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Review

Comparison of Organic and Integrated Nutrient Management Strategies for Reducing Soil N_2O Emissions

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Abstract: To prevent nutrient limitations to crop growth, nitrogen is often applied in agricultural systems in the form of organic inputs (e.g., crop residues, manure, compost, etc.) or inorganic fertilizer. Inorganic nitrogen fertilizer has large environmental and economic costs, particularly for low-input smallholder farming systems. The concept of combining organic, inorganic, and biological nutrient sources through Integrated Nutrient Management (INM) is increasingly promoted as a means of improving nutrient use efficiency by matching soil nutrient availability with crop demand. While the majority of previous research on INM has focused on soil quality and yield, potential climate change impacts have rarely been assessed. In particular, it remains unclear whether INM increases or decreases soil nitrous oxide (N_2O) emissions compared to organic nitrogen inputs, which may represent an overlooked environmental tradeoff. The objectives of this review were to (i) summarize the mechanisms influencing N_2O emissions in response to organic and inorganic nitrogen (N) fertilizer sources, (ii) synthesize findings from the limited number of field experiments that have directly compared N_2O emissions for organic N inputs vs. INM treatments, (iii) develop a hypothesis for conditions under which INM reduces N_2O emissions and (iv) identify key knowledge gaps to address in future research. In general, INM treatments having low carbon to nitrogen ratio C:N (<8) tended to reduce emissions compared to organic amendments alone, while INM treatments with higher C:N resulted in no change or increased N_2O emissions.

Keywords: integrated nutrient management (INM); nitrous oxide emissions; organic nitrogen inputs; inorganic nitrogen fertilizer

1. Introduction

Soil nitrous oxide (N_2O) emissions are one of the largest sustainability concerns facing agriculture. Atmospheric N_2O concentrations have been increasing since the mid 19th century when humans started applying nitrogen (N) fertilizer to cultivated land [1]. Nitrous oxide is naturally produced through the denitrification and nitrification in the nitrogen (N) cycle, there is a clear link between increased N application rates and increased N_2O emissions [2,3]. Agricultural soil management accounts for approximately 75% of anthropogenic N_2O emissions in the United States [4]. Nitrous oxide is a key greenhouse gas contributing to global climate change, with a global warming potential nearly 300 times that of carbon dioxide (CO_2) over a 100-year period and an atmospheric lifespan of about 120 years [5]. Moreover, N_2O contributes to roughly 6% of the overall radiative forcing in the atmosphere and is considered to be the single most important ozone-depleting substance in our atmosphere [6]. Due to these harmful environmental impacts, and the fact that emissions are largely anthropogenic in nature, it is critical to identify options for reducing N_2O emissions from agriculture. Although it results in increased N_2O emissions, additional N is often applied either in the form of inorganic N fertilizers or organic amendments (e.g., crop residues, manure, compost etc.) to prevent N limitations to crop growth. Soil organic matter is an important, yet sometimes overlooked, source of nutrients in agricultural systems. The current challenge of large amounts of reactive N losses from agricultural systems is largely driven by inorganic fertilizer N inputs, while low-input cropping systems that primarily rely on organic amendments and soil organic matter are thought to be more sustainable. Organic amendments can promote soil health by building organic matter content, increasing aeration, and enhancing microbial abundance and diversity [7,8]. Organic amendments also provide plant-available nutrients and often act as a slow-release fertilizer throughout the growing season. However, it is difficult to achieve the soil health and nutrient-provisioning benefits of organic N sources. High-quality organic amendments with a low carbon to nitrogen ratio (C:N) decompose quickly and contribute less to stable organic matter in the soil, whereas amendments with a high C:N (low quality) decompose slowly and may not supply sufficient N to meet crop demand [9], potentially resulting in lower yields. By contrast, inorganic N fertilizers easily dissolve in soil solution and are quickly available for plant uptake upon application. Given their contrasting properties, the integrated use of both organic amendments and inorganic fertilizers may contribute to improved soil quality without sacrificing crop nutrition or yield.

