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Nutrient uptake and biomass accumulation for eleven different field crops

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Oil hemp (*Cannabis sativa* L.), quinoa (*Chenopodium quinoa* Willd.), false flax (*Camelina sativa* (L.) Crantz), caraway (*Carum carvi* L.), dyer's woad (*Isatis tinctoria* L.), nettle (*Urtica dioica* L.), reed canary grass (RCG) (*Phalaris arundinacea* L.), buckwheat (*Fagopyrum esculentum* Moench), linseed (*Linum usitatissimum* L.), timothy (*Phleum pratense* L.) and barley (*Hordeum vulgare* L.) were grown under uniform conditions in pots containing well fertilised loam soil. Dry matter (DM) accumulation was measured repeatedly, and contents of minerals N, P, K, Ca and Mg at maturity. Annual crops accumulated above-ground biomass faster than perennials, while perennials had higher DM accumulation rates below ground. Seeds had high concentrations of N and P, while green biomass had high concentrations of K and Ca. Stems and roots had low concentrations of minerals. Concentrations of K and P were high in quinoa and caraway, and that of P in buckwheat. Hemp and nettle had high Ca concentrations, and quinoa had high Mg concentration. N and P were efficiently harvested with seed, Ca and K with the whole biomass. Perennials could prevent soil erosion and add carbon to the soil in the long term, while annuals compete better with weeds and prevent erosion during early growth. Nutrient balances in a field could be modified and nutrient leaching reduced by careful selection of the crop and management practices.

Key-words: allocation, biomass, nitrogen, nutrient, phosphorus, roots, uptake

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Introduction

Modern agriculture is typified by large areas of cereal crops, carefully managed to optimise production and to return the best economic results. In the EU cereals covered in 2007 about 52% of the arable land, with wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) together comprising 67% of the area under cereals (FAO 2008). In many countries the area sown to the most common crops is increasing (Chloupek et al. 2004), leading to fewer crops being produced. Fields of conventionally cultivated annual cereals are, however, associated with higher nutrient leaching (Ulén and Mattson 2003, Kyllmar et al. 2006) and lower soil organic matter (SOM) (Schjønning et al. 2007) than fields under perennials such as forage or biomass grasses. Cultivation of perennial crops reduces soil erosion (Kort et al. 1998) and increases SOM, thereby reducing soil compaction, improving the water economy of the soil and promoting natural microbial processes (Kort et al. 1998, McLaughlin and Walsh 1998, Bolinder et al. 2007, Hutchinson et al. 2007, Schjønning et al. 2007). The growth and dry matter (DM) accumulation of roots of different annual crops also vary significantly. For instance, in a one year field experiment, the root DM of oilseed rape (*Brassica rapa* L.), barley and oats (*Avena sativa* L.) was 110, 160 and 260 g DM m^{-3}, respectively, and that of ryegrass (*Lolium multiflorum* Lam. var. *italicum*) 340 g DM m^{-3} at 0–60 cm depth (Pietola and Alakukku 2005).

The extent of potential nutrient leaching from soil to the surrounding water systems depends on the crop and crop rotation (Ulén and Mattsson 2003, Beaudoin et al. 2005). A significant amount of nutrients is removed from the field with the yield, depending on the crop and the magnitude of the yield (Aronsson et al. 2007). For instance, barley cultivated in Scandinavia accumulated a maximum of 155, 23.5 and 109 kg ha^{-1} of nitrogen (N), phosphorus (P) and potassium (K), respectively, in aerial biomass. Of these nutrients, the harvested grains contained about 75% of the accumulated N, 84% of P, but only 26% of K, the remaining being present in the straw (Arvidsson 1999). Climatic conditions and management practices also affect the accumulation and removal of nutrients from the field. For example, in the case of crop failure, easily soluble fertiliser nutrients not accumulated in the yield can simply leach. The nutrients bound in straw biomass can be removed from the field for e.g. bioenergy use, or be incorporated into the soil, where they serve as long-term nutrient reserves.

The most productive agricultural areas in Finland are bordered with rivers and other catchment areas, and also the Baltic Sea. Eutrophication of waters, especially the Baltic Sea, is of constant concern, and leaching of N and P from agricultural areas is considered to be mostly responsible for it. These concerns have led to reductions in fertiliser application rates, in order that the inputs as fertilisers do not exceed the outputs as yield. As a result, the net N balances of cultivated fields in Finland have decreased from 90 kg ha^{-1} in 1990 to 50 kg ha^{-1} in 2005 (Salo et al. 2007) and the net P balances from 35 kg ha^{-1} to 8 kg ha^{-1} at present (Uusitalo et al. 2007). Nevertheless, as both N and P balances are still heavily positive, the nutrient leaching risks continue to be high. In the future, leaching risks will intensify, with climatic change resulting in higher temperatures and increased precipitation in the wintertime, i.e. ideal conditions for SOM combustion, and for mineralisation and leaching of nutrients (Jylhä et al. 2004, IPCC 2007). Moreover, drought during the growing season may diminish yields also at high latitudes and thus result in an increased leaching risk of unused nutrients (IPCC 2007, Ketterings et al. 2006). As crop rotations and cultivation methods all affect soil qualities, nutrient balances and field water economy (Kort et al. 1998, McLaughlin and Walsh 1998, Beaudoin et al. 2005, Kyllmar et al. 2006, Aronsson et al. 2007, Chung et al. 2007, Hutchinson et al. 2007), long-term planning of crop rotations and innovative choice of crops could help reduce problems with nutrient leaching from agricultural areas as reductions in fertiliser application levels seem not to work well enough. If the farmers, while aiming at better sustainability of their management practices, at the same time secured better economic returns and higher yields via enhanced soil quality, higher soil organic matter content and improved water and nutrient economy, the incentive for more sustainable crop management and careful planning of crop rotations could increase. Greater variety of crops in the rotation systems and increased cultivation of perennial or autumn-sown crops also would function as a buffer against changing environmental conditions.

In the present study, the DM accumulation patterns and nutrient balance traits above and below ground of six annual and five perennial crops were compared. The main criteria for choosing an individual crop were their special nutrient usage characteristics, high biomass production above and/or below ground and flowering traits promoting field biodiversity. An important issue was also their potential as cultivated crops and their economic feasibility for production.

Of the six annual crops, spring barley represents a typical globally cultivated crop for which there has been long experience of successful development in breeding and management practices. In 2007, forage barley alone occupied 18.3% of the total cultivated field area in Finland (TIKE 2008). Buckwheat (*Fagopyrum esculentum* Moench), false flax (later, camelina) (*Camelina sativa* (L.) Crantz), linseed (*Linum usitatissimum* L.), oil hemp (*Cannabis sativa* L.) and quinoa (*Chenopodium quinoa* Willd.) represent underutilised annual crops, at least in Finland, exhibiting a wide variety of flowering traits and establishment patterns in the spring. Of these crops, camelina is currently contract-grown on about 5000 ha (0.2% of total field area in Finland) for health-promoting vegetable oil and margarine. Linseed and flax together are grown on less than 2000 ha, and oil hemp practically not at all (TIKE 2008). Buckwheat flour is being studied for its nutritional value (Steadman et al. 2001, Keskitalo et al. 2007). Buckwheat and quinoa could be used by the growing number of people suffering from celiac disease. However, buckwheat is currently grown in Finland only on a few hundred hectares, and quinoa on a very limited area.

Of the five perennial crops, timothy (*Phleum pratense* L.) represents a typical forage grass with long traditions of cultivation in Finland. Reed canary grass (later, RCG, *Phalaris arundinacea* L.) grown mainly for bioenergy, and caraway (*Carum carvi* L.) grown for seed spice, have already expanded in cultivation area to about 1% of the total field area in Finland. Nettle (*Urtica dioica* L.), a potential source of fine textile fibre for luxury products, and dyer's woad (later, woad, *Isatis tinctoria* L.), a potential source of blue dye for handicraft textiles, are at the moment cultivated on areas less than one hectare each.

The minor crops in this experiment are known for various physiological traits potentially affecting their suitability in crop rotations and effects on soil qualities. Hemp and RCG have large and deep root systems and high potential for removing excess nutrients from the soil (Adler et al. 1996, Ivonyi et al. 1997, Miao et al. 1998, Filipek and Olek 1999, Partala et al. 2001, Saijonkari-Pahkala 2001, Fraser et al. 2004). Caraway also produces a large root system; up to 8–12 t ha^{-1} (Siuliauskas and Liakas 1999). Nettle can grow in polluted areas (Khan and Joergensen 2006). It accumulates readily nutrients, especially N, but its litter also decomposes readily and the nutrients can leach unless the biomass is collected in time (Scheu 1997). Quinoa and buckwheat belong to the order Caryophyllales, which is known for high shoot K and Mg concentrations, and thus high root cation exchange capacity (Broadley et al. 2004). Buckwheat can accumulate sparingly soluble P from soils (van Ray and van Diest 1979, Zhu et al. 2002) and can grow in low pH soils (Dwivedi 1996). This makes buckwheat a good candidate for a first crop on cleared forest or dried swamp fields. As many species in the order Caryophyllales (Broadley et al. 2004), quinoa can tolerate and accumulate salt (Jacobsen et al. 2001). It is also a caesium collector (Broadley and Willey 1997), and could be used in cleaning soil of it. Although the root systems of camelina and linseed are small, they are known to accumulate nutrients from the soil efficiently (Kranz and Jacob 1977a, Kranz and Jacob 1977b).

The aim of this study was to establish how the different crops differ in their nutrient uptake and biomass accumulation above- and below-ground. The rate of establishment above and below-ground was of interest for practical management strategies, e.g. affecting the need for weed control and risk of soil erosion. The acquisition of minerals and accumulation of DM in yield and other plant parts influence the effect of a crop on soil nutrient balances and SOM levels, thereby affecting need for fertilisation and risks of nutrient leaching in different management strategies.

Materials and methods

Setup of the experiment

The experiment was conducted at Jokioinen, Finland (60°49'N, 23°29'E). The experiment was performed in pots under semi-controlled growing conditions to 1) completely harvest all plant parts, including the roots, and 2) exclude differences in soil nutrient and water status, as well as variations in temperature and precipitation. The plants were sown at field density and harvested at maturity or at the end of the growing season to best simulate the actual situation in the field. The fertiliser regime in this experiment was the same throughout to reveal relative differences in nutrient uptake and usage among the crops.

Seeds of eleven crops (Table 1) were sown in four sets of pots, each set for one sampling time, with five replicates (220 pots in total). Small pots (7.5 l) were used for early growth phase sampling (four and six weeks after sowing). Large pots (14 l) were used for sampling at eight weeks after sowing (approximate flowering time of annual crops in this experiment) and at maturity. The diameter of the smaller pots was 22.5 cm and of the large ones 28 cm, corresponding to 397 and 615 cm^2 surface area. The pots were filled with very fine sandy loam soil taken in the spring from a Jokioinen field. Before use the soil was sieved with a double screen (outer mesh 15 mm, inner mesh 10 mm). 12 kg (11 l) of soil was used for large pots and 6 kg (5.5 l) for smaller pots. The soil pH was 5.9, carbon content 1.5%, and total N content 0.1%. The soluble N content was 8 mg kg^{-1} soil (NO_3 and NH_4 combined), and other mineral contents (soluble in acid ammonium acetate) were (kg^{-1} of soil): 26 mg P, 127 mg K, 951 mg Ca and 42 mg Mg. The soil was fertilised (pot^{-1}) with 1.5 g N (25% NH_4NO_3, 75% $Ca(NO_3)_2 \times 4\ H_2O$), 0.6 g P and 1.5 g of K

Table 1. Species and varieties, sowing densities and final plant densities pot^{-1} (the same in both pot sizes).

