The effect of season and management practices on soil microbial activities undergoing nitrogen treatments - interpretation from microcosm to field scale

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ABSTRACT

The warming of Arctic regions is causing higher winter and spring temperatures, less snow cover and intensifying seasonal patterns, which in turn have led to a longer growing season in colder regions. In Iceland the climate has become warmer and wetter with lengthening of the growing season and a corresponding increase in arable production. The aim of this study was to assess the effect of seasons and management practices on soil microbial biomass, nitrification, enzymatic activities and labile C availability. A parallel soil microcosms study was conducted to identify the key drivers in a controlled environment. Seasons had a more pronounced effect on soil microbial attributes (dehydrogenase activity, soil microbial biomass and labile C) than soil management with microbial attributes being greater in warmer summer months. This was an indication that continuing climate change and corresponding increase in dehydrogenase activity and soil microbial biomass in soils may increase carbon decomposition and hence loss of organic carbon from cultivated soils in Iceland. Management had a greater impact on soil N dynamics than seasons. There was evidence that precipitation promoted immobilisation of NO_3^- -N in soils suggesting that the wetter climate developing in Iceland might reduce the availability of NO_3^- -N to crops. Labile C was a governing factor in soil microbial activity as was demonstrated both in the field and the laboratory.

Keywords: Subarctic soils, seasons, management, nutrient dynamics, field to microcosms scale

YFIRLIT

Loftlagsbreytingar á norðurhveli jarðar hafa aukið hitastig bæði yfir vetrar og sumarmánuði, skerpt skil milli árstíða, minnkað snjóhulu, og þar með aukið landnýtingarmöguleika á norðlægum slóðum. Svipaðar breytingar hafa verið að þróast hér á landi þar sem hita- og rakastig í andrúmslofti hefur hækkað og lengt vaxtatímabilið auk þess sem hlutdeild ræktarlands stækkar. Megin markmið þessarar rannsóknar var að rannsaka áhrif árstíða og landnýtingar á jarðvegslífmassa, umsetningu niturs, virkni ensíma og aðgengilegt, auðbrjótanlegt lífrænt kolefni í jarðvegi en allir þessir þættir gegna veigamiklu hlutverki í næringarefnahringrás jarðvegs. Samhliða

tilraunum við náttúrulegar aðstæður voru gerðar tilraunir við staðlaðar aðstæður inn á rannsóknastofu til að öðlast dýpri skilning á umhverfisbreytum á borð við árstíðabundnar hitastigsbreytingar sem og breytilegum styrk auðbrjótanlegs kolefnis frá plönturótum við náttúrulegar aðstæður. Í heildina höfðu árstíðir meiri áhrif á virkni vetnissvipta ensíma, heildar lífmassa og auðleysanlegt kolefni en landnýting, en einnig var virknin meiri yfir hlýrri sumarmánuði. Þetta telst vera vísbending um að hlýnandi veðurfar hér á landi gæti aukið niðurbrot lífrænna efna í jarðvegi og þar með aukið losun kolefnis út í umhverfið. Landnýting hafði hins vegar afgerandi áhrif á niturhringrás (umsetningu og bindingu) jarðvegsins í samanburði við árstíðir. Aukin úrkoma benti til þess að binding NO_3^- -N jókst innan lífmassa jarðvegsins en aukin úrkoma í tengslum við hlýnandi veðurfar á Íslandi gæti þar með minnkað aðgengi ræktarplantna á NO_3^- -N. Örveruvirkni jarðvegsins var háð framboði auðleysanlegs kolefnis í jarðveginum en bæði mælingar við náttúrulegar og staðlaðar aðstæður sannreyndu þá niðurstöðu.

