Comparing the nitrogen use efficiency of a permaculture livestock farm in Albemarle County, Virginia to conventional farms

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Abstract

Sustainable farming is one proposed method to reduce nitrogen pollution incurred by farming, but reactive nitrogen loss rates from sustainable farming vary and require further study. The overarching objective of this study was to determine how the nitrogen use efficiency of a permaculture livestock farm compares to that of conventional farms. Two comparison metrics were used: farm nitrogen budgets and virtual nitrogen factors.

For the first comparison method, a farm nitrogen budget was constructed for Timbercreek Organics Farm (TCO), a permaculture livestock farm in Albemarle Country, Virginia. The budget found that the total intended farm N inputs (e.g., feed, legume biological nitrogen fixation, purchased livestock) increased from 32 kg N ha^{-1} yr^{-1} in 2012 to 49 kg N ha^{-1} yr^{-1} in 2013. The intended farm N outputs (e.g., meat products, slaughter by-products) tripled from 5 to 14 kg N ha^{-1} yr^{-1}. The overall TCO farm nitrogen use efficiency (NUE) doubled from 14% in 2012 to 28% in 2013. When compared to conventional farms from the literature, the 2013 TCO NUE (28%) was comparable or exceeded that of beef farms, but the TCO NUE was less than that of conventional pork, poultry, and layer farms. The TCO N surplus (difference between nitrogen inputs and outputs) at TCO was 2-10 times lower than conventional farms, suggesting that TCO has a lower local environmental impact than conventional. TCO required more 15-60% more time and 37-720% more land area to produce meat and animal products than conventional farms, although beef production at TCO utilized 95% less land than conventional.

For the second comparison method, virtual nitrogen factors (VNF) were used to compare the nitrogen efficiency of a permaculture livestock farm to conventional farms. VNF, which describe the reactive nitrogen lost to the environment per unit of nitrogen contained in a food product, were calculated for beef (0.1), pork (3.6 in 2012 and 2.5 in 2013), poultry (5.7 in 2012 and 4.4 in 2013), and egg (4.0 in 2012 and 5.5 in 2013) production at TCO. The TCO beef VNF was substantially lower than the beef VNF for conventional farms because TCO beef is grass-fed and natural forage inputs were not considered. When considering calculated uncertainty, the TCO pork, poultry, and egg VNF were as efficient as conventional production.

An exploratory field monitoring exercise was conducted between June 2013 and April 2014 to begin studying whether TCO has an influence on the inorganic nitrogen flux in the streams that flow through the property. The highest measured stream water nitrate and nitrite concentration (2.5 mg N L^{-1}) was well below the US EPA drinking water standard for nitrate (10 mg N L^{-1}). On more than half of the 13 sampling events, the flux of inorganic N entering the property exceeded the flux of inorganic N exiting the property. Although more research is needed, a likely explanation for the nitrogen stream inputs exceeding the nitrogen stream outputs is the low TCO N losses per unit area coupled with an on-farm holding pond that is effective for stormwater management.

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1. Introduction

Reactive nitrogen (Nr; defined as all species of nitrogen except N_2) is required in some form by all living systems. Humans consume their usable nitrogen (N) as protein in food. The food production process requires the input of Nr, such as by the addition of fertilizer. However most of the Nr used in the food production process is lost to the environment (Galloway et al. 2007) where it contributes to a series of environmental and human health problems such as smog, acid rain, climate change, eutrophication, stratospheric ozone depletion, and biodiversity loss (Vitousek et al. 2009; Erisman et al. 2008; Galloway et al 2008). The nitrogen cascade magnifies the impact of any created Nr (Galloway et al. 2003). This presents a nitrogen challenge: the use of Nr in food production must be optimized to increase the nitrogen use efficiency and minimize the negative impacts resulting from its use.

Food production, especially meat production, is the largest anthropogenic source of Nr to the environment (Steinfeld et al. 2006, Galloway et al. 2007). Nr is created for the food production process through the production of synthetic fertilizer (i.e., the Haber-Bosch process) and the cultivation of legumes (i.e., biological nitrogen fixation or BNF). This Nr can then be lost to the environment at each stage of the food production process, such as from fertilizer runoff, crop processing waste, livestock manure, and household food waste.

Sustainable agriculture, which has increased in popularity in recent years, is one proposed solution to the environmental damage incurred by food production (Youngberg and DeMuth 2013). First introduced by Wes Jackson, the term “sustainable agriculture” is a broad term describing a variety of farming practices (Jackson 1980). Although definitions of sustainable agriculture vary, one commonly referenced definition by John Ikerd describes sustainable agriculture as “capable of maintaining their productivity and usefulness to society indefinitely.

Such systems… must be resource-conserving, socially supportive, commercially competitive, and environmentally sound" (Duesterhaus 1990). The Food, Agriculture, Conservation, and Trade Act of 1990 (i.e., Farm Bill; FACTA 1990) established the following definition: "the term sustainable agriculture means an integrated system of plant and animal production practices have a site-specific application that will, over the long term:

- Satisfy human food and fiber needs;
- Enhance environmental quality and the natural resource base upon which the agricultural economy depends;
- Make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls;
- Sustain the economic viability of farm operations; and
- Enhance the quality of life for farmers and society as a whole."

Sustainable farming methods recommended by the United States Department of Agriculture (USDA) include ecological insect and weed management, rotational grazing, conservation tillage, use of cover crops, and nutrient management (SARE 2005). Agricultural systems that use a specific set of sustainable practices can be identified by labels like biodynamic farming, grass-based farming, low-input agriculture, natural farming, organic farming, permaculture farming, and precision farming (USDA 2007). Only a few of these systems, such as organic farming and biodynamic farming, have standardized certification systems, some of which are managed by private organizations. The variability in sustainable farming practices can lead to a range of Nr losses, requiring further study to better understand the impact of different management practices (Watson et al. 2002; Vitousek et al. 2009; Seufert et al. 2012).

Permaculture farming is a method of sustainable farming whose name was derived from the term “permanent agriculture” by Bill Mollison in the late 1970s (USDA 2007). This method of farming strives to model the natural environment and promote the cycling of nutrients within the farm, such as by returning manure directly to the field (Mollison 1988). Permaculture farmers endeavor to design a system that is efficient and requires little maintenance as a result of the careful placement of farm elements. The farm landscape is designed with plant and animal functions in mind so that the farm simulates native ecosystem processes (Mollison 1986). The Worldwide Permaculture Network reports that over 1,300 permaculture projects have been registered in their database, although these include some non-agricultural projects like permaculture forestry (Worldwide Permaculture Network 2013). Although many books, magazines, and web resources on permaculture are available (e.g., Mollison 1988, *Permaculture Activist* magazine, the Permaculture Research Institute), peer-reviewed publications are limited. Ferguson and Lovell (2013) conducted a review of permaculture literature in which they determined that most literature on permaculture is found in non-scientific publications. They found 50 journal articles, but many of these articles were not peer-reviewed, did not focus on food production, and did not include an experimental design or statistical analysis. Given the growth of the permaculture farming movement, new research is important to address questions about the efficiency and potential environmental impacts of permaculture farms.

The majority of meat and animal products sold in the United States are conventionally produced. For example, despite rapid growth, organic food products still only made up 4% of total food sales in the US in 2012; meat and animal product sales were less than 25% of all organic food sales (Greene 2013). Conventional farms typically have higher yields than organic farms. In a review of 91 studies, Badgley et al. (2006) reports that organic grain and vegetable yields are about 10% lower than conventional in food production in developed countries. However, Seufert et al. (2012) report greater variability in the yield comparison, finding that organic crop yields are 5-34% lower than conventional crop yields. Badgley et al. (2006) also considered meat and animal products; on average, the yield for meat and animal products was about 5% less than conventional.

Conventional meat production is becoming more concentrated into fewer, larger production facilities. For example, less than 5% of beef cattle feed lots have over 1,000 head but make up over 80% of fed cattle (USDA 2013). An average chicken production building of 1000 m^2 can hold 15,600 chickens (Castellini et al. 2006). For over 50 years, 85% of broiler production in the United States has been through production contracts in which a contractor or poultry processor provides the chickens and feed while a grower provides the broiler house and labor (USDA 2013). Conventional pig production generally uses confinement to allow for year-round production (USDA 2013). Pig production facilities have decreased in number by over 70% over the last 15 years as existing facilities have grown larger.

Although production rates of conventional farming are high per unit area, the concentration of livestock has had consequences. The conventional production system requires substantial external inputs of nutrients and energy and leads to significant quantities of manure, which can contain pathogens and is often treated as waste (Kleinman et al. 2012). To increase growth rates and keep livestock healthy, livestock are often fed antibiotics and hormones, which can then be released to the environment. Animal production uses about 80% of all antibiotics produced in the US; once in the environment, these antibiotics could contribute to the development of antibiotic-resistant bacteria, which could compromise the effectiveness of existing antibiotics in treating human health (Lee et al. 2007). The large volume of hormones excreted by livestock has been shown to lead to both the decline of some species and sex changes in fish. The high production rates of conventional farming methods feed the growing global demand for meat (Steinfeld et al. 2006), but the environmental and human health consequences must also be considered.

Given the current global nitrogen pollution problems caused by food production, the nitrogen use efficiency of food production must be increased (Andrews & Lea 2013). Farms with high nitrogen use efficiency convert more of the nitrogen invested in the food production process into the final food product. Two metrics that can be used to directly compare the nitrogen use efficiency of different farms are farm budgets (section 1.1.1) and virtual nitrogen factors (section 1.1.2). Because sustainable farming has been suggested as one way to reduce pollution from food production, understanding the nitrogen use efficiency of sustainable farming methods is an important step in determining how to produce food with less nitrogen pollution.

1.1. Comparing farm nitrogen use efficiencies

The nitrogen use efficiency of permaculture and conventional farms can be compared through two methods: a farm nitrogen budget and virtual nitrogen factors.

1.1.1. Farm budgets

Farm nitrogen budgets quantify the nitrogen entering (i.e., inputs) and leaving (i.e., outputs) a farm (Leip et al. 2011; Watson & Atkinson 1999). The overall goal of a farm N budget is to understand the efficiency with which a farm uses nitrogen. These budgets can then be used to educate farmers, identify points of inefficiency, and even inform policymakers (Schröder et al. 2003). Farm N budgets also can be used to compare the efficiency of farms that vary in area and production level (Sassenrath et al. 2012). Farm N budgets range in complexity, but can generally be described with a set of three budget types with an increasing level of complexity (Table 1). Generally the least complex budget (e.g., farm-gate budget) considers the farm to be a black box and only includes overall inputs and outputs. A second type of budget (e.g., soil budget) then incorporates processes at the landscape or soil surface scale, such as nutrient inputs of fertilizer to the soil surface and crop uptake of nutrients. The third and most complex budget (e.g., soil system budget) adds nutrient cycling at the soil scale, such as changes in storage and the impact of microbial processes. This complex budget is typically the only kind that can allocate nutrient losses to specific loss pathways (e.g., leaching, denitrification), although some exceptions exist.

Table 1. Types of farm budgets, showing three different levels of farm budget complexity and a description of each level of farm budget complexity.

Authors	**Farm budgets:** **Least complex →→→→→→→→→→→→→ Most complex**		
Budget description	Simple budget that considers overall inputs and outputs to the farm property	Moderately complex budget that also accounts for some soil processes, such as nitrogen fixation	Complex budget that considers all soil processes and links nutrient losses to specific loss pathways
Watson & Atkins (1999)	Economic Input:Output budget	Biological Input:Output budget	Transfer:Recycle: Input:Output budget
Oenema et al. (2003)	Farm-gate budget	Soil budget	Soil system budget
Leip et al. (2011)	Farm budget	Land budget	Soil budget

Multiple metrics can be used to describe and compare farm N budgets (Table 2). Inputs include any N entering a farm property, such as fertilizer, feed, and atmospheric deposition (Oenema et al. 2003). Outputs include any N leaving a farm, such as nitrogen contained in crops, animal products, and manure. These components include both the N that is a direct result of farm activities (e.g., fertilizer inputs) as well as N that is not directly related to farm activities (e.g., atmospheric deposition). These farm N flows can be categorized into intended and unintended inputs and outputs to describe whether the N inputs and outputs are intentionally directed towards farm production. Intended inputs and outputs are generally easier to measure directly, whereas unintended inputs and outputs can vary more with space and time. Unintended outputs can be calculated as the difference between total inputs and intended outputs. With this method, the fate of the unintended outputs is not clear; that nitrogen may be lost to the environment outside of the farm, denitrified, or stored in the farm's soils or vegetation. These unintended outputs to the environment (or the difference between total inputs and intended outputs) can also be defined as the nitrogen surplus or nitrogen balance (Oenema et al. 2003, Leip et al. 2011). Another important metric to describe and compare farm N budgets is the farm nitrogen use efficiency (NUE), which is equal to the intended outputs divided by the intended inputs. This metric describes how much of the nitrogen invested into farm production actually makes it into the intended food products (i.e., the intended outputs).

Table 2. Metrics for a farm nitrogen budget: Specific farm inputs and outputs (intended and unintended) and nitrogen efficiency metrics to describe and compare overall farm budgets (nitrogen surplus, nitrogen use efficiency).

Specific inputs and outputs		
Metric	**Intended**	**Unintended**
Inputs	Purchased feed, purchased fertilizer, purchased livestock, purchased bedding material, biological N fixation by legumes, energy use	Atmospheric deposition
Outputs	Exported meat and animal products, slaughter by-products	Atmospheric volatilization, leaching, runoff, denitrification, storage in soil and vegetation
Nitrogen efficiency metrics		
Nitrogen surplus	N surplus = Intended inputs – intended outputs	
Nitrogen use efficiency (NUE)	NUE = Intended outputs / intended inputs	

1.1.2. Virtual nitrogen factors

Virtual N factors (VNF) describe the amount of reactive N lost to the environment during the food production process per unit of N consumption by food type (Leach et al. 2012). Virtual N includes any reactive N used in the food production process that is not contained in the final consumed food product; this virtual N is all released to the environment. These factors allow for the upstream N losses of a given food product to be estimated. Leach et al. (2012) developed virtual N factors that describe conventional food production in the United States for major food categories (Figure 1). Similar to a life cycle analysis, VNF consider the N lost at each stage of the food production process, including fertilizer application, crop processing, manure waste, and food waste. These factors use a consistent and comparable methodology to describe Nr losses during the food production process for any food type. Therefore, new virtual N factors can be developed for specific food production methods or for other regions/countries and can then be compared to those available for conventional production in the United States.

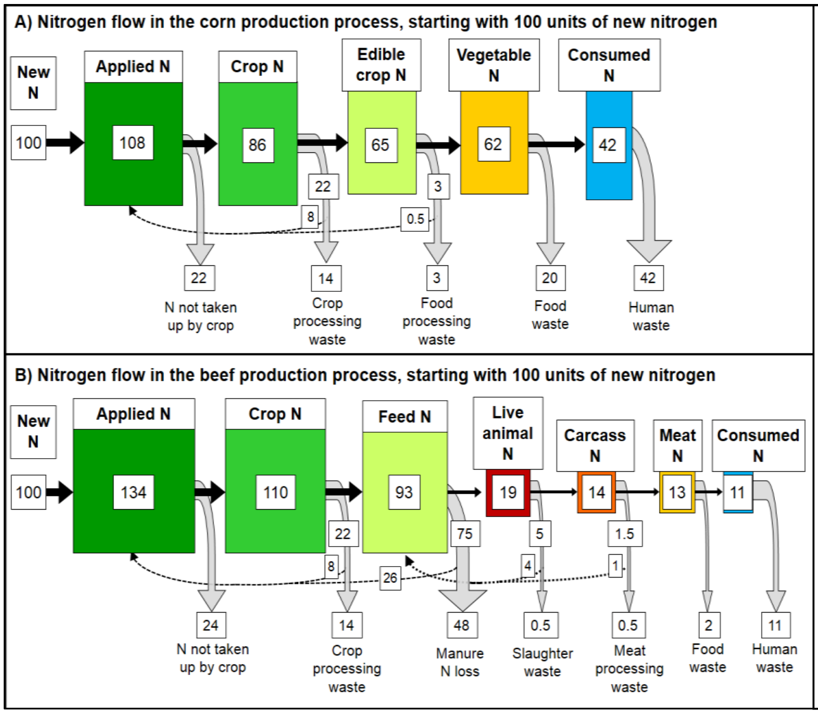


Figure 1. Virtual nitrogen factors: Reactive N flow in conventional (A) corn and (B) beef production processes in the United States, each starting with 100 units of new nitrogen. *Notes:* 1) The colored boxes show the available Nr at each stage of the food production process, with their areas reflecting the magnitude of Nr; 2) The black arrows show Nr that makes it to the next stage; 3) The start of the grey arrows is the total Nr wasted, and the end of the grey arrows is Nr lost to the environment; 4) The dotted arrows show Nr recycled, which is subtracted from Nr wasted to find Nr lost to the environment; and 5) The diagrams show the summation of multiple iterations of the calculations; the iterations determine how recycled Nr is distributed throughout the system. *Leach et al. 2012.*

1.2. Research objectives

The overarching objective of this study was: Determine how the nitrogen use efficiency of a permaculture livestock farm compares to that of conventional farms. This objective was addressed through the first two research questions (below). The third research question then begins to characterize the impact of a permaculture livestock farm on inorganic nitrogen in surface waters on that farm.

(1) Farm nitrogen budget:

   a. How does the farm nitrogen budget of Timbercreek Organics (a permaculture livestock farm) compare to that of conventional livestock farms?

(2) Virtual N factors:

   a. What are the virtual nitrogen factors (i.e., food production nitrogen losses) for pig, beef-cattle, poultry, and egg production at Timbercreek Organics?
   b. How do these losses compare to the conventional farm virtual nitrogen factors (i.e., food production nitrogen losses) in the United States?

(3) Exploratory field-monitoring exercises at Timbercreek Organics:

   a. Does Timbercreek Organics have an influence on the inorganic nitrogen (NO_3^- + NO_2^- and NH_4^+) concentration in the streams flowing through the property and on the nitrogen fluxes from the property?

2. Methods

2.1. Research site

The permaculture farm studied in this analysis was Timbercreek Organics (TCO), which is a livestock farm located in Albemarle County, Virginia (38.1° N, 78.6° W, elevation of 160 m;

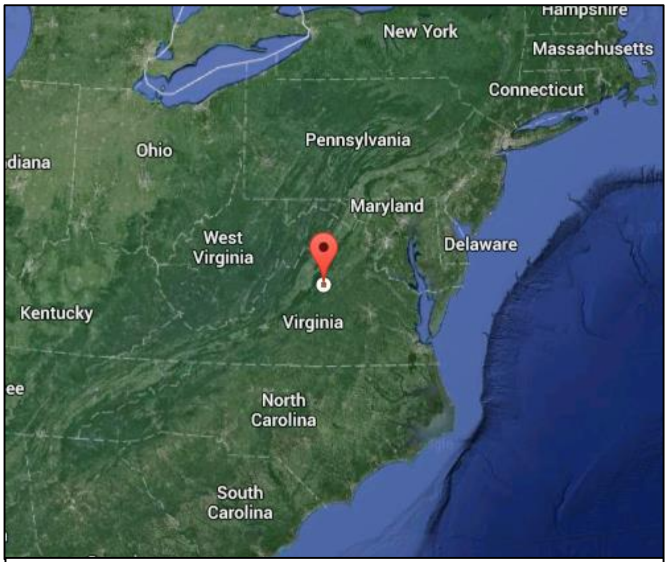


Figure 2. Map of the eastern United States showing the location of Timbercreek Organics Farm in Albemarle County, Virginia (38.1° N, 78.6° W, elevation of 160 m).

Figure 2). This region has an average annual temperature of 13.1°C, and the average seasonal temperature ranges from 2.8°C to 23.2°C (NOAA 2014). Total annual average precipitation is 108 cm.

Totaling 165 ha in area, TCO is made up of 49 ha pasture, 65 ha forest, 32 ha silvopasture (mixed pasture and forest), and 19 ha other land uses (e.g., residential). The farm property is located in a rural residential area; the surrounding property is predominantly residential land and farmland. The soils at TCO are dominated by loam (80%) and clay loam (20%) (USDA-NRCS 2010).

TCO opened in 2010; this study focuses on production in 2012 and 2013. Major farm purchases include feed, livestock, and bedding; the major farm products are beef, poultry, pork, and eggs (Table 3). Between 2012 and 2013, feed purchases increased by 120% and farm production increased by 200%. In 2012, TCO raised about 8,000 chickens, 150 pigs, 120 beef cattle, 60 turkeys, and 800 laying hens (Zach Miller, personal communication). In 2013, TCO raised about 8,000 chickens, 150 beef cattle, 75 turkeys, 600 ducks, and 800 laying hens. Because management practices are similar and separate meat weights were unavailable, the three meat birds (broiler chickens, turkeys, and ducks) were combined into a single poultry category.

Table 3. Timbercreek Organics Farm: Major products purchased or sold in 2012 and 2013 based on farm records (Zach Miller, personal communication).

	2012	**2013**	**% Change**
Feed			
Corn (kg)	60,500	136,640	126%
Soybeans (kg)	35,150	74,650	112%
Oats (kg)	6,840	13,640	99%
Alfalfa pellets (kg)	1,010	2,520	150%
Fishmeal (kg)	2,270	2,410	6%
Kelp (kg)	910	1,810	99%
Hay (no. bales)	120	190	58%
Other			
Bedding (kg)	15,800	26,330	67%
Purchased livestock			
Pigs (number)	150	80	-47%
Cattle (number)	100	0	-100%
Poultry (number)	8,000	8,000	0%
Layers (number)	800	912	14%
Farm products			
Pork (kg)	3,720	11,070	198%
Beef (kg)	4,990	22,830	358%
Poultry (kg)	4,540	11,960	163%
Eggs (number)	72,000	133,320	85%

TCO employs managed intensive rotational grazing patterns, a common practice of permaculture farming (Figures 3, 4). Beef cattle are moved to new plots of land daily, and the land is then given at least 4-6 weeks to recover before being grazed again (Table 4). The diet for the beef-cattle consists almost entirely of grasses during grazing; the diet is only supplemented with hay (both purchased and produced on-farm) in the winter when less vegetation is available. Broilers or meat chickens spend four weeks in a brooder, followed by four weeks in mobile chicken coops. These coops are 12 feet by 12 feet and hold about 60 broiler chickens. These coops have fencing so that they are open to the air and the chickens have direct access to the ground. The broiler coops move 12 feet daily. The layers move to a different field on the farm daily in a larger mobile hen house to prevent nesting, but they are allowed to roam freely. The chickens eat grass and insects; their diet is regularly supplemented with grain feed. Other poultry types (e.g., ducks, turkeys) are also occasionally raised at TCO; their grazing patterns and diets follow those of the broilers. The pigs graze in the forest, and they are moved once a month. The pigs' diet consists of grain feed and foraged acorns. All livestock types except the broilers are raised year-round; the broilers are only raised from March through October. The rotational grazing patterns at TCO strive to cycle nutrients through the farm and allow the vegetation adequate time for recovery between grazing events.

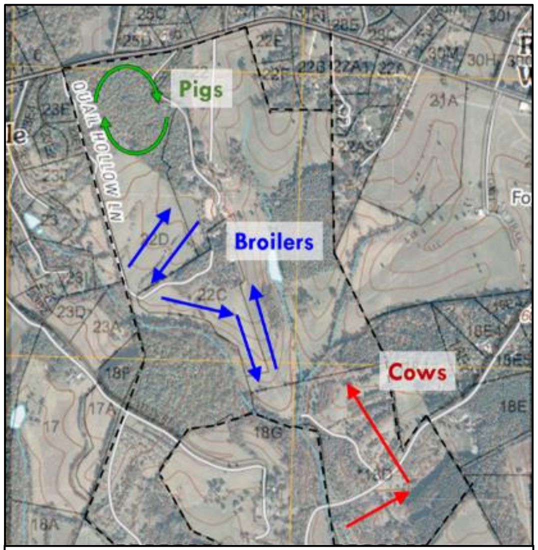


Figure 3. Example rotation grazing pattern at Timbercreek Organics Farm. Farm property is outlined in black dashed line with county land parcels outlined in a solid line. Example livestock grazing rotation pattern for pigs (green line arrows), broilers (blue arrows), and cows (red arrows). Layers are not depicted because they are moved far distances daily to prevent nesting.

Figure 4. Livestock at Timbercreek Organics Farm in Albemarle Country, Virginia: cattle, which are moved daily through the pasture; pigs, which are moved once a month through the forest; broilers, which are moved daily across the pasture in mobile chicken coops, and layers, which are moved daily through the pasture in a large mobile hen house.

Table 4. Timbercreek Organics (TCO) livestock types, grazing patterns, feed sources, and lifespans. Source: Zach Miller (farmer at Timbercreek Organics), personal communication.

Livestock type	**Grazing**		**Diet**		**Lifespan**	
	Rotation frequency	**Location**	**Purchased feed**	**Natural sources**	**Age at TCO arrival**	**Age at slaughter**
Pigs	Monthly	Forests	Grain feed	Acorns	6 weeks	8 months
Cattle	Daily	Pasture	Hay	Grass	Born on-farm and purchased at 6-8 months[a]	2 years (for meat) or 8 years (for breeders)
Broilers	Daily	Pasture	Grain feed	Insects, grass	1 day	8 weeks
Layers	Daily	Pasture	Grain feed	Insects, grass	6 months	2.5 years

[a] *In 2013, all cattle were born on the farm.*

Although TCO self-identifies as a permaculture farm, it is important to note that Zach Miller characterizes his farm as approaching permaculture practices. A true permaculture farm integrates both crop and animal production to achieve a closed nutrient cycle that does not require nutrient inputs. For example, the crops that are grown on the farm feed the livestock, and the manure from the livestock fertilizes the crops. In addition, when compared to 50 other permaculture farms throughout the US, TCO was generally larger in area, had higher production levels, and had more infrastructure and equipment (Rafter Sass Fergusson, personal communication). Findings from this study could be extended to other livestock permaculture farms but would not be appropriate for crop or mixed crop and livestock permaculture farms. In the coming years, TCO plans to integrate feed crop production, which will bring TCO closer to the defined permaculture farming methods.

