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Effects of green manure herbage management and its digestate from biogas production on barley yield, N recovery, soil structure and earthworm populations

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ABSTRACT

In repeatedly mown and mulched green manure leys, the mulched herbage contains substantial amounts of nitrogen (N), which may only slightly contribute to the following crops' nutrient demand. The objective of the present work was to evaluate the effect of alternative strategies for green manure management on the yield and N recovery of a subsequent spring barley crop, and their short term effects on soil structure and earthworm populations. A field trial was run from 2008 to 2011 at four sites with contrasting soils under cold climate conditions. We compared several options for on-site herbage management and the application of anaerobically digested green manure herbage. Depending on the site, removal of green manure herbage reduced the barley grain yield by 0% to 33% compared to leaving it on-site. Applying digestate, containing 45% of the N in harvested herbage, as fertilizer for barley gave the same yields as when all herbage was mulched the preceding season. Overall, the apparent N recovery was enhanced from 7% when all herbage was mulched, to 16% when returned as digestate. A positive effect on earthworm density and biomass was seen after one season of retaining mulch material, rather than removing it. Digestate did not affect the earthworm population, but contributed to higher soil aggregate stability. In conclusion, for spring barley production after green manure ley, the digestate strategy increased N recovery and reduced the risk of N losses. The yield of the succeeding barley crop yield was reduced when N in herbage was not returned as mulch or digestate.

1. Introduction

Green manure leys are commonly used in organic cereal crop rotations to maintain soil fertility on stockless farms. Such full season grass-clover leys may increase yields through improved nitrogen (N) supply and through non-nutritional benefits such as improved soil structure, suppression of diseases and weeds, more earthworms and increased mycorrhizal activity (Cherr et al., 2006; Janzen and Schaalje, 1992; Riley et al., 2008). The green manure leys are generally grown as set-aside; managed by leaving the chopped herbage as mulch after frequent mowing during the growing season (Cormack et al., 2003; Stopes et al., 1996). The mowing is done as a means to control weeds and to keep the clover in a vegetative state and thus sustain high N_2 fixating activity and low C/N ratio (Dahlin and Stenberg, 2010).

Due to the accumulation of easily degradable N in green manure crops, current practice with repeatedly mowing and mulching means that substantial amounts of N in the herbage are at risk of being lost from the cropping system, both as gaseous emissions (NH_3, N_2O, NO and N_2) and through surface runoff or leaching of nitrate (NO_3^-) and soluble organic N (Askegaard et al., 2005; Korsaeth, 2012; Larsson et al., 1998; Möller and Stinner, 2009). Further, it is an expensive practice, using the land, establishing and managing the green manure for a whole season with no direct income, only the expectance of higher income from future crops on the field.

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That on-site mulched herbage contributes only slightly to the fulfilment of the following crops' nutrient demand has been demonstrated in several Scandinavian field trials (Engström et al., 2007; Frøseth et al., 2008; Solberg, 1995). As a consequence of herbage removal, one might expect decreased soil inorganic N availability for the green manure crop, which could enhance clover and N_2 fixation and thereby compensate for the lack of mulching in N pre crop effect. Hatch et al. (2007) found that removing cuttings from a grass-clover ley increased fixation, compared with mulching, but Dahlin and Stenberg (2010) found no differences. Neither of these studies included the N effect of these strategies on subsequent crops.

In spring barley, availability of inorganic N at the early tillering stage is a key factor for N uptake and dry matter (DM) yield (Hauggaard-Nielsen et al., 1998). Growing spring barley, based on the nutrients from a preceding green manure crop and without any additional nutrient input, is challenging under the cold Nordic climatic conditions with a short growing season. Borgen et al. (2012) concluded that there is a limited potential for improving N-use efficiency by management changes, in for example the time of ploughing and/or crop rotation, in stockless organic cereal production systems in Norway. For more substantial improvements, alternative strategies appear to be necessary. Application of digestate from green manure foliage digested anaerobically in a biogas plant may be a promising option for improving yields and N recovery instead of mulching (Möller and Müller, 2012; Stinner et al., 2008). In biogas plants, the easily degradable organic matter is digested, releasing methane for heating or fuel and residues (digestate). The latter contain plant available nutrients that may be applied as fertilizer in the subsequent season. To our knowledge, this strategy has not been compared previously with other strategies for green manure management under Nordic conditions.

Soil structure is important for the development of the barley crop (Arvidsson, 1999), both to create good conditions for root growth and for the turnover of soil organic matter (Breland and Hansen, 1996). The processes and mechanisms involved in soil aggregation is complex and can be affected through management practices (Bronick and Lal, 2005). Earthworm activity influences and normally improves soil structure and aggregate stability (Bronick and Lal, 2005; Edwards and Lofty, 1977; Marinissen, 1994). Although earthworm species have different feeding strategies, their excrements (casts) contain more plant available nutrients than does bulk soil (e.g. Buck et al., 1999; Haynes et al., 2003; Pommeresche and Løes, 2009). This finding supports the idea that one intensive year of "feeding" the soil with mulch material may improve soil structure and soil nutrient status.

The effects on earthworms when green manure herbage is removed and subsequently returned as digestate, instead of being mulched, have been little studied. Because the easiest available carbohydrates are converted to methane and removed, less energy and organic carbon (C) will be available for earthworms and other soil fauna. Ammonium and sulphide, which are toxic to earthworms (Curry, 1976) are formed by anaerobic digestion. Thus mulched green manure herbage may be more favourable to earthworms than anaerobically digested herbage.

The objective of the present work was to evaluate the effect of various strategies for green manure management on the yield and N recovery of a subsequent spring barley crop, and its short term effects on soil structure and earthworm populations in contrasting soils under cold climate conditions. The strategies involved different options for on-site herbage management and the application of anaerobically digested green manure herbage. The following hypotheses were tested:

- Removal of herbage, compared with mulching, will not affect the yield of a subsequent spring barley crop.
- Digestate applied as fertilizer for spring barley, compared with mulching the preceding season, will increase the crop yield and the proportion of N input by the green manure herbage that is recovered.
- Compared to herbage removal, mulching will not increase the amount of soil N available for a subsequent spring barley crop. On the contrary, digestate application will increase plant available N.
- Soil structure and earthworm populations will be negatively affected by removing the green manure herbage or by one application of digestate.

2. Materials and methods

2.1. Experimental sites, soil and weather conditions

Four field trials were established in 2008 at sites differing in soil characteristics and climatic conditions.

2.1.1. Weather and climate

The two neighbouring sites Kvithamar (63°29′ N, 10°52′ E) and Værnes (63°27′ N, 10°57′ E) share the same humid coastal climate in central Norway. Apelsvoll (60°42′ N, 10°51′ E) is situated inland, in eastern Norway with a drier climate and lower winter temperature. Ås (59°39′ N, 10°46′ E), in southeast Norway, represents an intermediate climate with respect to precipitation and winter temperature, but has the highest summer temperature of the sites. The normal values (1961–1990) for annual precipitation at Kvithamar/Værnes, Apelsvoll and Ås are 896, 600 and 785 mm, respectively, of which respectively 465, 319 and 382 mm occur during the growing season (May–September). The amounts of rainfall during the growing seasons of 2008/2009/2010 were 351/624/401 at Kvithamar/Værnes, 376/404/421 at Apelsvoll and 463/433/489 mm at Ås. The mean corresponding growing season temperatures in 2008/2009/2010 were 12.5/12.8/11.7, 12.8/13.1/12.4 and 13.4/13.8/13.1 °C, which are close to or above the normal values. During the winter prior to the barley crop (October 2009 – April 2010), the mean temperatures were −1.4, −3.2 and −1.7 at Kvithamar/Værnes, Apelsvoll and Ås. The corresponding amounts of precipitation were 534, 461 and 324 mm.

2.1.2. Soil properties

The soil at the sites is classified as a Mollic Gleysol, Arenic Fluvisol, Endostagnic Cambisol and Typic endoaqualf (IUSS Working Group WRB, 2006) for Kvithamar, Værnes, Apelsvoll and Ås. The soils at Ås and Kvithamar are derived from marine clay with relatively high silt contents, whilst that at Værnes overlies a coarse freshwater alluvium and that at Apelsvoll is developed from glacial till. The silty clay loam topsoil at Kvithamar is highly drought-resistant, but it overlies a very compact plough pan layer and compact subsoil with gley spots, both of which have low air and available water capacities. The clay loam topsoil at Ås is relatively drought-resistant and has a moderate air capacity, whereas the deeper soil layers are more compact, with low air and available moisture-holding capacities. At Værnes the soil is sandy loam and reasonably drought-resistant and well-aerated down to 0.5 m, but deeper layers have very low water-holding capacity and support little root growth. The soil at Apelsvoll is well-aerated sandy loam and relatively drought-resistant at all depths, and has few physical limitations to plant growth. The deeper subsoil (>0.6 m) is very compact. Information on the basic physical properties within soil profiles at the trial sites was obtained from previous studies performed at or close to the present locations (Table 1).

