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Kathryn Ann Slebodnik

University of New Hampshire, Durham, kad325@wildcats.unh.edu

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Effects of Silvopasture Establishment on Aqueous and Gaseous Soil N Losses at
the University of New Hampshire Organic Dairy Research Farm

Kathryn Slebodnik
Thesis Advisor: Dr. Alexandra Contosta
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Abstract

The expansion of local agriculture in the New England region is putting increased pressure on farmers to expand their arable land base. While clear-cutting is a traditional method of converting forested land to agriculture, it is known for having adverse ecological impacts. To minimize these impacts, farmers can create a silvopasture which incorporates a portion of the original forest canopy into pastures or crop fields. This study evaluates the impact of land-use changes for agriculture on soil nitrogen (N) retention. In particular, this study investigates the differences in soil N turnover, gaseous loss, and aqueous loss among an established forest, established pasture, clear-cut converted pasture, and converted silvopasture systems over a 30-day incubation period. We found significant differences in N mineralization, immobilization, and denitrification among treatments, with evidence that a forest-to-silvopasture conversion can successfully support soil N retention within the first two years of implementation. This may have been due to the presence of coarse woody debris inputs from forest cutting and its effect on the soil carbon (C) to N ratio. Nitrogen retention in silvopastures may also result from partial preservation of the forest canopy. Our results suggest that farmers looking to expand their agricultural land base through forest clearing may be able to use silvopastures for as a way of retaining soil nutrients while at the same time putting land into production.

1. Introduction

As of 2014, only 5% of land in New England was used for agriculture, and approximately 90% of the food supply came from outside the region (Donahue et al., 2014). Initiatives such as *A New England Food Vision* aim to change this and have 50% of food products consumed in New England sourced within the area by 2060. Movements like this would support local farmers, promote a more sustainable, self-reliant food supply, and provide more nutritious options for local shoppers (Donahue et al., 2014). However, since much of New England is forested, a current solution for farmers to relieve this growing pressure is to transform forested areas of their properties into new fields or pastures (Martinez et al. 2010; Timmons et al. 2008). Traditionally, this land-use change would be accomplished through clear-cutting techniques. While clear-cutting maximizes the available space for agricultural production, it carries ecological consequences, particularly for ecosystem nitrogen (N) retention.

The disruption of ecosystem services due to land-use changes is especially visible in soil nutrient transformations. In the soil, nutrients are held by soil particles and decomposing litter, and stabilized in soil organic matter. Nitrogen is of particular importance to farmers since it is a macronutrient which acts as a limiting factor to forage and crop growth. Clear-cutting forests may liberate N in the soil, as well as remove vegetation which usually takes it up. The processes determining when and in what form N exits the soil is regulated by a variety of physical, chemical, and biological characteristics of the surrounding environment. These include soil temperature, moisture content, pH, the presence or absence of specific microbial communities, and vegetative ground cover, which all vary among land-uses. In aquatic ecosystems, the clearing of land can decrease pH and increase sediment load, temperature, and N concentrations (Holmes and Zak 1999; Pardo et al., 1995). Following a clear-cut experiment at Hubbard Brook Experimental forest in Woodstock, NH, it was estimated that the amount of N lost from the system in the first year was equal to the amount of N turned over in an undisturbed ecosystem, taking the ecosystem from a net gain of 4.5 kg/ha of N to a net loss of 52.8 kg/ha of N. This influx of N was noted particularly in surrounding streams suffering from elevated ammonium (NH_4^+) and nitrate (NO_3^-) concentrations (Bormann et al., 1968). Land-use conversion can also increase production of greenhouse gasses due to changes in physical and chemical soil characteristics such as redox potential (Bowden and Bormann, 1986). In more reduced environments, the complete denitrification of aqueous NO_3^- to di-nitrogen gas (N_2) is not thermodynamically favorable, causing more NO_3^- to exit the soil as nitric oxide (NO) or nitrous oxide (N_2O) gases.

In an effort to mitigate these negative impacts, farmers may turn to alternatives such as the creation of silvopastures. A silvopasture is an agroforestry technique which incorporates 35-50% of the original forest canopy with livestock pasture or forage crop production beneath (NRCS 2011). This practice has the potential to be both economically and environmentally advantageous. The presence of trees allows for the production of multiple products to support local economies, while providing environmental services that are not associated with traditional clear-cut ecosystems. These services may include increased C sequestration, improved soil nutrient retention, improved water quality, minimized temperature increases, reduced erosion potential, as well as providing habitat for wildlife (NRCS 2011).