INTRODUCTION

Arctic regions are rapidly warming with higher winter and spring temperatures, warming soil temperatures and less snow cover (Serreze et al. 2000). This has led to a prolonged growing season in colder regions (Weintraub & Schimel 2005) with a subsequent intensification of agriculture. It has been argued that the temperature increase in the Arctic will intensify seasonal patterns (IPCC 2007), which will in turn strongly affect soil microbial biomass and as a consequence the release of nitrogen (N) and other nutrients from soil organic matter (SOM) (Orlandini et al. 2008, Stoate et al. 2009). There is a lack of peer reviewed literature regarding seasonal variations in soil microbial biomass and activity under field conditions in soils of higher latitudes (Nielsen et al. 2009, Ge et al. 2010). Experiments that have been conducted under field conditions have mainly focused on the short growing period and spring snowmelt and hence rarely include winter scenarios, which might be because of difficult field accessibility during Arctic winters (Brooks et al. 1996, Brooks & Williams 1999, Bardgett et al. 2007). Such studies have, however, used microcosms under controlled laboratory conditions (Laakso & Setala 1999). While these studies are valuable to understand the effect of predetermined variables on soil nutrient dynamics, they often fail to take into account the impact of plants, release of root exudates and water dynamics, as many use unvegetated soil cores (Johnson et al. 2000). For microcosm experiments to be successful there is a need to translate the findings to empirical values at the field scale (Etchebers et al. 2007) and surprisingly few studies use both scales to better understand soil processes.

Soil enzymes produced by soil microorganisms play the main role in SOM. They enhance the decomposition of soil organic substrates, release plant nutrients and can determine whether soil organic carbon (SOC) is sequestrated or depleted (Fansler et al. 2005). Extracellular enzymes like phosphatase (PHOS) and dehydrogenase (DH) also participate in the decomposition of SOM (Bell et al. 2010). The soil microbial biomass gives an indication of changes in SOC and responds readily to changes in soil management (Laik et al. 2009), while seasonal variations have not been widely documented. Labile C derived from decomposition of SOM is an important driver for soil heterotrophic activity and has been considered as an indicator of soil quality (Laik et al. 2009). Labile C has also been reported to be sensitive to management practices (Cambaredlella 1998) and increasing environmental temperatures (Hagedorn et al. 2010). Soil N mineralisation and immobilisation determine the availability of N from soil to plants and have been reported to be greatly influenced by management (Beier et al. 2008) as well as differing markedly between summer and winter (Miller et al. 2009).

Most studies of the responses of biological processes to climate change have focussed on high Arctic soils (Clein & Schimel 1995, Lipson & Monson 1998, Mikan et al. 2002, Schimel & Mikan 2005) but fewer have considered subarctic environments which are more

likely to be cultivated (Miller et al. 2007). In Iceland, which is a subarctic mountainous island (average altitude of 500 m above sea level) situated close to the Arctic circle between latitudes 63°23'N and 66°32'N, the more favourable growing conditions related to a warmer and wetter climate have already led to the intensification of grazing on improved and cultivated land and barley cultivation have increased steadily since 1980 for the supply of animal fodder (Bergthórsson et al. 1987, Björnsson et al. 2008, Icelandic Agricultural Statistics 2009). Increased cultivation coupled with a warming climate may result in increased soil biological activity, accelerated decomposition of organic matter and nutrient release. To the authors' best knowledge no studies have been published on the impact of seasons on cultivated soil biological activity in Iceland. Understanding the fundamental aspects of seasonal variations on cultivated soils may be of considerable interest and crucial for maintaining sustainable agriculture in the fragile northern ecosystem of Iceland. The aim of this study was therefore to assess the impact of seasonal variations (precipitation, snow cover, soil and air temperature) and management practices (pasture and barley) on soil biological properties (microbial biomass C, labile C availability, enzymatic activity, nitrification and ammonification) under field conditions. The study was coupled with a laboratory unvegetated soil microcosm study to better identify the impact of field seasonal variables.