Integrated nutrient management (INM) is the concept of using a combination of organic, inorganic, and biological amendments to increase nitrogen use efficiency (NUE) and reduce nutrient loss by synchronizing crop demand with nutrient availability in soil [10]. There are three main principles that govern INM: (1) use all possible sources of nutrients to optimize their input; (2) match soil nutrient supply with crop demand spatially and temporally; and (3) reduce N losses while improving crop yield [11]. Integrated nutrient management is a broad concept and particular versions of this approach have gained popularity in different regions. For example, Integrated Soil Fertility Management (ISFM) has a long history of research and application in smallholder farming systems of Africa. To meet current food security challenges, ISFM is now viewed as an important framework for boosting crop productivity while improving soil quality by several international initiatives [12]. A meta-analysis of the effects of applying both inorganic fertilizer and organic amendments together found that combining the two increased maize yield between 60% and 114% compared to either N source alone [13]. A two-year experiment in hybrid rice systems using INM reported higher yield, NUE, and soil organic carbon compared to both organic and inorganic amendments alone [14]. Javaria and Kahn analyzed several studies with tomatoes and found that INM improved yield, overall crop quality, and soil fertility [15]. Importantly, the principles of INM are broadly applicable and the concept of combining organic with inorganic N sources can either be integrated into low-input systems to increase soil nutrient supply or high-input systems to potentially reduce N fertilizer requirements. Given this adaptability and the numerous cropping system benefits that it provides, INM will likely expand as a practice to address nutrient losses from agriculture in the future.

Global NUE ranges from approximately 20–65% [16]. Nutrient imbalances are common in agricultural systems with N fertilizer often being over- or under-applied [17], indicating significant room for increased efficiency. A meta-analysis of experiments in sub-Saharan Africa found that combining inorganic and organic amendments significantly improved nutrient efficiency [12]. Although much research has been dedicated to the effects of INM on crop productivity, NUE, and aspects of soil quality, it remains unclear how INM impacts N_2O emissions. Importantly, increasing NUE by combining organic and inorganic fertilizers may reduce N_2O emissions, which would represent an additional positive cropping system benefit. However, available studies show that N_2O emissions from INM can both increase or decrease depending on cropping system context and management [18,19]. It is generally thought that organic N inputs would lead to lower N_2O emissions compared to INM because organic N must be mineralized before becoming susceptible to losses. Yet it is also possible that increases in labile carbon (C) and microbial activity associated with organic inputs may increase nitrification and denitrification processes, contributing to higher overall N_2O emissions. Reducing soil N_2O emissions without negatively impacting yields is a critical sustainability challenge facing global agriculture, particularly because N_2O emissions can represent more than half of the total C footprint of crop production systems. To gain a holistic understanding of the environmental performance of INM, the potential for increased N_2O emissions represents an environmental tradeoff that needs to be considered.

To our knowledge, no attempt has been made to synthesize current evidence regarding the potential climate-change impacts of N_2O emissions from INM as compared to systems entirely dependent on organic amendments. The purpose of this paper is to: (1) review the mechanisms influencing how organic and inorganic N amendments affect N_2O emissions; (2) synthesize findings from the limited number of field experiments that have directly compared INM and organic N input systems; (3) develop a hypothesis for conditions under which INM reduces N_2O emissions; and (4) identify key knowledge gaps to address in future research.

2. Effect of Organic vs. Inorganic N Sources on N_2O Emissions

2.1. Summary of Research

There is no scientific consensus on whether N_2O emissions are lower in systems using inorganic N fertilizers or organic N amendments. In fact, a recent meta-analysis found that there was no significant difference in N_2O emissions between the two soil management approaches [20]. A comprehensive analysis focused on maize production in the Midwestern U.S. found higher N_2O emissions from soils receiving manure than soils receiving inorganic N fertilizer [21]. However, these authors noted that N_2O emissions may have been greater in manure-amended experiments because the N application rate in some studies were greater for manured fields than the inorganic N application rate. By contrast, other reviews have reported lower N_2O emissions from soils managed with organic inputs compared to conventional systems using inorganic N inputs, particularly when assessed on an areal basis [22–24]. Lower emissions with organic inputs in these comparisons could be due to a number of confounding factors, including significantly lower N inputs in the organic systems [25]. There is a direct relationship between N_2O emissions and N addition [26], therefore a reduction in N inputs in organic systems is likely to reduce N_2O emissions [27]. However, it should be considered that a reduction in N rates may also contribute to lower crop yields, which may have implications for global food production [28,29]. Despite the demonstrated relationship between N inputs and N_2O emissions, many other environmental and crop management factors can influence the complex process of N_2O loss from soil [30].

