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Title

The nitrogen footprint of organic food in the United States

Authors

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Keywords

organic, agriculture, footprints, nitrogen, virtual nitrogen factors

Abstract

We estimated the reactive nitrogen (Nr) lost per unit food Nr consumed for organic food production in the United States and compared it to conventional production. We used a nitrogen footprint model approach, which accounts for both differences in Nr losses as well as differences in productivity of the two systems. Additionally, we quantified the types of Nr inputs (new versus recycled) that are used in both production systems.

We estimated Nr losses from organic crop and animal production to be of comparable magnitude to conventional production losses, with the exception of beef. While Nr losses from organic vegetables are possibly higher (+37%), Nr losses from organic grains, starchy roots, legumes are likely of similar magnitude to conventional production (+7%, +6%, -12%, respectively). Nr losses from organic poultry, pigmeat, and dairy production are also likely comparable to conventional production (+9%, +10%, +12%, respectively), while Nr losses from organic beef production were estimated to be higher (+124%). Due to the high variability and high uncertainty in Nr efficiency in both systems we cannot make conclusions yet on the statistical significance of these potential differences.

Conventional production relies heavily on the creation of new Nr (70-90% of inputs are from new Nr sources like synthetic fertilizer) whereas organic production primarily utilizes already existing Nr (0-50% of organic inputs are from new Nr sources like leguminous N fixation).

Consuming organically produced foods has little impact on an individual's food N footprint but changes the percentage of new versus recycled Nr in the footprint. With

the exception of beef, Nr losses from organic production per unit N in product are comparable to conventional production. However, organic production requires the creation of less new Nr, which could reduce global Nr pollution.

1. Introduction

Humans create reactive nitrogen (Nr; all chemical species of N except N_2) both for agriculture and from energy production (Galloway *et al* 2008). In the last 75 years, anthropogenic Nr creation has helped to dramatically increase agricultural yields and, along with it, feed a growing human population (Erisman *et al* 2008). However, most Nr used in agriculture is lost to the environment during food production (Erisman *et al* 2008). This Nr moves through the nitrogen (N) cycle and creates a cascade of detrimental environmental and human health impacts (Galloway *et al* 2003). Some suggest that we have surpassed the planetary boundary for Nr creation (Rockstrom *et al* 2009, De Vries *et al* 2013, Steffen *et al* 2015). The N challenge therefore consists of maximizing the benefits of Nr, while minimizing its negative impacts.

Agricultural production methods vary in terms of their Nr efficiency and therefore are key determinants of Nr losses to the environment. More than 95% of the food grown and raised in the United States (US) is produced through conventional methods (USDA 2012).

To minimize the negative environmental impacts of modern conventional agriculture, we need to develop more sustainable farming systems that can efficiently produce food for humans while balancing ecological functioning and reducing Nr losses (Bennett and Balvanera 2007, Erisman *et al* 2016, Foley *et al* 2011, Tilman *et al* 2002). Organic agriculture is an example of a clearly defined and certified type of agriculture that could be a sustainable alternative to conventional agriculture (Reganold and Wachter 2016, Scialabba and Hattam 2002, Tilman 1998).

Foods that are certified organic by the United States Department of Agriculture

(USDA) must be produced and processed according to strict guidelines set out in the Organic Foods Production Act of 1990 (USDA 2000). These guidelines are extensive, including prohibiting the use of synthetic fertilizer and requiring livestock access to pasture; therefore, organic farming relies on careful management of Nr through soil quality best practices, crop rotations, composting, biological soil amendments and other practices (USDA 2000).

Many studies have compared and contrasted organic and conventional agricultural practices, productivity and environmental impacts. Organic yields per unit land tend to be 10-35% lower than conventional yields (De Ponti *et al* 2012, Ponisio *et al* 2015, Seufert *et al* 2012). However, the differences between organic and conventional practices in terms of environmental performance are variable (Meier *et al* 2015, Mondelaers *et al* 2009, Tuomisto *et al* 2012, Seufert and Ramankutty 2017, Clark and Tilman 2017). For Nr pollution specifically, Kirchmann and Bergstrom (2001) argued (based on a qualitative review of the literature) that there is no difference between organic and conventional production and several meta-analyses have reached similar conclusions, especially when comparing Nr pollution per unit product (e.g., Mondelaers *et al* 2009, Tuomisto *et al* 2012, Seufert and Ramankutty 2017). A recent meta-analysis, however, found that organic systems have a higher eutrophication potential per unit of food, but comparable greenhouse gas emissions and acidification potential per unit of food (Clark and Tilman 2017). Nr losses per unit land may be lower for organic farms as compared to conventional farms (Cambardella *et al* 2015, Hansen *et al* 2000, Kramer *et al* 2006). But lower yields and reliance on biological nitrogen fixation (BNF) as a Nr source for organic also mean that more land may be needed per unit food product (Connor 2008). These debates highlight the need for evaluating Nr losses from organic production relative to conventional systems with a particular focus on a per unit product basis.

Nr inputs to agriculture can be categorized into two types: new and recycled Nr. New Nr created for human use increases the total global pool and adds to the total amount of Nr that negatively impacts the environment (Erisman *et al* 2008, Erisman *et al* 2016). Modern agricultural production relies heavily on new Nr sources, like synthetic fertilizer and cultivation induced BNF (Erisman *et al* 2008). It is estimated that 70-85% of the Nr inputs to conventional agriculture are in the form of new Nr, while about 15-30% are from recycled Nr sources like animal manure, compost, or crop residues (Sobota *et al* 2013, Ladha *et al* 2016). Due to the prohibition of synthetic Nr inputs, organic agriculture most likely relies more strongly on recycled Nr sources than conventional agriculture. But the portion of Nr inputs to organic systems from new or recycled Nr inputs has not yet been quantified.

Environmental footprints, like the N footprint model, are one way of evaluating the potential impact of consumption choices based on current production systems (Galli *et al* 2012, Leach *et al* 2012). A N footprint is defined as 'the total amount of Nr released to the environment as a result of an entity's resource consumption' (Leach *et al* 2012). Losses of Nr during food production are called virtual N, which is defined as 'N used in the food production process [that is] not in the food product that is consumed' (Leach *et al* 2012). Virtual N losses are estimated with virtual N factors (VNF), which describe the N lost to the environment per unit N consumed (Leach *et al* 2012).