MATERIALS AND METHODS

The field scale

The field experiment was conducted at the field experimental station, Korpa, established in 1965 in the south-west of Island (64°09'N). The field site was on a slope of 0°, with a mean annual temperature of +5°C and mean annual precipitation for the area of 410 mm, (mean of 15 years of precipitation of the area, Icelandic Meteorological Office). This multi-factorial replicated field experiment had 12 plots (7x14 m). The plots consisted of three treatments which included 2 cultivation practices (barley and pasture) and control plots (not cultivated). Plots were set up in 2003 and had undergone four years of cultivation prior to this experiment, which was conducted in June - December 2007. Plots represented common management practices and N amendments used by farmers in Iceland to represent actual cultivation scenarios. Barley plots were fertilised with 80 kg ha^{-1} N (NH_4NO_3), ploughed and harvested each year. Grassland plots were fertilised with 120 kg ha^{-1} N harvested each year. Control plots were not fertilised or cultivated. Plots were sampled randomly (two replicates within each plot) at the beginning of each month (top 15 cm) from the beginning of June to December. The research soil type has been classified as a Gleyic Andosol (Guicharnaud 2002, Arnalds 2004). The soil had a silty loam texture with a granular and sub-angular structure (Guicharnaud 2002).

Seasonal variables

Climate data at the field site (Korpa) (daily air and soil temperature, precipitation and snow cover) were gathered throughout the 6 month of the field experiment for assessment of seasonal variations.

The microcosms scale

The microcosm experiment consisted of 40 unvegetated plant plots (volume of 0.25L) containing sieved (<3.75 mm) soils from the control plots at the field experimental site. Soil microcosms were adjusted to 60% water holding capacity and incubated at 14°C throughout the 9 week experiment. Pots were incubated in phytotrons (14°C) for 4 weeks prior to the experiment to allow equilibration. The first treatment soils were amended with the equivalent of 120 kg ha^{-1} of N, the second treatment soils with the equivalent of 80 kg ha^{-1} of N. The third treatment soils were not subjected to fertiliser additions. Soil microcosms were sampled every two weeks during the 9 weeks of the experiment and subjected to disruptive sampling.

Soil biological analyses at the field scale and microcosm scale

All biological analyses were conducted within two days of sampling, both at the field and microcosm scales. Biological analyses were conducted at the field scale on field moist (<3.75 mm) samples. Procedural blanks were included for all biological measurements and all results were expressed on a dry weight basis (24 hr, 105°C).

Soil biological analyses

Soil microbial biomass C (mic_c) was measured by the chloroform fumigation extraction method (Vance et al. 1987). Soil extractable C (DOC) was determined in fumigated (24 h fumigation) and non-fumigated soil samples by extracting soils with 0.5M K_2SO_4. Extracts were analysed in an aqueous carbon analyser (LABTOC Pollution and Process Monitoring) with UV digestion and an infrared detector. The K_{EC} factor used was 0.33 for mineral soils (Sparling & West 1988). The 0.5M K_2SO_4 extractable DOC from non-fumigated soil samples was used to characterise the soil labile carbon pool (Guicharnaud et al. 2010).

Soil dehydrogenase activity (DH) was determined by a modified method of Trevors (1984) with 0.1M iodonitetrazolium chlorine (within the buffer 0.5M N-tris [hydroxylmethyl] methyl 1-2 aminoethane-sulfonic acid [TES] adjusted to pH 7.8 with 5M NaOH). Soil samples were incubated and shaken for 18 hr and analysed by spectrophotometry (Cecil Instrument CE373) at 490 nm. Calibration responses were determined using iodonitetrazolium formazan (INTF).

Soil phosphatase activity (PHOS) was measured according to Tabatabai & Bremner (1969) with 0.015M p-nitrophenyl phosphate. Samples were incubated at 37°C for 1 h and analysed by spectrophotometry at 400 nm. Standard curves were determined using p-nitrophenol.

The relative activity of enzymes was calculated by dividing measured dehydrogenase activity and phosphatase activity with the measured mass of soil microbial biomass C (*q*DH and *q*PHOS) (Bell et al. 2010). KCl extractable NH_4+ -N and NO_3^- - N were measured in 2M KCl extracts in a flow injection analyser (FIAstar 5010 analyser) (Blakemore et al. 1987). The concentration of KCl extractable NH_4^+ -N and NO_3^- -N was used to estimate ammonification, nitrification and immobilisation by calculating the difference between the initial and final of NH_4^+ -N and NO_3^- -N concentrations of each experiment (Raison et al. 1987, Miller et al. 2007).