The topsoil at Kvithamar has a high C content, whereas the content is moderate at Apelsvoll and Ås and low at Værnes (Table 2). The C content in deeper horizons is very low, especially at Værnes and Ås. The level of total N is considerably higher at Kvithamar than

Table 1
Soil particle size distribution, bulk density, air capacity and moisture retention capacity.

Depth (m)	Sand	Silt	Clay	Gravel in whole sample	Bulk density	Air capacity[a]	Available water[b]	Wilting point[c]
	% of fine earth			%	g cm^{-3}	vol%		
Kvithamar[d]								
0–0.21	3	70	27	3	1.13	6	36	15
0.21–0.36	2	64	34	2	1.81	3	13	17
0.36–0.65	0	63	37	2	1.71	5	10	24
Værnes[e]								
0–0.30	51	43	6	0	1.53	8	27	6
0.30–0.50	73	25	2	0	1.62	9	26	3
0.50–0.62	92	7	1	0	1.54	33	4	1
Apelsvoll[f]								
0–0.25	55	31	14	11	1.47	12	21	10
0.25–0.50	55	32	13	12	1.52	14	18	9
0.50–0.60	51	32	17	11	1.5	16	16	10
Ås[g]								
0–0.30	22	43	35	8	1.36	9	20	19
0.30–0.39	14	46	40	4	1.62	5	9	27
0.39–0.70	15	46	39	4	1.58	5	10	26

[a] At 10 kPa.
[b] 10–1500 kPa.
[c] >1500 kPa.
[d] From profile no. 6 in Sveistrup et al. (1994).
[e] From profile 20177 in Solbakken (1987).
[f] Six profiles from Riley (unpublished).
[g] Østre Voll in Sveistrup et al. (1994).

at the other sites. In general the total N level followed that of C, with C/N ratios mostly in the ranges of 11–15 at Kvithamar, Værnes and Apelsvoll and 8–11 at Ås. The C and N was analysed using the Dumas combustion method (Bremmer and Mulvaney, 1982) on a Leco CHN 1000 analyzer (LECO Corp., St. Joseph, MI, USA).

The soil reaction in the topsoil, measured in water, was slightly above pH 6 at all sites. The topsoil contents of plant-available phosphorus and potassium were measured in 2008 by the ammonium acetate lactate method (AL, 0.1 M ammonium lactate and 0.4 M acetic acid, pH 3.75, ratio of soil weight to solution volume of 1:20, Égner et al. (1960)) as practice in Norway. The phosphorus level (P-AL) was very high at Værnes (155 mg kg^{-1}), medium at Kvithamar and Apelsvoll (66 and 75 mg kg^{-1}) and low at Ås (40 mg kg^{-1}). The potassium level (K-AL) was low at Værnes (36 mg kg^{-1}) and medium at the other sites (75 mg kg^{-1} at Ås, 89 mg kg^{-1} at Apelsvoll and 98 mg kg^{-1} at Kvithamar).

At Kvithamar, the soil had been farmed organically and according to a rotation dominated by grass-clover leys fertilized with animal manure from 1993 until 2003. From 2003 and until the start of the present experiment, the site had been cropped with cereals with low rates of fertilization and with breaks of green manure leys. At Værnes the soil had not been farmed organically. Here the crop rotations were dominated by annual crops until 2000 and by grass from 2001 to 2006. In 2007 the crop was cereals. The previous rotation at Apelsvoll was dominated by organically managed arable crops. In 2007 the field was fallowed with repeated harrowing. At Ås the soil had been managed organically since 1993 with ley-arable crop rotation until about 2000, then mainly with spring cereals and undersown clover every year until 2008. Chemical weed control with glyphosate was performed before ploughing in spring 2008.

2.2. Crop management and experimental treatments

The green manure was a grass-clover ley established in spring as an undercrop in cereals. The year after, the ley was cut several times and the herbage was chopped and left on the stubble (mulched), which is according to the most common practice for management of green manure leys in Norway. In addition to mulching, the treatments included removal of the herbage and application of digestate in the following year (Table 3). A control treatment with repeated cereal cropping was also included. An overview of crops and management is given in Table 4.

In spring 2008 the green manure plots were sown with 2 g m^{-2} seed mixture consisting of 20% red clover (*Trifolium pratense* L. cv. Nordi), 10% timothy (*Phleum pratense* L. cv. Grindstad), 35% meadow fescue (*Festuca pratensis* L. cv. Fure) and 35% perennial ryegrass (*Lolium perenne* L. cv. Napoleon), as an undercrop in unfertilized spring barley (*Hordeum vulgare* L. cv. Sunnita at 16 g m^{-2}). On the control plots, unfertilized spring barley was sown in pure stand. The barley straw was removed after grain harvest.

In 2009 the green manure leys (G) were cut three times. The chopped herbage was either mulched after all cuts (mulched three times = G-3M), or removed twice and mulched after the last cut (mulched one time = G-1M), or removed after all three cuts (mulched zero times = G-0M). The first cut was carried out when

Table 2
Means (±SD) of total C and N (% of fine earth) at various sampling depths (cm) at the four sites. Samples taken from all treatments were pooled blockwise before analysis (n = 4).

Depth	Total-C				Total-N			
	Kvithamar	Værnes	Apelsvoll	Ås	Kvithamar	Værnes	Apelsvoll	Ås
0–20	4.90 (1.57)	1.39 (0.07)	2.14 (0.17)	2.08 (0.08)	0.40 (0.11)	0.11(0.01)	0.21(0.03)	0.20 (0.01)
20–30	4.40 (1.37)	1.26 (0.05)	1.76 (0.25)	1.61 (0.26)	0.36 (0.10)	0.09 (0.01)	0.17 (0.03)	0.15 (0.02)
30–60	1.08 (0.47)	0.38 (0.04)	0.79 (0.14)	0.46 (0.08)	0.09 (0.04)	0.01[a]	0.07 (0.02)	0.05 (0.01)

[a] n = 1.

Table 3
Overview of treatments in the 3-year crop rotation. 2008 was a preparatory year with establishing of green manure (G) in spring barley. In 2009 the green manure herbage was removed (0 M) or mulched (1 M or 3 M). Unfertilized oats (C) was control. In the following spring, green manure was ploughed under and barley was sown and fertilized with digestate (D) at 11 g N m^{-1}, inorganic fertilizer (I) at 8 g N m^{-1} fertilization or unfertilized.

Term	2008	2009	2010
G-3M	Barley with G undersown	G 3 cuts mulched	Barley
G-1M	Barley with G undersown	G 2 cuts removed, 3rd mulched	Barley
G-0M	Barley with G undersown	G 3 cuts removed	Barley
G-0M-D	Barley with G undersown	G 3 cuts removed	Barley + digestate
C-D	Barley	Oats	Barley + digestate
C-I	Barley	Oats	Barley + fertilizer

timothy reached late stem elongation, i.e. just before inflorescences were visible on 10% of the shoots, next after 600–650 day degrees (base temperature 0 °C) from the first cut and the third in mid-September. The stubble height of the green manure was 5–8 cm.The control plots (C) were sown with unfertilized oats (*Avena sativa* L. cv. Gere, Table 3). The oat straw was removed at all sites except Apelsvoll. After grain harvest in plots without undercrop in 2008 and 2009, some native white clover (*Trifolium repens* L.), couch grass (*Elymus repens* L.) and dicotyledonous weeds emerged. These were removed by hand weeding or frequent mowing using a small lawn mower with a rotor working at the soil surface.

