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Agronomic performance, seed quality and nitrogen uptake of *Descurainia sophia* in response to different nitrogen rates and water regimes

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ABSTRACT

Descurainia sophia (flixweed) is an annual weed widely distributed in cultivated crops, forage and rangelands throughout the world. This weed, in particular its seed, is used for food, medicinal and industrial purposes. The objective of this study was to investigate the effects of irrigation management and different application rates of nitrogen on morphological traits and yield components of this weed as a means of enhancing production and economic returns. A two-year field experiment was conducted in a semi-arid region in Iran during the 2009–2010 and 2010–2011 growing seasons. The experiment was a split plot in a randomized complete block design with three replicates, with irrigation treatments as main plots and nitrogen rates as sub plots. The three irrigation regimes consisted of 0.1 maximum allowable depletion or deficiency (MAD) of available soil water (ASW), 0.2 MAD of ASW, 0.4 MAD of ASW in 2010 and 0.2 MAD of ASW, 0.4 MAD of ASW and 0.8 MAD of ASW in 2011. The plants were grown at three nitrogen rates of 0, 200, and 300 kg N ha^{-1}. Generally there were significant increases in seed yield, biomass, straw yield, harvest index, number of siliques (pods) per plant, seed weight, plant height, time to maturity, water use efficiency, protein concentration in seed, straw N concentration, nitrogen uptakes and nitrogen harvest index each growing season by applying nitrogen at all irrigation treatments. There was a decreasing trend in number of plants per m^2, nitrogen utilization efficiency and oil concentration with increasing nitrogen application under all the irrigation treatments. Seed yield response to irrigation treatments and N rates seemed to be more related to number of plants per m^2 and number of siliques per plant. The highest seed yield was obtained at the plant population of 686 plants per m^2. The results obtained here suggest that nitrogen application can improve the seed yield and seed quality of *D. sophia* grown under different irrigation regimes. Averaged over both years, the application of 300 kg N ha^{-1} under 0.2 MAD of ASW resulted in the highest revenue; 200 kg N ha^{-1} was not significantly different to 300 kg N ha^{-1}.

1. Introduction

Descurainia sophia (L.) Webb ex Prantl (flixweed) is an annual weed (Brassicaceae family), widely distributed in cultivated crops, forage and rangelands throughout the world (Mitich, 1996; Baskin et al., 2004; Blackshaw et al., 2005; Hernandez Plaza et al., 2011; Li et al., 2011). This weed, in particular its seed, is used for food, medicinal and industrial purposes (Mitich, 1996; Peng et al., 1997; Bekker et al., 2005; Sun et al., 2005; Mohamed and Mahrous, 2009; Li et al., 2010; Mosaddegh et al., 2012). *D. sophia* seeds contain over 25% protein, 22–44% oil, 3.5–4% ash and around 7.6% fiber (Tkachuk and Mellish, 1977; Duke and Ayensu, 1985; Peng et al., 1997; Bekker et al., 2005). In general, the economic value of *D. sophia* production is determined primarily by the attainable seed yield and less by the seed compounds such as oil concentration.

Processes of yield formation are highly variable and depend on genetic, environmental and agronomic factors as well as their interactions (Rathke et al., 2006). Among the various inputs, water and fertilizer (nutrients) are considered as the two key inputs making maximum contribution to plant productivity (Lenka et al., 2009). Water is considered the most limiting factor for plant production

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Table 1
Physico-chemical properties of different layers of the experimental soil before the beginning of experiment.

Soil parameters	Soil depth (cm)		
	0–20	20–40	40–60
Sand (%)	64	68	66
Silt (%)	20	18	18
Clay (%)	16	14	16
Bulk density (g cm^{-3})	1.20	1.40	1.48
FC (0.033 MPa, % by wt.)	15.38	19.53	14.89
PWP (1.5 MPa, % by wt.)	7.19	8.39	6.26
Organic C (%)	1.79	1.56	1.09
pH	7.74	7.74	7.74
EC (dS m^{-1})	1.3	1.3	1.3
Available N (kg ha^{-1})	29.03	34.07	43.3
Available P (kg ha^{-1})	195.52	227.36	214.304
Available K (kg ha^{-1})	2085.2	2304.4	2465.68

The soil characteristics were determined according to Tandon (1995).
FC (field capacity) and PWP (permanent wilting point) were determined according to Al-Rumikhani (2002).

in arid and semi-arid regions. In these regions, the unfavorable distribution of rain over the growing season and the year-to-year fluctuations represent a major constraint to plant growth. In crop production systems, more production per unit water applied is the main concern (Rostamza et al., 2011). During greenhouse trials measuring water use efficiency, *D. sophia* displayed inefficient usage of water (Anderson and Best, 1965). Nitrogen is currently the most widely used fertilizer nutrient and the demand for it is likely to grow in future. Since nitrogen is a component of protein and nucleic acid, when nitrogen amount in soil is not optimal, growth is reduced (Sepaskhah and Barzegar, 2010). There are some reports indicating that *D. sophia* responds positively to nitrogen fertilization (Bischoff and Mahn, 2000; Blackshaw et al., 2005).

Increasing the plant production and enhancing economic returns is highly correlated with the application of optimum amount of water and nitrogen fertilizer. To our knowledge, there are no studies which assess production ability, water use efficiency and nitrogen uptake behavior of *D. sophia* under different conditions of water and nitrogen. Therefore, the main objective of this study was to investigate the effects of irrigation management and different application rates of nitrogen on this industrial-medicinal plant taking into account both quantity and quality aspects.

2. Materials and methods

2.1. Site description

A two-year field experiment was conducted at Research Field of Tarbiat Modares University (35°44′N, 51°09′E, and 1265 masl), Iran during the 2009–2010 and 2010–2011 growing seasons (referred hereafter as 2010 and 2011, respectively). This area has arid to semi-arid climate (according to the Köppen climate classification) with the long-term (30 years) mean annual rainfall and temperature of 232.6 mm and 17.6 °C, respectively. Daily weather data were obtained from the Chitgar weather station (35°44′N, 51°10′E, and 1305 masl), which is one kilometer from the experimental site. The meteorological data recorded during the experiment period in each growing season are given in Fig. 1. The soil texture was sandy loam. The physical and chemical properties of different layers of the experimental soil are shown in Table 1.

