Growth and nutrient response of flax and durum wheat to phosphorus and zinc fertilizers

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Jiao, Y., Grant, C. A. and Bailey, L. D. 2007. **Growth and nutrient response of flax and durum wheat to phosphorus and zinc fertilizers**. Can. J. Plant Sci. **87**: 461–470. Flax (*Linum usitatissimum* L.) and durum wheat (*Triticum turgidum* L.) are important agricultural crops that enter the human food chain. Effective nutrient management considering nutrient interactions is important in order to increase crop yield and improve crop nutrient concentration. The objective of this study was to investigate the effect of P and Zn fertilizers on the yield and nutritional value of flax and durum wheat. A pot culture experiment conducted in a growth chamber using a calcareous clay-loam soil showed that P fertilizers can restrict flax growth by reducing Zn absorption but can increase the seed yield of both crops by enhanced dry matter translocation to the seed/grain. Among the P sources, commercial monoammonium phosphate (CMAP) and commercial triple superphosphate (CTSP) had similar effects on growth and yield, but different impacts on the nutrient concentrations of both crops, indicating the importance of selecting P source to improve crop quality. Zinc addition with reagent grade P decreased the concentrations of P, K, Ca, Mg and Cu in flax but not in durum wheat. We conclude that proper combination of P and Zn fertilizers is necessary to optimize crop yields, but that P had a proportionally greater effect in promoting yield in durum wheat than in flax. In contrast, Zn had a greater impact on mineral composition in flax than in durum wheat, which can affect the nutritional quality of the crop as a component of the human diet.

Key words: Flax, durum wheat, P and Zn fertilizers, nutrient, essential trace elements

Jiao, Y., Grant, C. A. et Bailey, L. D. 2007. **Croissance et qualité nutritive du lin et du blé dur consécutivement à l'usage d'amendements de phosphore et de zinc**. Can. J. Plant Sci. **87**: 461–470. Le lin (*Linum usitatissimum* L.) et le blé dur (*Triticum turgidum* L.) sont d'importantes cultures destinées à la chaîne alimentaire humaine. Il est capital de bien gérer les nutriments sans perdre de vue leurs interactions si l'on veut accroître le rendement de la culture et sa concentration d'éléments nutritifs. L'étude devait préciser l'incidence des engrais P et Zn sur le rendement et la valeur nutritive du lin et du blé dur. La culture en pot sur un loam argileux dans un phytotron révèle que les engrais P ralentissent la croissance à cause de l'effet antagoniste du Zn mais augmentent le rendement grainier dans les deux cas grâce à une meilleure translocation de la matière sèche vers la semence ou le grain. Parmi les sources de P, le phosphate d'ammonium diacide et le superphosphate triple vendus dans le commerce ont une incidence analogue sur la croissance et le rendement, mais leur impact sur la concentration d'éléments nutritifs diffère chez les deux plantes, signe qu'il est important de bien choisir la source de P pour améliorer la qualité de la culture. L'addition de Zn à du P de qualité réactif diminue la concentration de P, K, Ca, Mg et Cu dans le lin mais pas dans le blé dur. Les auteurs en concluent qu'une combinaison adéquate des engrais P et Zn est essentielle à l'optimisation du rendement, mais que le P est proportionnellement plus efficace sur le rendement du blé dur que sur celui du lin. En revanche, le Zn agit davantage sur la composition minérale du lin que sur celle du blé, ce qui peut avoir des répercussions sur la qualité nutritive de la culture quand elle est destinée à l'alimentation humaine.

Mots clés: Lin, blé dur, engrais P et Zn, éléments nutritifs, oligoéléments essentiels

Flaxseed and durum wheat are both crops that can enter the human food chain. Flaxseed, while historically used for production of industrial oil, has emerged in recent years as an important functional food. Flaxseed contains high levels of dietary fiber, alpha-linolenic acid (an essential omega-3 fatty acid) and lignans (antioxidants), which may all promote health, prevent disease and reduce cancer risk (Hasler 2001; Vaisey-Genser and Morris 2003). Incorporation of small amounts of flax into the human diet may therefore have health benefits. Durum wheat grain is rich in gluten and is used for the production of semolina – a relatively coarse granular product used in the production of pasta and couscous (Matsuo 1993), which are food staples in many countries. Canada is the leading exporter of both flaxseed and durum wheat, with annual exports averaging 580 000 t for flaxseed and 3.45 million t for durum wheat from 1992 to 2002 (Canada Grains Council 2002).

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Abbreviations: **CMAP**, commercial monoammonium phosphate; **CTSP**, commercial triple superphosphate; **RMAP**, reagent monoammonium phosphate; **RTSP**, reagent triple superphosphate

Phosphorus and Zn are essential nutrients for crop production due to their ubiquitous physiological functions. Phosphorus is a structural component of nucleic acids and plays a crucial role in reproductive growth. Zinc is a metal component in protein synthesis (Foy et al. 1981) and a constituent of auxins which regulate crop growth (Bennett 1993).

Levels of P are often marginal to deficient for optimal crop production on many agricultural soils. Also, P application may induce crop Zn deficiency even in the soils not at Zn deficient levels (> 0.5 mg DTPA-Zn kg^{-1} soil). Therefore, application of P with Zn fertilizers is often required to meet the P and Zn requirements of crops. In a growth chamber study, Spratt and Smid (1978) found that dry matter yields of flax shoot were not increased significantly by residual soil P between 6.7 to 43.4 mg P kg^{-1} soil ($NaHCO_3$ extractable). However, shoot Zn concentration was markedly decreased from 33 to 17 mg kg^{-1} DW and Cu from 4.5 to 2.5 mg kg^{-1} DW. Grant and Bailey (1989) reported P application (mixed with soil) did not increase dry matter yield, but increased Mg and decreased Zn concentration in flax shoots. Addition of Zn did not increase yield, but decreased shoot P concentration in a growth chamber study with a calcareous soil.

Durum wheat may differ from flax in the response to nutrient applications. Grant and Bailey (1998) reported that P application increased grain yield, while Zn addition had little effect on the yield of durum wheat during a 3-yr field experiment. In another 3-yr field study, Grant et al. (2002) found application of P as monoammonium phosphate decreased grain Zn concentration of durum wheat. Although wheat was classified as Zn efficient and had a low response to Zn application in a study that included 30 crop species (Robertson and Lucas 1976), different wheat cultivars may differ markedly in exploiting soil Zn (Mengel and Kirby 2001). In a field experiment, Cakmak et al. (1997) found that durum wheat had lower capacity to access Zn from soil and was more sensitive to Zn deficiency as compared with bread wheat.