In spring 2010 the leys were ploughed under, and spring barley (*Hordeum vulgare* L. cv. Tiril at 20 g m^{-2}) was sown (Table 4). Prior to sowing, herbage-based digestate (D) was applied to half of the plots where green manure herbage had been removed (G-0M-D), and to half of the plots with preceding oats (C-D, Table 3). The digestate contained 11 g total N and 6 g ammonia N m^{-2}, which corresponded to about 45% of the total N harvested as herbage, and in addition 1.6 g P m^{-2} and 7.7 g K m^{-2}. It was applied on the soil surface and harrowed down on the same day, or by the Direct Ground Injection (DGI) technique to 6–8 cm depth in 0.3 m rows (Apelsvoll). On control plots (C-I), 8 g N, 1.5 g P and 9 g K m^{-2} were applied as inorganic fertilizers. The proportion of NO_3-N of the total fertilizer N, varied from 20% (Apelsvoll) to 90% (Ås).

After harvesting of barley grain and straw, the fields were harrowed to control perennial weeds, except at Kvithamar where such

Table 4
Overview of crops and operations at the four sites during the experiment.

	Treatment dates			
	Kvithamar	Værnes	Apelsvoll	Ås
Preparatory year 2008				
Ploughing	28 October 07	15 April	30 October 07	19 May
Soil sampling	28 April	29 April	21 May	20 May
Barley sowing	28 April	29 April	21 May	20 May
Green manure sowing	29 April	29 April	21 May	22 May
Barley harvest	12 August	16 August	18 September	1 September
Green manure sampling	22 September	23 September	6 October	7 October
Soil sampling	22 October	23 October	23 October	4 November
Green manure 2009				
Soil sampling	28 April	29 April	6 May	4 May
Oats sowing	29 April	29 April	6 May	5 May
Green manure first cut	1 June	5 June	17 June	3 June
Soil sampling	1 June	5 June	17 June	8 June
Soil sampling	11 June	15 June	26 June	15 June
Soil sampling	20 June	25 June	7 July	24 June
Irrigation[a]	–	–	2 June	26 June, 2 July
Green manure second cut	17 July	22 July	6 August	17 July
Oats harvesting	27 August	25 July	21 August	23 August
Green manure third cut	15 September	15 September	24 September	15 September
Green manure sampling	21 October	21 October	19 October	24 October
Soil sampling	21 October	21 October	13 October	30 October
Barley cropping 2010				
Soil sampling	23 April	22 April	5 May	22 April
Ploughing	7 May	26 April	6 May	23 April
Digestate application	11 May	6 May	24 May	12 May
Fertilizer application	14 May	8 May	20 May	12 May
Harrowing	14 May	7 May	–	12 May
Barley sowing	14 May	12 May	24 May	14 May
Weed harrowing	21 May	19 May	31 May	–
Soil sampling	31 May	27 May	7 June	31 May
Barley sampling	20 June	15 June	26 June	11 June
Barley sampling	5 July	1 July	5 July	28 June
Irrigation[b]	–	–	–	29 June, 9 July
Barley harvesting	26 August	19 August	2 September	31 August
Harrowing	–	10 September	6 September	7 September
Soil sampling	27 August	20 August	3 September	1 September
Soil sampling	29 October	2 November	15 October	26 October
Carry over effect 2011				
Soil sampling	16 May	18 May	19 May	20 May

[a] Apelsvoll: 30–35 mm; Ås: 25 mm each time.
[b] Ås: 20–25 mm and 25–30 mm.

a treatment was considered to increase the growth of weeds and native clover (Table 4). No further management was carried out until field trials were terminated at the end of May 2011.

The experimental lay out was a randomized block design with 4 replicates, but the plots with the two control treatments were always placed beside each other for practical reasons. The gross size of individual plots depended on the implements available at each site, and varied from 48 to 60 m^2.

2.3. Harvest, plant and soil sampling

2.3.1. Plant sampling

Yields of barley (grain and straw separately) and of the three leys cuts were harvested with experimental plot harvesters on 1.5 m × 4–5 m subplots. From the harvested grass-clover herbage (and barley straw), representative subsamples were sorted manually and later dried for determination of species composition. N and moisture content in the straw and herbage were determined plot-wise in other sub-samples dried at 60 °C. On G-3M and at the last cut of G-1M, the raw herbage was, after weighing, manually redistributed on the harvested area and finely chopped with a stubble cutter.

Samples of the standing green manure biomass were taken as late as possible (late October) before frost in 2008 and 2009 (Table 4), by cutting plants at the soil surface on 0.25 m^2 within each plot. In 2010 above-ground biomass of barley was sampled twice early in the growing season (Table 4), by cutting two subplots of 0.25 m^2 at ground level on each plot, first at 250–330 day degrees from plant emergence (base temperature 0 °C), then at flag leaf sheath opening (growth stage 47 in the BBCH scale, Lancashire et al., 1991). The biomass of the stubble left after harvest was recorded similarly. It was only recorded on plots receiving digestate (G-0M-D and C-D), because stubble biomass is found to be relatively little affected by fertilizer treatments (Bleken, 1990).

Dried plant samples were finely milled (Cyclotec, mesh size 1 mm) before determination of total N using the Dumas method mentioned earlier.

2.3.2. Soil sampling

The content of inorganic N (NO_3-N and NH_4-N) was determined in soil samples collected to 20 cm depth on 12 sampling dates selected for their likelihood of showing differences in mineral N fluxes (dates are given in Table 4). In addition, late very autumn and in spring 2010 and 2011 soil was sampled in three more layers to 80 cm depth (20–30, 30–60 and 60–80). Composite sample of 6 soil cores were taken on each plot and stored frozen. Before all the differences between treatments were established, samples from equally treated plots within each block were pooled. Approximately 300–500 g of soil was coarsely ground without thawing and a subsample of 100 g was used for gravimetric determination of moisture content by drying at 105 °C. Another subsample of 40 g was extracted with 200 ml 1 M KCl, and the supernatant analysed by spectrophotometry on a FIAstar™ 5000 Autoanalyser (Foss Tecator AB, Höganäs, Sweden, Application Notes 5232 and 5226 (2001) for NO_3-N and NH_4-N, respectively). Results were expressed on a dry weight basis and converted to area units using appropriate bulk density values (Table 1).

Total soil C and N were analysed in samples taken at the end of the trial, as described for inorganic N. Samples from treatments within the same block were pooled, ground in a mortar and analysed by the Dumas method mentioned earlier.

In order to assess possible effects on soil structure of two years with green manure crops versus continuous cereal growing, sampling was performed after ploughing and harrowing in spring 2010 soon after digestate application. Five subsamples were taken by spade, altogether 5–6 dm^3 of soil, from the seedbed down to 5–6 cm depth on each plot with treatments G-3M, G-0M-D and C-D. The samples were air dried in open containers at room temperature for several months before analysis.

Aggregate size distribution (5 groups: <2 mm, 2–6 mm, 6–10 mm, 10–20 mm, >20 mm) was found by dry sieving for 2 min on a reciprocating shaker containing sieves with mesh openings of 2, 6, 10 and 20 mm. Stones were removed. Aggregate size groups were calculated on a weight basis and the mean weight diameter was expressed using the formula of Van Bavel (1949), assuming a maximum clod size of 35 mm.

The stability of aggregates to simulated rainfall was measured for aggregate sizes of 2–6 and 6–10 mm, using similar apparatus as that described by Njøs (1967). These aggregate size fractions accounted for 50% of the total soil samples at Ås, 42% at Kvithamar, 37% at Apelsvoll and 24% at Værnes. Two subsamples (40 g) of each size group were placed within a radius of 0.15 m and subjected to simulated rain for 2 min (pressure 1 bar, Hardi 4110-20 nozzles, nozzle height 0.35 m and ca. 70 passes). Aggregate stability is given as the weight percentage of aggregates remaining on the sieve.

2.4. Apparent recovery of nitrogen

The apparent recovery of N in grain or above-ground biomass of barley from mulched green manure or digestate was assessed by subtracting total N yield in the treatment with no mulch left behind (N $\text{yield}_{\text{G-0M}}$) from the total N yield (N yield) in treatments receiving mulch (G-3M or G-1M) or digestate (G-0M-D), and expressed as a percentage of the amounts of N applied as mulch or digestate (N applied):

$$\text{Apparent N recovery}\,(\%) = 100 \times \frac{\text{N yield} - \text{N yield}_{\text{G-0M}}}{\text{N applied}} \tag{1}$$

2.5. Earthworm sampling and analysis

Earthworms were sampled at Kvithamar and Værnes after the last cut in 2009 and after grain harvest in 2010. Two soil cubes (0.2 m × 0.2 m × 0.2 m) were removed in all plots of the four treatments G-3M, G-0M, G-0M-D and C-D. The earthworms were sorted from the cubes by hand. Their total biomass was recorded as g m^{-2} after a short storage in 75% alcohol. The density, individuals m^{-2}, included both juvenile and adult worms. All earthworms were identified to species according to the identification key of Sims and Gerard (1999).