In converted pasture and silvopasture areas, it is normal to see the addition of coarse woody debris to the land surface following forest removal (Orefice et al., 2016). Due to the limiting nature of N in microbial decomposition dynamics, this influx of C-rich debris may increase the soil C:N ratio and spur the microbial immobilization of N. In past studies, the application of woody debris has been found to decrease soil NO_3^- concentrations by up to 30% and NH_4^+ concentrations by 36%. These results were accompanied by 93% NH_4^+ retention in extraction studies (Homyak et al., 2008). In forested soils, concentrations of leached nitrate have been negatively correlated with C:N ratios (Gundersen et al., 1998). Although land-use changes are associated with high levels of nutrient loss, the application of woody debris may support N retention. The effect of wood-chip addition on soil C:N ratio or greenhouse gas production has not been directly assessed in the past, and could have an influence on the production of greenhouse gases from soils in clear-cut or silvopasture areas.

In order to understand how soil N retention dynamics differ among forest-to-pasture conversion strategies, we compared potential soil N transformations and losses at sites undergoing land-use conversion from forest to pasture or forest to silvopasture at the University of New Hampshire Organic Dairy Research Farm (UNH ODRF). Through this study, we aimed to answer three main questions: 1) How do soil N mineralization and immobilization processes differ among land uses? 2) Which land use will demonstrate the highest degree of N retention? and, 3) Within each land use, will N exit the environment in an aqueous phase, gaseous phase, or both? Based on the results of this study we will gain insight into the potential for silvopastures to sustainably extend New England's arable land base as compared to traditional land-clearing techniques.

2. Methods

2.1 Site Description

The UNH ODRF is located in Lee, New Hampshire, USA. The farm consists of 48 ha of forested land and 40 ha of certified organic pastures divided into 14 fields. Two of these pastures are managed for intensive rotational grazing of Jersey cows and the rest are used for hay production. The soils in this area belong to the Hollis-Charlton series, characterized as marine terraces with glacial till parent material and a loamy sand to silt loam texture. The established forest on this site is mainly composed of red oak (*Quercus rubra*), red maple (*Acer rubrum*), white pine (*Pinus strobus*), eastern hemlock (*Tsuga canadensis*), and American beech (*Fagus grandifolia*).

The four treatments for this project consisted of one established forest, one established pasture, one converted, clear-cut pasture, and one converted silvopasture. Each treatment included a one hectare area with three sampling locations. The converted pasture and converted silvopasture were established in January and February of 2015. The silvopasture area was thinned to ~30% of the original canopy cover. Trees were removed in both the clear-cut and silvopasture, and the remaining slash was mulched and spread across the site using a FECON wood chipper.

2.2 Sample Collection

Soil samples were collected on 7 June 2016 at the UNH ODRF where soils were sampled from the four, 1 hectare treatments. Each treatment area contained three sampling sites, with sites placed at decreasing elevation (Figure 1). Six soil samples were collected at each site for a total of 72 samples. For sampling, the litter layer was brushed aside and soils were sampled to a depth of 10 cm using a tulip bulb corer. Individual samples were placed in Ziploc bags inside a cooler, transported to the University of New Hampshire, and kept at 4°C pending analysis.

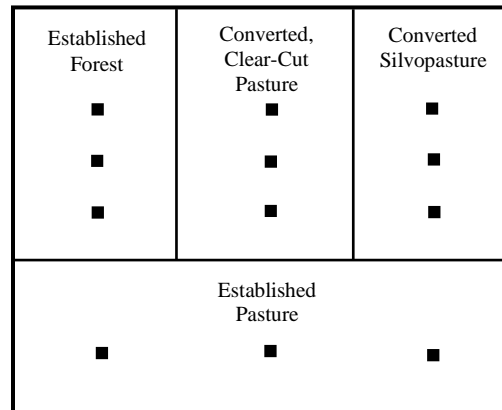


Figure 1: Schematic representation of the four treatment plots and permanent sampling sites and the UNH ODRF.

2.3 Soil Processing

Each individual sample was processed through a 2 mm sieve to remove rocks and debris. After sieving, the individually collected samples were bulked by sampling site to produce 12 working samples. After bulking was completed, field moisture capacity (FMC) was determined for each working sample as described in Saxton and Rawls (2006). Subsamples were then adjusted to FMC to be used in the 30-day incubation study.