2.2. Question 1: How does the farm nitrogen budget of Timbercreek Organics (a permaculture livestock farm) compare to that of conventional livestock farms?

Farm N budgets were developed for permaculture and conventional farms. The Oenema et al. (2003) definition of a farm-gate N budget (Table 1) was utilized because this type of budget can describe the overall farm efficiency and is commonly used and cited in the literature (e.g., Watson et al. 2002, Bassanino et al. 2007). The farm-gate N budget is referred to as the farm N budget throughout this paper.

First, a farm N budget for permaculture livestock farm Timbercreek Organics was developed for the years 2012 and 2013. Second, N budgets describing other farms were collected and developed for comparison to the TCO budget using two methods: (1) literature research of existing budgets and (2) the construction of a budget using average factors from the literature. The farms from the literature were categorized as one of the following types: conventional, organic, grazing: fertilized, and grazing: unfertilized. These budgets describe total N inputs and outputs associated with each farm type. The TCO farm N budget was compared to the literature and constructed farm N budgets using the following four metrics:

1) N surplus / ha land,
2) Nitrogen use efficiency (NUE),
3) Land required / intended outputs, and
4) Time required / intended outputs.

These four comparison metrics address different aspects of food production that can affect both the environment and the availability of the food products. Metrics 1 and 2 describe overall farm nitrogen efficiency; a higher value in metric 1 means greater N losses to the environment per unit area and a higher value in metric 2 means more efficient use of available N. Metrics 3 and 4 vary by livestock type; a lower value for both metrics 3 and 4 indicates a more efficient use of time and land, respectively.

2.2.1. Farm nitrogen budget for Timbercreek Organics Farm

2.2.1.1. Timbercreek Organics Farm nitrogen inputs and outputs

The intended N inputs considered for Timbercreek Organics were feed (including hay), purchased livestock, purchased bedding, pasture biological nitrogen fixation (BNF), and energy use (Figure 5). The unintended N inputs were forest BNF and atmospheric deposition. Forest BNF was categorized as an unintended N input because the forests do not provide a significant source of feed nitrogen and because the input was expected to be very small. The atmospheric N deposition was categorized as an unintended N input because it was not an intentional input to farm productivity. The intended N outputs were the farm's meat products and any recycled slaughter by-products. Unintended N outputs were not directly measured in this study.

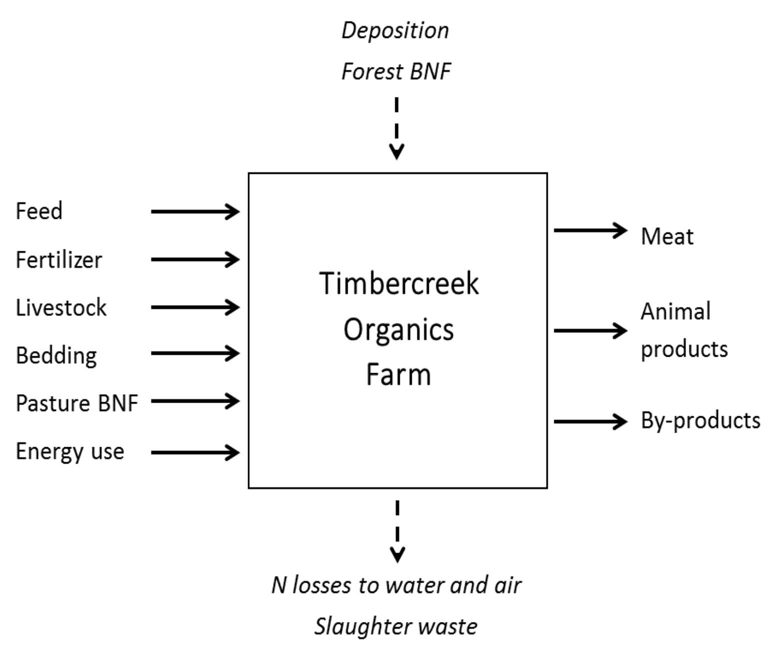


Figure 5. Flow diagram of a farm nitrogen budget, such as for Timbercreek Organics Farm. Solid arrows and normal font indicate intended inputs and outputs, and dashed arrows and italicized font indicate unintended inputs and outputs.

The farm N budget for Timbercreek Organics was developed primarily with data from the farm's records (Table 5). A detailed data template (Appendix A) was constructed and reviewed with the farmer, Zach Miller, who provided the necessary data for both 2012 and 2013. Data reported directly by the farmer include feed and hay purchases, feed and hay protein content, bedding purchases, livestock purchases, weight loss during slaughter, weight of final meat products, and energy use statistics. Data regarding the amount and use of slaughter by-products were reported by the Harrisonburg, Virginia, slaughterhouse T&E Meats (Travis Miller, personal communication). It was assumed that data reported directly by the farmer and slaughterhouse were accurate, and uncertainty associated with that value (e.g., weight of feed purchased) was not calculated.

Table 5. Data collected for the farm nitrogen budget and farm comparison metrics for Timbercreek Organics (TCO).

FARM N BUDGET		
N budget component	**Data types collected**	**Data source**
N inputs: Intended	• Feed and supplements, by animal type • Fertilizer[a] • Livestock • Bedding • Pasture legume biological N fixation • Energy use (e.g., electricity, fuel)	• TCO • TCO • TCO • TCO • Field survey and literature • TCO
N inputs: Unintended	• Forest legume biological N fixation • Atmospheric deposition	• Field survey and literature • National Atmospheric Deposition Program
N outputs: Intended	• Meat and eggs • Slaughter waste repurposed at TCO (e.g., for compost)	• TCO and literature • TCO

	- Slaughter waste repurposed at the slaughterhouse (e.g., offal for pet food)	- TCO and T&E Meats
N outputs: Unintended	- Difference between total inputs and intended outputs	- Calculation
FARM EFFICIEINCY COMPARISON METRICS		
Farm metric	**Data types collected**	**Data source**
Nitrogen use efficiency	- Farm intended inputs and intended outputs	- TCO
N surplus / ha land	- Grazing land area by livestock type - N budget data, described above	- TCO - TCO
Land utilized / intended outputs	- Land used by livestock type - Intended outputs, described above	- TCO - TCO
Time required / kg carcass	- Lifespan by livestock type - Slaughter weight by livestock type	- TCO - TCO

[a] *Timbercreek Organics Farm does not use any purchased fertilizer.*

For the farm inputs and outputs reported by TCO, the nitrogen content of each component was calculated. The farmer provided some of the protein contents (for feed and bedding), and the remaining protein contents were collected from the literature (for livestock, meat products, animal products, and slaughter by-products) (Appendix B, Table B1). It was assumed that the protein contents reported by the farmer were accurate and were set as the average. For all protein contents, multiple estimates were collected and averaged. The maximum and minimum values found were used to represent uncertainty bars in the calculations.

Fossil fuel emissions associated with farm energy use were calculated as an intended N input. Types of energy used include purchased electricity and diesel fuel for the farm vehicles and farm truck. Average US emission factors for the purchased electricity (0.0003 kg N kwh^{-1}) and diesel fuel (0.0002 kg N km^{-1}) were applied (Leach et al. 2012).

Atmospheric deposition was determined based on the area of the farm (160 ha) and average rates of wet (NADP 2014) and dry (EPA 2014) nitrogen deposition. Data from the

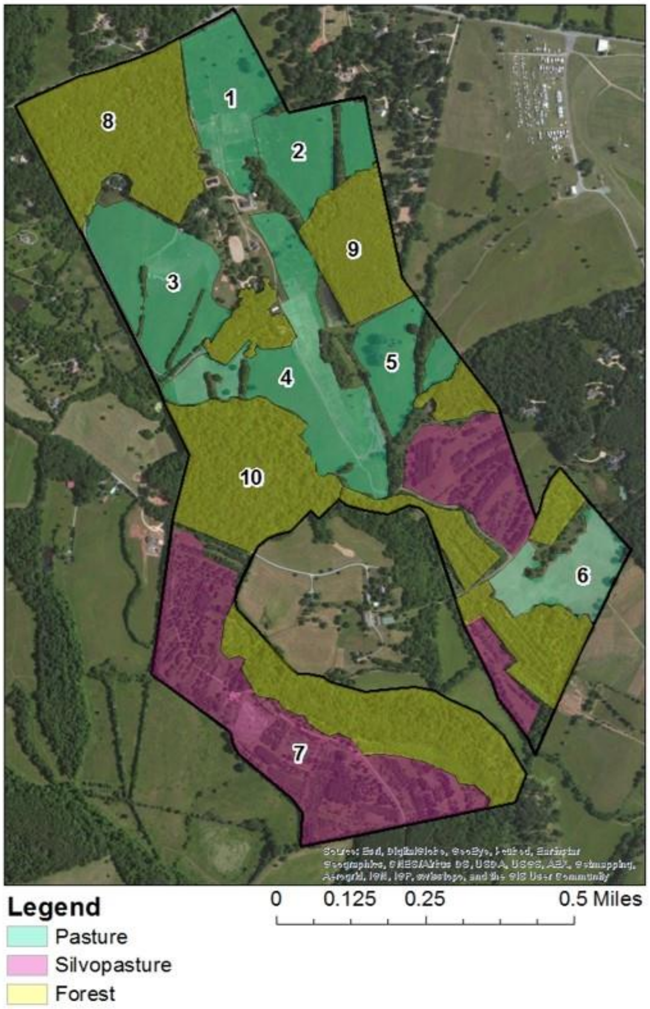
Charlottesville, Virginia, and Prince Edward, Virginia, monitoring stations were collected for 2012 (the most recent year available) and averaged. The regional wet and dry deposition rates were 3.3 kg N ha^{-1} yr^{-1} and 0.9 kg N ha^{-1} yr^{-1}, respectively, for a total N deposition rate of 4.2 kg N ha^{-1} yr^{-1}.

2.2.1.2. A vegetation survey to estimate legume N-fixation at Timbercreek Organics

A vegetation survey was conducted to better characterize the rate of legume nitrogen-fixation on the TCO property. Two components were considered: biological nitrogen-fixation by legumes in the pastures (e.g., white clover, hop clover, alfalfa) and by legumes in the forests (e.g., black locust, black alder). The vegetation survey was conducted in early June 2014; it was assumed that the observed vegetation coverage in June 2014 was representative of coverage in both 2012 and 2013.

For the pasture vegetation survey, seven distinct fields were identified that were assessed separately due to their geographic separation and different land use histories (Figure 6). All forested areas were designated as forests; fields were identified as either pasture (i.e., dominated by grasses with few trees) or silvopasture (i.e., a mixture of grasses and trees). In these fields, the point line transect survey method was used (Abrahamson et al. 2011). The transect site in each field was selected to represent that field’s vegetation coverage and to capture a change in elevation. One 50 m transect was completed in each of the seven fields. Every 50 cm, a pencil attached to a string was dropped. The plant closest to the point (at least within 0.5 cm) was identified as one of three categories: legume, grass, or bare. If the plant was a legume, the species was identified. If the plant was a grass, the species was identified when possible.

Although recent mowing prevented the identification of many grasses, the species of grass was not necessary to identify the nitrogen-fixation rate.



Source: Esri, DigitalGlobe, GeoEye, i-cubed, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 6. Timbercreek Organics Farm property separated into seven distinct fields (#1-7) and three distinct forests (#8-10) for a vegetation survey of the property. The fields were divided into both pasture fields (i.e., dominated by grasses with few trees) and silvopasture fields (i.e., a mixture of grasses and trees).

The 100 measurements collected on each transect were then used to develop a species distribution. It was assumed that the legume species distribution observed in the transect for each field was representative of the species distribution in that entire field. GIS maps were developed to measure the area of each of the seven fields. The total nitrogen fixation in each field was determined by multiplying the field area by the percent coverage of each legume species and the appropriate legume-nitrogen fixation rate; the N fixation of each legume species was summed to determine the total field N fixation (Equation 1). The calculated nitrogen fixation for all seven fields was then summed to determine the farm’s total pasture N fixation.

Equation 1. Pasture nitrogen fixation.

$$NF_{field} = \sum_{i=1}^{n} A_{field} C_i R_i$$

> Where NF_{field} = field N-fixation (kg N yr^{-1}), A_{field} = field area (ha), C = Percent coverage for given legume species (%), R = nitrogen fixation rate for given legume species (kg N ha^{-1} yr^{-1}), and *i* corresponds to each identified legume species.

Three estimates of pasture VNF were made: ineffective, effective, and observed. The first estimate (i.e., ineffective or 0% BNF) assumed that all legumes had ineffective root nodules and were not fixing nitrogen. The second estimate (i.e., effective or 100% BNF) assumed that all legumes had effective root nodules and were fixing nitrogen. The third estimate (i.e., observed) used observations of legume samples collected from TCO to assess whether nitrogen fixation was likely to occur. One sample of legumes of approximately 10 cm by 10 cm was collected from each field. The number of individual legume plants in each sample was counted and the species were identified. The legume roots were viewed under a dissecting microscope to determine through visual observation if they could be effective N-fixing root nodules. Nodules were considered "effective" if they were relatively large and had a pink color (Williams et al. 1991). If a plant had at least one potentially effective nodule, then that plant was counted as "effective." The percent of effective plants was recorded for each field. Given the limited number of samples, an overall farm average weighted by field area was calculated, and that average of percent effective legumes was applied to the entire pasture area of the farm for the third BNF estimate (i.e., observed).

Nitrogen-fixation rates for each legume species identified were collected from the literature (Table 6). The appropriate N-fixation rate was then applied to the vegetation coverage and field area to determine each of the three estimates of BNF (Equation 1). The pasture BNF estimates were summed to estimate total farm pasture BNF.

Table 6. Biological nitrogen-fixation rates of legumes identified at Timbercreek Organics Farm. The maximum N-fixation rate is an average of reported maximum values in a range, the minimum N-fixation rate is an average of reported minimum values in a range, and the average is an overall average of all data points.

Species name	**Common name**	**Type**	**Nitrogen-fixation rate (kg N ha^{-1} yr^{-1})**			**Source**	**Number of studies**
			Avg.	**Max.**	**Min.**		
Medicago sativa [b]	Alfalfa	Perennial	169	234	88	1,2,3,4,5	13
Trifolium campestre [c]	Hop clover	Annual	96[a]	153[a]	42[a]	1,2,3,4,5	6
Trifolium repens [d]	White clover	Perennial	155	240	67	1,2,3,4,5	22
Robinia pseudoacacia [e]	Black locust	Tree	48	75	33	6	1
Alnus glutinosa [f]	Black alder	Tree	266	316	199	7	1

[a] *Used average N-fixation rates for other annual clovers (e.g., trifolium vesiculosum, trifolium nigrescenes, trifolium incarnaturm) when rates for hop clover were unavailable.*

[b] *Studies took place in the US (New York, Kentucky, Minnesota, Alaska), Australia, Austria, Canada, and Sweden.*

[c] *Studies took place in the US (Georgia, New Jersey) and Australia.*

[d] *Studies took place in the US (Georgia, Kentucky, Minnesota), Denmark, Netherlands, New Zealand, Switzerland, and the UK.*

[e] *Study took place in North Carolina*

[f] *Study took place in the Hubbard Brook Experimental Forest in New Hampshire*

Sources: (1) Ball et al. 2007; (2) Brady 1983; (3) Carlsson & Huss-Dannell 2003; (4) Havlin et al. 1999; (5) Johnson et al. 1997; (6) Boring & Swank 1984; (7) Bormann et al. 1993.

For the forest vegetation survey, three distinct forests were identified based on geographic separation (Figure 6). In each forest, five circular quadrats with a 5 m radius were surveyed. The quadrat sites were selected to represent the variation in the forests. At least one quadrat on the edge of each forest was surveyed. For each quadrat, the central point was identified and GPS coordinates were recorded. A range finder was used to determine which trees were within the 5-meter radius. All trees whose middle point was within the 5-meter radius were included. For each tree in the quadrat, the diameter at breast height (DBH) was recorded to calculate the coverage by that tree species. Only trees with a DBH greater than 10 cm were recorded.

All trees were categorized as either “nitrogen-fixing tree” (NFT) or “other” for trees that do not fix nitrogen. All NFT were identified by species. The species of the “other” trees were identified when possible, but were not necessary to determine the rate of BNF. The percent coverage by NFT was determined for each quadrat using the tree DBH. The NFT percent coverage for each quadrat in a given forest was averaged to describe that forest’s NFT percent coverage.

Nitrogen-fixation rates for each tree legume species identified were collected from the literature (Table 6). GIS mapping was utilized to determine the area of each forest (Figure 6). The given forest’s area, average NFT percent coverage, and the appropriate N-fixation rates were used to determine that forest’s total N fixation (e.g., as in Equation 1). The N fixation for the three forests was summed to determine the total forest N fixation. The total forest BNF was added to the farm nitrogen budget.

2.2.1.3. Efficiency metrics to describe Timbercreek Organics Farm

The data collected for the farm N budget were used to calculate the farm N surplus (Equation 2) and NUE (Equation 3). The categories of data collected for the N budget were identified as intended and unintended N inputs and outputs. The intended N inputs for TCO included in the farm metrics were the following: feed, fertilizer, purchased livestock, purchased bedding, legume BNF, and energy use. Unintended N inputs (i.e., atmospheric deposition) were not considered due to the definitions of N surplus and NUE.

Equation 2. N surplus

$$N\ Surplus = \sum Intended\ N\ inputs - \sum Intended\ N\ outputs$$

Where *Intended N inputs* (kg N yr^{-1} or kg N ha^{-1} yr^{-1}) describe the intended N inputs to the farm (i.e., feed, legume BNF, purchased livestock, bedding, energy use) and *Intended N outputs* (kg N yr^{-1} or kg N ha^{-1} yr^{-1}) describes the N contained in the food product(s) produced by the farm, including recycled slaughter by-products. *N Surplus* can be in either units of total kg N yr^{-1} or kg N ha^{-1} yr^{-1}.

Equation 3. Nitrogen Use Efficiency (NUE)

$$NUE = \frac{Intended\ N\ outputs}{Intended\ N\ inputs}$$

Where *Intended N outputs* (kg N yr^{-1} or kg N ha^{-1} yr^{-1}) describe the N contained in the food product(s) produced by the farm, including recycled slaughter by-products; and *Intended N inputs* (kg N yr^{-1} or kg N ha^{-1} yr^{-1}) describe the intended N inputs to the farm (i.e., feed, legume BNF, purchased livestock, bedding, energy use). *NUE* can be a ratio or percentage (%).

The final two metrics, land utilization per intended outputs (Equation 4) and time required per intended outputs (Equation 5), were calculated using additional farm data (Table 5). The land-utilization metric describes the amount of land used to produce a meat products. In the case of TCO, the metric does not necessarily describe the land required to produce meat products because TCO has not yet reached its maximum grazing capacity (Zach Miller, personal communication). The land-utilization metric considered both land used during feed production as well as grazing land.

To calculate the feed land component, the amount of feed used by livestock type over each year was determined based on TCO livestock-specific feed mixtures (Zach Miller, personal communication). US conventional production yields for corn, oats, soybeans, and hay were collected (USDA-ERS 2014a; USDA-ERS 2014b); five-year averages for 2010 through 2014 were taken because data were reported on a national scale (Appendix B, Table B2). The hay yield was assigned to alfalfa pellets and the corn yield was assigned to fishmeal (assuming the fish were grain-fed) because yield data for these two crops were not available in the USDA-ERS database. The feed yields were then used to determine the total amount of land used to produce the feed used at TCO for each livestock type over one year. Because feed data were specific to a given year, the land utilization metric was calculated for both 2012 and 2013 at TCO.

Equation 4. Land utilization

$$Land\ utilization = \frac{Feed\ land\ area + \ Grazing\ area}{Intended\ outputs}$$

> Where *Feed land area* (m^2 land) is the total cropland area used to produce feed for a given livestock type, *Grazing area* (m^2 land) is the total farmland area that a livestock type grazes and *Intended outputs* (kg meat) describe the N contained in the food product(s) produced by the farm, including recycled slaughter by-products. *Land utilization* is in units of [m^2 land/kg meat].

To calculate the grazing land component, farmland at TCO was allocated to specific livestock species. Only the pigs graze the forests (16 ha). However, the cattle, poultry, and layers all graze an overlapping area of 65 ha. This land area was distributed among the 3 livestock types with a weighted distribution based on the weights of beef, poultry, and eggs produced over one year. The land area could not be distributed based on the amount of time spent on the land by the different livestock types because these data were unavailable. The cattle graze an additional 15 ha of land not grazed by the poultry or layers.

The land used to produce feed and for grazing was summed for each livestock type. This total land utilization by livestock type was divided by the total annual meat production to determine the land utilization (Equation 4).

To calculate the time-required metric, supplemental data on livestock production were collected, including information on livestock lifespan, age at farm arrival, age at slaughter, and weight at slaughter (Appendix A, Table A3). The time-required metric was based on an individual head of livestock. The average total lifespan of that livestock type in days was divided by the average live weight at slaughter (Equation 5).

Equation 5. Time required

$$Time\ required = \frac{Lifespan}{Slaughter\ weight}$$

Where *Lifespan* (days) is the age of the animal at slaughter and *Slaughter weight* (kg/head) describes the total live weight of 1 head of livestock at slaughter. *Time required* is in units of [days/kg live weight].

2.2.2. Farm nitrogen budgets for conventional farms

Farm N budgets describing conventional and alternative farms were determined using two methods: (1) budgets collected directly from literature sources and (2) a budget constructed with average data from the literature. In this study, the type of farming method (e.g., conventional) is categorized based on how the farm is described in the literature.

2.2.2.1. Conventional farm N budget: Approach 1

For the first approach, a literature survey was conducted to collect data on existing farm nitrogen budgets. Data were collected on the overall farm N budget broken down into specific inputs and outputs, the type of farm (e.g., cattle, pig, poultry, layers), the farming method (e.g., conventional, organic, grazing: fertilized, grazing: unfertilized), and its location (Table 7). The specific inputs and outputs for each N budget were evaluated to ensure that they were comparable to those used in the TCO N budget. Mixed farms with crop production were only included if crop production made up less than 10% of the farm's intended nitrogen outputs per year. If the crop N products exceeded 10% of the total farm N products, then both the crop N products and the fertilizer N inputs were removed from the given budget analysis. For example, a mixed grazing beef farm produced a total of 15 kg N ha^{-1} yr^{-1} (Domburg et al. 2000). However, because the crop products for this farm totaled 7 kg N ha^{-1} yr^{-1} (over 10% of the farm's intended N outputs), both the crop N products and the fertilizer N inputs were removed from the budget calculation. Both the crop products and fertilizer inputs were removed from analysis so that the budget focused only on meat products and the inputs going towards meat production.

Table 7. Data collected from farm nitrogen budgets in the literature.

Data category	**Information collected**
N inputs: Intended	Purchased feed, purchased fertilizer, purchased livestock, purchased bedding material, biological N fixation by legumes
N inputs: Unintended	Rate of atmospheric deposition, land area
N outputs: Intended	Exported meat and animal products, slaughter by-products, crop products
N inputs: Unintended	Calculated difference between total inputs and intended outputs
Type of farm	Cattle, pigs, poultry, eggs, or mixed
Farming method	Conventional, organic, grazing: fertilizer, grazing: unfertilized
Location	Location by state or country

A total of twelve review papers with 112 farm budgets were collected from the literature. 37 of the farm budgets collected were themselves averages representing multiple farms or production at the country level. However, 90 budgets were excluded from the analysis for one of the following reasons: insufficient data detail, crop production was too high, or dairy production was too high. Ultimately 9 beef farm budgets (4 were averages), 8 pork farm budgets, (all were averages), 3 poultry farm budgets (all were averages), and 1 layer farm budget (was an average) were used (Appendix C, Table C1). Averages were determined for each budget category; averages were weighted when a budget from the literature represented multiple farms. The average farm N budgets collected from literature research were then compared to the TCO budget using the two farm N efficiency metrics: N Surplus (Equation 2) and NUE (Equation 3). The N Surplus could not be calculated for the pork, poultry, and layer farm N budgets because these budgets were on the farm scale and did not report the N flows per unit area.

2.2.2.2. Conventional farm N budget: Approach 2

For the second approach, a farm N budget describing conventional livestock farms was constructed using average data from the literature. This farm budget was constructed so that it was set to the same level of meat production as Timbercreek Organics so that the two farm budgets were directly comparable (Table 8). The value of this constructed budget is that it is based on the same levels and types of meat production as TCO, whereas the farm budgets from the literature (i.e., the first approach) typically describe a specific type of livestock production (e.g., beef-cattle or pigs).

Table 8. Methods and components for a constructed farm nitrogen budget describing conventional farms for comparison to Timbercreek Organics Farm (TCO).

N flow	**Budget component**	**Calculation for constructed budget**
Intended N inputs	Feed inputs	Calculated using average feed requirements per head of livestock from Oenema et al. 2006
	Legume biological N fixation	Set as equal to TCO
	Livestock imports	Set as equal to TCO
	Bedding purchases	Set as equal to TCO
Intended N outputs	Meat and slaughter by-products	Set as equal to TCO

This constructed farm N budget was developed with a bottom-up approach, meaning that data were collected from the literature on a per-product basis to scale up to the size of TCO. The N feed requirements associated with an individual cow, pig, broiler, and layer were determined based on average factors in the literature (Table 9). Weighted feed protein contents were used based on the feed mixtures currently used at TCO. The remainder of the farm N inputs (e.g., livestock purchases, bedding purchases) were set as equal to TCO because these components were not expected to be different (e.g., livestock purchases) or were expected to have a small contribution to the overall budget (e.g., energy use). The N Surplus (Equation 2) and NUE (Equation 3) were then calculated.

