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Reduced N cycling in response to elevated CO2, warming, and drought in a Danish heathland: Synthesizing results of the CLIMAITE project after two years of treatments — Source link

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Published on: 01 May 2011 - Global Change Biology (Wiley-Blackwell Publishing Ltd.)

Topics: Nitrogen cycle, Deschampsia flexuosa and Ecosystem

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Journal:	*Global Change Biology*
Manuscript ID:	GCB-10-0587
Wiley - Manuscript type:	Primary Research Articles
Date Submitted by the Author:	16-Jul-2010
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Keywords: Climate driver interactions, C/N ratio, multi-factor climate change experiment, nitrogen cycling, nitrogen mineralization, N2O, soil fauna

Abstract:

Field-scale experiments simulating realistic future climate scenarios are important tools for investigating the effects of current and future climate changes on ecosystem functioning and biogeochemical cycling. We exposed a semi-natural Danish heathland ecosystem to elevated atmospheric carbon dioxide (CO2), warming, and extended summer drought in all combinations. Here, we report on the short-term responses of the nitrogen (N) cycle after two years of treatments.

Elevated CO2 significantly affected above-ground stoichiometry by increasing the carbon to nitrogen (C/N) ratios in the leaves of both co-dominant species (Calluna vulgaris and Deschampsia flexuosa), as well as the C/N ratios of Calluna flowers and by reducing the N concentration of Deschampsia litter. Below-ground, elevated CO2 had only minor effects, whereas warming increased N turnover, as indicated by increased rates of microbial NH4+-N consumption, gross mineralization, potential nitrification, denitrification and N2O emissions. Drought reduced below-ground gross N mineralization and decreased fauna N mass and N mineralization. Leaching was unaffected by treatments but was significantly higher across all treatments in the second year than in the much drier first year indicating that ecosystem N loss is highly sensitive to changes and variability in amount and timing of precipitation. Interactions between treatments were common and although some synergistic effects were observed, antagonism dominated the interactive responses in treatment combinations, i.e. responses were smaller in combinations than in single treatments. Nonetheless, increased C/N ratios of photosynthetic tissue, decreased litter N production, and decreased fauna N mineralization prevailed in the full treatment combination indicating reduced N turnover in the simulated future climate scenario, which could act to reduce the potential growth response of plants to elevated atmospheric CO2 concentration.

In conclusion, effects observed in single-factor studies should be evaluated with caution. Multi-factor climate experiments are needed for improving realistic estimation of the combined ecosystem responses to future climate changes.

Title: Reduced N cycling in response to drought, warming, and elevated CO_2 in a Danish heathland: Synthesizing results of the CLIMAITE project after two years of treatments

Running title: Effects of climate change on N cycling

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Elevated CO_2 significantly affected above-ground stoichiometry by increasing the carbon to nitrogen (C/N) ratios in the leaves of both co-dominant species (*Calluna vulgaris* and *Deschampsia flexuosa*), as well as the C/N ratios of *Calluna* flowers and by reducing the N concentration of *Deschampsia* litter. Below-ground, elevated CO_2 had only minor effects, whereas warming increased N turnover, as indicated by increased rates of microbial NH_4^+-N consumption, gross mineralization, potential nitrification, denitrification and N_2O emissions. Drought reduced below-ground gross N mineralization and decreased fauna N mass and N mineralization. Leaching was unaffected by treatments but was significantly higher across all treatments in the second year than in the much drier first year indicating that ecosystem N loss is highly sensitive to changes and variability in amount and timing of precipitation. Interactions between treatments were common and although some synergistic effects were observed, antagonism dominated the interactive responses in treatment combinations, *i.e.* responses were smaller in combinations than in single treatments. Nonetheless, increased C/N ratios of photosynthetic tissue, decreased litter N production, and decreased fauna N mineralization prevailed in the full treatment combination indicating reduced N turnover in

the simulated future climate scenario, which could act to reduce the potential growth response of plants to elevated atmospheric CO_2 concentration.

In conclusion, effects observed in single-factor studies should be evaluated with caution. Multi-factor climate experiments are needed for improving realistic estimation of the combined ecosystem responses to future climate changes.

Introduction

Climate change with elevated atmospheric CO_2, increased temperature and altered precipitation will fundamentally affect key drivers for ecosystem functioning and lead to adverse effects in terrestrial ecosystems across the globe (IPCC, 2007). These climate-driven changes may affect ecosystem functioning directly, *e.g.* through CO_2-stimulated photosynthesis and growth (Luo *et al.* 2006; de Graaff *et al.* 2006), warming-induced increased nutrient mineralization (Emmett *et al.* 2004) or drought-induced growth limitation (Penuelas *et al.* 2007). They may also act indirectly *e.g.* through impacts on species composition (Penuelas *et al.* 2007).

Growth in many natural and semi-natural terrestrial ecosystems is limited by nitrogen and characterized by strong competition for nitrogen between plants and the soil communities of fungi and bacteria (Marion *et al.* 1989; Jonasson *et al.* 1996). Consequently, ecosystem N availability is an important factor controlling the carbon uptake in terrestrial ecosystems and therefore also plays a dominant role in controlling the feedback between the biosphere and the atmosphere in a warmer and more CO_2 enriched world. The theory of nitrogen as a limiting factor constraining the carbon uptake in terrestrial ecosystems in response to elevated CO_2 is conceptualized in the PNL framework (Progressive Nitrogen Limitation) (Luo *et al.* 2004) describing how increased carbon sequestration driven by elevated CO_2 requires increased access to nitrogen in order to balance the carbon input. Accordingly, without additional inputs of plant-available N, nitrogen will progressively limit further carbon uptake. But increased N availability has also been shown as a consequence of increased availability of labile soil carbon substrate (Zak *et al.* 1993) and increased soil moisture content due to improved plant water use efficiency (WUE) (Zak *et al.* 1993; Hungate 1999), as well as increased N mineralization in response to warming (Schmidt *et al.* 2004; Emmett *et al.* 2004). The interaction between the carbon and nitrogen cycles clearly illustrates how sensitive ecosystems are to changes in nitrogen pools and turnover, current input of N, and other nutrients, and changes in the water regime. This is particularly important for N limited systems, such as natural and semi-natural ecosystems with relatively low nitrogen inputs and internal N turnover rates of the mineral N pool as fast as a few days (Davidson *et al.* 1990; Lipson & Näsholm 2001; Schimel & Bennett 2004; Vervaet *et al.* 2004). In systems with very high internal turnover rates of nitrogen, the N turnover has also been shown to be very sensitive to changes in natural climatic variations such as reduced water availability (Jamieson *et al.* 1999), potentially leading to a high sensitivity of these systems to climate-driven changes in the internal processes regulating the demand or supply of nitrogen.

Most of the experimental evidence of PNL and the role of nitrogen in constraining carbon uptake is based on modeling studies (Rastetter *et al.* 1997) or on experiments involving elevated CO_2 alone or in combination with various levels of nitrogen addition to demonstrate the role of N in stimulating CO_2 sequestration responses (Lutze & Gifford 2000; Lutze *et al.* 2000; van Heerwaarden *et al.* 2005; de Graaff *et al.* 2006; Reich *et al.* 2006). However, in a future CO_2 enriched world, the nitrogen limitation and the CO_2 response in N limited systems will to a large extent be regulated by the climate change-associated responses of the internal nitrogen cycle, which are not well captured in a CO_2 alone experiment. For instance, it has been demonstrated that warming can stimulate internal nitrogen mineralization, leading to increased N availability (Emmett *et al.* 2004) and even increased N leaching (Lukewille & Wright 1997; Schmidt *et al.* 2004). Correspondingly, changes in water availability, such as water limitations by droughts, can reduce N mineralization and N availability (Emmett *et al.* 2004). On the other hand, increased water availability due to increased precipitation or to CO_2 stimulated increase in WUE can increase N mineralization and N availability under water limited conditions (Hungate 1999). Since the future climate change will involve changes in all of these factors, it is important to understand the possible interactions between different climate drivers on N availability and nitrogen limitation. Therefore, studies involving all factors simultaneously are needed.

In the present study, we aim to synthesize the overall impacts of changes in the nitrogen cycle in response to warming, elevated atmospheric CO_2 concentration and increased summer drought events after two years of treatments. We compare the responses of the three-factor treatment with responses to treatments including only one, or pair wise combinations of the factors.