2.6. Statistical analysis

Analysis of variance (ANOVA) was performed using a general linear model (GLM) on soil inorganic N data, plant yields, N uptake, N concentrations and clover proportion. Analyses were performed for all sampling occasions for each site and in total using recordings for single plots as input data and block as random effect. For the barley yields in 2008, before the different treatments took place, we tested that the variance between plots was smaller than between blocks. For multiple comparisons tests, Tukey HSD procedure was used. The statistical software package R was used for these calculations (R Core Team, 2012).

For soil aggregate data ANOVA were performed, using a split-plot design with trial site as the main factor and green manure treatment as the split-plot factor (Minitab 15, Minitab Inc. State College, Pennsylvania, USA). For multiple comparisons the tests LSD procedure was used. For earthworm parameters, ANOVA was performed for each site and year separately, using the two samples in each plot as separate input data, and block as random effect. Biomass was analysed by a linear mixed model (MIXED), while the number of earthworms was analysed by the generalized linear

Table 5
Green manure 2009: Biomass (g DM m^{-2}), N content (g m^{-2}) and clover proportion in three consecutive cuts (±S.E), where the herbage was either mulched (G-3M) or removed (G-0M).

	1st cut	2nd cut		3rd cut	
	G-3M/G-0M	G-3M	G-0M	G-3M	G-0M
Kvithamar					
Biomass	296 (9)	461 (27)	495 (7)*	286 (13)	290 (8)
Nitrogen	7.1 (0.3)	10.3 (1.0)	10.8 (0.3)	8.4 (0.3)	7.8 (0.3)
Clover fraction	0.55 (0.10)	0.54 (0.10)	0.65 (0.05)	0.43 (0.04)	0.53 (0.04)
Værnes					
Biomass	321 (14)	439 (23)	429 (8)	173 (8)	178 (3)
Nitrogen	8.3 (0.5)	9.3 (0.5)	8.8 (0.6)	5.0 (0.1)	5.6 (0.3)
Clover fraction	0.71 (0.03)	0.84 (0.05)	0.83 (0.02)	0.69 (0.06)	0.64 (0.03)
Apelsvoll					
Biomass	355 (11)	316 (24)	383 (12)*	52 (6)	99 (4)*
Nitrogen	8.5 (0.5)	8.5 (0.6)	9.1 (0.5)	1.8 (0.3)	3.1 (0.3)*
Clover fraction	0.83 (0.03)	0.87 (0.02)	0.95 (0.01)*	0.63 (0.04)	0.70 (0.05)
Ås					
Biomass	366 (8)	174 (9)	182 (6)	326 (20)	327 (12)
Nitrogen	6.9 (0.3)	4.8 (0.3)	5.1 (0.3)	7.6 (0.6)	7.9 (0.1)
Clover fraction	0.34 (0.05)	0.67 (0.03)	0.74 (0.04)	0.79 (0.01)	0.85 (0.02)

* $P \leq 0.05$ for the test G-3M ≠ G-0M for each site × cut combination.

mixed model (GLIMMIX, with negative binomial distribution and *ln* as link function), both by SAS (SAS 9.2, SAS Institute Inc., Cary, NC, USA). For multiple comparisons tests, Tukey procedure was used.

In all tests, significance was assumed at *P*-levels < 0.05.

3. Results

3.1. Nitrogen and dry matter yields

3.1.1. Green manure and cereals, 2008–2009

In the establishment year, the green manure undercrop reduced grain yield compared to the pure stand, by 22% at Kvithamar, 15% at Apelsvoll and 7% at Værnes ($P = 0.058$), but no reduction was seen at Ås. At the four sites the mean grain DM yield of barley with undersown green manure ranged between 194 and 262 g m^{-2}. The standing herbage biomass and N content of the green manure in late autumn 2008 was markedly higher at the two northern sites than at the others, likely caused by earlier grain harvesting at the northern sites. The biomass was 297 and 240 versus 76 and 113 g DM m^{-2} at Kvithamar, Værnes, Apelsvoll and Ås, respectively. The corresponding N contents were 8.9 and 6.7 versus 1.7 and 3.0 g N m^{-2}.

All leys survived the winter well. In 2009, the average for the two treatments in accumulated herbage biomass for three cuts was 1071, 929, 808 and 873 g DM m^{-2} at Kvithamar, Værnes, Apelsvoll and Ås (Table 5). Herbage removal increased the DM yield of the second and third cuts at Apelsvoll and of the second cut at Kvithamar, but it did not affect the regrowth at Værnes and Ås. Similarly, herbage removal had either no effect on the total amount of N at the second and third cut, or slightly increased it in the case of Apelsvoll.

The estimated C/N ratio in the herbage ranged between 12 and 22, based on measured N (Table 5) and C contents in similar plant material analysed by Marstorp and Kirchmann (1991) and Thorup-Kristensen (1994). In general, the estimated lowest C/N ratio is for the herbage in the third cut.

Clover was already abundant at the first cut, and dominated over grasses at the second and third cuts (Table 5). Mulching significantly reduced the proportion of clover at Apelsvoll. Similar trends were seen at Kvithamar and Ås but not at Værnes. The clover biomass was significantly ($P < 0.05$) larger after herbage removal for Kvithamar, Apelsvoll and Ås averaged over the three sites (data not shown). The total N yield in the harvested herbage (G-0M) ranged between 19 and 26 g N m^{-2}, with the largest N yield at Kvithamar (Table 5). The standing biomass in late autumn 2009 contained between 2.4 and 4.7 g N m^{-2}. Again the highest biomass and N yield was observed at Kvithamar, and there was no effect of previous herbage management.

3.1.2. Barley, 2010

Early above-ground biomass and N content in the barley ranged the treatments approximately in the order C-I ≥ C-D ≥ G-0M-D ≥ G-3M > G-0M (Table 6). This indicates that green manure provided less readily available N than did digestate or the use of 8 g N m^{-2} fertilizer. Furthermore, removal of the herbage, rather than mulching, reduced the N supply to the young barley crop. Later, at the flag leaf stage, DM and N content still followed the same pattern. At Apelsvoll, however, digestate had a less positive effect on the young barley crop than at the other sites, with no differences between G-0M and G-0M-D. The biomass and especially the N uptake was higher on the sandy soil at Værnes than on the clay soil at Kvithamar, and the differences increased from the first to the second sampling date, in spite of the facts that the N yield of the green manure had been somewhat higher at Kvithamar (Table 5) and that the two sites were exposed to the same cold weather in early summer 2010. Early in the growing season, chlorosis typical of N deficiency was observed in the treatments where the herbage had been removed the previous year (G-0M and G-1M), particularly on the two clay soils (Kvithamar and Ås). It was most severe at Kvithamar, where the average soil temperature at 10 cm depth was 10.6 °C from plant emergence to 1st sampling, compared to 13.3 °C at Ås.

In order to explore the N state of the young plants we plotted them against published critical and minimum N dilution curves for winter and spring wheat (Justes et al., 1994; Ziadi et al., 2010). In all cases N concentration was far below the critical dilution curves, and very close or even below the minimum curves (Fig. 1), particularly in the case of plots where the green manure herbage had been removed (G-0M).

Barley grain yields in 2010 were close to the national average for conventional farming, about 300 g DM m^{-2}, except at Kvithamar, where the yield was only half of that. The barley crop there was particularly low on one of the blocks, apparently due to poor soil structure. At Ås, high precipitation after ripening delayed harvesting and reduced the recovered yield, especially on the most productive plots, where up to 90% lodging occurred and at least 10% of the ears remained on the ground after harvest. No correction was made for these losses.

Table 6
Biomass (g DM m^{-2}) and nitrogen (g m^{-2}) in barley plants in 2010 at 250–330 day degrees, DD, (with base temperature 0 °C) and at growth stage 47 (flag leaf sheath opened) according to the BBCH scale. Abbreviations for the treatments are explained in Table 3. Within a site, treatment means (±S.E) which do not share any letter in common are significantly different ($P < 0.05$) by Tukey HSD method. The highest value is shown as a.