Table 9. Amount of animal feed needed for the production of desired animal products. Oenema et al. 2006.

Feed conversion ratio (kg kg^{-1})	Chicken	Pork	Beef	Eggs
Feed into live weight	2.5	5	10	n/a
Feed into edible animal product	4.5	9.4	25	2.3
Feed protein into edible protein	5	10	25	3.3

2.2.2.3. Other efficiency metrics for conventional farms

The farm metrics describing the land and time required to produce products were also calculated for conventional farms. For the land-utilization metric (Equation 4), data from the literature were collected describing the land area used to produce 1 kg of pork, beef, poultry, and eggs. The land-utilization metric considered land used for both feed crop production and livestock grazing. For the time-required metric (Equation 5), data from the literature were collected on the average lifespan and slaughter weight for pigs, beef-cattle, and poultry.

2.3. Question 2: What are the virtual nitrogen factors (i.e., food production nitrogen losses) for pig, beef-cattle, poultry, and egg production at Timbercreek Organics? How do these losses compare to conventional farm virtual nitrogen factors (i.e., food production nitrogen losses) in the United States?

2.3.1. Virtual nitrogen factors for Timbercreek Organics Farm

Virtual nitrogen factors (VNF) were developed for pig, beef, chicken, and egg production at Timbercreek Organics Farm. The approach used considers each stage of the food production process from feed production to human consumption (Figure 1) (Leach et al. 2012). The virtual N factors consider the following steps:

1. Feed crop N uptake
2. Feed crop processing
3. Live animal production
4. Slaughter
5. Processing
6. Food waste

For each step, a percentage was calculated that describes how much of the N entering that step moves to the next step. Unless recycled, the difference is considered to be lost to the environment. For example, the percentage of applied N fertilizer that is taken up by the crop could be 60%, which would be the factor for step 1. The virtual nitrogen factor is then calculated by dividing the sum of the N lost to the environment over all stages of food production by the N in the final food product (Equation 6). This virtual nitrogen factor describes the N released to the environment per unit of N in the food product. VNF only consider N inputs of fertilizer and legume BNF; energy use is not considered in this calculation.

Equation 6. Virtual N factor calculation

$$Virtual\ N\ Factor = {\sum N\ Losses}/_{Product\ N}$$

Where *N Losses* (kg N) describe the N released to the environment at each step of the food production process and *Product N* (kg N) describes the N contained in the final produced food product.

One modification was made to the VNF calculation process for this study: the final step (#6, food waste) was not considered. Typically, virtual N factors have this final step to capture distribution and household level food waste (Leach et al. 2012). However, this step was removed from the TCO VNF calculation because it does not reveal additional information about the efficiency of TCO. Given this, VNF from this study are not directly comparable to VNF that include the food waste step. However all VNF in this study have been modified so that they do not include the final food waste step.

Data were collected from both farm records and literature research to describe each step of the food production process for pork, beef, poultry, and egg production at Timbercreek Organics Farm (Table 10).

Table 10. Data requirements for virtual nitrogen factors, by step of the food production process

Virtual N factor step	Data requirements	Data source
Feed production 1. Feed crop N uptake 2. Feed crop processing	• Types, amounts, and N content of feed by livestock type • Average crop N uptake • N loss during processing of feed • Rates of recycling for feed N loss	• Farm records • Literature research
Live animal 3. Live animal production	• Total live animal/product N per year • Total feed N per year • Individual animal/product N • Recommended feed per animal/product • Recycling rates of animal manure	• Farm records • Literature research
Slaughter and processing	• % weight loss from slaughter • Total animal/product N	• Farm records • Literature research

4. Slaughter 5. Processing	• Animal/product slaughter by-product N • Recycling rate of slaughter/processing waste	

For step one (feed crop N uptake), the feed mixture used at Timbercreek Organics for each livestock type that consumes feed (pigs, poultry, layers) was used to determine a weighted nitrogen uptake factor for each livestock type's feed. The nitrogen uptake factors from the US conventional VNF (Leach et al. 2012) were used for the various feed types. These factors were used for two reasons. First, TCO is currently purchasing conventionally produced feed. Secondly, average nitrogen uptake factors are not yet available in the literature for organic production. The calculated uncertainty for this step was based on the range of feed protein contents used in the farm N budget (Appendix B, Table B1).

For step 2 (feed crop processing), both the percent N retained during processing and the percent N recovered through recycling were set to the same values as the US VNF for conventional production because the feed is conventionally produced. An uncertainty range was not calculated for this step because it was set to conventional production.

For step 3 (live animal production), two distinct methods were used to calculate the N accreted by a live animal. The first method uses actual TCO feed data and will be considered the result representative of farm activities; the second method uses feed recommendations and will be used for comparison to assess farm efficiency. Unless otherwise stated, the VNF only consider the consumption of feed grain and not the consumption of natural forages (e.g., grass, acorns). The percent contribution of natural forages to the livestock diets at TCO is unknown and should be explored in future studies.

The first method for step three considered the total amount of feed used at the farm per livestock type over the course of one year. Because this method uses data on actual feed use at TCO, it will be considered the best result for step 3 of the VNF. To calculate the factor using this approach, the contribution of each feed type and the associated protein contents were used to determine how much feed N was used over one year for pig, poultry, and egg production. Because beef cattle do not consume purchased grain feed, the N input for the beef cattle feed step was the sum of the average farm legume BNF estimate and purchased hay. These two inputs were the only ones considered because the VNF methodology only considers inputs of new nitrogen to a system (e.g., fertilizer, BNF). The N contained in the final meat/animal product produced over one year was divided by the feed N used over that year to determine how much of the feed N was converted into live animal weight or product. Different factors were calculated for 2012 and 2013. The uncertainty range was calculated based on a range of protein contents for both the live animal/product and feed (Appendix B, Table B1).

The second method for step 3 considered feed recommendations used at TCO to purchase feed and make livestock-specific feed mixes. Since this method is based on recommendations and not actual farm data, it will be considered the theoretical result for step 3 for comparison purposes. The comparison between this method and method 1 could reveal feeding inefficiencies at the farm. To calculate the VNF factor for step 3 using this approach, the feed required to produce a single head of livestock or animal product was determined based on feed recommendations used by TCO (Table 11). Cattle are entirely grass-fed, so this calculation method was not used for beef cattle production. For eggs, the feed consumed while the hen was not producing eggs for the first 6 months of its life was distributed across the 550 eggs assumed to be produced over the 2 years it is at TCO (Xin et al. 2013). Literature values were used for lifetime egg production rather than TCO data because TCO has a high hen mortality rate due to predation and the number of hens on the farm was not tracked (Zach Miller, personal communication). The N contained in each head of livestock (or animal product) was then divided by the feed N recommendation to determine what percent of recommended feed N was converted into live animal weight of product. Because the same feed recommendations were used in both 2012 and 2013, this theoretical virtual N factor was the same for both years. The uncertainty range was calculated based on a range of protein contents for meat/products and slaughter by-products (Appendix B, Table B1).

Table 11. Feed requirement recommendations used by Timbercreek Organics Farm for pork, poultry, and egg production. The feed requirement is the weight of feed needed for the animal to reach its slaughter weight or for the animal product (e.g., egg) to be produced.

	Pig	Poultry	Egg
Slaughter weight or animal product weight (kg)	145	2.7	0.06
Feed required to reach desired weight (kg)	480	7	0.2

Source: Zach Miller, personal communication

Step 3 also requires a factor for manure recycling. Because all manure is applied directly to the field at TCO and can contribute to vegetation growth, it was assumed that 100% of manure is recycled.

For step 4 (slaughter), the weight of meat/product nitrogen and slaughter by-product nitrogen for a single animal was determined based on its live weight at slaughter, the percent recovery at the slaughterhouse, and the appropriate protein contents. The factor was determined as the percent of N contained in the meat/product compared to the N contained in the entire live animal. For eggs, it was assumed that 5% of the animal product is lost to the environment to account for any farm-level losses, such as when hens lay eggs in locations other than the hen house. The percent recycling of slaughter by-products was set to 90%—the same level as for the conventional VNF—because of the self-reported high percentage of recycling at T&E Meats (Travis Miller, personal communication). An uncertainty range was calculated based on a range of protein contents for the meat products and slaughter by-products (Appendix B, Table B1).

For step 5 (processing), the factors for both % N retained during processing and for % recycling were set to 100%. This was because a second level of processing does not exist for T&E Meats or for TCO. The product that returns from T&E Meats (for pigs and cattle) or that is slaughtered at TCO (for poultry) is the product that is sold directly to the consumer. Therefore all slaughter and processing losses were captured in the previous step. An uncertainty range was not calculated for this step.

Ultimately three estimates of VNF were developed at TCO for the listed product types:

(1) VNF for 2012 based on actual feed use (pork, beef, poultry, eggs)
(2) VNF for 2013 based on actual feed use (pork, beef, poultry, eggs)
(3) Theoretical VNF based on feed recommendations used by TCO (pork, poultry, eggs)

The overall uncertainty range for each VNF was determined by calculating the VNF with the minimum efficiency (i.e., the highest VNF) and the maximum efficiency (i.e., the lowest VNF) based on the calculated uncertainty range for each step of the VNF process.

2.3.2. Virtual nitrogen factors for conventional farms

Virtual N factors for pork, beef, poultry, and egg production at TCO were compared to the established virtual N factors, which are available for conventional production in the United States (Leach et al. 2012, updated), Europe (Stevens et al. 2014), Austria (Pierer et al. 2014), Japan (Shibata et al., submitted), and Tanzania (Hutton et al., submitted) (Table 12). The US

VNF have been updated since Leach et al. 2012 to incorporate new data on the final food processing step (Gustavsson et al. 2011). To be comparable with the TCO VNF, the final step of the VNF calculation process (distribution- and household-level food waste) was removed from all of the country-specific VNF. These updated VNF were compared directly to the TCO VNF. Potential reasons for any observed differences were considered. Uncertainty ranges were not available for any of the country-specific VNF.

Table 12. Virtual nitrogen factors for the United States, Europe, Austria, Japan, and Tanzania. These factors describe a raw food product ready for consumption; distribution and household level food waste is not considered.

	USA[1]	Europe[2]	Austria[3]	Japan[4]	Tanzania[5]
Pork	3.6	3.6	2.9	4.4	3.3
Beef	6.6	6.6	4.5	8.4	7.0
Poultry	2.6	2.6	2.0	4.1	0.8
Eggs	3.6	3.6	2.9	4.4	0.5

Sources: (1) Leach et al. 2012, updated; (2) Stevens et al. 2014; (3) Pierer et al. 2014; (4) Shibata et al., submitted; (5) Hutton et al., submitted.

3. Results

3.1. Results for question 1: How does the farm nitrogen budget of Timbercreek Organics (a permaculture livestock farm) compare to that of conventional livestock farms?

3.1.1. Timbercreek Organics Farm: Vegetation survey and legume biological N fixation

The pasture vegetation survey determined the percent coverage by legumes and the types of legumes in June 2014 to estimate an appropriate legume BNF for TCO. The total legume N fixation was applied to both the 2012 and 2013 TCO farm N budget.

Of the seven fields surveyed, two had low legume coverage of 0-16% and the rest had moderate to high coverage of 28-48% (Figure 7). Only 1 transect was surveyed in each of the fields, so estimates of variability are unavailable. Three types of legumes were observed: *Trifolium repens* (white clover), *Trifolium campestre* (hop clover), and *Medicago sativa* (alfalfa).

There was uncertainty in the identification of *Medicago sativa*, but the collected samples most closely resembled *Medicago sativa* seedlings and the farmer confirmed that *Medicago sativa* had been planted in some fields on the farm in previous years. One tree was surveyed in field 7, but it was not a nitrogen-fixing tree.

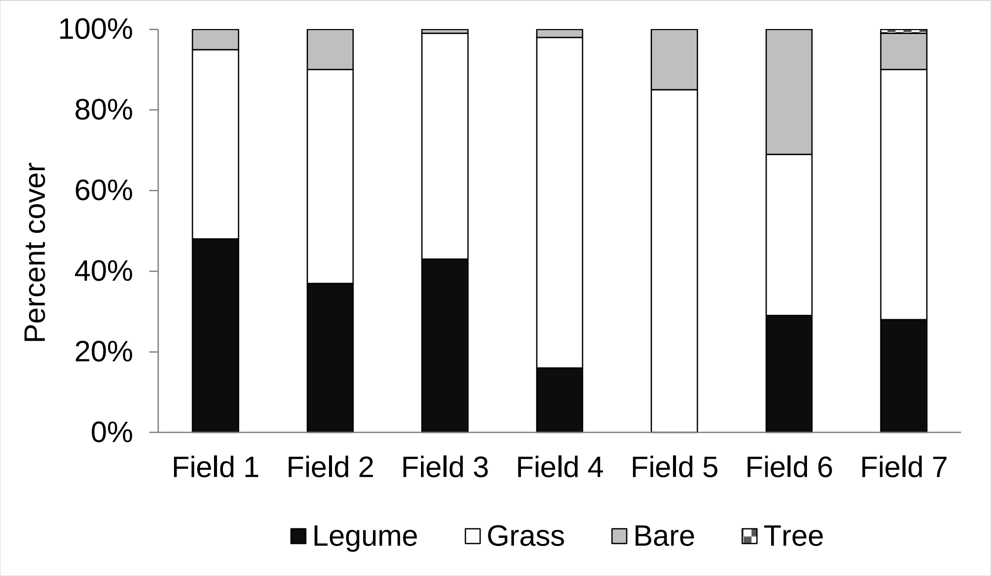


Figure 7. Land coverage determined from vegetation survey of seven distinct pasture fields at Timbercreek Organics Farm in June 2014. Black bars indicate legumes, white bars indicate grasses, gray bars indicate bare spots, and checkered bars indicate trees.

Of the collected legume samples, root nodules were observed on all legumes (Table 13). Samples of *Medicago sativa, Trifolium repens,* and *Trifolium campestre* were collected. The number of individual legume plants from each field varied from 2 to 17. Four of the fields' legume samples had no effective nodules; these nodules were very small and white in color. In two of the fields, about 30% of the samples observed had at least one effective nodule; one field was 47% effective. An overall weighted average based on the fields' areas determined that 18% of the legumes at TCO have effective N-fixing root nodules. However given the limited number of samples collected and the associated uncertainty, the observed effective rate was rounded to 20% for this study.

Table 13. Observations of effective nitrogen-fixing root nodules on legumes collected from 7 fields at Timbercreek Organics Farm in June 2014.

	Field 1	Field 2	Field 3	Field 4	Field 5	Field 6	Field 7
Type of legume(s)	*Trifolium repens*	*Trifolium repens*	*Medicago sativa*	*Trifolium campestre, Trifolium repens*	*Trifolium repens*	*Medicago sativa*	*Trifolium repens*
Nodules observed?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of legumes	3	10	15	2	2	17	3
Number of legumes with ≥1 effective nodule [a]	0	2	0	0	0	8	1
% effective	0%	20%	0%	0%	0%	47%	33%
Average % effective [b]	18%						

[a] *Effective nodules were large and had a pink coloration (Williams et al. 1991)*

[b] *Average % effective is a weighted average based on the field areas.*

The forest vegetation survey led to the identification of no nitrogen-fixing trees. At least 5 quadrats were surveyed in each of the three identified forests. In addition, the trees outside of the quadrats were also considered, but no nitrogen-fixing trees were found. Given that no nitrogen-fixing trees were observed, the forests were assumed to contribute no new nitrogen to the TCO farm N budget.

Three levels of legume BNF estimates were made: 100% effective root nodules, 0% effective root nodules, and 20% effective root nodules (i.e., observed). The estimates of total pasture legume BNF at TCO range from 0 t N yr^{-1} (0 kg N ha^{-1} yr^{-1}; ineffective nodules) to 5.3 t N yr^{-1} (32 kg N ha^{-1} yr^{-1}; 100% effective nodules and maximum N-fixation rate) (Table 14).

However, given that only some effective nodules were observed, a more likely estimate of total legume BNF was determined to be 0.7 t N yr^{-1} (4 kg N ha^{-1} yr^{-1-}; 20% effective nodules and average N-fixation rate); this estimate of total BNF is used in this study because it uses an average fixation rate and the observed root nodule effectiveness. The uncertainty estimate used in the farm N budget analysis is based on the observed root nodule effectiveness (20%) along with the minimum and maximum N-fixation rates (Table 14).

Table 14. Estimates of total biological nitrogen fixation at Timbercreek Organics Farm in 2013 based on a range of nitrogen-fixation rates (average, maximum, minimum; see Table 6) and three levels of root nodule effectiveness (effective, ineffective, and observed). Weighted averages for legume species observed in the seven surveyed fields were used to determine the total N fixation. The rate of observed root nodule effectiveness (20%) was based on an overall average percentage observed in collected samples. The value to be used in this study is 0.7 t N yr^{-1} (bolded).

	Percent of effective root nodules	Average N fixation		Maximum N fixation		Minimum N fixation	
		t N yr^{-1}	kg N ha^{-1} yr^{-1}	t N yr^{-1}	kg N ha^{-1} yr^{-1}	t N yr^{-1}	kg N ha^{-1} yr^{-1}
Effective	100%	3.5	21	5.3	32	1.5	9
Ineffective	0%	0	0	0	0	0	0
Observed	20%	**0.7**	4	1.1	6	0.3	2

3.1.2. Timbercreek Organics Farm: Nitrogen budget and other efficiency metrics

Feed was the largest nitrogen input to the TCO farm, and it increased substantially between 2012 (3.1 t N yr^{-1}) and 2013 (6.5 t N yr^{-1}) (Figure 8). Purchased livestock N inputs (i.e., day-old chickens, 6-week-old pigs, 6-month-old calves) decreased between 2012 (0.8 t N yr^{-1}) and 2013 (0.1 t N yr^{-1}). The next largest contributors were legume BNF, atmospheric deposition, and hay—all of which contributed between 0.6 and 0.7 t N yr^{-1} in both 2012 and 2013. Bedding and energy use each contributed less than 0.1 t N yr^{-1} to the farm N inputs. The farm N outputs grew substantially: meat production increased from 0.5 t N yr^{-1} in 2012 to 1.5 t N yr^{-1} in 2013. In both years, the meat outputs were greater than the slaughter by-product outputs. See Appendix D for detailed data on farm N inputs and outputs.

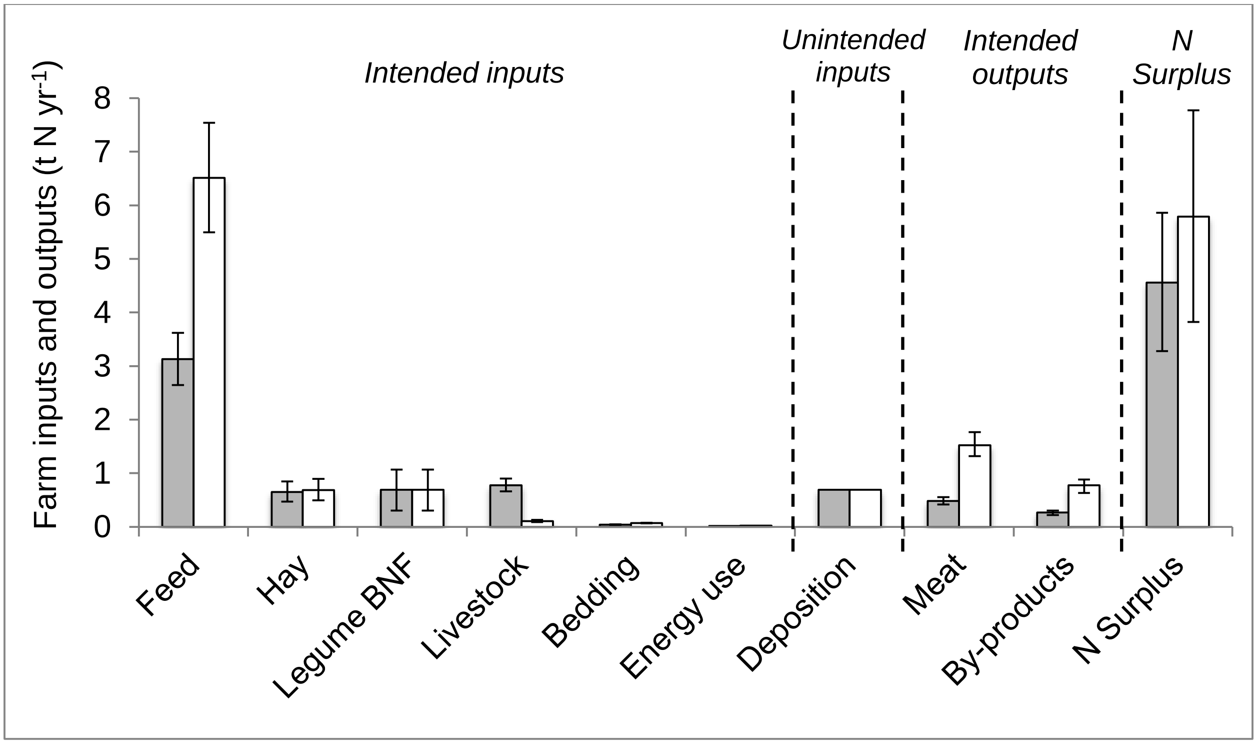


Figure 8. Nitrogen inputs and outputs to Timbercreek Organics Farm in 2012 (gray bars) and 2013 (white bars) in t N yr^{-1}. Error bars represent the following: Feed, livestock, bedding, meat, and by-products: range of protein contents; hay: range of weights per bale and protein contents; legume BNF: observed root nodule effectiveness and a range of N-fixation rates; and N surplus: maximum and minimum inputs and outputs based on their respective calculated range. Uncertainty bars were not calculated for energy use and atmospheric deposition because of their small contribution and exclusion from farm efficiency calculations, respectively.

The farm increased both its intended N inputs and intended N outputs on a total and per-hectare basis between 2012 and 2013 (Table 15). The total farm N surplus grew from 4.6 t N yr^{-1} (28 kg N ha^{-1} yr^{-1}) in 2012 to 5.8 t N yr^{-1} (35 kg N ha^{-1} yr^{-1}) in 2013. Despite the greater surplus, the NUE doubled from 14% in 2012 to 28% in 2013.

Table 15. Timbercreek Organics Farm nitrogen budget and nitrogen efficiency metrics in t N yr^{-1} and kg N ha^{-1} yr^{-1} in 2012 and 2013. Detailed farm N budget data can be found in Appendix D.

Farm metric	Farm total		Per unit area	
	2012	2013	2012	2013
	t N yr^{-1}	t N yr^{-1}	kg N ha^{-1} yr^{-1}	kg N ha^{-1} yr^{-1}
Intended N inputs	5.3	8.1	32	49
Unintended N inputs	0.7	0.7	4	4
Intended N outputs	0.8	2.3	5	14
N Surplus	4.6	5.8	28	35
Nitrogen use efficiency (%)	14%	28%	14%	28%

The time required to raise livestock to slaughter weight at TCO is greater than conventional farms (Table 16, Figure 9). The lifespan of pigs at TCO (282 days) is about 60% greater than that of conventionally raised pigs (173 days). However, pigs at TCO are reported to weigh 145 kg at slaughter—about 30% greater than the 114 kg average at conventional farms. Cattle at TCO also have a longer lifespan (730 days) than at conventional farms (481 days); however TCO beef cattle weigh about 10% less (530 kg) than conventional beef cattle (571 kg). The lifespan of TCO poultry (56 days) is about 20% longer than the industry average for conventional farms (46 days); broilers at TCO are reported to weigh about the same (2.7 kg) as conventional broilers (2.6 kg). These data were used to determine the average time required to produce a kilogram of live weight by livestock type (Table 16). Poultry had by far the highest time required at 21 days/kg live weight for TCO, compared to 18 days/kg live weight at conventional farms. The time required metrics for pork (1.9) and beef (1.4) were also greater than those for pork and beef produced at conventional farms (1.5 and 0.8, respectively). Overall meat products at TCO take 15-75% more time to produce than at conventional farms.

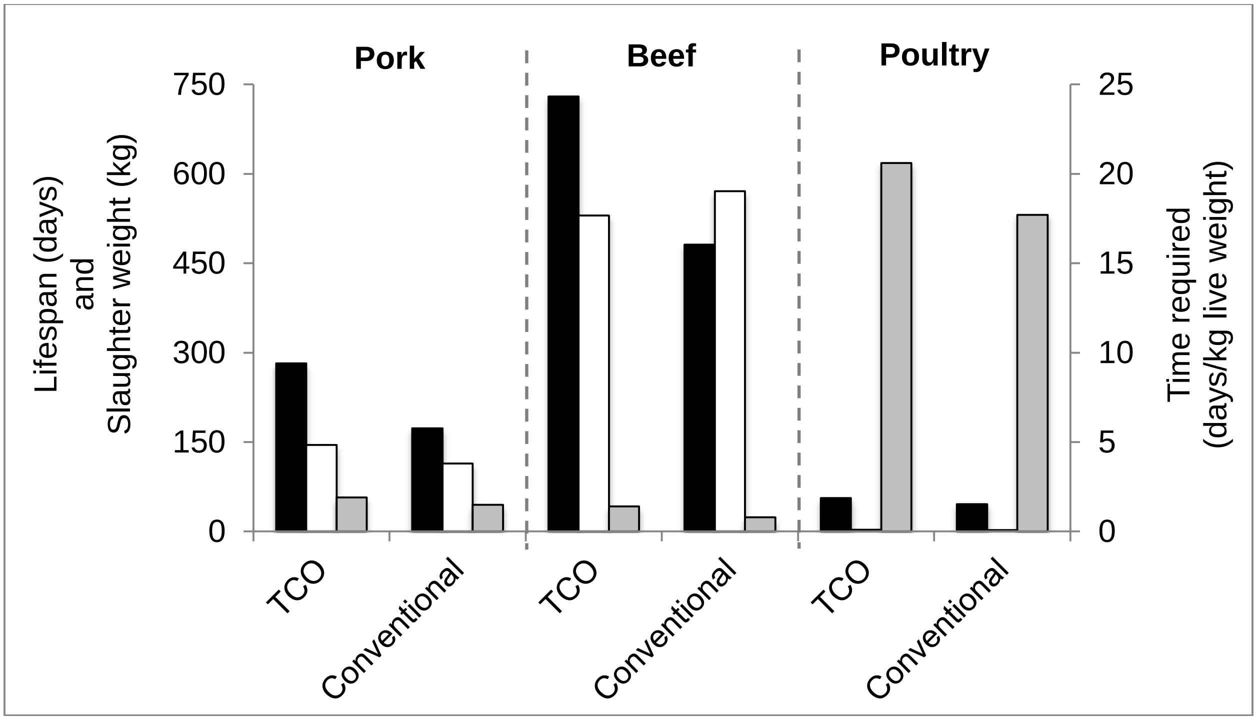


Figure 9. Lifespan (black bars), slaughter weight (white bars), and time required (gray bars) to produce pork, beef, and poultry at Timbercreek Organics Farm (TCO) and at conventional farms.

