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1 **Title page**

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

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6

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13

14 **Abstract**

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

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

35

36 **1 Introduction**

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

53 Many factors affect catch crop growth and their P content. For example, in measurements
54 made 8 weeks after sowing, Eichler-Löbermann et al. (2008) observed about three-fold above-
55 ground biomass and almost two-fold P uptake in oilseed radish, phacelia and ryegrass (*Lolium*
56 *westerwoldicum*) than in buckwheat (*Fagopyrum esculentum*) and serradella (*Ornithopus*
57 *sativus*). In addition, Eichler-Löbermann (2004) reported that phacelia and oilseed radish had
58 high P uptake efficiency on loamy soils and that buckwheat and serradella performed best on

59 sandy soils. Other factors, such as climate, also play an important role. For instance, Brant et al.
60 (2011) demonstrated that precipitation before sowing of catch crops and mean air temperature
61 during the growing season are important for final above-ground biomass production by catch
62 crops. In regions with short autumns, as in the Scandinavian countries, it is of particular
63 importance to maximise the growing season of catch crops so as to ensure good biomass
64 production and nutrient uptake (Thorup-Kristensen et al. 2003). Consequently, under-sowing of
65 catch crops in a main crop, allowing their growing season to be prolonged, is an important
66 practice in Scandinavian conditions.

67 There are a considerable number of reports on above-ground biomass production by catch
68 crops (e.g. Ohlander et al. 1996; Eichler-Löbermann et al. 2008; Brant et al. 2011; Brennan &
69 Boyd 2012). However, information on below-ground biomass production by common catch
70 crops such as perennial ryegrass, oilseed radish, phacelia and white mustard is scarce and
71 uncertain (De Baets et al. 2011). This is mainly because of difficulties in measuring root biomass
72 and wide variations in existing results. This variation is probably caused by differences in the
73 species and varieties tested, soil characteristics, growing period length and weather conditions.
74 Information on root properties is very important for the use of catch crops as green manure or for
75 reducing nutrient leaching (Vos et al. 1998; Thorup-Kristensen et al. 2003; Munkholm & Hansen
76 2012). Therefore roots should be included in catch crop studies in order to provide a complete
77 picture of their role in P retention. It has been reported that the roots of phacelia, mustard, oats,
78 rye and radish account for approximately 5-25% of total plant biomass (MESAM 2007), while
79 the roots of grass catch crops can comprise as much as 60-90% (Reicosky & Forcella 1998). In a
80 greenhouse study on catch crop retention of P, where eight different species were sown

81 simultaneously in pure sand, Liu et al. (2013) observed a generally higher root:shoot biomass
82 ratio in perennial species (0.4-1.3) than in annual species (0.3-0.6) at harvest.

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

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

97 **2 Materials and Methods**

98 **2.1 Experimental sites**

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

103 and three at Lanna (58°21'N, 13°10'E) in south-west Sweden, in 2009/2010 (Lan-9/10),
104 2010/2011 (Lan-10/11) and 2011/2012 (Lan-11/12). These experimental sites have been used
105 previously for collecting lysimeters for a P leaching study (Liu et al. 2014). All six sites had a
106 clay (<0.002 mm) content of 44-45% and silt (0.002-0.0625 mm) content of 42-52% in the
107 topsoil (0-0.25 m). The soil at all three locations is classified as silty clay according to the USDA
108 Texture Classes (USDA 1994). The Lanna soil was observed to be firmer and denser than the
109 other two soils. Brunnby and Linnés Hammarby have a long-term (1961-1990) mean annual
110 temperature of 5.3 °C and precipitation of 565 mm, while the corresponding values for Lanna are
111 6.1 °C and 558 mm. During the recent five years (2007-2012), the annual average number of
112 days with mean air temperature below zero was 78 days at Brunnby, 84 days at Linnés
113 Hammarby and 74 days at Lanna. Moreover, the average day of first autumn frost during this
114 period was day 314 at Brunnby, day 309 at Linnés Hammarby and day 317 at Lanna.