	G-3M	G-0M	G-3M-D	C-D	C-I
	250–330 DD				
Kvithamar					
Biomass	43 (7) bc	31 (4) c	65 (7) ab	70 (7) a	58 (4) ab
Total N	1.17 (0.20) bc	0.72 (0.15) c	1.49 (0.23) abc	1.85 (0.22) ab	2.11 (0.14) a
Værnes					
Biomass	42 (9) bc	20 (1) c	79 (8) a	88 (10) a	70 (9) ab
Total N	1.80 (0.35) bc	0.92 (0.07) c	2.81 (0.38) ab	3.38 (0.49) a	3.18 (0.47) ab
Apelsvoll					
Biomass	60 (5) b	54 (6) b	53 (5) b	40 (8) b	110 (16) a
Total N	1.92 (0.13) ab	1.64 (0.14) bc	1.79 (0.15) bc	1.16 (0.20) bc	3.19 (0.54) a
Ås					
Biomass	70 (3) bc	64 (3) c	83 (3) bc	109 (2) ab	139 (2) a
Total N	2.05 (0.15) b	1.78 (0.15) b	2.16 (0.13) b	2.68 (0.02) b	3.88 (0.18) a
Growth stage 47					
Kvithamar					
Biomass	129 (22) bc	87 (7) c	159 (16) bc	186 (25) ab	245 (18) a
Total N	1.71 (0.29) b	1.11 (0.15) b	1.84 (0.23) b	2.20 (0.28) b	3.97 (0.32) a
Værnes					
Biomass	168 (10) b	62 (6) c	263 (12) a	270 (11) a	259 (20) a
Total N	3.68 (0.16) b	1.69 (0.14) c	4.29 (0.22) ab	4.28 (0.26) ab	5.20 (0.58) a
Apelsvoll					
Biomass	149 (13) b	125 (11) b	126 (9) b	118 (28) b	218 (16) a
Total N	3.45 (0.28) ab	2.59 (0.22) b	3.36 (0.20) ab	2.38 (0.36) b	4.02 (0.15) a
Ås					
Biomass	111 (15) bc	103 (26) c	136 (13) bc	177 (8) ab	226 (14) a
Total N	3.04 (0.45) ab	2.48 (0.31) b	3.20 (0.40) ab	3.89 (0.38) ab	5.66 (1.22) a

At all sites there was a consistent trend for grain DM and N yields in the order C-I ≥ G-0M-D ≥ G-3M ≥ C-D ≥ G-1M ≥ G-0M (Table 7). Relative to the early growth stage, the ranking of the G-3M and G-0M-D treatments had improved, but that of C-D was less good. N uptake after growth stage 47 up to maturity was lowest in treatment C-D and highest on treatment G-0M-D (1.8 and 4.6 g N m^{-2}, respectively, averaged over all sites). Furthermore, C-D had the lowest N harvest index, i.e. proportion of N in grain relative to the total N in the above-ground biomass (data not shown). The mulching of even a single cut (G-1M) improved grain DM and N yields, compared to G-0M, and mulching three times raised them evidently (Table 7). At site level, the latter was significant on the two sites with sandy loam (Værnes and Apelsvoll). The increased N yield in grain caused by previous green manure stubble and roots, as seen by comparing G-0M-D and C-D, ranged from 0.1 to 1.8 g N m^{-2} (Table 7).

The N concentration of the grain was higher after green manure than in C-I at the two northern sites (Kvithamar and Værnes), and a similar tendency was present at Ås (Table 7). This indicates that mineralization of green manure residues during late summer contributed positively to grain protein. At Kvithamar and Værnes, application of digestate on green manure (G-0M-D) diluted the grain N% to the same level as that of the C-I plots.

The biomass of the barley stubble, found in G-0M-D, and used for the calculations for the apparent N recovery, contained 0.46, 0.69, 0.26 and 0.28 g N m^{-2} for Kvithamar, Værnes, Apelsvoll and Ås.

3.2. Apparent recovery of nitrogen

The apparent N recovery from mulched green manure herbage or digestate in above-ground barley biomass or grain was low and in the order of G-0M-D > G-1M > G-3M (Table 8). The ranking reflects the level of N input to the systems, but also the lower N yield of G-1M relative to the other treatments.

3.3. Inorganic nitrogen in soil

No high levels of inorganic N caused by mulching were found in either the top-soil (Fig. 2) or in deeper soil layers (data not shown).

In spring 2009, one year after the green manure ley was established, the level of NO_3-N in the soil was lower in plots with green manure than in the control plots with barley stubble only, at all sites except Kvithamar (Fig. 2).

Ten and twenty days after the first cut, there were no significant differences in inorganic N in the soil layer 0–20 cm, whether or not the green manure herbage had been mulched.

At all sites, the NO_3-N or inorganic N in soil in late autumn 2009 was higher with G-3M than with G-0M, but both levels were below 1 g m^{-2}. From late autumn 2009 until spring 2010, the level of inorganic N at 0–20 cm increased in all treatments by 0.4–1.0 g N m^{-2}. The temperature at 10 cm depth after soil sampling in autumn was on average 2 °C for 1.5–2 months, then below freezing for 3.5 months and finally 2–4 °C for 10–20 days before sampling in spring.

In spring 2010, before the green manure was ploughed under, there was at all sites a higher level of inorganic N in soil with mulched green manure (G-3M), compared to the other treatments. However, 3–5 weeks after ploughing, two weeks after germination of the barley crop, there were no differences in the levels of inorganic-N in the top-soil between treatments G-3M and G-0M. Application of digestate (G-0M-D) tended ($P = 0.057$) to enhance the amount of inorganic N in the top-soil at Apelsvoll compared to mulching. No such differences at the other sites, and in general a lower soil inorganic N content, may be a consequence of higher precipitation from digestate application to soil sampling at these sites (45–78 mm) than at Apelsvoll (8 mm).

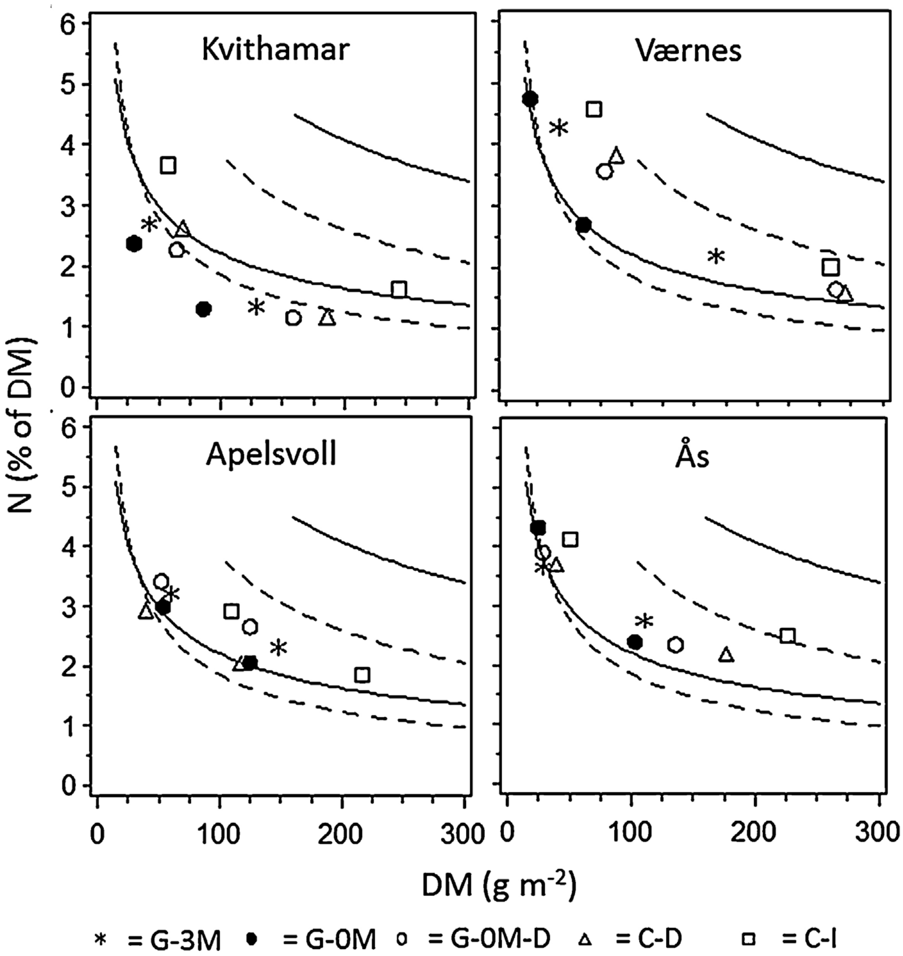

Fig. 1. N concentration (% of DM) versus standing biomass (g DM m^{-2}) at 250–330 day degrees and at growth stage 47. Weighted averages of fours replicates. Upper lines are the critical N dilution curve according to Justes et al. (1994) (continuous line) or Ziadi et al. (2010) (dashed line). Lower lines are the minimum N concentration curves by the same authors. Abbreviations for the treatments are explained in Table 3. The statistical differences between the treatments are given in Table 6.

