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Biomass production and phosphorus retention by catch crops on clayey soils in southern and central Sweden

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Abstract

Catch crops are a potential option to reduce phosphorus (P) losses, but little is known about their establishment success and capacity to retain P on clayey soils in regions with short autumns, e.g. Sweden. This study screened biomass production and P retention by eight catch crop species: the perennials chicory (*Cichorium intybus* L.), cocksfoot (*Dactylis glomerata* L.), perennial ryegrass (*Lolium perenne* L.) and red clover (*Trifolium pratense* L.) and the annuals phacelia (*Phacelia tanacetifolia* L.), white mustard (*Sinapis alba* L.), oilseed radish (*Raphanus sativus* L. *oleiformis*) and white radish (*R. longipinnatus*). The catch crops were grown at six field sites, where the perennial species were under-sown with barley and the annual species were after-sown following barley harvest. Biomass production, P content in above-ground and below-ground plant parts and content of available P in the soil were determined in autumn and survival rate of the catch crops in the following spring. Biomass production and P retention in autumn both differed significantly between species ($p<0.0001$), and were greatly affected by site-specific conditions and time of sowing, which differed between experiments. Growth of catch crops can also be suppressed by low precipitation. Content of P in roots varied substantially between species, a factor which must be considered in species comparisons. The under-sown species produced more or equivalent amounts of biomass, retained more or equivalent amounts of P in autumn and survived better over winter than the after-sown species. Thus under-sown catch crops generally seem more suitable as catch crops for P.

Keywords: Cover crop, Cropping system, Freezing-thawing cycle, Phosphorus retention, Root, Soil condition

1 Introduction

Mitigation of phosphorus (P) and nitrogen (N) losses from agricultural land to waters is a major challenge for modern agriculture. Crops and cropping systems that can efficiently remove surplus soil nutrients, which would otherwise potentially be lost, needs to be identified. A catch crop (or 'cover crop') can be grown to reduce nutrient losses in the period between two main crops when there is otherwise no crop cover. At present, catch crops are mainly used to mitigate N losses from sandy soils, where N leaching is often a concern (Meissner et al. 1995). Catch crops commonly reduce N leaching by 20-80%, depending on species, with on average a 70% reduction by grass or brassica species and a 20% reduction by legumes (Meisinger et al. 1991; Dabney et al. 2001; Dabney et al. 2010). However, there is lack of knowledge on catch crops for P retention, particularly their potential use on cracking clay soils, which are susceptible to P leaching due to the fast transport of P through the macropores (Jarvis 2007). Successful establishment of catch crops with a high P recovery rate may be the first step in selecting appropriate species, since catch crops with limited biomass and poor root systems probably have limited ability to retain soil P and reduce P losses. On the other hand, catch crops must not compete with main crops for nutrients or water or affect main crop production if they are under-sown.

Many factors affect catch crop growth and their P content. For example, in measurements made 8 weeks after sowing, Eichler-Löbermann et al. (2008) observed about three-fold above-ground biomass and almost two-fold P uptake in oilseed radish, phacelia and ryegrass (*Lolium westerwoldicum*) than in buckwheat (*Fagopyrum esculentum*) and serradella (*Ornithopus sativus*). In addition, Eichler-Löbermann (2004) reported that phacelia and oilseed radish had high P uptake efficiency on loamy soils and that buckwheat and serradella performed best on sandy soils. Other factors, such as climate, also play an important role. For instance, Brant et al. (2011) demonstrated that precipitation before sowing of catch crops and mean air temperature during the growing season are important for final above-ground biomass production by catch crops. In regions with short autumns, as in the Scandinavian countries, it is of particular importance to maximise the growing season of catch crops so as to ensure good biomass production and nutrient uptake (Thorup-Kristensen et al. 2003). Consequently, under-sowing of catch crops in a main crop, allowing their growing season to be prolonged, is an important practice in Scandinavian conditions.

There are a considerable number of reports on above-ground biomass production by catch crops (e.g. Ohlander et al. 1996; Eichler-Löbermann et al. 2008; Brant et al. 2011; Brennan & Boyd 2012). However, information on below-ground biomass production by common catch crops such as perennial ryegrass, oilseed radish, phacelia and white mustard is scarce and uncertain (De Baets et al. 2011). This is mainly because of difficulties in measuring root biomass and wide variations in existing results. This variation is probably caused by differences in the species and varieties tested, soil characteristics, growing period length and weather conditions. Information on root properties is very important for the use of catch crops as green manure or for reducing nutrient leaching (Vos et al. 1998; Thorup-Kristensen et al. 2003; Munkholm & Hansen 2012). Therefore roots should be included in catch crop studies in order to provide a complete picture of their role in P retention. It has been reported that the roots of phacelia, mustard, oats, rye and radish account for approximately 5-25% of total plant biomass (MESAM 2007), while the roots of grass catch crops can comprise as much as 60-90% (Reicosky & Forcella 1998). In a greenhouse study on catch crop retention of P, where eight different species were sown simultaneously in pure sand, Liu et al. (2013) observed a generally higher root:shoot biomass ratio in perennial species (0.4-1.3) than in annual species (0.3-0.6) at harvest.