2.2. Cultural practices and experimental design

The experimental area had dense, pure stand and even distribution of naturally occurring populations of *D. sophia*. After field preparations, this area was divided into 27 experimental units. Plots were 6 m long and consisted of three rows, 0.6 m apart. Between all main plots, a 2 m alley was kept to eliminate all influence of lateral water movement. Treatments were arranged in a split plot experiment based on randomized complete block design with three replicates, with irrigation regimes in the main plots and nitrogen rates in the sub plots. The irrigation treatments consisted of irrigation scheduling based on maximum allowable depletion or deficiency (MAD) over 60 cm soil depth (Behera and Panda, 2009). The three irrigation treatments consisted of 0.1 depletion of available soil water (ASW), 0.2 of ASW, 0.4 of ASW in 2010 and 0.2 of ASW, 0.4 of ASW and 0.8 of ASW in 2011 which are abbreviated to I1, I2, I4 and I8, respectively. Immediately following the preparation of plots, the first irrigation of the field was applied on 15 December in 2009, and 14 October in 2010. Equal volumes of water were applied to each plot up to the beginning of blooming (growth stage BBCH 51-59, Lancashire et al., 1991) (87 DABI (days after the beginning of irrigation) in 2010 and 73 DABI in 2011) for uniform emergence and establishment of seedlings before starting the irrigation treatments. The total number of irrigations was 20–27 (I1), 11–14 (I2), 6–8 (I4) in 2010 and 26–29 (I2), 15–16 (I4), and 11 (I8) in 2011. Soil water content in each plot was measured using a TRIME-FM TDR (Time Domain Reflectometry, IMKO Micromodultechnik, Ettlingen, Germany). The TDR was calibrated over different ranges of soil water content. In both years, access tubes were set at the center of each plot to measure soil water content in 0–20, 20–40, and 40–60 cm layers of soil profile. The TDR was calibrated in the field, and readings were then converted to volumetric soil water content. The percentage of maximum allowable depletion of ASW in the effective root zone was estimated by Eq. (1) (Martin et al., 1990):

$$\mathrm{MAD} = \frac{1}{n}\sum_{1}^{n}\frac{\mathrm{FC}_i - \theta_i}{\mathrm{FC}_i - \mathrm{PWP}_i} \tag{1}$$

where n is the number of layers in the effective rooting depth used for the soil moisture sampling, FC_i is the soil volumetric moisture at field capacity in the ith layer, θ_i is the soil volumetric moisture in ith layer and PWP_i is the soil volumetric moisture at permanent wilting point in the ith layer.

The volume of required water based on predefined MAD was calculated as Eqs. (2) and (3):

$$\mathrm{ASW}\frac{1}{n}\sum_{1}^{n}\mathrm{FC}_i - \mathrm{PWP}_i \tag{2}$$

$$V_d = \mathrm{MAD} \times \mathrm{ASW} \times R_z \times 10 \tag{3}$$

where ASW is equal to 12.732 cm m^{-1} soil depth, V_d is the volume of irrigation water (mm), and R_z is the effective rooting depth (0.6 m), and 10 is the conversion constant of cm to mm. A hose (4 cm diameter) with a gauge was used to deliver the required volume of water.

The plants were grown at three nitrogen rates (0, 200, and 300 kg N ha^{-1}, hereafter N0, N200, and N300, respectively). Nitrogen was hand applied as urea (46% N) in three equal splits at the leaf development stage (growth stage BBCH 10-19), the start of inflorescence emergence (growth stage BBCH 50), and the end of flowering (growth stage BBCH 69) in 2010, and in two equal splits at the end of stem elongation (growth stage BBCH 39), and the beginning of flowering (growth stage BBCH 60) in 2011. Irrigation was done immediately after urea application to avoid volatilization losses.

Seed numbers of *D. sophia* in the soil seed bank were determined using soil cores. Seven soil cores (2.5 cm in diameter and 9 cm deep) were randomly collected from each plot. Each core was split into three sections of 3 cm. The soil samples from the same layer of each core were bulked, air-dried and pulverized. Three subsamples were taken from each of the three layers and weighed.

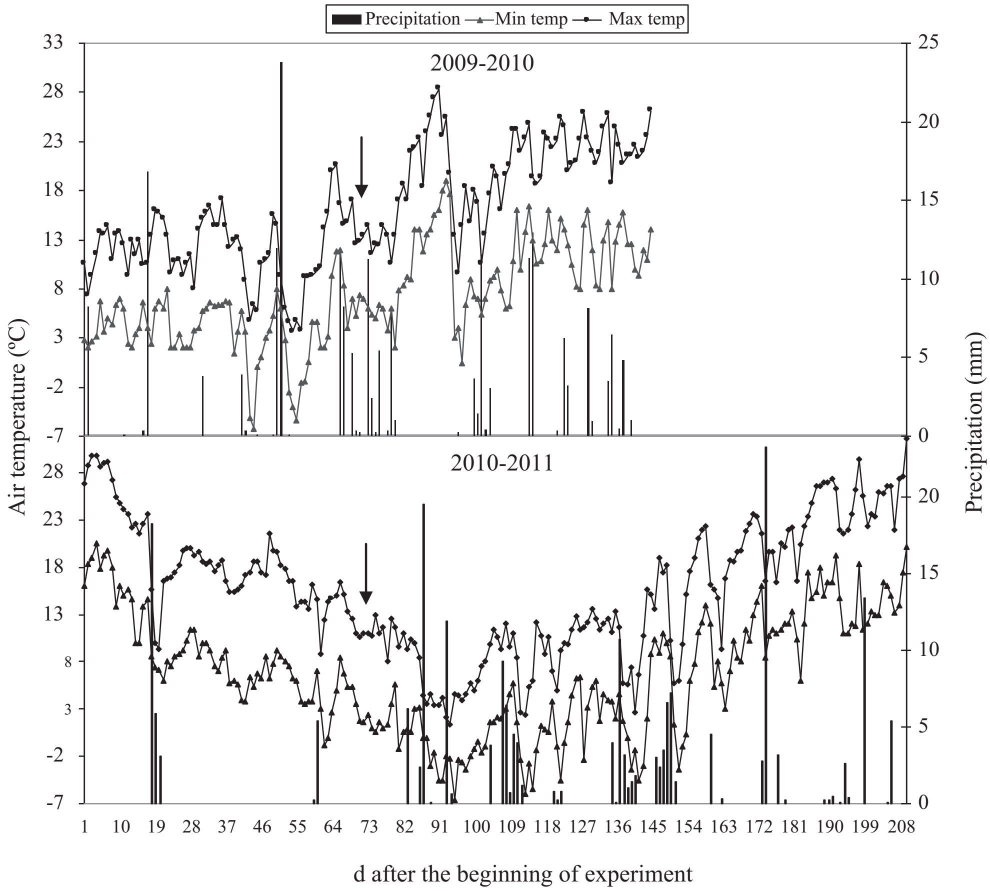

Fig. 1. Daily maximum and minimum air temperatures (°C), and precipitation (mm) recorded during the growing season in 2009–2010 and 2010–2011. The arrows show the start of inflorescence emergence in both growing seasons.