In response to elevated CO_2, we expected to observe increased plant tissue and litter C/N ratios (Paterson *et al.* 1999; Lutze & Gifford 2000; van Heerwaarden *et al.* 2005; Finzi *et al.* 2006; Chen *et al.* 2007; Hovenden *et al.* 2008). In the short term, we further expected that the increased water use efficiency under elevated CO_2 (Ainsworth & Long 2005; Leuzinger & Körner 2007; Ainsworth & Rogers 2007; Albert *et al.* 2010) would stimulate plant growth, and increase plant N demand and biomass, and that concomitant increased rhizodeposition would lead to increased microbial biomass activity and mineralization. Warming was expected to increase plant growth and increase mineralization (Rustad *et al.* 2001), whereas extended summer drought was expected to reduce plant N demand and decrease N mineralization and nitrification rates (Emmett *et al.* 2004; Schmidt *et al.* 2004; Sowerby *et al.* 2008) as a product of direct or indirect effects on microbial activity. Assuming simple addition of these single treatment effects, we expected that drought effects would be reduced in combination with both warming and elevated CO_2 and, consequently, that increased N mineralization and plant growth in response to both warming and elevated CO_2 would dominate over decreases caused by drought in the full combination of treatments.

Materials and methods

Experimental site and climate change manipulations

The CLIMAITE experimental site is a dry, temperate heathland situated approximately 50 km NW of Copenhagen, Denmark (55°53' N, 11°58'E). The vegetation is dominated by the evergreen dwarf shrub *Calluna vulgaris* (L.), the perennial grass *Deschampsia flexuosa* (L.) and various mosses and herbs. The soil is a well-drained, nutrient-poor sandy deposit with a pH of 4-5 and an organic top layer ranging from 2 to 5 cm in depth. Long-term annual mean air temperature is 8.0 °C, annual mean precipitation is 613 mm (Danish Meteorological Institute 2009) and the total N bulk deposition at the site was 1.27±0.07 and 1.35±0.04 g N $m^{-2}y^{-1}$ in 2006 and 2007, respectively (Larsen KS, unpublished data). The experimental area covers approximately 2 ha and consists of twelve 7m diameter octagons laid out pair-wise in 6 blocks (= 6 replicates). Each block consists of two octagons, one with ambient (A) atmospheric CO_2 and one receiving elevated atmospheric CO_2 concentration (CO_2) (510 ppm in a free air CO_2 enrichment setup (FACE)). Each octagon is separated into 4 subplots receiving in addition to the ambient or elevated CO_2 1) one month summer drought (D) by rain-out shelters, 2) passive warming (T) of air and soil by night time warming curtains 50 cm above ground, 3) a combination of drought and warming (TD) or 4) no drought or temperature treatment. In total, the experiment provides a full factorial design with all 7 combinations of D, T and CO_2 and an untreated control for reference (A). Details on the experimental setup are described by Mikkelsen *et al.* (2008).

The treatments were initiated in October 2005 and the first summer drought was applied in July/August 2006. The warming treatment elevated temperature at 5 cm depth by 0.3 °C in the winter to 0.7 °C in the summer months, on average. The maximum mean daily temperature elevation was 1.2, 2.1 and 2.8 °C in the 5 cm depth, soil surface and 20 cm height sensors, respectively (4 October 2005 - 31 December 2007). The drought campaigns removed 52 mm and 94 mm of precipitation, resulting in peak reductions of soil water content of 11 and 13 % v/v over 0-20 cm soil depth in 2006 (3-20 July and 26 July-4 August) and 2007 (21 May-22 June), respectively . The drought campaigns were stopped when soil water content reached about 5 % v/v over 0-20 cm soil depth.

N stocks in plants, litter, microbes and soil, C/N ratios, extractable N concentrations

Above-ground biomasses N of *Calluna* and *Deschampsia* were estimated from non-destructive point intercept measurements in two 50 x 50 cm subplots within each plot combined with a linear regression model linking point intercept measurements and biomass obtained from destructive harvesting of similar plots outside the treatment plots (Jonasson 1988; Kongstad *et al.* 2010; Riis-Nielsen & Schmidt 2010). To compensate for pre-treatment differences between the initial biomass values in individual sub-plots and the subsequent development during the experiment, treatment effects on above-ground plant biomasses were normalized and scaled to the average biomass development in the ambient plots while maintaining the observed relative variance. Briefly, a regression was fitted between the pre-treatment plant biomass and the treatment biomass at a given time point, within each treatment. The slope of the regression in the ambient treatment defined the ambient or control response; the normalized treatment effect was determined as the difference between the predicted control response and the predicted treatment response for a given treatment. See van der Linden *et al.* (2010) for further description.

Calluna and *Deschampsia* plants as well as mosses from the experimental plots were harvested in August 2007. The C and N concentrations measured in green tissue, flowers, wood/stem and roots or whole plants (mosses) (Andresen *et al.* 2010a) were used to calculate

C/N ratios. The N concentrations were used in combination with the non-destructive above-ground biomass estimates to calculate the total N stock of these pools. Concurrent with plant harvest, soil samples from each plot (0-10 cm soil depth) were taken to measure plant root biomasses, microbial biomass N and, soil organic matter N (SOM-N) and soil extractable NO_3-N, NH_4-N and dissolved organic nitrogen (DON) (Andresen *et al.* 2010a). Litter production by *Deschampsia* was estimated from point intercept-based difference between seasonal minimum and maximum biomass of live and dead fractions of *Deschampsia* leaves multiplied with N concentrations in the litter (Kongstad *et al.* 2010; Riis-Nielsen & Schmidt 2010).

Soil fauna

Soil cores within each plot (0-10 cm soil depth) were sampled in October and November 2007 for biomass estimation of protozoa/nematodes and enchytraeids/microarthropodes, respectively. For estimation of protozoan biomass, a soil suspension was prepared by blending 5 g of soil with 100 ml of Amoeba Saline (AS, Page 1988) for 1 min. Three-fold dilution series of the soil suspension were prepared in microtiter plates being inspected for protozoa after one and three weeks of growth at 15^{o}C with a modified version of the Most Probable Number method (Darbyshire *et al.* 1974; Rønn *et al.* 1995). Nematodes were extracted from between 10 and 11 g (fresh weight) of soil by a modified Baermann tray extraction method (Georgieva *et al.* 2005). Samples were extracted for 48 h, and nematodes were then counted at 40× magnification using a dissecting microscope. Biomass N of protozoa and bacterivorous nematodes were calculated according to Stout & Heal (1967) and Sohlenius & Sandor (1987), respectively. N mineralization (excretion and turnover) of microfauna was calculated assuming bacterivore turnover rate of 0.16 d^{-1} (Zwart *et al.* 1994) for both nematodes and protozoans and setting yield ratios of protozoans and nematodes on bacteria to 0.4 and 0.04 (Coleman *et al.* 1978). The total biomass of enchytraeids was determined as described by Maraldo *et al.* (2008). The density of microarthropods was determined as described by Holmstrup *et al.* (2007), and the biomass of dominating taxonomic groups was estimated using representative values from Petersen & Luxton (1982). The pool of N contained in the biomass was calculated assuming nitrogen concentrations of 11.5 % and 10 % of dry weight in enchytraeids and microarthropods, respectively (Persson 1983). The yearly turnover rate of biomass N was assumed to be 1.2 for enchytraeids (Standen 1973), and 1.8 for microarthropods (De Ruiter *et al.* 1993). The annual mineralization (excretion and turnover) of NH_4^+-N by enchytraeids and microarthropods was estimated based on biomass as described by Persson (1983).

N_2O emissions and N_2O reductase

Fluxes of N_2O were measured with a static chamber method using white PVC chambers (height 15 or 45 cm depending on vegetation height) placed on metal collars (60 × 60 cm) permanently installed in the soil. Enclosure times were 2 to 2.5 h, during which headspace air was sampled four times and later analyzed for N_2O concentration by gas chromatography. The N_2O flux was calculated using linear regression. Nine N_2O measuring campaigns including all eight treatments were carried out from June 2006 to March 2007, and from April to June 2007 five campaigns were conducted in five of the treatments, *viz.* A, CO_2, D, DCO_2 and $TDCO_2$. Annual cumulative N_2O fluxes were derived by interpolation between measurement days and by extrapolating the emission from the treatments T, TD and TCO_2 for the period March- June 2007. Further methodological description is found in Carter *et al.* (2010).

