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Short-term consequences of spatial heterogeneity in soil nitrogen concentrations caused by urine patches of different sizes

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ABSTRACT

The scale of spatial heterogeneity in soil nitrogen (N) concentrations varies considerably in grazed systems, because grazers vary in the volume of urine they excrete. This could affect how urine-N is processed, and subsequently how much N is lost from the system, as diffusion and plant effects on soil nutrient concentrations can be scale-dependent. Two field experiments were performed; one measured the impact of urine patch size (small, medium or large) on soil inorganic N pools and fluxes over time, and the other assessed whether urine patch size affected plant responses and system N retention even if the same total amount of urine was applied. Soil from inside small urine patches retained inorganic N for shorter amounts of time, resulting in lower plant biomass and N uptake than that inside larger patches. Although system nitrogen retention was not affected by patch size, it appeared that larger patches had a greater potential to lose N due to the longer period over which soil inorganic N concentrations remained high. This suggests that systems grazed by larger organisms are more prone to lose N through patch size effects than those grazed by smaller ones.

1. Introduction

A common cause of spatial heterogeneity in soil resources in many systems is the excretion of urine by grazing animals, which results in patches of soil with extremely high concentrations of nitrogen (N) (Haynes and Williams, 1993; Williams et al., 2000). This N can be taken up by plants, lost from the system through abiotic processes such as volatilisation, or processed biotically by soil microbes (Haynes and Williams, 1993). Processing of N by soil microbes can also result in the loss of N from the system in the form of nitric oxide, nitrous oxide or dinitrogen gases produced during nitrification and denitrification, or in the form of nitrate, which can be leached from the soil (Haynes and Williams, 1993). As well as reducing system N retention, these biotic processes can have a detrimental effect on the environment: nitrous oxide is a potent greenhouse gas (Forster et al., 2007), and nitrate leaching can result in eutrophication (Galloway et al., 2004). Reducing or controlling these types of environmental impacts is a strong focus of governments worldwide (e.g. the European Union Nitrate Directive 91/676/EEC, Kyoto Protocal), increasing our need to fully understand the factors that regulate N processing by soil microbes.

Most research to date has focused on how urine chemistry and soil properties affect N processing in patches of a uniform size (e.g. Allen et al., 1996; Clough et al., 2003; Bol et al., 2004; van Groenigen et al., 2005). However, because the volume of urine deposited by different grazers varies (Doak, 1952; Haynes and Williams, 1993), the size of their urine patches and therefore the scale of the spatial heterogeneity in N concentrations they create will vary considerably. This variability has the potential to affect how urine-N is processed, and therefore our ability to predict how much N is retained in a system and how urine deposition will affect the environment.

There are two primary mechanisms by which patch size could affect urine-N processing. The first of these is diffusion of N away from the edges of the patch due to the steep N concentration gradient there (Koops et al., 1997). Fick's First Law of diffusion states that the diffusive flux is dependent on the distance over which a change in concentration occurs; the smaller the distance, the greater the flux (Fick, 1855). This suggests that the smaller horizontal distance over which concentrations vary in small patches should result in greater lateral diffusion out of the patch, which may subsequently mean that the concentration of N in small patches decreases more quickly than that in large patches. Such a change in N concentrations could in turn affect urine-N processing as the amount of N available has been shown to have a significant effect on both nitrification and denitrification rates (Clough et al., 2003; Petersen et al., 2004).

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The second mechanism is mediated by plant responses to spatial heterogeneity in soil N concentrations. Plant responses to nutrient-rich patches within a system can be physiological, such as increased nutrient uptake capacity (Hodge, 2004) and increased root exudation (Paterson et al., 2006), or morphological, such as root proliferation (Cahill and Casper, 1999; Fransen et al., 2001; Hodge, 2004). Where the nutrient-rich patch is caused by urine addition, roots can also be killed by scorching (Williams and Haynes, 2000). These responses could have an impact on the concentration of N available for microbial processing, the availability of labile C sources used during heterotrophic denitrification, and the demand of soil microbes for N. Plant responses to spatial heterogeneity in soil resources can also depend on the scale of that heterogeneity: the smaller the size of the patches the greater the proportion of plants within a given area that will be able to access the nutrients within them (Day et al., 2003), but the more difficult it is for plants to detect patches and respond (Hutchings et al., 2003; Hutchings and John, 2004). These trends suggest that the response of plants to spatial heterogeneity in soil N concentrations caused by urine patches of different sizes could have an impact on urine-N cycling and thus nutrient loss from the system.

This study aimed to determine whether urine patch size and variation in the scale of spatial heterogeneity in N concentrations, caused by urine patches of different sizes, has an impact on N transformations and plant responses and subsequently on system N retention. Specifically, we hypothesised that: (1) less N will be transformed into nitrate and lost as nitrous oxide in small urine patches compared to large patches due to greater diffusion of N out of patches, (2) plant biomass and N uptake inside small urine patches will be lower than inside larger patches, as less N will remain inside urine patches, and (3) at the population level, fine-scale heterogeneity of soil N concentrations caused by small urine patches will result in greater plant N uptake and biomass and therefore greater system N retention than coarse-scale heterogeneity caused by large urine patches, because a greater proportion of plants within a given area will be able to access the N.