Many previous studies have focused on the crop yield and the concentrations of P and Zn in crops as influenced by fertilizers, but few studies have evaluated the interactive effects of P and Zn fertilizers on crop quality factors such as seed/grain content of N and essential trace elements. In the developing countries, many people suffer from micronutrient malnutrition due to high intakes of high carbohydrate staple foods, but low consumption of nutrient-dense animal products, fruits and vegetables. Thus, an international effort is underway to develop staple food crops with high concentrations of bioavailable micronutrients (Bouis 2003). Fertilizer management may be a cost-effective way to attain this goal, since proper fertilizer management can optimize both crop yield and crop nutrient content. Information is needed to determine how fertilizers will influence both the yield and the nutrient concentration of crops that enter the food chain.

Monoammonium phosphate is the preferred P source in the Canadian prairies, as the NH_4^+ may improve P absorption by crops (Follett et al. 1981), while triple superphosphate is a common P fertilizer in many regions of the world. The acidifying tendency of these fertilizers may influence availability of both the P applied and other nutrients, such as Zn, present in the soil. Commercial P fertilizers normally contain Zn, which may also influence uptake of Zn and other nutrients by the crops. The effect may differ between flax and durum wheat, as these crops differ in their rooting patterns, formation of mycorrhizal associations, and methods of mobilization of soil nutrients (Mengel and Kirby 2001; Sylvia et al. 2005).

Therefore, a growth chamber study was conducted to explore the interactive effects of P and Zn fertilizers on nutrient composition of durum wheat and flax. It may provide useful information on fertilizer management for field crop production to optimize both seed/grain yield and nutritional value.

MATERIALS AND METHODS

Soil

The soil, fertilizer treatments and pot culture have been described in a previous publication (Jiao et al. 2004). Briefly, the soil had a pH of 7.85 and electrical conductivity of 355.5 µS cm^{-1} (measured on a soil/deionized water ratio of 1:2 wt/wt), contained sodium bicarbonate extractable N of 8.63 mg kg^{-1} and P of 11.40 mg kg^{-1}, DTPA extractable Cu of 1.35 mg kg^{-1} and Zn of 0.97 mg kg^{-1}, determined according to the soil sampling and methods of analysis described in Carter (1993).

Fertilizer Treatments

There were 13 fertilizer treatments as listed in Table 1. Reagent ammonium sulphate was used to balance the S applied with the reagent grade zinc sulphate ($ZnSO_4 \cdot 7H_2O$) to bring the total S applied in each of the 13 treatments to 10 mg S kg^{-1} soil. Commercial grade ammonium nitrate was used to balance the N applied with the monoammonium phosphate and ammonium sulphate and to bring the total N applied in each of the 13 treatments to 150 mg N kg^{-1} soil. Two kg of soil was placed in 3.5-L plastic pots with no drainage holes. Phosphorus was placed in solid form while the other fertilizers were dissolved in distilled-deionized water and applied in solution form. After watering to field capacity, determined with the cylinder method (Klute 1986) using deionized water, pots were placed in a growth chamber for a 14-d incubation period at 22°C.

Pot Culture

Twelve seeds of flax (cv. Norlin) or ten seeds of durum wheat (cv. AC Melita) were seeded in a pot and the soil was watered to field capacity. The growth chamber was maintained at a 16 h light/8 h dark photoperiod with temperature at 22°C day/15°C night. The soils were watered to field capacity with deionized water when the moisture content decreased to around 70% of field capacity by weight. All the pots were weighed, watered to the weight of field capacity and rerandomized every week. Seedlings were thinned to six per pot for flax and five per pot for durum wheat. An additional 50 mg N kg^{-1} soil as commercial grade ammonium

Table 1. Fertilizer treatments in the pot experiment conducted in a growth chamber

Treatment	Fertilizer rate P (mg kg^{-1} soil)	Fertilizer rate Zn (mg kg^{-1} soil)	Content
1. Control (no P)	0	0	Control
2. RMAP	100	0	Reagent monoammonium phosphate (containing no Zn)
3. RMAP + Zn1	100	10	Reagent monoammonium phosphate + reagent zinc sulfate
4. RMAP + Zn2	100	20	Reagent monoammonium phosphate + reagent zinc sulfate
5. CMAP	100	0	Commercial monoammonium phosphate (containing 3.1 g Zn kg^{-1})
6. CMAP + Zn1	100	10	Commercial monoammonium phosphate + reagent zinc sulfate
7. CMAP + Zn2	100	20	Commercial monoammonium phosphate + reagent zinc sulfate
8. RTSP	100	0	Reagent triple superphosphate (containing no Zn)
9. RTSP + Zn1	100	10	Reagent triple superphosphate + reagent zinc sulfate
10. RTSP + Zn2	100	20	Reagent triple superphosphate + reagent zinc sulfate
11. CTSP	100	0	Commercial triple superphosphate (containing 1.8 g Zn kg^{-1})
12. CTSP + Zn1	100	10	Commercial triple superphosphate + reagent zinc sulfate
13. CTSP + Zn2	100	20	Commercial triple superphosphate + reagent zinc sulfate

nitrate was dissolved and watered into the soil surface of each pot after 3 wk of growth, to avoid N defiiciency. The aboveground portion of the plants in one block of each crop was harvested at the flowering (flax) or heading (durum wheat) stage. At maturity, the aboveground portion of the plants in the remaining blocks was harvested and separated into straw and grain. In all treatments except 3, 6, 9 and 12 (Table 1), the roots were separated from the soil by washing under tap water and rinsing with deionized water. Plant materials, including roots, were dried at 65°C until they reached a constant weight (around 24 h), then weighed and ground (except flaxseed which was left unground).

Laboratory Analysis

A 0.250-g sample of durum wheat flour was digested with sulphuric acid (Westman 1990) and N concentration in the digest was determined on an autoanalyzer. A 1-g sample of plant material was digested with $HNO_3/HClO_4$ (Westman 1990) and the concentrations of P, K, Ca, Mg, S, Fe, Mn, Cu and Zn in the digest were determined on an ARL 3520 (Chermside, Queensland, Australia) inductively coupled plasma (ICP). To check the reproducibility of the analytical procedure, one blank and two standard samples of durum wheat flour were included in every batch of 40 samples.

Experimental Design and Statistical Analysis

In the growth chamber, flax and durum wheat each shared half of the area. Each crop was repeated in two blocks for two harvests and in each block, three independent replicates of each fertilizer treatment were arranged in a completely randomized design. This provided 2 crops × 2 harvest dates × 13 treatments × 3 replicates for a total of 156 pots in the trial. Excluding the control, the 12 remaining treatments comprised a factorial design, which included four P sources (RAMP, CMAP, RTSP and CTSP) and three Zn levels (Zn0, Zn1 and Zn2), as indicated in Table 1.