In this paper, we examine the N footprint of organically produced foods and compare it to the conventional food N footprint for the U.S. Our objectives are to: (1) quantify the virtual N factors (VNFs) of organic crop and animal production in the U.S.; (2) calculate the N footprint of a 100% organic diet in the U.S.; (3) assess how much new Nr organic agriculture contributes to the global Nr pool, as a percent of total inputs; and (4) compare these results to conventional production.

2. Methods

2.1 N footprint and Virtual N Factors (VNFs)

We used the N footprint calculator as developed by Leach *et al* (2012) to quantify Nr losses during organic crop and animal production and consumption. This analysis will focus only on the food production and food consumption portions of the N footprint in the U.S. The N footprint of an entity (e.g. an individual, institution or country) represents the total amount of Nr released by the entity's food consumption patterns. The associated VNFs used to calculate the food production N footprint depict the nitrogen losses and efficiency of the production system (from Nr created and applied all the way to Nr consumed), highlighting areas where efficiencies are low. Figure 1 provides an overview of the different steps of the food supply chain as used in the N footprint model, including the steps at which Nr losses occur.

An entity's total food N footprint has two parts: the amount of Nr they consume, which enters the wastewater stream and may be treated (Consumed N, Fig. 1), plus the Nr lost during the production of that food (i.e. the sum of the grey arrows in Fig. 1 except the arrow for human waste). Food consumption N is calculated based on average per capita consumption of different food groups (FAO 2016) and on the protein content of those foods (N is contained in protein). We assume the average U.S. diet and protein contents for both the organic and conventional N footprint calculations; therefore, the data inputs, calculations, and results are the same for the organic and conventional food consumption N calculations (Leach *et al* 2012). In reality, individuals choosing to consume only organic food products may or may not have a diet similar to the average U.S. diet (for example, they may consume less animal protein).

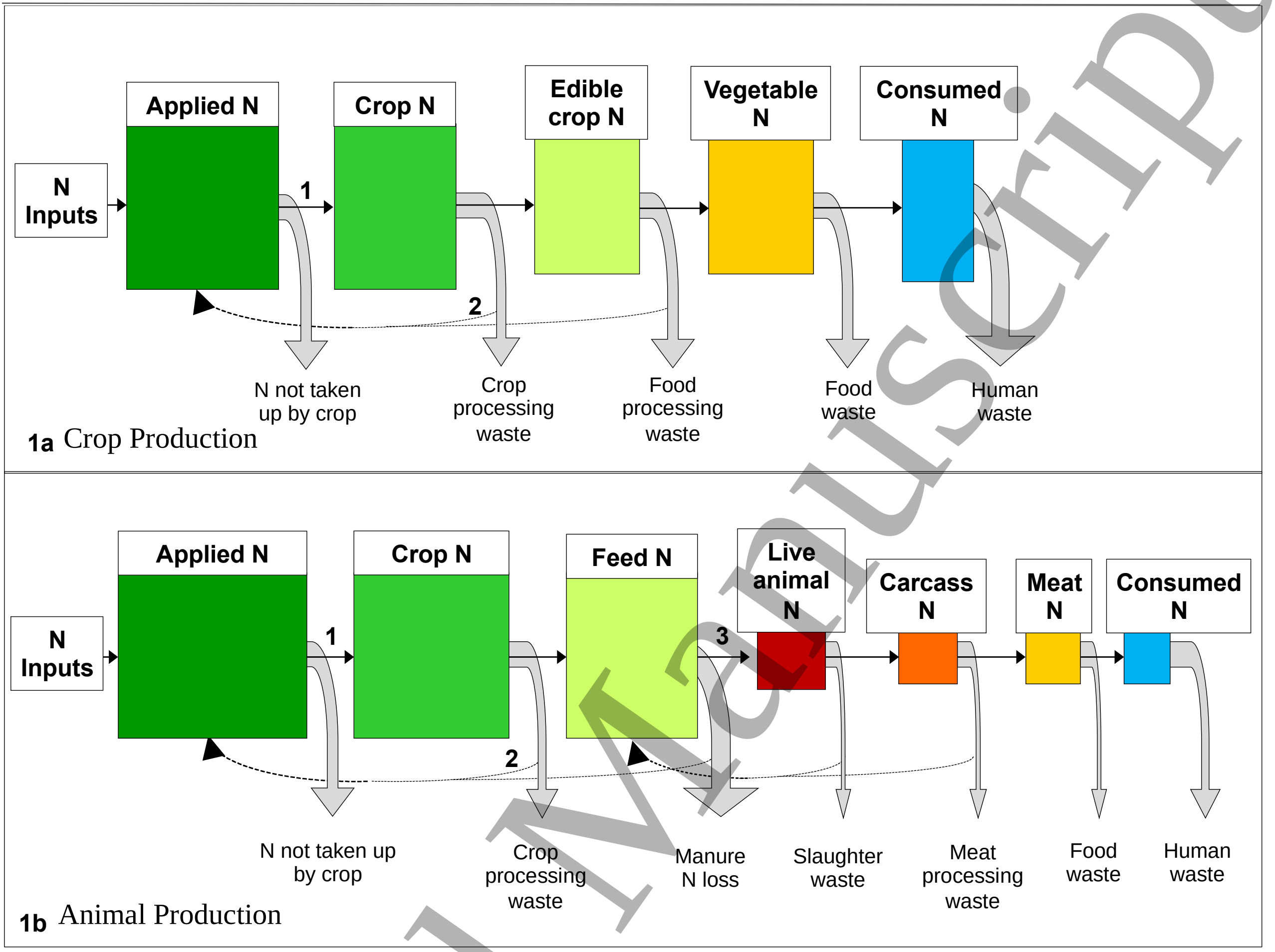


Figure 1. Reactive nitrogen (Nr) flow in crop (a) and animal (b) production systems. Black arrows indicate flow of Nr from one phase of production to the next. The size of each box approximates the Nr flow through that step. Black arrows with doted lines show Nr recycled from later steps back to earlier steps in the production. Downward pointing grey arrows indicate Nr lost to the environment or virtual nitrogen. Virtual Nitrogen Factors (VNFs) are calculated as total virtual N(except human waste) divided by consumed N. The organic VNFs use the same parameter inputs as conventional except for 1) whole plant N uptake (=1- N loss C1) 2) recycling rate and 3) live animal N uptake (=1 – N loss A3). These are labeled 1 through 3 in the diagram. See Methods and SM Methods for full description of calculations. *Adapted from Leach et al 2012.*