Statistical analyses

After confirmation that the data were normally distributed, they were analysed using ANOVA to assess significant differences between treatments and with time using SAS 9.1. (SAS Institute Inc.). Correlations and regression analyses were performed in Sigma Plot 9.9 for Windows (Systat Software Inc.) to study relationships between measured biological parameters under field conditions and for assessing the effect of environmental variables such as soil temperature and rainfall. All levels of significance were expressed at $p \leq 0.05$.

RESULTS

Seasonal changes measured soil biological factors

The mean air temperature was 10.8°C in summer and 2.8°C in winter. The mean soil summer temperature was 11.0°C and 4.8°C in winter. Precipitation was lower in summer (June to beginning of September) than winter (October to December) with a mean monthly precipitation of 95 mm and 197 mm respectively. A mean 3 cm snow cover was recorded in October but snow melt occurred in November (no snow cover recorded). A mean 12 cm snow cover was measured in December (Table 1). No significant correlations were found between seasonal variables (soil temperature and precipitation) on each individual sampling date and measured soil biological parameters with the exception of soil DH, which correlated positively with soil temperature ($r=0.96$ $P=0.02$). Differences were detected on the other hand between soil biological activity in relation to

Table 1. Experimental field climatic conditions throughout the seasonal field experiment from June to December. Soil temperature was measured at 10 cm depth.

Month	Air temperature			Soil temp.	Field precipitation		Snow cover	
	Mean	Max	Min	Mean	Monthly	Max daily	Day	Max daily
					mm	mm	cm	cm
June	11.2	21.2	4.2	5.7	50	21.6		
July	13.5	22.1	3.6	11.7	45	12.4		
August	11	19.6	0.6	14.6	112	28.8		
September	7.6	13.9	-3.8	11	171	25.5		
Mean Summer	10.8	19.2	1.2	10.8	94.5	22.1		
October	5.6	12.4	-6	7.5	212	31.4	3	2
November	2.3	10.1	-9.7	5.3	144	17.1		
December	0.6	9.9	-13.6	1.7	236	36.8	12	13
Mean Winter	2.8	10.8	-9.3	4.8	197.3	28.4	7.5	7.5

Table 2. Monthly mean field concentrations of soil microbial biomass (mic_c), dehydrogenase activity (DH), phosphatase activity (PHOS) and labile C (DOC) throughout the growing season (June - September) and during the winter period (October to December).

The Field	Treatment	June	July	Aug	Sept	Mean	Oct	Nov	Dec	Mean
Scale	kg ha^{-1} -N					Summer				Winter
Mic_c mg kg^{-1}	120	2485	4202	2919	5059	3666	2826	784	4458	2689
	80	2775	4406	3887	5343	4103	2635	628	4708	2657
DH µg g^{-1} h^{-1}	120	8.3	15.4	18	7.4	12	0.04	0.32	0.07	0.14
	80	10.1	14.9	18.9	7.1	13	0.48	0.26	0.06	0.27
	0	12.2	19.2	18.7	7.9	14	0.23	0.47	0.06	0.25
PHOS µg g^{-1} h^{-1}	120	144	92	50.6	508	199	375	183	164	241
	80	145	106	56.5	607	229	742	382	274	466
	0	151	109	53.2	915	307	862	247	230	446
Labile C mg kg^{-1}	120	358	275	159	143	234	124	159	148	144
	80	219	274	193	158	211	153	177	168	166
	0	443	279	199	161	270	201	210	190	200

summer (June-September) and winter scenarios (October-December).

Changes in mic_c throughout the summer and winter were significant with the mean mic_c being higher in summer than winter ($P < 0.01$) for all fertiliser treatments (Table 2).