Statistical analysis was conducted using the GLM procedure (SAS for Windows, Version 8.2). Contrast analysis was performed between the control and P application without Zn addition. A factorial analysis was performed on the combination treatments of P and Zn fertilizers. If the interaction of P × Zn was significant, the effect of Zn levels at each P source was separated. Differences in both contrast and factorial analyses were considered significant at $P < 0.05$.

RESULTS AND DISCUSSION

Growth of Flax and Durum Wheat as Affected by P and Zn Fertilizers

Flax seedlings demonstrated visual responses to fertilizer treatments at 22 d after sowing. The flax seedlings grew best when both P and Zn fertilizers were applied, ranking in the order of Zn2 > Zn1 > Control > Zn0 for all P sources and replicates (Fig. 1a). The P fertilizers apparently induced plant Zn deficiency, as indicated by the appearance of yellow spots in the bottom leaves. Approximately two to six leaves in100% of the flax plants grown with reagent grade P fertilizers, in 35% of the flax plants grown with CMAP and in 30% of the flax plants grown with CTSP showed yellow spots, in the absence of Zn addition. These visual symptoms were eliminated when Zn was applied with the P fertilizers (Fig. 1b), indicating that the yellow spots were caused by Zn deficiency. The commercial P fertilizers (CMAP and CTSP) alleviated the severity of Zn deficiency as compared with reagent grade fertilizer, probably due to the content of Zn in the commercial fertilizers (Table 1).

The aboveground biomass of flax at flowering (shoot) was reduced by P fertilizers as compared with the no-P control ($P = 0.0217$) (Table 2). However, P application apparently increased conversion of biomass to seed since the seed yield and the ratio of seed to straw + root were greater with P addition than in the no-P control (Table 2). There was no difference in the growth and yield of flax among P sources. Flax shoot biomass at flowering was significantly increased when Zn fertilizer was added. Flax height at flowering was in the order Zn2 > Zn1 > Control > Zn0 (Fig. 1c) for all the P sources, and the same trend was observed at maturity (plant height averaged 80 cm with Zn2, 77 cm with Zn1 and 73 cm with Zn0). Zinc addition increased the flax height and caused the flax to mature 3- to 5-d earlier, as illustrated by the yellow coloration in the lower part of flax plants (Fig. 1c). Apparently, Zn addition enhanced the growth of flax

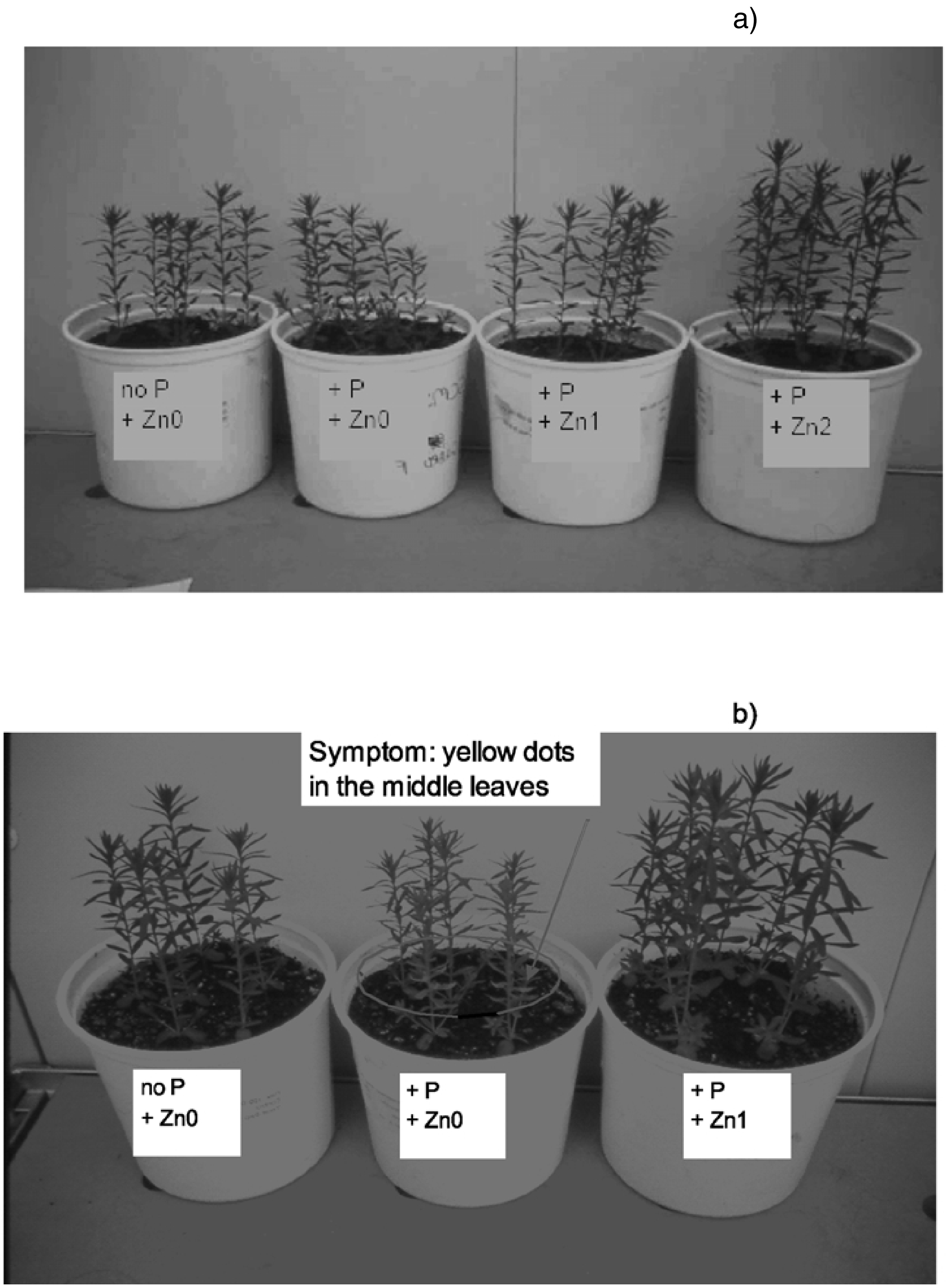

Fig. 1. Flax growth as affected by P and Zn fertilizers: (a) flax growth was better in the soil of the control (no P + Zn0) than in the treatment receiving only P application (+P +Zn0); (b) the symptom of Zn deficiency caused by P fertilizers; (c) early maturity with Zn2 addition. Note: All the P sources showed the same trend as illustrated.