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

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

No.	Exp.	Site	Coordinates	Year	Clay ^a %	pH (H ₂ O)	Total-C — % —	Total-N — % —	P-AL ^b mg kg ⁻¹
<u>Central Sweden</u>									
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)
<u>South-west Sweden</u>									
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)

127 ^aFraction <0.002 mm; ^bP extracted with the ammonium lactate method (Egnér et al. 1960).

128

129 2.2 Experimental design and measurements

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

139

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

Site	Sowing				Sampling Date	Survival rate determination Date
	Under-sown ^a		After-sown ^b			
	Species	Date	Species	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

142 ^aPerennial species under-sown in barley; ^bannual species after-sown following after harvest of barley; CH=chicory,
 143 CO=cocksfoot, PR=perennial ryegrass, RC=red clover, OR=oilseed radish, PH=phacelia, WM=white mustard,
 144 WR=white radish.

145 Sowing of catch crops and management in the field are described in detail in Liu et al.
 146 (2014). In brief, a randomised complete block design was used, with catch crop species as
 147 treatments and with four replicates. At all sites, the perennial species (seed rate 8 kg ha⁻¹) were
 148 under-sown in spring barley (*Hordeum vulgare* L.) in May (Table 2). The annual species (20 kg
 149 ha⁻¹) were sown in early August, one day after harvest of barley, at all sites except Lan-11/12,
 150 where the annual crops were sown 11 days after harvest due to heavy rain in the days after
 151 harvest of barley. This resulted in sowing of annual species at Lan-11/12 taking place 7-10 days
 152 later than at other sites (Table 2). At Brunn-9/10, only two replicate plots, located at each end of
 153 the field, were used for white radish. At the time of barley sowing, mineral fertiliser (80 kg N ha⁻¹
 154 ¹, 20 kg P ha⁻¹ and 20 kg K ha⁻¹) was applied according to general practice for barley production
 155 in the area. An additional 25 kg N ha⁻¹ were applied at sowing of the annual species to reduce the
 156 risk of N limiting catch crop growth. For each plot, barley grains together with straw were
 157 harvested with a combine and their fresh weight was determined; above-ground biomass of

158 barley was calculated based on the fresh weight in the plot and dry matter content that was
 159 determined after drying of a subsample.

160 Meteorological data, including daily air temperature, daily precipitation and solar radiation
 161 during the 3-year experimental period, were measured at the nearest weather station. Air
 162 temperature sum and precipitation sum during barley growth and during annual catch crop
 163 growth and the number of FTCs over winter are shown in Table 3. Full details of monthly air
 164 temperature sum and precipitation sum during the period from under-sowing of catch crops to
 165 determination of catch crop biomass in autumn are presented in Suppl. Table 1. Values of
 166 weather variables differed considerably between sites. In particular, low precipitation was
 167 observed during day 1 to day 30 (24 mm) after under-sowing of catch crops and again during day
 168 61 to day 90 (22 mm) at Linby2-11/12. Even lower precipitation was observed during day 61 to
 169 day 90 (1 mm) at Lan-11/12 (Suppl. Table 1).

170 Table 3 Meteorological variables (air temperature sum, precipitation sum, solar radiation sum
 171 and number of freezing-thawing cycles (FTCs)) at the experimental sites during the catch crop
 172 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

173 ^aFrom sowing of barley to harvest; ^bfrom sowing of annual catch crops to autumn sampling; ^cfrom autumn sampling
 174 to spring survival rate determinations. For specific dates of sowing, sampling and survival determinations, see Table
 175 2.

