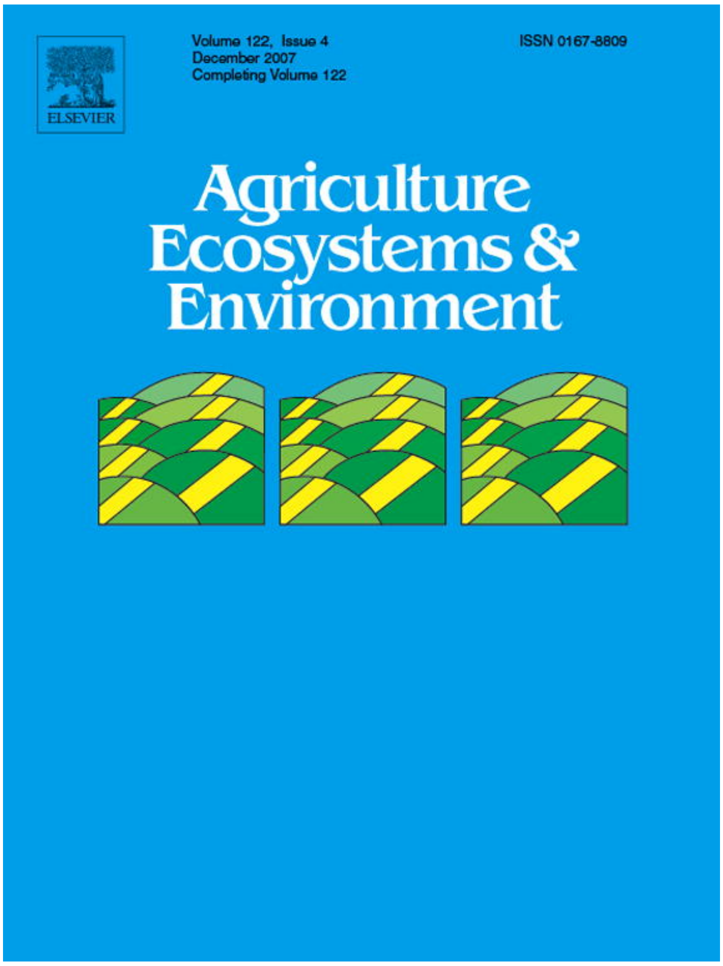
Volume 122, Issue 4
December 2007
Completing Volume 122
ISSN 0167-8809
ELSEVIER
Agriculture
Ecosystems &
Environment

Available online at www.sciencedirect.com
ScienceDirect
Agriculture, Ecosystems and Environment 122 (2007) 471–478
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Assessing ecosystem variance at different scales to generalize about pasture management in southern Wisconsin

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Received 30 January 2007; received in revised form 15 March 2007; accepted 19 March 2007
Available online 25 April 2007

Abstract

Pasture-based agroecosystems are an expanding enterprise in the northcentral U.S., but their structure and function have received little attention. We implemented a manipulative experiment to test pasture management effects on several agroecosystem variables at a university research farm in southcentral Wisconsin. In concert, we established a mensurative experiment across eight grass-based farms in the same region where we measured the same variables under existing land uses. Here we describe how total and relative variation in greenhouse gas fluxes, ground cover, soil arthropods, and soil inorganic N were distributed across nested spatial scales, management treatments, and unexplained realms of these systems. This approach seeks to improve our understanding of pasture management effects on agroecosystem stocks and fluxes, while expanding our inferential space to a wider geographical area. Greenhouse gas fluxes (CH_4 and N_2O) were an order-of-magnitude more variable than soil N pools, ground cover, or arthropod abundances. Most of the variance in these fluxes was at the subsample level, indicating the need for either more sampling chambers per management treatment or an efficient stratification scheme or both. Methane was more variable farm-to-farm than among management treatments within farms, while N_2O showed the opposite pattern indicating that farmers are likely to have more influence on N_2O fluxes via management than they can have on CH_4 fluxes. Variability in arthropod groups and ground cover was rather uniformly distributed across nested spatial scales, with the exception of beetles and harvestmen, which displayed little subsample variability. Soil inorganic N pools were more variable from farm-to-farm than among management treatments, but most variation was at the subsample level. The least variable response was from the greenhouse gas CO_2, which is driven by both auto- and heterotrophic organisms. Calculation of total and relativized coefficients of variation allowed for a standardized comparison of agroecosystem variables possessing disparate units of measure and facilitated conclusions about the generality of results across a broader geographical area than just a single farm.