2.4 Initial Soil Characteristics

Initial soil pH was determined with a Mettler Toledo AG 8603 pH meter and InLab Expert Pro ISMIP67 probe (Mettler Toledo, Columbus, OH, USA) following the Kellogg Biological Station soil pH protocol using a 1:2 soil to water ratio. Initial soil total C, total N, and C:N ratio were determined using a Costech ECS 4010 CHNS-O elemental analyzer based on an Atropine standard curve (Costech Analytical Technologies, Valencia, CA, USA). Initial average soil pH, total C, total N, C:N ratio, and moisture content are presented in Table 1.

Table 1: Average initial soil characteristics with 95% confidence intervals including soil pH, total C, total N, C:N ratio, and gravimetric moisture content.

Treatment	pH	Total C (%)	Total N (%)	C:N Ratio	Moisture (g H ₂ O/g dry soil)
Forest	4.65 (0.20)	178.58 (30.60)	6.22 (1.18)	28.37 (7.70)	0.47 (0.25)
Silvopasture	4.63 (0.11)	258.48 (10.99)	8.61(0.69)	30.70 (4.30)	0.43 (0.08)
Clear-Cut	3.81 (0.05)	196.25 (63.98)	8.00 (2.00)	24.63 (0.20)	0.44 (0.17)
Pasture	5.89 (0.03)	102.18 (1.06)	7.36 (0.37)	13.87 (0.60)	0.33 (0.02)

2.5 Incubation Experiment

A 30-day incubation experiment was used to determine rates of mineralization, immobilization, and CO₂ and N₂O production among treatments. For this incubation, 10 g of soil was placed in a 16-ounce mason jar fitted with rubber septum, with six analytical replicates for each sample. Jars were kept in a climate controlled environment at 25°C at FMC. Field moisture capacity was maintained during the incubation by recording the initial mass of the jar plus soil at FMC. Jars were weighed weekly and any decrease in mass was replaced with deionized water. Samples were covered with parafilm and allowed to equilibrate with the controlled environment for 5 days prior to the first headspace measurement. Samples were allowed to incubate for 24 hours between measurements and flushed to ambient conditions before being sealed for the next incubation period. Carbon dioxide flux measurements were taken daily using a syringe and analyzed using a LI-COR LI-6252 infrared gas analyzer (LI-COR Biosciences, Lincoln, NB, USA). Flux rates were calculated on a daily basis, and then summed to calculate cumulative flux over the entire incubation period.

Nitrous oxide was measured following the CO₂ analysis protocol and sampled every 2-3 days. Measurements were collected using a syringe and analyzed using a Shimadzu GC-8A gas chromatograph with electron capture detection (Shimadzu Scientific, Kyoto, Japan). Nitrous oxide flux rates were calculated for each collection period, and then summed to calculate cumulative flux over the entire incubation period. Since N₂O production was not measured daily, values were linearly interpolated between collection periods.

Nitrogen mineralization and immobilization were determined by measuring NH₄⁺ and NO₃⁻ concentrations in soils at the start and end of the 30-day incubation. Both forms of N were measured using potassium chloride (KCl) extraction techniques to quantify total species present in both the soil solution and on exchange sites. A water extraction process based on this protocol was used to quantify the N forms present in the soil solution only, as a proxy for potential aqueous loss. Ammonium was quantified using the indophenol-blue method adapted for microtiter plates (Sims et al. 1995). Nitrate was quantified by the vanadium (III) reduction reaction (Braman and Hendrix 1989) modified for microplate analysis (Miranda et al., 2001). Both sets of extraction solutions were frozen at -20°C until analysis using a BioTek Synergy HT microplate reader (BioTek Instruments, Winooski, Vermont, USA).

2.6 Data Analysis

All statistical analysis was performed in JMP 2016 statistical analysis software based on non-parametric statistical methods due to the non-normal distribution of variables (SAS Institute, Cary, NC, USA). Significant differences in moisture content, pH, total C, total N, C:N ratio,

KCl and H₂O-derived ammonification, KCl and H₂O-nitrification, KCl and H₂O-derived mineralization, and CO₂ and N₂O production among treatments were determined using a one-way, ANOVA analysis. Statistical tests were performed with treatment as the independent variable using Wilcoxon/Kruskal-Wallis test statistics to determine significant differences among means, and the Wilcoxon Each Pair test to determine significant pairwise differences. To determine how gaseous losses related to physical and chemical soil characteristics, we performed multivariate regressions with CO₂ and N₂O production as the dependent variables. The relationships between CO₂ and N₂O production and moisture content were analyzed using quadratic polynomial and three-parameter exponential regression analyses, respectively. The relationship between N₂O production and KCl-derived nitrification was analyzed in the same manner using a three-parameter exponential regression.