176 Plant material and soil (0-0.25 m deep) were sampled in late October or early November,
177 before first frost but during the winter hardening process, when no more growth was expected,
178 on the dates shown in Table 2. An above-ground plant sample (0.25 m²) was taken in each plot at
179 all sites, while root samples (0.03 m², 0-0.25 m depth) were taken in one or two blocks at each
180 site in 2010 and 2011, respectively, as described by Liu et al. (2014). Dry matter yield was
181 determined after drying the material at 50 °C for 72 hours. Total-P concentration in each sample
182 was determined using inductively coupled plasma spectrometry (ICP; Perkin Elmer, Wellesley,
183 America) after digesting the sample with concentrated HNO₃. Biomass (kg ha⁻¹) and plant P
184 concentration (mg kg⁻¹) data were used to calculate plant P content (kg ha⁻¹) in the different plant
185 fractions and on a whole-plant basis. As root samples were not taken in 2009, mean root:shoot
186 biomass ratio and root P concentration for each species in 2010 and 2011 were used for
187 calculation of whole-plant P content at the respective site within the same cropping region. The
188 number of soil samples for determination of basic soil properties differed between sites. At
189 Brunn-9/10, Lan-9/10 and Lan-10/11, one sample, comprising four subsamples (one from each
190 block), was taken for each species. At Linby1-10/11, Linby2-11/12 and Lan-11/12, one sample,
191 comprising eight subsamples (one from each species), was taken from each block. Plant-
192 available P in the soil was determined as ammonium lactate-extractable P (P-AL) according to
193 Egnér et al. (1960). All plant and soil data presented in this paper are on a dry matter (DM) basis
194 unless otherwise stated.

195 **2.3 Catch crop survival and coverage**

196 Survival rate and catch crop coverage of the soil surface were determined in spring (Table 2), in
197 order to estimate the destructive effects of winter on the catch crops. The crop survival rate in
198 each plot was estimated by counting the number of surviving plants as a percentage of the total

199 number of living and dead plants observed within an area of 0.25 m². The coverage was
200 estimated by an experienced field researcher. The coverage in spring was compared with that in
201 the previous autumn, determined on the same day as sampling. The survival and coverage rates
202 were then used to indicate P retention in the catch crops after winter. The number of FTCs at the
203 experimental sites during the period from sampling in autumn to survival rate determination in
204 spring was estimated by assuming that each FTC represented a change in daily mean air
205 temperature from below to above zero (Colleuille et al. 2007).

206 **2.4 Data analyses**

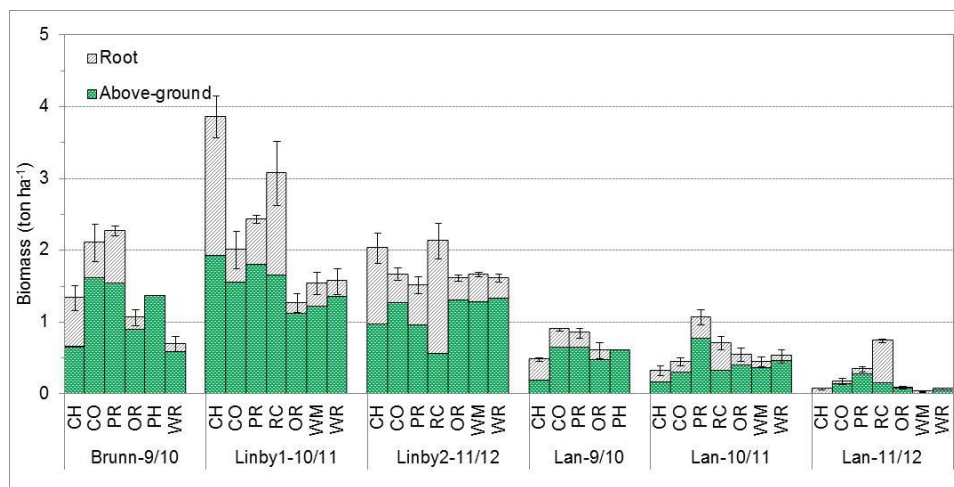
207 The Mixed model (Littell et al. 2006) in SAS (Version 9.2) was used to test for differences in
208 catch crop biomass, P concentration and P content between sites and species. Statistical analyses
209 were performed for individual sites and all sites. In tests for an individual site, species was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

216 **3 Results**

217 **3.1 Catch crop biomass**

218 Above-ground and total biomass both differed significantly between catch crop species
219 ($p < 0.0001$). Based on statistical analysis of the whole dataset, ryegrass and cocksfoot had the
220 largest amount of above-ground biomass among the perennial species under-sown in barley,