Plant species	Variety (origin)	Plant density in field (m^{-2})	Target plant number pot^{-1}	Sown seeds pot^{-1}	Final plant number pot^{-1}
barley	Artturi (FI)	400–500	20	25	20
buckwheat	Anita (BR)	160	8	15	8
camelina	Calena (FI)	150–300	14	20	14
caraway	Bleja (NL)	400	18	25	18–20
hemp	Finola (FI)	100–200	9	15	9
linseed	Helmi (FI)	600–800	35	50	34–35
nettle	- (FI)	9	8	40	6–8
quinoa	Olav (DK)	45	4	10	3–4
RCG	Palaton (US)	400–800	35	60	35–37$^{1)}$ 35–40$^{2)}$
timothy	Tuukka (FI)	1000	46	100	46–50
woad	- (D)	30–50	3	10	3

Origin of variety/strain: (BR) Belorussia, (DK) Denmark, (FI) Finland, (D) Germany, (NL) The Netherlands, (US) The USA.

RCG=reed canary grass, Woad= dyer's woad. 1) Large pots, 2) Small pots.

(K_2HPO_4), 1.61 g Ca ($Ca(NO_3)_2 \times 4\ H_2O$), 0.45 g Mg ($MgSO_4 \times 7H_2O$), 0.06 g Na (NaCl), 0.015 g Fe ($FeSO_4 \times 7\ H_2O$), Zn ($ZnSO_4 \times 7\ H_2O$) and Mn ($MnSO_4 \times H_2O$), 0.0075 g Cu ($CuSO_4 \times 5\ H_2O$), and 0.0015 g B (H_3BO_3) and Mo ($Na_2MoO_4 \times 2\ H_2O$) in the large pots and with half of the nutrient volumes in the smaller pots. The pH and total contents of main minerals and SOM before and after fertilisation, and after crop growth are presented in Table 2. The 220 pots were arranged in 10 groups of 11 plant species, with each plant species represented twice in one group (two sampling times for both smaller and large pots). The 22 pots within a group were arranged randomly. In addition, 10 control pots (five large ones and five small ones) were left unsown, but were otherwise fertilised and treated as the pots with the plants.

Sowing was on 27–28 May 2003 at typical soil depth and seedlings were thinned to typical field plant densities after emergence (Table 1). The number of sown seeds was the same in both smaller and large pots. For the slow-growing nettle, plant density was increased somewhat relative to field density to ensure sufficient biomass for yield determinations. For barley and caraway, the plant density was decreased slightly relative to field density to ensure adequate rooting volume.

After sowing the pots were placed outdoors in a covered area. The site was open from the sides, but covered by a glass roof. The temperature in the area was thus slightly (on average 1 °C both in the night and during the day) elevated relative to ambient temperatures. The light intensity was reduced by the glass roof by 10 to 20% relative to outside, depending on the measuring position and position of the sun. On a bright sunny day this meant that the photosynthetically active (PAR) light intensities under the covered area were 1100 to 1600 µmol

Table 2. pH of soil and amounts of minerals and carbon (mg or g pot^{-1}) ± SE in the large pots before fertilisation (BF), after fertilisation before sowing seeds (AF), at the end of growing season in empty pots (END) and at the end of growing season in sown pots after removal of crops (listed separately).

	Ca (g)	K (g)	Mg (g)	P (mg)	N (mg)	C (g)	pH
BF	11.42±0.28	1.54±0.04	0.50±0.01	317±5	97±2	187±3	5.90
AF	11.79±0.18	2.79±0.09	1.09±0.11	430±14	588±46	184±2	5.58
END	12.68±0.18	3.10±0.02	1.09±0.02	394±3	671±83	176±3	5.56
barley	11.91±0.11	1.99±0.03	1.00±0.01	350±4	38±2	176±1	5.67
buckwheat	12.00±0.11	1.86±0.05	1.00±0.01	346±3	26±2	188±6	5.79
camelina	11.70±0.18	2.17±0.02	1.05±0.02	353±6	41±2	180±3	5.70
caraway	12.07±0.22	1.18±0.05	1.02±0.02	334±5	12±2	182±3	5.66
hemp	11.15±0.20	2.28±0.05	1.01±0.01	317±3	31±3	183±3	5.69
linseed	12.10±0.11	1.96±0.03	1.11±0.02	362±4	23±2	176±2	5.84
nettle	11.47±0.16	2.06±0.05	1.00±0.03	338±8	20±2	180±2	5.64
quinoa	11.87±0.10	1.16±0.04	0.85±0.02	318±5	24±2	180±3	5.54
RCG	12.62±0.28	1.65±0.05	1.18±0.03	361±6	11±1	185±2	5.87
timothy	12.16±0.34	1.77±0.07	1.08±0.04	373±10	13±3	180±3	5.78
woad	12.17±0.22	2.13±0.08	1.07±0.03	389±10	45±5	182±2	5.78

RCG=reed canary grass, woad=dyer's woad, n=5, SE of pH values is between 0 and 0.04.

photons m^{-2} s^{-1}, when under ambient conditions they were 1300 to 1800 µmol photons m^{-2} s^{-1}.

The pots were watered individually when needed with 200–1000 ml of deionized water (depending on the plant growth and thus need for water). When the pots with sown plants were watered, the empty control pots were also watered with on average the same water amount as most of the sown pots.

Sampling and DM determination

The plants were sampled four times: 24 June, 7 July, 21 July and at maturity (barley, 6 August; camelina, 20 August; buckwheat, 25 August and linseed, 26 August). Species that failed to mature by 1 September (hemp, quinoa, nettle), and species that did not form seed during the first year (caraway, woad, timothy, RCG), were harvested on 1–5 September. Because of the large number of species, the samplings were conducted by replicate (one replicate per day - sampling over 5 days). For mature species, all replicate pots of one species were harvested in a day.

At each sampling time, the whole plant biomass was removed from the pot. This was separated (when applicable) into roots, stem, leaves, flowers and seed. After separation, the DM of each component was determined after oven drying at 105 °C for one hour and then overnight at 60 °C. Before DM determination the roots were washed. The bulk of roots that had been attached to the plants and major roots in the soil were washed when still fresh under slowly running cold water, on a mesh preventing loss of root material. After removing these roots, the soil was dried and the fine roots were sieved out and washed. All the washed roots from both separation stages were combined to give the total DM of roots in each pot. All of the roots were reliably recovered with this method, but the process took a long time, and some root weight may have been lost through metabolic processes and respiration of the root tissue.

Determination of mineral contents in plant biomass and soil

The N concentration of the harvested biomass was determined using the Kjeldahl method (Kjeltec Auto 1030 Analyzer; FOSS, Höganäs, Sweden). A timothy sample was used as the Kjeldahl reference material. The concentrations of K, Ca, Mg and P in biomass samples were determined by inductively coupled plasma emission spectrometry (ICP-OES) (IRIS Advantage, Thermo Jarrell Ash Corp., Franklin, MA, USA). Dried samples (5 g) were dry ashed at 500 °C overnight, dissolved in 100 ml 6 M HCl and filtered. An in-house Hay-reference material was included in every batch of 24 samples. The concentrations of K, Ca, Mg, and P in seed samples were also determined by ICP-OES, but following acid digestion. Dried samples (0.5–2 g) were digested in concentrated nitric acid (p.a.) by first incubating overnight at about 50 °C and then cooking at 120 °C for 3–4 hr. After evaporating the sample volume to 1–2 ml, the samples were diluted to 50 ml with deionized water, and filtered (Kumpulainen and Paakki 1987). An in-house Hay-reference material was included in the batch of 35 samples.

The soil pH and nutrient levels and SOM pot^{-1} (large pots) were measured before and after fertilisation, and after the growing season in 5 sample pots kept free of plants, and in 55 pots with plants (Table 2). From the latter, root-free samples were taken immediately after removal of plants at the final harvest. The total N and C contents in the pot soil were determined with a LECO CN-2000 analyzer (LECO, St. Joseph, MI, USA). In this analysis, the minimum detectable content was 0.12% C and 0.9% N. The soluble ammonium-N and nitrate-N contents were determined spectrophotometrically from samples extracted with KCl with a 2-channel Skalar Autoanalyzer 5101 (Scalar

Analytical, Breda, the Netherlands), using the flow method. Other soil minerals (K, Ca, Mg and P) were extracted from air-dried samples with 0.5 M ammonium acetate and 0.5 M acetic acid (pH 4.65, AAAc) (1:10, 1h, Vuorinen and Mäkitie 1955), and the concentrations of Ca, K and Mg measured with ICP-OES (as above). The P content of samples was measured using a Bran Luebbe Auto Analyzer 3 and ammonium molybdate complexation.

Statistical methods

Data for the four different sampling times and different plant parts were analysed separately. The experimental design for each time point was a randomised complete block design with five blocks and 11 treatments (species). The model used for all responses for an observation of the i^{th} plant species within the j^{th} block had the form:

$$y_{ij} = \mu \pm t_i \pm b_j \pm e_{ij}$$

where μ is the overall mean, t_i is the fixed effect of species i, b_j is the random effect for block j and e_{ij} is the random error term. The random variables b_j and e_{ij} were assumed to be mutually independent and normally distributed with zero means and variances σ_b^2 and σ^2, respectively. Also, b_j were assumed to be independent of the e_{ij}. Appropriateness of the model was studied through residual analyses. The residuals were checked for normality using box plots (Tukey 1977) and the Shapiro-Wilk statistic. Furthermore, the residuals were plotted against the fitted values. For some responses log or square-root transformations were used to make model assumptions hold. Square-root transformation was used for above-ground biomass and log transformation was used for the following nutrient contents: 1) roots: all, 2) shoots: all, except K, 3) residue: Ca and K. Log transformations were also used for all seed nutrient concentrations, except for Mg. In the case of outliers, the model was fitted with and without outliers in order to study their influence on the results. Since their influence was minor, results based on all data are presented. Comparisons between plant means were made with two-sided t-type tests.

The models were fitted by using the residual maximum likelihood (REML) estimation method. The degrees of freedom were computed using the method described by Kenward and Roger (1997). The analyses were performed using the MIXED procedure (Littell et al. 1996) of SAS/STAT software version 9.1.3 (SAS Institute Inc., Cary, NC, USA).