A substantial amount of plant P may be released from catch crop materials following exposure to freezing-thawing (Bechmann et al. 2005; Liu et al. 2013). This poses an increased risk of P losses to water (Sharpley & Smith 1991; Miller et al. 1994). In particular, the P lost from catch crop tissues is a great concern on clayey soils, where the presence of macropores facilitates fast transport of water and P (Riddle & Bergström, 2013). In a laboratory lysimeter study, Liu et al. (2014) found that repeated freezing-thawing cycles (FTCs) increased potential P leaching from clay soils with catch crops, in particular from soils with perennial ryegrass and oilseed radish. Therefore, the winter hardness and survival rate of catch crops must be considered when selecting appropriate species to mitigate P losses under conditions such as those in northern Europe (Brandsæter & Netland 1999; Brandsæter et al. 2008).

The present study was conducted at six field sites in central and southern Sweden. The main objectives were to determine potential P retention by various catch crops grown on clayey soils in areas with cold winter conditions and a short growing season and to identify factors influencing retention capacity.

2 Materials and Methods

2.1 Experimental sites

Field sites on clayey soils in central and southern Sweden were selected for the study since P losses from agricultural fields via tile drains are a concern in this region. The experimental sites were: Brunnby (59°36'N, 16°39'E), which was used in 2009/2010 (Brunn-9/10); two at Linnés Hammarby (59°49'N, 17°48'E), in 2010/2011 (Linby1-10/11) and 2011/2012 (Linby2-11/12);

and three at Lanna (58°21'N, 13°10'E) in south-west Sweden, in 2009/2010 (Lan-9/10), 2010/2011 (Lan-10/11) and 2011/2012 (Lan-11/12). These experimental sites have been used previously for collecting lysimeters for a P leaching study (Liu et al. 2014). All six sites had a clay (<0.002 mm) content of 44-45% and silt (0.002-0.0625 mm) content of 42-52% in the topsoil (0-0.25 m). The soil at all three locations is classified as silty clay according to the USDA Texture Classes (USDA 1994). The Lanna soil was observed to be firmer and denser than the other two soils. Brunnby and Linnés Hammarby have a long-term (1961-1990) mean annual temperature of 5.3 °C and precipitation of 565 mm, while the corresponding values for Lanna are 6.1 °C and 558 mm. During the recent five years (2007-2012), the annual average number of days with mean air temperature below zero was 78 days at Brunnby, 84 days at Linnés Hammarby and 74 days at Lanna. Moreover, the average day of first autumn frost during this period was day 314 at Brunnby, day 309 at Linnés Hammarby and day 317 at Lanna.

The three experimental sites at Lanna had similar topsoil properties, with plant-available P content of between 34 and 42 mg kg^{-1}, which was also similar to Brunn-9/10 and Linby2-11/12 (Table 1). However, Linby1-10/11 had a much higher available P content in the topsoil, which together with a satisfactory soil structure based on visual inspections provided the best soil conditions for catch crop growth of the six sites tested. The soil at Linby1-10/11 has received large inputs of manure in the past, and later manure and fertilisers, when used for arable crops over the centuries. The site was located upstream of a ditch. Site Linby2-11/12 was located downstream of the same ditch and was historically used for producing animal forage without manure, which resulted in the highest contents of total-C and total-N in the soil of all sites tested, but a lower P content than site Linby1-10/11.

Table 1 Experimental sites, years and mean values of selected physical and chemical properties of the topsoil (0-0.25 m), with standard errors in brackets (n = 4-8)

No.	Exp.	Site	Coordinates	Year	Clay[a]	pH (H_2O)	Total-C	Total-N	P-AL[b]
					%		—— % ——		mg kg^{-1}
Central Sweden									
1	Brunn-9/10	Brunnby	59°36'N, 16°39'E	2009/10	44	6.3 (0.1)	1.7 (0.1)	—	41 (1)
2	Linby1-10/11	Linnés H.	59°49'N, 17°48'E	2010/11	44	6.4 (0.1)	1.9 (0.1)	0.18 (0.01)	142 (12)
3	Linby2-11/12	Linnés H.	59°49'N, 17°48'E	2011/12	44	5.8 (0.2)	6.1 (0.2)	0.47 (0.01)	50 (4)
South-west Sweden									
4	Lan-9/10	Lanna	58°21'N, 13°10'E	2009/10	45	6.5 (0.1)	2.2 (0.1)	0.16 (0.01)	34 (1)
5	Lan-10/11	Lanna	58°21'N, 13°10'E	2010/11	45	6.9 (0.1)	—	—	39 (1)
6	Lan-11/12	Lanna	58°21'N, 13°10'E	2011/12	45	6.8 (0)	—	—	42 (2)

[a]Fraction <0.002 mm; [b]P extracted with the ammonium lactate method (Egnér et al. 1960).