c)

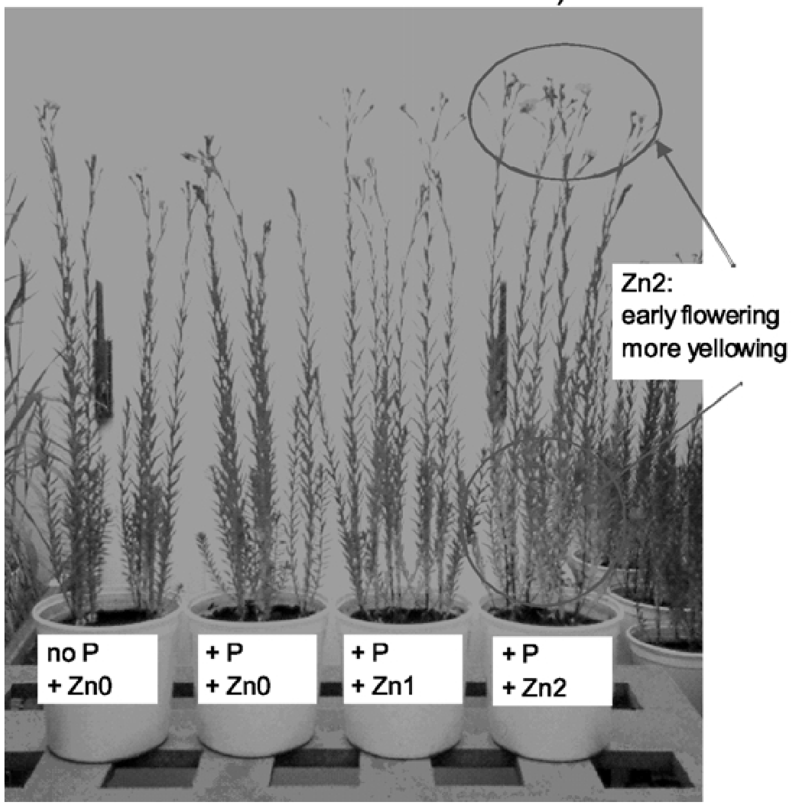

Fig. 1. *Continued.*

and increased the seed yield (Table 2). A similar result was reported by Moraghan (1993), who found that application of Zn at 8 mg kg^{-1} soil advanced the appearance of mature bolls by 15 d and increased the yield of flaxseed by 33% in a greenhouse study with a calcareous soil.

In contrast to the response of flax, P fertilizers improved seedling growth and increased shoot biomass at heading in durum wheat as compared with the no-P control (P = 0.0009) (Table 2). However, both crops showed an increase of seed or grain yield with P application (Table 2). There was no difference in the shoot biomass of durum wheat among the four P sources, but RMAP produced lower final grain yield than the other three P sources. Zinc addition increased shoot biomass, grain yield and the ratio of grain to straw + root (Table 2). It was observed that Zn addition enhanced tillering but decreased plant height, averaging 84 cm with Zn0, 80 cm with Zn1 and 76 cm with Zn2 at final harvest. Compared with the control, the combination of P and Zn fertilizers produced grain that was less amber in colour and less transparent, indicating the lower protein content in the durum grain.

Nutrient Composition of Flax and Durum Wheat as Affected by P and Zn Fertilizers

N, P and K

Total N concentration in the grain of durum wheat was less with P application compared with the no-P control (Control vs. P + no Zn: $P < 0.0001$) (Table 2), and was less with Zn addition (Zn1 or Zn2) than P application only (Zn0), except CMAP (Fig. 2a). Grain N concentration reflects the protein content, since it is the most important constituent of protein and various amino acids. Thus, P and Zn fertilizers may increase durum wheat yield, but may negatively affect grain quality by decreasing grain N concentration and lower the market value through dilution/concentration effects if N supply becomes limiting. For example, class-1 durum wheat must meet a minimum protein content of 9.5% (Canadian Grain Commission 2006). The protein content in the current study, calculated as protein = 5.7 × N%, was 10.7% in the grain of durum wheat from the no-P control, but was reduced to 9.1% with P application, averaged across the four P sources (Table 2). Apparently, in this study, N fertility was not sufficient to optimize protein quality for durum wheat. Researchers have shown that N fertilizers can increase grain N concentration and grain protein content (Abad et al. 2004). Thus, N application rate should be increased when yield potential is increased by P and Zn fertilizers in durum wheat production in order to maintain the protein content and the food quality.

The concentration of P in flax shoot and seed was significantly greater with P fertilizers than in the no-P control (Table 3). Among P sources, commercial phosphates produced significantly lower P concentrations in the shoot and seed of flax than reagent phosphates, suggesting that Zn in

Table 2. Flax and durum wheat yield and total N concentration in durum wheat grain as affected by P and Zn fertilizers

		Flax			Durum wheat			
Fertilizer	*n*	Shoot (g pot^{-1})	Seed (g pot^{-1})	Seed/(straw+root)[z]	Shoot (g pot^{-1})	Grain (g pot^{-1})	Grain/(straw+root)[y]	Grain N (g kg^{-1})
Control (no P)	3	8.01	4.82	0.41	15.7	10.7	0.55	18.7
P source								
RMAP	9	8.10*a*[x]	5.53*a*	0.47*b*	20.5*a*	15.4*b*	0.59*b*	15.3*a*
CMAP	9	7.89*a*	5.76*a*	0.51*a*	19.6*a*	16.2*a*	0.66*a*	15.4*a*
RTSP	9	7.97*a*	5.56*a*	0.50*a*	19.7*a*	16.6*a*	0.65*a*	15.2*a*
CTSP	9	7.76*a*	5.72*a*	0.50*a*	19.5*a*	16.1*a*	0.70*a*	15.0*a*
Zn level								
Zn0	12	7.19*b*[w]	5.41*b*	0.50*a*	18.7*b*	14.7*b*	0.61*b*	16.0*a*
Zn1	12	8.47*a*	5.71*a*	ND[v]	20.7*a*	16.9*a*	ND	15.0*b*
Zn2	12	8.13*a*	5.81*a*	0.49*a*	20.1*a*	16.6*a*	0.69*a*	14.7*b*
Analysis of variance	*df*			*Pr > F*				
Control vs P+no Zn (Zn0)	1	0.0217	0.0036	<.0001	0.0009	<.0001	NS	<.0001
P source	3	NS[u]	NS	0.0308	NS	0.0173	0.0077	NS
Zn level	2	<.0001	0.0061	NS	0.0020	<.0001	0.0014	0.0001
P× Zn	6	NS	NS	NS	NS	NS	NS	0.0045

[z]Calculated as: seed yield/(straw yield + root yield), at maturity.
[y]Calculated as: grain yield/(straw yield + root yield), at maturity.
[x]Values within a column followed by same letters were not significantly ($P > 0.05$) affected by P sources.
[w]Values within a column followed by same letters were not significantly ($P > 0.05$) affected by Zn levels.
[v]ND, not determined because of labour involved.
[u]NS, not significant ($P > 0.05$).