Results

Biomass accumulation

Above-ground biomass

The annual crops accumulated above-ground DM faster than the perennials (Fig. 1). At the end of the experiment the above-ground DM remained higher in annuals than in perennials, with RCG being the only exception (Fig. 1, Table 3). The most commonly grown annual crop, barley, established above-ground biomass faster than any other crop in this experiment (Fig. 1), having significantly highest above-ground DM at the first sampling date 24 June ($p<0.0001$) (Table 3). On the second sampling date (7 July) the above-ground DM of the annual crops, hemp, camelina, linseed and buckwheat, was no longer statistically different from that of barley, but the above-ground DM of perennials ($p<0.0001$), and also of quinoa ($p<0.001$), was still lower than that of barley. At the third sampling date, above-ground DM of barley was significantly higher than that of any other species except linseed and buckwheat ($p<0.001$) (Table 3). At harvest, the above-ground DM pot^{-1} of quinoa (76 g), buckwheat (77 g) and RCG (76 g) were significantly higher than that of barley (62 g) ($p<0.0001$). DM of linseed (64 g) was the same, and above-ground DM of hemp (44 g) ($p<0.0001$), camelina (53 g) ($p<0.05$) and the perennials, woad (10 g), nettle (34 g), caraway (33 g) and timothy (30 g), were still lower than that of barley (Fig. 1, Table 3). If these figures (pot area 615 cm^2) are extrapolated to the field-scale, the above-ground

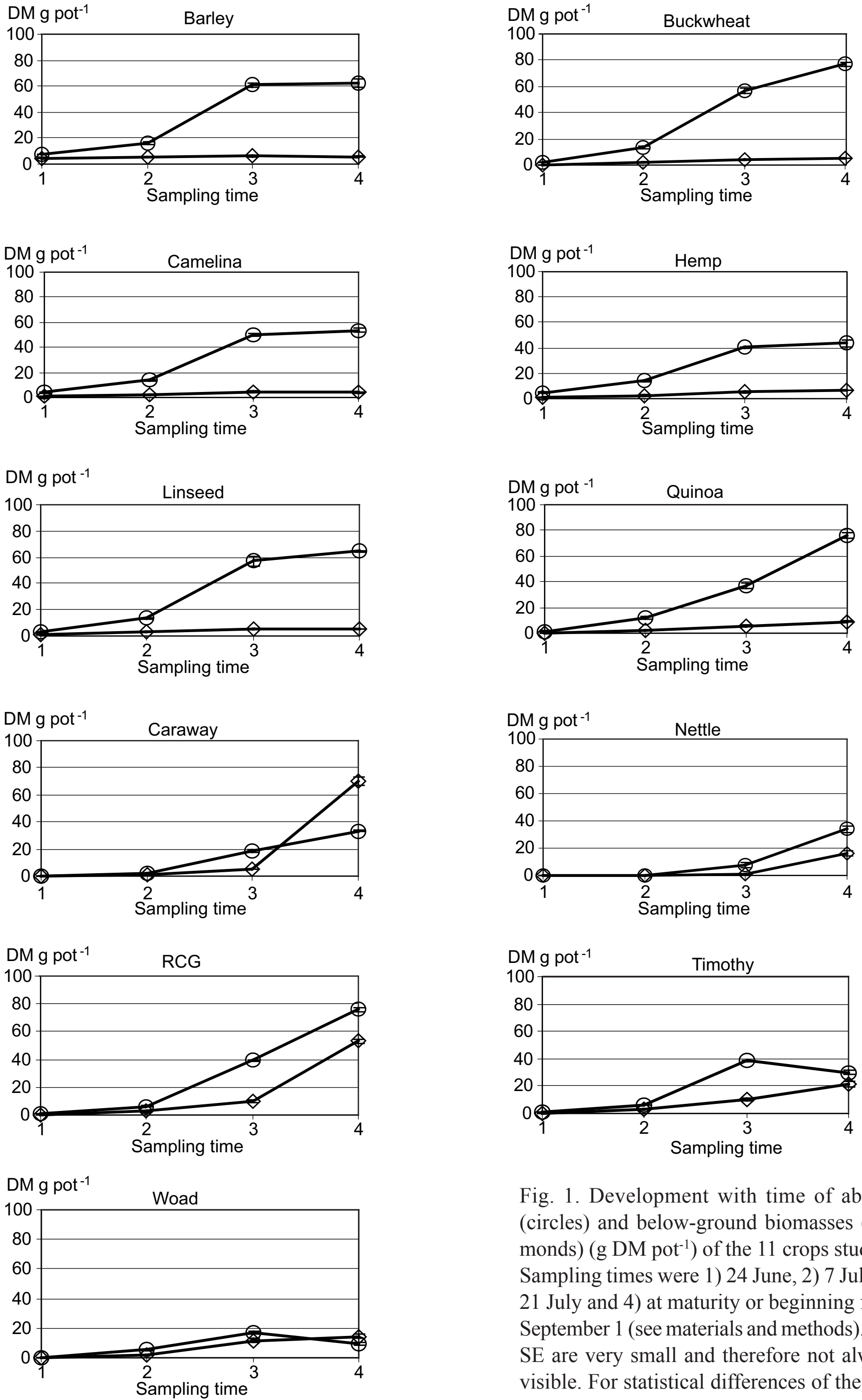

Fig. 1. Development with time of above- (circles) and below-ground biomasses (diamonds) (g DM pot^{-1}) of the 11 crops studied. Sampling times were 1) 24 June, 2) 7 July, 3) 21 July and 4) at maturity or beginning from September 1 (see materials and methods). The SE are very small and therefore not always visible. For statistical differences of the biomasses, see Table 3.

Table 3. Significance of differences between the biomasses of the 11 studied crops at different sampling times.

sample 1

Root biomass	barley	buckwheat	camelina	hemp	linseed	quinoa	caraway	nettle	RCG	timothy	woad
barley		3	3	3	3	3	3	3	3	3	3
buckwheat			ns	ns	ns	ns	1	3	ns	ns	2
camelina				ns	ns	2	3	3	1	ns	3
hemp					ns	3	3	3	3	1	3
linseed						3	3	3	3	1	3
quinoa							ns	1	ns	ns	ns
caraway								ns	ns	1	ns
nettle									2	3	ns
RCG										ns	ns
timothy											2
woad											

sample 2

Root biomass	barley	buckwheat	camelina	hemp	linseed	quinoa	caraway	nettle	RCG	timothy	woad
barley		3	3	3	3	3	3	3	3	3	3
buckwheat			ns	ns	1	ns	3	3	ns	1	ns
camelina				ns	ns	ns	3	3	ns	ns	ns
hemp					ns	ns	3	3	ns	ns	ns
linseed						ns	3	3	ns	ns	2
quinoa							3	3	ns	ns	ns
caraway								3	3	3	2
nettle									3	3	3
RCG										ns	ns
timothy											2
woad											

sample 3

Root biomass	barley	buckwheat	camelina	hemp	linseed	quinoa	caraway	nettle	RCG	timothy	woad
barley		ns	ns	ns	ns	ns	ns	3	1	1	3
buckwheat			ns	ns	ns	ns	ns	3	3	3	3
camelina				ns	ns	ns	ns	3	3	3	3
hemp					ns	ns	ns	3	2	3	3
linseed						ns	ns	3	2	2	3
quinoa							ns	3	2	2	3
caraway								3	2	3	3
nettle									3	3	3
RCG										ns	ns
timothy											ns
woad											

sample 4

Root biomass	barley	buckwheat	camelina	hemp	linseed	quinoa	caraway	nettle	RCG	timothy	woad
barley		ns	ns	ns	ns	ns	3	3	3	3	3
buckwheat			ns	ns	ns	2	3	3	3	3	3
camelina				ns	ns	3	3	3	3	3	3
hemp					ns	ns	3	3	3	3	3
linseed						1	3	3	3	3	3
quinoa							3	3	3	3	1
caraway								3	3	3	3
nettle									3	ns	ns
RCG										3	3
timothy											2
woad											

sample 1

Above ground biomass	barley	buckwheat	camelina	hemp	linseed	quinoa	caraway	nettle	RCG	timothy	woad
barley		3	3	3	3	3	3	3	3	3	3
buckwheat			3	3	ns	ns	3	3	3	3	3
camelina				ns	2	3	3	3	3	3	3
hemp					3	3	3	3	3	3	3
linseed						2	3	3	3	3	3
quinoa							2	3	ns	ns	1
caraway								ns	ns	ns	ns
nettle									ns	ns	ns
RCG										ns	ns
timothy											ns
woad											

sample 2

Above ground biomass	barley	buckwheat	camelina	hemp	linseed	quinoa	caraway	nettle	RCG	timothy	woad
barley		ns	ns	ns	ns	3	3	3	3	3	3
buckwheat			ns	ns	ns	ns	3	3	3	3	3
camelina				ns	ns	ns	3	3	3	3	3
hemp					ns	ns	3	3	3	3	3
linseed						ns	3	3	3	3	3
quinoa							3	3	3	3	3
caraway								ns	2	2	1
nettle									3	3	3
RCG										ns	ns
timothy											ns
woad											

sample 3

Above ground biomass	barley	buckwheat	camelina	hemp	linseed	quinoa	caraway	nettle	RCG	timothy	woad
barley		ns	3	3	ns	3	3	3	3	3	3
buckwheat			ns	3	ns	3	3	3	3	3	3
camelina				2	ns	3	3	3	3	3	3
hemp					3	ns	3	3	ns	ns	3
linseed						3	3	3	3	3	3
quinoa							3	3	ns	ns	3
caraway								3	3	3	ns
nettle									3	3	2
RCG										ns	3
timothy											3
woad											

sample 4

Above ground biomass	barley	buckwheat	camelina	hemp	linseed	quinoa	caraway	nettle	RCG	timothy	woad
barley		3	1	3	ns	3	3	3	3	3	3
buckwheat			3	3	3	ns	3	3	ns	3	3
camelina				2	2	3	3	3	3	3	3
hemp					3	3	2	2	3	3	3
linseed						3	3	3	2	3	3
quinoa							3	3	ns	3	3
caraway								ns	3	ns	3
nettle									3	ns	3
RCG										3	3
timothy											3
woad											

Ns= not significant, 1= significant at the level $p<0.05$, 2= significat at the level of $p<0.01$, 3= significant at the level of $p<0.001$.
Sampling times: 1) 24 June, 2) 7 July, 3) 21 July and 4) at maturity or beginning from 1 September, n=5.

biomasses would range from 12 500 (buckwheat, quinoa, RCG) to 1600 kg ha^{-1} (woad).