2.2. Mechanisms Controlling N_2O Emissions

Nitrous oxide is produced by the activity of soil microorganisms through two phases of the nitrogen cycle: nitrification and denitrification [31,32]. A number of variable and interacting factors within the soil system control these phases of the N cycle. Soil texture, freeze/thaw cycles, precipitation events and temperature all significantly effect N_2O emissions but cannot be easily controlled through management [33]. Factors affecting N_2O emissions that can be more easily altered by crop management practices include: soil organic C content, nitrate and ammonium concentrations in soil solution, N application rate, type, and technique, soil oxygen status, microbial abundance and activity, soil pH, soil drainage and moisture, and crop species [3]. Application of inorganic versus organic N fertilizer will influence many of the above factors [34], and a number of potential interactions are expected to occur among factors, which will ultimately determine the relative change in N_2O emissions (e.g., changes in soil moisture will influence microbial activity and subsequently inorganic N concentrations). Important factors that are differentially affected by organic N amendments and inorganic N fertilizer are briefly discussed below: soil organic carbon, soil structure and moisture, soil pH, soil N status. For a more general review of microbial processes regulating N_2O emissions, the reader is referred to the following papers [32,34–37].

2.2.1. Soil Organic Carbon

Carbon availability is a key component of the denitrification process. Early research showed that denitrification is greatly influenced by C availability, with denitrification rates of (nitrate) NO_3-N remaining low when C was unavailable despite high N concentrations, but increasing rapidly in response to C addition [38]. Depending on the source of organic N amendments, addition of organic material to soils may increase N_2O emissions by providing the necessary C substrates for driving microbial nitrification and denitrification processes [34,39]. Similarly, N_2O emissions tend to increase with the C:N of soil, due in part to the potential for reduced plant N uptake and increased microbial consumption of inorganic N during soil organic matter decomposition [20]. Manure application increases total organic C and total N pools in soil at levels proportional to the application rate [40]. When comparing soil with a history of manure application to a non-manured soil, it was found that N_2O emissions were nearly 25 times greater from manured soil [41]. In contrast to organic amendments, inorganic N fertilizers do not provide additional C substrate, but this will not necessarily lead to lower emissions. Moreover, addition of inorganic N fertilizer can have a priming effect on soil microbial communities which facilitates more rapid decomposition of soil organic matter [42], potentially also increasing N_2O emissions.

2.2.2. Soil Aggregation, Drainage, and Moisture

The relationship between water-filled pore space (WFPS), drainage, and N_2O emissions is not completely understood. Generally, N_2O emissions are greatest following a significant increase in soil water content after a rainfall or irrigation event [22], likely due to a flush of microbial activity from soil wetting and drying events [43]. Both denitrification and nitrification processes contributing to N_2O emissions are stimulated at high WFPS, with nitrification playing a larger role as soils dry down [32]. Soils with restricted drainage, even if they are not completely water-saturated, are particularly prone to greater N_2O emissions [2]. For example, fine-textured soils that typically are associated with greater soil water content tend to have higher N_2O emissions [20]. Thus, an important opportunity for decreasing emissions is to increase soil aeration, potentially through soil amendments or changes in soil structure. Increased aggregate stability can create larger soil pores between aggregates in fine-textured soils, and greater pore sizes may increase oxygen (O_2) content, which has been shown to decrease N_2O emissions [32]. Accordingly, soils managed with organic amendments tend to have greater aggregate stability compared to those managed with inorganic fertilizer [25], therefore the addition of organic amendments may reduce N_2O emissions, especially in fine-textured soils.

At the same time, it must be considered that organic amendments can increase soil water holding capacity, particularly for coarse-textured soils. In addition, because O_2 concentrations in soil pores are determined by water content as well as microbial activity, elevated microbial respiration in response to higher C availability in organic inputs may decrease O_2 content and increase N_2O emissions [34]. The extent to which these physical and biological processes may interact to increase or decrease soil water content will largely depend on initial soil texture. Soils with lower water holding capacity may be more likely to experience increases in soil water content following addition of organic N inputs, whereas soils with initially higher water holding capacity may benefit more greatly from increased pore size, in turn leading to increased O_2 concentrations and decreased N_2O emissions.

2.2.3. Soil pH

Denitrification-associated N_2O emissions are generally greater in acidic soils (pH < 6) which may either be due to increased activity of relevant soil microbes in these conditions or inhibition of enzymes necessary for complete denitrification, including nitrous oxide reductase [20,37,44]. As such, the ratio of N_2O:N_2 production is generally higher in soils that are acidic to neutral compared with alkaline soils [2]. Soils receiving primarily organic inputs tend to have slightly higher pH than those managed with inorganic fertilizer due to the acidifying potential of inorganic N fertilizer [9,20,25]. Considered in isolation of other interacting effects discussed above (e.g., soil moisture and C:N), maintenance or increase of soil pH following repeated organic amendment may help to mitigate N_2O emissions from soil.