2. Materials and methods

2.1. Experimental design

In order to assess whether spatial heterogeneity in soil N concentrations caused by the addition of urine patches of different sizes has an impact on the processing of urine-N, two experiments were set up. Experiment 1 aimed to determine the effect of urine patch size on N transformations and the activity and biomass of soil microbes. This involved applying one of four treatments: no urine, a small (0.15 m × 0.15 m), a medium (0.3 m × 0.3 m), or a large (0.6 m × 0.6 m) urine patch to pasture, and measuring changes in N pools and fluxes over the following 30 d. The volume of urine added per area was the same for all patches; 0.125 l was added to small patches, 0.5 l to the medium patches, and 2 l to the large patches. The patch size and volume used for the large patches is within the range typically created by cattle (Haynes and Williams, 1993), and that used for small patches is within the range typically created by sheep (Doak, 1952). Urine patches were at least 0.45 m apart to eliminate interference with each other, and each patch was used for measurements at one time point only.

Experiment 2 aimed to determine the effect of the scale of spatial heterogeneity in soil N concentrations on plant and soil responses and consequently the amount of N retained in the system. Spatial heterogeneity was created by applying 2 l of urine to 0.36 m^2 within a 2.48 m^2 plot in varying patterns that corresponded to the patch sizes used in Experiment 1. Thus, the coarse-scale treatment consisted of a centrally placed single large 0.60 m × 0.60 m patch, the medium-scale treatment consisted of four 0.30 m × 0.30 m medium urine patches, and the fine-scale treatment consisted of sixteen 0.15 m × 0.15 m small urine patches per plot (Fig. 1). Plots were divided into quarters or sixteenths and urine patches placed in the middle of these squares for medium- and fine-scale heterogeneity treatments respectively. There was also a control plot that remained unamended and at the natural moisture content of the soil. This design allowed us to determine the effect of urine patch size on N retention in the system without confounding results by adding different amounts of N. The experiment was harvested 35 d after the addition of urine. Both experiments were set up at the same time so that climatic conditions were the same, and the same urine was used for each. Treatments were blocked, randomly assigned and replicated five times for both experiments.

2.2. Site preparation

The experiments were performed at Lincoln University, New Zealand (43°38.8S, 172°27.3E), on a paddock with a history of sheep grazing. The site has a mean annual rainfall of 630 ml yr^{-1}, and a mean July and January temperature of 6 and 17 °C respectively. The soil type was a Wakanui silt loam on sandy loam (Mottled immature pallic, NZ soil classification (Hewitt, 1998)). The experimental area was fenced off several months before beginning the experiment to allow the system to recover from previous grazer inputs. To reduce spatial variability within the plots, the original vegetation was removed by spraying, the soil rotovated several times, rolled, and remaining large clumps of vegetation removed. The site was then drilled with Meridian AR1 ryegrass (*Lolium perenne*) (10 kg ha^{-1}) at the end of November 2006. Drilled rows were 7.5 cm apart. It was fertilised with urea at a rate of 25 kg N ha^{-1} on the 20/12/06 and on the 12/1/07 to encourage grass growth and tillering. To control the growth of other plant species that might create patches of different nutrient conditions, the site was sprayed with Pulsar at 5 l ha^{-1} on the 24/12/06 and with Versatile at 700 ml ha^{-1} on the 8/1/07. Immedi-

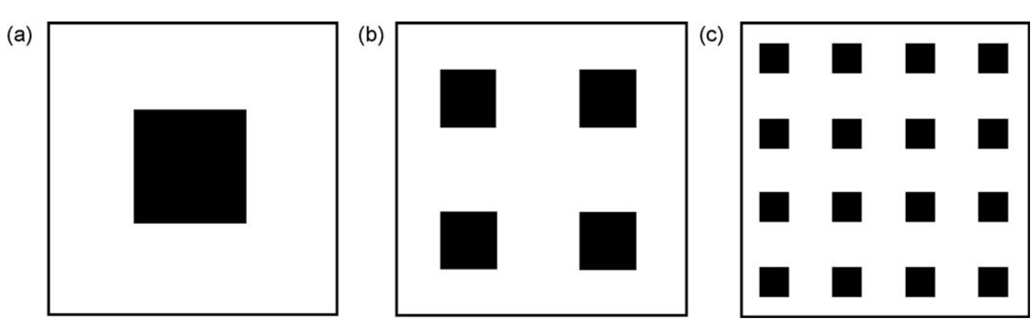

Fig. 1. Layout of urine patches in the 2.48 m^2 plots (outside line) in the (a) coarse, (b) medium and (c) fine-scale heterogeneity treatments used in Experiment 2. The area covered by urine is the same for all treatments (0.36 m^2), and is indicated by the black squares.