To determine N_2O reductase activity, nitrate was removed from sub samples of the soil cores taken in November 2007 for fauna biomass estimation by vortexing 10 g fresh soil and 30 ml of phosphate buffered saline (PBS) for 5 sec followed by centrifugation for 10 min at 3500 x G and 5 °C. The supernatant was discarded and the pellet resuspended in 30 ml PBS. After the third centrifugation the pellet was resuspended in 15 ml of 0.5 mM glucose, 0.5 mM sodium acetate, and 0.5 mM sodium succinate and transferred to a 100 ml incubation bottle. The bottle was sealed with a butyl rubber stopper, flushed with N_2 for 2 min, added 100 ppm N_2O (final concentration), placed horizontally on a shaker (200 rpm), and incubated at 22 °C. After 0, 1, 3, 6 and 24 h, 3 ml of headspace was transferred to a pre-evacuated 3 ml Venoject vial before analysis of N_2O by gas chromatography. The N_2O reductase activity was calculated from the consumption of N_2O during the incubation.

Nitrogen mineralization and immobilization

Gross rates of N mineralization and immobilization were determined by the isotope pool-dilution approach applied in laboratory incubations. Soil cores within each plot were sampled in September 2007 (0-5 and 5-10 cm soil depth, respectively), sieved and stored at 5 °C for about one week until incubations were initiated. Fresh samples (10 g) were weighed in 250 ml poly-ethylene bottles and mixed thoroughly with 400 µl of a $^{15}N\text{-}NH_4Cl$ solution (5 atm % ^{15}N) to provide 5 µg N g^{-1} soil. One set of samples was analyzed immediately upon substrate application, and a second set was analyzed after 7 days of incubation at 20 °C. Contents of mineral N and the ^{15}N contents were determined upon extraction and micro-diffusion (Sørensen & Jensen 1991). Gross daily rates of mineralization and immobilization were calculated according to equations given by Kirkham & Bartholomew (1954). Upscaling to annual rates was done using the mean annual soil temperatures in 5 cm depth (10 °C) at the experimental site and assuming a Q_{10} of 2.

Potential nitrification and denitrification

Subsamples from the soil cores taken in November 2007 were gently homogenized by hand and major roots were removed. Soil samples were stored at 4 °C until analysis (less than 24 h). Potential nitrification was determined in 3 g soil samples by a modification of the method described by Belser & Mays (1980) but without adding chlorate. Potential nitrification rates were estimated from the increase in nitrite+nitrate concentrations. Potential denitrification rates (Wolsing & Prieme 2004) in 10 g soil samples were estimated from linear regression of increase in headspace N_2O concentration during 180 min incubation.

Water percolation and nitrogen leaching

Leachate water was collected monthly from passive PVC soil water draining collectors below the organic soil layer (approximately 5 cm depth) and polytetrafluoroethylene (PTFE) suction cups with continuous sub-atmospheric pressure (Prenart Super Quarz, Frederikberg, DK) below the main rooting zone (60 cm depth). Concentrations of NH_4^+-N, NO_3^- -N, and total N (by UV-persulphate oxidation) were analyzed on an Autoanalyzer 3 (Bran+Luebbe Gmbh, Germany). DON was calculated as total N minus inorganic N. Precipitation was measured at the site and the volume of percolating water was estimated by simulation with the CoupModel model (Jansson & Moon 2001; Svensson *et al.* 2008) – a coupled ecosystem model with a balance of abiotic and biotic processes in the soil-plant-atmosphere system. The basic structure of the model is a depth profile of the soil, and calculations of water and heat flows are based on common soil properties. The model was parameterised using measured soil layer properties and against time series of soil temperature and moisture content, using on site measurements of radiation, precipitation and wind speed as driving data and a generalised likelihood uncertainty evaluation approach. Percolation of water below 60 cm was calculated as an output of the simulations and leaching of nitrogen at that depth was calculated as the product of the sum of water percolation and the concentration measured in the soil water for each water collection period (Schmidt *et al.* 2004).

Statistical analyses

Statistical analyses were conducted using the multiple linear regression procedure PROC MIXED of SAS (SAS Institute 2003). The statistical model included a random statement that accounted for the experimental design (*Random* Block octagon octagon*D octagon*T). The same model was used for all tested variables and included the three main factor effects (CO_2, D, and T) as well as all possible interactions (D*CO_2, T*CO_2, T*D, and T*D*CO_2). P-values ≤ 0.05 were considered significant. Data were transformed when necessary to obtain normality and homogeneity of variance. Differences of Least Squares Means (DLSM) were used to interpret significant treatment interactions. During the DLSM evaluation, each significant interaction was categorized as either *antagonistic*, *i.e.* the combined effect led to a reduction of the observed individual effects or *synergistic*, *i.e.* the combined effect led to either a) an amplification of the observed individual effect(s) or b) to a significant effect only when treatments were combined. The DLSM evaluation also revealed if interactions were due to significant single treatment effects, *i.e.* effects observe in single treatment plots only, which disappear in combination with other treatments. Furthermore, DLSM evaluation of significant interactions revealed if significant main factor effects were effects observed only when in combination with other treatments or if it was significant also as a single treatment effect. Finally, we noted simple additive effects when two of the treatments both showed significant main factor effects but with no interactions.

Results

Ecosystem N balance

The N cycle at the site is dominated by higher internal N turnover in comparison to the inputs and losses by leaching and gaseous emission to the atmosphere (Fig. 1). Gross mineralization (6.7 ± 0.96 g N $m^{-2}y^{-1}$) is five times higher than bulk deposition (1.35 ± 0.04 g N $m^{-2}y^{-1}$), an order of magnitude higher than losses by leaching (0.80 ± 0.37 g N $m^{-2}y^{-1}$) and two orders of magnitude higher than gaseous losses in form of N_2O (0.031 ± 0.006 g N $m^{-2}y^{-1}$). Negligible N_2O reductase activity was observed in the soil samples with N_2O uptake rates less than 1 ng N g^{-1} dw h^{-1} in all samples and N_2 production is therefore assumed to be negligible (data not shown). Above ground, about 90 % of N is found in the two dominant species *Calluna* (~60 %) and *Deschampsia* (~30 %). Below ground, most N is stored in the SOM pool (~90 %) with *Deschampsia* roots (~4 %), *Calluna* roots (~3 %) and soil microbial (~1.5 %) pools dominating the remaining fraction. Soil fauna biomass was ~10 % of microbial biomass but their mineralization of N is estimated to 5.0 ± 0.6 g NH_4^+-N $m^{-2}y^{-1}$, *i.e.* an amount of labile N much larger than the N input to the system by N bulk deposition. The system retained 0.53 g N $m^{-2}y^{-1}$ of bulk deposition in the ambient, non-manipulated plots in 2007 as estimated by difference between bulk deposition and sum of total N leaching below 60 cm soil depth and N_2O emission. While bulk deposition in 2006 (1.27 ± 0.07 g N $m^{-2}y^{-1}$) was similar to the deposition in 2007 (1.35 ± 0.04 g N $m^{-2}y^{-1}$), total N leaching across all treatments was significantly lower ($P < 0.0001$) in 2006 (0.13 ± 0.06 g N $m^{-2}y^{-1}$) than in 2007 (0.56 ± 0.20 g N $m^{-2}y^{-1}$) with no significant treatment effects in either 2006 (data not shown) or in 2007 (Table 1). The major cause of this interannual difference was a wet summer in 2007 (202 mm precipitation in July) with extensive leaching compared to a dry summer in 2006 (60 mm precipitation in July) when summer leaching was absent.

Plant responses to climate manipulations

The above-ground biomass N of the dominant plant species *Calluna* and *Deschampsia* did not respond to the climate manipulations (Table 1). Root biomass N of *Deschampsia* was also unaffected by the treatments, whereas root biomass N of *Calluna* increased in response to drought (Table 1, P = 0.04) indicating a change in the root:shoot N allocation pattern. While N in above-ground biomasses were unaffected by treatments, the C/N ratios of *Calluna* flowers as well as leaves from both *Calluna* and *Deschampsia* increased in response to elevated CO_2 (Table 1, P = 0.02, 0.04, and 0.01, respectively). The evaluation by DLSM of the three-way interaction for the C/N ratio of mosses (Table 1, P = 0.003) showed that the interaction was due to significantly higher C/N ratios in the single treatments of drought and elevated CO_2, while ratios were unchanged when drought and elevated CO_2 were combined with each other as well as when they were combined with warming. The observed increases in C/N ratios in new plant tissue of leaves and flowers were not seen in whole-plant C/N ratios of *Deschampsia* or in the green tissue or wood fractions of *Calluna*. Yet, the N concentration of *Deschampsia* litter decreased under elevated CO_2 (Table 1, P = 0.05), indicating that the changes in C/N ratios starting in the leaves, are already beginning to cascade through the system, after only two years of treatments (Fig. 2a).