The total number of seeds in each sub-sample was counted using a stereomicroscope and seed density was expressed as the number of seeds m^{-2}. Between the end of emergence (growth stage BBCH 09) and the early stage of leaf development (growth stage BBCH 13), seedling counts were made in two 0.24 m^2 quadrats in all plots and were expressed per m^2. The seedling emergence of *D. sophia* can usually occur from 3 cm upper layer of soil. Average seed density of *D. sophia* in this layer was 800,000 m^{-2}. The experimental field had dense and uniform emergence with the average of about 2000 seedlings m^{-2} in both growing seasons.

2.3. Growth parameters

To avoid possible border effects, a 1.2 m^2 area at the center of each plot was sampled. The plants were cut at ground level, morphological traits and yield components measured, and oven-dry weight of seeds and remainder of the plant determined. Harvest index (HI) was calculated as the ratio of seed yield to total biomass.

2.4. Water use efficiency calculation

For each water treatment, the water use (WU) was determined by means of water balance calculation for the period between the beginning of irrigation (experiment) up to harvest, adopting Eq. (4) (Rostamza et al., 2011; Cosentino et al., 2012):

$$WU = I + P - D_p \pm \Delta C \tag{4}$$

where WU is the water use (mm); I is the water supplied by means of irrigation (mm); P is the precipitation (mm); D_p is the deep percolation (mm); ΔC is the difference between soil water content at the beginning of experiment and soil water content at harvest in the first 60 cm of depth. The water use efficiency (WUE), expressed as the ratio between seed production (kg ha^{-1}) at final harvest and water used (mm) by the plant (WU), was calculated.

2.5. N analysis, uptake and efficiency

For chemical analyses, different parts of *D. sophia* plants were ground thoroughly either in a mortar-pestle (for seeds) or in a household food grinder (for straw). After the wet digestion, total Kjeldahl nitrogen was measured (Tandon, 1995). The nitrogen percentage was multiplied by 6.25 to calculate the protein percentage (g 100 g^{-1}). Nitrogen utilization efficiency (NutE; kg kg^{-1}) for seed was calculated by dividing the seed yield (kg ha^{-1}) by total N present in it (kg ha^{-1}). Total nitrogen uptake were determined as follows:

$$\text{Total N uptake}\,(\text{kg ha}^{-1}) = (\text{seed yield} \times \text{N concentration in seed}) + (\text{straw yield} \times \text{N concentration in straw}) \tag{5}$$

Nitrogen harvest indices (NHI) are defined as the ratio of seed nitrogen contents to nitrogen contents of total biomass (seed plus straw).

2.6. Determination of oil concentration

Soxhlet extraction was employed to determine the total oil concentration of the *D. sophia* seed. In the Soxhlet extraction procedure, 5 g of the milled seeds was packed in a paper extraction and the oils were extracted using 300 ml of petroleum benzene (b.p. 40–60 °C,

Table 2
Main effects and interactions of irrigation regimes (I) and nitrogen application (N) treatments on seed yield, total biomass, straw yield and harvest index of *D. sophia* in 2010 and 2011; summary of *F* significance from analysis of variance for the effects of main factors and interactions.

Treatment	Seed yield (kg ha^{-1})		Total biomass (kg ha^{-1})		Straw yield (kg ha^{-1})		Harvest index	
	2010	2011	2010	2011	2010	2011	2010	2011
I1	1261.4	–	6707.9	–	5446.5	–	0.19	–
I2	1342.5	734.6	7291.6	5716.2	5949.1	4981.7	0.18	0.13a
I4	1310.6	538.3	7142.2	4478.9	5831.6	3940.6	0.18	0.12ab
I8	–	418.6	–	3945.1	–	3526.6	–	0.11b
F-test	ns	ns	ns	ns	ns	ns	ns	*
N0	916.9b[a]	416.4b	5271.1b	3519.3b	4354.2b	3102.9b	0.18	0.12
N200	1463.9a	616.1a	7925.7a	5249.6a	6461.8a	4633.4a	0.18	0.12
N300	1533.7a	658.9a	7944.9a	5371.3a	6411.2a	4712.4a	0.19	0.12
F-test	**	**	**	**	**	**	ns	ns
I1 × N0	634.0b	–	3723.0	–	3089.0	–	0.18	–
I1 × N200	1598.8a	–	8607.0	–	7008.0	–	0.18	–
I1 × N300	1551.5a	–	7793.0	–	6242.0	–	0.20	–
F-test	*	–	ns	–	ns	–	ns	–
I2 × N0	1102.7b	587.0b	6180.0	4454.7	5077.0	3867.7	0.18	0.13
I2 × N200	1283.3b	800.0a	7210.0	6400.0	5927.0	5600.0	0.18	0.12
I2 × N300	1641.4a	816.7a	8485.0	6294.0	6843.0	5477.3	0.20	0.13
F-test	*	*	ns	ns	ns	ns	ns	ns
I4 × N0	1014.1	396.7	5910.0	3654.7	4895.9	3258.0	0.17	0.11
I4 × N200	1509.5	581.7	7960.0	4960.7	6450.5	4379.0	0.19	0.12
I4 × N300	1408.1	636.7	7556.7	4821.3	6148.5	4184.7	0.19	0.13
F-test	ns	ns	ns	ns	ns	ns	ns	ns
I8 × N0	–	265.7	–	2449.0	–	2183.0	–	0.11
I8 × N200	–	466.7	–	4388.0	–	3921.3	–	0.11
I8 × N300	–	523.3	–	4999.0	–	4475.3	–	0.10
F-test	–	ns	–	ns	–	ns	–	ns
Grand mean	1304.8	563.8	7074.2	4713.4	5742.4	4149.6	0.19	0.12
I × N (*F*-test)	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	19.7	18.0	22.1	24.0	23.0	24.1	9.3	7.5

ns, not significant at the 0.05 probability level; –, data not measured.
* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
[a] Means within a column followed by the same letter are not significantly different according to the LSD at the 0.05 probability level.

obtained from Merck Chemical Co., Germany) in a Soxhlet extractor for 4 h. Based on whole seed, the oil concentration was expressed as percentage (g 100 g^{-1}).