Table 3. P and K concentrations (g kg^{-1}) in flax and durum wheat as affected by P and Zn fertilizers

		Flax				Durum wheat[z]		
		Shoot		Seed		Shoot	Grain	
Fertilizer	*n*	P	K	P	K	P	P	K
Control (no P)	3	1.65	20.3	2.97	6.11	0.99	1.60	3.51
P source								
RMAP	9	3.93*a*[y]	18.8*ab*	5.20*a*	7.95*a*	2.43*a*	3.32*a*	4.51*ab*
CMAP	9	3.47*b*	19.6*a*	4.92*b*	7.74*b*	2.20*b*	3.19*b*	4.37*b*
RTSP	9	4.02*a*	18.4*b*	5.33*a*	7.86*ab*	2.46*a*	3.37*a*	4.47*ab*
CTSP	9	3.55*b*	19.1*ab*	5.04*b*	7.38*c*	1.97*c*	3.02*c*	4.59*a*
Zn level								
Zn0	12	5.16*a*[x]	19.8*a*	5.78*a*	8.40*a*	2.21*a*	3.31*a*	4.45*a*
Zn1	12	3.10*b*	18.5*b*	4.90*b*	7.53*b*	2.32*a*	3.16*b*	4.47*a*
Zn2	12	2.96*b*	18.6*b*	4.68*c*	7.26*c*	2.26*a*	3.20*b*	4.54*a*
Analysis of variance	*df*			*Pr > F*				
Control vs P+no Zn (Zn0)	1	<.0001	NS[w]	<.0001	<.0001	<.0001	<.0001	<.0001
P source	3	0.0047	NS	<.0001	<.0001	<.0001	<.0001	0.0393
Zn level	2	<.0001	0.00522	<.0001	<.0001	NS	0.0117	NS
P× Zn	6	0.0172	NS	NS	0.0298	NS	0.0255	NS

[z]There was no difference ($P > 0.05$) in the shoot K concentration among P sources or Zn levels (mean value: 18.2 g K kg^{-1}).
[y]Values within a column followed by same letters were not significantly ($P > 0.05$) affected by P sources.
[x]Values within a column followed by same letters were not significantly ($P > 0.05$) affected by Zn levels.
[w]NS, not significant ($P > 0.05$).

the commercial P fertilizers may have an antagonistic effect on P uptake by flax and P translocation to the flaxseed. The antagonistic effect was clearly demonstrated by the lower P concentration in flaxseed when Zn was applied (Table 3). The P concentration in durum wheat was only about half of that in flax, but response of P concentration in grain to P and Zn fertilizers was similar in durum wheat to the response of flax. However, a strong P × Zn interaction occurred in durum grain (Fig. 2c), but not in flax seed.

There was no difference in K concentration in flax shoots due to P application, but K concentration in flaxseed was significantly greater with P fertilizers than no-P control (Table 3), indicating that the higher P concentration in flax shoot increased K translocation to the seed. Flaxseed K concentrations were lower with CMAP than RMAP, lower with CTSP than RTSP, and lower with Zn addition than P application only (Table 3, Fig. 2b). For durum wheat, grain K concentration was increased by P fertilizers. A similar result