Virtual N represents the proportion of Nr used during the food production process (e.g. applied as fertilizer to agricultural fields) that is not recovered in the human diet (Leach *et al* 2012). We thus use a mass balance approach that assumes that any Nr that is applied to a field and does not end up being consumed is lost to the environment (after accounting for any recycling) in a given production system. The total Nr losses during food production are calculated using Virtual N Factors (VNFs), which represent the units of Nr released per unit of Nr consumed in different food products (Leach *et al* 2012); they can also be calculated as units of Nr release per units of product consumed. VNFs represent the sum of Nr losses throughout the food production process, including (1) Nr in the applied fertilizer that is not taken up by the whole plant, (2) crop residue Nr that is not recycled, (3) Nr in feed that is not recovered in animal weight or animal products (i.e. lost from manure) for animal production, (4) Nr lost during food processing (which includes Nr losses from slaughter waste, and meat processing waste for animal production), and (5) Nr lost as food waste (i.e. the grey arrows in Figure 1, except for human waste).

2.2 Organic crop products VNFs

The crop production VNFs were calculated for 4 different crop groups: grains (average of wheat, corn, barley, oats), vegetables (average of tomatoes, lettuce, spinach, peppers), starchy roots and legumes.

There were two key steps of the conventional VNFs food supply chain calculations that were modified to represent organic crop production: (1) the Nr uptake of applied

Nr by the whole plant (i.e. the first grey arrow in Fig. 1a; N Loss C1), and (2) the crop residue N that is recycled (i.e. the first recycling arrow in Fig. 1b; N Loss C2). Nr not taken up by crops (N Loss C1) represents the difference between Nr applied to the field and the Nr taken up by the whole plant. Data on Nr application rates and yields of organic crop products were collected using a literature review of peer-reviewed studies (a full list of observations and sources is included in Table S2). The second N loss ('N loss C2') where the organic crop VNFs differed from the conventional calculations concerns the amount of crop residues that are recycled and re-applied for crop production (see Fig. 1) versus lost from the system.

Table 1. Key parameters used in virtual N factor (VNF) calculation for organic crop products (with uncertainty ranges shown in parenthesis) that differed from the parameters used in conventional VNFs. The number of observations for conventional is the fertilizer N application rates across all state observations used in the analysis. Some states may be represented twice if a specific product is produced in the same state. See SM for details on the calculations and a full list of references. See Leach *et al* submitted for details on conventional data.

Crop Categories	Production System	Products	# Studies	# Obs.	1) Whole Plant N Uptake (=1-N loss C1)	2) Recycling Rate
Grains	Organic	corn, wheat, barley, oat	14	38	0.73 (0.63-0.82)	0.50[a]
	Conventional	corn, wheat, rice	-	83	0.85 (0.66-1.0)	0.35[b]
Legumes	Organic	soybean	7	13	0.92 (0.85-0.99)	0.50[a]
	Conventional	soybean	-	28	0.92 (0.88-0.96)	0.35[b]
Starchy Roots	Organic	potato	6	15	0.54 (0.39-0.69)	0.50[a]
	Conventional	potato	-	27	0.57 (0.52-0.61)	0.35[b]
Vegetables	Organic	lettuce, tomato, pepper, spinach	9	60	0.34 (0.19-0.48)	0.50[a]
	Conventional	lettuce, tomato, onion	-	75	0.35 (0.25-0.53)	0.35[b]

[a] from Cavigelli *et al* 2008

[b] from Leach *et al* 2012

2.3 Organic animal products VNFs

Animal VNFs (calculated for poultry, pigmeat, beef and dairy) depend both on livestock diet composition (which differs between organically and conventionally raised livestock) as well as the efficiency with which animals convert feed into weight or animal product over the course of their lifespan.

The two variables described above that were adjusted for organic crop production were also adjusted for feed crop production and weighted by livestock feed composition (see SM Methods for details). One additional VNF step was adjusted for organic animal products: the nitrogen feed conversion ratio (i.e., the percent of *Feed N* taken up into *Live animal N*, ‘N loss A3’, Fig. 1). Data for organic feed composition and organic feed conversion efficiencies were derived from a literature review of primary studies, while data for conventional animal production came from literature sources and extension services (Table 2, see Table S5 for organic sources, Leach *et al* submitted for conventional sources).

Table 2. Key parameters used in virtual N factor (VNF) calculations for organic animal products (with uncertainty ranges shown in parenthesis) that differed from the ones used in conventional VNFs. All plant uptake steps are weighted based on diet composition of each animal product. Animal N uptake step (Fig. 1) for milk shows N in milk/N in feed. For conventional, 'studies' indicates the number of state extension agencies used and 'observations' indicates the number of feed conversion ratio (FCR) or feed efficiency ratio (FER data points). See SM for details on calculations and a full list of references.