Keywords: Mixed-effects models; Grassland ecology; Manipulative and mensurative experiments; Pasture agroecosystems

1. Introduction

Livestock grazing of pastures is a growing phenomenon in the upper Midwest. As of 2003, ~23% of all dairy farms in Wisconsin utilized pasture for grazing compared to ~8% in 1993 (Taylor and Foltz, 2006). Grazing dairy livestock in pasture is a stark contrast to confinement livestock production systems where feed is mechanically harvested and transported to a centralized location where livestock spend most if not all of their time. Social and economic benefits of a particular form of grazing management, Management-intensive Rotational Grazing (MIRG), have been demonstrated in many settings (Parker, 1992; Fales et al., 1995; Frank et al., 1995; Paine et al., 1999). More specifically, MIRG, which entails livestock grazing in relatively small paddocks at high densities (150–250 animal units ha^{-1}), but for short durations (1–3 days), has been touted as beneficial to both graziers and grazers (Undersander et al., 1993; Paine et al., 2000). Dairy operators seem

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0167-8809/$ – see front matter
doi:10.1016/j.agee.2007.03.004

to appreciate the transition from spending days harvesting and transporting feed for confined milk cows to maintaining fences, monitoring forage composition, and moving livestock. While the grazing operations typically result in lower livestock production and output, this approach requires lower capital inputs, thereby decreasing the economic risk and increasing the flexibility and profit of the individual dairy farmer (Frank et al., 1995).

While MIRG's benefits for agronomic production are increasingly well established, its ecological consequences remain mostly anecdotal, with frequent declarations from members of the grazing community that MIRG is better for the environment than annual cropping systems and confinement operations with respect to soil erosion, C sequestration, nutrient retention, and biodiversity. However, randomized, replicated, and controlled experiments to support these claims have not been conducted. Moreover, Ostrom and Jackson-Smith (2000) found that a large percentage of grass-farmers claiming to use MIRG, actually employ grazing practices more similar to continuous or extensive grazing, where animals are moved infrequently, if ever, over a larger pasture. This phenomenon seems common amongst beef cattle operators of southwestern Wisconsin as well, but data for this sector do not exist.

We were interested in understanding how pasture management affects the structure and function of perennial grassland agroecosystems along a gradient of management intensities in this region. We devised a manipulative experiment at a research station comparing several ecosystem variables under MIRG, continuous grazing (CONT), harvesting grass for hay (HARV), and grassland removed from agronomic production (NONE). However, concern about the generality of our results led us to conduct a mensurative experiment (sensu Hurlbert, 1984) where similar management "treatments" to those applied in our manipulative experiment were located on eight grass-based farms in southcentral Wisconsin. Response variables for both the manipulative and mensurative experiments included arthropod abundances, vegetation structure, net N mineralization in soils, and greenhouse gas fluxes.

Many have promoted a focus on variance rather than averages (Landres et al., 1999; Thrush et al., 2000; Benedetti-Cecchi, 2003). Here we describe how total and relative variation in response variables were distributed across nested spatial dimensions of these systems. This information should: (1) improve our ability to determine treatment effects in future work by showing us which scales to allocate costly sampling effort, (2) allow us to assess the generality of results by comparing variances between manipulative and mensurative experiments, (3) compare results from many agroecosystem components possessing disparate measurement units, and (4) help us understand the spatial scale at which different parts of the agroecosystem are more or less sensitive to pasture management.