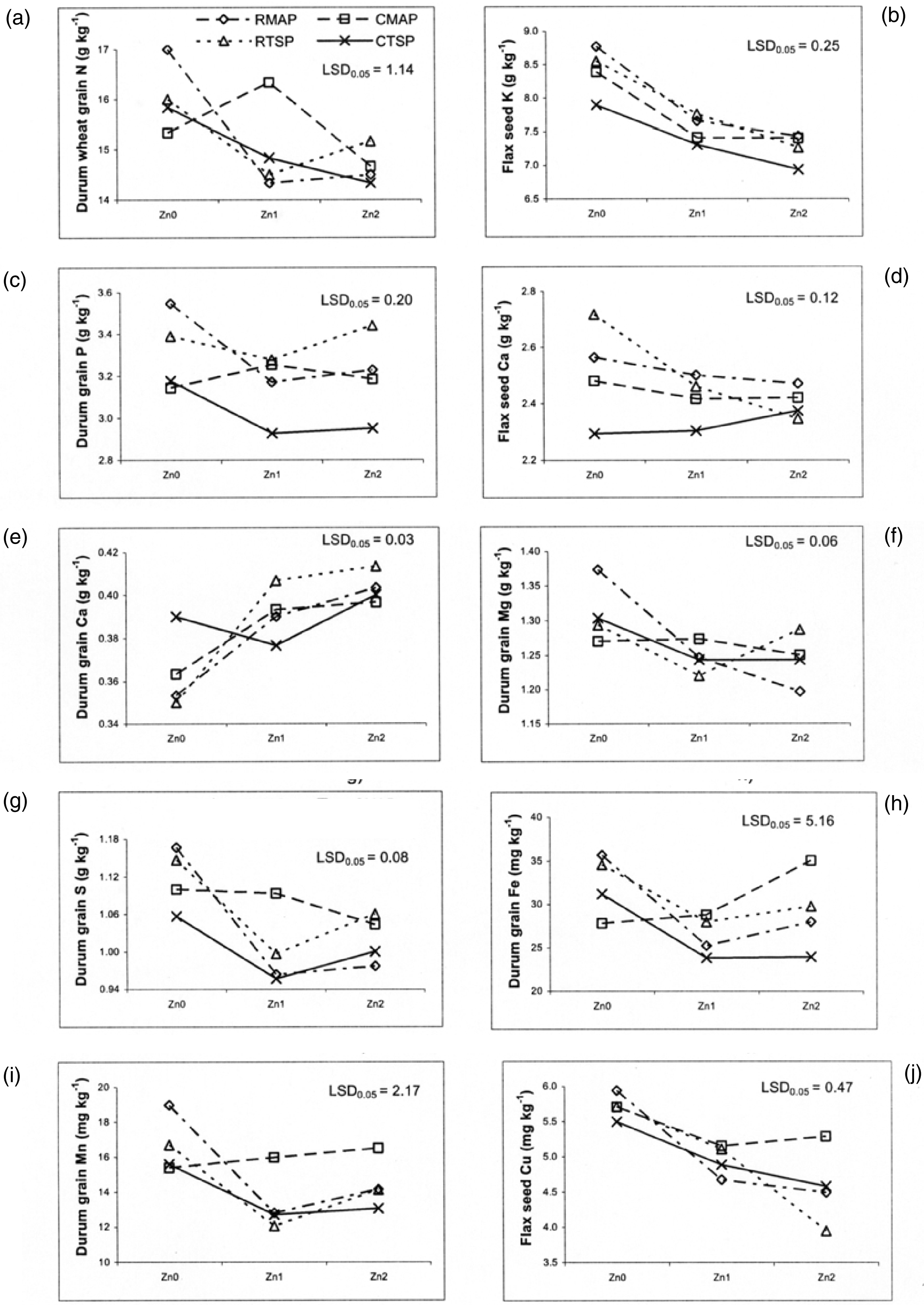

Fig. 2. Interactive effect of P and Zn fertilizers on nutrient concentrations in flaxseed or durum grain. Note: This graph shows the seed/grain nutrient concentrations across Zn levels at each P source when the P × Zn interaction was significant in Tables 2–5.

Table 4. Ca, Mg and S concentrations (g kg^{-1}) in flax and durum wheat as affected by P and Zn fertilizers

		Flax						Durum wheat[z]		
		Shoot			Seed			Grain		
Fertilizer	*n*	Ca	Mg	S	Ca	Mg	S	Ca	Mg	S
Control (no P)	3	15.3	3.09	2.66	2.02	2.95	1.98	0.46	0.98	1.33
P source										
RMAP	9	15.3*a*[y]	3.25*a*	2.39*c*	2.51*a*	3.63*a*	1.89*c*	0.38*a*	1.27*a*	1.04*ab*
CMAP	9	15.6*a*	3.30*a*	2.62*ab*	2.44*b*	3.56*bc*	1.98*b*	0.39*a*	1.26*a*	1.08*a*
RTSP	9	15.6*a*	3.28*a*	2.49*bc*	2.51*a*	3.58*ab*	1.92*c*	0.39*a*	1.27*a*	1.07*a*
CTSP	9	16.1*a*	3.23*a*	2.65*a*	2.32*c*	3.51*c*	2.04*a*	0.39*a*	1.26*a*	1.00*b*
Zn level										
Zn0	12	17.0*a*[x]	3.78*a*	2.53*ab*	2.51*a*	3.77*a*	1.95*a*	0.37*b*	1.31*a*	1.12*a*
Zn1	12	14.5*b*	3.00*b*	2.46*b*	2.42*b*	3.52*b*	1.95*a*	0.39*a*	1.24*b*	1.00*b*
Zn2	12	15.4*b*	3.02*b*	2.62*a*	2.40*b*	3.42*c*	1.97*a*	0.40*a*	1.25*b*	1.02*b*
Analysis of variance	*df*					*Pr > F*				
Control vs P+no Zn (Zn0)	1	0.0416	<.0001	NS	<.0001	<.0001	NS	<.0001	<.0001	<.0001
P source	3	NS[u]	NS	0.0089	<.0001	0.0081	<.0001	NS	NS	0.0150
Zn level	2	0.0003	<.0001	NS	0.0013	<.0001	NS	<.0001	<.0001	<.0001
P× Zn	6	NS	NS	NS	0.0009	NS	NS	0.0219	0.0021	0.0319

[z]There was no difference ($P > 0.05$) in the Ca, Mg and S concentrations in the durum shoot among P ssources, or Zn levels (mean values: 4.96 g Ca kg^{-1}, 1.66 g Mg kg^{-1} and 1.46 g S kg^{-1}). Shoot Mg was significantly different ($P = 0.0015$) in Control vs. P+no Zn (Zn0): 1.22 vs. 1.61 g Mg kg^{-1}.
[y]Values within a column followed by same letters were not significantly ($P > 0.05$) affected by P sources.
[x]Values within a column followed by same letters were not significantly ($P > 0.05$) affected by Zn levels.
[w]NS, not significant ($P > 0.05$).

was reported by Ryan et al. (2004), who observed that grain K was significantly greater with soluble P fertilizer (3.7 g K kg^{-1}) than in the unfertilized soils (3.5 g K kg $^{-1}$). In contrast to flax, durum wheat showed no response on K uptake to the Zn fertilizer and no P × Zn interaction for K uptake. Also, grain K concentration of durum wheat was only about half of that in flaxseed for all the combinations of P and Zn fertilizers.

Ca, Mg and S

Phosphorus fertilizers increased the concentration of Ca in the shoot and seed of flax (Table 4). The CMAP produced lower Ca concentration in flaxseed than RMAP across the Zn levels (Fig. 2d) and Zn addition reduced Ca concentration in flaxseed except with CTSP (Fig. 2d). In contrast, there was no effect of P and Zn fertilizers on Ca concentration in durum wheat shoot (Table 4, footnote z), but durum wheat grain concentration of Ca concentration was lower with P application as compared with the control and higher with Zn addition than where no Zn was applied (Table 4), except when CTSP was the source (Fig. 2e).

Phosphorus fertilizers enhanced Mg concentration in the shoot and seed or grain of both crops (Table 4). This result supported the assumption of Grant and Bailey (1993) who reported that the increase of Mg concentration in flax tissue by banded P application was presumably due to an effect on the absorption-translocation system within the plant. The CMAP and CTSP produced lower Mg concentration in the flaxseed than RMAP and RTSP, respectively. Zn addition consistently reduced Mg concentration in flaxseed with all the P sources (Table 4). These results suggest that Zn present in commercial P fertilizers can reduce Mg uptake by flax. No clear trend was observed for durum wheat since a strong interaction exists between P sources and Zn levels (Fig. 2f).

Phosphorus fertilizers had no effect on the concentrations of S in the shoot and seed of flax compared with the no-P control (Table 4). However, there were differences in P sources for both shoot and seed S in flax. Commercial P fertilizers produced higher S concentrations in flax than their reagent-grade counterparts (Table 4). Zinc addition had no effect on the S concentration in flaxseed. However, both P and Zn fertilizers decreased S concentrations in durum grain, probably due to a dilution effect (Table 4; Fig. 2g). A similar result was reported by Ryan et al. (2004) who found that superphosphate produced lower grain S (1.3 g S kg^{-1}) than the unfertilized soil (1.5 g S kg^{-1}). Since S is an important component of proteins, the decrease of S concentration may affect the nutritional quality of durum wheat.