Below-ground biomass

The accumulation of root DM was faster in barley than in other species at the beginning of the experiment (Fig. 1, Table 3). This superiority was lost by the third sampling date, when the root DM of perennials had already exceeded that of barley and other annuals ($p<0.01$). At this stage, the perennial/biennial woad ($p<0.001$), RCG ($p<0.05$), and timothy ($p<0.05$) had significantly higher root DM than barley (Table 3). The root DM of nettle was still significantly lower ($p<0.0001$) than that of barley at that date. At maturity in August-September, the below ground DM was considerably greater in perennials than in annuals ($p<0.0001$), and all the annual crops had statistically lower root DM than the perennial ones (at $p<0.05$ –$p<0.0001$), the root DM pot^{-1} ranging from 4 (camelina) to 9 g (quinoa) (Fig. 1, Table 3). Of the overwintering perennials, caraway had the highest root DM (70 g), RCG the second highest (53 g), and then, at considerably lower root DM level, timothy (21 g), nettle (16 g) and woad (14 g), with timothy having significantly higher root DM than woad, but not nettle (Fig. 1, Table 3). The root DM equivalents calculated per hectare were from 11 400 (caraway) to 2300 kg ha^{-1} (woad) for the perennials and from 600 (camelina) to 1500 kg ha^{-1} (quinoa) for the annuals at the end of the experiment.

Root to shoot ratio

The root to shoot ratio of annuals and perennials did not clearly differ at the first sampling date (Fig. 2). From the second sampling date on, perennials had clearly higher root to shoot ratios than annuals, with the exception of barley, which still at the

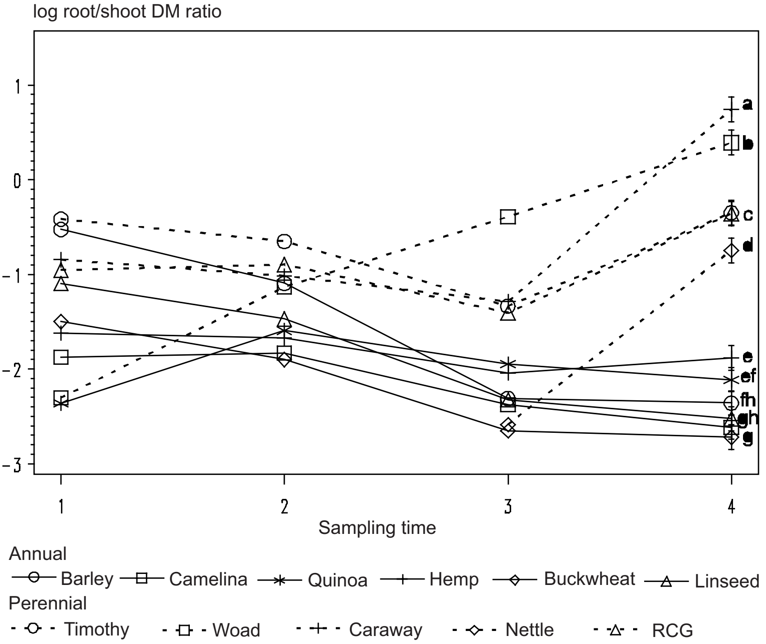

Fig. 2. Development with time of the root to shoot ratio of the 11 crops studied. The results are shown as model based mean estimates of the log of the ratio, positive results denoting higher root than shoot weight. Sampling times were 1) 24 June, 2) 7 July, 3) 21 July and 4) at maturity or beginning from September 1 (see materials and methods). The last measurements (4. sampling time) are marked with letters and 95% confidence intervals for the means. Results with a different letter differ significantly at 0.05 level (i.e. $p<0.05$).

second sampling date had as high root to shoot ratio as woad, caraway and RCG (Fig. 2). At the third sampling date, there was a significant difference between perennials and annuals, the perennials, with the exception of nettle, having clearly higher root to shoot ratios than the annuals ($p<0.01$). At the last sampling date, caraway and woad root weight exceeded shoot weight (root to shoot ratio 2 and 1.5, respectively, or a positive log ratio, Fig. 2), while the root weight was at least half shoot weight in RCG, timothy and nettle (log ratio higher than –1). The annual crops, including barley, at this stage, had root to shoot log ratios of –3 to –2 (root to shoot ratios of 0.06 to 0.15) (Fig. 2).

Biomass allocation and nutrient contents in different plant parts and soil at final harvest

The allocation patterns of biomass into root, stem, biomass yield, seed and harvest residue in different plant species at the final harvest are shown in Fig. 3. The harvested plant parts in hemp and linseed were stem and seed. Stem of linseed is not routinely harvested, although it has potential as a fibre crop (Sankari 2000). The hemp variety in this experiment was oil hemp and the stem is not normally used for fibre. However, considering the high stem biomass weight of oil hemp, it is possible for the stem to be baled and removed from the field for, for example, bioenergy purposes. Thus, in the present experiment, both hemp and linseed stem fractions were considered to be harvestable. In nettle and RCG stems would be harvested, as the plants would be left on the field for the winter, and most of the leaves would be shattered during winter or during harvesting in the spring. In camelina, quinoa, barley and buckwheat the seed would be harvested, in timothy and woad the green biomass. The nutrient concentrations were measured from roots, harvestable plant parts and other biomass (harvest residue). From biennial caraway, seed would have been harvested during the second growing season, so here there was no harvestable yield in 2003 and the nutrient concentration was measured only from roots and above-ground biomass (in Fig. 3, residue).

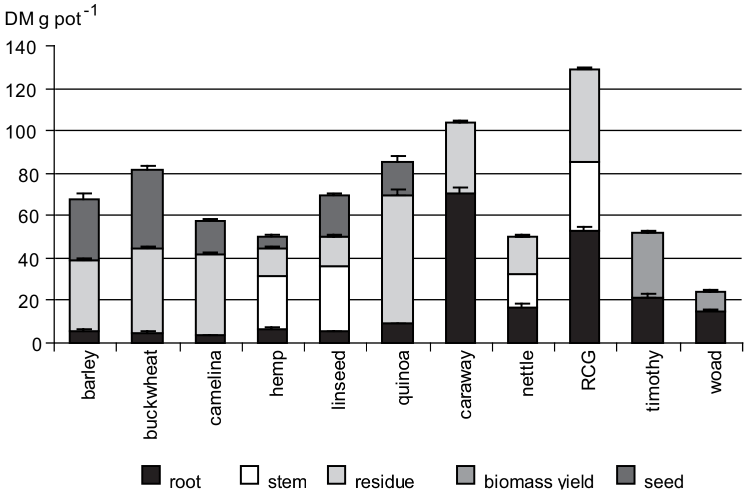

Fig. 3. Distribution of biomasses (± SE) at final harvest in different plant parts of the 11 crops studied, g DM pot^{-1}.

Nutrient concentration and distribution within the plant canopy

All pots were given the same amount of nutrients. The fertilisation provided was calculated to exceed growth requirements as the objective of the study was to reveal differences in nutrient uptake and allocation among the species. Nutrient concentrations in plant tissue were generally lower in root and stem than in seed and biomass yield/green harvest residue (Table 4). RCG was exceptionally poor in nutrients in the stem fraction. Nettle and woad were very rich in nutrients in both root and biomass fractions. Woad biomass was especially rich in K and nettle harvest residue in Ca and N. Caraway was especially rich in K and hemp in Ca in the biomass/harvest residue section. Seeds were generally particularly rich in N and P, whereas green biomass was rich in Ca and K (Table 4).

Because nutrient concentrations are significant in plant nutrient cycling only relative to biomass, the actual rating in nutrient accumulation levels between plant species could be quite different from the measured nutrient concentrations. For example, nettle and woad were rich in nutrients, but their total nutrient accumulation was modest because of their small final biomass (Fig. 3, Table 5). On the other hand, nutrient content in roots made up more than half of the total N, P and Mg in caraway and woad, and a large part of total nutrients in other perennials as well (Table 5), even though the concentrations of nutrients in roots were lower than in other plant parts (Table 4).

Nutrient content in biomass yield

The entire above-ground biomass was harvested in timothy and woad. Both accumulated similar amounts pot^{-1} of Ca and Mg by the end of the growing season (Table 5). However, the total harvested biomass of timothy was more than twice that of woad (Fig. 3), suggesting lower concentrations of these nutrients in the biomass, as is also shown in Table 4. Timothy accumulated more K, N and P in the biomass than woad as a result of higher biomass accumulation, the concentration of P being similar and that of K and N lower in timothy than in woad (Tables 4 and 5). In this one season experiment the biomass yield of timothy was quite low, and it would have been considerably higher in the second year, which in field conditions would be the first harvest year.

Nutrient content in stem yield

Stems were harvested from RCG, hemp, linseed and nettle. RCG had exceptionally low nutrient concentrations in the stem (Table 4). Even relative to stem yield, the accumulated Ca and Mg concentrations pot^{-1} were clearly lower than in the other three stem biomass crops (Fig. 4). Nettle, again, had exceptionally high nutrient concentrations in the stem, but because of lower stem biomass, the contents of nutrients pot^{-1}, with the exception of N, were not higher than with the other three stem yield crops (Fig. 4).

Nutrient content in seed yield

Only annual crops yielded seeds. Nettle produced seed, but it is treated here as harvest residue, as it is normally not harvested. The content of N and P was especially high in the seed fraction. Buckwheat produced the highest seed yield (Fig. 3) and had accordingly accumulated large amounts of N, K and P in the seed fraction pot^{-1} (Fig. 5). Linseed, which yielded modestly, accumulated almost equal amounts of nutrients in the seed (Fig. 5). Barley, which produced the second highest seed yield in this experiment, accumulated considerably less Ca in seed yield pot^{-1} (10 mg) than camelina (55 mg), linseed (46 mg) and buckwheat (32 mg) (Fig. 5). In general, seeds contained very large amounts of N and P. Only hemp, with very low seed yield, accumulated relatively few nutrients in this fraction.