Animal Product	**Production System**	**# Studies**	**# Obs.**	**1) Crop N Uptake (=1-N loss A1)**	**3) Live Animal N Uptake (=1-N loss A3)**
Poultry	Organic	12	50	0.85 (0.77-0.92)	0.29 (0.25-0.33)
	Conventional	10	12	0.80 (0.72-0.88)	0.38 (0.35-0.41)
Pigmeat	Organic	6	22	0.85 (0.77-0.93)	0.23 (0.22-0.25)
	Conventional	3	46	0.95 (0.91-0.98)	0.23 (0.22-0.25)
Beef	Organic	5	13	0.68 (0.64-0.72)	0.08 (0.07-0.09)
	Conventional	4	6	0.88 (0.85-0.91)	0.15 (0.13-0.17)
Milk	Organic	8	24	0.61 (0.58-0.64)	0.34 (0.23-0.46)
	Conventional	3	44	0.82 (0.79-0.86)	0.28 (0.27-0.29)

To calculate ‘N loss A3’ we collected data from a literature review of peer-reviewed studies on feed conversion ratios (FCRs, i.e. units of kg feed required per kg weight gain) for different organic meat products (see Table S8 for a list of sources), as well as feed efficiency ratios (FERs, i.e. milk production per unit feed consumption) for dairy (see Table S9 for a list of sources) to estimate the Nr uptake by the live animal (see SM Methods for details on equations used).

2.4 Uncertainties around crop and animal VNFs

Uncertainties around overall crop and animal VNFs were calculated by using the lower and upper values of individual key parameters, including Whole Plant N Uptake and Live Animal N Uptake (see SM Methods of how uncertainties around individual parameters were calculated). Ranges around organic crop VNFs essentially represent variation between the results of different primary studies, while ranges around conventional crop VNFs represent variation between different states. Ranges around organic and conventional animal VNFs represent high and low efficiencies from crop production for feed, as well as variation in FCR values between primary studies for both organic and conventional production.

2.5 New versus recycled N inputs

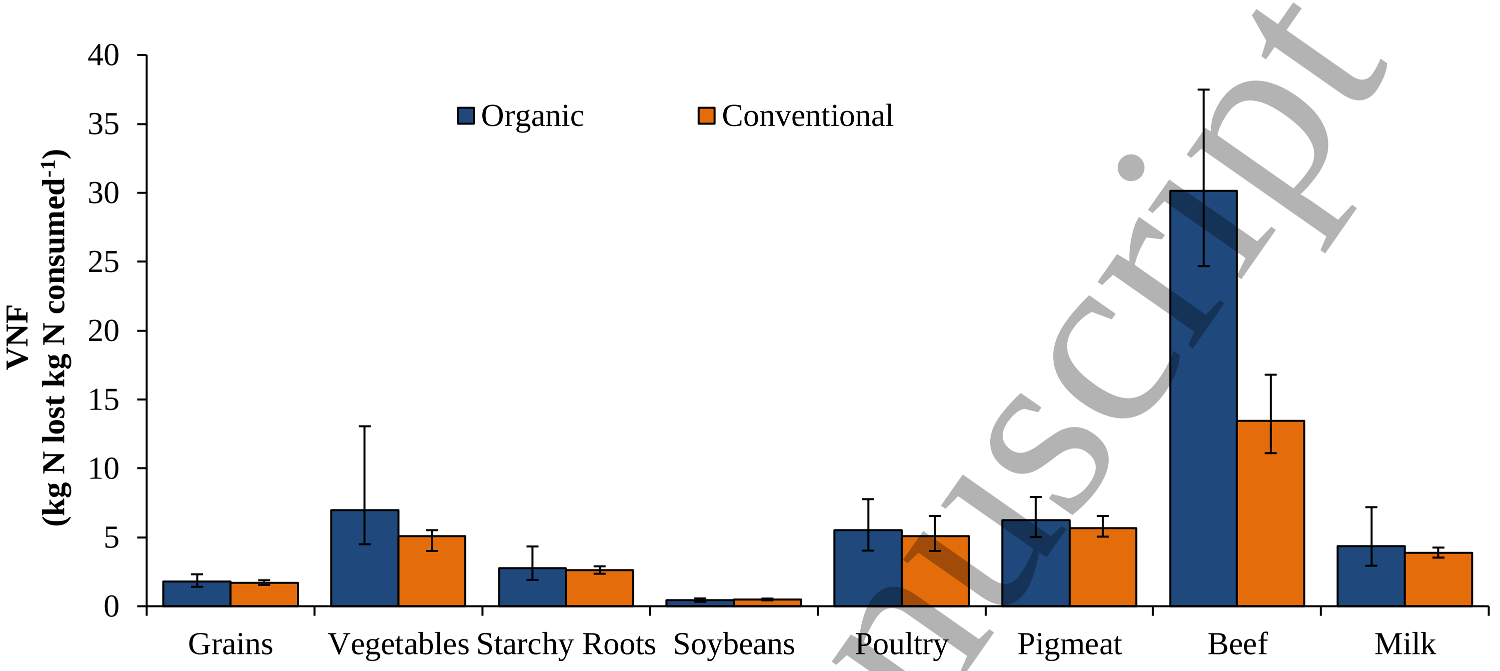
This analysis also quantified the sources and types of Nr inputs into both organic and conventional systems. New Nr sources include synthetic fertilizer (Nr created via Haber-Bosch), BNF by the crop itself (i.e. soybean), and BNF by a green manure (i.e. legumes). Recycled Nr sources include BNF by another crop in the rotation (such as by a soybean in a corn-soybean rotation), animal manures or any animal by-products, crop residues, non-legume green manures, and compost. Data on the Nr sources applied to organic and conventional cropping systems were collected using a literature review of peer-reviewed studies (see list of sources in Table S12). For animal products, Nr input types were weighted based on diet composition (see Table S6).