Table 16. Lifespan, slaughter weight, and time required to produce pork, beef, and poultry at Timbercreek Organics Farm and at conventional farms.

Meat product	Lifespan (days)			Slaughter weight (kg)			Time required (days/ kg live weight)	
	TCO[1]	Conven-tional	Data sources [a]	TCO[1]	Conven-tional	Data sources [a]	TCO	Conven-tional
Pork	282	173±12	2,3,4	145	114±11	2,3,5,6,7	1.9	1.5
Beef	730	481±117	8,9,10,11,12	530	571±37	5,6,7,8,9,10,11,12	1.4	0.8
Poultry	56	46±5	6,13	2.7	2.6±0.7	5,6,13	20.6	17.7

[a] *Data sources only describe conventional farms*

Sources: (1) Zach Miller, personal communication; (2) FAO 1991; (3) Boyd & Cady 2012; (4) USDA 2013; (5) FAO 2009; (6) USDA-ERS 1992; (7) USDA-NASS 2014a; (8) Mathews & Johnson 2013; (9) Jordan et al. 2002; (10) Bennett et al. 1995; (11) Fernandez and Woodward 1999; (12) Lacy 2007; (13) USDA-NASS 2014b.

The total grazing area used at TCO—including both pasture and forested areas—is about 97 ha (Table 17). About 65 ha of grazing area at TCO was shared by beef cattle, poultry, and layers; this land area was distributed to the different livestock types based on annual production.

As such, beef had the largest share of grazing land in both 2012 (40 ha) and 2013 (51 ha). An additional 15 ha of grazing land was used exclusively by beef cattle in both years, and the pigs are the only livestock type to graze in 16 ha of forested areas.

Table 17. Grazing area and land used to produce pork, beef, poultry, and eggs at Timbercreek Organics Farm and at conventional farms. The TCO distributed grazing area distributes shared grazing land based on farm production. The land utilization includes land used for both feed crop production and pasture grazing.

Meat product	Distributed grazing area (ha)		Land utilized (m^2/kg meat)					
	TCO 2012[1]	TCO 2013[1]	TCO 2012[1]		TCO 2013[1]		Conventional[2]	
			Feed	Pasture	Feed	Pasture	Feed	Pasture
Pork	16	16	12	24	8	8	12±6	0
Beef	40	51	8	44	2	15	34±8	289±32
Poultry	21	18	15	34	12	11	8±2	0
Layers	20	12	13	47	17	18	4±2	0

Sources: (1) Zach Miller, personal communication; (2) Eshel et al. 2014

The land used (for both feed production and grazing) per kg of meat decreased at TCO between 2012 and 2013 for all meat types (Figure 10; Table 17). The largest reduction was for TCO beef, which decreased by 68% from 52 m^2/kg meat in 2012 to 17 m^2/kg meat in 2013. The land use reductions between 2012 and 2013 for pork (-54%), poultry (-53%), and layers (-41%) were also large. For almost all livestock types, the pasture land use exceeded the feed production land use. The smallest feed land utilization was for cattle (8 and 2 m^2/kg meat in 2012 and 2013, respectively), and the largest was for poultry and layers. Layers had the greatest pasture land use in both 2012 (47 m^2/kg meat) and 2013 (18 m^2/kg meat).

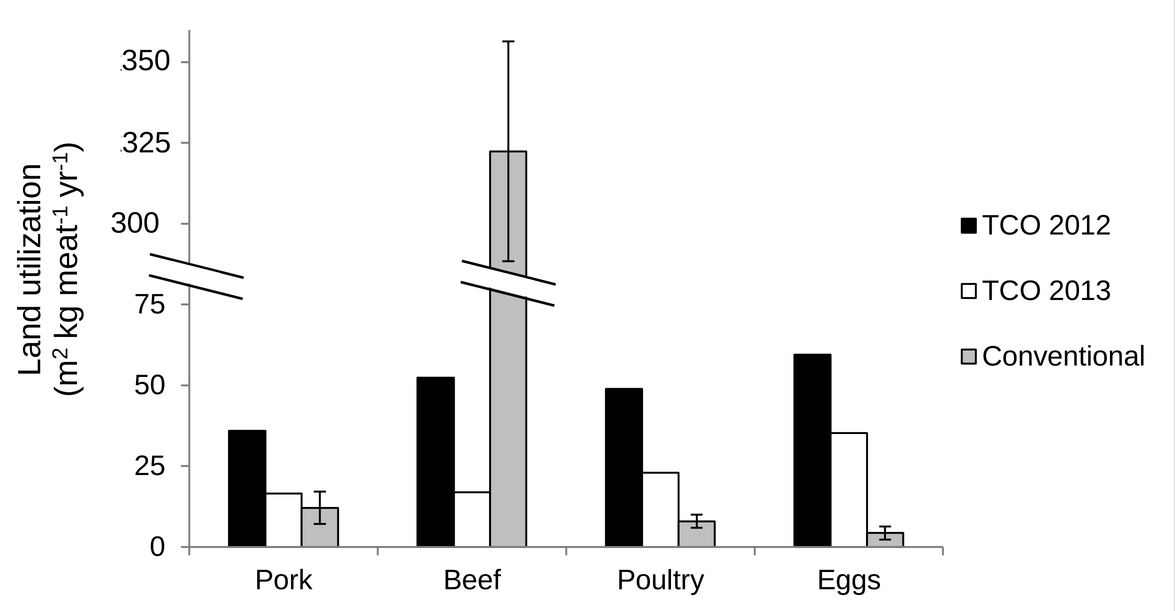


Figure 10. Land used to produce pork, beef, poultry, and eggs at Timbercreek Organics Farm (TCO) in 2012 (black bars) and 2013 (white bars) and at conventional farms (gray bars). The land utilization includes both land used to grow feed crops and grazing land. The error bars for conventional land use show standard deviation.

The average TCO land use exceeded that of conventional for all product types except beef (Table 17, Figure 10). All conventional products had land use from feed crop production, but only beef also had a pasture land component as well. When compared to 2013 TCO land utilization, the TCO pork land use was only slightly higher (37%) than conventional, but TCO land utilization was much higher than conventional for poultry (190%) and layer (720%) production. On the other hand, TCO land use for beef in 2013 (17 m^2/kg meat) utilized 95% less land than that for conventional production (322 m^2/kg meat).

3.1.3. Comparison to farm nitrogen budgets from the literature

The N budget and NUE of TCO were compared to other livestock farm N budgets from the literature (Table 18). Nitrogen budgets for conventional pork, beef, poultry, and layer farms were collected. For beef, three other production system budgets were available: grazing (unfertilized), grazing (fertilized), and organic.

Table 18. Comparison of farm nitrogen budget results for Timbercreek Organics Farm (TCO) and farms from the literature. The number of farms represented in a category is reported, although some of the farms represented were averages themselves. See Appendix C for detail about individual farm N budgets.

Type	Category	Number of farms	Intended inputs (kg N ha^{-1} yr^{-1})	Intended outputs (kg N ha^{-1} yr^{-1})	N Surplus (kg N ha^{-1} yr^{-1})	NUE (%)	NUE Std. dev. (%)	Data source
TCO	TCO: 2012	1	32	5	28	14%	N/A	1
TCO	TCO: 2013	1	49	14	35	28%	N/A	1
Pork	Conventional	34	453	178	275	38%	6%	2,3,4,5
Beef	Conventional	27	172	46	127	24%	4%	2
Beef	Grazing: Unfertilized	5	97	20	76	18%	13%	4,5,6
Beef	Grazing: Fertilized	2	386	44	343	12%	7%	5,6
Beef	Organic	1	N/A	N/A	N/A	20%	3%	7
Poultry	Conventional	2	N/A	N/A	N/A	55%	6%	4,5,8
Layers	Conventional	1	N/A	N/A	N/A	35%	N/A	5

Sources: (1) Zach Miller, personal communication; (2) Bassanino et al. 2007; (3) Nielsen & Kristiensen 2005; (4) Domburg et al. 2000; (5) Oenema 2006; (6) Watson & Atkinson 1999; (7) Watson et al. 2002; (8) Schröder et al. 2003.

On a per-hectare basis, the farm N inputs and outputs at TCO were substantially lower than beef and pork N flows in budgets from the literature (Figure 11). For example, the TCO N inputs in 2013 were less than 50 kg N ha^{-1} yr^{-1}, whereas the intended N inputs for beef and pork farms ranged from 97 kg N ha^{-1} yr^{-1} (an unfertilized beef grazing farm) to 453 kg N ha^{-1} yr^{-1} (a conventional pork farm). Nitrogen input and output data for the poultry and layer farms were unavailable on a per-hectare basis because these budgets only reported total N flows at the farm scale.

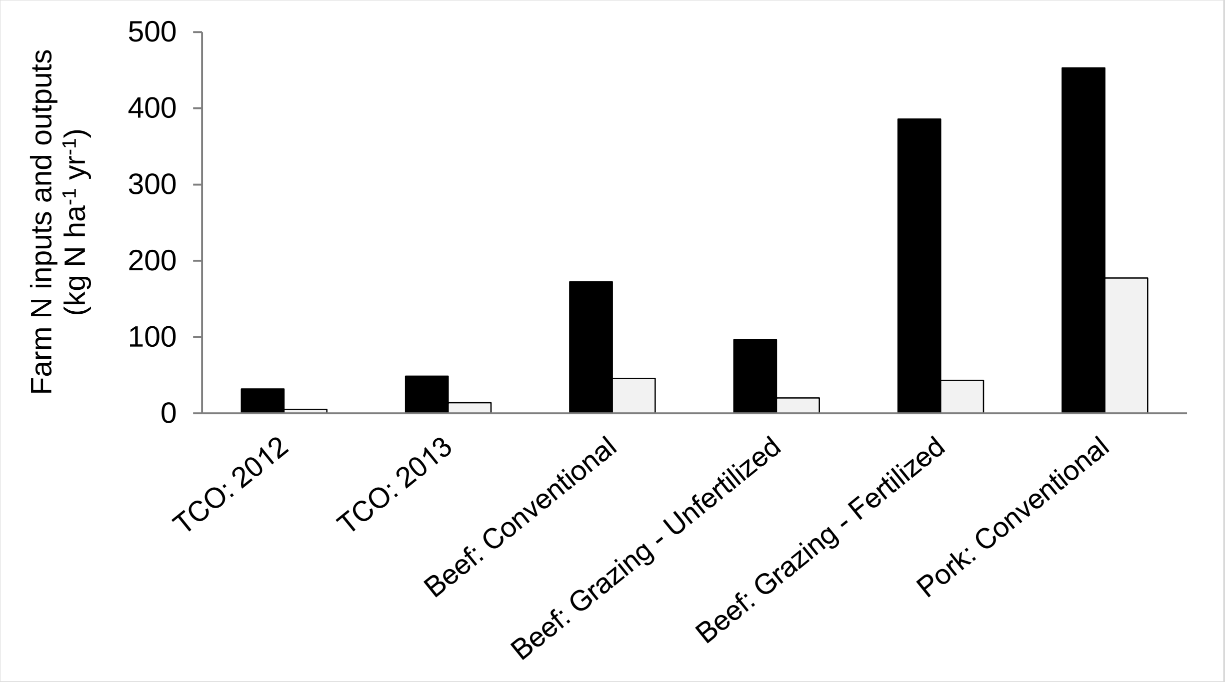


Figure 11. Comparison of intended farm nitrogen inputs (black bars) and intended farm nitrogen outputs (gray bars) for Timbercreek Organics Farm (TCO) and different types of beef and pork farms in kg N ha^{-1} yr^{-1}. Input and output data were unavailable for poultry and layer farms.

When the farm NUE were compared, the TCO results were more similar to the farms from the literature (Figure 12). The lowest average NUE of the farms from the literature was the fertilized beef grazing farm (12%), although its standard deviation overlaps with both the organic and unfertilized grazing beef farms. Of the beef farms from the literature, the conventional farm had the highest NUE (24%). This NUE is comparable to that of TCO in 2013 (28%). The conventional pork, poultry, and layer farms had NUE ranging from 35% to 55%, exceeding the NUE of TCO. The highest NUE of all of the farming systems was for the conventional poultry farm (55%).

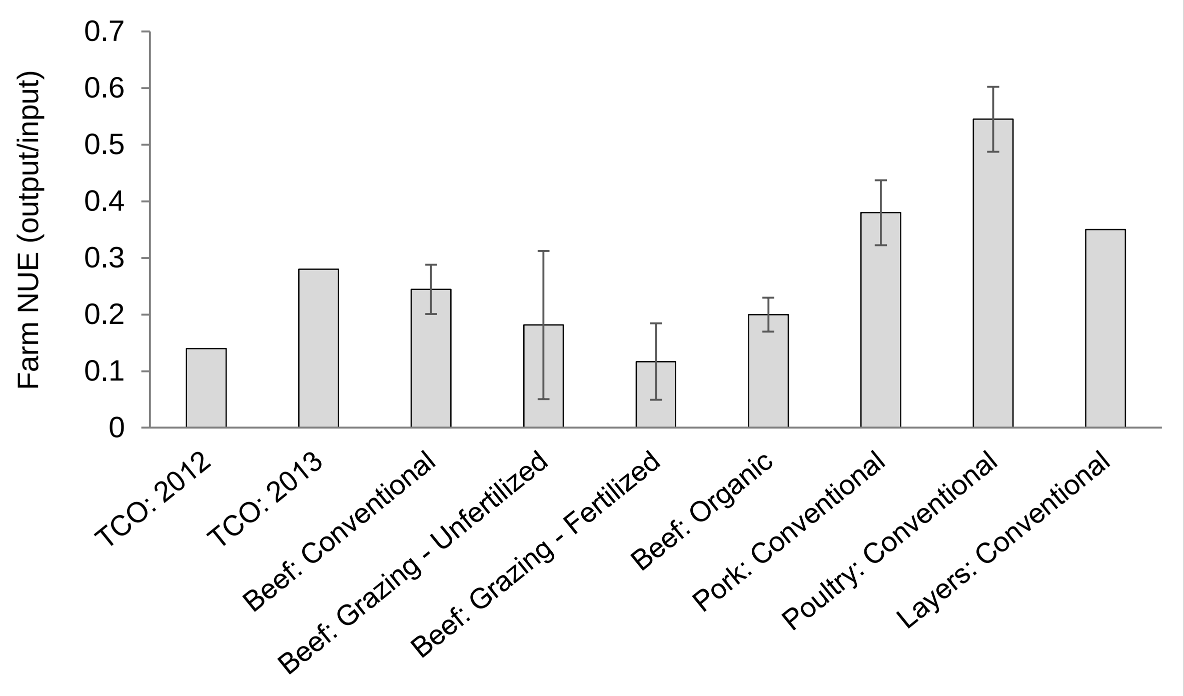


Figure 12. Comparison of farm nitrogen use efficiency (NUE) for Timbercreek Organics Farm (TCO) and different types of beef, pork, poultry, and layer farms. Error bars represent standard deviation when available.

3.1.4. Comparison to a farm nitrogen budget constructed from average livestock feed requirements

The TCO farm N budget was also compared to a farm N budget constructed from average livestock feed requirements for conventional systems from Oenema et al. 2006. All farm N outputs and most of the farm N inputs were set equal to TCO; the only factor that was varied was the feed N inputs. The predicted feed requirements were higher than the actual feed purchased at TCO in both 2012 and 2013 (Figure 13). However the difference was greatest in 2013 when the actual feed purchase was 7 t N yr^{-1} and the predicted feed requirement was 23 t N yr^{-1}. The increased feed requirements in the constructed budget greatly reduced the NUE in comparison to TCO (Table 19). In 2012, the TCO NUE (14%) was slightly greater than that for the constructed budget (11%). However in 2013, the TCO NUE (28%) was much greater than that for the constructed budget (10%).

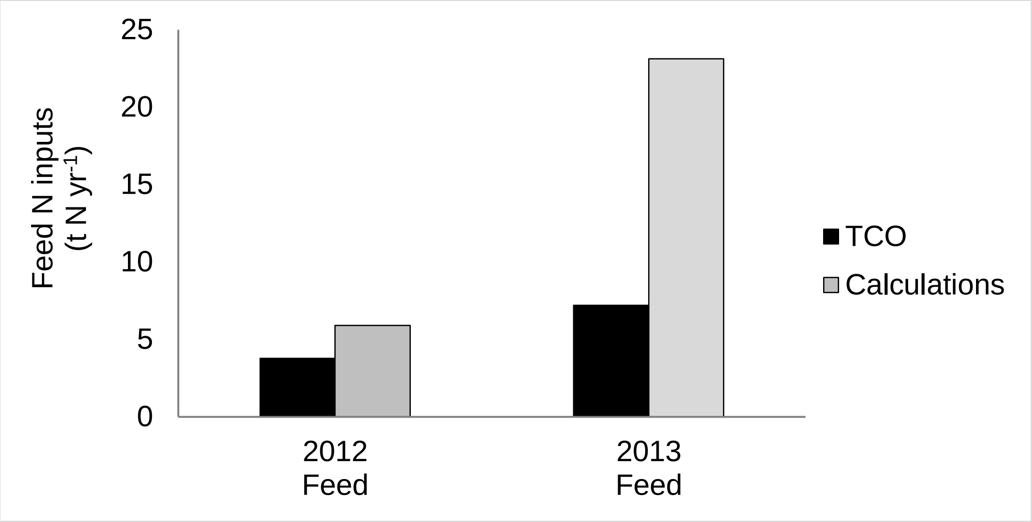


Figure 13. Comparison of feed nitrogen actually used at Timbercreek Organics Farm (black bars) to calculated feed requirements based on the meat and animal products produced and Timbercreek Organics Farm and feed conversion ratios (gray bars).

Table 19. Comparison of farm nitrogen inputs, nitrogen outputs, and nitrogen use efficiency (NUE) of Timbercreek Organics Farm (TCO) in 2012 and 2013 to a constructed farm N budget based on livestock feed requirements in Oenema et al. 2006. All N inputs and outputs in the constructed N budget are set as equal to those at TCO except for the feed requirements.

N metric	2012		2013	
	TCO	Constructed budget	TCO	Constructed budget
	t N yr^{-1}	t N yr^{-1}	t N yr^{-1}	t N yr^{-1}
Feed	3.8	5.9	7.2	23.1
Other N inputs	1.5	1.5	0.9	0.9
N outputs	0.8	0.8	2.3	2.3
NUE	14%	11%	28%	10%

In summary, farm N budgets for TCO in 2012 and 2013 were compared to farm N budgets from the literature using two approaches (compiled directly from the literature and constructed based on conventional feed recommendations). For the first approach, the TCO N surplus per unit area was 2-10 times lower than that for the pork, beef, poultry, and layer farms from the literature. However the TCO NUE was comparable to that of beef farms with different production methods, but lower than that of conventional pork, poultry, and layer farms. For the second approach, the NUE of TCO was 20% to 60% greater than the NUE for the constructed N budget based on feed requirements—especially in 2013 when the TCO NUE was almost 3 times greater than that of the constructed budget. These results imply that TCO overall is as efficient as conventional farms in terms of nitrogen, especially when considering the more efficient 2013 NUE. Potential reasons will be discussed in section 4.

3.2. Results for question 2: What are the virtual nitrogen factors (i.e., food production nitrogen losses) for pig, beef-cattle, poultry, and egg production at Timbercreek Organics? How do these losses compare to conventional farm virtual nitrogen factors (i.e., food production nitrogen losses) in the United States?

3.2.1. Virtual nitrogen factors for Timbercreek Organics Farm

The VNF step factors that varied the most among livestock types and in comparison to conventional production were steps 1 (feed crop N uptake), step 3 (live animal production), and step 4 (slaughter/first processing). The TCO factors for step 2 (feed crop processing) were set as equal to those for conventional production. The TCO factors for step 3 (final processing) were set to 100% because all slaughter losses were accounted for in the previous step.

In step 1 of the TCO VNF calculation (crop N uptake), the weighted feed crop N uptake was calculated using conventional crop N uptake percentages and the livestock-specific feed mixture used by TCO (Appendix E). The largest crop N uptake was for layers (87%) due to the dietary emphasis on soybeans and corn; the crop N uptake was lowest for poultry (79%) due to the incorporation of fishmeal in the diet.

In step 3 of the VNF calculation (live animal production), the following two methods were used to calculate the % N converted from feed into live animal weight: (1) based on actual feed use and (2) based on theoretical feed requirements (Table 20, Appendix E). For the first method, layers had the lowest conversion efficiency in 2012 (11%), followed by poultry (14%), pigs (22%), and cattle (24%). The same rank order occurred in 2013, but the efficiency for all products except layers increased. The efficiency for beef cattle increased beyond 100% due to the low inputs of purchased hay and legume BNF. For calculation method two (theoretical feed requirements), the rank order changed: eggs were still the lowest (17%), followed by pigs (19%) and poultry (35%). This method was not used to calculate the beef VNF. All feed conversion efficiencies calculated with method 2 were greater than method 1 except for pigs.

Table 20. Average feed conversion efficiency at Timbercreek Organics in 2012 and 2013. Calculated factors describing the conversion of feed into live animal weight for pork, beef, poultry, and layer production at Timbercreek Organics Farm. These data are used for step 3 (live animal production) of the virtual nitrogen factor calculation. Data used for uncertainty ranges can be found in Appendix E.

Meat/animal product	Feed conversion efficiency: Method 1, Actual feed use		Feed conversion efficiency: Method 2, Theoretical feed requirement
	2012	2013	(Same both years)
Pork	22%	31%	19%
Beef	24%	100+%	N/A
Poultry	14%	18%	35%
Eggs	11%	8%	17%

For step 4 of the VNF calculation, the N retained during the slaughter process was calculated. The lowest N retention from live weight to meat product was observed in cattle (48%), followed by pork (53%) and poultry (69%) (Appendix E). It was assumed that N retention during this step for egg production was 95% due to potential inefficiency in egg collection or transport.

The average VNF for pork, poultry, and eggs produced at TCO varied between 2012 and 2013 and also varied based on which of the two calculation methods were used (Figure 14). Based on VNF calculation method 1 (i.e., based on actual feed use at TCO), the average pork VNF decreased from 3.6 in 2012 to 2.5 in 2013. The poultry VNF also decreased (5.7 to 4.4), but the egg VNF increased (4 to 5.5). Using method 1, pork had the lowest overall average VNF, followed by poultry and eggs. However when considering VNF calculation method 2 (i.e., based on feed requirements), the rank order for the meat and animal products was different. Poultry had the lowest VNF (2.2), followed by eggs (2.6) and pork (4.2).

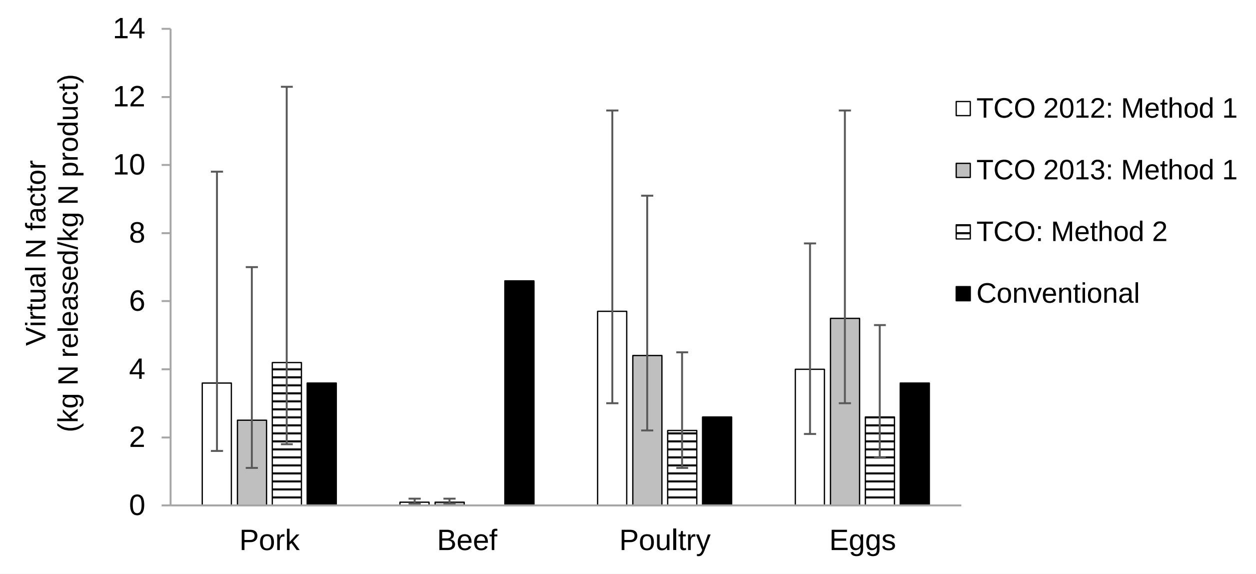


Figure 14. Comparison of virtual nitrogen factors for pork, beef, poultry, and egg production for Timbercreek Organics Farm (TCO) in 2012 and 2013 and conventional farms in the United States. Two different calculation methods of the virtual N factors for TCO are presented: (1) Total feed use at the farm, which is different in 2012 and 2013; and (2) Feed recommendations per head of livestock, which is the same in 2012 and 2013. Uncertainty range represent the range of factors possible based on minimum and maximum protein content, feed, and legume biological nitrogen fixation. The uncertainty range was not available for conventional virtual N factors.