Soil DH differed between seasons (Table 2). Generally DH was considerably higher in summer for all treatments plots compared to winter activity ($P < 0.01$). Soil DH was temperature dependent and changed as a response to temperature ($r=0.96$ $P=0.02$). Seasonal differences in the relative activity of DH per unit mic_c (*q*DH) were detected and were higher in summer compared to winter ($P<0.05$) (Table 3). Seasonal changes were observed in measured PHOS in all experimental plots and these values were significantly higher ($P<0.01$) in winter compared to summer (Table 2). An increase in PHOS was observed in autumn (September and October) but decreased thereafter (Table 2). Soil relative PHOS activity (*q*PHOS) was likewise higher in winter than summer ($P<0.01$) (Table 3). Soil labile C varied with season and was higher in all treatments in summer compared to winter ($P<0.01$) (Table 2).

Seasonal changes between summer and winter in ammonification (increase in NH_4^+ -N), nitrification (increase in NO_3^- -N) and immobilisation (reduction of either NH_4^+ -N or NO_3^- -N) are shown in Figure 1 and 2. When comparing summer and winter processes of N dynamics at the field scale, a significant difference was measured between NH_4^+ -N and NO_3^- -N processes. Ammonification occurred during summer and winter in all plots except the grassland treatment with (80 kg ha^{-1} N) where immobilisation of NH_4^+ -N was the dominant process. In all treatment plots, net ammonification during winter exceeded ammonification in summer (Figure 1). During the summer period,

nitrification occurred but NO_3^- - N immobilisation was the dominant process in winter. Soil NO_3^- - N immobilisation was lowest in grassland treatment plots receiving the highest amount of fertiliser N and greatest in control soils with no N amendments (Figure 2).

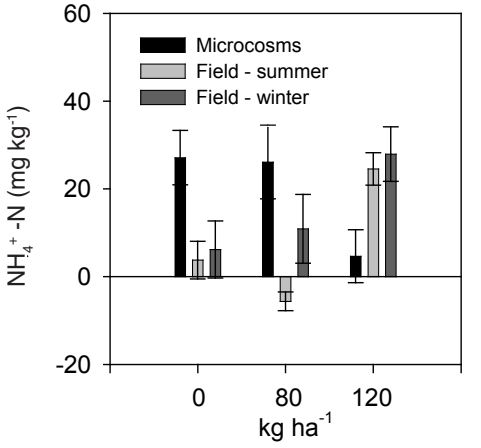

Figure 1. Ammonification and immobilization of NH_4^+-N in microcosms and in the seasonal field experiment during summer (June - September) and winter periods (October to December).

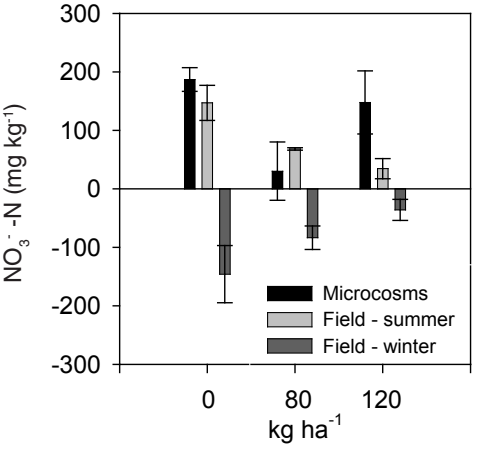

Figure 2. Nitrification and immobilization of NO_3^- - N in microcosms and in the seasonal field experiment during summer (June - September) and winter periods (October - December).

The effect of N application on measured soil biological factors

Different fertiliser amendments did not affect the mic_c size ($P>0.05$) (Table 2).

Fertiliser amendments and management practices did not affect mean DH activity in all treatment plots. Soil mean relative DH activity (*q*DH) was highest, however, in control plots ($P>0.01$), both during the summer and winter period, and lowest in grassland plots amended with the highest fertiliser N concentrations (Table 3). Fertiliser amendments and management practices had an impact on mean PHOS activity, with lowest concentrations measured in grassland plots receiving the highest fertiliser N amendments in summer and winter (Table 2). In summer the relative PHOS activity was also greatest in control plots ($P<0.01$) (Table 3).