3. Results

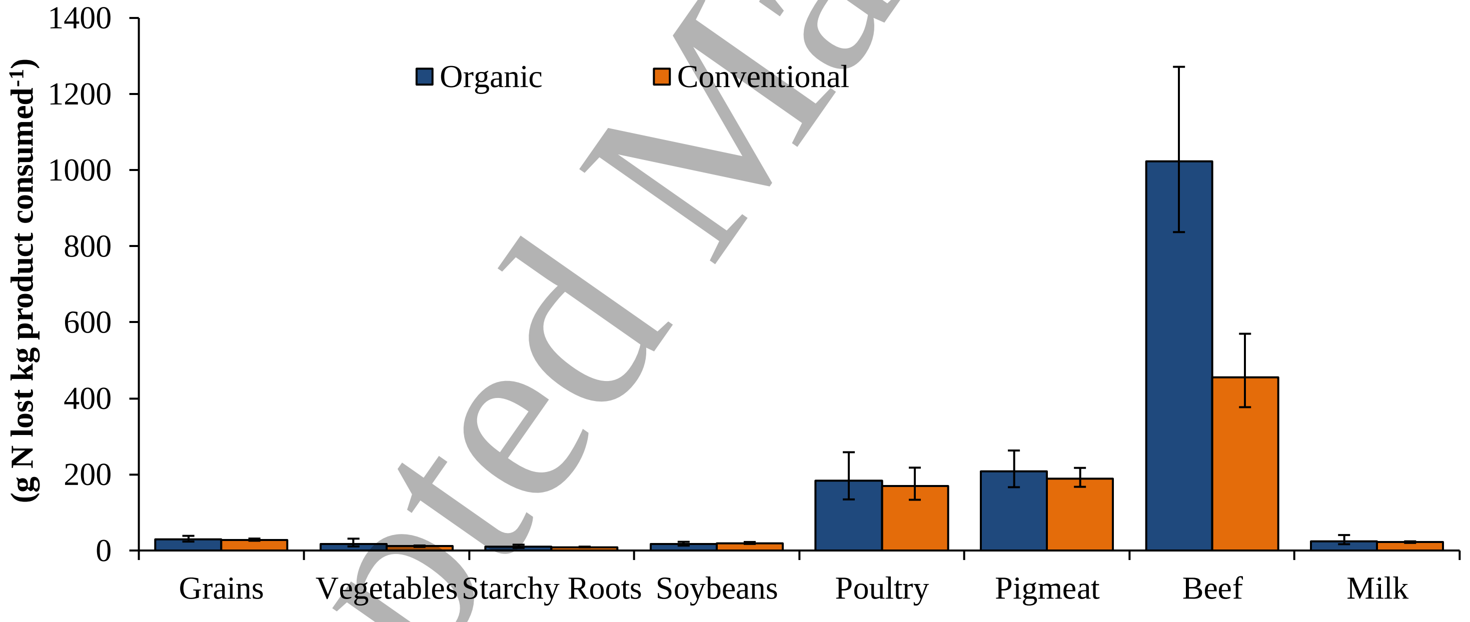
Our analysis finds that there is little difference between organic and conventional food production in terms of 1) the virtual Nr losses or 2) the total food N footprint, with the exception of beef production. Both organic and conventional production systems are inefficient and a large percentage of Nr inputs are lost throughout the food supply chain before consumption (Fig. 1). For both organic and conventional crop production, the majority of Nr losses occur during the whole plant N uptake step. However, compared to conventional production, organic crop residue N recycling is higher (Table 1, Figure S1). For organic animal production, the highest rate of Nr losses occurs during the N feed conversion ratio step, but we estimate relatively efficient Nr recycling in organic feed production (Table 2, Figure S2).

The overall amount of Nr lost between application of Nr to the field and consumption of Nr by the consumer (i.e, the VNFs) is somewhat higher under organic management for vegetables, and it is comparable to conventional for organic grains, starchy roots and legumes (Fig. 2). Organic poultry, pigmeat and dairy VNFs are comparable to conventional, while the organic beef VNF is greater than conventional (Fig. 2).

Because of variation among different primary studies, the organic VNFs have wide uncertainty ranges. However, there is also a wide uncertainty range for the conventional VNFs because of variation among different states. Note that because organic and conventional VNFs were calculated using different data sources (see Methods), it is not possible to make any conclusions regarding the statistical significance of these differences, despite the standardized use of methods and calculations. However, because the estimated VNF uncertainty ranges are so large for both, it is unlikely that there is a significant difference between organic and conventional production.



2a Losses per unit N



2b Losses per unit product

Figure 2. Virtual N factors (VNFs) for food produced organically (blue) and conventionally (orange). VNFs are calculated as total N lost to the environment per unit N consumed (a) and total N lost per unit product consumed (b). The higher VNF values, the higher the losses of Nr to the environment during the production process. Bars show model output with uncertainty range based on uncertainty ranges around key parameters (see Methods and SM Methods for more details). Note that these uncertainty ranges do *not* represent confidence intervals in a statistical sense.

Assuming similar diets and consumption patterns, the average total food production footprint for a U.S. consumer who only consumes organic food is 30-52 kg N year^{-1}, compared to 22-31 kg N year^{-1} for the average U.S. consumer who only consumes conventional food (Fig. 3, Leach *et al* submitted). This higher footprint of organic consumption is mainly driven by the higher footprint of organic compared to conventional beef production (Leach *et al* submitted).