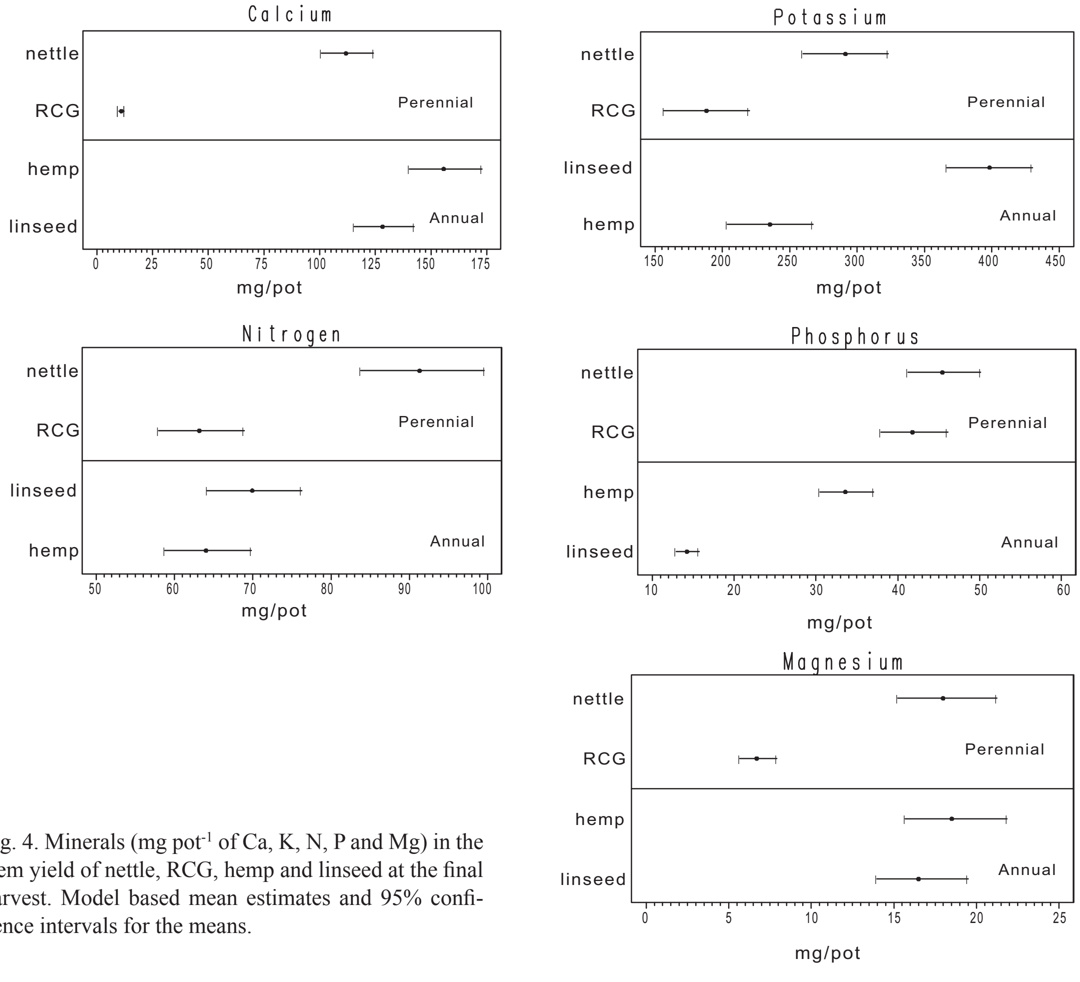

Fig. 4. Minerals (mg pot^{-1} of Ca, K, N, P and Mg) in the stem yield of nettle, RCG, hemp and linseed at the final harvest. Model based mean estimates and 95% confidence intervals for the means.

Table 4. Concentrations (g kg^{-1} DM) ± SE of minerals in different plant parts of the 11 crops at final harvest.

	Ca	K	Mg	P	N
Biomass yield					
timothy	3.83±0.02	22.64±0.62	1.53±0.02	3.80±0.09	11.24±0.20
woad	13.96±0.61	45.64±1.18	2.48±0.16	3.97±0.18	23.18±0.92
Stem yield					
hemp	6.35±0.34	9.59±0.57	0.75±0.03	1.37±0.08	2.60±0.05
linseed	4.14±0.09	12.84±0.30	0.53±0.02	0.46±0.01	2.26±0.08
nettle	7.04±0.16	18.04±0.62	1.14±0.08	2.86±0.08	5.76±0.23
RCG	0.34±0.01	5.83±0.10	0.21±0.00	1.3±0.05	1.96±0.04
Seed yield					
barley	0.35±0.01	7.75±0.05	1.72±0.02	4.90±0.07	19.04±0.53
buckwheat	0.85±0.02	7.59±0.10	2.21±0.02	3.89±0.05	14.38±0.26
camelina	3.59±0.12	11.64±0.20	3.75±0.06	8.67±0.12	36.26±0.53
hemp	2.16±0.03	10.47±0.18	5.21±0.06	12.22±0.15	32.62±0.46
linseed	2.37±0.03	11.12±0.17	4.13±0.03	8.19±0.04	34.44±0.94
quinoa	0.80±0.03	12.28±0.37	2.75±0.05	5.62±0.10	17.24±0.30
Harvest residue					
barley	4.99±0.14	25.5±0.50	1.58±0.02	2.09±0.07	3.82±0.27
buckwheat	12.36±0.52	25.86±0.77	2.97±0.15	4.13±0.10	5.36±0.28
camelina	14.04±0.48	16.54±0.48	1.53±0.05	0.63±0.05	4.20±0.13
caraway	13.46±0.41	60.14±1.46	3.16±0.07	4.88±0.28	11.96±0.20
hemp	66.46±2.20	24.02±0.89	7.56±0.40	5.80±0.25	11.00±0.20
linseed	18.03±0.35	29.02±0.58	1.03±0.04	1.95±0.13	5.08±0.07
nettle	48.42±3.29	23.52±0.56	4.02±0.25	5.33±0.36	14.76±0.95
quinoa	12.69±0.81	39.30±2.51	4.77±0.24	4.60±0.26	6.36±0.27
RCG	4.50±0.09	17.02±0.22	1.616±0.06	3.26±0.13	7.94±0.14
Roots					
barley	1.52±0.01	5.18±0.31	0.60±0.02	1.71±0.04	9.46±0.24
buckwheat	6.77±0.18	6.68±0.28	3.63±0.06	1.70±0.13	7.44±0.27
camelina	3.89±0.05	5.97±0.72	0.60±0.03	1.36±0.16	6.04±0.10
caraway	3.27±0.15	10.15±0.40	1.64±0.06	2.48±0.05	5.44±0.07
hemp	4.57±0.36	7.90±0.36	1.35±0.10	1.83±0.12	6.14±0.49
linseed	5.27±0.14	5.79±0.35	2.10±0.06	1.21±0.04	6.46±0.26
nettle	4.77±0.25	12.16±0.35	2.40±0.14	3.74±0.12	12.12±0.68
quinoa	4.38±0.79	10.24±0.31	2.93±0.32	0.86±0.08	5.00±0.31
RCG	1.18±0.03	9.65±0.45	0.59±0.02	1.86±0.06	5.92±0.10
timothy	3.13±0.06	4.64±0.26	1.05±0.08	1.50±0.04	7.62±0.10
woad	5.59±0.37	8.64±0.24	1.85±0.06	2.92±0.03	17.54±0.54

RCG=reed canary grass, woad=dyer's wood, n=5.

Table 5. Amounts of minerals (mg pot-1 ± SE) in harvested plant parts, harvest residue and roots of the 11 crops studied.

	Ca	K	Mg	P	N
Harvested yield					
barley1)	10±1	227±17	50±4	144±11	561±54
buckwheat1)	32±2	287±7	84±3	147±5	544±21
camelina1)	55±1	180±10	58±3	134±8	560±23
hemp2)	169±10	293±13	47±2	100±5	242±17
linseed2)	174±4	612±8	96±3	172±4	732±26
nettle3)	113±7	291±27	19±2	46±3	92±4
quinoa1)	15±2	223±29	52±6	105±13	312±29
RCG3)	11±0	188±6	7±0	42±2	63±2
timothy4)	115±5	676±10	46±2	113±2	336±9
woad4)	136±15	444±43	25±4	39±5	229±31
Harvest residue					
barley	164±9	839±33	52±2	69±5	127±14
buckwheat	481±11	1013±57	116±5	161±7	209±11
camelina	533±16	628±16	58±1	24±1	159±2
caraway*	448±10	2006±70	106±4	162±7	399±12
hemp	881±40	320±22	100±3	77±5	147±10
linseed	256±9	412±15	15±1	28±2	72±2
nettle	871±97	419±21	73±8	94±6	263±19
quinoa	780±30	2398±160	289±5	277±11	359±22
RCG	196±2	740±15	70±2	142±6	345±6
Roots					
barley	9±0	31±3	4±0	10±1	56±3
buckwheat	34±2	34±2	18±1	9±1	38±2
camelina	15±1	24±3	2±0	5±1	24±1
caraway	231±20	715±45	116±7	175±9	382±13
hemp	31±3	53±5	9±1	12±1	41±4
linseed	28±2	30±3	11±1	6±1	34±3
nettle	77±6	198±19	39±3	61±6	194±14
quinoa	45±11	94±3	29±4	8±1	47±6
RCG	63±3	511±26	31±2	99±4	314±10
timothy	68±7	100±12	23±3	32±3	164±15
woad	80±8	124±11	27±3	42±4	253±2

RCG=reed canary grass, woad=dyer's woad, n=5 except for quinoa, where n=4.

1) Yield is seed,2) Yield is seed and stem, 3) Yield is stem, 4) Yield is green biomass.

*Whole biomass of biennial caraway is left in the field for the winter, yield is formed and harvested on the second year.

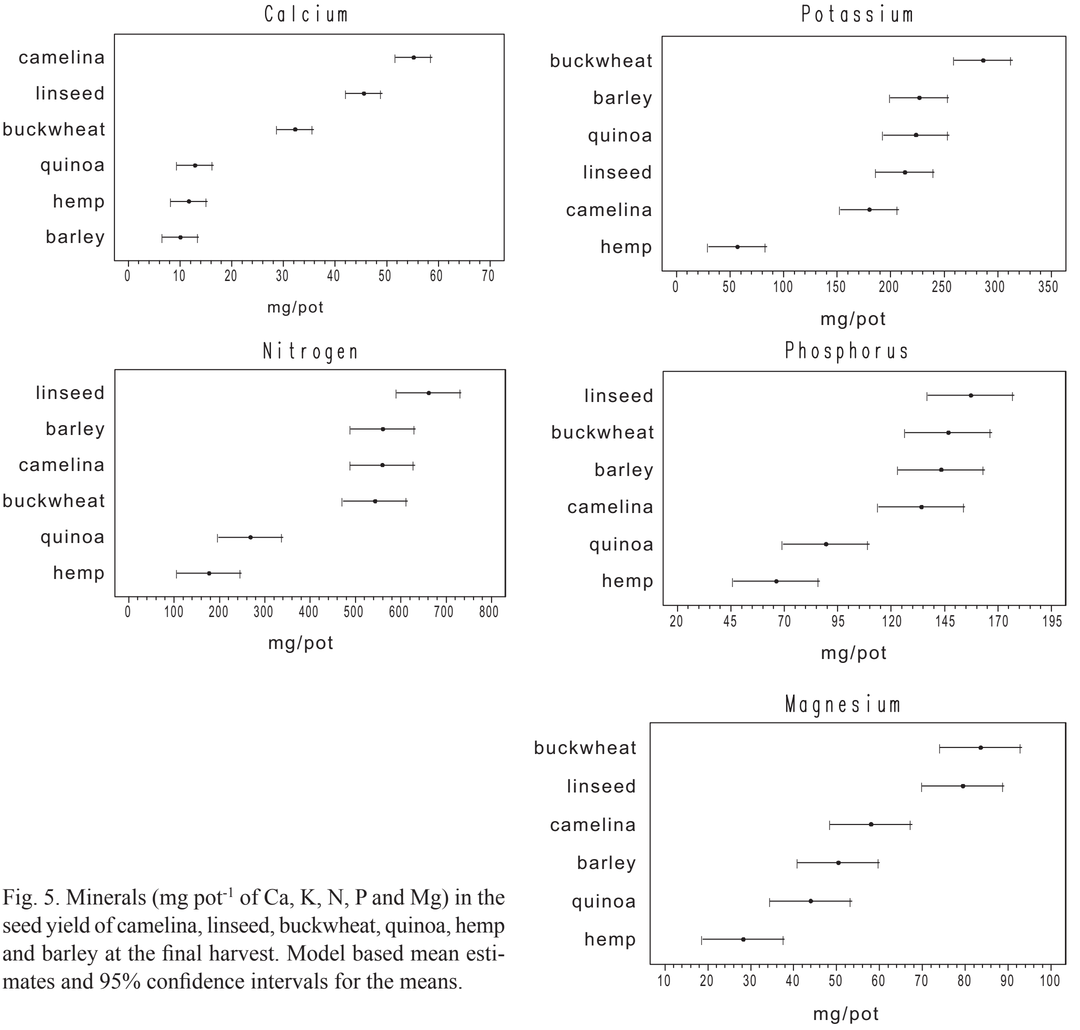

Fig. 5. Minerals (mg pot^{-1} of Ca, K, N, P and Mg) in the seed yield of camelina, linseed, buckwheat, quinoa, hemp and barley at the final harvest. Model based mean estimates and 95% confidence intervals for the means.