Deschampsia leaves and also mosses (single treatment only) responded to drought with increased C/N ratios (Table 1, P = 0.002 and P ≤ 0.05, respectively) whereas *Calluna* leaves were unaffected (Table 1, Fig. 2b). Also, the pool of N in the annually produced *Deschampsia* litter decreased in response to drought (Table 1, P = 0.01). The warming treatment had fewer effects on above-ground processes than the other treatments, showing only an increase of N concentration in *Deschampsia* litter (Table 1, $P = 0.03$, Fig 2c).

When all treatments were combined (Fig. 2d), the lack of interactions between single treatment effects for leaf level C/N ratios indicates that the effect is found also in treatment combinations. Consequently, increased C/N ratios of leaves as well as decreased *Deschampsia* litter N production are found in the full combination of treatments, *i.e.* in the simulation of the projected future climate scenario. In contrast, the C/N ratio of mosses increases in two of the three single treatments and N concentrations in *Deschampsia* litter either increase or decrease depending on treatment but these effects disappear when all treatments are combined.

Responses of below-ground processes to climate manipulations

The below-ground N turnover was significantly affected by the climate manipulations, primarily by the warming and drought treatments (Table 1, Fig. 3) showing changes cascading through pools and processes. Elevated CO_2 as a main factor had no effects below ground but the analysis of DLSM when evaluating the interactions revealed reductions in leachate concentrations in 5 cm soil depth of NO_3^--N, NH_4^+-N and DON (Table 1, Fig. 3a) in the single CO_2 treatment. These effects were reduced when elevated CO_2 was combined with other treatments causing the significant interactions for these three variables (Table 1).

The drought treatment reduced the N pools of enchytraeids and protozoans and their NH_4^+-N mineralization (Table 1, $P = 0.03$ and 0.04, respectively), decreased gross mineralization (Table 1, $P = 0.03$), and reduced the pool of NH_4^+-N (Table 1, $P = 0.02$), thus indicating an overall decrease in the N turnover in response to drought (Fig. 3b). In contrast, warming stimulated microbial ammonium consumption in the top 5 cm of soil (Table 1, P =

0.04) as well as the gross mineralization rate (single treatment only, Table 1, $P \leq 0.05$) and nitrification rates (Table 1, P = 0.004), leading to both increased denitrification (Table 1, P = 0.02) and N_2O emission (Table 1, P = 0.05). Overall, the below-ground response to the warming treatments was therefore an increase in N turnover (Fig. 3c).

While no direct main effects of elevated CO_2 were observed, it influenced the responses to drought and warming primarily by reducing some of the significant individual effects in the three-factor combination. Still, the drought-induced decrease of fauna-N and fauna N mineralization as well as the warming-induced increased denitrification did not interact significantly with the other treatments and consequently remained in the full treatment combination.

Interactions between climate manipulations

Across the 47 variables reported (Table 1) the drought treatment lead to the highest number of significant main effects (11) followed by warming and CO_2 treatments (6 and 4, respectively). Simultaneously there were a large number of interactions between the three treatments (14). Interestingly, the analysis of the interactions revealed a dominance of antagonistic effects (Fig. 4) with more than twice as many antagonistic effects as synergistic effects. Furthermore, simple additive effects were less frequent than both antagonistic and synergistic effects.

Discussion

Overall ecosystem N turnover

The N cycle at the experimental site is characterized by higher internal N turnover than bulk N deposition and losses by leaching and N_2O production as generally seen in natural and semi-natural ecosystems. In comparison to our estimated annual gross mineralization rate (6.7 ± 0.96 g N $m^{-2}y^{-1}$), Emmett *et al.* (2004) reported net mineralization rates of 3.8 to 6.6 g N $m^{-2}y^{-1}$ from another Danish dry heathland and Aerts (1993) reported rates ranging from 4.4 to 12.6 g N $m^{-2}y^{-1}$ under different plant species in wet and dry Dutch heathlands, where atmospheric deposition is 2-3 times higher than in Denmark. Inter-annual variability in N leaching was significant, while treatment differences after two years of treatments were not significant. The observed difference in leaching between 2006 and 2007 shows that the ecosystem N loss by leaching is highly dependent on the amount and timing of precipitation. In a future climate with more precipitation distributed in fewer, but more severe rain events, N leaching is likely to increase in this ecosystem. The inter-annual variability in leaching may also indicate that the ecosystem is close to N saturation as also suggested from an adjacent short-term experiment where N and phosphorus (P) addition resulted in only a modest increase in fine root biomass of *Deschampsia*, and no effects on *Calluna* roots (Nielsen *et al.* 2009). Furthermore, *Deschampsia* responded more when both N and P were added indicating that this species is currently more limited by P than N availability. If nitrogen availability should decrease due to progressive nitrogen limitation as the treatment exposure continues, this, in combination with the P limitation for *Deschampsia*, would be beneficial to the slower growing *Calluna*. However, other climate factors, *i.e.* water availability and temperature increase, are likely to influence the overall competitive relationship, potentially disturbing the balance of the equilibrium, especially if the rates of mortality of *Calluna* are increased.

The mineralization of NH_4^+-N by soil fauna is often neglected but contributes significantly to the pool of plant available N in the soil (Osler & Sommerkorn 2007). In the present study, we calculated fauna N mineralization from estimated biomasses and literature values of the turnover times and yields of microfauna and mesofauna. Obviously, upscaling of *e.g.* enumeration of bacterivorous protozoa and nematodes to gross nitrogen mineralization should be evaluated with caution. Values for bacterivore biomass, turnover, and growth yield on bacteria are all needed to perform the upscaling and very few references exist in the literature on such values. This said, the value for fauna-related N mineralization in the ambient treatment based on this calculation seems trustworthy based on the gross N mineralization from the pool dilution assay of 6.7 g N $m^{-2}y^{-1}$. The assumption that most bacterial mineralization is facilitated through predation and mineralization by the soil fauna implies that N mineralization by bacteria is responsible for approximately 75% of the total activity, the rest being due to fungi.

Responses to elevated CO_2, warming and drought

Elevated atmospheric CO_2 concentration is known to induce down-regulation of photosynthetic capacity, *e.g.* via reduced content of Rubisco in the leaves (Ainsworth & Long 2005; Ainsworth & Rogers 2007) and reduction of leaf nitrogen content and increased C/N ratios of leaves (Paterson *et al.* 1999; Lutze & Gifford 2000; van Heerwaarden *et al.* 2005; Finzi *et al.* 2006; Chen *et al.* 2007; Hovenden *et al.* 2008). At our experimental site, we observed reduced photosynthetic capacity (Albert *et al.* 2010) and leaf nitrogen under elevated CO_2 for the dominant species, *Calluna* and *Deschampsia*, as well as increased leaf

C/N ratios. However, the increased C/N ratios observed in leaves, and for *Calluna* also observed in flower biomass were after two years of treatments not large enough to affect whole plant biomass C/N ratios, which were not affected by the treatments. Previous studies have found increasing C/N ratios in other plant tissues than leaves (McGuire *et al.* 1995; Cotrufo *et al.* 1998), but the change often is much weaker than that observed for leaves (McGuire *et al.* 1995), indicating that the C/N effect of elevated CO_2 is closely linked to the processes involved in the carbon sequestration in the photosynthetic apparatus (Körner 2000). As hypothesized, however, N concentration in *Deschampsia* litter after two years of treatments was also reduced by elevated CO_2, possibly showing that the effect is beginning to cascade from leaf level to other ecosystem N pools, although the effect disappears in the full treatment combination. Together with the observed increased concentration of tannins (Schmidt *et al.* 2007) in plant tissues, we anticipate that the changes in C/N ratios will affect litter decomposition rates as the experimental treatments continue.

In contrast to our expectations, the above- and below-ground plant N pools were not increased by elevated CO_2. However, total root biomass N of *Calluna* increased unexpectedly in response to drought. It is inherently difficult to estimate total roots from small soil samples due to the large spatial heterogeneity in root distribution and, at the same time, collection of larger samples is problematic due to the destruction of the experimental plots. We are therefore reluctant to put too much emphasis on this result and conclude overall that total biomass N of both dominant species as well as mosses after two years of treatments were only marginally affected by the applied climate drivers.