2.7. Simple analysis of economic prospects

Net economic profit for each treatment was calculated from Eqs. (6)–(8):

$$R = Y \times P \tag{6}$$

$$\mathrm{TC} = (\text{water used} \times \text{water price}) + (\text{nitrogen used} \times \text{nitrogen price}) \tag{7}$$

$$\mathrm{NEP} = R - \mathrm{TC} \tag{8}$$

where R is the revenue (US\$ ha^{-1}), Y is the seed yield (kg ha^{-1}), P is the lowest local price of *D. sophia* seed, equal to 2 US\$ kg^{-1}, TC is the total costs (US\$ ha^{-1}) and NEP is the net economic profit (US\$ ha^{-1}). The price of 50 kg urea fertilizer and 1000 m^{-3} of water were considered to be 8 US\$, and 12.5 US\$, respectively (Rostamza et al., 2011). It is necessary to note that other costs were the same for all treatments.

2.8. Statistical analyses

Main and interaction effects of experimental factors were determined from analysis of variance (ANOVA) using the GLM procedure in SAS (SAS Institute, 2002). The PROC UNIVARIATE within SAS was used to test the assumptions of variance analysis, and residuals were normally distributed. *F*-tests were conducted using the appropriate error term. When the *F*-test was significant, differences between treatment means were compared using the least significant difference (LSD) at the 0.05 probability level. The analysis of interactions (nitrogen at I1; nitrogen at I2; nitrogen at I4; nitrogen at I8) was done with by-processing in SAS. Pearson correlation coefficients were calculated using the PROC CORR in SAS.

3. Results and discussion

Productivity and yield components of *D. sophia* were higher in 2010 than in 2011 (Tables 2 and 3). Most of this difference can be attributed to differences between weather conditions in 2010 and 2011. The temperature changes and extremes seen in Fig. 1 were different before and after the start of inflorescence emergence in both growing seasons. In fact, several freezing temperatures (less than 0 °C) occurred after the start of inflorescence emergence in 2011. Most winter plants such as winter rapeseed have their greatest cold tolerance during the rosette stage, but will become very susceptible to low temperatures from flowering onwards (Lardon and Triboi-Blondel, 1995). Cold stress is a major cause of reduced crop productivity and quality in many temperate and arid zone crops. Cold temperature induces flower abortion, pollen and ovule infertility, causes breakdown of fertilization and affects seed filling, leading to low seed set and ultimately low grain yield (Thakur et al., 2010).

Table 3
Main effects and interactions of irrigation regimes (I) and nitrogen application (N) treatments on yield components and plant height of *D. sophia* in 2010 and 2011; summary of *F* significance from analysis of variance for the effects of main factors and interactions.

Treatment	Number of plants (m^{-2})		Number of siliques ($plant^{-1}$)		Number of seeds ($silique^{-1}$)		1000-seed weight (mg)		Plant height (cm)	
	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
I1	707.8	–	44.0	–	28.7b	–	160.1a	–	91.9	–
I2	757.3	365.6a	40.7	40.1	31.1a	30.5	148.6b	156.6	99.0	80.0
I4	710.0	296.7b	39.5	37.6	32.6a	31.0	153.0b	149.7	90.0	79.6
I8	–	280.0b	–	29.7	–	33.3	–	154.4	–	72.2
F-test	ns	*	ns	ns	*	ns	*	ns	ns	ns
N0	952.2a[a]	307.8	20.1b	25.3b	30.1	30.9	153.4	155.9	89.0	71.8b
N200	587.3b	304.4	53.0a	41.2a	30.9	32.3	154.2	148.3	97.2	80.6a
N300	635.6b	330.0	51.1a	40.9a	31.4	31.6	154.1	156.4	94.7	79.4a
F-test	**	ns	**	**	ns	ns	ns	ns	ns	**
I1 × N0	1013.3a	–	14.9b	–	26.7	–	151.7b	–	76.7b	–
I1 × N200	523.3b	–	65.4a	–	28.5	–	161.3ab	–	106.7a	–
I1 × N300	586.7b	–	51.7a	–	31.0	–	167.3a	–	92.3ab	–
F-test	*	–	**	–	ns	–	*	–	*	–
I2 × N0	1000.0a	333.3	21.0b	32.3c	31.0	30.0	149.3	160.7	98.7	73.3
I2 × N200	522.0c	330.0	54.3a	49.7a	30.5	29.8	144.2	152.7	100.0	86.7
I2 × N300	750.0b	433.3	46.7a	38.3b	31.8	31.6	152.2	156.3	98.3	80.0
F-test	**	ns	**	**	ns	ns	ns	ns	ns	ns
I4 × N0	843.3a	303.3	24.3c	26.3b	32.7	29.6	159.3	151.3	91.7	75.3
I4 × N200	716.7b	293.3	39.3b	44.2a	33.7	31.2	157.0	140.7	85.0	81.7
I4 × N300	570.0c	293.3	54.9a	42.3a	31.5	32.3	142.7	157.0	93.3	81.7
F-test	**	ns	**	*	ns	ns	ns	ns	ns	ns
I8 × N0	–	286.7	–	17.3c	–	33.0	–	155.7	–	66.7b
I8 × N200	–	290.0	–	29.8b	–	35.9	–	151.7	–	73.3ab
I8 × N300	–	263.3	–	42.0a	–	31.0	–	156.0	–	76.6a
F-test	–	ns	–	**	–	ns	–	ns	–	*
Grand mean	725.0	314.1	41.4	35.8	30.8	31.6	153.9	153.6	93.6	77.3
I × N (*F*-test)	*	ns	**	**	ns	ns	*	ns	*	ns
CV (%)	13.4	17.4	15.2	11.3	7.7	5.9	4.6	6.2	8.3	6.6

ns, not significant at the 0.05 probability level; –, data not measured.
* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
[a] Means within a column followed by the same letter are not significantly different according to the LSD at the 0.05 probability level.