Nutrient content in harvest residue

There was no clear difference between annual and perennial species in accumulating nutrients in the non-harvestable above-ground fraction (leaves, immature seeds and flowers, non harvestable stem) (Table 5). Nettle, hemp and quinoa accumulated most Ca in this fraction, even though their biomass of this fraction was among the lowest in this experiment. Caraway above-ground green biomass was not much higher than that of timothy (Fig. 3), but it accumulated considerably higher amounts of Ca, K, P and Mg than timothy (Table 5). Caraway and quinoa accumulated most K, caraway, RCG and quinoa most N and quinoa most P and Mg (Table 5) in the non-harvestable fraction. Quinoa had the highest mass in this fraction (Fig. 3), which explains some of the high mineral accumulation. Harvest residue, including caraway biomass, and the nutrients therein, would normally remain in the field for the winter.

Nutrient content in roots and soil and carbon content in soil

Perennials with higher root volume than annuals had higher contents of minerals in the root fraction (Table 5, Fig. 6). This was especially evident in caraway and RCG. The mineral contents in the soil changed according to plant mineral acquisition (Tables 2 and 5). The most evident change was the efficient depletion of soluble N in every pot. All the species took up less than given in the fertiliser nutrients, except quinoa and caraway, which took more K (2.5 g) than given in the fertiliser (1.5 g), removing 83% of the total K in the pot. Quinoa also took a marked portion of added Mg from the soil. Because all roots were harvested from the soil sample, their carbon content is not included in the SOM values, and there was no net change in the values at the end of the experiment (Table 2). The carbon contained in roots, would, however, be a part of the SOM pool later, depending on the crop rotation and management methods. The pH of the soil decreased with fertilisation (5.58), and was brought back to near the original level (5.90) at the end of the experiment by RCG (5.87), linseed (5.84), buckwheat (5.79) and woad and timothy (5.78).

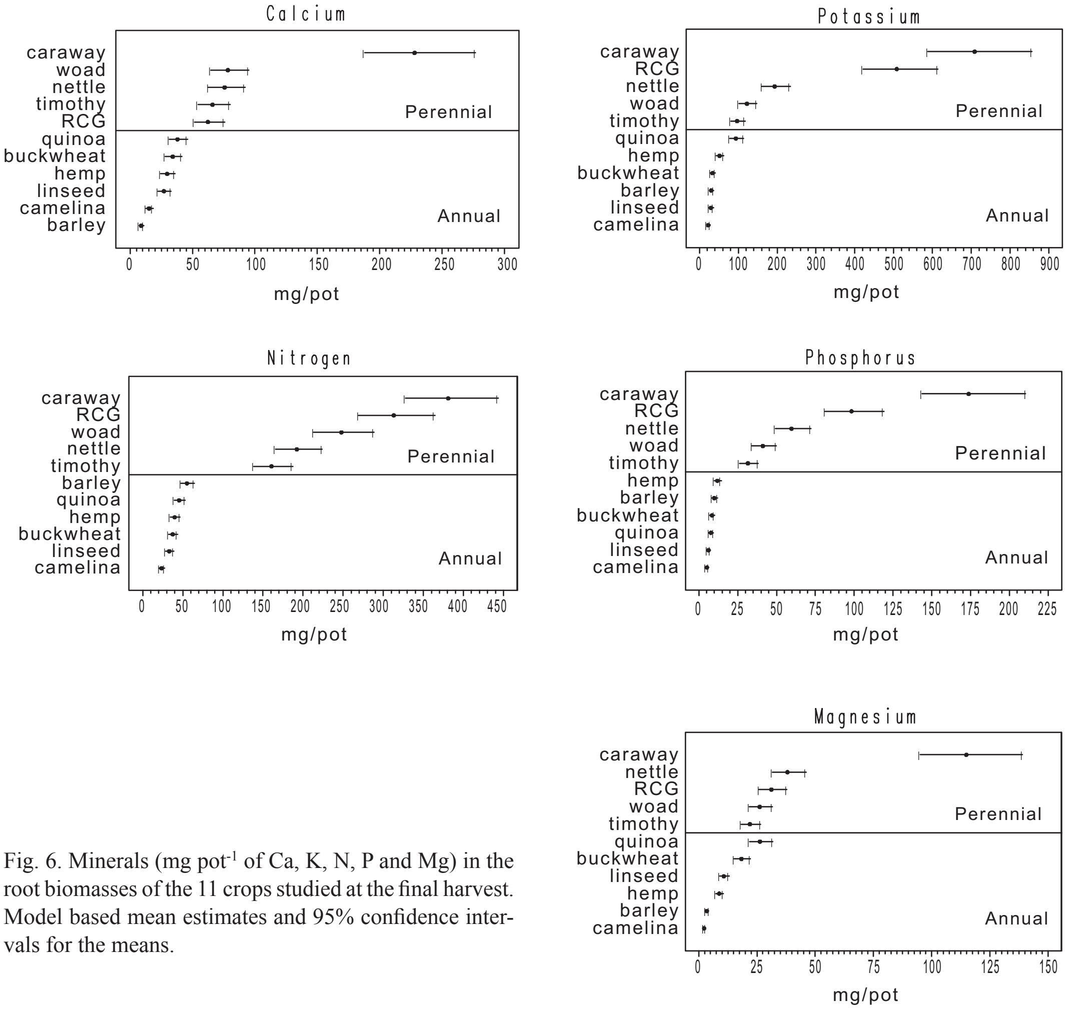

Fig. 6. Minerals (mg pot^{-1} of Ca, K, N, P and Mg) in the root biomasses of the 11 crops studied at the final harvest. Model based mean estimates and 95% confidence intervals for the means.

Discussion

Biomass production

Plant growth was faster in annual than in perennial crops and barley had particularly early growth both above and below ground (Fig. 1). Rapid establishment is beneficial as it permits crops to compete with weeds and reduces erosion and nutrient leaching early in the season. Slow growing plants such as nettle, woad, caraway and timothy require special care during early growth. Timothy is usually undersown with a fast growing annual species in the spring and the first harvest year is the year after sowing. Woad can be directly sown under good conditions, but there is the risk of pest and weed problems during early growth. Nettle establishes so slowly that under field conditions it has to be planted as seedlings to reduce competition with weeds. Even if the initial growth was inferior in the perennials, over time they would form a complete vegetative cover, out-competing weeds, increasing the field SOM and reducing soil erosion (Kort et al. 1998, Hutchinson et al. 2007).

Root growth was initially faster in annuals than in perennials, just as was the growth of above-ground biomass (Fig. 1). Early root establishment is important in preventing erosion early in the season and acquisition of water and nutrient reserves in the field, especially for annuals as they yield already in the first growing season. In this experiment root growth in barley was significantly faster than in any other species during the first six weeks of growth. However, from the third sampling (21 July), the perennials had the largest root systems. This was expected, as their winter survival and spring growth initiation largely depend on root viability and nutrient and carbohydrate reserves invested below-ground (Li et al. 1996, Partala et al. 2001, Hakala and Pahkala 2003, Roumet et al. 2006). In the highest biomass producers, caraway and RCG, nearly half of (RCG) or more than half (caraway) of the total biomass was allocated below-ground (Fig. 2). Timothy, however, was a modest root producer during this one year experiment.

Roots store not only nutrient and carbohydrate reserves for plants, but they also host microbes (Chung et al. 2007) and add organic matter to the soil (Gale and Cambardella 2000). In this experiment, an equivalent of 2.3 t (woad) to 8 t (RCG) or 11 t (caraway) ha^{-1} of root DM would have been sequestered in the field by the perennials during the first growth season, whereas the amount would have been from 0.6 t (camelina) to 1.5 t (quinoa) ha^{-1} for the annual crops (Figs 1 and 3). Especially high root production rates of caraway (8–12 t ha^{-1}, Siuliauskas and Liakas 1999) and RCG (3–5 t ha^{-1}, Partala et al. 2001) were also reported for field experiments. Growing caraway as a part of crop rotation would be beneficial for soil SOM content, as root volumes develop quickly and the fields are ready for the next crop already in the autumn of the second growing season. In the longer term, the root biomass of the other perennials would also increase, while resown annuals would produce similar root masses the following year. The effect of any of the plants in this experiment, but especially the annuals, on SOM would depend on crop rotation and management practices such as using direct drilling or incorporation of crop residues into the soil. In the latter quinoa would be especially efficient, with above-ground harvest residue being 1.5 times that in other annuals (Fig. 3).

Nutrient uptake and harvest

In seed yielding plants, most N and P were found in the seed (Table 4), as expected from previous studies (Gusewell 2004). With the other nutrients Ca, K and Mg, trends similar to earlier studies were also found. E.g. caraway (order Apiales) and quinoa (order Caryophyllales) had exceptionally high K concentrations in their biomass, while barley and RCG (order Poales) had exceptionally low Ca and Mg concentrations and hemp exceptionally high Ca concentrations in their biomass (Table 4) (Broadley et al. 2003, Broadley et al. 2004). Quinoa and buckwheat had rather high Mg concentrations in their biomass, as found earlier (Broadley et al. 2004), but only in the root fraction was the concentration clearly higher than in other crops. Nettle biomass was exceptionally high in N, as expected by earlier studies (Scheu 1997).

Because all aerial biomass of timothy and woad is harvested, most accumulated nutrients are removed from the field, with only root and stubble nutrients remaining over the winter. This management practice makes them good candidates for reducing nutrient leaching risk from catchment areas, at least when they are fertilised very moderately late in the season. When data from the pot experiments are presented on a field scale, 37 kg of N and 6 kg of P ha^{-1} would have been removed from the field with woad, and 55 kg N and 18 kg P ha^{-1} with timothy (Table 5). Timothy would thus remove more P than woad, relative to N removal, and would thus be a better option for fields with P leaching problems. If RCG and nettle were harvested green (as in this experiment), their total above-ground biomass would contain 66 kg N and 30 kg P (RCG) and 58 kg N and 23 kg P (nettle) ha^{-1}, which would represent better P control efficacy for both crops compared with woad and timothy. In the field, the amount of nutrients removed with timothy biomass is in fact higher than in the present experiment, as timothy can be cut 2–3 times a year, with a total yield of 10 000 kg ha^{-1} (Kangas et al. 2007), while in this experiment the DM yield was 30 g per pot, or 4878 kg ha^{-1} (Fig. 3).