Table 7
Barley grain and straw DM and N yield (g m^{-2}), and grain N concentration (%), at the different sites in 2010. Abbreviations for the treatments are explained in Table 3. Within a site, treatment means (±S.E) which do not share any letter in common are significantly different ($P < 0.05$) by Tukey HSD method. The highest value is shown as a.

		G-3M	G-1M	G-0M	G-0M-D	C-D	C-I
Kvithamar	Grain DM	140 (15) bc	122 (11) bc	89 (9) c	155 (20) b	156 (14) b	264 (8) a
	Grain N conc.	1.52 (0.05) a	1.50 (0.02) ab	1.50 (0.03) ab	1.29 (0.04) c	1.23 (0.04) c	1.35 (0.01) bc
	Grain N yield	2.1 (0.2) b	1.8 (0.1) b	1.3 (0.3) b	2.0 (0.2) b	1.9 (0.2) b	3.6 (0.1) a
	Grain + straw DM	360 (31) b	337 (26) b	276 (22) b	385 (32) b	386 (29) b	568 (11) a
	Grain + straw N yield	3.3 (0.1) b	2.8 (0.2) b	2.3 (0.1) b	3.3 (0.5) b	3.3 (0.3) b	5.7 (0.4) a
Værnes	Grain DM	327 (16) ab	260 (28) bc	217 (16) c	362 (11) a	310 (10) ab	392 (29) a
	Grain N conc.	1.83 (0.02) a	1.76 (0.03) a	1.84 (0.03) a	1.64 (0.02) b	1.48 (0.01) c	1.63 (0.03) b
	Grain N yield	6.0 (0.3) ab	4.6 (0.3) bc	4.0 (0.2) c	5.9 (0.4) ab	4.6 (0.1) bc	6.4 (0.5) a
	Grain + straw DM	613 (24) bc	481 (31) cd	474 (51) d	689 (22) ab	666 (20) b	803 (36) a
	Grain + straw N yield	7.6 (0.4) ab	5.6 (0.4) c	5.5 (0.6) c	7.2 (0.3) abc	6.0 (0.2) bc	8.4 (0.5) a
Apelsvoll	Grain DM	322 (11) ab	260 (15) bc	249 (10) c	347 (15) a	253 (21) bc	372 (14) a
	Grain N conc.	1.74 (0.05)	1.75 (0.13)	1.61 (0.02)	1.75 (0.02)	1.70 (0.01)	1.68 (0.14)
	Grain N yield	5.6 (0.2) a	4.5 (0.1) b	4.0 (0.2) b	6.1 (0.1) a	4.3 (0.4) b	6.2 (0.3) a
	Grain + straw DM	482 (22) b	376 (20) c	377 (22) c	523 (25) b	397 (27) c	573 (24) a
	Grain + straw N yield	6.6 (0.1) a	5.2 (0.1) b	4.7 (0.2) b	7.3 (0.3) a	5.3 (0.5) b	7.3 (0.3) a
Ås	Grain DM	254 (18) b	252 (25) b	241 (13) b	313 (24) ab	279 (12) ab	356 (18) a
	Grain N conc.	1.95 (0.05)	1.92 (0.07)	1.83 (0.05)	1.72 (0.05)	1.71 (0.04)	1.89 (0.08)
	Grain N yield	4.9 (0.4) ab	4.8 (0.3) b	4.4 (0.5) b	5.4 (0.4) ab	4.8 (0.3) b	6.7 (0.6) a
	Grain + straw DM	427 (38) d	424 (35) d	397 (18) d	499 (41) c	508 (24) b	637 (40) a
	Grain + straw N yield	6.5 (0.6) b	6.6 (0.4) b	6.2 (0.8) b	7.8 (1.2) ab	7.7 (1.0) ab	9.7 (0.7) a
All sites	Grain DM	260 (21) bc	223 (18) cd	199 (18) d	291 (23) ab	249 (17) bcd	346 (15) a
	Grain N yield	4.7 (0.4) bc	3.9 (0.3) cd	3.4 (0.3) d	4.8 (0.5) b	3.9 (0.3) cd	5.7 (0.4) a
	Grain + straw DM	402 (24) bc	336 (17) c	312 (21) d	453 (29) b	421 (25) bc	573 (21) a
	Grain + straw N yield	6.2 (0.4) b	5.3 (0.3) bc	4.7 (0.4) c	6.3 (0.6) b	5.6 (0.5) bc	7.8 (0.4) a

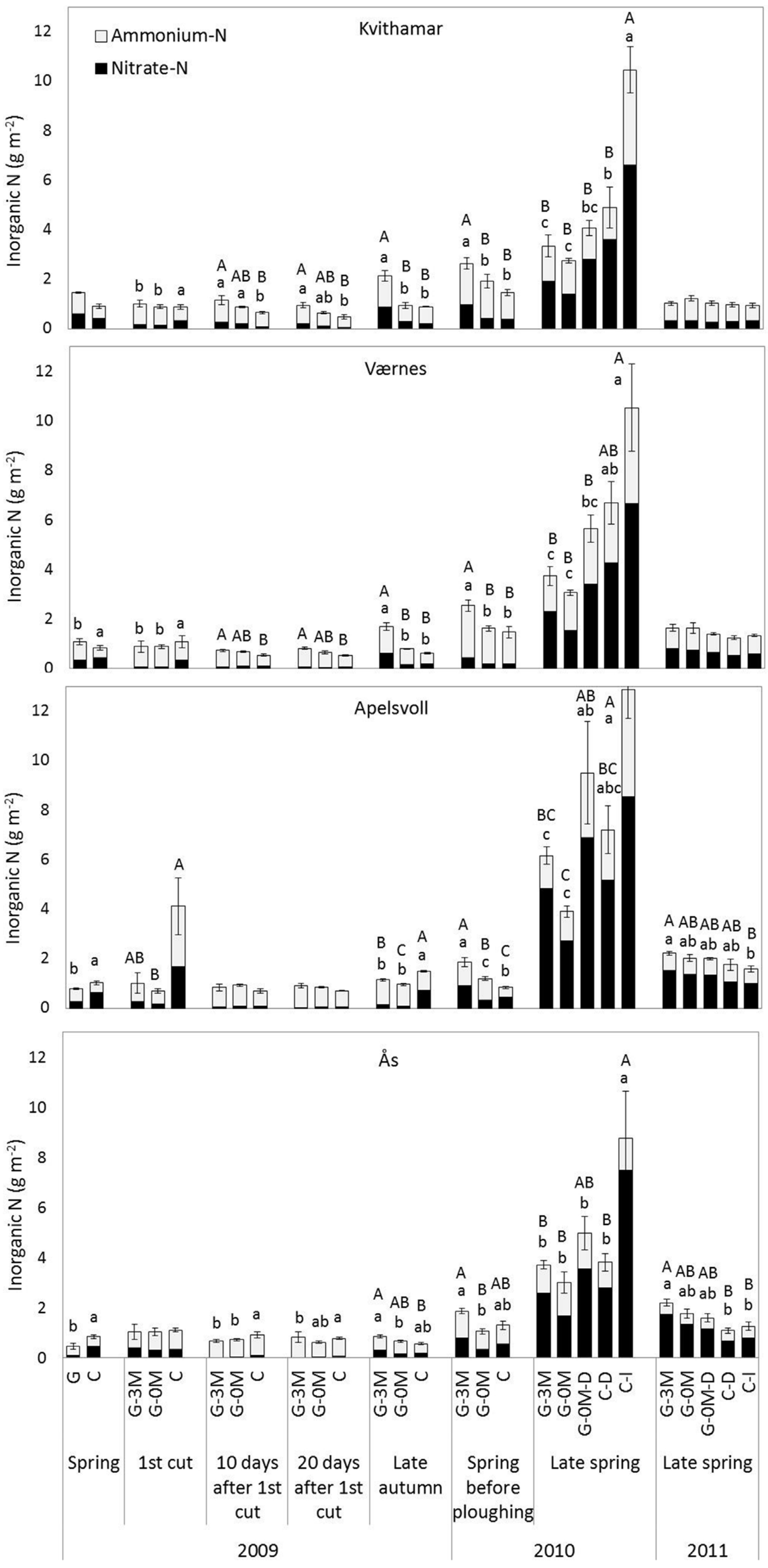

Fig. 2. Inorganic N in soil (0–20 cm depth) in spring 2009, at first cut and until 20 days after, in late autumn after the green manure treatments, in spring 2010 before ploughing and 7–10 days after the germination of the barley crop, and in May 2011. Abbreviations for the treatments are explained in Table 3. Bars (±S.E) within each sampling which do not have any letter in common are significantly different ($P < 0.05$) by Tukey HSD method. Upper case letters show inorganic N and lower case letters show nitrate-N.