221 while phacelia and white radish had the most above-ground biomass among the annual species
 222 after-sown following harvest of barley. However, red clover had significantly higher or similar
 223 amounts of total biomass than all other species at the four sites where it was grown (Figure 1).
 224 Moreover, chicory had rather high amounts of total biomass at sites Linby1-10/11 and Linby2-
 225 11/12. The high ranking of red clover and chicory was mainly attributable to their high amount
 226 of root biomass, which contributed 47-80% of total biomass in red clover and 50-69% in chicory,
 227 but only 12-37% in the other species (Figure 1). In addition, total catch crop biomass differed
 228 significantly with experimental conditions ($p < 0.0001$), decreasing in the order Linby1-10/11 >
 229 Brunn-9/10 \approx Linby2-11/12 > Lan-9/10 \approx Lan-10/11 > Lan-11/12 (Figure 1). The two sites at
 230 Linnés Hammarby produced similar amounts of catch crop biomass when the catch crops were
 231 sown after harvest of barley, but Linby1-10/11 produced much more biomass of the under-sown
 232 species than Linby2-11/12. Site Lan-11/12 produced low biomass of both under-sown and after-
 233 sown species.



234
 235 Figure 1 Above-ground and root biomass of catch crops in autumn at the six field sites. Error
 236 bars indicate standard error of total biomass (n = 2 for white radish in Brunn-9/10; otherwise n =
 237 4). CH = chicory; CO = cocksfoot; PR = perennial ryegrass; RC = red clover; OR = oilseed
 238 radish; PH = phacelia; WM = white mustard; WR = white radish.

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

243 Table 4 Mean barley biomass (sum of grain and straw, ton ha⁻¹) in plots with under-sown catch
 244 crops and a control without a catch crop at harvest in August, with standard error in brackets (n =
 245 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)

246

247 3.2 Phosphorus in catch crops in autumn

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

256

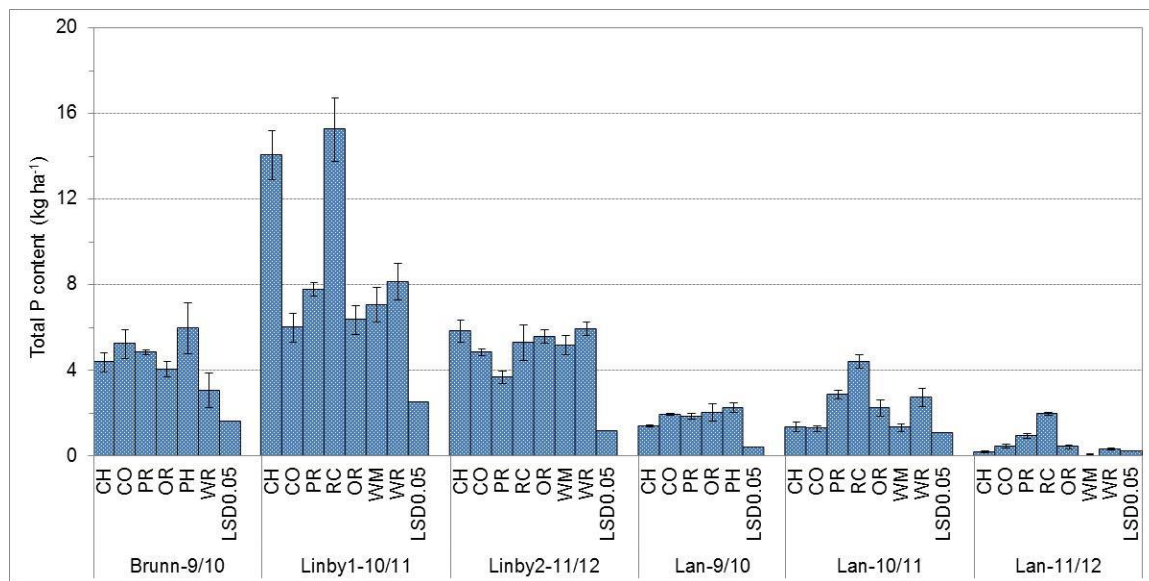
257 Table 5 Mean concentration of total-P (g kg^{-1} DM) in above-ground plant parts ($n = 2$ for white
 258 radish in Brunn-9/10; otherwise $n = 4$, standard errors in brackets) and roots ($n = 1$ or 2) of catch
 259 crops in autumn