Increased rhizodeposition is a common plant response to elevated CO_2 (Pendall *et al.* 2004; Allard *et al.* 2006), and strong effects on below-ground C cycling have been observed in response to elevated CO_2 in the current experiment, *e.g.* increased soil respiration rates (Selsted *et al.* 2010) and increased production of dissolved organic carbon (Andresen *et al.*

2010a). However, in contrast to our expectation, we observed very few direct effects of elevated CO_2 on below-ground N processes. Still, the decreased concentrations of organic and inorganic N leachate water at 5 cm soil depth imply that mineralization processes are affected or possibly that root N uptake has increased. In contrast to the lack of direct changes in response to elevated CO_2, soil processes were more sensitive to the drought and warming treatments. Our study supports previous observations of increased below-ground N turnover in response to warming (Rustad *et al.* 2001; Schmidt *et al.* 2004). We observed increased microbial NH_4^+-N consumption, gross mineralization, potential nitrification, and denitrification from lab incubations of soils, as well as increased *in situ* N_2O emissions. Soil and litter incubations *in situ* also showed that warming promoted N cycling (Andresen *et al.* 2010b). Previous field studies with artificial warming also showed no warming effect on N_2O emission rates (Peterjohn *et al.* 1994; Mchale *et al.* 1998). However, we interpret our observation of five variables that all responded in the same direction to warming as a strong indicator that the warming effect on N turnover was real.

The below-ground N turnover was reduced by drought as observed by reduced gross N mineralization and fauna N mineralization. Reduced N mineralization in response to drought has previously been observed (Emmett *et al.* 2004; Schmidt *et al.* 2004; Sowerby *et al.* 2008) but the negative effects of drought on N mineralization are often attributed directly to reduced microbial activity. The importance of soil fauna to the N mineralization shown in this study, together with the negative effects of drought on top soil layer populations of enchytraeids (Maraldo *et al.* 2010) and other fauna groups and their decreased N mineralization rates, indicate that the fauna response plays a significant role in the observed decrease in N turnover in drought-exposed plots. Furthermore, while the warming effects were generally reduced in combination with drought and elevated CO_2, the negative effect of drought on fauna N biomass and N mineralization was not reduced by interactions.

Consequently, the effect prevailed in the full combination of treatments, indicating that N mineralization will be reduced in the full future climate scenario. Therefore, despite the fact that this ecosystem currently show no clear sign of N limitation of plant growth, we cannot rule out the possibility that progressive nitrogen limitation will play a role in the longer term, as the impacts of increased CO_2 on C/N ratios of leaves combined with the drought induced reduction of mineralization and litter N production continues to reduce the availability of N in the ecosystem.

Importance of climate driver interactions

We thoroughly investigated the background for all significant interactions observed in the 47 variables reported in Table 1 by evaluating the DLSM from the mixed model statistical output. This analysis revealed a clear dominance of antagonistic effects over synergistic and simple additive effects when several treatments were combined (Table 1 and Fig. 4), *i.e.* the ecosystem is more robust when more than one factor is changed. For instance, the C/N ratio of mosses increased in both single treatments of drought and elevated CO_2 but was unaffected when treatments were combined. Similarly, the increased gross mineralization rate observed in the single warming treatment was reduced especially in combination with elevated CO_2. Furthermore, two of the three additive effects observed (*Deschampsia* litter N concentration and N_2O emissions) were additive responses with opposing directions, which therefore acts to reduce the observed effects in treatment combinations.

Previous studies have investigated interactions between elevated CO_2 and *e.g.* N supply (Lutze & Gifford 2000; Lutze *et al.* 2000; van Heerwaarden *et al.* 2005; Reich *et al.* 2006), warming (Peltola *et al.* 2002; Tingey *et al.* 2003; Hovenden *et al.* 2008; Dijkstra *et al.* 2010), biodiversity (Reich *et al.* 2001; Niklaus *et al.* 2001) and water relations (Morgan *et al.*

2004; Nowak *et al.* 2004). A review by Barnard *et al.* (2005) of 25 multi-factor studies concluded that interactions were generally rare. These 25 studies were dominated by experimentally elevated CO_2 combined with increased N supply. The lack of interactions could be due to the common trend that most ecosystems respond strongly to increased N supply, which hides weaker interactive responses. Luo *et al.* (2008) analyzed and modeled interactions between elevated CO_2, warming and changes in precipitation in 7 multi-factor studies and found that three-way interactions were rare while two-way interactions were more common. Generally, interactions were positive between elevated CO_2 and warming and negative between elevated CO_2 and reduced precipitation with respect to net primary production (NPP).

A general pattern of most published studies is the focus on a few important variables, *i.e.* overall changes in NPP or biomasses or specific studies focusing on processes, *e.g.* nitrification and denitrification. As interactions are only sometimes significant, investigating a small number of variables prevents a more general interpretation of the importance of interactions. Furthermore, assuming that three-way interactions are more uncommon than two-way interactions, important three-way interactions could be missed when fewer variables are analyzed. Out of 14 interactions observed across 47 N related variables in the present study, 5 were three-way interactions. This suggests that insufficient interactions between elevated CO_2, warming and changes in precipitation were included in the ecosystem models applied by Luo *et al.* (2008) and reinforces the need for further multi-factor ecosystem manipulation experiments focusing on interactive effects.

When analyzing the interactions, we found a predominance of antagonism in the combined responses. The consequence of the dominance of antagonistic interactions in combined climate driver responses is that ecosystem changes caused by climate change may be less pronounced than judged from single factor experiments. Based on these results we raise the hypothesis that combined effects of all future climate change are dampened compared to expected effects based on simple addition of single treatment responses. If this pattern prevails for ecosystem responses to future climate change in general it highlights 1) that single factor studies are likely to overestimate responses and should be evaluated with caution, and 2) that multi-factor field-scale ecosystem experiments are critical in order to be able to predict realistic response strengths as well as for developing a conceptual framework for understanding interactions among climate drivers. Our multi-variable approach may aid the latter point if tested in other multi-factor studies and by including variables not only constraint to the nitrogen cycle.

Conclusions

The drought treatment effects dominated over effects of warming and elevated CO_2 in observed responses of the nitrogen cycle after two years of treatments. In contrast to our expectations, we did not observe increased growth of the N pools of the dominant plant species, *Calluna* and *Deschampsia* in response to elevated CO_2. While previous studies have usually found interactions to be rare, interactions were commonly observed and antagonism dominated over synergism in combined responses, *i.e.* the ecosystem response to the combination of several climate drivers is dampened compared to single treatment responses. Still, the observed negative response to drought of soil fauna biomass and N mineralization and *Deschampsia* litter N production prevailed in the full treatment combination and so did the increased leaf C/N ratios of the dominant species *Calluna* and *Deschampsia*. If persistent, these changes are likely to lead to reduced N availability and possibly to progressive nitrogen limitation as the experimental treatments continue.

Acknowledgements

We wish to thank Preben Jørgensen and Poul Sørensen for their great efforts in maintaining the CLIMAITE field site. We gratefully acknowledge Claus Thorn Ekstrøm and Anders Tolver Jensen for their help with the statistical model setup and statistical output interpretation. The CLIMAITE experiment is sponsored by the Villum Kann Rasmussen foundation with substantial co-funding from Air Liquide, DONG Energy and SMC Pneumatic A/S. Measurements of N_2O emissions were part of NitroEurope IP funded by the European Commission.

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Figure captions

Figure 1

Measured N pools in August 2007 (**bold**, g N m^{-2}) and annual fluxes (*italic*, g N m^{-2}y^{-1}) in ambient plots down to 10 cm soil depth (leaching below 60 cm depth) in 2007. Abbreviations: *Calluna vulgaris* (Cal), *Deschampsia flexuosa* (Des), dissolved organic nitrogen (DON), microbial biomass nitrogen (Mic-N), soil organic matter nitrogen (SOM-N), Gross mineralization (Gross min). Data of litter N mass and litter N production was only available for *Deschampsia*. Estimates of fauna biomass and mineralization includes enchytraeids, microarthropods, nematodes, and protozoans. Dashed line indicates the major components involved in N mineralization. The annual N balance was +0.53 g N m^{-2}y^{-1}.

Figure 2

Observed above-ground changes in N pools, C/N ratios, litter N production of *Deschampsia* and percentage N in litter of *Deschampsia* caused by single treatments factors (a – c) and when all treatments are combined (d). *Calluna vulgaris* (Cal), *Deschampsia flexuosa* (Des). See Table 1 for statistical significance of observed changes.

Figure 3

Observed below-ground changes in N pools, N fluxes/processes and N concentrations caused by single treatments factors (a – c) and when all treatments are combined (d). Dissolved organic nitrogen (DON), microbial biomass nitrogen (Mic-N), mineralization (min). See

Table 1 for statistical significance of observed changes.