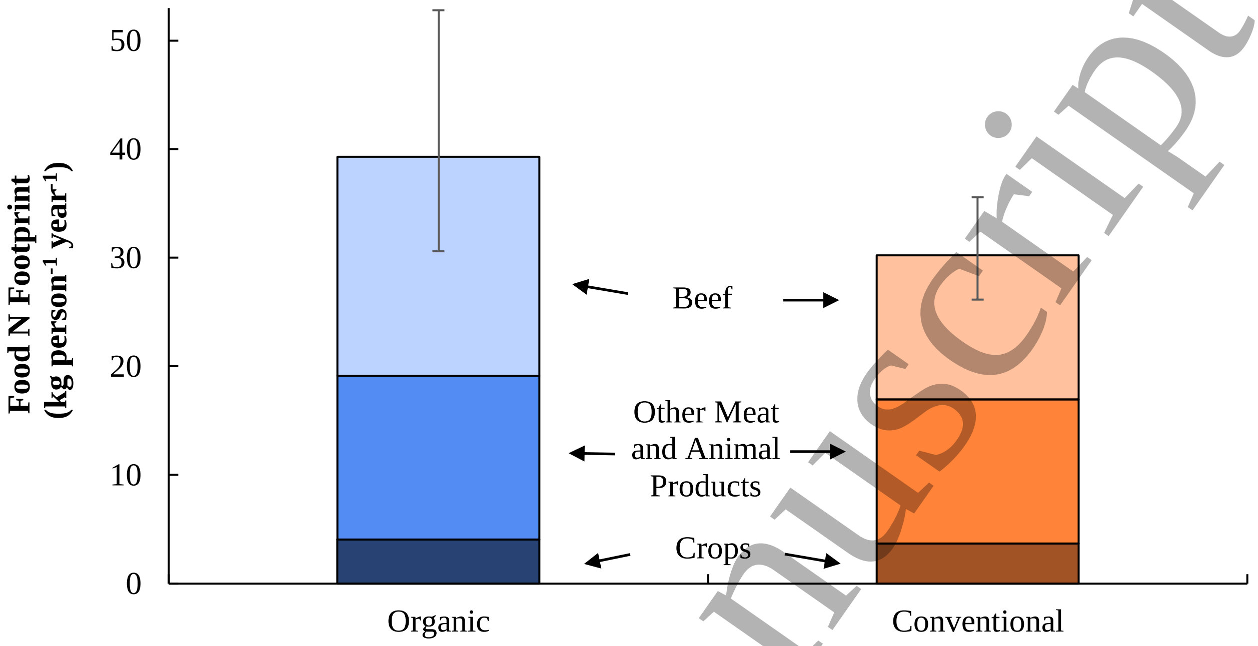


Figure 3. The food N footprint, or virtual N, for a person consuming an average diet in the United States for one year for 100% organic food versus 100% conventional food. The bars are split into 3 diet components: 'Beef' (lightest section), 'Meat and Animal Products (AP)' (medium section) includes poultry, pigmeat, dairy, eggs and other miscellaneous animal products; 'Crop Products' (darkest section) includes vegetables, grains, starchy roots, soybeans and other miscellaneous crop products. Bars show high and low estimates based on high and low estimates of VNFs (see Fig. 2).

The Nr input types (new versus recycled) differ between organic and conventional agriculture (Fig. 4). Organic agriculture uses less new Nr than conventional per unit Nr consumed, suggesting that organic contributes less new Nr to the global pool. Organic production of grains, starchy roots, vegetables and legumes primarily utilizes recycled or already existing Nr (0-50% of inputs are from new Nr sources, all from BNF) (Fig. 4a). Conventional production of these same products relies heavily on the creation of new Nr (70-90% of inputs are from new Nr sources, primarily synthetic fertilizer) (Fig. 4b). Feed inputs for organic production of poultry, pigmeat, beef and dairy are 30-50% new Nr, primarily from BNF from feed crops and cover crops (Fig. 4a). For conventional production of poultry, pigmeat, beef and dairy, feed inputs are 80-100% new Nr (Fig. 4b). Across all food groups, organic production in the US has the potential to release 50% less new Nr to the environment than conventional production per unit Nr consumed by people.

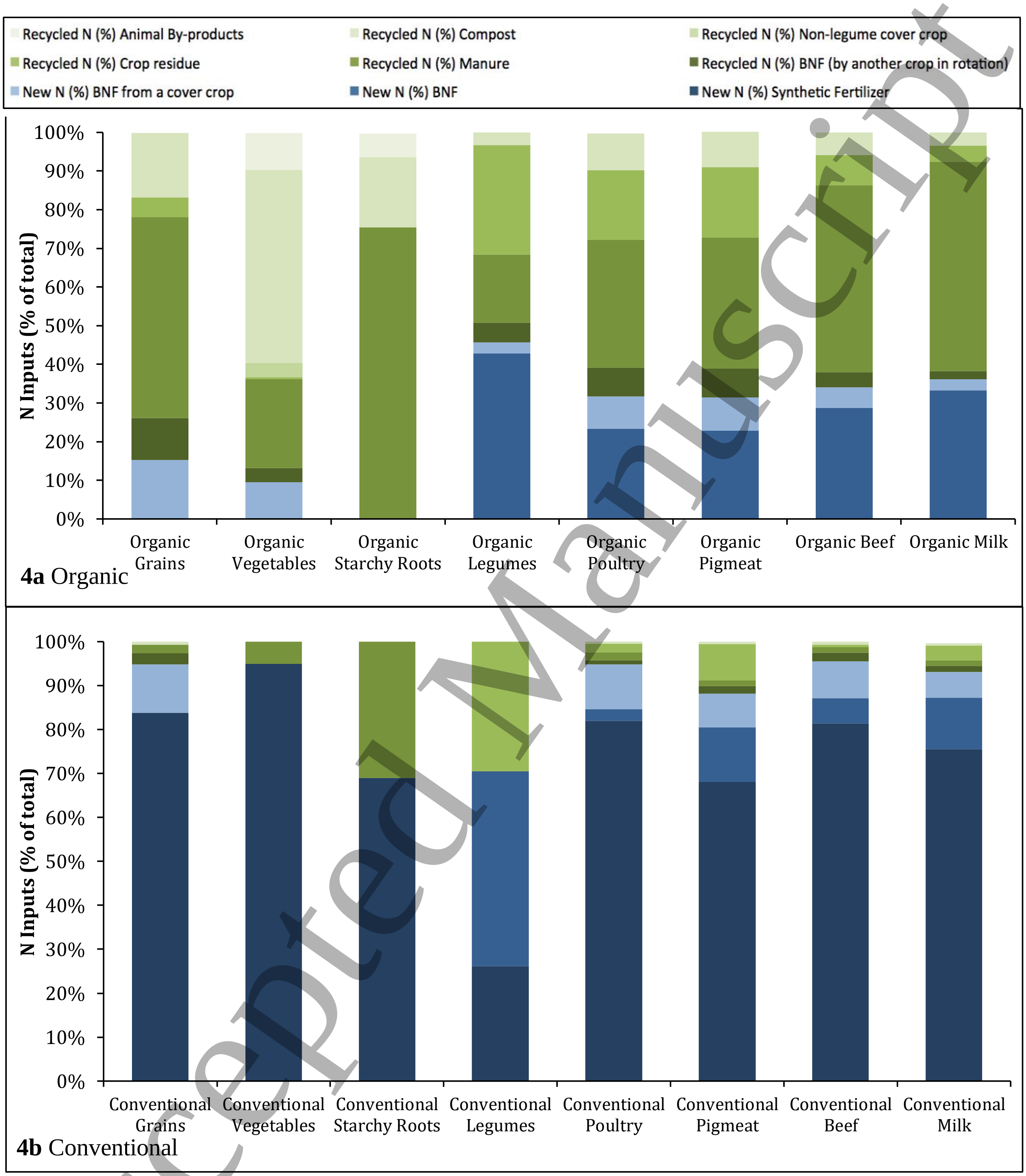


Figure 4. N input types for organic (a) and conventional (b) food production from new (blue) and recycled (green) sources. New N Inputs include 1) synthetic N fertilizer, 2) biological nitrogen fixation