3. Results

3a. Initial Soil Characteristics

Initial soil characteristics varied significantly for pH, total C, total N, C:N ratio, and moisture content among treatments (Tables 1 and 2). Soil pH varied significantly, with the pasture and clear-cut treatments differing from all other treatments. Total soil C varied, with the silvopasture and pasture differing from all other treatments. Total soil N also varied significantly, with the silvopasture differing from the forest and pasture treatments, and the forest differing from the silvopasture and clear-cut treatments. The initial carbon to nitrogen ratio varied significantly among treatments, where the forest and silvopasture differed from the clear-cut and pasture treatments. Here, the clear-cut also differed from the pasture. Soil FMC varied significantly, with the forest and silvopasture differing from the pasture.

Table 2. Wilcoxon/Kruskal-Wallis test statistics for all treatments. An asterisk (*) denotes a significant difference among treatment means.

Variable	P-value	ChiSquare
pH	<0.0001*	60.41
Total C (%)	<0.0001*	41.54
Total N (%)	0.0005*	17.71
C:N Ratio	<0.0001*	54.64
Moisture Content (g H ₂ O/g dry soil)	0.0078*	11.87

3b. Incubation Study

Soil nitrogen cycling differed significantly among land-use treatments during the 30-day incubation period. However, the magnitude of these impacts differed among treatments (Table 3).

Table 3. Wilcoxon/Kruskal-Wallis test statistics for all treatments. An asterisk (*) denotes a significant difference among treatment means.

Variable	P-value	ChiSquare
Cumulative CO ₂ Production	< 0.0001*	41.02
Cumulative N ₂ O Production	0.10	6.36
Moisture Content	0.01*	11.87
KCl Ammonification	< 0.0001*	51.32
H ₂ O Ammonification	< 0.0001*	30.49
KCl Nitrification	< 0.0001*	43.30
H ₂ O Nitrification	< 0.0001*	57.97
KCl Net Mineralization	< 0.0001*	42.74
H ₂ O Net Mineralization	< 0.0001*	26.44

Ammonification for both KCl and H₂O showed significant differences among treatments. The forest and silvopasture treatments, where trees were present, demonstrated the highest rates of KCl-derived ammonification (Figure 2A). These treatments, with the addition of the clear-cut treatment, also demonstrated the highest rates of H₂O-derived ammonification (Figure 2B). Like ammonification, both KCl and H₂O-derived nitrification rates varied significantly between treatments. The pasture treatment had significantly higher KCl-derived nitrification rates compared to all other treatments (Figure 2C). Treatments without trees, the pasture and clear-cut, also produced the highest H₂O-derived nitrification rates (Figure 2D). These nitrification results were similar to rates of net N-mineralization among treatments.

As with ammonification and nitrification, net N-mineralization rates were significantly different among treatments for both KCl and H₂O. Like nitrification, the highest rates of KCl-derived N-mineralization occurred in the pasture treatment, while the highest rates of H₂O-derived N-mineralization occurred in the clear-cut and the pasture treatments where trees were absent (Figures 2E and 2F).