Labile C did not differ significantly ($P>0.05$) between management practices and fertiliser application in all treatment plots.

Fertiliser doses and management practices affected ammonification during the winter period, when ammonification increased gradually with decreasing amounts of fertiliser applied (Figure 1). Ammonification was significantly greater in control plots during summer and winter (Figure 1). Fertiliser doses and management practices affected nitrification because a gradual significant increase was recorded with decreasing amounts of fertiliser application in summer. In winter immobilisation of NO_3^- - N increased significantly with decreasing amounts of fertiliser (Figure 2).

Comparison of measured biological factors between the field and microcosms scale

Mic_c differed significantly between field ($P= 0.004$) and microcosms (Tables 2 and 4) for all treatments with concentrations being significantly higher in the field. The same pattern was revealed with soil DH, which generally differed significantly in field and microcosms, with higher activity in the field samples. Soil PHOS did not differ significantly between field and microcosms independent of fertiliser appli-

Table 3. Calculated relative activity of dehydrogenase activity (*q*DH) and phosphatase activity (*q*PHOS) for each fertiliser treatment during the six month experiment.

Relative enzymatic activity	Treatment kg ha^{-1}	June	July	Aug	Sept	Mean Summer	Oct	Nov	Dec	Mean Winter
qDH µg g^{-1} h^{-1}	120	3.5	3.8	6.3	1.5	3.8	0.02	0.40	0.01	0.14
	80	3.8	3.5	4.9	1.4	3.4	0.18	0.42	0.01	0.21
	0	5.8	5	5.5	1.3	4.4	0.08	0.67	0.01	0.25
qPHOS µg g^{-1} h^{-1}	120	60	31	17	100	52	232	130	39	134
	80	54	24	15	115	52	450	286	87	274
	0	67	36	16	154	68	269	311	58	213

Table 4. Mean concentrations of soil microbial biomass (mic$_c$), dehydrogenase activity (DH), phosphatase activity (PHOS) and label C (DOC) throughout the 9 week incubation experiment of unvegetated soil microcosms.

The Microcosm Scale	Treatment kg ha^{-1} -N	Days 0	Days 14	Days 28	Days 49	Days 56	Mean
Mic$_c$ mg kg^{-1}	120	1702	1982	874	729	1002	1322
	80	302	2160	1248	965	864	1169
	0	1269	1747	2070	1069	813	1539
DH µg g^{-1} h^{-1}	120	2	4.3	11.5	11.6	6.3	7.3
	80	2.2	4.2	18.2	10.4	5.2	8.7
	0	2.4	3.7	8.39	10.9	5.4	6.3
PHOS µg g^{-1} h^{-1}	120	335	47.3	48.7	127	118	139
	80	330	44.7	72.2	131	116	144
	0	389	45.4	57.4	125	117	154
Labile C mg kg^{-1}	120	428	361	277	624	437	422
	80	428	384	322	491	429	406
	0	348	318	233	470	467	342

cation (P >0.05). Labile C in microcosms was significantly higher (P <0.01) in soil microcosms compared to field samples. The greatest labile C values were measured in soil microcosms receiving the highest amount of fertiliser N (equivalent of 120 kg ha^{-1}N) and lowest in control microcosms with no fertiliser amendments (Table 4).

During the 56 day incubation experiment at a fixed temperature of +14°C significant differences were detected between sampling weeks in all microcosm treatments for all measured parameters (P <0.01).

Ammonification differed significantly between the field and microcosms with ammonification being the dominant process in all microcosm treatments (Figure 1). In the field grassland plots (80 kg ha^{-1} of N) immobilisation of NH_4^+ occurred. Ammonification in amended microcosms significantly exceeded ammonification in the field. In microcosms, ammonification was lowest in the control treatment but ammonification was significantly highest in field controls.