Of the four food items produced at TCO, beef had the lowest virtual N factor (0.1) in both 2012 and 2013 (Figure 14). The TCO beef VNF was lower than the US conventional production beef VNF of 6.6—the highest of all conventionally produced meat and animal products in the US. VNF calculation method 2 was not used to calculate the beef VNF because feed recommendations are not used at TCO for the grass-fed cattle.

The calculated uncertainty range for the pork, poultry, and eggs VNF was large. When considering the uncertainty calculated for TCO, the range of possible VNF for the pork, poultry, and eggs produced at TCO overlapped with the VNF for conventional production, suggesting that TCO production is as efficient as conventional on a per-product basis.

3.2.2. Comparison of virtual N factors for Timbercreek Organics Farm to other countries

The TCO VNF were also compared to the VNF for other countries (Figure 15). The TCO VNF calculated using method 1 (i.e., based on actual feed use) were compared to the VNF for conventionally produced meat and animal products in the US, Europe, Austria, Japan, and Tanzania. The beef VNF for TCO (0.1) was much lower than that for any other country. Other than TCO, the lowest beef VNF was 4.5 (Austria) and the highest was Japan (8.4). The average poultry VNF for TCO (5.7 in 2012 and 4.4 in 2013) was higher than any other country. In most countries, poultry had the lowest VNF, ranging from 0.8 (Tanzania) to 4.1 (Japan). The egg VNF at TCO was also higher than most countries. The 2013 pork VNF at TCO (3.6 in 2012 and 2.5 in 2013), however, was less the other country’s pork VNF, which ranged from 2.9 (Austria) to 4.4 (Japan).

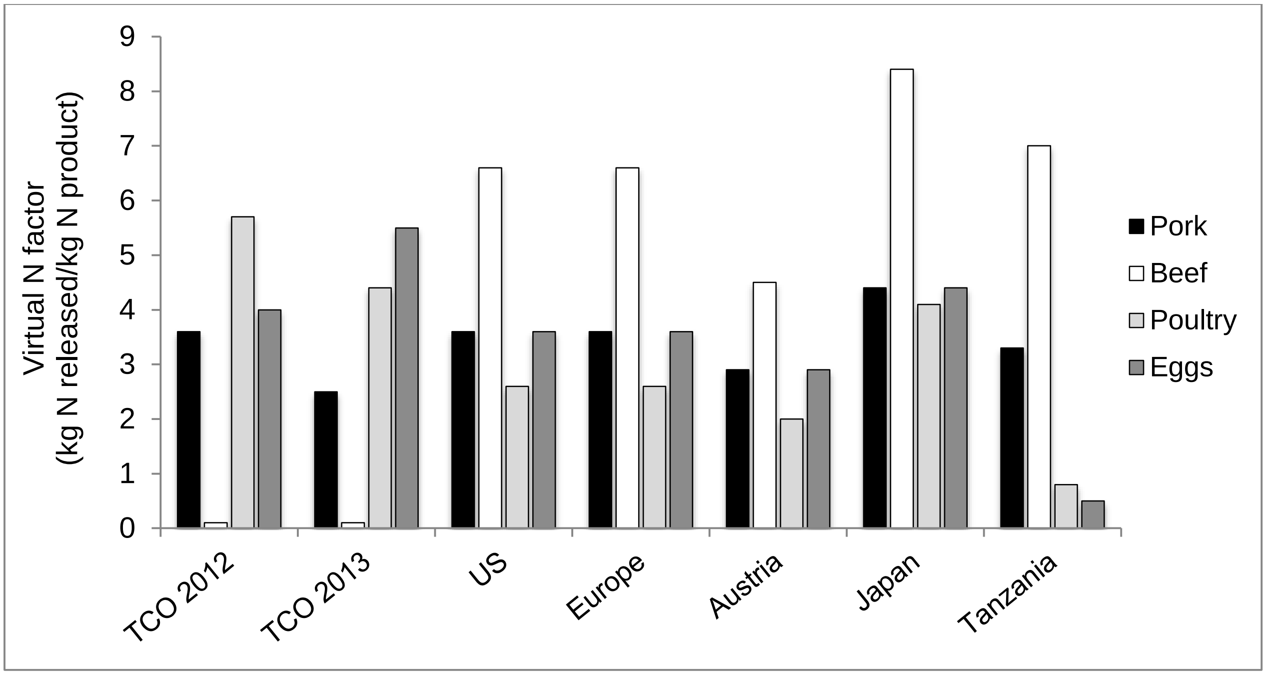


Figure 15. Comparison of virtual nitrogen factors for pork (black bars), beef (white bars), poultry (light gray bars), and egg production (dark gray bars) at Timbercreek Organics Farm in 2013 to virtual nitrogen factors for conventional production in the United States, Europe, Austria, Japan, and Tanzania. All virtual N factors are for edible food products; food waste is not considered. Virtual N factors for Timbercreek Organics were calculated based on actual feed use and meat production flows (i.e., VNF method 1).

In summary, virtual nitrogen factors were developed for pork, beef, poultry, and egg production at TCO in 2012 and 2013 and compared to established VNF for conventional production in the US, Europe, Austria, Japan, and Tanzania. The average TCO beef VNF was by far the lowest TCO VNF (0.1) and was less than that of any other country. The average TCO pork VNF decreased between 2012 and 2013, when it was the lowest of any of the countries considered. The average TCO poultry and egg VNF were both greater than most of the comparison countries. When the calculated uncertainty of the TCO VNF is considered, the TCO and conventional VNF are comparable for all food products except beef. These results imply that TCO pork and beef production are as efficient as conventional production in developed countries on a per-product basis. Poultry and egg production may be as efficient when the calculated uncertainty is considered.

4. Discussion

4.1. Discussion for question 1: How does the farm nitrogen budget of Timbercreek Organics (a permaculture livestock farm) compare to that of conventional livestock farms?

4.1.1. Timbercreek Organics Farm nitrogen budget

4.1.1.1. TCO farm N budget: Inputs, outputs, and nitrogen use efficiency

The TCO farm intended N inputs increased by 53% from 5.3 t N yr^{-1} in 2012 to 8.1 t N yr^{-1} in 2013, but the intended N outputs increased by 188% from 0.8 t N yr^{-1} in 2012 to 2.3 t N yr^{-1} in 2013 (Figure 8; Table 15). As a result, the farm N surplus in 2012 (4.6 t N yr^{-1}) increased by just 26% in 2013 (5.8 t N yr^{-1}). Despite the large increase in the intended N inputs, the intended N outputs more than doubled, which improved the farm efficiency overall.

With the markedly increased intended N outputs in 2013, the TCO NUE increased from 14% in 2012 to 28% in 2013 (Figure 12; Table 15). The largest N input to the farm in both 2012 and 2013 was feed. Farm N outputs also grew between 2012 and 2013, but they increased more than feed N inputs. Beef production made up 32% of total farm N meat and animal product production in 2012; this grew to 46% in 2013. With a 350% increase in total beef production between 2012 and 2013, beef is the fastest-growing product from TCO. Given that beef production grew considerably and that beef do not require feed N inputs other than small purchases of hay, it is likely the increased beef production led to the observed increase in NUE.

There is a high level of confidence associated with all purchased farm inputs (i.e., feed, hay, livestock, bedding, and energy use). Despite this, future studies of the TCO N budget should better characterize the uncertainty associated with reported farm N flows. The current uncertainty estimates generally only capture the range of protein contents associated with the inputs and outputs. Future studies should consider the potential uncertainty associated with the actual flows, such as the amount of feed or bedding purchased.

The legume BNF estimate has a low level of certainty. A range of estimates (0 to 5.3 t N yr^{-1}) was presented (Table 14). This large range likely represents the full spectrum of legume BNF possible at the farm based on the vegetation survey. Given that very few effective root nodules were observed in the collected samples, it is unlikely that the N-fixation rate would be on the upper end of the reported range. In addition, the maximum N-fixation rates describe fields where effective legumes dominate the vegetation, which was found not be the case at TCO. However, pockets of high rates of N fixation that were not observed in the survey could lead to a higher N-fixation rate than was used in this study. More research is needed to better characterize the legume N-fixation rate at TCO.

4.1.1.2. TCO farm N budget: Land utilization and time requirements

In addition to the actual farm N inputs and outputs, other metrics describing the farm production efficiency (i.e., land utilization and time required) were considered. Despite its contribution to increasing the NUE, beef production's land and time requirements must also be considered. Of the three meat products at TCO, beef cattle used the second most land in 2012 (52 m^2/kg meat) and in 2013 (17 m^2/kg meat) (Figure 10; Table 17). Egg production used the most land in both 2012 (59 m^2/kg meat) and in 2013 (35 m^2/kg meat), probably due to the lower product weight for eggs in comparison to the other TCO products.

The land utilization per kg meat decreased substantially for all meat types between 2012 and 2013 because of the higher meat production rates in 2013. The farm has not yet achieved its maximum stocking capacity, as described by permaculture farming principles (Zach Miller, personal communication). The land utilization per kg meat could theoretically continue to decline with higher stocking rates of livestock and with higher farm production rates. However, increasing production indefinitely would lead to a greater local environmental impact. Higher stocking rates could reduce the vegetation coverage and impair the soil and water quality (Steinfeld et al. 2006). The farmers could continue to reduce the land utilization metric, but care should be taken to avoid intensified local environmental consequences.

The grazing land shared between cattle, poultry, and layers was distributed among the three livestock types by product weight. The estimate could be improved by considering the amount of time spent on the land by the livestock types, but these data were unavailable. The current estimate probably underestimates land utilization for cattle and overestimates land utilization for poultry and layers because the cattle move through larger areas of land more quickly.

The time required to produce one kg of live weight was the lowest for beef (1.4 days) followed by pigs (1.9 days) and poultry (21 days) (Table 16; Figure 9). It was unexpected for beef cattle to have the shortest time required per kg of live weight. Beef cattle have the longest lifespan of two years, but they also reach the highest live weight at slaughter; these two factors reduce the time required per unit produced. The poultry time-required metric was the greatest by far because of the much lower live weight that poultry reach. The TCO poultry only have a lifespan of 56 days, but they also only weigh 2.7 kg, leading to the relatively higher time-required metric.

The data for the land-utilization and time-required metrics for TCO were directly from farm data. However because much of the land was shared, the metrics for the livestock that share the land were uncertain. The time-required metric was in units of days/kg live weight. Had the metric been in units of days/kg meat, the time required would have increased due to losses during the slaughter process. However the units in live weight were used to focus solely on raising the live animal (and therefore ignoring potential inefficiencies in the slaughter process) and to be comparable with the units for conventional farms.

In summary, the results of the 2012 and 2013 TCO farm N budget show that TCO increased both its production and its NUE between 2012 and 2013, both of which are largely due to increased production of grass-fed beef cattle. TCO also reduced its land utilization per kg meat for all livestock types between 2012 and 2013.

4.1.2. Comparison of TCO N budget to conventional farm nitrogen budgets

4.1.2.1. Approach 1: Comparison to literature farm nitrogen budgets

The 2013 TCO NUE (28%) was comparable or exceeded that of beef farms considered in this study, but the TCO NUE was less than that of conventional pork, poultry, and layer farms (Figure 12). The 2012 TCO NUE (14%) was lower than most farm types. The TCO NUE describes overall farm production: pork, beef, poultry, and eggs. Given that the TCO NUE accounts for these four different products, it would be expected that the TCO NUE would represent an average efficiency of these four individual meat and animal products. The 2013 TCO NUE does in fact fall within the range of NUE reported from literature studies for a variety of livestock types. This suggests that the permaculture method of farming could produce meat and animal products as efficiently as conventional farms, in terms of nitrogen.

Although the TCO NUE is comparable to other farms, TCO uses more time and land than the comparison farms from the literature (Tables 16; Table 17). The time requirement per unit of live weight was moderately elevated for TCO, ranging from requiring 15% to 75% more days to produce 1 kg live weight at TCO. However the land utilization at TCO was much larger than conventional for some products, ranging from using 37% (pork) to 720% (eggs) more land than conventional production. However, TCO beef production used 95% less land than conventional, likely due to the large feed land area requirements associated with conventional beef production. TCO's farm N production per unit area was, on average, 20% lower than that of conventional farms. Given the generally increased time and space requirements at TCO coupled with lower production per unit area, such a farming method is unlikely to meet increasing global demands for meat and animal products without negative impacts to ecosystem and human health. For example, increased land utilization would require extensification, which can lead to deforestation and climate change (Foley 2011). However, permaculture farms like TCO could replace a small percentage of conventional production while maintaining a comparable NUE.

The TCO N input per hectare of land was lower than any other farm in this comparison study (Figure 11; Table 18). The TCO N surplus was 28 kg N ha^{-1} yr^{-1} in 2012 and 35 kg N ha^{-1} yr^{-1} in 2013, which was 2-10 times less than any of the comparison farms. The lower TCO N surplus shows that TCO has much lower nitrogen losses to the environment per unit area and therefore a greatly reduced local environment impact than conventional farming. The reduced N surplus at TCO is probably due to lower stocking rate than the comparison farms. Such a method is central to permaculture farming. TCO allows at least 4-6 weeks for vegetation to recover between grazing events to maintain the vegetation cover and reduce erosion. This method does require more land, but it avoids releasing as concentrated an amount of nitrogen as the comparison conventional farms from the literature. Although TCO does have a reduced farm productivity per unit area, TCO also has a reduced nitrogen impact per unit area (2-10 times lower than conventional), which limits negative impacts to local ecosystem and human health.

4.1.2.2. Approach 2: Comparison to constructed farm N budget

The constructed farm N budget (i.e., approach 2) is likely the better comparison to Timbercreek Organics Farm than the literature budgets (i.e., approach 1) because its production volume and products are set equal to TCO. The constructed budget represents the same types of livestock as TCO in the same proportions and quantities. The actual feed use at TCO was much lower than the predicted feed requirements based on conventional feed recommendations: the TCO actual feed use was 56% lower in 2012 and 220% lower in 2013 (Figure 13; Table 19).

The grass-fed cattle at TCO can explain the majority of the difference in TCO actual feed use compared to the calculated conventional feed recommendation. The constructed budget assumed that the TCO cattle consumed grain feed, which is typical of conventional farms. However, cattle at TCO are entirely fed by grass and hay. This finding could also suggest that TCO livestock are consuming less feed, which means they may reach a lower slaughter weight than their conventional counterparts or require more time to reach slaughter weight. The average slaughter weight at TCO is generally comparable to that of conventional (Figure 9; Table 16). However the time required to produce TCO products was found to be 15-75% greater than that of conventional, which could explain TCO’s lower feed requirements than conventional. TCO livestock that consume feed (i.e., pigs, poultry, and layers) could also be obtaining some of their nutrients from natural sources, such as grass, insects, and acorns. The percent contribution of natural forages to the livestock diet could help explain the growth and efficiency of TCO livestock; however, these data are currently unavailable and should be explored in future studies.

4.1.2.3. Uncertainty and implications of results

Limited farm N budgets were available in the literature. In particular, budgets describing only conventional farming systems were available for pork, poultry, and eggs. Farm budgets for these products describing alternative farming systems (e.g., organic, grazing) would have provided more context for the comparison to TCO. Many of the budgets available from the literature were for international farms, especially in Europe, probably due to mandated nutrient management plans for European Union food production (Dalgaard et al. 2012). Although the climates, soils, and production methods in these countries generally differ than those in the US, this comparison is still valid due to international trade. In addition, conventional production in the developed world is generally similar, as shown by the country VNF comparison (Figure 15).

In summary, these results imply that overall average animal protein production at TCO is as efficient as conventional beef production but could be less efficient than conventional pork, poultry, and layer production. Additionally, TCO also requires more time and land than conventional production, the latter of which can have negative impacts to ecosystem and human health.

4.2. Discussion for question 2: What are the virtual nitrogen factors (i.e., food production nitrogen losses) for pig, beef-cattle, poultry, and egg production at Timbercreek Organics? How do these losses compare to conventional farm virtual nitrogen factors (i.e., food production nitrogen losses) in the United States?

Virtual N factors were developed for pork, beef, poultry, and egg production at TCO in 2012 and 2013 using two approaches: (1) actual feed use and (2) theoretical feed recommendations. The TCO VNF calculation and comparison to VNF for conventional production suggest that TCO beef and pork production are at least as efficient as conventional, whereas poultry and egg production have a comparable efficiency to conventional production.

VNF for meat and animal products were originally developed to describe conventional production for which feed (e.g., grain) is grown and fed to livestock (Leach et al. 2012). The VNF concept had not yet been applied to grass-fed livestock. Because the TCO cattle do not consume grain feed, the only inputs for the beef VNF were legume BNF and hay. These inputs ignore any stored N on the property that went into growing the vegetation that the cattle then ate. This means that the beef VNF is likely an underestimate of the actual Nr losses associated with beef production. The current calculation meets the definition and methodology of the VNF, but the VNF concept was developed to describe conventional production. The VNF methodology should be expanded to account for other sources of N inputs, such as grass for grass-fed beef.

The crop N uptake factors for conventional feed production were used to describe TCO feed production (Appendix E). Although TCO did purchase conventional feed in 2013, organic feed was purchased in 2012. The crop N uptake factors for organic production would likely be lower than conventional due to the reduced yields for organic agriculture (Badgley et al. 2006, Seufert et al. 2012), which would increase the overall organic VNF. However, organic crop N uptake factors are not yet available for the VNF.

The calculated feed conversion efficiency for pigs, poultry, and layers at TCO (Table 20) may appear to be higher than it is (and VNF lower than they actually are) because feed conversion efficiency only considers feed N inputs. None of the natural forages (e.g., insects and grass for poultry, acorns for pigs) are accounted for in the calculation. This is considered “free nitrogen” in this system.

For all TCO VNF, it was assumed that 100% of manure is recycled through direct application to the farm fields or through composting (Appendix E). Although the manure is indeed recycled in this way, it is not recycled for feed grain production. The conventional VNF, which are based on inputs of feed, assume that 35% of manure is recycled and that it goes towards feed grain production for the next iteration of livestock production. The manure recycling factor for conventional production is lower because large volumes of manure are produced and the manure often must be collected and transported before application to feed crops (Leach et al. 2012). If the TCO VNF required that manure must be recycled for feed grain production (and therefore be collected and transported), the manure recycling rate would be lower and the VNF would be higher because losses would occur during manure collection and transport. The definition for VNF should be expanded to more directly account for grazing systems and their associated N pathways.

Calculation method 1 (i.e., actual feed use) is likely a better representation of the actual VNF than calculation method 2 (i.e., feed recommendations used by TCO) because the former uses real feed purchase data. However the difference between the two can help inform farmers about inefficiencies on the farm. For example, in the case of pork, the average VNF for method 1 is lower than for method 2, suggesting that TCO is using less feed N for the pigs than their feed mix recommendations suggest (Figure 14). On the other hand, in the case of both poultry and eggs, the average VNF for method 1 is greater than method 2. This suggests that TCO is actually using more feed for these poultry and layers than their feed mix and recommendations suggest. This discrepancy for poultry and egg production suggests that the amount of feed allocated towards poultry and egg production is too high or that there are inefficiencies in delivering the feed, such as feed spills.

The comparison between TCO VNF and VNF for other production systems and countries helped put TCO into context with international animal protein production. The average poultry and egg VNF at TCO are greater than those for all countries in the analysis (Figure 15). In addition, the ranking of meat/animal product VNFs within TCO is different than most countries. In all countries except Tanzania, the order generally proceeds as follows from smallest to largest: poultry, eggs, pork, and beef. However at TCO, the smallest VNF is beef, followed by pork, and either poultry or eggs depending on the year. The beef TCO VNF was substantially lower than any country due to the issues of the grass-fed beef VNF calculation discussed above.

In summary, these results suggest that average TCO meat and animal production is as efficient as conventional production on a per-product basis. However, the TCO VNF could be over-estimated (e.g., due to the assumption of conventional feed processing efficiency). It is more likely that the TCO VNF are underestimated (e.g., due to the conventional crop N uptake factors or the exclusion of natural forages as feed N inputs); the level of uncertainty is high. To help address this, the VNF definition and calculation should be expanded to better represent grazing farms like TCO.

4.3. Potential pathways for the N surplus at Timbercreek Organics Farm

This study did not address what happens to the nitrogen surplus (i.e., the difference between intended inputs and outputs) at TCO. To consider all potential Nr losses to the environment, the unintended N inputs (i.e., atmospheric deposition) must also be considered. The difference between the total farm N inputs (including atmospheric deposition) and intended farm

N outputs was 32 kg N ha^{-1} yr^{-1} in 2012 (87% of total N inputs) and 39 kg N ha^{-1} yr^{-1} in 2013 (74% of total N inputs) (Table 15). The fate of this nitrogen is very important in determining whether this nitrogen will have detrimental impacts to human or ecosystem health. There are four major possible pathways for this nitrogen surplus:

1. Volatilization to the atmosphere as NH_3 or N_2O
2. Leaching to the groundwater or runoff to streams as NO_3^-, NO_2^-, NH_4^+, or organic N
3. Denitrification in the soils or in the groundwater or stream water
4. Storage on the property in the soils, in the vegetation, and/or in a holding pond

It is likely that some of the nitrogen surplus meets each of these fates. However the proportions at TCO are unknown.

Detailed farm N budgets from the literature quantify these different N loss pathways. Two studies of fertilized beef grazing farms and three studies of unfertilized beef grazing farms measured the ammonia loss, leaching and runoff losses, and denitrification in units of kg N ha^{-1} yr^{-1} (Table 21). For all of these beef N budgets, leaching/runoff was the largest quantified N loss, followed by ammonia volatilization and denitrification. For example for the two fertilized beef farms, the leaching losses (160 and 218 kg N ha^{-1} yr^{-1}) were 1-3 times greater than their respective NH_3 losses (80 and 60 kg N ha^{-1} yr^{-1}) and 3-7 times greater than denitrification losses (40 and 28 kg N ha^{-1} yr^{-1}). The fertilized beef grazing farms had much greater N losses than the unfertilized grazing farms for all loss pathways: leaching/runoff (1-43 times greater), NH_3 losses (1-23 times greater), and denitrification (1-19 times greater).

Table 21. Detailed farm nitrogen budgets from the literature that quantify unintended nitrogen loss pathways from beef farms, including manure export, ammonia volatilization, leaching/runoff, and denitrification. Farm N inputs and intended N outputs are reported for Timbercreek Organics Farm (TCO) in 2012 and 2013, but unintended N loss pathways were not measured.

Farm type	Production method	Farm N inputs (kg N ha^{-1} yr^{-1})		Farm N outputs (kg N ha^{-1} yr^{-1})				Inputs – outputs (kg N ha^{-1} yr^{-1})
		Intended	Atm. dep.[a]	Intended	NH_3 loss	Leaching and runoff	Denitri-fication	
Beef [1]	Grazing: Fertilized	420	15	29	80	160	40	126
Beef [2]	Grazing: Fertilized	352	15	58	60	218	28	0
Beef [1]	Grazing: Unfertilized	8	12	3	3	5	2	10
Beef [1]	Grazing: Unfertilized	160	15	23	10	23	4	115
Beef [2]	Grazing: Unfertilized	209	12	52	45	109	15	0
TCO	2012	32	4	5	N/A[b]	N/A[b]	N/A[b]	N/A[b]
TCO	2013	49	4	14	N/A[b]	N/A[b]	N/A[b]	N/A[b]

[a] *Atm. dep. = Atmospheric deposition*

[b] *Indicate nitrogen flows not measured for TCO*

Sources: (1) Oenema 2006; (2) Watson 1999

The difference between total farm N inputs and total measured farm N outputs was calculated for the detailed beef farm N budgets (Table 21). Two of the N budgets had a difference of 0, meaning that all N flows were balanced and captured in the study. However the remaining three budgets still had a surplus; these ranged from 10 to 126 kg N ha^{-1} yr^{-1}. This remaining N surplus could be lost via another N pathway (e.g., manure exports), it could be due to calculation error, or it could be stored on the farm property in the soils or vegetation. Given that the major N pathways were already accounted for and two of the values (126 and 115 kg N ha^{-1} yr^{-1}) were probably too large to be due to calculation error, it is likely that this remaining balance is stored on the farm properties.

These findings can be applied to TCO to better understand potential N loss pathways. The difference between the total farm N inputs and intended farm N outputs at TCO was 32 kg N ha^{-1} yr^{-1} in 2012 and 39 kg N ha^{-1} yr^{-1} in 2013; this can be described as the remaining N surplus whose fate is one of the four possible pathways described above (i.e., volatilization, leaching/runoff, denitrification, storage). The literature beef farm N budgets (Table 21) suggest that the largest N loss pathway on grazing livestock farms is N leaching and runoff. However an exploratory analysis of stream water nitrogen fluxes on TCO (see Section 5) suggested that TCO is not responsible for adding much inorganic nitrogen to the streams and that the farm may in fact be a sink for inorganic nitrogen. Given that TCO stream water N losses were low, it could be expected that all TCO N losses to the environment are low. This possibility is confirmed by TCO's N surplus per unit area, which was 2-10 times lower than that of conventional farms (Table 18). These results suggest that TCO is having a small nitrogen impact on its local environment.