Figure 4

Observed significant interactions ($P \leq 0.05$) from the PROC MIXED analysis of 47 individually tested variables (see Table 1) followed by analysis of Differences of Least Squares Means (DLSM) were categorized as antagonistic, *i.e.* combination leads to reduction of effects, or as synergistic, *i.e.* combination leads to amplification of single effects or significant effect is only observed in combination. Number of observed simple additive effects is also shown, *i.e.* cases where two significant individual effects were observed without significant interaction. Note that the sum of antagonistic and synergistic effects are 15 because one three-way interaction (potential nitrification – see Table 1) was caused by both antagonistic and synergistic effects.

Table 1. Pools and fluxes of N (g N m^{-2}), C/N ratios and N concentrations (mg L^{-1}) in 2007. Data are means with SE for ambient (A) and means with SE normalized to the mean of the ambient treatment (all other treatments than A). 1) Significant P values (P ≤ 0.05) from statistical analysis. Direction of main treatment effects is indicated with arrows. Significant interactions are indicated as antagonistic (§), or synergistic (‡). Additive effects of multiple significant main effects are also indicated (+). 2) Significant single treatment effects as indicated by evaluation of main effects plus interaction(s) by analysis of DLSM (see text for further details). Direction of effects is indicated with arrows. n.s. = not significant.

									main treatment effects 1)			Interactions 1)				single treatment effects 2)		
	A	CO_2	D	T	DCO_2	TCO_2	TD	$TDCO_2$	CO_2	D	T	$D*CO_2$	$T*CO_2$	T*D	$T*D*CO_2$	CO_2	D	T
Above-ground biomass N																		
Calluna	6.74 ± 25%	1.01 ± 0.09	0.88 ± 0.09	0.96 ± 0.21	0.80 ± 0.19	0.97 ± 0.20	0.84 ± 0.13	0.67 ± 0.14										
C/N ratio of *Calluna* leaves	26.4 ± 7%	1.17 ± 0.05	1.07 ± 0.04	1.03 ± 0.09	1.14 ± 0.08	1.15 ± 0.12	0.97 ± 0.03	1.15 ± 0.09	**0.02↑**							**0.02↑**		
C/N ratio of *Calluna* flowers	29.5 ± 4%	1.17 ± 0.09	1.09 ± 0.05	1.04 ± 0.07	1.16 ± 0.06	1.15 ± 0.05	1.09 ± 0.04	1.21 ± 0.04	**0.04↑**							**0.04↑**		
C/N ratio of *Calluna* green tissue	28.1 ± 5%	0.94 ± 0.08	0.94 ± 0.08	0.90 ± 0.07	1.09 ± 0.04	0.88 ± 0.06	0.97 ± 0.05	0.98 ± 0.06										
C/N ratio of *Calluna* wood	56.7 ± 9%	0.97 ± 0.08	1.00 ± 0.10	0.94 ± 0.07	1.03 ± 0.06	0.95 ± 0.08	1.06 ± 0.08	1.16 ± 0.02										
Deschampsia	2.99 ± 20%	0.89 ± 0.07	1.20 ± 0.27	0.97 ± 0.27	0.94 ± 0.21	1.05 ± 0.18	0.73 ± 0.17	0.78 ± 0.06										
C/N ratio of *Deschampsia* green leaves	22.2 ± 6%	1.16 ± 0.02	1.16 ± 0.12	1.05 ± 0.07	1.39 ± 0.07	1.27 ± 0.11	1.18 ± 0.05	1.40 ± 0.07	**0.01↑**	**0.002↑**		+				**0.01↑**	**0.002↑**	
C/N ratio of *Deschampsia* whole plant	23.3 ± 8%	1.08 ± 0.06	0.92 ± 0.09	1.07 ± 0.14	1.25 ± 0.15	0.90 ± 0.04	1.07 ± 0.10	1.12 ± 0.06										
Mosses	0.930 ± 53%	3.20 ± 1.10	3.95 ± 1.65	2.57 ± 0.89	1.54 ± 0.73	1.95 ± 0.67	2.48 ± 1.20	1.77 ± 1.22										
C/N ratio of mosses	19.4 ± 5%	1.44 ± 0.15	1.31 ± 0.15	1.24 ± 0.09	1.12 ± 0.18	0.97 ± 0.13	1.16 ± 0.15	1.02 ± 0.11							**0.003§**	**0.05↑**	**0.05↑**	
Litter N																		
Deschampsia	0.095 ± 52%	0.56 ± 0.19	0.19 ± 0.04	0.15 ± 0.04	0.64 ± 0.32	0.46 ± 0.17	0.21 ± 0.15	0.58 ± 0.17										
Deschampsia litter N conc.	0.936 ± 12%	0.76 ± 0.11	1.05 ± 0.08	1.07 ± 0.12	0.75 ± 0.12	0.88 ± 0.09	1.15 ± 0.15	1.06 ± 0.08	**0.05↓**		**0.03↑**		+			**0.05↓**		**0.03↑**
Deschampsia litter N production	1.42 ± 28%	0.92 ± 0.22	0.69 ± 0.28	1.05 ± 0.51	0.64 ± 0.18	1.17 ± 0.20	0.73 ± 0.25	0.77 ± 0.14		**0.01↓**							**0.01↓**	
Plant root biomass N (0-10 cm)																		
Calluna	7.56 ± 35%	0.98 ± 0.24	1.73 ± 0.34	1.47 ± 0.35	1.90 ± 0.42	0.86 ± 0.29	1.71 ± 0.31	1.23 ± 0.38		**0.04↑**							**0.04↑**	
Deschampsia	10.3 ± 29%	0.67 ± 0.22	0.60 ± 0.14	0.56 ± 0.10	0.67 ± 0.18	0.65 ± 0.22	0.45 ± 0.10	0.59 ± 0.15										
Soil microbial biomass N and soil fauna N (0-10 cm)																		
Microbes	3.55 ± 16%	1.46 ± 0.39	1.32 ± 0.20	1.46 ± 0.20	1.27 ± 0.36	1.16 ± 0.28	1.03 ± 0.15	1.02 ± 0.22										
Enchytraeids	0.197 ± 10%	1.62 ± 0.50	0.71 ± 0.15	1.19 ± 0.38	1.00 ± 0.26	1.02 ± 0.15	0.53 ± 0.10	1.14 ± 0.39		**0.03↓**							**0.03↓**	
Microarthropods	0.064 ± 28%	2.18 ± 0.82	1.53 ± 0.38	1.84 ± 0.53	1.36 ± 0.49	1.61 ± 0.33	1.92 ± 0.27	1.82 ± 0.47										
Nematodes	0.007 ± 12%	1.46 ± 0.32	0.84 ± 0.18	1.21 ± 0.27	1.31 ± 0.48	0.95 ± 0.11	1.05 ± 0.19	0.97 ± 0.16										
