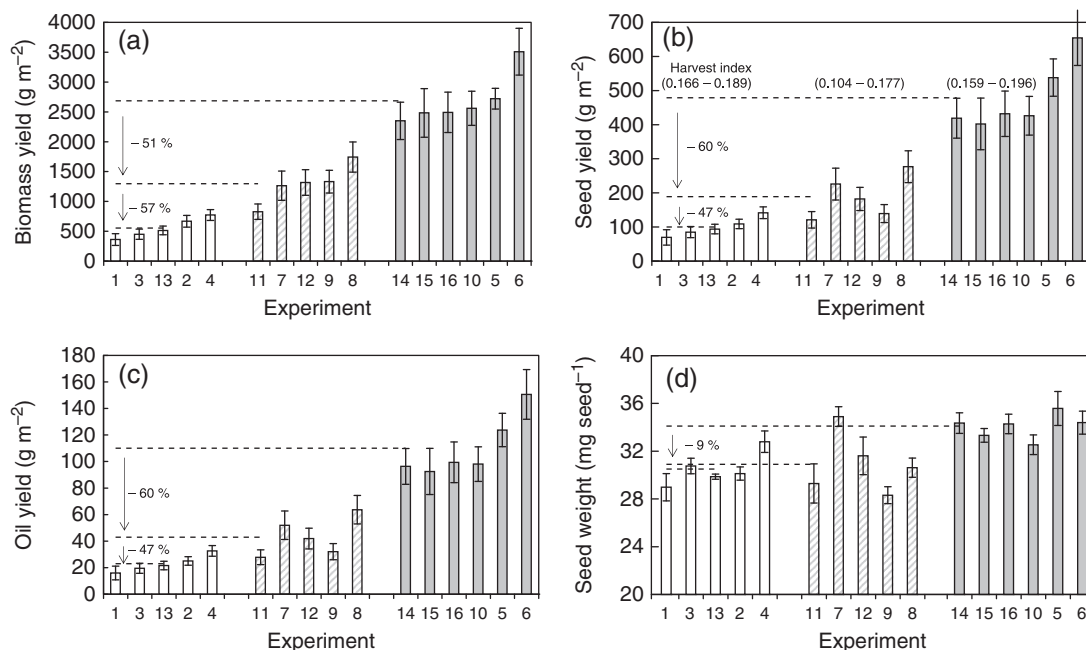


Fig. 6 (a) *Cynara cardunculus* average (\pm standard deviation) biomass yield, (b) seed yield (calculated from Eqn 2a), (c) oil yield (estimated at 23% of SY) and (d) individual seed weight (calculated as SY/SN) for 16 experiments carried out in Greece in 2007–2009. Open columns represent the 1st cropping cycle experiments (group 1). Partially and fully gray columns refer to experiments from 2nd to 6th growing cycle, for dry (group 2) and aquatic (group 3) soils, respectively. Details on the experiments are provided in Tables 1 and 2. Broken lines refer to average values per group (as in Table 8) while arrows accompanied by a percentage value indicate yield reduction from group 3 to group 2 and from group 2 to group 1. The range of seed harvest index (g g^{-1} ; leaves were excluded in calculations) per group is also provided in panel b.

Table 7 *Cynara cardunculus* seed composition ($n = 3$) as affected by seed size

Seed size (mg)		Oil		Crude protein		Cellulose	Ash	FFA	Moisture
Range	Average	%	mg	%	mg	%	%	%	%
<20	17a	17.01a	2.73a	19.76a	3.06a	24.31a	4.41a	2.40a	6.39a
20–30	26b	21.38b	5.57b	19.46a	5.05b	21.95a	3.97b	1.61a	6.38a
30–40	35c	23.20b	8.06c	18.21a	6.26c	21.48a	3.44c	0.93a	5.69a
40–50	46d	23.09b	10.62d	16.98a	7.81d	21.74a	3.44c	0.61a	5.53a
>50	52e	22.53b	11.94d	19.32a	10.23e	21.96a	3.28c	0.51a	5.24a
Mean	35.07	21.81	7.81	18.68	6.44	22.09	3.61	1.18	5.85

Different letter within a column indicates significant difference at $P < 0.05$.

FFA, free fatty acids.

Table 8 Major fatty acid composition ($n = 2$) of the seed oil obtained from different seed sizes

Seed mg (range)	C16:0 (palmitic)	C18:0 (stearic)	C18:1 (oleic)	C18:2 (linoleic)
< 20	15.47a	4.84a	28.83a	47.66a
20–30	11.96a	3.70a	27.64a	54.58a
30–40	11.10a	3.20a	24.89a	59.12a
40–50	11.10a	3.42a	28.18a	55.25a
>50	11.19a	3.53a	29.98a	53.44a
Mean	12.16	3.74	27.90	54.01

Different letter within a column indicates significant difference at $P < 0.05$.