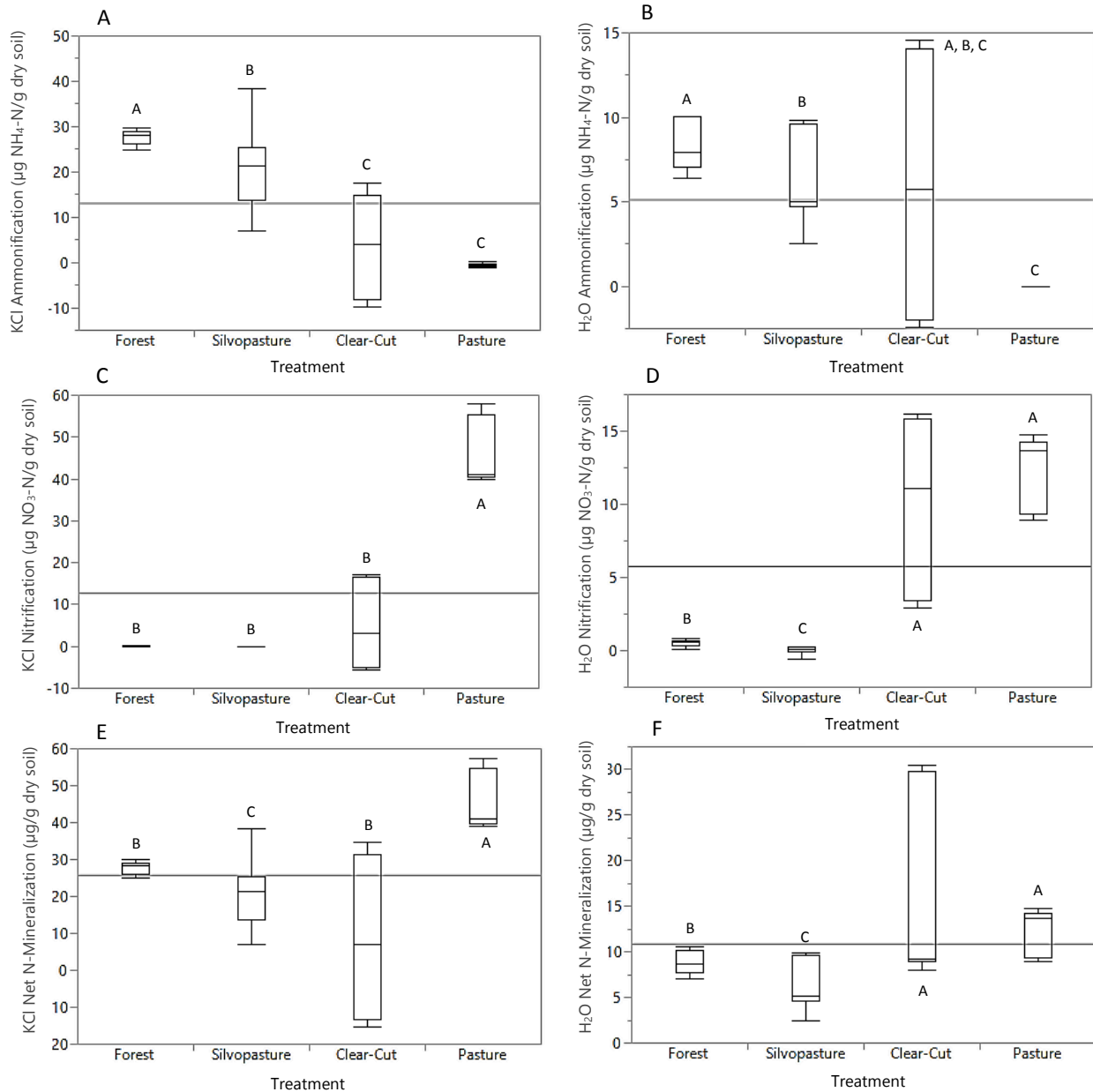


Figure 2: Average rates of KCl ammonification (A), nitrification (B), net mineralization (C), and H₂O ammonification (D), nitrification (E), and net mineralization (F) among all treatment sites. Letters above boxes indicate pairwise differences between treatment means.

Significant differences were not only noted in soil N turnover, but also in gaseous losses such as N₂O. A significant difference was not found for N₂O production among all treatments, but pairwise differences were found between the clear-cut and pasture treatments as well as the clear-cut and silvopasture treatments where production was highest in the clear-cut treatment (Figure 3A). Nitrous oxide production was the most highly variable within the clear-cut treatment, while the other three treatments shared a similar degree of variability.

Carbon dioxide production also showed a significant difference among all treatments, as well as pairwise differences between treatments (Figure 3B). Treatments that contained trees, the forest

and the silvopasture, exhibited the highest rates of CO₂ production. While CO₂ and N₂O production rates differed among treatments, comparisons of these rates with physical soil properties identified soil moisture content as a key factor affecting both sets of production rates.