Protozoans	0.011 ± 44%	0.55 ± 0.13	0.82 ± 0.19	1.47 ± 0.47	0.36 ± 0.11	1.29 ± 0.82	0.61 ± 0.15	0.37 ± 0.09		**0.04↓**							**0.04↓**	
Annual enchytraeid mineralization	0.592 ± 10%	1.62 ± 0.50	0.71 ± 0.15	1.19 ± 0.38	1.00 ± 0.26	1.02 ± 0.15	0.53 ± 0.10	1.14 ± 0.39		**0.03↓**							**0.03↓**	
Annual microarthropod mineralization	0.191 ± 28%	2.18 ± 0.82	1.53 ± 0.38	1.84 ± 0.53	1.36 ± 0.49	1.61 ± 0.33	1.92 ± 0.27	1.82 ± 0.47										
Annual nematode mineralization	2.63 ± 12%	1.46 ± 0.32	0.84 ± 0.18	1.21 ± 0.27	1.31 ± 0.48	0.95 ± 0.11	1.05 ± 0.19	0.97 ± 0.16										
Annual protozoan mineralization	1.58 ± 44%	0.55 ± 0.13	0.82 ± 0.19	1.47 ± 0.47	0.36 ± 0.11	1.29 ± 0.82	0.61 ± 0.15	0.37 ± 0.09		**0.04↓**							**0.04↓**	
Soil organic and inorganic N pools and concentrations																		
SOM-N (0-10 cm)	180.2 ± 5%	1.19 ± 0.14	1.08 ± 0.11	0.81 ± 0.04	1.30 ± 0.36	0.85 ± 0.07	0.86 ± 0.09	1.11 ± 0.16										
Extractable soil NO_3^--N (0-10 cm)	0.004 ± 15%	1.37 ± 0.26	1.15 ± 0.19	1.06 ± 0.16	1.42 ± 0.47	1.02 ± 0.08	0.85 ± 0.09	1.13 ± 0.27										
Extractable soil NH_4^+-N (0-10 cm)	0.330 ± 52%	0.76 ± 0.47	0.58 ± 0.50	0.87 ± 0.33	0.72 ± 0.37	3.29 ± 0.99	0.19 ± 0.06	0.19 ± 0.05		**0.02↓**							**0.02↓**	
Extractable soil DON (0-10 cm)	1.59 ± 16%	1.07 ± 0.19	0.90 ± 0.10	1.25 ± 0.17	1.20 ± 0.23	0.71 ± 0.15	0.92 ± 0.12	0.85 ± 0.17					**0.04‡**					
Mean annual leachate NO_3^--N conc. (-5 cm)	7.39 ± 22%	0.24 ± 0.01	0.56 ± 0.07	1.01 ± 0.10	0.68 ± 0.08	0.93 ± 0.23	0.80 ± 0.06	0.71 ± 0.11			**0.01↑**	**0.002§**			**0.03§**	**0.05↓**	**0.05↓**	**n.s.**
Mean annual leachate NH_4^+-N conc. (-5 cm)	6.87 ± 18%	1.10 ± 0.09	1.76 ± 0.48	1.21 ± 0.13	1.05 ± 0.19	2.13 ± 0.51	1.35 ± 0.16	1.06 ± 0.09				**0.004§**					**0.05↑**	
Mean annual leachate DON conc. (-5 cm)	21.4 ± 16%	0.70 ± 0.05	1.25 ± 0.25	1.09 ± 0.08	0.89 ± 0.11	1.43 ± 0.28	1.06 ± 0.05	1.07 ± 0.09		**0.01↑**			**0.02§**			**0.05↓**	**0.01↑**	
Mean annual leachate total N conc. (-5 cm)	7.23 ± 10%	0.80 ± 0.04	1.45 ± 0.25	1.04 ± 0.05	0.96 ± 0.11	1.28 ± 0.13	1.03 ± 0.04	1.42 ± 0.15					**0.05§**			**0.05↓**		
Mean annual leachate NO_3^--N conc. (-60 cm)	2.04 ± 68%	0.27 ± 0.12	0.72 ± 0.30	0.57 ± 0.39	0.45 ± 0.23	0.58 ± 0.29	1.22 ± 0.51	0.30 ± 0.10										
Mean annual leachate NH_4^+-N conc. (-60 cm)	0.140 ± 20%	0.66 ± 0.05	1.46 ± 0.33	1.66 ± 0.67	1.81 ± 0.88	2.63 ± 1.56	0.81 ± 0.15	1.05 ± 0.39										
Mean annual leachate DON conc. (-60 cm)	2.60 ± 59%	0.37 ± 0.10	0.80 ± 0.25	0.63 ± 0.36	0.60 ± 0.24	0.74 ± 0.23	1.13 ± 0.45	0.42 ± 0.09										
Mean annual leachate total N conc. (-60 cm)	0.444 ± 30%	0.73 ± 0.17	0.94 ± 0.19	0.78 ± 0.32	0.95 ± 0.33	0.93 ± 0.20	0.97 ± 0.41	0.69 ± 0.11										
Gaseous fluxes																		
Annual N_2O emission	0.031 ± 18%	0.78 ± 0.35	0.89 ± 0.25	0.95 ± 0.21	0.52 ± 0.16	1.66 ± 0.23	1.07 ± 0.18	1.06 ± 0.21		**0.05↓**	**0.05↑**	**0.04‡**		+			**n.s.**	**0.05↑**
Mineralisation, immobilisation and nitrification																		
Annual NH_4^+ consumption (0-5 cm)	3.21 ± 19%	1.16 ± 0.17	1.18 ± 0.16	2.50 ± 0.54	1.76 ± 0.19	2.06 ± 0.39	1.87 ± 0.15	0.90 ± 0.06			**0.04↑**		**0.04§**	**0.01§**				**0.04↑**
Annual gross mineralisation (0-5 cm)	4.27 ± 9%	0.97 ± 0.09	0.93 ± 0.11	1.45 ± 0.22	1.41 ± 0.20	1.45 ± 0.15	1.25 ± 0.08	0.80 ± 0.03		**0.03↓**			**0.02§**		**0.03‡**		**0.03↓**	**0.05↑**
Annual NH_4^+ consumption (5-10 cm)	5.6 ± 70%	0.79 ± 0.13	1.89 ± 0.73	1.01 ± 0.32	0.45 ± 0.29	0.16 ± 0.04	0.17 ± 0.04	0.56 ± 0.11							**0.03§**		**0.05↑**	
Annual gross mineralisation (5-10 cm)	2.40 ± 24%	2.16 ± 0.61	2.75 ± 1.70	1.54 ± 0.29	1.74 ± 0.49	0.93 ± 0.36	0.87 ± 0.21	1.40 ± 0.36										
Potential nitrification (0-10 cm)	0.159 ± 44%	0.22 ± 0.20	1.01 ± 0.53	1.69 ± 0.61	1.23 ± 0.80	1.53 ± 0.63	3.15 ± 1.03	1.16 ± 0.54			**0.004↑**				**0.03§‡**			**0.004↑**
Potential denitrification (0-10 cm)	33.9 ± 29%	1.03 ± 0.26	1.24 ± 0.35	1.61 ± 0.58	0.99 ± 0.38	1.08 ± 0.36	1.95 ± 0.40	1.49 ± 0.36			**0.02↑**							**0.02↑**
N Leaching																		
Annual NO_3^--N leaching (-60 cm)	0.619 ± 62%	0.31 ± 0.16	0.73 ± 0.32	0.32 ± 0.18	0.39 ± 0.20	0.65 ± 0.28	1.00 ± 0.38	0.28 ± 0.09										
Annual NH_4^+-N leaching (-60 cm)	0.045 ± 27%	0.68 ± 0.06	1.48 ± 0.37	1.98 ± 0.46	2.01 ± 1.14	2.76 ± 1.40	0.74 ± 0.12	1.24 ± 0.49										
Annual DON leaching (-60 cm)	0.144 ± 24%	0.94 ± 0.24	1.02 ± 0.23	0.86 ± 0.29	1.35 ± 0.72	1.46 ± 0.39	0.90 ± 0.38	0.64 ± 0.11										
Annual total N leaching (-60 cm)	0.804 ± 53%	0.44 ± 0.16	0.83 ± 0.27	0.48 ± 0.20	0.64 ± 0.28	0.90 ± 0.27	0.95 ± 0.35	0.39 ± 0.08										