2. Methods

2.1. Manipulative experiment

In June 2005 we implemented a Randomized Complete Blocks Design (RCBD) with three blocks and four management treatment levels: MIRG, CONT, HARV, and NONE at the Franbrook Farm, a University of Wisconsin

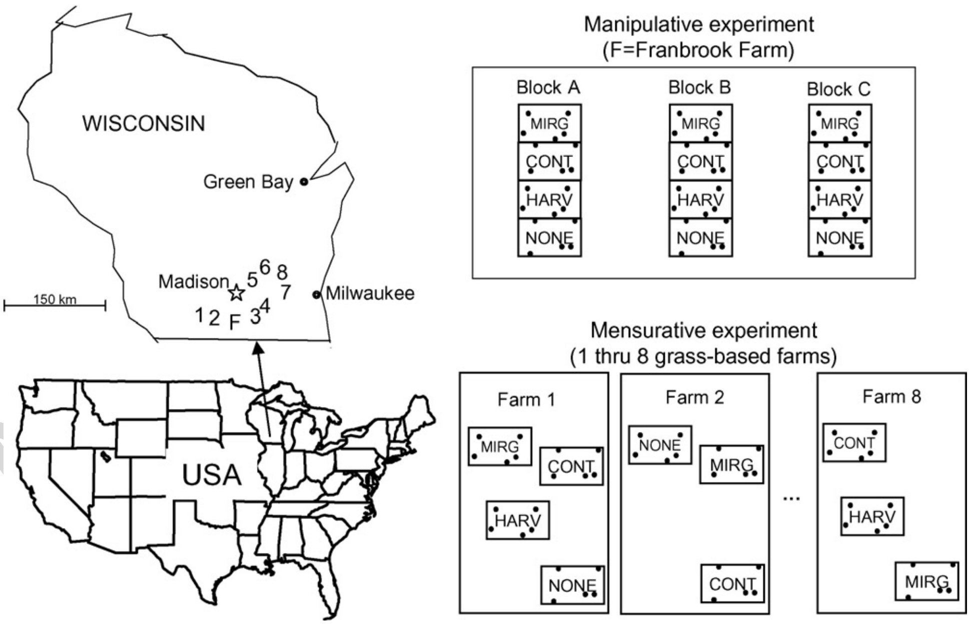

Fig. 1. Experimental layout at the manipulative experiment (Franbrook Farm) and the mensurative experiment (eight farms). On producer farms, management treatments (i.e. MIRG, CONT, HARV, & NONE) could not be randomly assigned and were not always available resulting in an unbalanced design. Dots within management areas represents random location of subsamples, which were an additional source of variability.

research property located 25 km S of Madison, WI, USA (Fig. 1). The CONT plots (~20 ha each) were grazed by separate herds of ~30 cow-calf pairs (1 pair = 1.5 animal unit [AU]) for 28–30 day month^{-1} (i.e. a stocking rate of ~65 AU day month^{-1}). Prior to implementation of the following three treatments, CONT was the land use for all experimental areas on the farm for about 5 years. MIRG paddocks (0.5 ha) were grazed at high stocking rates for 1–2 days (i.e. a stocking rate of 45–90 AU day month^{-1}) and then allowed to rest for the remainder of the month (Undersander et al., 1993). Grazing cycles began in June 2005 and continued through October 2005. To simulate the harvesting of hay (HARV), aboveground biomass was mechanically clipped and removed from ~0.2-ha paddocks in July and September 2005. Finally, we set aside 0.2-ha paddocks for no agronomic management (NONE).

2.2. Mensurative experiment

The mensurative experiment consisted of eight grass-based farms that were known to be practicing MIRG and were located within 50 km of Madison, Wisconsin (USA). With the assistance of the farmers at each farm, we located land-uses that resembled the four experimental treatments in place at the manipulative experiment (Table 1). Farmers used a variety of animals for grazing their pastures, varied the amount of time animals were in the MIRG paddocks, and sometimes mowed paddocks after animals had exited in order to stimulate plant production. Harvesting schedules were not consistent from farm to farm. Likewise, plant communities were often very different from ''treatment'' to ''treatment'' within a farm reflecting a combination of environmental and management differences. For instance, some of our NONE treatments were in topographic depressions dominated by the invasive *Phalaris arundinacea* (Reed canarygrass), while others were dominated by native prairie grasses established for enrollment in the U.S.D.A.'s Conservation Reserve Program. Further, each farm presented environmental variability in soil traits, slope and aspect, climate, land-use history, and human context.