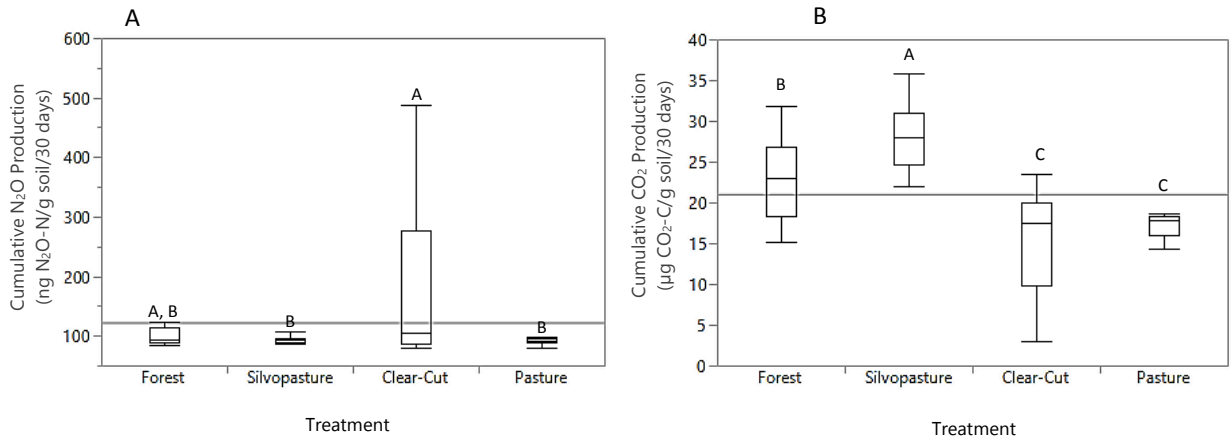


Figure 3: Cumulative production of N₂O (A) and CO₂ (B) among all treatment sites. Letters above the boxes are as in Figure 2.

A three-parameter exponential model described the relationship between N₂O and soil moisture, such that N₂O production increased exponentially with higher moisture (Figure 4A). This relationship is clearly exemplified by the clear-cut treatment, which had higher N₂O fluxes at the high end of the moisture spectrum and lower emissions where moisture was more limiting. A quadratic polynomial model described the relationship between CO₂ production and soil moisture content with the lowest levels of production at the high and low ends of the moisture content range (Figure 4B).

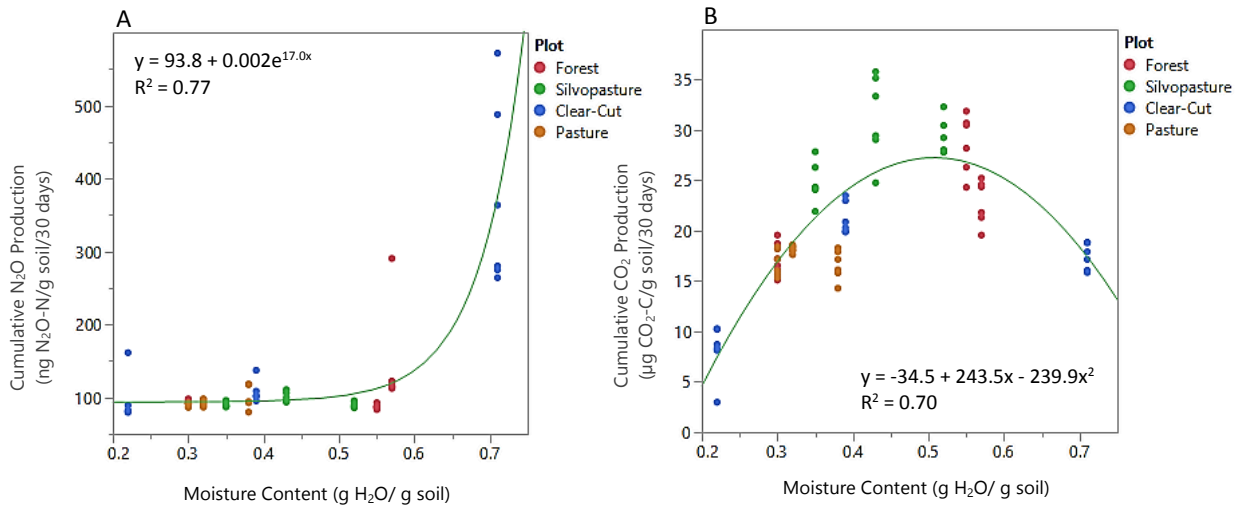


Figure 4: Cumulative N₂O (A) and CO₂ production (B) as a function of soil moisture content.

In addition to soil moisture content, N₂O production rates were also significantly related to KCl-derived nitrification rates. A three-parameter, negative exponential model described this relationship, where N₂O production was highest when net nitrification rates were lowest (Figure 4).