In addition to the N loss pathways described above, another possible fate of the remaining N surplus at TCO is storage on the farm property. Some nitrogen storage is considered probable for three reasons. First, the property has strong vegetation coverage throughout the year, which can reduce N leaching and runoff. This substantial vegetation coverage would also have high nitrogen demands and would be expected to assimilate NO_3^- from the soils. Second, the soils at TCO are dominated by loam (80%) and clay loam (20%), as reported by the USDA-NRCS Web Soil Survey (USDA-NRCS 2010). Both clay and organic matter have a negative charge, which give the soil the capacity to retain positively charged ions like NH_4^+ (Martel et al.

1978). The TCO soils do have some clay and could contain organic matter given the farm activity, although the organic matter content is unknown. The soils therefore have the capacity to retain some NH_4^+ but not NO_3^-, which makes up the majority of the inorganic N species observed in a stream water analysis at TCO (see Section 5). Finally, the stream water analysis suggests that the TCO property is not adding nitrogen to the stream water for most of the year. In fact, more N may be entering the property via the streams than exiting the property, implying that some of this nitrogen could be stored on the property.

In summary, the unexplained N surplus at TCO was 32 kg N ha^{-1} yr^{-1} in 2012 (83% of total inputs) and 39 kg N ha^{-1} yr^{-1} in 2013 (74% of total inputs). Based on detailed farm N budgets from the literature, the most likely N loss pathways in decreasing order are leaching/runoff, ammonia volatilization, and denitrification. Given the strong vegetation coverage, soil characteristics, and exploratory stream water analysis, it is expected that some nitrogen is stored on the property, although further study is needed to understand the magnitude of potential N storage.

4.4. Future work

The vegetation survey can be expanded to improve the accuracy of the BNF estimate. More transects should be taken in each field, and the survey should be conducted in different seasons. More legume samples should be collected to obtain a more accurate estimate of effective root nodules.

TCO emphasizes rotational grazing. This method allows the livestock to obtain some of their nutrients from natural forage, insects, and other natural sources. A question that would be important to better understand the nitrogen efficiency of permaculture farms and other grazing farms is the contribution of natural feed sources to livestock overall nutrient intake. Understanding how much of the livestock nutrients come from grain feed versus other sources would also help farmers better calculate the grain feed requirements of their livestock.

Continuing to track the farm N budget going forward would capture the increasing production and the evolving management strategies. For example, TCO recently partnered with a local farmer to grow feed. They aim to meet the fertilization requirements of the crops with manure from the livestock, such as by moving the chicken coops across. Incorporating feed production into the farm N budget will alter the scope, but it will begin to close the nutrient cycling loop on the farm because it will reduce farm nutrient imports.

Flows of nitrogen within the farm could be analyzed with a soil system nitrogen budget. Such a budget would consider volatilization of ammonia, losses of nitrogen to groundwater and stream water, and denitrification. An analysis of the soil at TCO would also be important to understand the potential nitrogen loss pathways. Although the USDA Soil Web Survey provides detailed information on the texture of soils at TCO, information on the soil's nitrogen, carbon, and organic matter content would help better characterize the property. A study of soil characteristics over time would show whether the activities of the still-young TCO farm are influencing the soil quality. Perhaps most illuminating would be the quantification of nitrogen storage on the property through a detailed soil system budget.

5. The impact of Timbercreek Organics Farm on inorganic nitrogen in stream water: An initial data set

5.1. Background

To better understand nitrogen dynamics at Timbercreek Organics and to help inform the development of future research questions, an exploratory field monitoring exercise was conducted to quantify one of the pathways through which unintended reactive N losses occur. The nitrogen loss pathway considered was inorganic Nr ($NO_3^- + NO_2^- + NH_4^+$) losses to stream water. Given time and resource constraints, this field experiment just begins to characterize Nr loss pathways for the establishment of an initial data set for future hypothesis testing. The following research question was addressed:

Question 3: Does Timbercreek Organics have an influence on the inorganic nitrogen (NO_3^- *+* NO_2^- *and* NH_4^+*) concentration in the streams flowing through the property and on the nitrogen fluxes from the property?*

Existing detailed farm N budgets (Table 21) suggest that leaching and runoff is the largest nitrogen loss pathway from livestock grazing farms. Other major Nr loss pathways typically quantified, in decreasing order, are ammonia volatilization and denitrification. Of these three major unintended Nr loss pathways, leaching and runoff accounted for 50% to 70% of the quantified Nr losses for five beef grazing farms (Table 21). Leachates may not quickly enter the stream water due to topography, proximity to the streams, and soil characteristics. Despite this, the balance of stream water nitrogen fluxes at TCO provides a first look at how farm activity is affecting a major potential Nr loss pathway.

5.2. Methods

5.2.1. Stream water sample collection

Stream water samples were collected near the upstream edges and downstream edges of the TCO property. Three tributaries flow through the property (two of which join on the property), and samples were collected at seven different points to identify the flux of inorganic reactive nitrogen entering and leaving the property (Figure 16). These stream water samples were taken weekly from June 2013 through November 2013 and monthly from November 2013 through April 2014. Two gaps in the data record occurred: November 2013 through January 2014 and February 2014 through March 2014. These data gaps occurred due to operational constraints, such as limited access to the lab and snow storms.

For each sampling site and date, two 125 mL bottles of sample were collected. Two field blanks and duplicate bottles were randomly assigned to sampling sites for each water-sampling event. The field blanks were treated the same as the water sample collection bottles except that they were filled with Nanopure® water upon returning to the lab. The purpose of the field blank was to ensure that there was no contamination during the sampling process. Water samples were kept on ice in the field and in the refrigerator in the lab until sample analysis, which occurred within 6 weeks of collection.

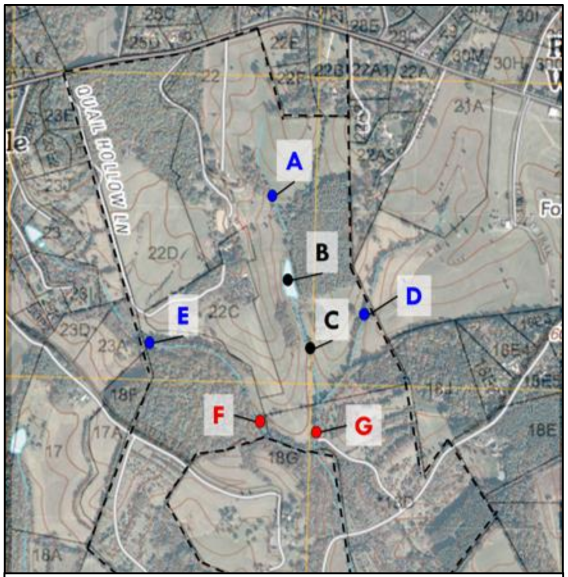


Figure 16. Stream water sampling sites on the property of Timbercreek Organics in Charlottesville, Virginia. A dashed line outlines the Timbercreek Organics property. Water sampling sites are noted with letters, where blue letters (A, E, D) indicate farm inputs, red letters (F, G) indicate farm outputs, and black letters (B, C) indicate on-farm monitoring sites.

5.2.2. Stream flow determination

In addition to water samples, measurements of stream velocity and cross-sectional area were taken at six of the sampling sites for each sampling event to determine stream discharge. Discharge measurements were not taken at site B, which is a pond. Velocity was measured with a Marsh-McBirney flow meter, and cross-sectional area was measured with width and depth measurements. The current-meter method (also called the velocity-area method) was used to calculate stream discharge (Buchanan & Somers 1969). At each stream, the channel bed shape was considered to determine how many velocity and area measurements were required. Channels were divided into rectangular subsections, and velocity and area measurements were taken for each. It was assumed that the velocity measurement in each subsection applied to that entire subsection. Rectangular-shaped channels only required one set of measurements; channels with an uneven bed required more. The velocity and cross-sectional area of each designated subsection were used to calculate the total discharge for each sampling site on each sampling event (Equation 7).

Equation 7. Stream discharge

$$Q = \sum_{i=1}^{n} w_i d_i v_i$$

Where Q = stream discharge (m^3 s^{-1}), w = stream width of given rectangular channel (m), d = stream depth of given rectangular channel (m), v = stream velocity for a given rectangular channel (m s^{-1}), and n indicates the total number of rectangular channels for a given stream.

5.2.3. Stream water sample analysis

The stream water samples were prepared for analysis by filtration in the lab within 48 hours of collection. Vacuum filtration was used with filters with a 0.45 μm pore size. Filtered water samples were placed in clean 125 mL bottles and stored in the refrigerator until lab analysis, which took place within 6 weeks of sample collection.

The water samples were analyzed for nitrate (NO_3^-) + nitrite (NO_2^-) and ammonium (NH_4^+) using a Lachat QuickChem 8500 Series Flow-Injection Autoanalyzer. At least one duplicate sample and one travel blank were run for each sampling date (i.e., at least one duplicate and one travel blank for every 7 samples) to ensure precision in the results. Results were reported in µM, which was converted to mg N L^{-1}. If the concentrations exceeded the range of analysis for the autoanalyzer based on the prepared standard solutions (i.e., greater than 45 µM), then samples were diluted and run again. Dilutions were made using Nanopure® water. After analysis, the concentrations were corrected based on the dilution.

A subset of the stream water samples was also analyzed for its organic nitrogen concentration. First, the organic nitrogen was converted to inorganic nitrogen through a digestion, which was performed by mixing 9 mL of stream water sample with 1 mL of persulfate oxidizing reagent in a glass ampule. To ensure that the digestion was occurring correctly and completely, organic standards were also mixed with the persulfate oxidizing reagent and analyzed. After the glass ampules were placed in an Autoclave for 1 hour, the samples were analyzed on the Lachat 8500 Autoanalyzer, as above. Because the organic N in the sample was converted the inorganic N, this analysis measured the total dissolved nitrogen (TDN). Organic N concentration could then be calculated by subtracting the inorganic N concentration and the persulfate N concentration from the TDN (Equation 8). The N concentration of the persulfate oxidizing reagent was also subtracted.

Equation 8. Organic N concentration

$$Organic\ N = TDN - inorganic\ N - persulfate\ N$$

> Where organic N = the calculated organic N concentration of a stream water sample (µM), TDN = total dissolved N concentration of a stream water sample (µM); inorganic N = the inorganic N concentration ($NO_3^- + NO_2^- + NH_4^+$) (µM); persulfate N = the N concentration of the persulfate oxidizing reagent (µM).

However, the results of the organic N analysis were unreliable and could not be used in this study. The results from this analysis and calculation (Equation 8) found negative organic N concentrations in the stream water. Two potential sources of error were identified. First, the digestion may not have been converting the organic N to inorganic N correctly. However, the organic standards that underwent the digestion did have the expected concentration when analyzed on the Lachat, suggesting that the digestion was successful. A second possible source of error was the dilution process. Added uncertainty from the dilution could have given negative organic N concentrations that should have actually been 0. Given the uncertainty of this analysis and that its results were not central to the stream water research question, analysis for organic N concentrations was not performed after this preliminary set of samples.

5.2.4. Inorganic nitrogen flux determination

The concentration and discharge data were used to determine the flux of nitrogen flowing into and out of Timbercreek Organics in g N hr^{-1}. The tributaries were allocated into two main tributaries. Tributary 1 included inflow from two sampling points (A and D) and outflow from one sampling location (G). Tributary 2 included inflow from one sampling location (E) and outflow from one sampling location (F). The total flux of inorganic N entering and leaving the farm was summed. The difference between the outflow and inflow was taken to determine how much inorganic N was staying on the Timbercreek property (i.e., a negative flux) or being added by the Timbercreek property (i.e., a positive flux).

Trends over time for N concentration, discharge, and N flux were noted. Factors considered to explain any observed trends included the livestock grazing schedule, livestock stocking rates, seasonal changes, and the extent of precipitation events.

5.3. Results

Stream water sampling was conducted 18 times from 12 June 2013 through 25 April 2014. However, to be part of the nitrogen flux analysis, complete data sets with both concentration and discharge data were necessary for sampling locations A, D, E, F, and G. Sites B and C were on-farm monitoring locations that were not necessary to the flux analysis. Complete stream water sampling data sets were available for 13 sampling events from 26 June 2013 through 25 April 2014 (Table 22). Concentration and discharge data for incomplete data sets are still reported in their respective sections, but those dates were not included in the farm nitrogen flux analysis.

Table 22. Data availability for stream water concentration and discharge for each sampling event at Timbercreek Organics from 12 June 2013 through 25 April 2014.

Date	Concentration data available?	Discharge data available?	Complete data set?
6/12/13	Incomplete	Unavailable	No
6/26/13	Complete	Complete	Yes
7/10/13	Complete	Unavailable	No
7/24/13	Complete	Unavailable	No
8/8/13	Complete	Unavailable	No
8/14/13	Complete	Complete	Yes
8/21/13	Complete	Complete	Yes
9/3/13	Complete	Complete	Yes
9/10/13	Complete	Complete	Yes
9/24/13	Complete	Complete	Yes

10/1/13	Complete	Complete	Yes
10/8/13	Complete [a]	Complete	Yes
10/22/13	Complete	Complete	Yes
11/5/13	Complete	Complete	Yes
1/27/14	Complete [a]	Unavailable	No
2/7/14	Complete	Complete	Yes
3/21/14	Complete	Complete	Yes
4/25/14	Complete	Complete	Yes

[a] *Missing concentration data for site B (on-farm pond). Flux calculations still possible.*

The stream water concentration of nitrate + nitrite (Figure 17) and ammonium (Figure 18) was measured for 17 sampling events.

The NO_3^- + NO_2^- stream water concentrations ranged from 0.08 mg N L^{-1} to 2.5 mg N L^{-1} (Figure 17). Standard deviation was calculated for the 58 duplicate samples that were analyzed. Standard deviation ranged from 0.0 to 0.5 mg N L^{-1}; the average standard deviation was 0.04 mg N L^{-1}. The concentrations at the sampling locations remained relatively consistent compared with each other over time. For example, the concentrations at site A were the highest throughout most of the sampling period (average of 1.6 mg N L^{-1}), whereas the concentrations at sites E and F (both with an average of 0.3 mg N L^{-1}) were the lowest. Different trends were also observed for tributary 1 (sampling sites A, B, C, D, and G) compared to tributary 2 (sampling sites E and F). Tributary 1 concentrations were all low in June 2013, and concentrations increased and remained relatively steady from July 2013 through October 2013. During winter 2014, all sites along tributary 1 peaked to a maximum concentration, which began to taper off in April 2014. On the other hand, the concentrations at tributary 2 were consistent and low (less than 0.5 mg N L^{-1}) throughout the entire sampling period.

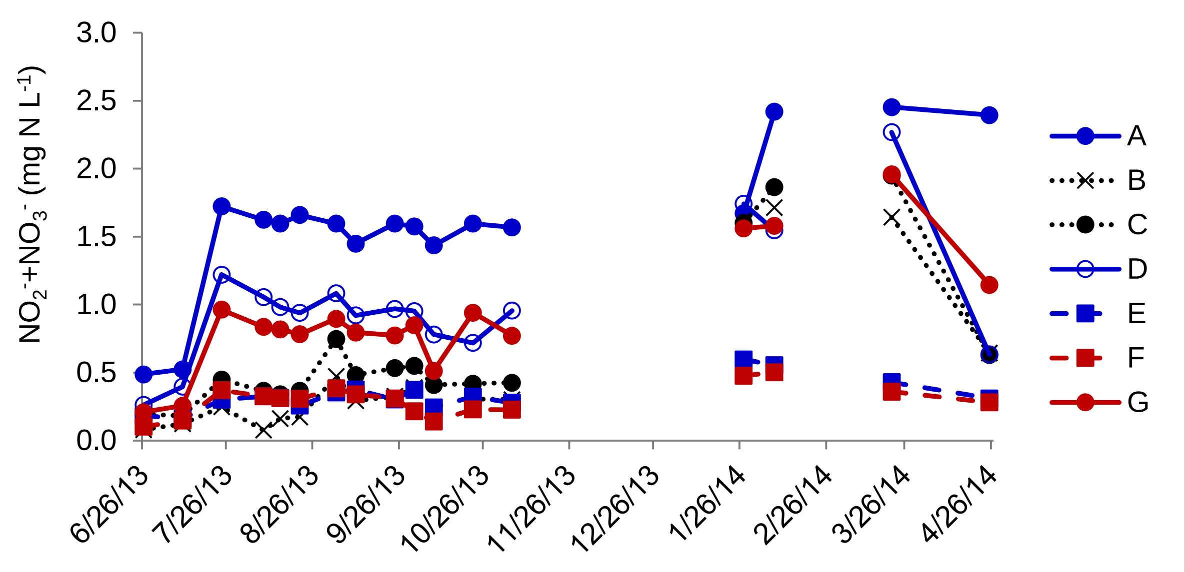


Figure 17. Concentration of NO_3^- + NO_2^- (mg N L^{-1}) in tributaries at Timbercreek Organics Farm. Blue lines indicate inflow sampling locations (A, D, E); red lines indicate outflow sampling locations (F, G); black lines indicate on-farm sampling sites (B, C). Sampling locations are grouped into two tributaries by line and marker: tributary 1 is a solid line with a circle marker; tributary 2 is a dashed line with square markers; on-farm sites are black dotted lines. Site C is on the farm (dotted line) but located along tributary 1 (circle marker). Standard deviation was calculated for 58 of the analyzed stream water samples. Standard deviation ranged from 0.0 to 0.50 mg N L^{-1}; the average was 0.04 mg N L^{-1}. Standard deviation was not shown on this graph to avoid visual complexity.

The NH_4^+ stream water concentrations ranged from 0.0 to 0.21 mg N L^{-1}, with most values falling below 0.05 mg N L^{-1} (Figure 18). Standard deviation was calculated for the 58 duplicate samples that were analyzed. Standard deviation ranged from 0.0 to 0.03 mg N L^{-1}; the average standard deviation was 0.004 mg N L^{-1}. Unlike the NO_3^- + NO_3^- findings, the NH_4^+ concentrations at the sampling locations were not consistent relative to each other nor were distinct trends observed for the two major tributaries. Concentrations for two sampling locations experienced multiple peaks in summer and fall 2013: site D (an inflow for tributary 1) and site B (an on-farm pond).

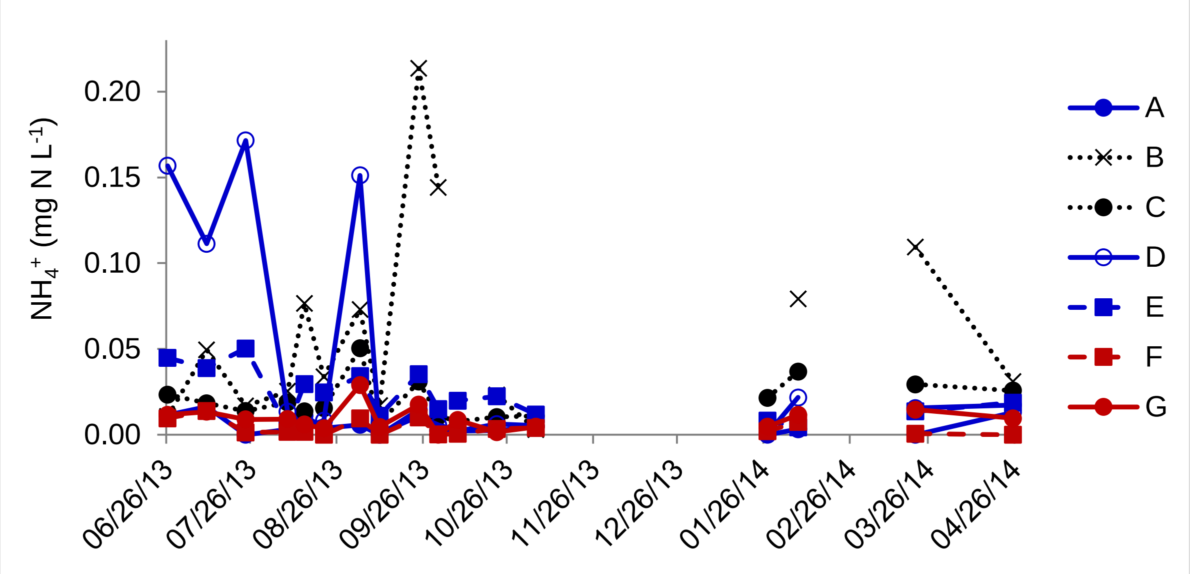


Figure 18. Concentration of NH_4^+ (mg N L^{-1}) in tributaries at Timbercreek Organics Farm. Blue lines indicate inflow sampling locations (A, D, E); red lines indicate outflow sampling locations (F, G); black lines indicate on-farm sampling sites (B, C). Sampling locations are grouped into two tributaries by line and marker: tributary 1 is a solid line with a circle marker; tributary 2 is a dashed line with square markers; on-farm sites are black dotted lines. Site C is on the farm (dotted line) but located along tributary 1 (circle marker). Standard deviation was calculated for 58 of the analyzed stream water samples. Standard deviation ranged from 0.0 to 0.03 mg N L^{-1}; the average was 0.004 mg N L^{-1}. Standard deviation was not shown on this graph to avoid visual complexity.

Discharge was calculated for sampling locations A, D, E, F, and G for 13 sampling events. The discharge was summed to represent the two major tributaries at TCO (Figure 19). The inflow discharge ranged from 23 m^3 hr^{-1} to 120 m^3 hr^{-1}, and the outflow discharge ranged from 19 m^3 hr^{-1} to 190 m^3 hr^{-1}. The discharge did not vary substantially during summer 2013, but increased during fall 2013 and winter 2014. After peaking in winter 2014, all discharge values began to decrease in spring 2014. The discharge exiting the property exceeded the discharge entering the property for most of the sampling events at both tributary 1 (54% of the sampling events) and tributary 2 (92% of the sampling events). For the overall farm, outflow exceeded inflow for 85% of the sampling events.

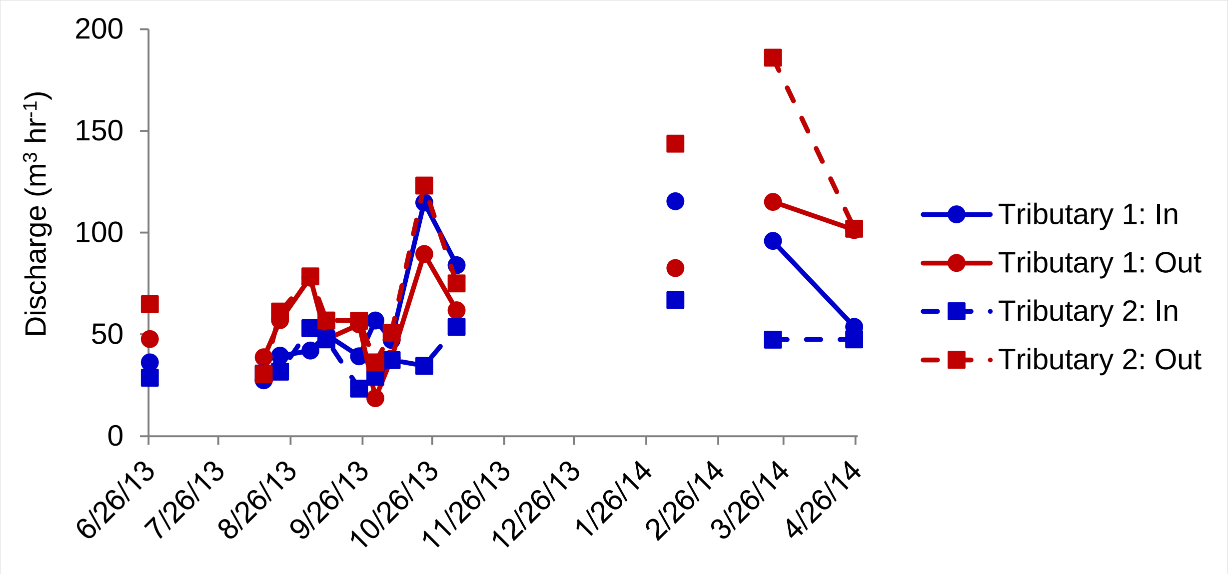


Figure 19. Water discharge (m^3 hr^{-1}) flowing into and out of Timbercreek Organics Farm for the two major tributaries. The following sampling locations correspond to each tributary: Tributary 1 inflow (blue solid line, circle) is the sum of sampling locations A and D; tributary 1 outflow (red solid line, circle) is sampling location G; tributary 2 inflow (blue dashed line, square) is sampling location E; tributary 2 outflow (red dashed line, square) is sampling location F.

As expected, the discharge results (Figure 19) did not generally follow the total monthly precipitation for Charlottesville, Virginia, during the time period of the study (Figure 20). For example, the month with the highest total precipitation (18 cm in June 2013) did not correspond to the highest discharge reading. Conversely, the highest discharge readings in February and March of 2014 were associated with months of below-average precipitation (7 and 6 cm month^{-1}, respectively). The precipitation events in February and March 2014 were dominated by snow.