3.1. Yield and growth parameters

Only the main effect of nitrogen was significant for seed yield, total biomass and straw yield in both years (Table 2). Significant harvest index response to irrigation treatments was only observed in 2011 (Table 2). In each growing season, nitrogen application increased all productivity parameters (Table 2). Application of 200 and 300 kg N ha^{-1} increased seed yield, biomass and straw yield by 37%, 34% and 33%; 40%, 34% and 32% in 2010 and by 32%, 33% and 33%; 37%, 35% and 34% in 2011, respectively, compared with the N0. Averaged over 2010 and 2011, applying 300 kg N ha^{-1} produced the highest seed yield, total biomass, straw yield and HI under the I2 irrigation treatment (Table 1). Thereby, the significant enhancements in seed yield under increased N applications resulted in a significantly enhanced HI (Table 2). These results are similar to those of Al-Jaloud et al. (1996) and Jackson (2000) who observed a close relationship between available N and the yield and biomass of canola. The highest biomass production was also observed by Giansoldati et al. (2012) when the highest dose of urea (200 kg ha^{-1}) was applied to *Brassica juncea*. As reported by Frenck et al. (2011) for oilseed rape, HI varied between 0.09 and 0.35 and was more affected by seed yield than biomass. As far as we know, N fertilization and irrigation effects or their interactions on the seed yield of *D. sophia* have not been evaluated up to now. In this study, the optimum N rate for maximum seed yield (averaged across years) was the same under different irrigation treatments. The mean seed yield values fluctuated from 265.7 to 1641.4 kg ha^{-1} by varying nitrogen doses and irrigation regimes in this two-year study (Table 2). In the scientific literature, it was reported that seed yield of *D. sophia* ranged from 775 to 3000 kg ha^{-1} (Peng et al., 1997; Li et al., 2005).

The two-way interaction between irrigation and nitrogen was significant for number of plants per m^2 in 2010, number of siliques (pods) per plant in both years, seed weight and plant height in 2010 (Table 3). The number of plants per m^2 was more than twofold higher in 2010 than that in 2011 (Table 3). Plant survival during winter is one of the key factors for successful growing of winter crops. Important plant development functions such as evapotranspiration, photosynthesis, water and nutrient absorption and other biological and chemical activities are regulated by temperature (Rapacz, 1998). In the present study, the beginning of experiment early in the second growing season mainly was connected with higher temperatures and smaller rainfall amounts during plant growth and development before the start of inflorescence emergence (Fig. 1). Higher temperatures often cause increases in plant growth, nutrient and water absorption. In fact, lower soil moisture and later nitrogen application in 2011 caused a reduction in seedling survivorship; consequently, reduced number of mature plants per m^{-2}. A good stand development could be an indicator of good growing conditions. The current importance of plant density (as determined by high winter survival) is in agreement with the findings of Lazzeri et al. (2004) and Annicchiarico et al. (2010). The lowest N level significantly increased number of plants per m^2 under all irrigation treatments in 2010 (Table 3). Similarly, Otteson et al. (2008) found tiller density decreased when N rate was increased. As may be expected, the presence of more N promoted higher plant growth rates and plant spacing was low enough to

Table 4
Main effects and interactions of irrigation regimes (I) and nitrogen application (N) treatments on number of days to maturity, water use, water use efficiency and nitrogen utilization efficiency (NutE) of *D. sophia* in 2010 and 2011; summary of *F* significance from analysis of variance for the effects of main factors and interactions.

Treatment	Number of days to maturity		Water use (mm)		Water use efficiency (kg ha^{-1} mm^{-1})		NutE (kg kg^{-1})	
	2010	2011	2010	2011	2010	2011	2010	2011
I1	138.8a[a]	–	452.0a	–	2.7	–	27.9	–
I2	135.2b	204.7	414.6b	669.9a	3.2	1.1	27.9	28.0
I4	131.1c	204.2	372.3c	618.3b	3.5	0.9	28.2	25.0
I8	–	205.9	–	610.6b	–	0.7	–	23.3
F-test	**	ns	**	*	ns	ns	ns	ns
N0	128.6c	204.1	382.0c	632.7	2.4b	0.6b	32.6a	29.1a
N200	135.8b	205.6	415.2b	633.9	3.6a	1.0a	25.4b	23.7b
N300	140.8a	205.1	441.6a	632.2	3.5a	1.0a	26.0b	23.5b
F-test	**	ns	**	ns	**	**	*	**
I1 × N0	129.0b	–	404.6b	–	1.6	–	27.7	–
I1 × N200	142.0a	–	469.4a	–	3.4	–	29.4	–
I1 × N300	145.3a	–	482.1a	–	3.2	–	26.6	–
F-test	**	–	**	–	ns	–	ns	–
I2 × N0	128.7c	204.7	385.9c	669.9	2.9	0.9b	39.1a	31.0
I2 × N200	135.0b	204.7	414.7b	669.9	3.1	1.2a	22.4b	27.5
I2 × N300	142.0a	204.7	443.1a	669.9	3.7	1.2a	22.1b	25.5
F-test	**	ns	**	ns	ns	*	*	ns
I4 × N0	128.0b	204.7	355.6b	619.9	2.8	0.6	30.9	30.5a
I4 × N200	130.3b	204.7	361.6b	619.9	4.2	0.9	24.2	22.8b
I4 × N300	135.0a	203.3	399.7a	614.9	3.5	1.0	29.3	21.8b
F-test	**	ns	**	ns	ns	ns	ns	**
I8 × N0	–	203.0	–	608.1	–	0.4	–	25.8a
I8 × N200	–	207.3	–	611.8	–	0.8	–	21.8b
I8 × N300	–	207.3	–	611.8	–	0.9	–	22.3b
F-test	–	ns	–	ns	–	ns	–	*
Grand mean	135.0	204.9	413.0	632.9	3.2	0.9	28.0	25.4
I × N (*F*-test)	**	ns	**	ns	ns	ns	*	ns
CV (%)	1.0	1.6	1.5	1.5	19.1	19.5	17.9	10.5

ns, not significant at the 0.05 probability level; –, data not measured.
* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
[a] Means within a column followed by the same letter are not significantly different according to the LSD at the 0.05 probability level.

permit additional plants per m^2. Significant plant density response to irrigation treatments was only observed in 2011, but this did not occur in terms of nitrogen treatments, because there was a lower plant density in this year (Table 3). The number of plants per m^2 was higher in low volume high frequency irrigation (I2) than the high volume low frequency irrigation (I8) (Table 3). It is observed that the daily distribution of precipitation received during the second growing season was unfavorable (Fig. 1). The I2 irrigation regime mitigated the unfavorable conditions and resulted in the better performance of plant.