2.2 Experimental design and measurements

Eight catch crop species were included in the study. These were four perennial species: ryegrass (*Lolium perenne* L. var. Helmer), cocksfoot (*Dactylis glomerata* L. var. Luxor), chicory (*Cichorium intybus* L. var. Puna) and red clover (*Trifolium pratense* L. var. Vivi); and four annual species: phacelia (*Phacelia tanacetifolia* L. var. Stala), white mustard (*Sinapis alba* L. var. Achilles), oilseed radish (*Raphanus sativus* var. *oleiformis* 'Adios') and white radish (*R. sativus* var. *longipinnatus* 'Structurator'). Each species was tested at four or six sites except phacelia, which was included only at two sites in 2009/2010 (Table 2), as it was obviously sensitive to frost and thus considered unsuitable for Swedish climate conditions (Liu et al. 2014). Full details of these catch crops, including descriptions on roots, can be found in Liu et al. (2013).

Table 2 Catch crop species grown at the six different sites and dates of sowing, biomass and soil sampling, and survival rate determination

Site	Sowing				Sampling	Survival rate determination
	Under-sown[a]		After-sown[b]			
	Species	Date	Species	Date	Date	Date
Brunn-9/10	CH, CO, PR	12 May, 09	OR, PH, WR	7 Aug., 09	6 Nov., 09	—
Linby1-10/11	CH, CO, PR, RC	12 May, 10	OR, WM, WR	7 Aug., 10	27 Oct., 10	5 Apr., 11
Linby2-11/12	CH, CO, PR, RC	5 May, 11	OR, WM, WR	10 Aug., 11	25 Oct., 11	4 Apr., 12
Lan-9/10	CH, CO, PR	12 May, 09	OR, PH, WR	7 Aug., 09	16 Nov., 09	7 Apr., 10
Lan-10/11	CH, CO, PR, RC	12 May, 10	OR, WM, WR	7 Aug., 10	3 Nov., 10	6 Apr., 11
Lan-11/12	CH, CO, PR, RC	4 May, 11	OR, WM, WR	17 Aug., 11	8 Nov., 11	3 Apr., 12

[a]Perennial species under-sown in barley; [b]annual species after-sown following after harvest of barley; CH=chicory, CO=cocksfoot, PR=perennial ryegrass, RC=red clover, OR=oilseed radish, PH=phacelia, WM=white mustard, WR=white radish.

Sowing of catch crops and management in the field are described in detail in Liu et al. (2014). In brief, a randomised complete block design was used, with catch crop species as treatments and with four replicates. At all sites, the perennial species (seed rate 8 kg ha^{-1}) were under-sown in spring barley (*Hordeum vulgare* L.) in May (Table 2). The annual species (20 kg ha^{-1}) were sown in early August, one day after harvest of barley, at all sites except Lan-11/12, where the annual crops were sown 11 days after harvest due to heavy rain in the days after harvest of barley. This resulted in sowing of annual species at Lan-11/12 taking place 7-10 days later than at other sites (Table 2). At Brunn-9/10, only two replicate plots, located at each end of the field, were used for white radish. At the time of barley sowing, mineral fertiliser (80 kg N ha^{-1}, 20 kg P ha^{-1} and 20 kg K ha^{-1}) was applied according to general practice for barley production in the area. An additional 25 kg N ha^{-1} were applied at sowing of the annual species to reduce the risk of N limiting catch crop growth. For each plot, barley grains together with straw were harvested with a combine and their fresh weight was determined; above-ground biomass of barley was calculated based on the fresh weight in the plot and dry matter content that was determined after drying of a subsample.

Meteorological data, including daily air temperature, daily precipitation and solar radiation during the 3-year experimental period, were measured at the nearest weather station. Air temperature sum and precipitation sum during barley growth and during annual catch crop growth and the number of FTCs over winter are shown in Table 3. Full details of monthly air temperature sum and precipitation sum during the period from under-sowing of catch crops to determination of catch crop biomass in autumn are presented in Suppl. Table 1. Values of weather variables differed considerably between sites. In particular, low precipitation was observed during day 1 to day 30 (24 mm) after under-sowing of catch crops and again during day 61 to day 90 (22 mm) at Linby2-11/12. Even lower precipitation was observed during day 61 to day 90 (1 mm) at Lan-11/12 (Suppl. Table 1).

Table 3 Meteorological variables (air temperature sum, precipitation sum, solar radiation sum and number of freezing-thawing cycles (FTCs)) at the experimental sites during the catch crop growing period

Site	Pre-growth[a]		Growth[b]			Post-growth[c]				
	Temp. sum (Day °C)	Prec. sum (mm)	Temp. sum (Day °C)	Prec. sum (mm)	Solar radiation sum (MJ m^{-2})	Temp. mean (°C)	Temp. min (°C)	Temp. max (°C)	FTCs no.	Prec. sum (mm)
Brunn-9/10	1290	223	960	209	—	-3.5	-21.4	9.9	5	233
Linby1-10/11	1410	245	830	213	695	-4.1	-25.3	8.9	17	172
Linby2-11/12	1570	124	910	233	684	0.7	-19.3	10.7	11	201
Lan-9/10	1330	178	1020	147	376	-3.4	-18.5	9.2	5	171
Lan-10/11	1280	275	920	158	763	-3.0	-14.6	6.9	13	138
Lan-11/12	1550	281	930	223	569	1.4	-15.1	10.9	14	142

[a]From sowing of barley to harvest; [b]from sowing of annual catch crops to autumn sampling; [c]from autumn sampling to spring survival rate determinations. For specific dates of sowing, sampling and survival determinations, see Table 2.