Figure 1

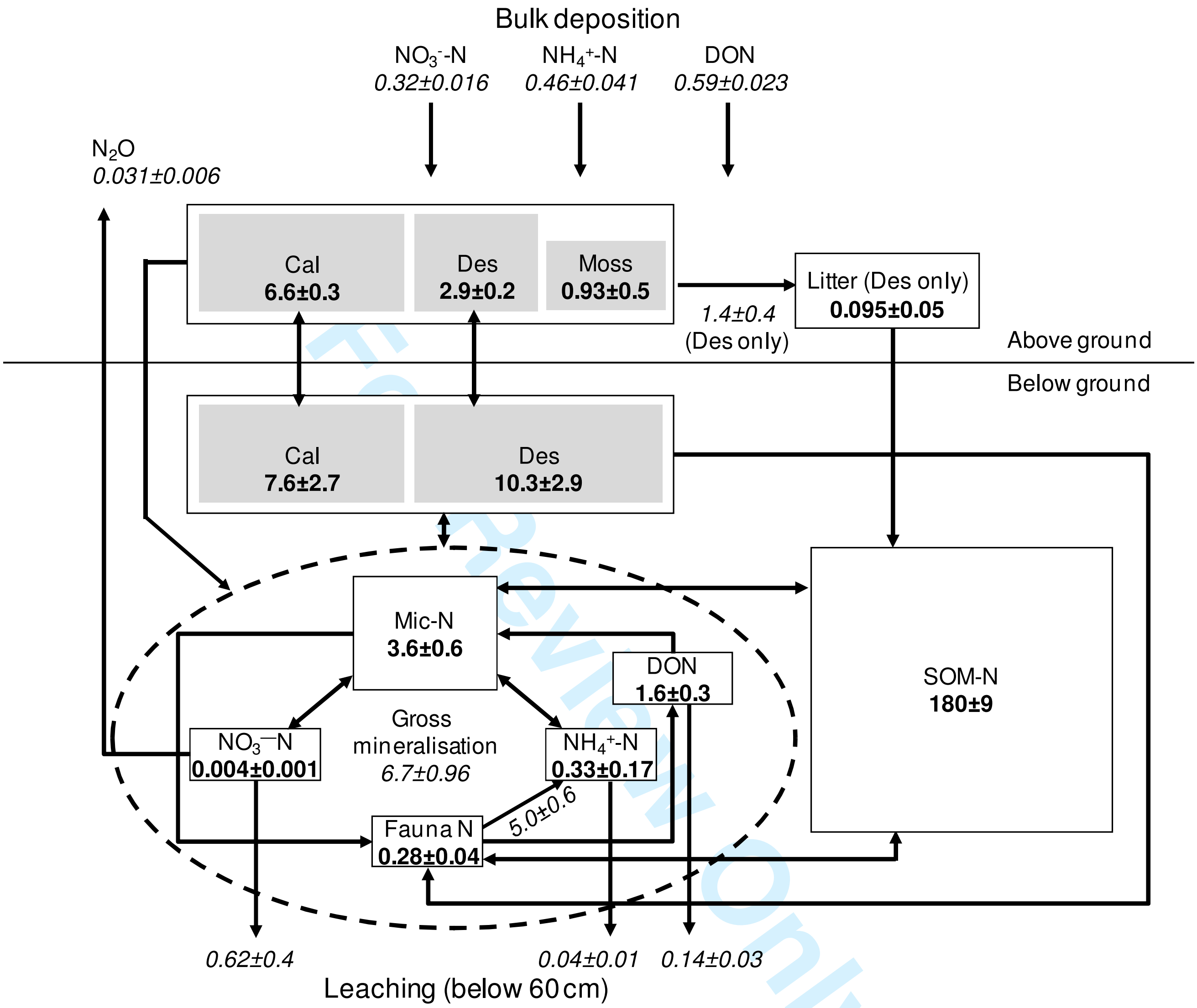
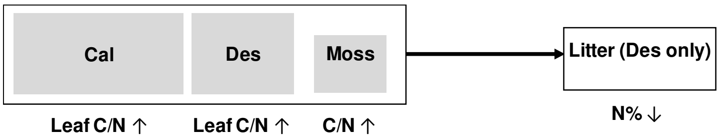
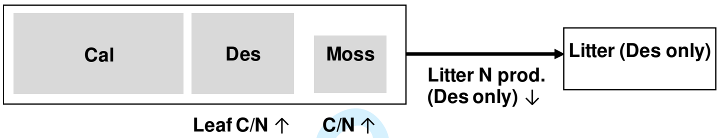

Bulk deposition
NO3--N
0.32±0.016
NH4+-N
0.46±0.041
DON
0.59±0.023
N2O
0.031±0.006
Cal
6.6±0.3
Des
2.9±0.2
Moss
0.93±0.5
1.4±0.4
(Des only)
Litter (Des only)
0.095±0.05
Above ground
Below ground
Cal
7.6±2.7
Des
10.3±2.9
Mic-N
3.6±0.6
DON
1.6±0.3
SOM-N
180±9
Gross
mineralisation
6.7±0.96
NO3–N
0.004±0.001
NH4+-N
0.33±0.17
Fauna N
0.28±0.04
5.0±0.6
0.62±0.4
0.04±0.01
0.14±0.03
Leaching (below 60 cm)

Figure 2

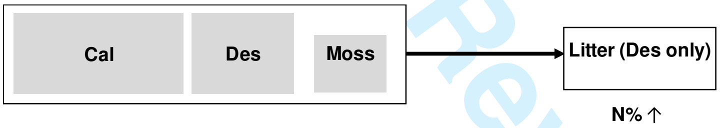
(a) CO$_2$



(b) Drought



(c) Warming



(d) CO$_2$, drought and warming

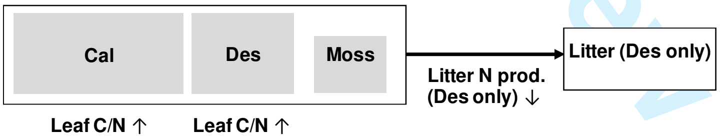


Figure 3

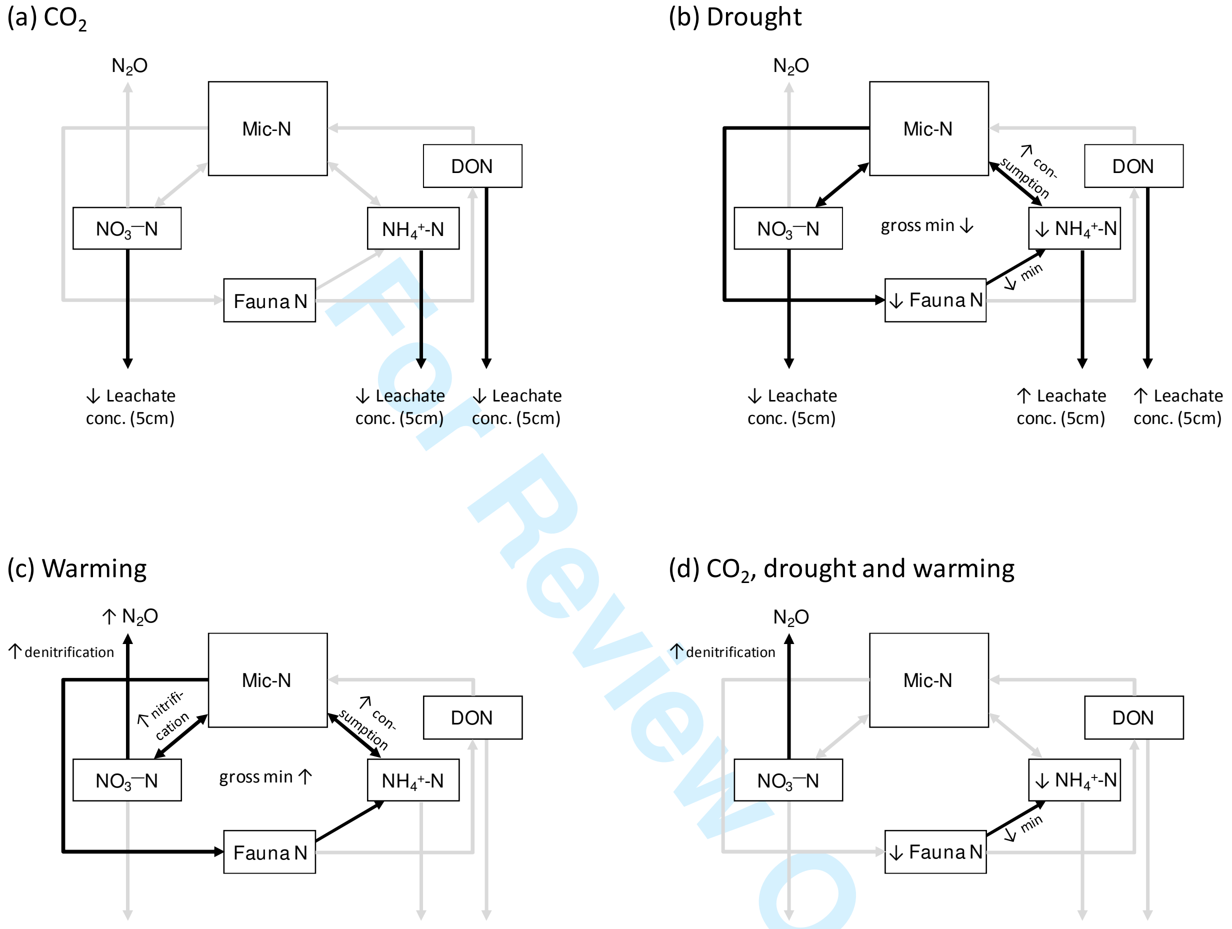

(a) CO₂
N₂O
Mic-N
DON
NO₃–N
NH₄⁺-N
Fauna N
↓ Leachate conc. (5cm)
↓ Leachate conc. (5cm)
↓ Leachate conc. (5cm)
(b) Drought
N₂O
Mic-N
↗ con-sumption
DON
NO₃–N
gross min ↓
↓ NH₄⁺-N
↓ min
↓ Fauna N
↓ Leachate conc. (5cm)
↑ Leachate conc. (5cm)
↑ Leachate conc. (5cm)
(c) Warming
↑ N₂O
↑ denitrification
Mic-N
↑ nitrifi-cation
↗ con-sumption
DON
NO₃–N
gross min ↑
NH₄⁺-N
Fauna N
(d) CO₂, drought and warming
N₂O
↑ denitrification
Mic-N
DON
NO₃–N
↓ NH₄⁺-N
↓ min
↓ Fauna N

Figure 4