Values expressed in %.

died (Table 7). Crude protein concentration (%) was not significantly affected by seed size (average 18.7%; $P = 0.252$), but for protein content (mg protein seed⁻¹), the effect proved significant ($P < 0.001$). Seed ash concentration significantly decreased with increasing seed size ($P = 0.01$), whereas cellulose (mean: 22.1%), free fatty acids (mean: 1.18%) and seed moisture (mean: 5.9%) contents were not affected by seed size ($P > 0.05$; Table 7). Seed samples collected from different environments (2008), showed similar oil ($P = 0.132$) and protein ($P = 0.992$) concentrations (data not shown). Across four different sites, *C. cardunculus* seed oil concentration ranged from 20.9 to 25.9%, while crude protein ranged from 14.1% to 20.9% (average: 18%).

Oil composition

The oil composition for different SW is provided in Table 8. Gas chromatography allowed to separate methyl esters of fatty acids from C12:0 (lauric) to C24:0 (lignoceric). No significant differences were observed for any of the studied gas chromatography parameters ($P > 0.05$), indicating that chemical composition of cynara seed oil was conservative. The average fractions of the major fatty acids were: 12.2% palmitic (C16:0), 3.7% stearic (C18:0), 27.9% oleic

(C18:1) and 54.0% linoleic (C18:2). These four acids amounted to 97.8% of the total, while the remaining 2.2% was divided over several minor acids (C14:0 = 0.14%, C16:1 = 0.23%, C17:0 = 0.05%, C18:3 = 0.06%, C20:0 = 0.40%, C22:0 = 0.13%, C24:0 = 0.23%, etc.). The effect of location on oil profile was not significant (data not shown).

Cynara yields in Greece

Figure 6 presents average biomass, seed and oil yields per experiment. During the year of establishment, *C. cardunculus* biomass productivity was about 550 g m⁻², while during subsequent cycles, the biomass productivity increased to 1300 g m⁻² on dry and to 2700 g m⁻² on aquatic soils, respectively (Fig. 6a). Harvest index ranged from 0.104 to 0.196 g g⁻¹ (Fig. 6b), and the lower values were obtained on dry soils. Seed yields ranged from 100 g m⁻² during the first cycle to 190 (dry soils) and to 480 g m⁻² (aquatic soils) during subsequent crop cycles (Fig. 6b). The range of *C. cardunculus* oil yield potential in Greece was 23–110 g m⁻² (Fig. 6c). Seed number ranged from about 3200 (first cycle) to 6000 on dry soils and finally to 14 000 seeds m⁻² on aquatic soil types, respectively (data not shown).

By combining Eqns (2a) and (4) the average SW per m^{-2} was calculated for each experiment ($32 \pm 4 \text{ mg seed}^{-1}$; Fig. 6d). Despite the great variation in biomass, seed yield and seed number across experiments (e.g. Fig. 6a and b), the average seed weight (mg seed^{-1}) was rather invariant and varied only by 10%.

Discussion

This paper provides information on head weight, head number, seed quantity and seed quality of *C. cardunculus*. We provide an easy and robust methodology for estimating seed yield under varying management \times environmental conditions, thus improving our understanding of the reproductive allometry of this perennial species.

Seed yield in relation to inflorescence traits

This study documented that in *C. cardunculus* the threshold head weight required to support seed set is 6.8 g head^{-1} and that of all additional biomass investments in the head a fraction of 0.43 is allocated to the seeds (Fig. 1a). These allometric coefficients were the same for different growing situations in Greece (e.g. crop age, location, soil types etc.; Table 4). Environmental as well as management variables affect seed yield through their effects on μ and *HN* (Figs 5 and 6). Based on these parameters (H_w , μ and *HN*) we presented a variety of allometric models, which can be used from organ- to land-level studies, depending on the research interest.