Perennial wetland grasses such as RCG could be used in catchment areas to evaporate water and capture nutrients (Fraser et al. 2004, Adler 2007). In order for nutrient removal to work properly, however, biomass has to be harvested when the plants are still green (Adler 2007). At the moment this is not the case, but e.g. bioenergy grasses and fibre crops are left in the field for the winter in order to get good quality nutrient-poor materials for further processing. Nutrients from the above-ground biomass are mostly transferred to the roots in the autumn, but part of the above-ground biomass is also shattered and decomposed on the field, with at least some of the nutrients being at risk of leaching during winter and spring (Partala and Mela 2000, Partala et al. 2001, Saijonkari-Pahkala 2001, Adler 2007). On the other hand, a perennial RCG canopy harvested in the spring needs less fertiliser than, for example, timothy used for fodder production, as a large proportion of nutrients in the above-ground biomass is transferred to the root system and stored there during the winter to be used for growth the following spring (Partala and Mela 2000, Partala et al. 2001). Whatever the management system, cultivation of perennials in catchment areas will help in increasing SOM and reducing erosion of soil and thus leaching of nutrients such as P.

For the crops grown for seed, most N and P would be removed with the seed, which on general contain more N and P than vegetative structures (reviewed by Gusewell 2004). On a per hectare basis, according to the present experiment, about 90 kg of N and 23 kg of P would be removed with camelina, barley and buckwheat seed, 51 kg N and 17 kg of P with quinoa seed, 119 kg of N and 28 kg P with linseed seed and 39 kg of N and 16 kg of P with hemp seed (Table 5). Most P relative to N would be removed with quinoa and hemp seed. If the stem biomass of hemp and linseed were also baled and removed from the field directly after seed harvest, e.g. for fibre or bioenergy use, 63 kg of N and 29 kg of P would be removed from the field with hemp and 131 kg of N and 32 kg of P with linseed. If these crops were left in the field after seed harvest and the stems harvested in the spring, most of the biomass nutrients would remain in the field as the residue fraction, which contains more nutrients than the stem fraction. Most N and P would then be lost through shattering and biomass decay. Even though buckwheat in this experiment accumulated the same amount of nutrients as barley and camelina, it usually needs very little fertilisation to produce yield (Schulte auf'm Erley et al. 2005). It would thus be a good candidate for collecting P and N from catchment areas, where high fertilisation levels could, under unfavourable conditions, lead to increased leaching of nutrients. However, the whole biomass of buckwheat should then be collected as the minerals mined from the sparingly soluble sources in the soil and accumulated in buckwheat biomass might leach more easily from decaying buckwheat biomass than they would in their original less soluble soil-bound form.

In general, harvesting is the best way to remove nutrients from the field. In a comparison with conventional and organic (green manure) farming, utilisation efficiency of N and P was higher and leaching of P less in the conventional system because the yields were higher and thus P was removed from the field more efficiently (Aronsson et al. 2007). It has been concluded, accordingly, that nutrient removal can be directly calculated from the amount of harvested biomass (Ketterings et al. 2006). This may be true in general, but in this experiment it was shown that RCG, with the highest biomass yield, was not the most efficient in total uptake of any of the nutrients studied (Table 5). On the other hand, as also shown here, the plants take nutrients in different proportions in their yield and they could thus be used in crop rotations to stabilise nutrient levels, or remove excess nutrients when needed. Management practices could also be tailored to the site, e.g. harvesting fibre yielding crops already in the autumn in case of leaching risk, and then removing excess nutrients under controlled conditions, and in the optimal case return the nutrients to the field for the next growing season.

In the future, collection of straw biomass from cereals seems very likely, as it can be used as source of bioenergy (Lal 2005). This would increase considerably the amount of nutrients transported from the field. For example, as much N was allocated in the harvest residue fraction (straw and seed coat) of hemp and quinoa as in the seed yield. In camelina, barley and buckwheat, an equivalent of 23–40% of seed yield N was in the harvest residue (Table 5). Camelina, barley and linseed invested most P in the harvestable fraction, while in hemp and buckwheat similar amounts and in quinoa almost three times the amount of P in seed yield was found in the residue fraction. Despite the economic benefit that harvesting straw might accrue to farmers, especially in the future with increasing energy prices, cleaning the fields of all crop residues would have fewer beneficial effects on soil organic matter and nutrient balances. Crop residue slows down the mineralisation and leaching of nutrients, functions as an energy source for microbes, protects the soil from erosion, and adds to the soil organic matter (Kort et al. 1998, Beaudoin et al. 2005, Hutchinson et al. 2007). Harvest residue also contains several times more K and Ca than the yield (Table 5), which would have to be taken into account when planning fertilisation of fields. Thus, the decision as to how much crop residue is removed from the field and used for bioenergy or other purposes and how much is left in the soil must be based on soil status and environmental conditions at each field site.

Conclusions

All the perennial species studied had higher root biomasses and root to shoot ratios than the annuals and could increase SOM through root formation better than annuals. For the annual species, the harvest residue fraction was higher in quinoa, camelina and buckwheat than in barley, which would increase SOM relative to barley, if incorporated in the soil. The harvest residue fractions of oil hemp and linseed would also be considerable, if they were not collected for bioenergy or fibre. In the future harvest residue might be collected for bioenergy much more efficiently than at present, leaving little residue of any crop in the field.

Most N and P was harvested and removed from the pots as seed yield, barley being one of the most efficient nutrient removers, with only linseed containing more nutrients in the seed yield. If biomass yield plants are harvested during the growing season (timothy) or in the autumn (RCG and nettle), and if linseed and hemp biomasses are also harvested directly after seed harvest, they would also be very efficient N and P removers, but with the exception of linseed, not superior to barley. On the other hand, plants such as buckwheat that need little fertilisation would be better than barley in nutrient harvesting in e.g. catchment areas, where fertilisation combined with crop failure would result in increased leaching of fertiliser nutrients. Because crops themselves accumulate nutrients in different proportions and the way they are managed also affects both nutrient and SOM balances, the choice of crops as well as management practices should be planned carefully according to SOM and nutrient balances in the field.

The development of above-ground biomass was fastest in barley and in general faster in annual than in perennial crops. Barley roots also grew the fastest. This is a clear advantage in reducing erosion in spring, increasing competition with weeds and thus reducing the need for herbicide application. In the long term, however, perennials would have the advantage of providing continuous soil cover and having larger root systems, preventing soil erosion more efficiently during autumn and winter.

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References

Adler, A. 2007. Accumulation of elements in Salix and other species used in vegetation filters with focus on wood fuel quality. Swedish University of Agricultural Sciences (SLU), Doctoral thesis. *Acta Universitatis Agriculturae Sueciae* 2007: 6. SLU Service/Repro, Uppsala 2007.

Adler, P.R., Summerfelt, S.T., Glenn, D.M. & Takeda, F. 1996. Evaluation of a wetland system designed to meet stringent phosphorus discharge requirements. *Water Environment Research* 68: 836–840.

Arvidsson, J. 1999. Nutrient uptake and growth of barley as affected by soil compaction. *Plant and Soil* 208: 9–19.

Aronsson, H., Torstensson, G. & Bergström, L. 2007. Leaching and crop uptake of N, P and K from organic and conventional cropping systems on a clay soil. *Soil Use and Management* 23: 71–81.

Beaudoin, N., Saad, J.K., Van Laethem, C., Machet, J.M., Maucorps, J. & Mary, B. 2005. Nitrate leaching in intensive agriculture in Northern France: Effect of farming practices, soils and crop rotations. *Agriculture, Ecosystems and Environment* 111: 292–310.

Bolinder, M.A., Janzen, H.H., Gregorich, E.G., Angers, D.A. & VandenBygaart, A.J. 2007. An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agriculture, Ecosystems and Environment* 118: 29–42.

Broadley, M.R. & Willey, N.J. 1997. Differences in root uptake of radiocaesium by 30 plant taxa. *Environmental Pollution* 97: 11–15.

Broadley, M.R., Bowen, H.C., Cotterill, H.L., Hammond, J.P., Meacham, M.C., Mead, A. & White, P.J. 2003. Variation in the shoot calcium content of angiosperms. *Journal of Experimental Botany* 54: 1431–1446.

Broadley, M.R., Bowen, H.C., Cotterill, H.L., Hammond, J.P., Meacham, M.C., Mead, A. & White, P.J. 2004. Phylogenetic variation in the shoot mineral concentration of angiosperms. *Journal of Experimental Botany* 55: 321–336.

Chloupek, O., Hrstkova, P. & Schweigert, P. 2004. Yield and its stability, crop diversity, adaptability and response to climate change, weather and fertilisation over 75 years in the Czech Republic in comparison to some European countries. *Field Crops Research* 85: 167–190.

Chung, H., Zak, D.R., Reich, P.B. & Ellsworth, D.S. 2007. Plant species richness, elevated CO_2, and atmospheric nitrogen deposition alter soil microbial community composition and function. *Global Change Biology* 13: 980–989.

Dwivedi, G.K. 1996. Tolerance of some crops to soil acidity and response to liming. *Journal of the Indian Society of Soil Science* 44: 736–741.

FAO 2008. Homepage of Food and agriculture organization of the United Nations. Updated 2008. Cited 29 August 2008. Available on the internet: http://faostat.fao.org.

Filipek, T. & Olek, J. 1999. Agricultural utilisation of sewage and eutrofication pressure of waters. *Folia Universitatis Agriculturae Stetinensis*, *Agricultura* 77: 93–97. (In Polish, partly in English.)

Fraser, L.H., Carty, S.M. & Steer, D. 2004. A test of four plant species to reduce total nitrogen and total phosphorus from soil leachate in subsurface wetland microcosms. *Bioresource Technology* 94: 185–192.

Gale, W.J. & Cambardella, C.A. 2000. Carbon dynamics of surface residue- and root-derived organic matter under simulated no-till. *Soil Science Society of America Journal* 64: 190–195.

Gusewell, S. 2004. N:P ratios in terrestrial plants: variation and functional significance. *New Phytologist* 164: 243–266.

Hakala, K. & Pahkala, K. 2003. Comparison of central and northern European winter rye cultivars grown at high latitudes. *The Journal of Agricultural Science* 141: 169–178.

Hutchinson, J.J., Campbell, C.A. & Desjardins, R.L. 2007. Some perspectives on carbon sequestration in agriculture. *Agricultural and Forest Meteorology* 142: 288–302.

IPCC 2007. Summary for Policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (es), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK and New York, NY, USA.

Ivonyi, I., Izsoki, Z. & van der Werf, H.M.G. 1997. Influence of nitrogen supply and P and K levels of the soil on dry matter and nutrient accumulation of fiber hemp (*Cannabis sativa* L.). *Journal of the International Hemp Association* 4: 84–89.