	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

260

261 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
 262 ha^{-1} at Linby1-10/11 (Figure 2), and differed significantly between species ($p < 0.0001$). The total
 263 P content and proportions of root P are presented in a related paper, in which the plant P content
 264 was related to P leaching (Liu et al. 2014). Contribution of roots to total P content followed a
 265 similar pattern to their contribution to biomass, indicating a relatively smaller influence of P
 266 concentration on P retention. The contribution of root P to total P was greater in red clover (56-
 267 86%) and chicory (45-67%) than in the other species (7-27%; Liu et al. 2014). On average for all

268 sites, this resulted in red clover having the significantly greatest whole-plant P content among all
 269 species tested and in chicory having a significantly greater P content than oilseed radish,
 270 cocksfoot and white mustard, despite red clover and chicory having overall medium or small
 271 amounts of above-ground biomass. Consistent with the biomass relationships, the under-sown
 272 perennials contained similar amounts of P as the annuals at Brunn-9/10, Linby2-11/12, Lan-9/10
 273 and Lan-10/11 and contained more P than the annuals at Linby1-10/11 and Lan-11/12
 274 ($p < 0.0001$).



275
 276 Figure 2 Whole-plant P content in autumn in catch crops at the six field sites. Mean with
 277 standard error as error bars ($n = 2$ for white radish in Brunn-9/10; otherwise $n = 4$). $LSD_{0.05}$ is
 278 shown as a column for each site.

279 **3.3 Catch crop survival over winter**

280 The rate of winter survival differed substantially between catch crop species (Table 6). On
 281 average, perennial species had a survival rate of $>70\%$ after 5-17 FTCs at the experimental sites
 282 during each winter. In spring, new shoots started to replace the old ones, which mostly died off,
 283 became dry and partly remained on the soil surface. The roots of perennial species seemed to
 284 survive the winter, although the extent of root damage by freezing-thawing or other winter

285 stresses is unknown. In contrast, all plants of the annual species were killed off at all sites, with
 286 dry shoots remaining on the surface, being carried off by water or wind or decomposing. In
 287 particular, the fleshy radish roots rotted and completely disappeared due to winter stresses and
 288 wash by percolating water. This may have resulted in release of most of the P they contained to
 289 the soil, which could have amounted to e.g. the 8 kg ha⁻¹ that was retained in white radish in
 290 autumn at Linby1-10/11. Phacelia seemed to be the most frost-sensitive species of all species
 291 tested in this study. At Brunn-9/10, observations made in December (one month after the field
 292 sampling), when only two FTCs had taken place, showed that 80% of phacelia was already frost-
 293 damaged, while the other species were only 0-15% damaged.

294 Table 6 Survival rate (%) of the catch crops over winter, as a percentage of the total number of
 295 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

296

297 **4 Discussion**

298 In autumn, biomass and whole plant P content varied widely between species. The perennial
 299 catch crop species frequently had greater total biomass and retention of P than the annual species,
 300 due to relatively larger root:shoot biomass ratio. This was despite the fact that the annual species
 301 had comparable (e.g. in Lan-9/10 and Lan-10/11) or even slightly larger (e.g. in Linby2-11/12)
 302 amounts of above-ground biomass and higher P concentrations than the perennials. Higher P
 303 concentrations in annuals than in perennial species have also been reported in a greenhouse study
 304 on catch crops sown simultaneously (Liu et al. 2013). The reason for the different concentrations
 305 is probably that annual species need to put more effort into reproduction and into sustaining a