Flax has a considerably higher concentration of Ca, Mg and S than durum wheat, with the Ca concentration in flaxseed being about six times of durum wheat grain (Table 4). The greater concentration in flax confirmed the general concept that Ca concentration in dicotyledonous species is greater than in monocotyledonous species. Additionally, it was reported that the proportion of soluble Ca in flaxseed is high (Muir and Westcott 2003).

Fe, Mn and Cu

Iron concentration in flax was not influenced by P application and there was no difference among P sources (Table 5). Also, Fe concentration in flax seed showed no difference among Zn levels. However, for durum wheat, grain Fe concentration was greater with P application than in the no-P control. A similar result was reported by Ryan et al. (2004), who observed that grain Fe concentration was increased to 28 mg Fe kg^{-1} in the superphosphate fertilized soil compared with the unfertilized soil (23 mg Fe kg^{-1}). The CTSP produced lower grain Fe concentration than RTSP (Table 5), and Zn addition with CTSP decreased grain Fe concentra-

Table 5. Fe, Mn and Cu concentrations (mg kg^{-1}) in flax and durum wheat as affected by P and Zn fertilizers

		Flax				Durum wheat[y]				
		Shoot		Seed		Shoot		Grain		
Fertilizer	*n*	Fe	Cu	Mn	Cu	Mn	Cu	Fe	Mn	Cu
Control (no P)	3	64.6	5.79	14.2	8.78	30.6	5.21	27.4	16.3	4.10
P source										
RMAP	9	53.7*a*[x]	4.05*b*	15.7*b*	5.03*b*	20.6*a*	3.57*a*	29.6*a*	15.3*ab*	2.40*b*
CMAP	9	54.4*a*	4.26*ab*	16.2*b*	5.38*a*	21.4*a*	3.55*a*	30.6*a*	16.0*a*	2.73*a*
RTSP	9	55.3*a*	4.08*b*	16.1*b*	4.92*b*	19.9*a*	3.56*a*	30.8*a*	14.3*bc*	2.69*a*
CTSP	9	56.2*a*	4.48*a*	16.8*a*	4.99*b*	21.1*a*	3.15*b*	26.3*b*	13.8*c*	2.01*c*
Zn level										
Zn0	12	61.1*a*[w]	4.57*a*	15.8*b*	5.71*a*	23.5*a*	3.43*ab*	32.3*a*	16.7*a*	2.57*a*
Zn1	12	50.8*b*	4.10*b*	16.5*a*	4.96*b*	19.6*b*	3.63*a*	26.5*c*	13.4*b*	2.31*b*
Zn2	12	52.8*b*	3.99*b*	16.3*ab*	4.58*c*	19.1*b*	3.31*b*	29.2*b*	14.5*b*	2.51*ab*
Analysis of variance	*df*					*Pr > F*				
Control vs P+no Zn (Zn0)	1	NS[v]	<.0001	0.0009	<.0001	<.0001	<.0001	0.0196	NS	<.0001
P source	3	NS	0.0321	0.0144	0.0040	NS	NS	0.0242	0.0088	<.0001
Zn level	2	<.0001	0.0004	0.0401	<.0001	<.0001	NS	0.0007	<.0001	NS
P× Zn	6	NS	NS	NS	0.0097	0.0289	0.0223	0.0075	0.0049	NS

[z]There was no difference ($P > 0.05$) in the shoot Mn and seed Fe concentrations among P sources or Zn levels (mean values: 98.6 g Mn kg^{-1} and 37.0 g Fe kg^{-1}.

[y]There was no difference ($P > 0.05$) in the shoot Fe concentration among P sources or Zn levels (mean value: 48.3 g Fe kg^{-1}).

[x]Values within a column followed by same letters were not significantly ($P > 0.05$) affected by P sources.

[w]Values within a column followed by same letters were not significantly ($P > 0.05$) affected by Zn levels.

[v]NS, not significant ($P > 0.05$).

tion (Fig. 2h). These results suggest that Zn present in the CTSP had a negative effect on Fe translocation to the durum grain although there was no effect on Fe uptake, as indicated by the similar shoot Fe concentration with P and Zn applications (Table 5).

Manganese concentration in flaxseed was greater with P application than in the no-P control. Among the P sources, CTSP produced higher seed Mn concentration than CMAP. Zinc addition generally enhanced Mn translocation to the seed since Zn addition produced higher Mn concentration in the flaxseed, but did not affect the shoot concentration (Table 5). In contrast, Mn concentration in durum grain was similar with P application to that in the no-P control. CTSP produced lower grain Mn concentration than CMAP, and Zn addition decreased the grain Mn concentration except when applied with CMAP (Fig. 2 i).

Copper concentration in flax was decreased when P fertilizers were applied (Table 5) and was further decreased when Zn fertilizer was added except with CMAP (Fig. 2j). A similar but less pronounced effect was obtained by P and Zn fertilizers on durum wheat. The results agree with numerous research reports summarized by Malhi and Karamanos (2006).

The well-controlled growth chamber study revealed the qualitative effects of P and Zn fertilizers on nutrient concentrations, i.e., no effect, increase or decrease on individual nutrients. For example, P application increased Fe content in durum grain to 32.3 mg Fe kg^{-1}, but Zn addition decreased the Fe content to 27.8 mg Fe kg^{-1}, similar to the no-P control. Therefore, if grain Fe concentration was below desirable levels, applying P fertilizers may be a possible way to increase the concentration. On the other hand, where Fe concentrations in food are marginal and Zn fertilizers are needed for optimal yield, it may be desirable to supply Fe with the Zn fertilizers to maintain or increase the Fe content of the crop. The results may serve as a guide for fertilizer management to enhance the nutritional value of these crops for the human diet. However, it is important to recognize that the results of pot studies cannot be applied directly to a field situation, since the magnitude of changes are likely to differ between field and pot culture.

CONCLUSION

Flax and durum wheat differed from one another in their growth response to both P and Zn fertilizers. Application of P fertilizers negatively affected flax growth by inducing Zn deficiency as compared with the no-P control, while Zn addition improved flax growth and increased seed yield. In contrast, P fertilizers enhanced the early growth of durum wheat. Zinc addition improving tillering and increased grain yield of durum wheat, but led to a reduction in durum wheat protein probably due to biological dilution when yield increased. It is important to ensure that N availability is optimized when crop yield potential increases. Generally, Zn fertilizer seems relatively more beneficial to flax than to durum wheat, while P fertilizers were relatively more beneficial to durum wheat than to flax.