Plant material and soil (0-0.25 m deep) were sampled in late October or early November, before first frost but during the winter hardening process, when no more growth was expected, on the dates shown in Table 2. An above-ground plant sample (0.25 m^2) was taken in each plot at all sites, while root samples (0.03 m^2, 0-0.25 m depth) were taken in one or two blocks at each site in 2010 and 2011, respectively, as described by Liu et al. (2014). Dry matter yield was determined after drying the material at 50 °C for 72 hours. Total-P concentration in each sample was determined using inductively coupled plasma spectrometry (ICP; Perkin Elmer, Wellesley, America) after digesting the sample with concentrated HNO_3. Biomass (kg ha^{-1}) and plant P concentration (mg kg^{-1}) data were used to calculate plant P content (kg ha^{-1}) in the different plant fractions and on a whole-plant basis. As root samples were not taken in 2009, mean root:shoot biomass ratio and root P concentration for each species in 2010 and 2011 were used for calculation of whole-plant P content at the respective site within the same cropping region. The number of soil samples for determination of basic soil properties differed between sites. At Brunn-9/10, Lan-9/10 and Lan-10/11, one sample, comprising four subsamples (one from each block), was taken for each species. At Linby1-10/11, Linby2-11/12 and Lan-11/12, one sample, comprising eight subsamples (one from each species), was taken from each block. Plant-available P in the soil was determined as ammonium lactate-extractable P (P-AL) according to Egnér et al. (1960). All plant and soil data presented in this paper are on a dry matter (DM) basis unless otherwise stated.

2.3 Catch crop survival and coverage

Survival rate and catch crop coverage of the soil surface were determined in spring (Table 2), in order to estimate the destructive effects of winter on the catch crops. The crop survival rate in each plot was estimated by counting the number of surviving plants as a percentage of the total number of living and dead plants observed within an area of 0.25 m^2. The coverage was estimated by an experienced field researcher. The coverage in spring was compared with that in the previous autumn, determined on the same day as sampling. The survival and coverage rates were then used to indicate P retention in the catch crops after winter. The number of FTCs at the experimental sites during the period from sampling in autumn to survival rate determination in spring was estimated by assuming that each FTC represented a change in daily mean air temperature from below to above zero (Colleuille et al. 2007).

2.4 Data analyses

The Mixed model (Littell et al. 2006) in SAS (Version 9.2) was used to test for differences in catch crop biomass, P concentration and P content between sites and species. Statistical analyses were performed for individual sites and all sites. In tests for an individual site, species was the sole fixed factor, while in tests for all sites both species and site were considered as fixed factors. The effects of block and plot were assumed to be random. The mean values presented are estimates from the model and values of $LSD_{0.05}$ (least significant difference at $\alpha = 0.05$) were calculated when the main effect was significant. A contrast statement was used to compare the differences between annual and perennial catch crops. The residuals of the data followed a normal distribution, according to tests carried out before analysis of treatment effects.

3 Results

3.1 Catch crop biomass

Above-ground and total biomass both differed significantly between catch crop species ($p<0.0001$). Based on statistical analysis of the whole dataset, ryegrass and cocksfoot had the largest amount of above-ground biomass among the perennial species under-sown in barley, while phacelia and white radish had the most above-ground biomass among the annual species after-sown following harvest of barley. However, red clover had significantly higher or similar amounts of total biomass than all other species at the four sites where it was grown (Figure 1). Moreover, chicory had rather high amounts of total biomass at sites Linby1-10/11 and Linby2-11/12. The high ranking of red clover and chicory was mainly attributable to their high amount of root biomass, which contributed 47-80% of total biomass in red clover and 50-69% in chicory, but only 12-37% in the other species (Figure 1). In addition, total catch crop biomass differed significantly with experimental conditions (p<0.0001), decreasing in the order Linby1-10/11 > Brunn-9/10 ≈ Linby2-11/12 > Lan-9/10 ≈ Lan-10/11 > Lan-11/12 (Figure 1). The two sites at Linnés Hammarby produced similar amounts of catch crop biomass when the catch crops were sown after harvest of barley, but Linby1-10/11 produced much more biomass of the under-sown species than Linby2-11/12. Site Lan-11/12 produced low biomass of both under-sown and after-sown species.