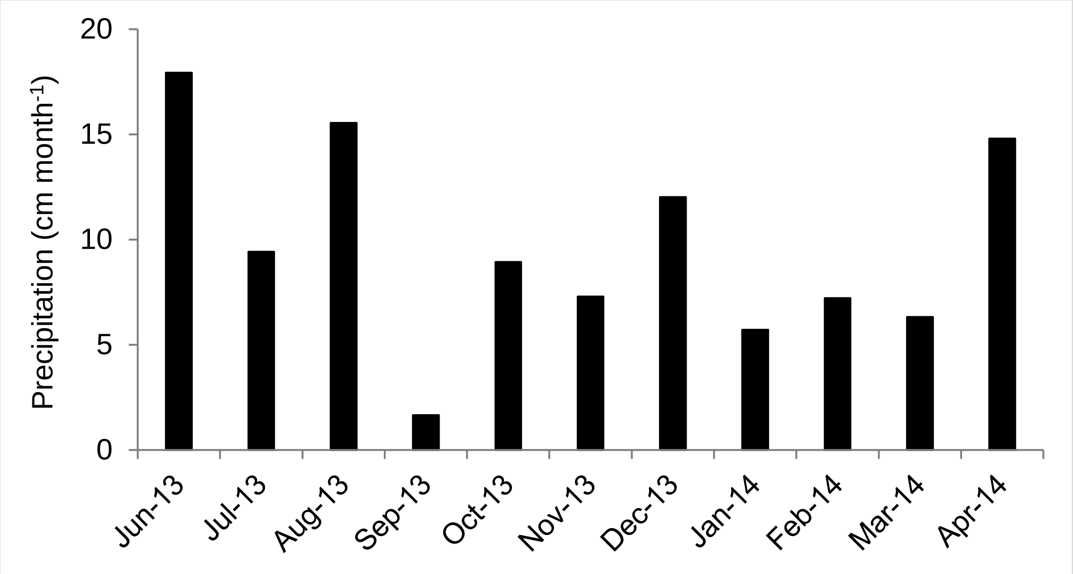


Figure 20. Monthly precipitation in Charlottesville, Virginia in cm month^{-1} from June 2013 through May 2014 (Weather Underground 2014).

The total flux of inorganic N entering and exiting the streams of the TCO property was determined for the two major tributaries and for the farm property overall (Figure 21). The range for the inorganic nitrogen flux entering for tributary 1 (5 g N hr^{-1} to 67 g N hr^{-1}) was greater than that of tributary 2 (2 g N hr^{-1} to 10 g N hr^{-1}). The range for the inorganic N flux exiting the property for tributary 1 (3 g N hr^{-1} to 63 g N hr^{-1}) was also greater than that for tributary 2 (2 g N hr^{-1} to 20 g N hr^{-1}). All of the fluxes were low in summer 2013, but the tributary 2 fluxes began to climb over the winter while the tributary 2 fluxes remained low. During winter 2014, the tributary 1 fluxes peaked in February 2014 with the inflow exceeding the outflow by 100 g N hr^{-1}. The tributary 2 fluxes also increased in winter 2014, but not as much as tributary 1. Dissimilar to tributary 1, the tributary 2 outflow of inorganic N exceeded the inflow in winter 2014. All fluxes began to decline dramatically in spring 2014.

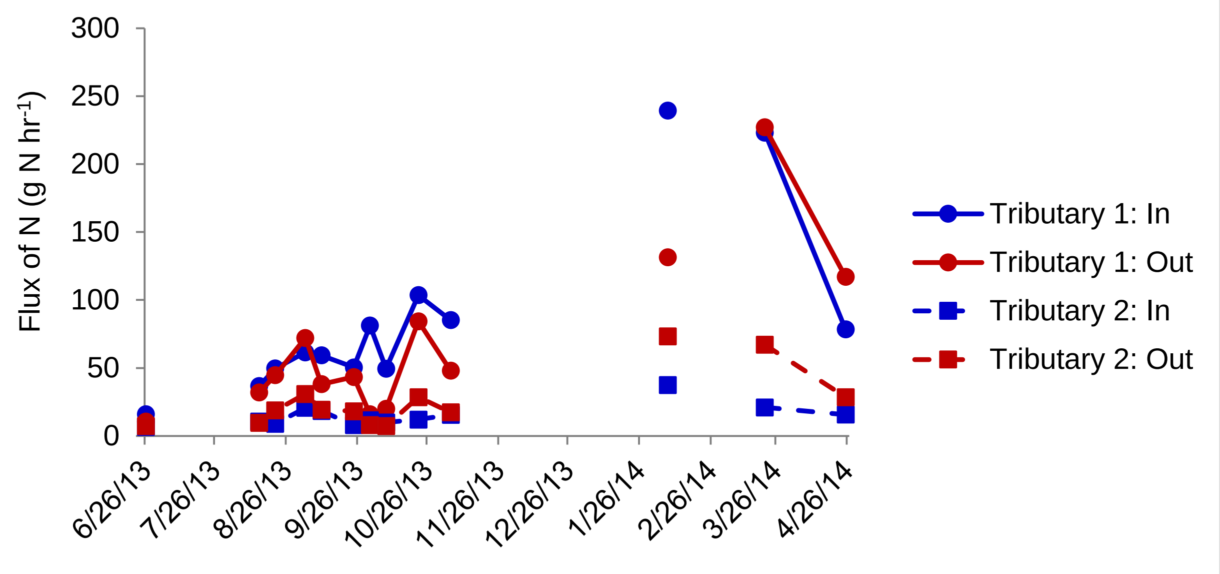


Figure 21. Flux of inorganic nitrogen (g N hr^{-1}) flowing into and out of Timbercreek Organics Farm through the two major tributaries. The following sampling locations correspond to each tributary: Tributary 1 inflow (black solid line, filled circle) is the sum of sampling locations A and D; tributary 1 outflow (black dashed line, open circle) is sampling location G; tributary 2 inflow (red solid line, filled triangle) is sampling location E; tributary 2 outflow (red dashed line, open triangle) is sampling location F.

The overall flux of inorganic N entering and exiting the property largely tracked the patterns of tributary 1 due to its larger contribution to the total inorganic nitrogen flux. The flux of inorganic nitrogen entering the property ranged from 7 g N hr^{-1} to 240 g N hr^{-1}, and the flux of inorganic N leaving the property ranged from 7 g N hr^{-1} to 230 g N hr^{-1} (Figure 22). The N flux increased steadily during summer and fall 2013, but generally remained below 100 g N hr^{-1}. During this time, the inflow and outflow were similar with only one instance in October 2013 when the fluxes differed by over 60 g N hr^{-1}. However in winter 2014, the flux of N entering and exiting the property increased by more than 160 g N hr^{-1}. Further, the outflow surpassed the inflow in March 2014 by over 50 g N hr^{-1}; this trend continued in April 2014, although both fluxes decreased to less than 150 g N hr^{-1}. Overall, the nitrogen flux entering the property exceeded the nitrogen flux leaving the property on 62% of the sampling events.

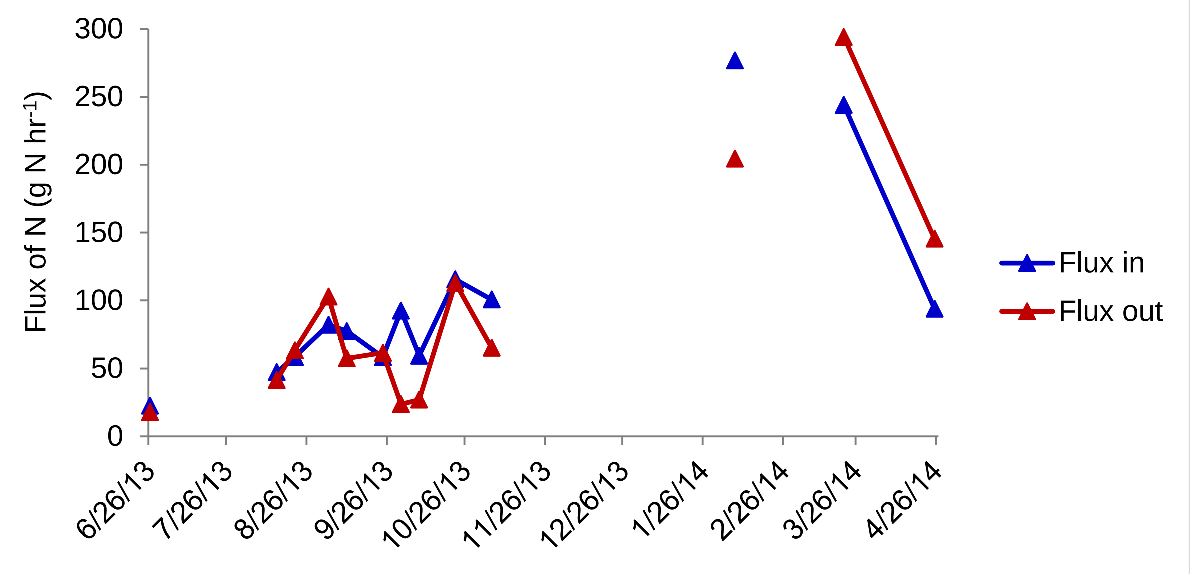


Figure 22. Total flux of inorganic nitrogen (g N hr^{-1}) flowing into (blue line) and out of (red line) Timbercreek Organics Farm through the streams.

In summary, the inorganic N stream water concentrations were dominated by NO_3^-+NO_2^- with a small contribution from NH_4^+. The NO_3^-+NO_2^- concentrations at the seven sampling sites remained in a relatively constant rank order, with concentrations being fairly constant over summer and fall 2013 but increasing over winter 2014. Clear trends were not apparent for the NH_4^+ concentration data. The stream discharge remained relatively steady and low in summer and fall 2013, but it increased substantially over winter 2014. The total farm N flux entering and exiting the property was lower in summer and fall 2013 and peaked in winter 2014. The N flux entering the property typically exceeded the N flux exiting the property for 62% of the sampling events. These results imply that TCO is not adding inorganic nitrogen to the stream water.

5.4. Discussion

5.4.1. Stream water concentrations of inorganic nitrogen

The highest stream water NO_3^-+NO_2^- concentration recorded over the year of sampling was 2.5 mg N L^{-1}, which is well below the EPA standard for nitrate in drinking water of 10 mg N

L^{-1} (US EPA 2009). This suggests that the N released to the environment from farm activity is too low to be a concern for drinking water. In addition, the rotational grazing method distributes the N losses across the fields and tributaries, further reducing concerns for human health from inorganic N.

Of the seven sampling sites on the farm, site A (an inflow point for tributary 1) frequently had the highest NO_3^-+NO_2^- concentrations (Figure 17). However, the discharge for this site was typically the lowest of all sampling sites (Figure 19), reducing its contribution to the overall farm N flux. This site's N concentration was probably higher because the sampling location was located directly on the TCO property on a field that is frequently grazed by cattle. It should be noted that sampling site A is not a true inflow because this stream surfaces on the farm property. However, the site was located close to where the stream surfaces. The highest stream water N concentrations measured throughout the study occurred at site A in February and March 2014. During this time period, cattle intensively grazed a field immediately uphill from sampling site A for 1-2 months. The vegetation coverage was reduced, encouraging erosion. In addition, because this event occurred over the winter when plant growth and therefore plant N demand were reduced, more of the applied N was susceptible to leaching and runoff. It is likely that this intensive grazing contributed to the increased stream water N concentrations.

The sampling site that regularly had the second highest NO_3^-+NO_2^- concentrations was site D—the second inflow point for tributary 1 (Figure 17). Upstream of this site are two activities that could contribute to the high N concentration: a grazing cattle farm that is fertilized and a horse racing property that is maintained with fertilizer. The discharge for this sampling site was also relatively low, but it was higher than site A.

Sampling sites A (inflow), B (on-farm pond), and C (on-farm monitoring site) were all located along a continuous stretch of tributary 1 during which no additional tributaries joined the stream flow. Given this, the stream water concentrations can be compared. The concentration at site A (average of 1.6 mg N L^{-1}) was about 2-3 times higher than that of site C (average of 0.7 mg N L^{-1}) for all sampling events. The holding pond was located between site A and C and likely acted as a site for inorganic N uptake, storage, or denitrification before the stream flow reached site C.

Tributary 2 experienced low NO_3^-+NO_2^- and NH_4^+ concentrations throughout the study (Figures 17, 18). Both the inflow and outflow sampling sites for this tributary are located adjacent to a TCO field that is less frequently grazed. Upstream land uses are dominated by residences without any farming activity.

Few trends can be observed in the NH_4^+ concentrations, which were generally much lower than NO_3^-+NO_2^- concentrations. Peaks in the NH_4^+ concentration occurred in two sites in the summer and fall of 2013: sampling site B and sampling site D (Figure 18). Site B is a holding pond located on the property. During the summer and fall, considerable algal growth was observed, which was likely due to high nutrient inflows. The peaks observed at site D could be due to the neighbor’s farming activity or fertilizer applications.

Duplicate sample analysis revealed low variance for measured stream water inorganic N concentrations, suggesting a high level of confidence in the stream water inorganic N concentrations.

5.4.2. Stream water discharge

The stream water discharge was relatively low and experienced little variability during the summer and fall of 2013 (Figure 19), whereas total monthly precipitation was highest in June and August 2013 (Figure 20). In addition, the months with the highest discharge (February and March 2014) had some of the lowest levels of precipitation. Given that the discharge measurements reflect a single point in time, the discharge measurements were not expected to parallel the amount of precipitation. Because of this, increased discharge for the 3 sampling events over winter 2014 should not lead to the conclusion that discharge increased over winter 2014. The winter sampling events could have simply fallen on dates shortly after precipitation events, whereas sampling events during the fall and summer did not. Future research should consider the impact of precipitation events by sampling before and after precipitation events.

5.4.3. Stream water nitrogen flux

When the flux of nitrogen leaving TCO exceeds the flux of nitrogen entering TCO (i.e., a positive flux), Timbercreek Organics Farm could be adding inorganic nitrogen to the stream water. When the opposite is true (i.e., a negative flux), nitrogen entering the property could be stored, assimilated by organisms, or denitrified on the property.

In tributary 1, the N flux entering the property exceeded the N flux exiting the property on 77% of the sampling events (Figure 21). The difference between N entering and N exiting ranged from -5 to -108 g N hr^{-1}, with an average flux of -30 g N hr^{-1}. One possible explanation is the farm holding pond, which is located along tributary 1. The holding pond can remove inorganic nitrogen from the stream flow by three main pathways. First, the holding pond allows sediments and associated nutrients to settle out. A second major pathway is denitrification, which could be increased in the anaerobic conditions in the pond. A third pathway is nitrogen uptake by biomass. Significant algal growth was observed on the holding pond throughout fall 2013, which suggests that a major nutrient source was available to support the algae growth.

In tributary 2, the N flux entering the property was less than the N flux exiting the property on 77% of the sampling events (Figure 21), suggesting TCO was adding inorganic N to this tributary. However the magnitude of these fluxes was less than tributary 1: the difference between the N entering and exiting TCO ranged from 1 to 45 g N hr^{-1}, with an average flux of 15 g N hr^{-1}. The N addition over the length of tributary 2 could be explained by groundwater infiltration. Tributary 2 is a single stream that is not joined by any other tributaries on the TCO property. At the inflow point, the stream is very narrow; at the outflow point, it has widened and the discharge has increased, perhaps due to groundwater inputs. There is not a holding pond in tributary 2, so the main pathway to remove N from the stream would be denitrification. However the stream length is short, limiting the capacity for denitrification.

For the overall TCO property, the N flux entering the property was greater than the N flux exiting the property on 8 of the 13 sampling events (Figure 22). Most of the nitrogen flux can be explained by tributary 1, which had higher overall N fluxes and experienced a greater N inflow than outflow for 76% of sampling events. The holding pond located on this tributary is the most likely explanation for the N flux reduction occurring on the farm property. Without the holding pond, it is possible that TCO would add inorganic N to the streams. This study highlights the importance of a holding pond as a stormwater management tool for grazing farms.

5.4.4. Seasonal trends

During winter 2014, the farm stream water inorganic N fluxes were about 3 times larger than during summer and fall 2013. The inorganic N concentrations increased only slightly during winter 2014, whereas the discharge grew more.

Multiple factors during winter 2014 could have increased both the inorganic N concentration and the discharge (Figures 17, 18, 19). With the colder temperatures, transpiration would have been reduced, meaning that more water could have contributed to runoff to the streams. Multiple large snow events occurred during the winter; the snowmelt could have contributed to the higher discharge. However, precipitation data suggest that winter 2014 actually received less precipitation than many other months (Figure 20). A reduced vegetation cover was also observed during the winter, which can partially be explained by the seasonal change causing annuals to die. However one particular field uphill from site A experienced 1-2 months of cattle grazing, which removed most of the vegetation coverage. The cattle stayed in a single field for an extended period of time due to calving issues. After removing the vegetation coverage, both runoff and erosion likely increased. The vegetation has since recovered in this field.

5.4.5. Data quality and recommendations for future study

This study of stream water inorganic N concentrations is intended to serve as a foundation for future studies of the nitrogen balance at TCO. Before any conclusions can be drawn, a more complete and longer data set is necessary. For example, the gaps in the data set in winter 2014 could obscure trends that were occurring. In addition, the discharge measurements were not taken based on the occurrence of precipitation events. To better capture the stream discharge, it is important that the streams also be sampled specifically preceding and following precipitation events.

From these preliminary results, a few insights have emerged. The farm did not exceed or even approach the EPA drinking water limit on nitrate. On more than half of the sampling events, the flux of inorganic N entering the property exceeded the flux of inorganic N exiting the property. Although more research is needed to better understand inorganic N fluxes around precipitation events, these results suggest inorganic N is not being added to the streams by TCO. The most likely explanation of this observation is the presence of a holding pond, which can remove nitrogen from the stream flow through sedimentation, denitrification, and biomass uptake. In addition, the increased inorganic Nr concentrations that were associated with intensive cattle grazing suggest that frequent livestock rotation is important to maintain vegetation coverage and limit runoff and erosion.

5.5. Future work

Stream water sampling at Timbercreek Organics is ongoing and will continue into fall 2014. The results presented in this analysis provide just one year of data and suggest the possibility of a seasonal trend. However the data gap in winter 2014, the availability of just 1 year of data, and the increasing stocking rates at TCO necessitate an ongoing record to better explain the trends.

6. Recommendations for Timbercreek Organics Farm

By far the largest nitrogen input to TCO is feed, so care should be taken to use the feed effectively. For example, the feed recommendations per head of livestock should be revisited and compared to the actual feed being used at the farm. The feed allotted for pigs is currently less than the recommendations suggest, whereas the feed allotted for poultry and layers is currently much greater than the recommendations. Reducing inefficiencies during the feeding process (e.g., feed spillage) could reduce overall farm feed N requirements.

Grass-fed beef production improves the efficiency of TCO from a nitrogen budget perspective because it does not require external feed inputs. However caution should be taken to avoid over-stocking the farm, which can result in reduced vegetation coverage and runoff of sediments and nutrients to the streams.

The legume coverage of the TCO property is as high as 50% in some of the fields, but the root nodules of the majority of the observed legume samples did not appear to be fixing nitrogen. Legumes often require specialized inoculants to activate nitrogen fixation. However because the vegetation coverage of the farm is already strong and root nodulation is limited, it is expected that the vegetation does not require increased nutrient inputs. If the vegetation in fact does not need more nutrients, then inoculation probably would not lead to higher rates of nitrogen fixation because the legumes would likely not expend energy to fix nutrients that are already available. The nutrient needs of the vegetation could be further explored by testing the nutrient concentration of the soils and the protein content of the vegetation from different fields.

TCO could be removing nitrogen from the stream flow, as suggested by the exploratory stream water inorganic N flux analysis. The most likely reason for this possible storage is the holding pond, which should be maintained to continue to serve this environmental benefit.

7. Conclusions

Timbercreek Organics Farm, a permaculture livestock farm in Albemarle Country, Virginia, is as efficient as conventional farms in terms of nitrogen. TCO's nitrogen use efficiency increased from 14% in 2012 to 28% in 2013, largely due to increased production of grass-fed beef. In addition, the N inputs per unit area at TCO were 2-10 times lower than those of conventional farms, suggesting that TCO has a lower local environmental impact than conventional. However both the time and land required to produce meat and animal products at TCO exceed those of conventional farming, with the exception of TCO beef requiring less land than conventional. Based on this study, permaculture farming could be a reasonable alternative to conventional farming if the farm production goals are to achieve a reasonable nitrogen use efficiency and reduce nitrogen impacts per unit area—although further research is needed to study the fate of nitrogen losses from TCO. However on a large scale, this method of farming could probably not meet growing global demands for food and especially meat due to its extensive land requirements.

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APPENDIX A

Timbercreek Organics Farm data collected from farm records.

Table A1. Timbercreek Organics Farm in 2012: Intended input and output data provided by the farmer, Zach Miller. Data in cells highlighted in grey were provided directly by the farmer, with some unit conversions.

INTENDED INPUTS							
Feed							
Type	Corn	Weight (kg)	60,500	Protein (%)	8%	Livestock	Pigs, poultry
Type	Soybeans	Weight (kg)	35,150	Protein (%)	35%	Livestock	Pigs, poultry
Type	Oats	Weight (kg)	6,840	Protein (%)	12%	Livestock	Pigs, poultry
Type	Alfalfa Pellets	Weight (kg)	1,010	Protein (%)	17%	Livestock	Pigs, poultry
Type	Fish Meal	Weight (kg)	2,270	Protein (%)	60%	Livestock	Pigs, poultry
Type	Kelp	Weight (kg)	910	Protein (%)	9%	Livestock	Pigs, poultry
Type	Hay	Bales (no.)	120	Protein (%)	11%	Livestock	Cattle
Fertilizer							
Type	None	Weight (kg)	0	Nitrogen (%)	N/A		
Other							
Type	Bedding	Weight (kg)	15,800	Protein (%)	1.6%		
Type	Compost	Weight (kg)	109,000	Nitrogen (%)	2.5%		
Purchased livestock							
Pigs	150	Number	42	Age (days)			
Cattle	100	Number	180	Age (days)			
Poultry	8,000	Number	1	Age (days)			
Layers	800	Number	180	Age (days)			
Energy use							
Electricity	54,000	kwh yr^{-1}					
Natural gas	500	gal yr^{-1}					
Farm truck	7,500	mi yr^{-1}					
INTENDED OUTPUTS							
Meat and animal products							
Type		Product amount					
Pork		3,720 kg					
Beef		4,990 kg					
Poultry		4,540 kg					
Eggs		72,000 eggs					

Table A2. Timbercreek Organics Farm in 2013: Intended input and output data provided by the farmer, Zach Miller. Data in cells highlighted in grey were provided directly by the farmer, with some unit conversions.

INTENDED INPUTS							
Feed							
Type	Corn	Weight (kg)	136,640	Protein (%)	8%	Livestock	Pigs, poultry
Type	Soybeans	Weight (kg)	74,650	Protein (%)	35%	Livestock	Pigs, poultry
Type	Oats	Weight (kg)	13,640	Protein (%)	12%	Livestock	Pigs, poultry
Type	Alfalfa Pellets	Weight (kg)	2,520	Protein (%)	17%	Livestock	Pigs, poultry
Type	Fish Meal	Weight (kg)	2,410	Protein (%)	60%	Livestock	Pigs, poultry
Type	Kelp	Weight (kg)	1,810	Protein (%)	9%	Livestock	Pigs, poultry
Type	Hay	Bales (no.)	190	Protein (%)	11%	Livestock	Cattle
Fertilizer							
Type	None	Weight (kg)	0	Nitrogen (%)	N/A		
Other							
Type	Bedding	Weight (kg)	26,330	Protein (%)	1.6%		
Type	Compost	Weight (kg)	90,700	Nitrogen (%)	2.5%		
Purchased livestock							
Pigs	80	Number	42	Age (days)			
Cattle	0	Number	N/A	Age (days)			
Poultry	8,000	Number	1	Age (days)			
Layers	912	Number	180	Age (days)			
Energy							
Electricity	65,900[a]	kwh yr^{-1}					
Natural gas	600	gal yr^{-1}					
Farm truck	10,500	mi yr^{-1}					
INTENDED OUTPUTS							
Meat and animal products							
Type		Product amount					
Pork		11,070 kg					
Beef		22,830 kg					
Poultry		11,960 kg					
Eggs		113,320 eggs					

Notes:

[a] Calculated based on usage in 2012 and increase in electricity bill in 2013

Table A3. Livestock production practices at Timbercreek Organics Farm in 2012 and 2013 provided by the farmer, Zach Miller. Information in cells highlighted in grey was provided by the farmer.

Data	Cattle	Pigs	Chickens: Broilers	Chickens: Layers	Turkeys and ducks
Breed(s)	Devin Angus hybrid	2012: Hampshire Yorkshire crosses 2013: Berkshire duroc	Cornish rock cross	2012: Red star (mix of leghorn and Rhode Island Red) 2013: Bard Rock	Turkeys: Broad-breasted white Ducks: White pekin
Number in 2012	120	150	8,000	800	60 turkeys
Number in 2013	150	80	8,000	800	75 turkeys; 600 ducks
% female	50%	50%	5%	99.6%	50%
% male	50%	50%	95%	0.4%	50%
Age when brought to farm	6 months in 2012 N/A for 2013	6 weeks	1 day	6 months	1 day
Average lifespan	Beef cattle: 2 years Breeders: 8-9 years	8 months	60 days	2 years	Turkeys: 20 weeks Ducks: 15 weeks
Live weight at slaughter	530 kg	145 kg	2.2 kg in 2012 2.7 kg in 2013	N/A	Turkeys: 8 kg Ducks: 3.3 kg
Types of feed	Pasture and hay	Grains and natural forages (e.g., acorns, worms)	Grains and natural forages (e.g., insects, grass)	Grains and natural forages (e.g., insects, grasses)	Grains and natural forages (e.g., insects, grasses)
Frequency of grazing rotation	Every day. Grazed in rotation with chickens, but cattle graze a field 3-4 times before chickens do.	Once per month	Move daily in mobile chicken coop. Grazed in rotation with cattle. 6 groups of chickens per year.	Move daily in mobile hen house. On pasture for 9 months; brooder for 3 months (winter). Graze 4 days behind the cattle.	First 6 and 4 weeks in brooder for turkeys and ducks, respectively. Remaining weeks are in larger mobile coops.