(BNF) by the leguminous crop, and 3) BNF by a leguminous cover crop or green manure immediately before the crop. Recycled N inputs include 1) N from BNF by another leguminous crop in the rotation, 2) manure, 3) crop residue, 4) a non-legume cover crop or green manure, 5) compost, and 6) animal by-products (like blood meal). Organic crop data is based on 115 observations from 31 studies. Conventional crop data is based on 59 observations from 33 studies. Both organic and conventional animal data are scaled by livestock diet composition of crop inputs. See SM for full list of references.

4. Discussion

4.1 Virtual Nr from Organic Crop Products

Overall, virtual Nr losses in organic crop systems in the U.S. are comparable to virtual Nr losses in conventional crop systems for grains, starchy roots and legumes, perhaps with the exception of vegetables. Organic crops have similar Nr application rates, but lower yields than conventional crops (Table S2 for organic and Leach *et al* submitted for conventional); together these variables reduce the crop N uptake, i.e. the proportion of Nr applied that is taken up by the plant (Fig. 1, Table 1, Fig. S1) and thereby increase the VNF. However, increased crop residue recycling under organic management later in the production system increases Nr efficiency and contributes to a small reduction in the VNF.

Lower yields at similar Nr application rates under organic management are due to the lower availability of Nr from organic inputs (Berry *et al* 2002). The timing of Nr availability for plant growth thus does not always match the periods of highest crop Nr demand (Berry *et al* 2002, Pang and Letey 2000).

For both organic and conventional production, legumes have the lowest VNF and vegetables have the highest VNF. Legumes have low Nr losses because little Nr is applied to them as they can meet most of their Nr requirements through BNF, and their yields have a high Nr content (IPNI 2014). Legumes are the only crops that show a slightly lower VNF under organic than conventional agriculture (-12%). This is most likely due to the relatively higher yields of organic legumes due to lower N limitation (Seufert *et al* 2012). However, both the organic and conventional VNF estimates are highly uncertain due to the difficulty of estimating BNF (Salvagiotti *et al* 2008).

Vegetables have the highest Nr losses of all crop products because they are often heavily fertilized and their yields have a low Nr content (IPNI 2014). Organic vegetable VNFs tend to be somewhat higher than those of conventional vegetables (+37%), most likely because of the relatively higher difference between yields of organically versus conventionally managed vegetables (Seufert *et al* 2012). This difference is caused by the high Nr demands of vegetables, which is difficult to meet with organic amendments (Delate *et al* 2015), but also due to often high application of external Nr inputs (e.g. from animal manure and composts) resulting from the high-value of vegetable crops (Watson *et al* 2002). Organically grown vegetables thus have a slightly lower nitrogen use efficiency (NUE) than conventionally grown vegetables (Fig. S1).

The large range around the organic and conventional crop estimates from our study (which is derived from low and high estimates for various key parameters in the N footprint model) indicates that there is large variation in both systems. This variation implies that management practices within either system have the potential to increase or decrease Nr efficiency and, indeed, these practices may be more important than the type of production system in determining virtual Nr losses. This observation is in line with the conclusion from Kirchmann and Bergstroem (2001) who argue that in terms of Nr losses there is a wider variation within organic and conventional systems than there is a clear difference between them. High N use efficiency (NUE), and a correspondingly low VNF, may be more dependent on good N management practices than on the utilization or avoidance of synthetic fertilizer inputs. Agricultural best management practices that reduce Nr loss include, for example, use of cover crops and crop rotations, timing of Nr application to meet crop demand, and appropriate Nr application rates to account for regional climate and local soil type (Berry *et al* 2002, Cherry *et al* 2008, Davis *et al* 2012). Both organic and conventional systems have the opportunity to increase NUE by implementing these practices.

One key factor that drives the N footprint of organic versus conventional crops in our analysis is crop yields. In contrast to many previous studies on Nr losses from organic versus conventional systems, our analysis estimates the Nr loss per unit Nr consumed. While organic agriculture thus might lose less Nr per unit area and have reduced impact at the farm level (Cambardella *et al* 2015, Hansen *et al* 2000, Kramer *et al* 2006, Stopes *et al* 2002), due to its generally lower yields (De Ponti *et al* 2012, Ponisio *et al* 2012, Seufert *et al* 2012), it appears as inefficient as conventional agriculture per unit output.

4.2 Virtual N from Organic Animal Products

Virtual Nr losses in organic animal systems are comparable to virtual Nr losses in conventional animal systems, with the exception of beef. In both systems, animal production has considerably higher Nr losses than crop production.

As with organic crop production, organic poultry and pigmeat production is characterized by some aspects that both increase and decrease its NUE relative to conventional management, which ultimately balance each other out. Organically raised animals consume more food to produce the same amount of weight gain compared to conventionally raised animals (Basset-Mens and der Werf 2005, Faerge *et al* 2001). However, in the organic poultry and organic pigmeat VNF calculations, this inefficiency in weight gain is balanced by lower Nr losses from organic feed mixtures (especially more legumes) and by greater recycling of Nr in organic feed production systems (Table 3).

Beef has the highest VNF of all food products, and organic beef is twice as inefficient as conventional beef production (Fig. 2). This low efficiency of organic production is driven by the low Nr content of pasture (a key component of organic cattle diets) and a correspondingly low feed conversion ratio (FCR) (Table 2, Fernandez and Woodward 1999). However, there continues to be uncertainty around the Nr efficiency of grazing systems and how local to regional variation (e.g., in climate, soil type, pasture composition) impacts the efficiency of particular farms (Ledgard 2001). Increased Nr efficiency in organic grazing systems would reduce Nr losses during organic beef production and is therefore a potential opportunity to improve the Nr use efficiency of organic beef and dairy production.