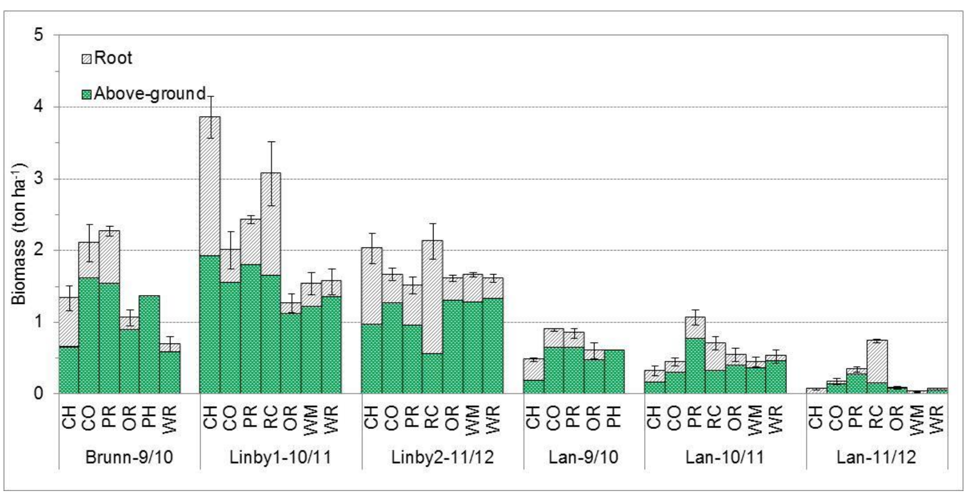

Figure 1 Above-ground and root biomass of catch crops in autumn at the six field sites. Error bars indicate standard error of total biomass (n = 2 for white radish in Brunn-9/10; otherwise n = 4). CH = chicory; CO = cocksfoot; PR = perennial ryegrass; RC = red clover; OR = oilseed radish; PH = phacelia; WM = white mustard; WR = white radish.

Despite the considerable biomass production by the catch crops that were under-sown in barley, they did not significantly affect barley biomass (sum of grain and straw) compared with the control without a catch crop at any site. Barley biomass ranged from 5.2 to 7.4 ton ha^{-1} in the control and from 5.3 to 7.7 ton ha^{-1} in the plots with catch crops (Table 4).

Table 4 Mean barley biomass (sum of grain and straw, ton ha^{-1}) in plots with under-sown catch crops and a control without a catch crop at harvest in August, with standard error in brackets (n = 4)

	Brunn-9/10	Linby1-10/11	Linby2-11/12	Lan-9/10	Lan-10/11	Lan-11/12
Chicory	5.59 (0.18)	5.89 (0.65)	6.06 (0.42)	7.69 (0.16)	5.68 (0.20)	7.01 (0.52)
Cocksfoot	5.37 (0.07)	5.63 (0.52)	6.06 (0.39)	7.73 (0.43)	5.25 (0.25)	6.83 (0.49)
Ryegrass	5.40 (0.33)	6.26 (0.54)	6.44 (0.12)	7.50 (0.30)	5.62 (0.36)	6.28 (0.36)
Red clover	—	6.29 (0.50)	6.24 (0.26)	—	5.30 (0.16)	6.80 (0.79)
Control	5.59 (0.22)	5.18 (0.66)	6.27 (0.25)	7.36 (0.68)	5.73 (0.28)	5.80 (0.31)

3.2 Phosphorus in catch crops in autumn

The concentration of P in above-ground parts of the catch crops differed significantly with species (p<0.0001) and site (p<0.0001). White radish had the highest P concentration of all species, followed by oilseed radish, white mustard, phacelia and the perennials (Table 5). Chicory had the highest P concentration of the perennials and red clover the lowest, with cocksfoot and ryegrass intermediate. All species except red clover and cocksfoot had higher P concentrations at Linby1-10/11, with its high soil P-AL, than at the other five sites. With regard to roots, the P concentration was generally higher in non-grass species than in grass species (Table 5).

Table 5 Mean concentration of total-P (g kg^{-1} DM) in above-ground plant parts (n = 2 for white radish in Brunn-9/10; otherwise n = 4, standard errors in brackets) and roots (n = 1 or 2) of catch crops in autumn

	Above-ground parts						Roots			
	Brunn-9/10	Linby1-10/11	Linby2-11/12	Lan-9/10	Lan-10/11	Lan-11/12	Linby1-10/11	Linby2-11/12	Lan-10/11	Lan-11/12
Chicory	3.53 (0.23)	3.98 (0.12)	2.70 (0.18)	3.01 (0.17)	3.73 (0.18)	3.35 (0.31)	3.16	2.34	3.03	2.62
Cocksfoot	2.53 (0.04)	3.18 (0.08)	3.13 (0.08)	2.50 (0.05)	3.73 (0.13)	3.01 (0.27)	2.37	2.23	1.30	1.24
Ryegrass	2.27 (0.04)	3.42 (0.09)	3.02 (0.22)	2.35 (0.08)	3.20 (0.11)	2.84 (0.08)	1.87	1.93	1.61	1.36
Red clover	—	2.52 (0.05)	2.74 (0.07)	—	2.74 (0.17)	2.63 (0.17)	3.68	3.27	4.25	4.45
Oilseed radish	3.84 (0.18)	4.99 (0.12)	3.56 (0.13)	3.28 (0.18)	4.83 (0.22)	4.84 (0.14)	3.78	2.50	3.60	3.87
Phacelia	3.67 (0.10)	—	—	3.03 (0.08)	—	—	—	—	—	—
White mustard	—	4.92 (0.15)	3.17 (0.26)	—	3.16 (0.21)	3.53 (0.19)	3.03	2.15	2.18	2.67
White radish	4.41 (0.42)	5.34 (0.15)	3.81 (0.20)	—	4.83 (0.06)	4.79 (0.05)	3.66	2.89	4.66	4.31