Averaged over both years, application of 200 kg N ha^{-1} at the I1 and I2 and 300 kg N ha^{-1} at the I4 and I8 resulted in greater number of siliques per plant (Table 3). Only the main effect of irrigation influenced number of seeds per silique and followed the trend I1 < I2 < I4 < I8 (Table 3). The leaf area represents the major source of photosynthesis until flowering. A sufficient application of nitrogen results in a rapid expanse of leaf canopy, enabling plants to intercept more solar radiation and thus resulting in higher photosynthesis. In addition, Mazher et al. (2007) stated that increasing irrigation intervals could enhance the content of photosynthetic pigments. Increasing photosynthesis is manifested in the plant producing more pods and seeds. It was pointed out that the order of effects of N is equal for leaf area index, number of pods per plant and number of seeds per pod, indicating that N operates by increasing the supply of assimilates to flowers and the young pods (Rathke et al., 2006).

At the highest when compared with the lowest N level, a significant increase of 15.6 mg in 1000-seed weight occurred under the I1 irrigation regime (Table 3). This increase in seed mass can be due to the increased nutrient availability from fertilization and indicates the importance of adequate nutrient levels for high seed production (Bedane et al., 2009).

The I1 × N and I8 × N interactions were significant for plant height in 2010 and 2011, respectively (Table 3). Using average values, the tallest plant height was obtained in the I1 × N200 treatment with 106.7 cm while the shortest plant height was observed in I8 × N0 treatment with 66.7 cm. There are a number of factors affecting plant height such as different agricultural practices, growing conditions, climatic and soil properties, and plant ecotypes (Özgüven et al., 2008). In the present study, the shortest plant height is because of the smallest nitrogen and irrigation. As a whole, the seed yield was significantly correlated with plant height (r = 0.87, P < 0.01). This shows that, as stated by Istanbulluoglu (2009), Marino et al. (2011) and Ünlü et al. (2011), plant height and seed production can not be increased under nitrogen- or water-stressed conditions and *D. sophia* does not equally benefits from the water during all growth stages. It seems that taller plants can support seed filling for a longer period because of their greater storage capacity of nitrogen and carbon reserves (Dordas, 2009). In some studies, plant heights of *D. sophia* were between 20.0 and 143.3 cm (Mitich, 1996; Peng et al., 1997).

In general, seed yield response to irrigation treatments and N rates seemed to be more related to number of plants per m^2 and number of siliques per plant. There was a significant quadratic association between seed yield and number of plants per m^2 (R^2 = 0.85; Fig. 2). This relationship indicated that the highest seed yield was

Table 5
Main effects and interactions of irrigation regimes (I) and nitrogen application (N) treatments on protein (Pr) and nitrogen (N) concentrations, N uptakes and N harvest index (NHI) of *D. sophia* in 2010 and 2011; summary of *F* significance from analysis of variance for the effects of main factors and interactions.

Treatment	Pr concentration in seed (%)		N concentration in straw (%)		Seed N uptake (kg ha^{-1})		Straw N uptake (kg ha^{-1})		Total N uptake (kg ha^{-1})		NHI	
	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
I1	22.6	–	1.42	–	45.3	–	75.2	–	120.5	–	0.37	–
I2	24.3	22.8	1.38	3.06	53.7	27.2	81.2	151.5	134.9	178.7	0.40	0.15
I4	22.9	25.6	1.46	2.88	48.8	22.7	87.4	114.7	136.2	137.3	0.38	0.16
I8	–	27.0	–	3.04	–	18.4	–	108.8	–	127.2	–	0.15
F-test	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
N0	20.3b[a]	21.9b	1.35	2.84	29.3b	14.4b	57.3b	89.4b	86.6b	103.8b	0.36	0.14
N200	25.0a	26.7a	1.47	3.12	58.2a	25.8a	95.6a	144.2a	153.8a	170.0a	0.39	0.15
N300	24.5a	26.8a	1.43	3.02	60.3a	28.0a	90.9a	141.4a	151.2a	169.3a	0.41	0.17
F-test	**	**	ns	ns	**	**	**	**	**	**	ns	ns
I1 × N0	22.6	–	1.49	–	23.1	–	40.3b	–	63.3	–	0.36	–
I1 × N200	21.3	–	1.50	–	55.0	–	103.7a	–	158.7	–	0.34	–
I1 × N300	23.7	–	1.27	–	57.9	–	81.7ab	–	139.6	–	0.43	–
F-test	ns	–	ns	–	ns	–	*	–	ns	–	ns	–
I2 × N0	16.8b	20.9	1.70	2.92	29.5b	19.8c	89.3	110.2b	118.8	130.0b	0.27b	0.15
I2 × N200	27.9a	22.8	1.20	3.37	57.5a	29.4b	70.7	185.0a	128.2	214.3a	0.45a	0.13
I2 × N300	28.2a	24.8	1.24	2.90	74.1a	32.4a	83.6	159.4a	157.7	191.8a	0.47a	0.17
F-test	**	ns	ns	ns	*	**	ns	**	ns	**	*	ns
I4 × N0	21.3	20.6b	0.86b	2.85	35.3	13.3b	42.4b	96.3	77.7b	109.5	0.45	0.13
I4 × N200	25.8	28.7a	1.71a	2.86	62.2	26.7a	112.4a	125.0	174.6a	151.7	0.37	0.18
I4 × N300	21.6	27.4a	1.80a	2.93	48.9	28.0a	107.5a	122.7	156.4a	150.7	0.31	0.19
F-test	ns	**	*	ns	ns	*	*	ns	**	ns	ns	ns
I8 × N0	–	24.3b	–	2.76	–	10.3	–	61.8	–	72.0	–	0.15
I8 × N200	–	28.7a	–	3.12	–	21.4	–	122.6	–	144.0	–	0.15
I8 × N300	–	28.1a	–	3.24	–	23.5	–	142.0	–	165.6	–	0.14
F-test	–	*	–	ns	–	ns	–	ns	–	ns	–	ns
Grand mean	23.3	25.1	1.42	3.00	49.3	22.7	81.3	125.0	130.6	147.7	0.38	0.15
I × N (*F*-test)	**	ns	*	ns	ns	ns	*	ns	ns	ns	**	ns
CV (%)	11.6	7.5	23.1	9.9	23.9	20.5	26.5	23.2	21.7	22.3	16.6	14.7

ns, not significant at the 0.05 probability level; –, data not measured.
* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
[a] Means within a column followed by the same letter are not significantly different according to the LSD at the 0.05 probability level.