With the exception of beef production, our results suggest that organic and conventional animal production systems have similarly low Nr efficiencies and similar impacts on a per unit output basis. However, the lower density of organic animal production could lead to lower impacts on a per unit land basis (Cederberg and Mattsson 2000, Dalgaard *et al* 1998, Hansen *et al* 2000, Mondelaers *et al* 2009) and thus lower N loss at the farm scale.

4.3 N Footprint: 100% Organic and 100% Conventional Diets

The food N footprint of an individual consuming only organic food is comparable to or somewhat higher than the food N footprint of an individual consuming only conventional food, when similar diets, portions and food waste rates are assumed. The exception is organic beef production, which has a larger food production N footprint compared to conventional (Fig. 3) due to its larger VNF (Fig. 2). This suggests that switching to an entirely organic diet is not a viable way to reduce one's N footprint. Instead, reducing consumption of animal protein generally and reducing food waste at the consumer level both have a more significant impact on the N footprint (Leach *et al* 2012, Stevens *et al* 2014). Consumption patterns such as diet choices, portion size, and food waste may be different for consumers choosing organic versus conventional food (Kesse-Guyot *et al* 2013); evaluating the impact of these differences is beyond the scope of this analysis, but these variables can have an impact on an individual's N footprint (Leach *et al* 2012, Poore and Nececek 2018).

4.4 N Input Types and N recycling

The comparison of Nr input types used in organic versus conventional food production tells a clear story: organic production uses mainly recycled Nr sources, whereas conventional production uses mainly new Nr sources. Conventional production of crop and animal products relies heavily on newly created Nr, particularly synthetic fertilizer created through the Haber-Bosch process (Fig. 4b). In contrast, organic production utilizes a wide variety of existing Nr sources, including animal manures, crop residues and composts (Fig. 4a). Our analysis thus implies that organic production adds less Nr to the global Nr pool per unit food product and therefore reduces the overall impact of anthropogenic Nr on the environment.

However, current organic agricultural practices are often dependent on recycled Nr inputs from conventional systems (Nowak *et al* 2013). How much of the Nr demand for food production could be met with recycled Nr sources remains a question to be answered. While Nr recycling rates should (and can) be improved, it is unlikely that all crop Nr demand could be met from recycled Nr, given that there are inevitable losses in the food production system (Schroder 2014).

No matter the origin of recycled Nr, it is clear that for a more sustainable use of Nr in food production and to reduce the Nr lost to the environment, we need to reduce the amount of new Nr added to the global system by increasing Nr recycling rates (Forkes 2007, Schroder 2014).

4.5 Limitations and Uncertainties

Our analysis is the first to use virtual N factors and the N footprint approach to estimate Nr losses from organic food production in the U.S. While this analysis provides an important contribution to our understanding of how organic systems could potentially contribute to more efficient use of Nr during food production, the analysis is limited by several methodological challenges. The most important limitation regards the availability of data on organic production. The USDA does not track rates of organic fertilizer application or recommendations on a national scale. Therefore, this analysis relied on data published in the scientific literature (including some data from outside the US); this data may or may not be representative of the variety of practices in organic production in the U.S.

Crop residue recycling rates are not well documented throughout the U.S. for conventional (Smil 1999) or organic production (Cavigelli *et al* 2008, Sarrantonio 1994). We assume that crop residues are left on the field at higher rates under organic management due to increased reliance on organic amendments and the emphasis on recycling resources in the USDA organic standards.

The storage of Nr in organic matter in the soil is not addressed in this study, nor is it accounted for in most available studies on Nr balances in crop systems. Because the virtual N factor is a loss-based metric, we assume here that soil organic Nr is at a steady state and does not change over time. But in fact, many organic systems increase organic matter and thus soil Nr content (Drinkwater *et al* 1998, Lin *et al* 2016, Torstensson *et al* 2006). How much of the additional Nr in organic matter is held in the soil rather than mineralized and taken up by crops or lost from the system, and how this influences NUE and Nr loss of organic systems, is unclear. But Lin *et al* (2016) show that accounting for differences in soil Nr content can move organic systems from lower to higher NUE relative to conventional systems in an experimental farming system trial in Germany; it is possible that a full accounting of soil N storage would lower the N footprint of organically produced foods.

4.6 Next steps

The N footprint and virtual N factor approach estimate the loss of Nr during the food production process (Leach *et al* 2012). The N footprint does not, however, link to the form of N species lost (e.g., NH_3, NO_3-, N_2O, N_2) and does not connect to environmental effects. While our study is thus able to compare the loss of Nr to the environment from organic versus conventional systems, it does not assess how Nr loss from the two systems will ultimately impact the environment. In addition, there are several additional knowledge gaps that need to be addressed to improve our understanding of how organic agriculture could contribute to reducing Nr loss to the environment, including 1) better data on organic production and Nr inputs to organic crops, 2) better understanding of Nr cycling in grazing-based systems, 3) better quantification of rates of Nr fixation in legumes and their role in Nr cycling in legume cropping systems and 4) better data on crop residue recycling rates under organic management 5) better data on the fate of surplus N from organic amendments to quantify the share of N really lost into the environment and N accumulated in the soil.

5. Conclusions

Consuming organically produced foods has only a modest impact on an individual's food N footprint but increases the percentage of recycled Nr in the footprint. Nr losses from organic production per unit N in the food product are likely comparable to conventional production; the exception is organic beef, which has higher Nr losses than conventional beef. Because of a greater reliance on recycled N inputs, organic production has the potential to introduce less new Nr to the global pool. Our analysis highlights the complexity of comparing the N sustainability of organic and conventional food production. However, it is clear that higher Nr efficiencies, particularly in animal production, are necessary in both systems.

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Data Availability Statement

Any data that support the findings of this study are included within the article.

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