Total P content (kg ha^{-1}) in whole plants ranged from 0.1-2 kg ha^{-1} at Lan-11/12 to 6-15 kg ha^{-1} at Linby1-10/11 (Figure 2), and differed significantly between species (p<0.0001). The total P content and proportions of root P are presented in a related paper, in which the plant P content was related to P leaching (Liu et al. 2014). Contribution of roots to total P content followed a similar pattern to their contribution to biomass, indicating a relatively smaller influence of P concentration on P retention. The contribution of root P to total P was greater in red clover (56-86%) and chicory (45-67%) than in the other species (7-27%; Liu et al. 2014). On average for all sites, this resulted in red clover having the significantly greatest whole-plant P content among all species tested and in chicory having a significantly greater P content than oilseed radish, cocksfoot and white mustard, despite red clover and chicory having overall medium or small amounts of above-ground biomass. Consistent with the biomass relationships, the under-sown perennials contained similar amounts of P as the annuals at Brunn-9/10, Linby2-11/12, Lan-9/10 and Lan-10/11 and contained more P than the annuals at Linby1-10/11 and Lan-11/12 ($p<0.0001$).

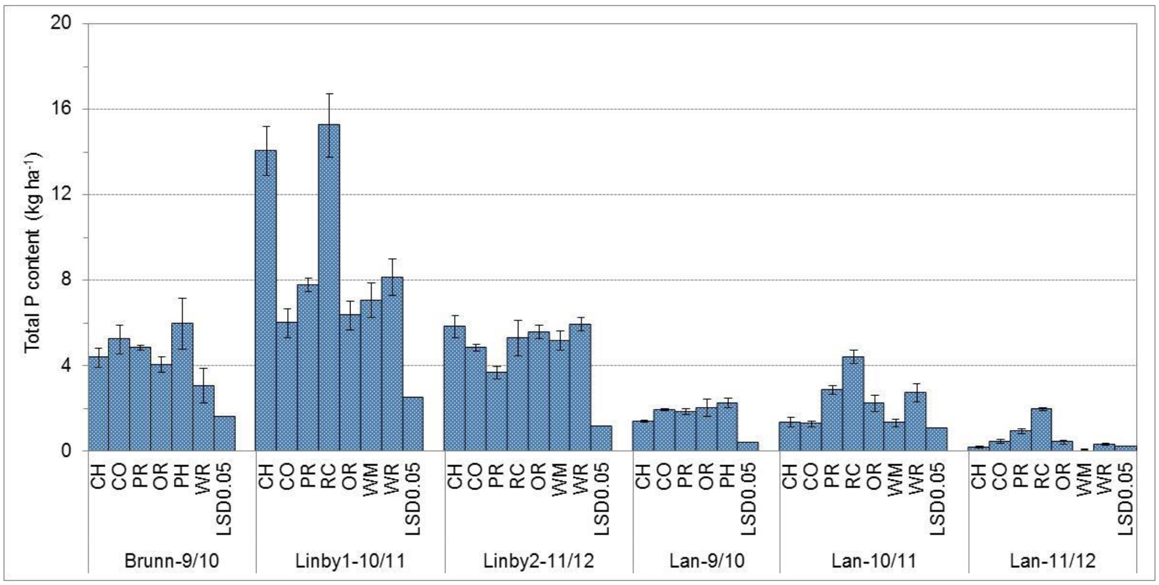

Figure 2 Whole-plant P content in autumn in catch crops at the six field sites. Mean with standard error as error bars (n = 2 for white radish in Brunn-9/10; otherwise n = 4). $LSD_{0.05}$ is shown as a column for each site.

3.3 Catch crop survival over winter

The rate of winter survival differed substantially between catch crop species (Table 6). On average, perennial species had a survival rate of >70% after 5-17 FTCs at the experimental sites during each winter. In spring, new shoots started to replace the old ones, which mostly died off, became dry and partly remained on the soil surface. The roots of perennial species seemed to survive the winter, although the extent of root damage by freezing-thawing or other winter stresses is unknown. In contrast, all plants of the annual species were killed off at all sites, with dry shoots remaining on the surface, being carried off by water or wind or decomposing. In particular, the fleshy radish roots rotted and completely disappeared due to winter stresses and wash by percolating water. This may have resulted in release of most of the P they contained to the soil, which could have amounted to e.g. the 8 kg ha^{-1} that was retained in white radish in autumn at Linby1-10/11. Phacelia seemed to be the most frost-sensitive species of all species tested in this study. At Brunn-9/10, observations made in December (one month after the field sampling), when only two FTCs had taken place, showed that 80% of phacelia was already frost-damaged, while the other species were only 0-15% damaged.

Table 6 Survival rate (%) of the catch crops over winter, as a percentage of the total number of living and dead plants observed and with standard error in brackets (n=4)

Catch crop	Linby1-10/11	Linby2-11/12	Lan-9/10	Lan-10/11	Lan-11/12	Mean
Chicory	91 (1)	91 (2)	70 (7)	56 (2)	71 (11)	76
Cocksfoot	92 (2)	89 (4)	96 (2)	64 (4)	79 (9)	84
Ryegrass	94 (1)	79 (1)	83 (3)	81 (1)	53 (5)	78
Red clover	94 (2)	90 (2)	—	84 (2)	20 (4)	72
Annuals	0	0	0	0	0	0