The human context for each farm includes the behavior and values that drives the decision-making processes that shape the farm over time. The eight MIRG farms will all exhibit some degree of variability as a result of these human dimensions. Hence, the mensurative experiment provides researchers the opportunity to explore whether work conducted on research farms is reflective of the range of practices in the ''real world'' and to understand what drives variation in farming practices and results. Moreover, this participatory approach engages the ''consumers'' or ''clientele'' of the research, i.e. the farmers, in the scientific method and the constraints inherent when applying it.

Table 1
Distribution of pasture management ''treatments'' among collaborating farms in the mensurative study

Farm	Grazing animal	County	Pasture management			
			MIRG	CONT	HARV	NONE
1	Beef cattle	Iowa	×	×	×	×
2	Beef cattle	Columbia	×	×	×	×
3	Beef cattle	Columbia	×	×	×	×
4	Dairy cows	Dane	×	×	×	×
5	Dairy cows	Columbia	×	×	×	×
6	Dairy cows	Columbia	×	×	×	
7	Sheep	Dane	×	×		×
8	Sheep	Iowa	×		×	×

2.3. Data collection

Each of the ecosystem responses discussed below were collected several times during the 2005 growing season. However, for the analyses discussed herein, we used only a cross-section of the data taken from late summer/early fall (depending on the variable) to eliminate additional complexity that would be introduced by analysis of repeated measures (Piepho et al., 2004).

2.3.1. Greenhouse gases

We used vented, static chambers to sample greenhouse gas fluxes between the atmosphere and the terrestrial environment (Livingston and Hutchinson, 1994). In each treatment plot, eight circular 25.4-cm diameter × 25.4-cm deep PVC collars were installed into the ground approximately 5 cm below ground surface. Vegetation was first hand clipped to 10-cm stubble height and removed to facilitate chamber installation. In an effort to reduce disturbance of the sample area, trampling was minimized during the installation of the chambers and during the sampling period. A 30-min lag period following installation allowed equilibration of the soil atmosphere.

Sampling began with the fitting of 20-cm diameter × 12-cm deep PVC hats over the previously installed collars. The PVC hats were fitted with a 2-mm diameter vent and a septum for syringe insertion. Immediately following installation of the hat, gas was extracted (t_0) using a 30-ml nylon syringe and a 23-gauge needle, and the procedure was repeated on the remaining collars. Extractions were again taken at 30-min (t_{30}). Gas samples were loaded into 30-ml glass vials fitted with 2-cm rubber septa. Field standards were collected, which consisted of ambient air and gas standards (10 ppm N_2O, 1000 ppm CO_2 and 10 ppm CH_4) to assess potential storage degradation prior to analysis. Vials were transported to UW-Madison where samples were analyzed by gas chromatography for CH_4 using a flame ionization detector (Shimadzu GC-14B, Shimadzu Analytical and Measuring Instruments Division, Kyoto, Japan). Hourly fluxes were determined as twice the difference between t_{30} and t_0 concentrations. Constant and linear fluxes were assumed (Holland et al., 1999).

2.3.2. Inorganic soil N

We removed five 5-cm diameter soil cores from the surface 15-cm in each treatment plot. Cores were labeled and placed into a cooler that was returned to UW-Madison where soils were stored at 4 °C until processed for inorganic soil N assay as described in Robertson et al. (1999). Roots and rocks were removed via hand homogenization. Ten grams of soil were weighed out in duplicate: one subsample for gravimetric water content determination (24 h at 105 °C) and one subsample for immediate extraction in 2 M KCl. Extracts were frozen prior to colorimetric NH_4^+ (method #12-107-06-2-A) and NO_3^- (method #12-107-04-1-B) determination on the Lachat QuikChem flow injection analyzer (Lachat Instruments, Milwaukee, WI).