Nitrification increased in all field treatment plots with decreasing fertiliser doses and was significantly higher in control plots. Such behaviour was not observed in microcosms (Figure 2). Nitrification in microcosms exceeded nitrification in the field under barley cultivation and in control plots, whereas nitrification in field grassland plots (80 kg ha^{-1} of N) was smaller in microcosms than in the field.

DISCUSSION

Seasonal changes in soil biological factors

Soil mic$_c$ in this study was higher in the warmer summer months of higher microbial activity, demonstrating the storing of soil nutrients within the soil biomass as a consequence of intensive nutrient demand by plants and soil microorganisms (Dilly et al. 2003, Ge et al. 2010). The fact that mic$_c$ did not correlate with precipitation suggests that mic$_c$ was rather

responsive to factors such as temperature and substrate availability, as has been previously reported in Icelandic soils (Guicharnaud et al. 2010).

Soil DH activity generally increases with temperature (Kang et al. 2009), as was the case in this study (Table 2). No such trend was observed with PHOS. Icelandic soil DH and PHOS were governed, however, by labile C availability (r=0.96 P=0.0001, r=0.94 P=0.001 respectively) a finding which was in agreement with previous research conducted on cultivated soils (Brzeziñska et al. 1998, Hagedorn et al. 2010, Quin et al. 2010). Guicharnaud et al. (2010) reported labile C to be a governing factor controlling heterotrophic activity in Icelandic soils whilst Schimel and Mikan (2005) and Boddy et al. (2008) confirmed the importance of labile C for soil microbial activity in colder latitude soils. The fact that the two enzymes were at their peak activity in different seasons (DH in summer and PHOS in winter) was a clear reflection of soil seasonal metabolisms.

Soil labile C was generally higher in summer compared to winter concentrations (Table 2), reflecting the effect of root exudation during the growing season. The decreasing labile C pool at the end of the growing season in all treatment plots reflected the reduction of the easily decomposable C pool metabolised during the summer months of high microbial activity.

In summer, N (NH_4^+ - N and NO_3^- - N) was not a limiting factor for soil microorganisms in cultivated Icelandic soils, as ammonification (with the exception of barley plots) and nitrification were measured throughout the summer period in all treatments plots, reflecting higher mineralisation rates and activity during the warmer months (Figure 1 and 2). N dynamics are commonly reported to differ between seasons (Lipson et al. 1999). In this study, when winter immobilisation of NO_3^- - N was the dominant process, ammonification occurred concurrently (Figure 1 and 2). The winter period of this research was a significantly wetter (mean rainfall of 197 mm) period than summer (mean rainfall of 94 mm). This could have promoted anaerobic conditions within treatment plots, enhancing denitrification measured as reduced NO_3^--N concentrations (Chantigny et al. 2002). Miller et al. (2007) reported similar results in subarctic soils. When soils had a high moisture content, ammonification occurred while NO_3^--N was being immobilised. Such observations have been explained by microorganisms accessing a greater proportion of soluble N rich materials at colder temperatures as a result of microbial cold acclimation strategies (Lipson et al. 1999, Schimel & Mikan 2005, Schimel et al. 2007). The fact that labile C concentrations were affected by the seasons suggests that soil labile C might be impacted by increasing temperature and seasonal variations. Moreover, the correlation found between labile C and both enzymes measured in the study, as well as such a relationship has been previously reported in Icelandic soil (Guicharnaud et al. 2010), indicates that labile C might be used as a suitable indicator of the potential of soil microbial activity.

The effect of N application on measured soil biological factors

Consistent with previous research (Emmerling et al. 2001, Dilly et al. 2003), fertiliser N did not have any impact on soil mic_c size after 5 years of cultivation, suggesting it may be irresponsive in the initial stages of cultivation or that these soils were not limited by N. A similar behaviour was reported for DH and PHOS, with their activity not being increased by fertiliser N application as has been previously recorded in cultivated soils (Olander & Vitousek 2000, Wang et al. 2008, Bell et al. 2010). In contrast, the specific activity of soil enzymes (enzyme activity per unit biomass) differed between management treatments with the specific activity being greater in undisturbed control plots. Disturbance of enzymatic activity through cultivation practices and fertiliser application has been documented (Dilly et al. 2003, Mijangos et al. 2006) with early evidence detected in this study, after 5 years of cultivation.