4 Discussion

In autumn, biomass and whole plant P content varied widely between species. The perennial catch crop species frequently had greater total biomass and retention of P than the annual species, due to relatively larger root:shoot biomass ratio. This was despite the fact that the annual species had comparable (e.g. in Lan-9/10 and Lan-10/11) or even slightly larger (e.g. in Linby2-11/12) amounts of above-ground biomass and higher P concentrations than the perennials. Higher P concentrations in annuals than in perennial species have also been reported in a greenhouse study on catch crops sown simultaneously (Liu et al. 2013). The reason for the different concentrations is probably that annual species need to put more effort into reproduction and into sustaining a high relative growth rate than the perennials, and therefore need a higher concentration of P for cell division at the growing points (Primack 1979; Garnier 1992). Red clover showed the greatest retention of P at three of the four sites at which it was sown, due to its great biomass, particularly in the roots. At the fourth site, its P retention did not differ significantly from the highest retention of other species. For the same reason, chicory retained a relatively large amount of P at the Linnés Hammarby and Brunnby locations. Red clover and chicory were under-sown with barley in spring, which allowed a longer period for root establishment and growth. However, ryegrass and cocksfoot, which were also under-sown with barley, had relatively low root biomass (21-37% of total biomass). In contrast, Reicosky and Forcella (1998) reported that roots can comprise as much as 60-90% of total biomass in grass catch crops. However, similarly to the present study, Zagal et al. (2001) observed that the root:shoot biomass ratio of chicory was 2.9-3.6 fold higher than that of ryegrass. This difference may be due to the fact that root characteristics differ between species. Liu et al. (2013) determined root characteristics of the same eight catch crop species as were used in the present investigation and observed a larger root volume per unit surface area in taproots of non-grass species (0.096-0.106 mm) than in fibrous roots of grasses (0.068-0.083 mm). Taproots may be able to store more P than fibrous roots due to both the larger root volume and the greater biomass. However, the low frequency of root sampling to a limited soil depth (0.25 m) and the subsequent washing of roots may have caused a slight underestimation of total-P content of grasses with their many tiny roots.

There is often concern about main crop production when under-sowing a catch crop in spring cereals. For example, Känkänen and Eriksson (2007) found that many of the 17 under-sown catch crop species they investigated reduced grain yield of spring barley due to strong competition for light, water and nutrients. However, this was not observed in the present study, where under-sowing of catch crops did not significantly affect barley biomass at any site (Table 4), as also reported by e.g. Ohlander et al. (1996). The seed rate used here was smaller than that used by Känkänen and Eriksson (2007), which might explain the different effects of catch crops on barley yield. Thus, in regions with cold winter conditions and a short growing season, perennial species can be under-sown at appropriate seed rates with the main crop to maximise removal of P from clayey soils, without causing a notable reduction in cereal yield.

A somewhat surprising finding was that temperature did not seem to affect growth of annual catch crops sown after harvest of barley. The three sites to the north, Brunn-9/10, Linby1-10/11 and Linby2-11/12, with fewer day degrees for catch crop growth during autumn, yielded more biomass of e.g. radishes than the Lanna sites. In particular, the biomass at Linby1-10/11 was very high for Swedish conditions, despite this site having a low temperature sum during growth of annual catch crops compared with the other sites (Table 3). Brant et al. (2011) concluded that mean air temperature during catch crop growing season can substantially affect biomass production. In the present study, however, there was no clear evidence that temperature could explain differences in biomass of catch crops between sites.

Biomass and P retention of the under-sown catch crops seemed to be greatly affected by precipitation sum during a certain period. Linby2-11/12 had much lower biomass of under-sown catch crops than Linby1-10/11, despite similar biomass of after-sown catch crops (Figure 1). Growth of under-sown catch crops at Linby2-11/12 was probably suppressed before harvest of barley. It was quite dry during day 1 to day 30 and during day 61 to day 90 after under-sowing of catch crops (both < 25 mm precipitation) at Linby2-11/12 (Suppl. Table 1). Schrøder et al. (1997) showed that high precipitation during summer promotes growth of under-sown catch crops during the whole season. The under-sown crops probably suffered more than the barley during the dry summer at Linby2-11/12. The barley biomass was not affected by the under-sown catch crops in spite of the competition, probably because the faster growing barley had better access to groundwater and was less dependent on rain (Table 4). Similarly, overall low biomass of under-sown catch crops at Lan-11/12 was likely to be a result of dry soil conditions (only 1 mm precipitation) during day 61-90 after under-sowing.

The catch crops at all sites were fertilised with 25 kg N ha^{-1} at sowing of annual species and this, together with N potentially mineralised in the soil, seemed to be enough to ensure catch crop needs at Lanna, where total biomass production was well below 1 ton ha^{-1} for most species during the three years (Figure 1). Thus, the relatively poorer biomass production and retention of P at the Lanna sites was most likely because despite having similar texture to the Brunnby and Linnés Hammarby soils, the Lanna soil was distinctly firmer and denser, which probably limited root penetration and catch crop growth. In a previous lysimeter study, Liu et al. (2014) observed generally poorer water infiltration in the Lanna soil than in the other two soils. This stresses the importance of soil structure in catch crop establishment on clayey soils. Moreover, crop biomass production and P retention in autumn seemed to be influenced by soil P content. The Linby1-10/11 soil, which had a very high content of P-AL, produced the largest mean biomass for all catch crops over all sites, and also resulted in the highest concentrations of P in most species.