306 high relative growth rate than the perennials, and therefore need a higher concentration of P for
307 cell division at the growing points (Primack 1979; Garnier 1992). Red clover showed the greatest
308 retention of P at three of the four sites at which it was sown, due to its great biomass, particularly
309 in the roots. At the fourth site, its P retention did not differ significantly from the highest
310 retention of other species. For the same reason, chicory retained a relatively large amount of P at
311 the Linnés Hammarby and Brunnby locations. Red clover and chicory were under-sown with
312 barley in spring, which allowed a longer period for root establishment and growth. However,
313 ryegrass and cocksfoot, which were also under-sown with barley, had relatively low root
314 biomass (21-37% of total biomass). In contrast, Reicosky and Forcella (1998) reported that roots
315 can comprise as much as 60-90% of total biomass in grass catch crops. However, similarly to the
316 present study, Zagal et al. (2001) observed that the root:shoot biomass ratio of chicory was 2.9-
317 3.6 fold higher than that of ryegrass. This difference may be due to the fact that root
318 characteristics differ between species. Liu et al. (2013) determined root characteristics of the
319 same eight catch crop species as were used in the present investigation and observed a larger root
320 volume per unit surface area in taproots of non-grass species (0.096-0.106 mm) than in fibrous
321 roots of grasses (0.068-0.083 mm). Taproots may be able to store more P than fibrous roots due
322 to both the larger root volume and the greater biomass. However, the low frequency of root
323 sampling to a limited soil depth (0.25 m) and the subsequent washing of roots may have caused a
324 slight underestimation of total-P content of grasses with their many tiny roots.

325 There is often concern about main crop production when under-sowing a catch crop in
326 spring cereals. For example, Känkänen and Eriksson (2007) found that many of the 17 under-
327 sown catch crop species they investigated reduced grain yield of spring barley due to strong
328 competition for light, water and nutrients. However, this was not observed in the present study,

329 where under-sowing of catch crops did not significantly affect barley biomass at any site (Table
330 4), as also reported by e.g. Ohlander et al. (1996). The seed rate used here was smaller than that
331 used by Känkänen and Eriksson (2007), which might explain the different effects of catch crops
332 on barley yield. Thus, in regions with cold winter conditions and a short growing season,
333 perennial species can be under-sown at appropriate seed rates with the main crop to maximise
334 removal of P from clayey soils, without causing a notable reduction in cereal yield.

335 A somewhat surprising finding was that temperature did not seem to affect growth of
336 annual catch crops sown after harvest of barley. The three sites to the north, Brunn-9/10, Linby1-
337 10/11 and Linby2-11/12, with fewer day degrees for catch crop growth during autumn, yielded
338 more biomass of e.g. radishes than the Lanna sites. In particular, the biomass at Linby1-10/11
339 was very high for Swedish conditions, despite this site having a low temperature sum during
340 growth of annual catch crops compared with the other sites (Table 3). Brant et al. (2011)
341 concluded that mean air temperature during catch crop growing season can substantially affect
342 biomass production. In the present study, however, there was no clear evidence that temperature
343 could explain differences in biomass of catch crops between sites.

344 Biomass and P retention of the under-sown catch crops seemed to be greatly affected by
345 precipitation sum during a certain period. Linby2-11/12 had much lower biomass of under-sown
346 catch crops than Linby1-10/11, despite similar biomass of after-sown catch crops (Figure 1).
347 Growth of under-sown catch crops at Linby2-11/12 was probably suppressed before harvest of
348 barley. It was quite dry during day 1 to day 30 and during day 61 to day 90 after under-sowing of
349 catch crops (both < 25 mm precipitation) at Linby2-11/12 (Suppl. Table 1). Schröder et al. (1997)
350 showed that high precipitation during summer promotes growth of under-sown catch crops
351 during the whole season. The under-sown crops probably suffered more than the barley during

352 the dry summer at Linby2-11/12. The barley biomass was not affected by the under-sown catch
353 crops in spite of the competition, probably because the faster growing barley had better access to
354 groundwater and was less dependent on rain (Table 4). Similarly, overall low biomass of under-
355 sown catch crops at Lan-11/12 was likely to be a result of dry soil conditions (only 1 mm
356 precipitation) during day 61-90 after under-sowing.