Table 8
Apparent recovery (%) by spring barley (grain or above-ground biomass) of N applied as mulched herbage (G-3M or G-1M) or digestate (G-0M-D). See Eq. (1) for calculations. For digestate, the results are calculated in total N, as well as for NH_4-N. Abbreviations for the treatments are explained in Table 3. Within sites, treatment means for total N which do not share any letter in common are significantly different ($P < 0.05$) by Tukey HSD method. The highest value is shown as a.

	G-3M$_{Total\ N}$	G-1M$_{Total\ N}$	G-0M-D$_{Total\ N}$	G-0M-D$_{NH4-N}$
Kvithamar				
Grain	3	7	6	12
Above-ground biomass	6	11	10	18
Værnes				
Grain	9	10	18	34
Above-ground biomass	9 ab	1 b	16 a	29
Apelsvoll				
Grain	8	16	19	36
Above-ground biomass	10	16	24	44
Ås				
Grain	3	5	9	17
Above-ground biomass	2	5	15	29
All sites				
Grain	6 b	10 ab	13 a	25
Above-ground biomass	7 b	8 ab	16 a	30

After the barley crop, there was no significant difference in the level of soil inorganic N related to herbage management, but soil inorganic N was in general higher with previous green manure than without, though in most comparisons at site level it was not statistically significant.

3.4. Soil aggregate size distribution and aggregate stability

There were significant overall differences between treatments on the stability of both aggregate size groups (2–6 and 6–10 mm), with no significant interaction with site (Table 9). Treatment G-0M-D gave greater stability than did treatments G-3M and C-D, whilst the latter had in most cases similar stability. Since there was no overall effect of treatment on any of the aggregate size fractions, these results are not presented.

3.5. Earthworms

In general, higher densities and biomass of earthworms were found in G-3M, where the green manure was mulched and left on the soil surface, than in treatments where it was removed (G-0M, G-0M-D) or where only cereals were grown (C-D) (Table 10, 2009). This difference was also seen in autumn 2010, but only for the number of worms in the clay soil at Kvithamar (Table 10). No significant effects of digestate were found, when comparing treatment G-0M-D and C-D with G-0M in 2010 (Table 10).

Table 9
Stability (%) to simulated rainfall of two aggregate fractions (2–6 mm and 6–10 m), given as means of each site and of three treatments with green manure and/or digestate application. Abbreviations for the treatments are explained in Table 3.

	2–6 mm	6–10 mm
Site		
Ås	61.0	77.6
Kvithamar	59.0	69.4
Apelsvoll	78.1	85.6
Værnes	40.1	52.7
LSD, 5%	18.3	13.0
Treatment		
G-3M	55.9	70.3
G-0M-D	64.8	74.6
C-D	57.9	69.0
LSD, 5%	5.5	4.9
Mean	59.5	71.3

Fieldworm (*Aporrectodea caliginosa*) was the main species found in both soils, 63% of the individuals at Kvithamar (K) and 86% at Værnes (V). Some *Lumbricus rubellus* (15% (K) and 11% (V)) and *Aporrectodea rosea* (14%) were found, the latter only at Kvithamar, as well as a few specimens of *Lumbricus terrestris*. More *L. rubellus* ($P < 0.01$) were found in treatment G-3M at Værnes in 2009 than in the other three treatments (species data not shown). This effect was not seen in 2010. At Kvithamar, in the clay soil, more *A. caliginosa* were found in the same treatment (G-3M) only in 2010 ($P < 0.01$). No effects of digestate were found on the species composition, when comparing treatment G-0M-D and C-D with G-0M in 2010.

4. Discussion

4.1. Effect on barley yield of removal versus mulching of herbage

Contrary to the hypothesis, we found that removing green manure herbage compared to mulching affected the subsequent spring barley yields negatively. Removal of herbage increased N-deficiency in the following barley crop (Fig. 1) at all sites, and this was reflected in a consistent trend with substantial and statistically significant yield loss at harvest on two of the sites. On the sandy and loam soils, mulching increased the grain yield by 23 and 33%. This

Table 10
Biomass (g m^{-2}) and number (m^{-2}) of earthworms (0–20 cm depth) at Kvithamar (silty clay loam) and Værnes (sandy loam) in autumn 2009 and 2010 ($n = 8$). Means (±S.E.) within each site, earthworm component and year, which do not share any letter in common, are significantly different ($P < 0.05$) by Tukey comparison method. The highest value is shown as a.

	G-3M	G-0M	G-0M-D	C-D
2009				
Kvithamar				
Number	206 (48) a	84 (26) b	94 (27) ab	72 (15) b
Biomass	137 (48) a	26 (12) b	35 (13) b	36 (8) b
Værnes				
Number	266 (43) a	184 (21) ab	131 (22) b	181 (23) b
Biomass	178 (33) a	72 (12) b	64 (18) b	78 (12) b
2010				
Kvithamar				
Number	172 (33) a	78 (7) b	78 (25) b	66 (15) b
Biomass	66 (12) a	34 (4) ab	42 (17) ab	20 (4) b
Værnes				
Number	197 (45) a	172 (21) a	216 (53) a	138 (25) a
Biomass	92 (23) a	95 (14) a	125 (30) a	74 (16) a

is comparable to the 20% yield increase of spring barley following vegetables mulched with a chopped grass-clover mixture on a nearby morainic loam, reported by Riley et al. (2003).

In the case of the clay soils, results varied. At Kvithamar, with colder weather during first part of the season (on average 2 °C), all treatments were severely N deficient and the yield considerably reduced, but the relative difference between the treatments were still high. At Ås, barley grew well, but likely differences between treatments were lost due to late season lodging caused by wet weather conditions after ripening. This delayed harvesting, and led to loss of grain. From visually observations we anticipate that the grain losses were greatest on the plots with best growth.

We expected higher clover proportion in the green manure ley caused by removal of herbage, and a positive effect of this on N availability for barley the following year. However, only at Apelsvoll the removal of herbage facilitated larger regrowth and proportion of clover. Even at Apelsvoll, the larger clover content did not result in larger availability of N the year after. In general, no effect of mulch for grass and clover regrowth may indicate that N is either lost or immobilized.

The C/N ratio is found to be the most important factor determining the mineralisation from fresh plant material (Thorup-Kristensen, 1994; Marstorp and Kirchmann, 1991). Net immobilization of N is likely since the estimated average C/N ratio of the grass-clover herbage is above 15, which is found by Marstorp and Kirchmann (1991) to be a turning point for legumes. Furthermore, high herbage yields overlying and shading the stubble may also have suppressed the ley regrowth.

The decomposition rate of plant material and N mineralization from soil organic matter have both been found to be slower in clay soils than in sandy soils (Hassink et al., 1993). Shah et al. (2013) found that the total plant N recovery of applied manure in ryegrass followed the same pattern as above with regard to soil type. The limited fertilization effect of mulching in our study on the clay soils, despite signs of N-deficiency in barley in G-0M, may have been caused by slower mineralization; an effect of soil type, especially in combination with cold and wet weather conditions as for the site Kvithamar. The in general low estimated fertilizer N recovery in the barley grain, and especially for Kvithamar, indicates poor growth conditions for the barley plants in early growing season.