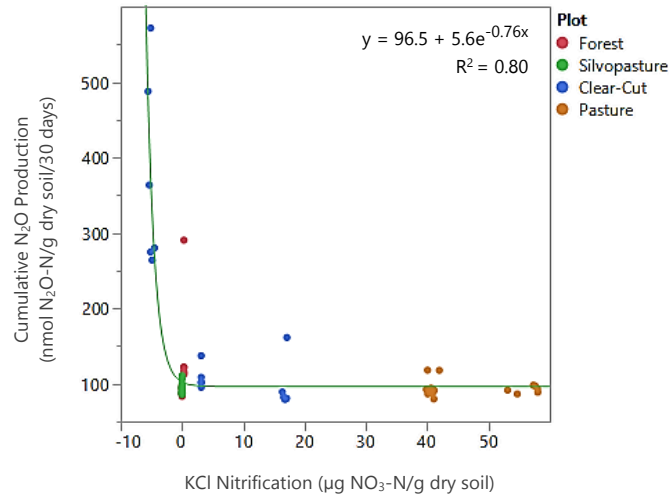


Figure 4: Cumulative N_2O production over a 30-day incubation period at $25^\circ C$ as a function of KCl nitrification rates among all treatment sites

4. Discussion

The results of our 30-day incubation indicate that the forest retained the most N, followed by the silvopasture, the pasture, and finally by the clear-cut treatment based on aqueous and gaseous N losses. The forest and silvopasture indicated minimal aqueous and gaseous N losses, while the pasture and clear-cut indicated major aqueous N losses with elevated gaseous N losses in the clear-cut treatment. Low N-retention in the clear-cut suggested the potential for substantial N loss following forest clear cutting for agriculture as well as the need for site-specific management practices to mitigate these losses.

4a. Forest

In the forest treatment, all rates of ammonification, nitrification, and mineralization as well as N_2O production indicated minimal disruption to forest N-cycling processes and therefore the highest degree of soil N-retention. The forest displayed characteristically high rates of both KCl and H_2O -derived ammonification due to the decomposition of soil organic matter (SOM) from litter inputs. While high concentrations of H_2O -derived ammonium would indicate a potential pathway for N-loss via leaching, trees present in the field would likely take up the ammonium and prevent major losses. This assumption was confirmed by low H_2O -derived ammonium concentrations initially present in the soil as well as low nitrification rates. In forest soils, such low nitrification rates are typically indicative of a C:N ratio sufficient to prevent NO_3^- leaching with leaching rates increasing dramatically as the ratio approaches the range of 27-24 (Gundersen et al., 1998). Since the C:N ratio in the forest treatment, 28.4, was just above this threshold, it likely prevented significant aqueous N loss. Despite low nitrification rates, soils from the forest treatment also had moderate rates of mineralization resulting from NH_4^+ turnover, indicating SOM decomposition. However, the highest amounts of mineralization occurred in the KCl-derived fraction, indicating that inorganic N was located mainly on the soil exchange sites and not readily available to be leached in solution. Finally, forest soils had low levels of N_2O

production. This is likely due to a combination of low initial NO_3^- concentrations and therefore low nitrification rates.

4b. Silvopasture

Soils from the silvopasture treatment indicated some N-retention and some N loss, and thus fell between the forest site and the clear-cut site in terms of N-cycling. We observed moderate KCl and H_2O -derived ammonification rates, which were likely due to the addition of high C-content slash to the site during forest conversion. High C-content wood chips have been shown to lower NH_4^+ concentrations in soils by as much as 42%, which would substantially decrease ammonification rates (Homyak et al., 2008). Wood chip additions may help to explain very low KCl and H_2O nitrification rates in silvopasture soils. Canopy removal typically increases nutrient losses through leaching in temperate forest ecosystems (Bormann et al., 1968). However, the application of wood-chips to a disturbed area decreases nitrification losses by limiting NH_4^+ availability (Homyak et al., 2008), which is consistent with the findings from our incubation. Analyzing ammonification and nitrification rates together through net N-mineralization rates, the silvopasture, like the forest, experienced the lowest rates of N-turnover, suggesting overall N-retention with minimal potential losses. Strong potential N retention in the silvopasture is further supported by low rates of N_2O production, which were not significantly different than the forest due to low concentrations of NO_3^- available for denitrification.

Although the silvopasture treatment did not show high potential N losses, it exhibited the highest CO_2 production rates. This may have been due to C availability in wood chips that provided a C-rich substrate for decomposition (Raich and Schlesinger, 1992). Moisture may also have played a role as the gravimetric moisture of the silvopasture soils appeared to be at ideal levels to maximize CO_2 production (Raich and Tufekciogul, 2000) according to our polynomial regression model.