2.3.3. Ground cover

At each treatment plot we walked five 1-cm × 20-m belt transects where the number of fecal pats were counted in various diameter classes (0–5, 6–10, 11–20, >20 cm). Total cover of fecal pats was calculated by calculating the summed area of all fecal pats and dividing by the area of the belt transect. In the same general area as the fecal pat surveys, we arbitrarily located five 20-cm × 50-cm quadrats where the percent cover of grasses and forbs were visually estimated.

2.3.4. Arthropod abundances

To examine differences in soil arthropod communities under the different management treatments, arthropods were collected with pitfall traps in all treatments. Traps were constructed by digging holes in the ground and sinking 400-ml plastic cups such that the upper lip was flush with the ground. Propylene glycol (50%, 50 ml) was added to each cup to preserve infalling organisms. A hardware cloth (3-cm × 3-cm openings) cover was placed over each pitfall and affixed to the ground with long nails to prevent entry of small mammals and vandalism by raccoons. Finally, as a rain cover we attached a plastic plate (30-cm diameter) to short wooden stakes at 5 cm over each pitfall trap. Ground crawling arthropods could move freely into the trap with this design. At Franbrook, we placed five pitfall traps in each of the treatments (MIRG, CONT, HARV, NONE). At each on-farm site we placed 4 traps in each MIRG, HARV and NONE areas where available. CONT areas were generally not sampled on farms because cattle would destroy the traps. Traps were established for 2 weeks starting 16 August 2005. Trap contents (arthropods) were filtered into collection vials and stored in 70% ethanol. In the laboratory, samples were sorted to order and all insects counted.

2.4. Data analysis

We used linear mixed effects models (S-plus v. 6.0, Insightful Corp., Seattle WA) to fit random effects (variance parameters) around a single fixed effect–the grand mean or intercept (β_0):

$$y_{ijk} = \beta_0 + b_i + b_{j(i)} + b_{k(ij)} + \varepsilon_{ijk}$$

Table 2
Analogous levels of organization between manipulative and mensurative experiments

Manipulative (Franbrook Farm)	Mensurative (eight farms)
Block-to-block	Farm-to-farm
Management (randomized)	Management (not randomized)
Subsample	Subsample
Residual	Residual

In addition to β_0 and the overall error term ε_{ijk}, we specified three random effects variance parameters to account for the variability at the *subsample* level [$k(ij)$], which was nested within *management treatments* [$j(i)$] nested within *farms* or *blocks* (i), depending on whether data were from the manipulative or mensurative experiments, respectively (Table 2). We performed these analyses for the combined manipulative and mensurative datasets to understand relative sources of variability. The same analyses were then applied to greenhouse gas fluxes from the manipulative and mensurative datasets separately to demonstrate how the approach can be useful for assessing the generality of findings from the research station.

Random effects parameter estimates are the standard deviations for each source of variation (Pinheiro and Bates, 2000). To compare the response of different ecosystem measurements to different sources of variation we standardized these parameter estimates by dividing by the grand mean for a given response variable, i.e. the coefficient of variation (CV%). With this metric we could compare variance components within a given response variable and variation among multiple responses-even those with different measurement units. We then relativized variability to create $CV\%_{rel}$ by dividing the CV% for each category by the sum of all CV% for a given ecosystem component.

3. Results and discussion

Our goal was to combine the findings of manipulative and mensurative studies to broaden the generality of findings from the research station. With our approach we were able to study how variation in various ecosystem components was partitioned among space, management, and residuals. This analysis helped us understand that fluxes of two of the three greenhouse gases were the most variable of our ecosystem components while the third (CO_2) was the least variable overall. We examined the effects of different sources of variation on multiple agroecosystem measurements simultaneously by comparing the total CV% (i.e. the R-hand y-axis values in Fig. 2). Nitrous oxide and CH_4 fluxes exhibited variability that was an order-of-magnitude greater than soil inorganic N pools, which had total CVs > 300%. By comparison, ground cover and arthropod abundances were more constrained with CVs ranging from 147 to 275%.