The lowest catch crop biomass production occurred at Lan-11/12. Low biomass of under-sown species is probably often a result of dry soil conditions, as discussed above, at least at the low yield levels seen in the present study. The low biomass of after-sown species could also be explained by dry conditions during establishment causing poor germination and early growth, but was probably largely determined by the time of sowing. It has been reported previously that late sowing greatly affects early growth of catch crops, consequently limiting their water and nutrient uptake efficiency and growth in later periods (Thorup-Kristensen et al. 2003). Moreover, crop failure and low nutrient uptake due to late sowing can be the result of unfavourable temperature, low radiation levels and N limitation if substantial N leaching occurs prior to sowing (Vos & van der Putten 1997), or if N is volatilised to the air. At Lan-11/12, a considerable amount of soil N might have been lost before establishment of the annual species, as the soil was very wet (80 mm precipitation) during the first two weeks after sowing. In autumn, the catch crops at Lan-11/12 showed 15-65% coverage of the soil surface, which was very low compared with the other sites (90-100%).

It has been reported that repeated FTCs of catch crop plants can cause up to 50-100% of the P release from above-ground parts and 60-100% of the P release from roots (Liu et al. 2013). In the present study, most of the above-ground parts and some of the roots of perennial species and all the biomass of annuals were damaged by frost or other stresses during winter. Most of the P previously stored in these damaged parts would potentially have been released and returned to the soil. This is meaningful for crop growth in the following growing season. However, part of the P released from the catch crop biomass is likely to have been lost from the system by surface runoff or leaching during winter and early spring, contributing to the risk of eutrophication in neighbouring streams. This is a particular concern on clayey soils such as those in this study, where P may be transported through macropore flow pathways before sufficient sorption occurs (Riddle & Bergström, 2013). For example, in a laboratory lysimeter study with intact clayey soils and catch crops sampled from the same sites as those used in the present study, the total-P concentration in leachate increased after FTCs compared with before in 95 out of 140 lysimeters (Liu et al. 2014). In addition, P losses from plant tissues can vary greatly in different climate conditions and can be strongly elevated by severe freezing-thawing episodes in early autumn followed by early snowfall, a prolonged period with snow coverage and relatively high winter temperatures (Sturite et al. 2007). Therefore, in regions where FTCs are coupled with high precipitation in winter (e.g. 5-17 FTCs and 138-233 mm precipitation during winters in this study), more attention should be paid to potential P losses from plant materials when catch crops are used. In such cases, high uptake and storage of P in catch crops in summer and autumn may be a disadvantage in terms of P losses to water.

5 Conclusions

Catch crop biomass production and P retention in autumn were greatly influenced by choice of species, but time of sowing and site-specific conditions seemed to have an even greater influence. We found no effect of temperature on biomass and P retention of catch crops sown after harvest of barley, but low precipitation greatly suppressed growth of catch crops under-sown in barley. Under-sown perennial species had higher or equivalent amounts of biomass and P in autumn, often because of their higher root yields, and survived better over winter than annual species sown after harvest of the main crop. The under-sown species therefore appear superior to the annual species as catch crops for P. Roots must be considered when comparing total catch crop biomass and P retention between species, as root:shoot ratio can differ substantially between species. Biomass seemed to have more influence than P concentration on content of P in each species. Further research is needed to investigate the effect of P retention by catch crops on P turnover in soil and P losses to water over their entire life cycle.

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Appendix A. Supplementary data

Supplementary data (Suppl. Table 1) associated with this article can be found in the online version.

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Supplementary Table 1: Temporal changes in meteorological variables (air temperature (Temp.) sum, precipitation (Prec.) sum and solar radiation sum) at the experimental sites during the period from sowing of barley and under-sowing of catch crops to determination of catch crop biomass in autumn

Site	Pre-growth[a]			Growth[b]		
	Day 1-30[c]	Day 31-60[c]	Day 61-90[c]	Day 91-120[c]	Day 121-150[c]	Day 151-180[c]
Temp. sum (Day °C)						
Brunn-9/10	345	480	544	469	295	117
Linby1-10/11	387	500	578	417	308	52
Linby2-11/12	380	507	547	477	391	172
Lan-9/10	366	503	520	481	313	132
Lan-10/11	368	445	516	433	328	127
Lan-11/12	340	461	513	468	387	242
Prec. sum (mm)						
Brunn-9/10	55	125	44	114	59	37
Linby1-10/11	71	63	131	85	76	32
Linby2-11/12	24	62	22	134	65	51
Lan-9/10	33	71	74	52	41	43
Lan-10/11	71	52	162	76	39	33
Lan-11/12	49	171	1	141	98	44
Solar radiation sum (MJ m^{-2})						
Brunn-9/10	–	–	–	–	–	–
Linby1-10/11	540	574	514	363	219	91
Linby2-11/12	548	574	529	413	269	118
Lan-9/10	297	268	192	171	121	48
Lan-10/11	526	693	475	383	240	116
Lan-11/12	553	611	537	434	270	123

[a]From sowing of barley to harvest; [b]from sowing of annual catch crops to autumn sampling; [c]days counted from sowing of barley and under-sowing of catch crops.