obtained at the plant density of 686 plants per m^2. The results of Zhang et al. (2012) have indicated that an increase of the plant density in a certain range is an effective means to increase the seed yield of winter oilseed rape. Among the yield components, number of siliques per plant had the highest positive correlation with seed yield (r = 0.62, P < 0.01). Gunasekera et al. (2006) indicated that among yield components of some mustard genotypes, pods per plant and seeds per pod are more sensitive to environmental changes and a decrease in seed yield appears to be directly related to a decrease in the number of pods per plant.

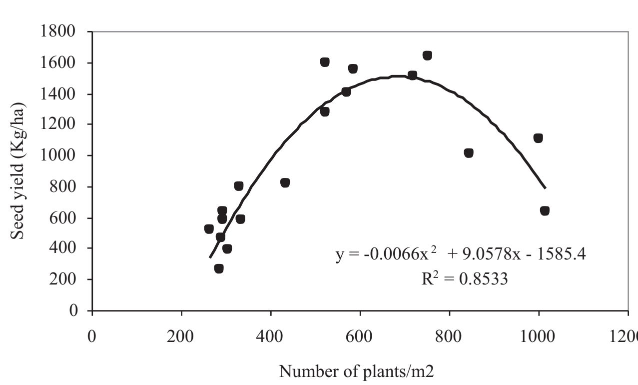

Fig. 2. Relationship between seed yield and plant density.

3.2. Water use and nitrogen utilization efficiencies

There was a significant interaction between irrigation treatments and nitrogen application rates on the average of the seasonal water use in 2010. Only the main effect of irrigation was significant for water use in 2011 (Table 4). In general, water use in 2010 was lower than those recorded in 2011. This is due to shorter growing season in 2010 (Table 4) based on the approximately 62 days delay in the beginning of experiment (irrigation) and the more favorable weather conditions in this year. Plants exposed to cold temperature, especially during the reproductive phase, show reduced growth rates leading to maturity retardations (Lardon and Triboi-Blondel, 1995). In the first growing season, N application (averaged across irrigation regimes) increased water use and the number of days required for *D. sophia* plants to reach maturity by an average of 33.2–59.6 mm and 7–12 days, respectively, compared with the N0. Jackson (2000) indicated that the linear relationship between total plant yield and N reflected the tendency of canola to exhibit an indeterminate growth habit when nutrients and water were essentially unlimited with no heat stress.

The WUE values were significantly different among N treatments. However, the WUE value was not affected by irrigation regimes (Table 4). Improvement in WUE was achieved in plots treated with N fertilizer. Although, an increasing trend was found between N0 and N200, more N did not could influence WUE (Table 4). Comparable results were reported by Al-kaisi and Yin (2003) and Rostamza et al. (2011). Therefore, 200 kg N ha^{-1} can be

Table 6
Main effects and interactions of irrigation regimes (I) and nitrogen application (N) treatments on revenue, total costs, net economic profit and oil concentration in seed of *D. sophia* in 2010 and 2011; summary of *F* significance from analysis of variance for the effects of main factors and interactions.

Treatment	Revenue (US$ ha^{-1})		Total costs (US$ ha^{-1})		Net economic profit (US$ ha^{-1})		Oil concentration (%)	
	2010	2011	2010	2011	2010	2011	2010	2011
I1	2522.8	–	114.5a	–	2408.3	–	35.1	–
I2	2684.9	1469.1	109.8b	141.7a	2575.1	1327.4	33.9	32.4
I4	2621.8	1076.7	104.5c	135.3b	2516.7	941.4	34.8	31.7
I8	–	837.1	–	134.3b	–	702.8	–	30.3
F-test	ns	ns	**	*	ns	ns	ns	ns
N0	1833.8b[a]	832.9b	47.8c	79.1c	1786.1b	753.8b	36.2a[a]	33.4a
N200	2927.8a	1232.2a	121.5b	148.8b	2806.3a	1083.4a	34.2b	31.4b
N300	3067.3a	1317.8a	159.6a	183.4a	2907.8a	1134.4a	33.3b	29.6c
F-test	**	**	**	**	**	**	**	**
I1 × N0	1267.9b	–	50.6c	–	1217.4b	–	35.7	–
I1 × N200	3197.6a	–	128.2b	–	3069.4a	–	35.0	–
I1 × N300	3102.9a	–	164.6a	–	2938.3a	–	34.5	–
F-test	*	–	**	–	*	–	ns	–
I2 × N0	2205.3b	1174.0b	48.2c	83.7c	2157.1b	1090.3b	37.2a	33.8a
I2 × N200	2566.7b	1600.0a	121.4b	153.3b	2445.3ab	1446.7a	32.4b	32.3ab
I2 × N300	3282.8a	1633.3a	159.7a	188.1a	3123.1a	1445.2a	32.0b	30.9b
F-test	*	*	**	**	*	*	**	*
I4 × N0	2028.2	793.3	44.5c	77.5c	1983.8	715.8	35.8	34.1a
I4 × N200	3019.1	1163.3	114.8b	147.1b	2904.3	1016.3	35.1	31.6b
I4 × N300	2816.3	1273.3	154.3a	181.2a	2662.0	1092.1	33.5	29.3c
F-test	ns	ns	**	**	ns	ns	ns	**
I8 × N0	–	531.3	–	76.0c	–	455.3	–	32.2a
I8 × N200	–	933.3	–	146.0b	–	787.3	–	30.1ab
I8 × N300	–	1046.7	–	180.8a	–	865.8	–	28.6b
F-test	–	ns	–	**	–	ns	–	*
Grand mean	2609.6	1127.6	109.6	137.1	2500.1	990.5	34.6	31.4
I × N (*F*-test)	ns	ns	**	ns	ns	ns	**	ns
CV (%)	19.7	18.0	0.7	0.9	20.6	21.8	2.6	2.6

ns, not significant at the 0.05 probability level; –, data not measured.
* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
[a] Means within a column followed by the same letter are not significantly different according to the LSD at the 0.05 probability level.

used as an alternative to 300 kg N ha^{-1} for *D. sophia* production in terms of WUE.