Data	Cattle, continued	Pigs, continued	Chickens: Broilers, continued	Chickens: Layers, continued	Turkeys, continued
General description of how they are raised	To ensure a healthy herd, its size equals the number of cattle wanted for production x 3. There is no finishing process for cattle.	Rotational grazing in oak woods. The herd is mixed in species and age. There is no finishing process for pigs.	First 4 weeks are spent in the brooder. The bedding (wood chips/shavings and manure) is composted and helps keep them warm. Last 4 weeks are spent in mobile chicken coops. Raised from March to October.	Purchased at 6 months. More aggressive than broilers with scratching and hunting. Raised year-round.	First 6 weeks in brooder. Turkeys and ducks are mixed in with chickens in brooder.
Fate of waste on farm (i.e., what happens to excrement)	Applied directly to field at time of production	Applied directly to field at time of production	Applied directly to field (mobile coops). Bedding from brooder is composted	Applied on field (pasture) or composted (winter housing)	Direct application (pasture), and composting (brooder)
Slaughter process	T&E Slaughterhouse	T&E Slaughterhouse	On-farm	Sold to external facility at 2.5 years	On-farm
% weight loss at slaughter	58%	52%	31%	N/A	31%
Types of weight lost from slaughterhouse	Guts, bones (except leg and rib bones), head	Guts, bones, head (exception: head and skin are available with scalding)	Heads (except those purchased by falcon trainer), feet, intestines	N/A	Same as broilers

Table A4. General information and practices for Timbercreek Organics in 2012 and 2013 provided by the farmer, Zach miller. Information in cells highlighted in grey was provided directly by the farmer.

Farm area	
Total area of farm	160 ha
Area for pig grazing	20 ha
Area for cattle grazing	80 ha*
Area for poultry grazing	65 ha*
Area for layers grazing	65 ha*
Area for crop production	0 ha
Other uses (primarily timber)	80 ha
Irrigation	
Type and area of irrigation used	N/A
Crops	
Type (species)	N/A

*Land area grazed by cattle, broilers, and layers is shared.

APPENDIX B

Factors used to calculate farm nitrogen budget and land utilization for Timbercreek Organics Farm.

Table B1. Nitrogen content for the components of the Timbercreek Organics farm nitrogen budget.

Budget component	**Nitrogen content (%)**			**Data Source**
	Average	**Maximum**	**Minimum**	
Farm inputs				
Feed				
Corn [a]	1.3%	1.4%	1.1%	1,2
Soybeans [a]	5.6%	6.6%	4.6%	1,2
Oats [a]	1.9%	2.2%	1.6%	1,2
Alfalfa pellets [a]	2.7%	3.2%	2.2%	1,2
Fishmeal [a]	9.6%	10.4%	8.8%	1,2
Kelp [a]	1.4%	2.1%	0.8%	1,2
Hay [b]	1.8%	2.1%	1.4%	1,3
Bedding [c]	0.3%	N/A	N/A	4
Purchased livestock				
Pigs [a]	2.3%	2.5%	2.1%	5
Cattle [a]	2.9%	3.1%	2.7%	5
Poultry [a]	2.6%	2.8%	2.4%	5
Layers [a]	2.4%	2.6%	2.2%	5
Farm outputs				
Meat/animal product				
Pork [b,d]	2.9%	3.4%	2.2%	6
Beef [b,d]	3.1%	3.7%	2.8%	6
Poultry [b,d]	3.0%	3.4%	2.7%	6
Eggs [b,d]	1.9%	2.0%	1.8%	6
Slaughter by-products				
Pork [b,e]	2.4%	2.9%	2.0%	7,8,9,10,11,12
Beef [b,e]	2.4%	3.1%	1.6%	7,8,9,10,11,12
Poultry [b,e]	3.1%	3.4%	2.8%	7,8,9,10,11,12

Notes:

[a] Minimum and maximum values represent standard deviation from cited source

[b] Minimum and maximum values represent range reported in cited source

[c] Minimum and maximum values were not recorded given its small contribution and limited variation

[d] Protein content of raw meat and animal products

[e] Weighted average of slaughter by-products

Sources:

(1) Zach Miller, personal communication; (2) Rayburn 1996; (3) Virginia Department of Agriculture and Consumer Services 2013; (4) Adams 1997; (5) NRC 2003; (6) USDA 2011; (7) Sjöberg 2009; (8) Auvermann et al. 2004; (9) FAO 2014; (10) FAO 1991; (11) Boushby & van der Poel 2000; (12) Field et al. 1974.

Table B2. Feed crop bushel weights and yields, presented as 5-year averages for 2010-2014.

Feed crop	Bushel weight kg bushel^{-1}	Yield Bushels acre^{-1}	Yield kg ha^{-1}	Yield kg m^{-2}
Corn[1,3]	25	149.5	9,380	0.94
Oats[1,3]	15	62.44	2,240	0.22
Soybeans[2,3]	27.2	42.125	2,830	0.28
Alfalfa pellets[a,1]	n/a	2.3[c]	5,250	0.53
Fishmeal[b,1,3]	25	150	9,380	0.94
Hay[1]	n/a	2.3[c]	5,250	0.53

[a] Applied hay yield to alfalfa pellets because yield data for alfalfa pellets were unavailable.

[b] Applied corn yield to fishmeal because yield data for fishmeal were unavailable. Assumed that fish were grain-fed and used little land during their production.

[c] Units are t ha^{-1}

Sources:

(1) USDA-ERS 2014a; (2) USDA-ERS 2014b; (3) USDA-ERS 2014c

APPENDIX C

Farm nitrogen budget data from the literature

Table C1a. Farm nitrogen budgets from the literature: Sources and data for beef farms.

Farm product	**Production method**	**Location**	**No. of farms**	**Intended N inputs** (kg N ha^{-1} yr^{-1})						**Unintended N inputs** (kg N ha^{-1} yr^{-1})	**Outputs: Intended** (kg N ha^{-1} yr^{-1})		**Data source**
				Feed	Fertilizer [a]	Livestock	Bedding	BNF	Other	Atm. Dep.	Meat	Crops	
Beef	Conventional	Italy	11	178	64	34	12	29		30	83	6	1
Beef	Conventional	Italy	16	38	50		5	30		30	16	35	1
Beef	Grazing: Unfertilized	UK	1					8		15	3		4
Beef	Grazing: Fertilized	UK	1		420					15	29		4
Beef	Grazing: Fertilized	UK	1	61	270	7	9	5		12	51		6
Beef	Grazing: Unfertilized	UK	1					160		15	23		4
Beef	Grazing: Unfertilized	UK	1	46		5	7	151		12	52		6
Beef	Grazing: Unfertilized	Scotland	Avg.	1	67	3		48	1	15	8	7	2
Beef	Grazing: Unfertilized	Scotland	Avg.	1	123	6		46	1	15	16	58	2
Beef	Organic	10 countries	5										7

Notes:

[a] Fertilizer total includes manure applied

Sources:

(1) Bassanino et al. 2007; (2) Domburg et al. 2000; (4) Oenema 2006; (6) Watson & Atkinson 1999; (7) Watson et al. 2002

Table C1b. Farm nitrogen budgets from the literature: Sources and data for pork, poultry, and layer farms.

Farm product	**Production method**	**Location**	**No. of farms**	**Intended N inputs** (kg N ha^{-1} yr^{-1})						**Unintended N inputs** (kg N ha^{-1} yr^{-1})	**Outputs: Intended** (kg N ha^{-1} yr^{-1})		**Data source**
				Feed	Fertilizer ^{a}	Livestock	Bedding	BNF	Other	Atm. Dep.	Meat	Crops	
Pork	Conventional	Italy	5	1,233	42	44		2		30	520	34	1
Pork	Conventional	Denmark	19	257	94			3	2	15	98	76	3
Pork	Conventional	Denmark	6	324	69		5	3	2	15	92	53	3
Pork	Conventional	Scotland	Average	824	113	62		10	5	10	449	61	2
Pork	Conventional	NL^{c}	Average	18,880^{b}		1,897^{b}					9,444^{b}		4
Pork	Conventional	NL^{c}	Average	21,210^{b}		1,490^{b}					8,130^{b}		4
Pork	Conventional	NL^{c}	Average	21,750^{b}		1,510^{b}					8,450^{b}		4
Pork	Conventional	NL^{c}	Average	22,470^{b}		1,040^{b}					8,010^{b}		4
Poultry	Conventional	NL^{c}	Average	21,486^{b}		284^{b}			18^{b}		10,569^{b}		4
Poultry	Conventional	NL^{c}	Average										5
Poultry	Conventional	Scotland	Average	824	113	62		10	5	10	449	61	2
Layers	Conventional	NL^{c}	Average	34,992^{b}		1,153^{b}			644^{b}		12,942^{b}		4

Notes:

^{a} Fertilizer total includes manure

^{b} Units are kg N farm^{-1} yr^{-1}

^{c} NL = Netherlands

Sources:

(1) Bassanino et al. 2007; (2) Domburg et al. 2000; (3) Nielsen & Kristiensen 2005; (4) Oenema 2006; (5) Schröder et al. 2003

Table C2. Farm nitrogen budgets from the literature: Nitrogen efficiency data.

Farm product	**Production method**	**Location**	**No. of farms**	**Total intended N inputs** (kg N ha^{-1} yr^{-1})	**Total intended N outputs** (kg N ha^{-1} yr^{-1})	**N Surplus** (kg N ha^{-1} yr^{-1})	**NUE** (%)	**Data source**
Beef	Conventional	Italy	11	317	89	228	28%	1
Beef	Conventional	Italy	16	73	16	57	22%	1
Beef	Grazing: Unfertilized	UK	1	8	3	5	38%	4
Beef	Grazing: Fertilized	UK	1	420	29	391	7%	4
Beef	Grazing: Fertilized	UK	1	352	58	294	16%	6
Beef	Grazing: Unfertilized	UK	1	160	23	137	14%	4
Beef	Grazing: Unfertilized	UK	1	209	52	157	25%	6
Beef	Grazing: Unfertilized	Scotland	Average	52	8	44	0%	2
Beef	Grazing: Unfertilized	Scotland	Average	54	16	38	0%	2
Beef	Organic	10 countries	5			112	20%	7
Pork	Conventional	Italy	5	1,321	554	767	42%	1
Pork	Conventional	Denmark	19	262	105	157	40%	3
Pork	Conventional	Denmark	6	334	94	240	28%	3
Pork	Conventional	Scotland	Average	1,015	510	510	50%	2
Pork	Conventional	Netherlands	Average	20,777^{a}	9,444^{a}	11,333^{a}	45%	4
Pork	Conventional	Netherlands	Average	22,700^{a}	8,130^{a}	14,570^{a}	35%	4
Pork	Conventional	Netherlands	Average	23,260^{a}	8,450^{a}	14,810^{a}	36%	4
Pork	Conventional	Netherlands	Average	23,510^{a}	8,010^{a}	15,500^{a}	33%	4
Poultry	Conventional	Netherlands	Average	21,788^{a}	10,569^{a}	11,219^{a}	48%	4
Poultry	Conventional	Netherlands	Average				61%	5
Poultry	Conventional	Scotland	Average	1,015	510	510	50%	2
Layers	Conventional	Netherlands	Average	36,789^{a}	12,942^{a}	23,847^{a}	35%	4

[a] Units are kg N farm^{-1} yr^{-1}

Sources:

(1) Bassanino et al. 2007; (2) Domburg et al. 2000; (3) Nielsen & Kristiensen 2005; (4) Oenema 2006; (5) Schröder et al. 2003; (6) Watson & Atkinson 1999; (7) Watson et al. 2002

APPENDIX D

Farm nitrogen budget: Detailed results for Timbercreek Organics Farm

Table D1. Nitrogen contained in feed inputs, meat outputs, and slaughter by-product outputs at Timbercreek Organics Farm estimated with minimum, maximum, and average nitrogen contents.

	Average N content (kg N)		Maximum N content (kg N)		Minimum N content (kg N)	
	2012	2013	2012	2013	2012	2013
Feed						
Corn	774	1,749	871	1,968	678	1,530
Soybeans	1,968	4,180	2,306	4,897	1,631	3,464
Oats	131	262	153	305	109	218
Alfalfa pellets	28	69	32	81	23	56
Fishmeal	218	231	236	250	200	212
Kelp	12	25	19	38	7	15
Hay	647	683	849	896	470	496
Bedding	40	67	44	74	36	61
Purchased livestock						
Pigs	46	24	59	31	34	18
Cattle	655	0	753	0	563	0
Poultry[a]	18	18	21	21	15	15
Layers	56	64	66	76	47	54
Meat/animal products						
Pork	108	323	126	376	83	246
Beef	154	706	184	843	138	633
Poultry[a]	138	365	155	409	121	319
Eggs	82	129	87	137	76	119
Slaughter by-products						
Pork	89	266	99	296	79	236
Beef	117	348	140	417	82	245
Poultry[a]	61	161	64	168	48	153

[a] *Poultry category includes broiler chickens, turkeys, and ducks.*

Table D2. Summary of total nitrogen inputs and outputs to Timbercreek Organics Farm in 2012 and 2013 in kg N yr^{-1}.

Farm metric	**Average** (kg N yr^{-1})		**Maximum** (kg N yr^{-1})		**Minimum** (kg N yr^{-1})	
	2012	**2013**	**2012**	**2013**	**2012**	**2013**
Intended inputs						
Feed	3,132	6,515	3,617	7,539	2,647	5,495
Hay	647	683	849	896	470	496
Legume BNF	693	693	1,067	1,067	304	304
Livestock	775	107	900	128	660	88
Bedding	40	67	44	74	36	61
Energy use	18	22	18	22	18	22
Total intended inputs	**5,305**	**8,088**	**6,496**	**9,727**	**4,137**	**6,466**
Unintended inputs						
Atmospheric deposition	691	691	691	691	691	691
Total unintended inputs	**691**	**691**	**691**	**691**	**691**	13,624
Intended outputs						
Meat	483	1,522	552	1,764	418	1,318
By-products	267	775	303	881	219	634
Total intended outputs	**750**	**2,297**	**856**	**2,645**	**637**	**1,951**

APPENDIX E

Virtual nitrogen factors: Detailed data for Timbercreek Organics Farm and conventional farms

Table E1. Virtual nitrogen factor data and results for pork production at Timbercreek Organics Farm (TCO) in 2012 and 2013 and for conventional (Conv.) production in the United States. Two methods for calculating virtual N factors for TCO are presented. Maximum and minimum values represent the uncertainty range for protein contents and feed crop N uptake factors.

Virtual N factor step	**Pork**						
	Timbercreek Organics Farm: 2012			Timbercreek Organics Farm: 2013			*Conv.*
	Average	Max	Min	Average	Max	Min	
Step 1: Feed crop N uptake							
% of feed protein: Corn and (% N uptake)	34% (80%)	34% (85%)	34% (66%)	34% (80%)	34% (85%)	34% (66%)	
% of feed protein: Soybeans and (% N uptake)	53% (90%)	53% (95%)	53% (80%)	53% (90%)	53% (95%)	53% (80%)	
% of feed protein: Oats and (% N uptake)	13% (80%)	13% (85%)	13% (66%)	13% (80%)	13% (85%)	13% (66%)	
% of feed protein: Alfalfa and (% N uptake)	0% (80%)	0% (85%)	0% (66%)	0% (80%)	0% (85%)	0% (66%)	
% of feed protein: Fishmeal and (% N uptake)	0% (22%)	0% (30%)	0% (16%)	0% (22%)	0% (30%)	0% (16%)	
Weighted feed N uptake (%)	**85%**	**93%**	**73%**	**85%**	**93%**	**73%**	*82%*
Step 2: Feed crop processing							
N retained during feed processing (%)	**75%**	**75%**	**75%**	**75%**	**75%**	**75%**	*75%*
Recycling of processing losses (%)	**35%**	**35%**	**35%**	**35%**	**35%**	**35%**	*35%*
Step 3: Live animal production							
Method 1: Feed used							
Total live animal/product N (kg N)	205	241	167	610	717	497	
Total feed N (kg N)	918	775	1,061	1,980	1,673	2,287	
Conversion to live weight (%)	**22%**	**31%**	**16%**	**31%**	**43%**	**22%**	*35%*
Method 2: Feed recommendations							
Individual animal/product (kg N)	3.2	3.9	2.5	3.2	3.9	2.5	
Feed per animal/product (kg N)	17.3	14.5	20.2	17.3	14.5	20.2	
Conversion to live weight (%)	**19%**	**27%**	**13%**	**19%**	**27%**	**13%**	*35%*
Recycling of manure (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*35%*
Step 4: Slaughter/first processing							
Animal/product N (kg N)	2.0	2.3	1.6	2.0	2.3	1.6	
Animal/product slaughter by-product N (kg N)	1.8	1.6	2.2	1.8	1.6	2.2	
N retained during slaughter/processing (%)	**53%**	**60%**	**42%**	**53%**	**60%**	**42%**	*75%*
Slaughter recycling/processing by-products (%)	**90%**	**90%**	**90%**	**90%**	**90%**	**90%**	*90%*
Step 5: Processing							
N retained during processing (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*95%*
Recycling of processing losses (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*90%*
Final virtual N factor							
TCO Method 1: Feed used	**3.6**	**1.6**	**9.8**	**2.5**	**1.1**	**7.0**	
TCO Method 2: Feed recommendation	**4.2**	**1.8**	**12.3**	**4.2**	**1.8**	**12.3**	
Conventional farms average							***3.6***

Table E2. Virtual nitrogen factor data and results for beef production at Timbercreek Organics Farm (TCO) in 2012 and 2013 and for conventional (Conv.) production in the United States. Two methods for calculating virtual N factors for TCO are presented. Maximum and minimum values represent the uncertainty range for protein contents and feed crop N uptake factors.

Virtual N factor step	**Beef**						
	Timbercreek Organics Farm: 2012			Timbercreek Organics Farm: 2013			*Conv.*
	Average	Max	Min	Average	Max	Min	
Step 1: Feed crop N uptake							
% of feed protein: Grass	100%	100%	100%	100%	100%		100%
% N uptake: Grass	100%	100%	100%	100%	100%		100%
Weighted feed N uptake (%)	100%	100%	100%	100%	100%		*82%*
Step 2: Feed crop processing							
N retained during feed processing (%)	100%	100%	100%	100%	100%	100%	*80%*
Recycling of processing losses (%)	100%	100%	100%	100%	100%	100%	*35%*
Step 3: Live animal production							
Method 1: Feed used							
Total live animal/product N (kg N)	317	393	246	1,451	1,799	1,125	
Total feed N (kg N)	1,340	774	1,916	1,376	800	1,963	
Conversion to live weight (%)	**24%**	**51%**	**13%**	**100%+**	**100%+**	**57%**	*20%*
Method 2: Feed recommendations							
Individual animal/product (kg N)	n/a	n/a	n/a	n/a	n/a	n/a	
Feed per animal/product (kg N)	n/a	n/a	n/a	n/a	n/a	n/a	
Conversion to live weight (%)	n/a	n/a	n/a	n/a	n/a	n/a	*20%*
Recycling of manure (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*35%*
Step 4: Slaughter/first processing							
Animal/product N (kg N)	6.8	8.2	6.1	6.8	8.2	6.1	
Animal/product slaughter by-product N (kg N)	7.4	4.9	9.4	7.4	4.9	9.4	
N retained during slaughter/processing (%)	**48%**	**62%**	**39%**	**48%**	**62%**	**39%**	*75%*
Slaughter recycling/processing by-products (%)	**90%**	**90%**	**90%**	**90%**	**90%**	**90%**	*90%*
Step 5: Processing							
N retained during processing (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*95%*
Recycling of processing losses (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*90%*
Final virtual N factor							
TCO Method 1: Feed used	**0.1**	**0.06**	**0.2**	**0.1**	**0.06**	**0.2**	
TCO Method 2: Feed recommendation	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	
Conventional farms average							***6.6***

Table E3. Virtual nitrogen factor data for poultry production at Timbercreek Organics Farm (TCO) in 2012 and 2013 and for conventional (Conv.) production in the United States. Two methods for calculating virtual N factors for TCO are presented. Maximum and minimum values represent the uncertainty range for protein contents and feed crop N uptake factors.

Virtual N factor step	**Poultry**						
	Timbercreek Organics Farm: 2012			Timbercreek Organics Farm: 2013			*Conv.*
	Average	Max	Min	Average	Max	Min	
Step 1: Feed crop N uptake							
% of feed protein: Corn and (% N uptake)	22% (80%)	22% (85%)	22% (66%)	22% (80%)	22% (85%)	22% (66%)	
% of feed protein: Soybeans and (% N uptake)	58% (90%)	58% (95%)	58% (80%)	58% (90%)	58% (95%)	58% (80%)	
% of feed protein: Oats and (% N uptake)	3% (80%)	3% (85%)	3% (66%)	3% (80%)	3% (85%)	3% (66%)	
% of feed protein: Alfalfa and (% N uptake)	5% (80%)	5% (85%)	5% (66%)	5% (80%)	5% (85%)	5% (66%)	
% of feed protein: Fishmeal and (% N uptake)	12% (22%)	12% (30%)	12% (16%)	12% (22%)	12% (30%)	12% (16%)	
Weighted feed N uptake (%)	**79%**	**88%**	**68%**	**79%**	**88%**	**68%**	*82%*
Step 2: Feed crop processing							
N retained during feed processing (%)	**75%**	**75%**	**75%**	**75%**	**75%**	**75%**	*75%*
Recycling of processing losses (%)	**35%**	**35%**	**35%**	**35%**	**35%**	**35%**	*35%*
Step 3: Live animal production							
Method 1: Feed used							
Total live animal/product N (kg N)	200	221	182	529	582	480	
Total feed N (kg N)	1,449	1,234	1,665	2,888	2,444	3,332	
Conversion to live weight (%)	**14%**	**18%**	**11%**	**18%**	**24%**	**14%**	*45%*
Method 2: Feed recommendations							
Individual animal/product (kg N)	0.09	0.10	0.08	0.09	0.10	0.08	
Feed per animal/product (kg N)	0.25	0.21	0.30	0.25	0.21	0.30	
Conversion to live weight (%)	**35%**	**47%**	**27%**	**35%**	**47%**	**27%**	*45%*
Recycling of manure (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*35%*
Step 4: Slaughter/first processing							
Animal/product N (kg N)	0.062	0.068	0.055	0.06	0.062	0.055	
Animal/product slaughter by-product N (kg N)	0.028	0.026	0.031	0.03	0.028	0.031	
N retained during slaughter/processing (%)	**69%**	**72%**	**64%**	**69%**	**72%**	**64%**	*75%*
Slaughter recycling/processing by-products (%)	**90%**	**90%**	**90%**	**90%**	**90%**	**90%**	*90%*
Step 5: Processing							
N retained during processing (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*95%*
Recycling of processing losses (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*90%*
Final virtual N factor							
TCO Method 1: Feed used	**5.7**	**3.0**	**11.6**	**4.4**	**2.2**	**9.1**	
TCO Method 2: Feed recommendation	**2.2**	**1.1**	**4.5**	**2.2**	**1.1**	**4.5**	
Conventional farms average							***2.6***

Table E4. Virtual nitrogen factor data and results for egg production at Timbercreek Organics Farm (TCO) in 2012 and 2013 and for conventional (Conv.) production in the United States. Two methods for calculating virtual N factors for TCO are presented. Maximum and minimum values represent the uncertainty range for protein contents and feed crop N uptake factors.

Virtual N factor step	**Eggs**						
	Timbercreek Organics Farm: 2012			Timbercreek Organics Farm: 2013			*Conv.*
	Average	Max	Min	Average	Max	Min	
Step 1: Feed crop N uptake							
% of feed protein: Corn and (% N uptake)	24% (80%)	24% (85%)	24% (66%)	24% (80%)	24% (85%)	24% (66%)	
% of feed protein: Soybeans and (% N uptake)	66% (90%)	66% (95%)	66% (80%)	66% (90%	66% (95%)	66% (80%)	
% of feed protein: Oats and (% N uptake)	4% (80%)	4% (85%)	4% (66%)	4% (80%)	4% (85%)	4% (66%)	
% of feed protein: Alfalfa and (% N uptake)	5% (80%)	5% (85%)	5% (66%)	5% (80%)	5% (85%)	5% (66%)	
% of feed protein: Fishmeal and (% N uptake)	0% (22%)	0% (30%)	0% (16%)	0% (22%)	0% (30%)	0% (16%)	
Weighted feed N uptake (%)	**87%**	**95%**	**75%**	**87%**	**95%**	**75%**	*82%*
Step 2: Feed crop processing							
N retained during feed processing (%)	**75%**	**75%**	**75%**	**75%**	**75%**	**75%**	*75%*
Recycling of processing losses (%)	**35%**	**35%**	**35%**	**35%**	**35%**	**35%**	*35%*
Step 3: Live animal production							
Method 1: Feed used							
Total live animal/product N (kg N)	83	90	76	131	141	120	
Total feed N (kg N)	752	632	873	1,623	1,363	1,882	
Conversion to live weight (%)	**11%**	**14%**	**9%**	**8%**	**10%**	**6%**	*35%*
Method 2: Feed recommendations							
Individual animal/product (kg N)	0.0012	0.0012	0.0011	0.0012	0.0012	0.0011	
Feed per animal/product (kg N)	0.0072	0.0060	0.0085	0.0072	0.0060	0.0085	
Conversion to live weight (%)	**17%**	**22%**	**13%**	**17%**	**22%**	**13%**	*35%*
Recycling of manure (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*35%*
Step 4: Slaughter/first processing							
Animal/product N (kg N)	N/A			N/A			
Animal/product slaughter by-product N (kg N)	N/A			N/A			
N retained during slaughter/processing (%)	**95%**	**95%**	**95%**	**95%**	**95%**	**95%**	*75%*
Slaughter recycling/processing by-products (%)	**95%**	**95%**	**95%**	**95%**	**95%**	**95%**	*90%*
Step 5: Processing							
N retained during processing (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*95%*
Recycling of processing losses (%)	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	*90%*
Final virtual N factor							
TCO Method 1: Feed used	**4.0**	**2.1**	**7.7**	**5.5**	**3.0**	**11.6**	
TCO Method 2: Feed recommendation	**2.6**	**1.4**	**5.3**	**2.6**	**1.4**	**5.3**	
Conventional farms average							***3.6***