4c. Clear-Cut

Relative to the forest and silvopasture, the clear-cut experienced a lower level of N-retention with notable losses due to potential leaching and N_2O production. Soils from the clear-cut treatment had moderate rates of H_2O -derived nitrification similar to those of the silvopasture and lower rates of KCl-derived ammonification, possibly due to the presence of slash. Similar results were observed for rates of ammonium leaching in Holmes and Zak (1999) which remained low following a clear-cut in a northern hardwood.

Although wood-chips were applied to the clear-cut site which has the potential to reduce the leaching of ammonium and nitrate, the clear-cut still experienced higher rates of nitrification, especially in the H_2O -derived fraction. This indicates that the nitrified species are potentially more readily available to be removed from the system since they were located in the soil solution rather than on the soil exchange complex. This result is not uncommon and has been well-documented in temperate forest ecosystems across the northeastern United States. Intensive harvesting methods such as clear-cuts cause changes in both soil and aquatic ecosystems with the most pronounced biogeochemical impacts manifesting as increased nitrate concentrations, decreased pH, and increased concentrations of base cations in the soil occurring in the first two

years after harvesting (Homyak et al., 2008). As a result of moderate ammonification rates and elevated nitrification, net N-mineralization rates were the highest among all four treatments.

Soils from the clear-cut treatment also had the highest rates of cumulative N₂O production. This result is also typical of clear-cut areas, as nitrification rates stimulate an influx of nitrate to be denitrified. At the clear-cut treatments at Hubbard Brook, whole-tree removal increased dissolved N₂O concentrations in the soil water by two orders of magnitude as compared to expected values based on atmospheric equilibrium starting approximately six months after harvest (Bowden and Bormann 1986). The clear-cut site at the UNH ODRF also experienced a higher moisture content which may have further supported elevated rates of N₂O production.

4d. Pasture

Similar to the clear-cut, the pasture treatment experienced notable potential N losses and relatively lower N-retention. Unlike the clear-cut where N₂O production may have accounted for a portion of potential N loss, the majority of N-losses in the pasture may occur through leaching. Both KCl and H₂O ammonification rates were low, typical of agricultural systems since NH₄⁺ can usually be readily converted to NO₃⁻ (Di and Cameron, 2002). Because ammonium is readily converted, nitrification rates tend to be elevated as they were in the pasture treatment. Nitrification processes may be further enhanced in the pasture treatment due to significant belowground SOM and root litter inputs from grasses as well as additional nitrogen loading in the pasture from the manure of grazing cows. Grazing pastures leach significantly more nitrate than mowed pastures since grazing animals return 60-90% of ingested N back into the environment as either urine or manure (Di and Cameron, 2002). As a result, moderate to high rates of net N-mineralization may have occurred in pasture soils as organic inputs were converted to inorganic forms. An important distinction between the clear-cut and pasture sites is the rate of N₂O production as compared to rates of nitrification. In clear-cut soils, nitrification rates were elevated, as were rates of N₂O production. However, in pasture soils, high rates of nitrification were not accompanied by similarly high rates of N₂O production. This difference highlights a notable area of potential N losses via leaching. This difference between treatments may be due to the lower moisture content of the soils in the pasture which would support soil conditions conducive to the complete denitrification of NO₃⁻.

5. Conclusion

Our results suggest that a forest-to-silvopasture conversion can be successfully implemented to reduce N losses in the first two years following conversion at the UNH ODRF.

Particular factors which may have supported N retention in the silvopasture treatment were the partial preservation of forest canopy to take up mobilized nutrients and the addition of some woody debris to: 1) increase the C:N ratio; 2) decrease rates of nitrification; and 3) retain moisture while not creating saturated conditions conducive to significant N₂O production.

Suggestions for land managers seeking to increase N retention during land-use conversions include the preservation of trees, application of carbon-rich organic matter, and soil moisture regulation. In a grazing pasture setting, moisture may be regulated by implementing specific

grazing techniques such as the rotation of day and night feeds, block grazing rather than strip grazing, ensuring sufficient pasture coverage, shifting fencing multiple times per day, or planting of longer grass species (Mickan, 2011).

Continued studies of the impacts of land-use changes on soil nutrient retention are necessary to understand the long-term implications of alternative management techniques on soil and greater ecosystem health. Future research projects should focus on monitoring nutrient cycling processes on a multi-year timescale, expanding to other alternative agroforestry techniques, and the future yield of these systems to better inform agricultural management techniques.

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