The progress and the level of N loss by leaching, runoff and gaseous emissions from the mulched herbage are strongly influenced by the weather conditions. Ammonia emission is more affected by precipitation than temperature or N-concentration in the herbage (Whitehead et al., 1988). Whitehead and Lockyer (1989) found that decomposing grass herbage placed on the stubble of a cut sward containing 3% N, lost 10% of its N as ammonia during 28 days with showery weather. However, emission levels twice as high as this, or even up to 39%, have also been found from grass with lower N content (Larsson et al., 1998; Whitehead et al., 1988).

At the Ås site, Nadeem et al. (2012) observed that mulching of the herbage only increased nitrous oxide (N_2O) emissions slightly. In the year with green manure, the emission was 0.037 g N_2O-N m^{-2} higher throughout the whole growing season than where herbage was removed. Some ammonia and N_2O emissions are likely to have occurred, especially after the second and third cuts at the two Northern sites, due to precipitation of 100–250 mm during the first 30 days after the cuts.

4.2. Effect on barley yield of digestate versus mulched herbage

When half of the N in green manure herbage was applied as biogas digestate in spring, the barley DM yields reached the same level as after mulching the herbage, and the apparent N recovery was higher, as hypothesized. The recovery in spring barley grains of NH_4-N applied in digestate on the two sites with the lightest soils, Værnes and Apelsvoll, was similar to the 29–38% recovery from manure (slurry) found by Olesen et al. (2007). In general, the digestate appeared to contribute more to the nutrient supply during early growth than did N mineralization from the green manure ley. The latter, contributed mainly later in the growing season and thus increased protein content more than the biomass. The low N harvest index in C-D indicates that an adequate early N supply to the crop was followed by a period of more severe N deficiency.

The low DM levels in the early growth stages of barley fertilized with digestate at Apelsvoll may have been a result of the DGI application technique. The row-spacing of the digestate applied with DGI was relatively large compared to the plant rows.

4.3. Effect of herbage management on plant available nitrogen in soil

Green manure herbage, if mulched, represents a high N input to the cropping system, but no high pulse of inorganic N caused by mulching was found in the soil on the sampling dates.

The latest measurements of soil inorganic N before barley crop nutrient uptake, 7–10 days after germination, showed a consistent trend in the order G-0M-D ≥ G-3M ≥ G-0M. Overall, only digestate application enhanced significantly the level of plant available N in soil compared to previous removal of herbage. This is in according to the hypothesis that plant available N will increase after digestate application, but not after mulching. However, in the case of mulching versus removal, on the soils most prone to leaching, we found a substantial yield response in barley from the mulched herbage. In accordance with the findings of Dahlin et al. (2011), this indicates that a considerable proportion of herbage N was incorporated into soil organic matter and mineralized during the growing season 2010.

Thorup-Kristensen and Dresbøll (2010) have recorded fast N mineralization under low temperatures after incorporation of catch crops in spring. Our results from N uptake in the barley plants indiates a slower N mineralisation from the ploughed under one year old mulched green manure ley, probably due to a higher C/N ratio of the plant material. The contribution of N from green manure root and stubble to the following grain yield was low. In general, higher levels of NO_3-N were found in the G treatments than in the C treatments in spring 2011. This indicates that N from green manure was released over a longer period.

Some mineralization in soil with and without green manure seems to have taken place during the winter of 2009 to 2010 (Fig. 2, comparing bars for inorganic N in autumn 2009 and spring 2010). This is in agreement with several studies that have shown substantial mineralisation of incorporated green manure at temperatures down to 1–3 °C (Cookson et al., 2002; Magid et al., 2001; Van Schöll et al., 1997). Our results also indicate that mineralization from stubble and below-ground green manure biomass occurs at low temperatures. The enhanced soil inorganic N content due to mulching that was found before ploughing the ley in spring 2010, corresponded to 4–7% of the total N added as mulch.

4.4. Effect of herbage management on soil structure and earthworms

The use of digestate improved soil aggregate stability, more than compensating for the herbage removal in treatment G-0M-D, as seen in the comparison to treatment G-3M. Further, it would seem that the use of digestate was effective in increasing the soil aggregate stability on plots previously cropped with cereals to the level found where mulching of green manure had been practiced. As found by Abiven et al. (2009), easily decomposable products are known to have an intense and transient effect on soil aggregate stability. Further, digestate of cattle slurry is found to stimulate the bacterial decomposer community more than undigested slurry, and in a similar way to that of inorganic fertilizers (Walsh et al., 2012).

In accordance to our hypothesis, a clear positive effect of mulching on the earthworm fauna was seen after only one season. It is well-known that systems with one or more years of grass and clover in the crop rotation, often host more earthworms than do all-arable systems (Edwards and Lofty, 1977; Pommeresche and Løes, 2009; Schmidt et al., 2003). In our study, the effect was consistent even the first year and was directly connected to the mulching of the plant material. One result of higher biomass of earthworms after mulching in 2009 was higher cast production. Pommeresche and Løes (2009) estimated that a density of 229 earthworms m^{-2} corresponds to 22.1 kg casts per m^{-2} $year^{-1}$. The casts contained 3 g total N kg^{-1}. Roughly estimated for our trials, this means 30 g more total N m^{-2} in casts in the mulched treatment. Almost the entire N content of the casts is organically bound and thereby protected against leaching until mineralization (Boström, 1988). In addition, dead earthworms contributes to the N mineralization as their body tissue contains 10–12% N of their dry weight and they decompose rapidly (Edwards and Bohlen, 1996).

The higher densities of *L. rubellus* and *A. caliginosa* after mulching are a response to the input of organic matter which increased both the survival of adults and juvenile recruitment. Among species, mulching gave diverging results in the two soils. At Værnes, the surface dwelling *L. rubellus* responded by increased population in the same season. Slower decomposition in the denser clay soil at Kvithamar, may explain the higher density of the soil-dwelling, soil-eating *A. caliginosa* here in 2010, compared to the lack of any effect on the earthworm parameters at Værnes in the same year.

The lack of any effects on the earthworm density or biomass after one digestate application is not in line with the hypothesis. However, one season is too short a time to conclude on possible longer term effects on earthworm parameters that may occur with repeated annual use of digestate. Ernst et al. (2008) tested effects on earthworms of cattle slurry and anaerobic digested mixture of cattle slurry and plant residue in a microcosm experiment. While the biomass of the litter-eating species (*L. terrestris* and *Apporectodea longa*) increased in both slurry treatments, that of the soil-eating species *A. caliginosa* decreased significantly in treatments with digested slurry. This is unfortunate as soil-eating species survive well with soil tillage and are the dominant species (80–100%) in arable soils in Norway (Chan, 2001; Pommeresche and Løes, 2009).

4.5. Implications

Our results indicate that in spring barley production under cold climatic conditions, the N supply may be limiting, even after a productive green manure ley. If the green manure herbage is removed, it can lead to further N deficiency. Mulching the last cut and removing the previous cuts will reduce the potential loss of N from the cut herbage, compared to mulching all cuts, but the subsequent barley DM yield may be also be lower.

Removing herbage from the field requires that it may be used as forage or to produce digestate in a biogas reactor. Möller and Müller (2012) concluded that biogas digestion of field residues, instead of mulching, resulted in a win-win situation, with additional energy yields, lower risk of N leaching and lower nitrous oxide emissions, although the risk of ammonia volatilization remains when applying the digestate. Halberg et al. (2008) also support this view from an energy self-reliance perspective on organic cash-crop farms.

In our trial, we applied nearly half of the N harvested in green manure herbage. At a farm scale, the surplus digestate would make it possible to fertilize other fields as well. However, running small farm-scale biogas plants solely based on green manure herbage is challenging. Cooperation with biogas plants with continuous feeding throughout the year would seem to be the best solution until new technology is developed for small farm-scale biogas plants based on grass/clover herbage.

5. Conclusions

When we evaluated the effect of various strategies for green manure management we found that both for DM yield and apparent N recovery in a subsequent barley crop, it mattered how the green manure herbage was managed. Herbage mulching compared to removal improved the barley yield, whilst herbage removal accompanied with return of about 45% of the removed N as digestate improved both yield and N recovery. The amount of N removed with the herbage was not compensated for by increased clover growth in the summer regrowth. The low effect of green manure on N supply to the following grain crop was most likely due to low net N mineralization. Lowest N recovery was found on the clay soils.

The mulched plant material gave an increase in earthworm density and biomass. Application of digestate increased aggregate stability measured shortly after application, but did not affect the biomass or density of earthworms.

Of the managements considered, the digestate strategy seems to be the most promising option as regards increasing N recovery and reducing the risk of N losses.

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