At head-level, using H_w as independent variable, the seed yield can be estimated very accurately ($r^2 = 0.96$; Eqn (1); Fig. 1a) while seed number can also be estimated but with somewhat lower accuracy ($r^2 = 0.86$; Eqn (3); Fig. 1b). This is attributed to the observed variability in seed number per head (Fig. 1b). Harper *et al.* (1970) stated that seed number and seed size represent alternative strategies in the allocation of reproductive resources, while Sadras (2007) mentioned that seed number is plastic and highly sensitive to resource availability. Owing to this sensitivity, the SN_{head} model [Eqn (3)] could not be as precise as the SY_{head} model [Eqn (1)]. Lastly, at organ level, a strong association between HI_{head} over varying H_w was presented (Fig. 1c). With larger heads ($>40 \text{ g}$) the initial investment (6.8 g) is supported by more seeds, resulting in a higher HI_{head} (average: 0.39) compared with smaller heads ($<20 \text{ g}$; average HI_{head} : 0.18; Fig. 1c), meaning that growers and researchers should aim for practices resulting in a higher number of large heads. In literature, Foti *et al.* (1999), Piscioneri *et al.* (2000), Fernández *et al.* (2005), Fernández *et al.* (2007) and Gominho *et al.*

(2009) reported HI_{head} from 0.18 to 0.40 g g^{-1} , which fits within our range.

At unit area-level, the parameters of Eqns (2a) or (2b) are two easily measurable inflorescence traits (*HW* and *HN*), which are commonly determined in cynara eco-physiological studies (e.g. Piscioneri *et al.*, 2000). The fact that *SY* model performed well ($r^2 = 0.93$; Fig. 3) across a wide range of published data (Foti *et al.*, 1999; Piscioneri *et al.*, 2000; Raccuia & Melilli, 2007a; Ierna & Mauromicale, 2010) and the current data (Table 5) including different management techniques, environmental conditions as well as different genotypes, implies the potential applicability of the present empirical model.

This model could also assist yield component analysis. Equation (2a) indicates that seed yield is determined by mean head weight (μ) and total head number per unit area (*HN*). Simply increasing the number of heads will be beneficial for seed yield as long as this does not put a too strong burden on μ . According to Fig. 5 and Table 5, the μ is largely dependent on management \times environment interactions.

Our analysis implies advantage can be gained from developing a crop with larger heads (higher μ) and secondly from increasing the number of heads, particularly in high yielding environments, in order to minimize the loss caused by the initial investment in heads before seed set. This view is confirmed by Raccuia & Melilli (2007b), who – while increasing planting density from 1 to 4–8 plants m^{-2} (first cycle) – noticed that branching and head number plant $^{-1}$ reduced, resulting in a higher μ , and consequently higher seed yield per unit area (more than double). Moreover, the same authors (Raccuia & Melilli, 2007a), found a great variability in seed yield among several (cultivated and wild cardoon) genotypes; indicating therefore that breeding programs can also assist in developing cultivars suitable for varying cropping systems.

This study also depicted the range of attainable yields of *C. cardunculus* (biomass, seed and oil) in representative parts of Greece. Maximum observed biomass production was 3500 g m^{-2} – in line with Dalianis *et al.* (1996) – and it was obtained on aquatic soils after a growth period of 16 months. Actually, at one of the sites with this soil type, the depth of cynara's main roots was measured up to 180 cm whereas the fine roots were found at a depth up to 330 cm (in May), providing evidence that the crop can make use of deep ground water. Across three growing seasons on aquatic soils the average biomass production was $2700 \text{ g m}^{-2} \text{ yr}^{-1}$, which was 51% higher than obtained in dry environments (see Fig. 6 and also Piscioneri *et al.*, 2000; Fernández *et al.*, 2005; Danalatos *et al.*, 2007). Similarly, the seed yield on aquatic soils ($480 \text{ g m}^{-2} \text{ yr}^{-1}$) was 60%

Table 9 Oil concentration and fatty acids composition of cynara, sunflower and maize seeds

Crop	Location	Oil (%)		Fatty acid composition (%)			
		Average	Range	C16:0	C18:0	C18:1	C18:2
Cynara*	Italy (40.9°N)†	20.7	18.6–23.6	7.7	3.6	26.1	61.5
Cynara*	Italy (37.2°N)‡	24.1	22.8–25.1	10.3	2.8	21.8	62.7
Cynara	Spain (37.2–41.3°N)§	25.0	20.0–32.4	10.6	3.7	24.9	59.7
Cynara	Portugal¶	24.3	–	10.9	3.3	23.1	61.2
Cynara*	Greece (39.2°N)	23.2	20.9–25.9	11.1	3.2	24.9	59.1
Sunflower	Greece (39.2°N)**	43.3	37.5–48.8	6.6	3.9	34.6	51.9
Maize	Greece (39.2°N)**	4.7	3.62–5.80	10.9	2.5	31.2	51.9

*cv. Bianco avorio.

†Piscioneri *et al.* (2000).

‡Maccarone *et al.* (1999), Raccuia & Melilli (2007a).