Labile C has been recognised to be the frac-

tion of C that is closely linked to soil fertility due to its capacity to furnish nutrients to plant and soil microbes as well as being generally sensitive to management practices (Fansler et al. 2005). No such evidence was found in the present study, suggesting that neither soil management nor the addition of N impacts the labile fraction of the cultivated Gleyic Andosols of this study following 5 years of cultivation.

Contrary to the soil biomass, enzymatic activity and labile C concentrations, N application and management did impact soil N dynamics. In agreement with previous research arguing that excess inorganic fertiliser application can have a negative impact on soil microbial activity (Bardgett et al. 1997, Sarathchandra et al. 2001), N mineralisation was lower in cultivated treatment plots, with both ammonification and nitrification being substantially higher in control field plots during summer compared to fertilised plots (Figure 1 and 2).

Comparison between the field and microcosm scales in measured soil biological factors

The microcosm scale demonstrated the effect of field variables like flow of root exudates and water dynamics, as well as temperature.

Greater measured mic_c field values compared to microcosms could be in part explained by the absence of roots and the occurrence of a seasonal labile C source (Stutter et al. 2007). Hence unvegetated microcosms are not always representative of field values. The higher DH in the field compared to microcosms (Table 2 and 4) was in agreement with Teuben and Verhoef (1992). Greater field DH values have been attributed to a greater supply of active C and N pools from roots or litter under field conditions (Brzezinska et al. 1998). PHOS did not differ between the field and microcosms and was independent of fertiliser treatment, reflecting different microbial pool than DH. Higher nitrification rates measured in the microcosms reflected better and more consistent environmental conditions than in the field (Sparling et al. 1990). Higher measured labile C concentrations in microcosms compared to field values reflected the lower metabolic cycling of C associated with the absence of microbial rhizosphere activity in unvegetated soil microcosms. The fact that all measured biological factors differed between sampling weeks, despite microcosms being kept at constant temperature, and the WHC demonstrated the importance of substrate availability in terms of soil biological activity.

The different behaviours of ammonification, nitrification and immobilisation in field and microcosms demonstrated that unvegetated microcosms are not representative of field processes (Figure 1 and 2). In this study, ammonification was greater in microcosms compared to the field, which was consistent with Teuben and Verhoef (1992) who assumed this to be related to the effect of plant roots, soil temperature and moisture dynamics associated in the field. Stutter et al. (2007) measured leaching of NH_4^+-N in both incubated microcosms and field soil cores with smaller concentrations of NH_4^+-N being measured in the field due to plant uptake of NH_4^+-N. Soil nitrification processes were similar in field and microcosms, with nitrification occurring in all treatment plots and microcosms. Nitrification in microcosms exceeded field values and was not related to fertiliser amendment, which was the case in the field. This was also reported by Teuben and Verhoef (1992) and Stutter et al. (2007) who suggested that this was related to the absence of active root uptake and soil leaching not accounted for in microcosms.

To conclude, seasonal variations had a greater impact on soil microbial biomass, enzymatic activity and labile C concentrations than management, while management treatments had a greater impact on soil nitrogen dynamics than did the changing seasons. Labile C from root exudates was microbially driven, which was demonstrated both in the field and the microcosms. The fact that labile C, DH activity and mic_c were greater during the higher summer temperatures indicates that future climate change in northern latitudes may increase soil carbon decomposition and hence the loss

of soil organic carbon. There were indications that precipitation promoted immobilisation of NO_3^--N in soils, suggesting that the wetter and warmer climate that has been developing in Iceland might reduce the availability of NO_3^--N to crops.

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