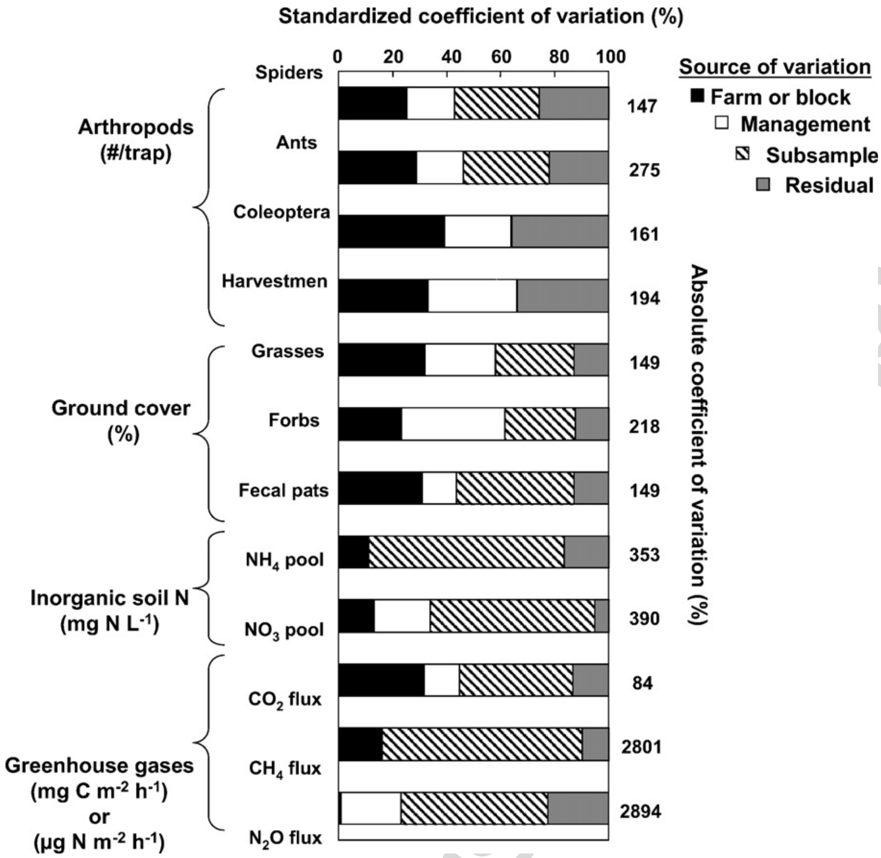

Fig. 2. Variability in SW Wisconsin pasture agroecosystem measurements (combined manipulative and mensurative datasets). The total coefficient of variation (CV%) is the standard deviation/grand mean for a given response variable. Relativized CV% sets total CV% to 100 so that relative contributions of each source of variation can be compared within and across variables.

3.1. Relative variability spurs hypotheses and helps us interpret management influences

Within the arthropod categories (now examining $CV\%_{rel}$ in Fig. 2) subsample variation was relatively high for spiders and ants, but beetles and harvestmen were more variable at the farm/block level with little or no subsample variation. Variation was rather evenly distributed amongst the four nested sources for grasses and forbs, but less was attributable to management for fecal pat cover because HARV and NONE treatments always had zero fecal pat cover—there are no livestock in these pastures. Residual error was relatively low for the ground cover group as it was for NO_3^-. While large subsample level variation was observed for both NO_3^- and NH_4^+, the latter showed little influence of management. Hence, NH_4^+ was little affected by management while NO_3^- pools were. This may reflect the fact that NH_4^+ is produced via breakdown of soil organic matter, which is strongly linked to site characteristics like soil texture and moisture regimes. Nitrate pools, on the other hand, stem not only from nitrification, but also may come directly from transformation of urea-N in livestock urine.