§Curt *et al.* (2002).

¶Carvalho *et al.* (2006).

||This study; based on medium-sized seeds (30–40 mg seed⁻¹; see Tables 7 and 8).

**Unpublished results (S.V. Archontoulis).

higher compared with yield on dry soils. Cynara seed yields are even close to sunflower grain yields obtained in Greece.

Great differences were also found for SN among 16 experiments. Nevertheless, the individual seed weight, SW, varied <10% among the 16 experiments (32 ± 4 mg seed⁻¹; Fig. 6d) and this might give an indication for the attainable sink capacity of *C. cardunculus* seeds under Greece conditions. Experimental average SW values are in accordance with literature data (Foti *et al.*, 1999; Raccuia & Melilli, 2007a; Ierna & Mauromicale, 2010). However, despite the great head-to-head variability in SW, it seems that the average SW at unit area level was rather conservative, similarly to most common grain crops (Sadras, 2007).

Seed quality

Four parameters define the potential of cynara as an oil crop: seed yield, seed oil content, fatty acid profile and heating value (Fernández *et al.*, 2006). This paper addresses three of those. The higher oil heating value has been measured at 33 MJ kg⁻¹ (Fernández & Curt, 2004). The current results on seed oil concentration are in close agreement (± 5%, Table 9) with data obtained in previous works from Spain (Curt *et al.*, 2002), Portugal (Carvalho *et al.*, 2006) and from Italy (Piscioneri *et al.*, 2000; Raccuia & Melilli, 2007a). Usually high temperatures during grain filling result in lower oil concentrations (Fernandez-Moya *et al.*, 2005). Under Greek conditions, cynara seed contains approximately 23% oil, which is lower than common annual oil seed crops growing in the Mediterranean region for biodiesel production (viz. sunflower, rapeseed: 40–46%; S. Archontoulis, unpublished results).

The observed stabilization/constancy of the seed-oil concentration at medium–large-sized seeds (Table 7) might be attributed to the oil distribution within the seed. Curt *et al.* (2002) reported that the seed fraction to hull (44.5%) and to kernel (55.5%) was similar between different seed sizes. Stabilization of oil concentration across different kernel weights has also been observed for maize (Borrás *et al.*, 2002).

The fatty acid composition of the oil determines its suitability for either food or industrial uses. The current findings have shown 10.9% higher palmitic, 4.5% lower stearic and 3.6% lower oleic acid and 3.5% higher linoleic acid compared with data on cynara oil profile from other countries (Table 9). When comparing the cynara oil profile with sunflower and maize oil profiles (Table 9), it can be inferred that cynara has a profile similar to sunflower oil and rather close to maize (Maccarone *et al.*, 1999). Moreover, Carvalho *et al.* (2006) found that cynara's fatty acid composition did not differ significantly also from canola, cannabis, and safflower, and that cynara oil is suitable for production of human nutrients after a refining process.

Regarding crude protein, results from Greece confirms the high nutritive value of cynara seeds in line with reports from Spain and Italy (Curt *et al.*, 2002; Raccuia & Melilli, 2007a). Cynara seeds scored high crude protein (viz. 18%), which is 10% lower than in sunflower seed and 47% higher than in maize kernels growing in the same environment in central Greece (S.V. Archontoulis, unpublished results).

Conclusions

The present work provides a robust and easily applicable methodology to estimate seed yield of *C. cardunculus*.

Our approach overcomes problems arising from the compound crop structure of inflorescences, and head (capitulum) structure as well. By measuring two simple inflorescence traits (total weight and number of all seed-bearing heads per unit area), the accuracy of seed yield prediction was >93%. In representative parts of Greece (16 experiments), attainable *C. cardunculus* seed yields (beyond first cycle) ranged from 190 to 480 g m⁻² yr⁻¹, on dry soils and on aquatic soils (shallow ground water level). During the first cropping cycle, seed yields were 57–80% lower than in subsequent cycles. This variation in seed yield was sufficiently explained by the analyses of head-weight distribution (small, medium and large heads) and variability of seed/head weight ratio at head level. Our proposed methodology can be easily applied in any environment as well as under variable management practices.

Seed quality characteristics such as oil (23%) and protein (18.7%) concentration was rather invariant through different seed sizes (range: 26–56 mg seed⁻¹) as well as growing environments meaning that under Greek conditions, these fixed values can be used to estimate seed oil and protein yields.

Seed/biomass as well as oil/seed fractions are now quantified precisely and this can assist (a) researchers to more efficiently estimate crop heating value for solid and/or liquid biofuel production; and (b) policy makers to better plan land uses.

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