Jacobsen, S.E., Quispe, H. & Mujica, A. 2001. Quinoa: an alternative crop for saline soils in the Andes. In: *Scientist and farmer: partners in research for the 21st Century.* Program Report 1999–2000. International Potato Center, Lima, Peru. p. 403–408

Jylhä, K., Tuomenvirta, H. & Ruosteenoja, K. 2004. Climate change projections for Finland during the 21st century. *Boreal Environment Research* 9: 127–152.

Kangas, A., Laine, A., Niskanen, M., Salo, Y., Vuorinen, M., Jauhiainen, L. & Nikander, H. 2007. Results of official variety trials 2000–2007. *MTT:n selvityksiä* 150. *Kasvintuotanto*. ISBN 978-952-487-146-4. (In Finnish, partly in English.)

Kenward, M.G. & Roger, J.H. 1997. Small sample inference for fixed effects from restricted maximum likelihood. *Biometrics* 53: 983–997.

Keskitalo, M., Ketoja, E., Kontturi, M., Mäki, M., Pihlava, J.-M., Rantamäki, P. & Tupasela, T. 2007. Buckwheat– an old crop with new health prospects. In: NJF Seminar 399: Beneficial health substances from berries and minor crops. Piikkiö, Finland, 14–15 March 2007 (p.23–26). *NJF Report* 3, 1/2007.

Ketterings, Q.M., Godwin, G., Kilcer, T.F., Barney, P., Hunter, M., Cherney, J.H. & Beer, S. 2006. Nitrogen, phosphorus, potassium, magnesium and calcium removal by brown midrib Sorghum Sudangrass in the Northeastern USA. *Journal of Agronomy and Crop Science* 192: 408–416.

Khan, K.S. & Joergensen, R.G. 2006. Decomposition of heavy metal contaminated nettles (*Urtica dioica* L.) in soils subjected to heavy metal pollution by river sediments. *Chemosphere* 65: 981–987.

Kort, J., Collins, M. & Ditsch, D. 1998. A review of soil erosion potential associated with biomass crops. *Biomass and Bioenergy* 14: 351–359.

Kranz, E. & Jacob, F. 1977a. The competition of *Linum* with *Camelina* for minerals. 1. The uptake of ^{35}S-sulfate. *Flora* 166: 491–503.

Kranz, E. & Jacob, F. 1977b. Competition for minerals between *Linum* and *Camelina*. 2. Uptake of ^{32}P-phosphate and ^{86}Rb. *Flora* 166: 505–516.

Kumpulainen, J. & Paakki, M. 1987. Analytical quality control program used by the trace elements in foods and diets sub-network of the FAO European cooperative network on trace elements. *Fresenius' Journal of Analytical Chemistry* 326: 684–689.

Kyllmar, K., Carlsson, C., Gustafson, A., Ulén, B. & Johnsson, H. 2006. Nutrient discharge from small agricultural catchments in Sweden. Characterisation and trends. *Agriculture, Ecosystems and Environment* 115: 15–26.

Lal, R. 2005. World crop residues production and implications of its use as a biofuel. *Environment International* 31: 575–584.

Li, R., Volenec, J.J., Joern, B.C. & Cunningham, S.M. 1996. Seasonal changes in nonstructural carbohydrates, protein, and macronutrients in roots of alfalfa, red clover, sweetclover, and birdsfoot trefoil. *Crop Science* 36: 617–623.

Littell, R.C., Milliken, G.A., Stroup, W.W. & Wolfinger, R.D. 1996. *SAS System for Mixed Models.* SAS Institue Inc, Cary, NC.

McLaughlin, S.B. & Walsh, M.E. 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass and Bioenergy* 14: 317–324.

Miao, G.Y., Yin, J., Zhang, Y.T., Zhang, A.L. & Box, J.E. 1998. A study of the root systems of main crops in Northern China. In: *Root demographics and their efficiencies in sustainable agriculture, grasslands and forest ecosystems*. Proceedings of the 5th Symposium of the International Society of Root Research 14–18 July 1996, Clemson University, South Carolina, USA. *Developments in Plant and Soil Sciences* 82: 345–356.

Partala, A. & Mela, T. 2000. Ruokohelven ravinnetaloustutkimukset. Research on nutrient balance of reed canary grass. In: Salo, R. (ed.). *Production of Biomass as Raw Material for Fibre and Energy.* Final Report, part I. Breeding and Cultivation of Reed Canary Grass. Publications of Agricultural Research Centre of Finland, Series A 84. Jokioinen, Finland. (In Finnish.). p. 50–65.

Partala, A., Mela, T., Esala, M. & Ketoja, E. 2001. Plant recovery of 15N-labelled nitrogen applied to reed canary grass grown for biomass. *Nutrient Cycling in Agroecosystems* 61: 273–281.

Pietola, L. & Alakukku, L. 2005. Root growth dynamics and biomass input by Nordic annual field crops. *Agriculture, Ecosystems and Environment* 108: 135–144.

Roumet, C., Urcelay, C. & Díaz, S. 2006. Suites of root traits differ between annual and perennial species growing in the field. *New Phytology* 170: 357–368.

Saijonkari-Pahkala, K. 2001. Non-wood plants as raw material for pulp and paper. *Agricultural and Food Science in Finland* 10, Suppl. No 1.

Salo, T., Lemola, R. & Esala, M. 2007. National and regional net nitrogen balances in Finland in 1990–2005. *Agricultural and Food Science* 16: 366–375.

Sankari, H. 2000. *Towards bast fibre production in Finland: stem and fibre yields and mechanical fibre properties of selected fibre hemp and linseed genotypes.* University of Helsinki, Faculty of Agriculture and Forestry, Doctoral thesis.

Scheu, S. 1997. Effects of litter (beech and stinging nettle) and earthworms (Octolasion lacteum) on carbon and nutrient cycling in beech forest on a basalt-limestone gradient: A laboratory experiment. *Biology and Fertility of Soils* 24: 384–393.

Schjønning, P., Munkholm, L.J., Elmholt, S. & Olesen, J.E. 2007. Organic matter and soil tilth in arable farming: Management makes a difference within 5–6 years. *Agriculture, Ecosystems and Environment* 122: 157–172.

Schulte auf'm Erley, G., Kaul, H.-P., Kruse, M. & Aufhammer, W. 2005. Yield and nitrogen utilization efficiency of the pseudocereals amaranth, quinoa, and buckwheat under differing nitrogen fertilization. *European Journal of Agronomy* 22: 95–100.

Siuliauskas, A. & Liakas, V. 1999. Caraway (*Carum carvi*) varieties in Lithuania. *Sodininkyste ir Darzininkyste* 18: 38–48. (In Lithuanian, partly in English.)

Steadman, K.J., Burgoon, M.S., Lewis, B.A., Edwardson, S.E. & Obendorf, R.L. 2001. Buckwheat seed milling fractions: description, macronutrient composition and dietary fibre. *Journal of Cereal Science* 33: 271–278.

TIKE 2008. Homepage of Information service of agricultural statistics in Finland. Updated 2008. Cited 29.8.2008. Available on the internet: www.matilda.fi.

Tukey, J.W. 1977. *Exploratory Data Analysis.* Addison-Wesley, Reading, MA.

Ulén, B. & Mattsson, L. 2003. Transport of phosphorous forms and of nitrate through a clay soil under grass and cereal production. *Nutrient Cycling in Agroecosystems* 65: 129–140.

Uusitalo, R., Turtola, E., Grönroos, J., Kivistö, J., Mäntylahti, V., Turtoa, A., Lemola, R. & Salo, T. 2007. Finnish trends in phosphorus balances and soil test phosphorus.

Agricultural and Food Science 16: 301–316.
van Ray, B. & van Diest, A. 1979. Utilization of phosphate from different sources by six plant species. *Plant and Soil* 51: 577–589.
Vuorinen, J. & Mäkitie, O. 1955. The method of soil testing in use in Finland. *Agrogeological Publications* 63: 1–44.
Zhu, Y.-G., He, Y.-G., Smith, S.E. & Smith, F.A. 2002. Buckwheat (*Fagopyrum esculentum* Moench) has high capacity to take up phosphorus (P) from a calcium (Ca) -bound source. *Plant and Soil* 239: 1–8.

SELOSTUS

Ravinteiden otto ja biomassan kertyminen yhdellätoista erilaisella peltokasvilla

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MTT

Tutkimuksen astiakokeessa kasvatettiin yhtenäisissä oloissa Suomessa vähän viljeltyjä, mutta ominaisuuksiltaan mielenkiintoisia viljelykasveja. Kasvit olivat öljyhamppu, (*Cannabis sativa* L.), kinua (*Chenopodium quinoa* Willd.), kitupellava (*Camelina sativa* (L.) Crantz), kumina (*Carum carvi* L.), värimorsinko (*Isatis tinctoria* L.), nokkonen **(***Urtica dioica* L.), ruokohelpi (RCG) (*Phalaris arundinacea* L.), tattari (*Fagopyrum esculentum* Moench) ja öljypellava (*Linum usitatissimum* L.). Lisäksi tavanomaisista viljelykasveista kasvatettiin timoteita (*Phleum pratense* L.) ja ohraa (*Hordeum ulgare* L.). Kasvien biomassan muodostusta mitattiin kasvun aikana. Ravinteiden typpi, fosfori, kalium, kalsium ja magnesium kokonaisotto kasvin eri osiin mitattiin kasvukauden lopulla. Yksivuotiset kasvit öljyhamppu, kinua, kitupellava, tattari, öljypellava ja ohra peittivät nopeasti maan pinnan, mutta kasvattivat vain vähän juuristoa. Kaksi- tai monivuotisilla morsingolla, kuminalla, nokkosella, ruokohelvellä ja timoteilla juuret kasvoivat nopeammin ja kasvukauden lopulla niiden massa jopa ylitti maanpäällisen kasvuston massan. Tulosten mukaan maan eloperäisen aineksen määrää voidaan lisätä, eroosiota vähentää ja maan kasvukuntoa parantaa viljelemällä kaksi- tai monivuotisia kasveja. Yksivuotiset kasvit sen sijaan olisivat parempia kilpailussa rikkakasveja vastaan. Siemenissä oli paljon typpeä ja fosforia, kun taas vihreässä kasvustossa oli runsaasti kaliumia ja kalsiumia. Juurissa ja varsisadossa (hampun, öljypellavan, ruokohelven ja nokkosen korjattava varsisato) oli vain vähän ravinteita. Kinua ja kumina keräsivät erityisen paljon kaliumia ja fosforia, tattari fosforia, hamppu ja nokkonen kalsiumia ja kinua magnesiumia. Siemensadon mukana korjattiin eniten ravinteita, etenkin typpeä ja fosforia. Jos sadon lisäksi koko biomassa korjattaisiin, pellolta poistuisi huomattavasti suurempi määrä ravinteita, typen ja fosforin lisäksi etenkin kalsiumia ja kaliumia. Koska kasvit keräävät eri osiinsa ravinteita eri tavalla ja kasvattavat juuristoa ja maanpäällistä massaa eri tavoin, viljelykasvin ja korjuustrategian valinnalla voitaisiin vaikuttaa pellon ravinnetaseisiin ja kasvukuntoon sekä ravinteiden huuhtoutumiseen pellosta.