There was a significant interaction between irrigation treatment and N rate for NUzE, and it varied with growing season (Table 4). The I2 × N interaction in 2010, and I4 × N and I8 × N interactions in 2011 were significant. The highest value of NUzE was achieved when no N was applied in all irrigation regimes (Table 4). In coincidence with the findings by Rostamza et al. (2011), NUzE decreased with more N availability. Probably, the inadequate sink capacity developed by the plants of *D. sophia* has to be considered as a limiting factor for NUzE.

3.3. N concentrations and uptakes

There were significant interactions between irrigation and nitrogen treatments over the two years of study on the average protein concentration in seed (Table 5). A significant increase in this trait occurred at higher N applications rate under all four irrigation regimes. Although there were no significant differences between N200 and N300 (Table 5) at any irrigation regime, the highest seed protein concentration was observed at N application rate of 300 kg ha^{-1} for the I2 regime in 2010 and that of 200 kg ha^{-1} for the I4 and I8 treatments in 2011. Furthermore, Sepaskhah and Barzegar (2010) reported similar results to our findings that by increasing N application rates the protein concentration in rice seed was enhanced.

Only the I4 × N interaction was significant for N concentration in straw in 2010 (Table 5). In this irrigation regime, there was a gradual significant increase in straw N concentration by increasing the applied N. This result is in accordance with Sepaskhah and Barzegar (2010) who reported an increase in straw N concentration with increasing N application from 0 to 80 kg N ha^{-1}.

Concentrations of protein and N in seed and straw were significantly greater in 2011 than 2010 (Table 4). More seed and straw yield in 2010 than 2011 probably resulted in less concentrations of protein and N per unit weight in 2010 which can be explained in terms of dilution effect.

No significant water by nitrogen interaction was observed for seed, straw and total N uptakes except for straw N uptake in 2010 (Table 5). N uptakes were improved by applying N fertilizer (Table 5). The N uptakes were not significantly different between the N application rates of 200 and 300 kg ha^{-1}. This non-significant difference might result from the changing ratio of shoot to root and increased N accumulation in the root. Grunes and Krantz (1958) indicated that application of N increased the growth of above-ground biomass at least as much as the growth of oat root. The N accumulation in the root of *D. sophia* was not measured in this study.

Nitrogen harvest index (NHI) represents the crop ability in partitioning the total N uptaken between the different plant organs (Albrizio et al., 2010). An average reduction of NHI was observed significantly in 2011 as a consequence of seed yield loss. Only the interaction between the I2 irrigation treatment and N rate on the NHI was significant in 2010. For this interaction, the NHI increased with increasing N rate, with the highest values of 0.47 and 0.45 through applying 300 and 200 kg N ha^{-1}, respectively (Table 5). These NHI values are lower than the 0.6 value reported by Jackson

(2000) for canola. In the present study, the increase in NHI is mainly because of a more than proportional increase in seed N uptake, which is in agreement with a previous investigation (Jackson, 2000). This shows that, under certain levels of N supply and meteorological conditions, *D. sophia* tended to partition absorbed N to seed, instead of using it to further increase straw; however, most of the plant N remains in the straw.

3.4. Oil concentration

The mean oil concentration ranged from 32.0 to 37.2% in 2010 and 28.6 to 34.1% in 2011 (Table 6). Perhaps, adverse weather conditions in 2011, in particular cold stress after the start of inflorescence emergence, resulted in a decrease in oil concentration. As indicated by Thakur et al. (2010), cold stress is a major cause of reduced crop quality in many temperate and arid zone crops.

In both years, there was a decreasing trend in oil concentration with increasing nitrogen application under all the irrigation treatments (Table 6). This might be due to N delaying plant maturity (Jackson, 2000) or due to relatively high seed yield for the high nitrogen treatments thus causing a dilution effect (Al-Jaloud et al., 1996). On the other hand, the highest plant densities were recorded in the lowest rates of nitrogen supply (Table 3). In the study of Zhang et al. (2012), the seed oil concentration was significantly increased with the increase in plant densities, since the presence of pod-bearing branch numbers having seeds with lower oil concentrations were decreased.

3.5. Economic evaluation

As presented in Table 6, revenue and net economic profit parameters were significantly unaffected by irrigation regimes. N fertilizer had a significant effect on revenue and net economic profit. The interaction of irrigation regimes and nitrogen rates was not significant for revenue and net economic profit. Averaged over both years, the application of 300 kg N ha^{-1} under the I2 irrigation treatment resulted in the highest value of revenue and net economic profit (2458 US$ ha^{-1} and 2284 US$ ha^{-1}, respectively). In contrast, the least revenue and net economic profit were obtained in plots that received no nitrogen (Table 6). Comparable results were reported by Rostamza et al. (2011) for pearl millet (*Pennisetum americanum* L.).

4. Conclusions

Flixweed is considered a potential industrial-medicinal weed. Nitrogen and water are two of the most important factors needed for plant growth and development. In the present study, the effect of nitrogen and water was determined on agronomic traits, water use and nitrogen utilization efficiencies, N concentrations and uptakes and oil concentration of *D. sophia*. In general, for most of the traits studied, response of *D. sophia* was mainly due to nitrogen rate rather than irrigation treatment, possibly because this species is adapted to semi-arid environments. There were significant increases in seed yield, biomass, straw yield, harvest index, number of siliques (pods) per plant, seed weight, plant height, time to maturity, WUE, protein concentration in seed, straw N concentration, N uptakes and NHI by increasing the applied N. The increases in number of siliques per plant and in time to maturity result in higher sink capacity and source potential, thereby leading to higher seed yield. Averaged over both years, the application of 300 kg N ha^{-1} under the I2 irrigation treatment resulted in the highest value of revenue and net economic profit. This study provides new information about the effect of nitrogen and water application on the quantity and quality aspects of *D. sophia*, but more experiments are necessary to fully understand the suitable timing and form of nitrogen application, particularly under water deficit conditions.

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