357 The catch crops at all sites were fertilised with 25 kg N ha⁻¹ at sowing of annual species
358 and this, together with N potentially mineralised in the soil, seemed to be enough to ensure catch
359 crop needs at Lanna, where total biomass production was well below 1 ton ha⁻¹ for most species
360 during the three years (Figure 1). Thus, the relatively poorer biomass production and retention of
361 P at the Lanna sites was most likely because despite having similar texture to the Brunnby and
362 Linnés Hammarby soils, the Lanna soil was distinctly firmer and denser, which probably limited
363 root penetration and catch crop growth. In a previous lysimeter study, Liu et al. (2014) observed
364 generally poorer water infiltration in the Lanna soil than in the other two soils. This stresses the
365 importance of soil structure in catch crop establishment on clayey soils. Moreover, crop biomass
366 production and P retention in autumn seemed to be influenced by soil P content. The Linby1-
367 10/11 soil, which had a very high content of P-AL, produced the largest mean biomass for all
368 catch crops over all sites, and also resulted in the highest concentrations of P in most species.

369 The lowest catch crop biomass production occurred at Lan-11/12. Low biomass of under-
370 sown species is probably often a result of dry soil conditions, as discussed above, at least at the
371 low yield levels seen in the present study. The low biomass of after-sown species could also be
372 explained by dry conditions during establishment causing poor germination and early growth,
373 but was probably largely determined by the time of sowing. It has been reported previously that
374 late sowing greatly affects early growth of catch crops, consequently limiting their water and

375 nutrient uptake efficiency and growth in later periods (Thorup-Kristensen et al. 2003). Moreover,
376 crop failure and low nutrient uptake due to late sowing can be the result of unfavourable
377 temperature, low radiation levels and N limitation if substantial N leaching occurs prior to
378 sowing (Vos & van der Putten 1997), or if N is volatilised to the air. At Lan-11/12, a
379 considerable amount of soil N might have been lost before establishment of the annual species,
380 as the soil was very wet (80 mm precipitation) during the first two weeks after sowing. In
381 autumn, the catch crops at Lan-11/12 showed 15-65% coverage of the soil surface, which was
382 very low compared with the other sites (90-100%).

383 It has been reported that repeated FTCs of catch crop plants can cause up to 50-100% of
384 the P release from above-ground parts and 60-100% of the P release from roots (Liu et al. 2013).
385 In the present study, most of the above-ground parts and some of the roots of perennial species
386 and all the biomass of annuals were damaged by frost or other stresses during winter. Most of the
387 P previously stored in these damaged parts would potentially have been released and returned to
388 the soil. This is meaningful for crop growth in the following growing season. However, part of
389 the P released from the catch crop biomass is likely to have been lost from the system by surface
390 runoff or leaching during winter and early spring, contributing to the risk of eutrophication in
391 neighbouring streams. This is a particular concern on clayey soils such as those in this study,
392 where P may be transported through macropore flow pathways before sufficient sorption occurs
393 (Riddle & Bergström, 2013). For example, in a laboratory lysimeter study with intact clayey
394 soils and catch crops sampled from the same sites as those used in the present study, the total-P
395 concentration in leachate increased after FTCs compared with before in 95 out of 140 lysimeters
396 (Liu et al. 2014). In addition, P losses from plant tissues can vary greatly in different climate
397 conditions and can be strongly elevated by severe freezing-thawing episodes in early autumn

398 followed by early snowfall, a prolonged period with snow coverage and relatively high winter
399 temperatures (Sturite et al. 2007). Therefore, in regions where FTCs are coupled with high
400 precipitation in winter (e.g. 5-17 FTCs and 138-233 mm precipitation during winters in this
401 study), more attention should be paid to potential P losses from plant materials when catch crops
402 are used. In such cases, high uptake and storage of P in catch crops in summer and autumn may
403 be a disadvantage in terms of P losses to water.

404 **5 Conclusions**

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

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420 **Appendix A. Supplementary data**

421 Supplementary data (Suppl. Table 1) associated with this article can be found in the online
422 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
<u>Temp. sum (Day °C)</u>						
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
<u>Prec. sum (mm)</u>						
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
<u>Solar radiation sum (MJ m⁻²)</u>						
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

^aFrom sowing of barley to harvest; ^bfrom sowing of annual catch crops to autumn sampling; ^cdays counted from sowing of barley and under-sowing of catch crops.