The small amount of subsample variation within management treatments for beetles and harvestmen compared to spiders and ants (Fig. 2) suggests a greater degree of patchiness in the distribution of these latter taxa. Rather than merely attribute this to random nuisance variation, however, we can use the information on the variation itself to generate hypotheses regarding what may be influencing one group of organisms and not another. For instance, ants and spiders may be more sensitive to small-scale micro-topographic variation in plant composition, litter accumulation, or organic matter distribution that may alter their spatial distribution within a plot (Langellotto and Denno, 2004; Nash et al., 2004). In contrast, the larger body size of beetles and harvestmen is likely correlated to greater dispersal capabilities, allowing these groups to experience a more fine-grained environment and therefore show lower subsample-level variation.

3.2. Generalizing from the research station to pasture agroecosystems

To this point we have interpreted variance from the combined manipulative and mensurative experiments. To generalize findings from the former, we examined variances separately for the two responses with the highest overall CV%, N_2O and CH_4 fluxes. With respect to $CV\%_{rel}$, the manipulative and mensurative datasets had almost identical patterns in N_2O fluxes (Fig. 3). Block-to-block and farm-to-

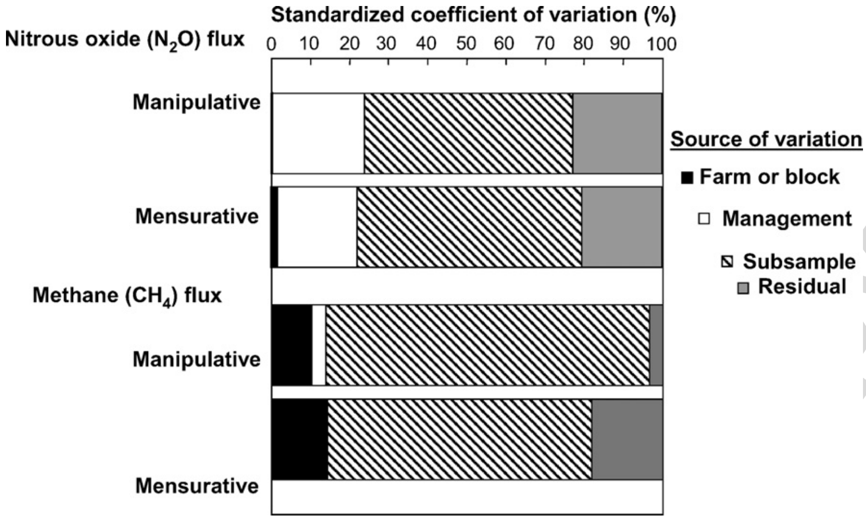

Fig. 3. Variability of nitrous oxide (N_2O) and methane (CH_4) fluxes at manipulative (Franbrook Farm) and mensurative (eight farms) experiments. The total coefficient of variation (CV%) is the standard deviation/grand mean for a given response variable. Relativized CV% sets total CV% to 100 so that relative contributions of each source of variation can be compared within and across variables.

farm variation was negligible relative to management, subsample, and residual variation. Alternatively, for CH_4 fluxes farm-to-farm and block-to-block variability was more influential than management (Fig. 3). Subsample variation was extremely large relative to other variance sources for both CH_4 and N_2O.

Production of both gases is largely controlled by redox conditions (Paul and Clark, 1996). Methane is produced in soils only under very low redox conditions (Schlesinger, 1997; Whalen, 2005) and typically diffuses into soil from the atmosphere when soils are not saturated (King, 1997; Robertson et al., 2000). Therefore, we would expect site differences – soil texture, topography, micro-climate, etc. – to affect CH_4 fluxes, whether they were positive or negative, most of the time. Alternatively, N_2O is a byproduct of denitrification under anaerobic conditions, but is also produced to a lesser extent during nitrification, an aerobic process that occurs in dry soils (Firestone, 1980; Firestone and Davidson, 1989). Here, not only site conditions (i.e. C and O_2 availability), but also anything affecting NO_3^- concentrations, such as urine, feces, fertilizer, and defoliation, will influence N_2O fluxes (Bouwman et al., 1993; Allen et al., 1996; Bouwman, 1996; Velthof et al., 1996; Veldkamp and Keller, 1997; Anger and Hoffmann, 2003).