There were significant impacts of P and Zn fertilizers on the nutrient composition of flax and durum wheat. Phosphorus fertilizers enhanced Fe but reduced Ca and S translocation to the grain in durum wheat although it increased K translocation to the seed or grain for both crops. Among the P sources, monoammonium phosphate and triple superphosphate had similar effects on nutrient composition. The reagent phosphates and commercial phosphates showed numerous different influences on the nutrient composition of flax, but seldom on durum wheat, indicating that flax is more sensitive than durum wheat to other materials, such as Zn, in the commercial fertilizers. Zinc addition significantly decreased the concentrations of P, K, Ca (except with CTSP), Mg and Cu in the flaxseed. However, in durum wheat, Zn addition had no effect on K, enhanced Ca (except with CTSP), but decreased S and Fe (except with CMAP) translocations to the grain. Nutrient practices to optimize both crop yield and quality must be therefore adjusted based on crop species.

Phosphorus and Zn fertilizers can influence the mineral nutrient composition in human food. As durum wheat is a staple food in many parts of the world, enhancing its nutritional content may have broad health benefits. Flaxseed is generally only included in small amounts into the human diet, but based on the nutrient uptake and accumulation in seed/grain, flaxseed can be a more concentrated source for K, Ca, Mg and Fe as compared with durum wheat grain. Based on the results of this study, fertilizer management may be used to enhance the nutritional value of these crops for human nutrition, although the magnitude of changes are likely to differ between field and pot culture.

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Abad, A., Lloveras, J. and Michelena, A. 2004. Nitrogen fertilization and foliar urea effects on durum wheat yield and quality and on residual soil nitrate in irrigated Mediterranean conditions. Field Crops Res. **87**: 257–269.

Bennett, W. F. (ed.) 1993. Nutrient deficiencies & toxicities in crop plants. APS Press, The American Phytopathological Society, St. Paul, MN.

Bouis, H. E. 2003. Micronutrient fortification of plants through plant breeding: can it improve nutrition in man at low cost? Proc. Nutr. Soc. **62**: 403–411.

Cakmak, I., Ekiz, H., Yilmaz, A., Torun, B., Koleli, N., Gultekin, I., Alkan, A. and Eker, S. 1997. Differential response of rye, triticale, bread and durum wheats to zinc deficiency in calcareous soils. Plant Soil. **188**: 1–10.

Canadian Grain Commission. 2006. Grain grading guide. Chapter 4: Wheat [Online]. Available: http://www.grainscanada.gc.ca/Pubs/GGG/ggg-e.htm [2006 Oct. 20].

Canada Grains Council. 2002. Statistical handbook 2002. Winnipeg, MB.

Carter, M. R. (ed.) 1993. Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL.

Follett, R. H., Murphy, L. S. and Donahue, R. L. 1981. Fertilizers and soil amendments. Prentice Hall, Englewood Cliffs, N.J.

Foy, C. D., Webb, H. W. and Jones, J. E. 1981. Adaptation of cotton genotypes to an acid manganese toxic soil. Agron. J. **73**: 107–111.

Grant, C. A. and Bailey, L. D. 1989. The influence of Zn and P fertilizer on the dry matter yield and nutrient content of flax (*Linum usitatissimum* L.) on soils varying in Ca and Mg level. Can. J. Soil Sci. **69**: 461–472.

Grant, C. A. and Bailey, L. D. 1993. Interactions of zinc with banded and broadcast phosphorus-fertilizer on the concentration and uptake of P, Zn, Ca and Mg in plant-tissue of oilseed flax. Can. J. Plant Sci. **73**: 17–29.

Grant, C. A. and Bailey, L. D. 1998. Nitrogen, phosphorus and zinc management effects on grain yield and cadmium concentration in two cultivars of durum wheat. Can. J. Plant Sci. **78**: 63–70.

Grant, C. A., Bailey, L. D., Harapiak, J. T. and Flore, N. A. 2002. Effect of phosphate source, rate and cadmium content and use of *Penicillium bilaii* on phosphorus, zinc and cadmium concentration in durum wheat grain. J. Sci. Food Agric. **82**: 301–308.

Hasler, C. M. 2001. Functional food. Pages 740–749 *in* B. A. Bowman and R. M. Russell, eds. Present knowledge in nutrition. 8th ed. International Life Sciences Institute Press, Washington, DC.

Jiao, Y., Grant, C. A. and Bailey, L. D. 2004. Effects of phosphorus and zinc fertilizer on cadmium uptake and distribution in flax and durum wheat. J. Sci. Food Agric. **84**: 777–785.

Klute, A. 1986. Methods of soil analysis. Part 1. Physical and mineralogical methods. ASA, Inc., SSSA, Inc., Madison, WI. pp. 901–924.

Malhi, S. S. and Karamanos, R. E. 2006. A review of copper fertilizer management for optimum yield and quality of crops in the Canadian Prairie provinces**.** Can. J. Plant Sci. **86**: 605–619.

Matsuo, R. R. 1993. Durum wheat – production and processing. Pages 779–808 *in* Grains & oilseeds: Handling, marketing, processing. Vol. II, 4th ed. Canadian International Grains Institute, Winnipeg, MB.

Mengel, K. and Kirby, E. A. 2001. Principles of plant nutrition. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Moraghan, J. T. 1993. Accumulation of cadmium and selected elements in flax seed grown on a calcareous soil. Plant Soil. **150**: 61–68.

Muir, A. D. and Westcott, N. D. 2003. Flax: The genus *Linum*. Taylor & Francis, London, UK.

Robertson, L. S. and Lucas, R. E. 1976. Zinc. Mich. Ext. Bul. E-1012.

Ryan, M. H., Derrick, J. W. and Dann, P. R. 2004. Grain mineral concentrations and yield of wheat grown under organic and conventional management. J Sci. Food Agric. **84**: 207–216.

Spratt, E. D. and Smid, A. E. 1978. Yield and elemental composition of flax as affected by P and micronutrients. Agron. J. **70**: 633–638.

Sylvia, D. M., Fuhrmann, J. J., Hartel, P. G. and Zuberer, D. A. 2005. Principles and applications of soil microbiology. 2nd ed. Pearson Education Inc., Upper Saddle River, NJ. pp. 263–282.

Vaisey-Genser, M. and Morris, D. H. 2003. Introduction: history of the cultivation and uses of flaxseed. Pages 1–21 *in* A. D. Muir and N. D. Westcott, eds. Flax: The genus *Linum*. Taylor & Francis, London, UK.

Westman, R. L. 1990. Soil testing and plant analysis. SSSA, Madison, WI.