The similar CV% between the manipulative and mensurative experiments indicates that our management at Franbrook is more or less mimicking on-farm pasture management. Hence, an assessment of management effects at our experimental farm would likely be reflective of effects of management across farms in the area. Though not a truly random sample of farms from southern Wisconsin, the eight farms we selected cut across significant variability in pasture management (e.g. livestock type, rotational frequency, fertilization regimes). Any significant effects determined from the mensurative experiment would be considered very strong effects indeed as they would constitute a signal through much noise.

3.3. *Variance components inform sample allocation for future studies*

Most of the variability in N_2O and CH_4 fluxes was at the subsample level, which confirms what is well known about trace gas dynamics in general, that they are inherently variable at very small spatial scales (Firestone, 1980; Robertson, 1989; Flessa et al., 1996; Jarvis, 2000). Hence, the variance assessment tells us that for better understanding of these fluxes we should spend less time and effort replicating the experiment from farm to farm and more trying to constrain variability within management treatment plots. For instance, we may need to stratify by microtopographic features within a management plot by choosing to randomly locate chambers in depressions, hummocks, or flat areas. On the other hand, farm-to-farm variability was a larger influence for CH_4 fluxes indicating that we should seek an understanding of the particular soil types, textures, and overall farm management to stratify and constrain this response variable.

3.4. *Complementary experimental approaches promoted dialogue between scientists and farmers*

An additional benefit of the experimental approach described here is that it increases interactions between academic researchers and individual farmers by driving the scientists into ‘‘real world’’ management scenarios to validate research station work. These farmers are the most likely beneficiaries and critics of this work. Importantly, they typically possess and are willing to share knowledge and expertise about management that should improve management treatment applications at research stations. As such, we expect to learn more about how the controlled manipulations we are imposing at the research station relate to what is actually being practiced by farmers, thereby elucidating the nature of the relationship between findings from each.

3.5. Conclusions

Our approach enabled us to conduct an intensive study at a single site, where we can feasibly sample on a weekly/monthly basis, while extrapolating our results to a wider region, where appropriate. Typically, this extrapolation is done *ad hoc* in the discussion sections of papers, but we incorporated it explicitly into our analyses. It is important to note that the variation introduced by repeated sampling in time could easily be incorporated into the mixed-effects modeling (Piepho et al., 2004). Furthermore, the analysis of mixed-effects model random effects allowed for a standardized comparison of agroecosystem variables possessing disparate units of measure and facilitated conclusions about the generality of results. Specifically, we found that:

- We should reallocate time and effort to reducing subsample error, especially with N_2O and CH_4 fluxes.
- N_2O and CH_4 fluxes were much more variable overall than arthropod abundance, ground cover, and inorganic soil N.
- N_2O fluxes were more sensitive to management than location, but the opposite was observed for CH_4 fluxes.
- Variability in arthropod groups and ground cover was rather uniformly distributed across nested spatial scales, with the exception of beetles and harvestmen, which displayed little subsample variability.
- Soil inorganic N pools were more variable from farm-to-farm than among management treatments, but most variation was at the subsample level.
- The least variable response was from the greenhouse gas CO_2, which is driven by both auto- and hetero-trophic organisms.

Acknowledgements

Comments by John Battles and two anonymous reviewers greatly improved this manuscript. Thanks to the eight collaborating farmers and the Franbrook Farm manager, Ralph Siegenthaler, who all provided land, labor, and insights for this study Thanks to Gary Oates, Jon Bleier, John Albright, Liz Froelich, Jesse Rucker, Mark Fanning, Ashley Bennett, Genya Erling, Devin Wixon Keller, Julie Doll, Ellen Hamingson, Anna Soper, Laura Dyer, Satya Miranpuri, Meagan Broman, Scott Myers, and Joe Kaser for data collection. This work was funded by a U.S.D.A. Special Grant to the University of Wisconsin's Center for Integrated Agricultural Systems, a UW-College of Agriculture and Life Sciences Interdisciplinary Hatch Grant, the UW Graduate School, and the Grazing Lands Conservation Initiative.

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