2.2.4. Soil N Availability

Increases in N inputs tend to increase soil inorganic N concentrations and N_2O emissions [45], through stimulation of both nitrification and denitrification microbial processes [32,46]. Addition of inorganic N fertilizer may cause large amounts of NO_3 to accumulate in soil because an available C source is needed to provide energy for microbial activity and C and N transformations [38]. Moreover, the ratio of N_2O:N_2 produced via denitrification increases with increasing soil NO_3 concentrations [38], suggesting higher N_2O emissions in soils with inorganic N application. By contrast, soils receiving primarily organic N sources tend to have lower levels of available NO_3 [47]. The majority of C and N added through organic amendments is stored in organic matter pools, which are less susceptible to N losses [48]. However, even if soil inorganic N concentrations do not increase with organic amendments, N losses are not always lower. For example, recent research indicates that when organic N sources contain a relatively high concentration of inorganic N (i.e., more than 0.3% dry weight), the percentage of applied N emitted as N_2O is generally greater than the expected ranged predicted by the Intergovernmental Panel on Climate Change default emission factors and may be higher than inorganic N addition [49].

3. INM and N_2O Emissions

3.1. Summary of Field Research

Research is limited on the effects of INM on N_2O emissions. We performed a literature search in Web of Science, Google Scholar and Scopus using the following search terms: nitrogen, organic amendments, inorganic fertilizer, integrated nutrient management, integrated soil fertility management, combined inorganic and organic amendments, nitrous oxide and N_2O emissions. Publications included in the review had to represent field experiments comparing N_2O emissions over the course of a growing season in four treatments: (1) unfertilized control plot; (2) organic-only; (3) inorganic-only, and a combination of organic and inorganic N inputs, which was considered to represent an INM approach for the purposes of this paper. A summary of experimental details and the overall effects of INM compared to organic N inputs on N_2O emissions for each study (n = 6) are presented in Table 1.

Meng et al. [50] compared N_2O emissions from maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) treated with composted manure, inorganic N fertilizer and a combined INM approach with equal amounts of N from both sources in China during 2002–2003 (treatments had been established in 1989). They found no difference in N_2O emissions among all treatments over the two growing seasons but still recommended combining inorganic and organic fertilizers to improve overall soil fertility. Emissions were positively correlated with WFPS and soil temperature, and the authors concluded that these factors, along with pH, likely accounted for the lack of difference between treatments. Yields in each treatment were not reported.

Researchers in Zimbabwe [18] measured N_2O emissions from seasonal wetland soils in rape (*Brassica napus*) production supplemented with a combination of ammonium nitrate and organic manure at varying levels. While higher N rates increased N_2O emissions, they found that INM reduced emissions compared to sole organic or inorganic treatments despite total N inputs for INM being slightly higher (125 for INM compared to 97.5 and 120 kg N ha^{-1} for organic and inorganic treatments, respectively). These authors noted that the INM treatment with the highest rate of manure led to increased N_2O emissions compared to lower rates from manure alone, which was due to increased N rate more than N source. Soil moisture was a poor predictor of N_2O emissions in this study, likely due to the consistently high moisture levels caused by irrigation. The INM treatment increased yield significantly compared to both inorganic and organic treatments.

Table 1. Description of field experiments reviewed in this paper including study location, crop, total nitrogen (N) rate, and mean nitrous oxide (N_2O) emissions from the selected organic amendment, inorganic N fertilizer, and Integrated Nutrient Management (INM) treatment comparisons, fertilizer-induced emission factor (EF) and carbon to nitrogen ratio (C:N) of the organic amendment treatment. The effect of INM on N_2O emissions and crop yield is summarized when reported.

Study	Country	Crop Rotation	Total N Rate (kg N ha^{-1})	Mean N_2O (mg N m^{-2})	EF * (%)	C:N of Org †	N_2O Trend	INM Yield
Meng et al. (2005) [50]	China	Maize, winter wheat	Org: 150 MC # Inorg ‡: 150 urea INM: 75 kg MC + 75 urea (150 total INM)	Control: 15 Org †: 85.6 INM: 81.8 Inorg ‡: 76.7	Org: 0.471 INM: 0.445 Inorg: 0.411	7.75	No significant differences	Not reported
Nyamadzawo et al. (2014) [18]	Zimbabwe	Rape	Org: 97.5 M § Inorg: 120 NH_4NO_3 INM: 65 M + 60 NH_4NO_3 (125 total INM)	Control: 250 Org: 1930 INM: 770 Inorg: 1200	Org: 17.231 INM: 4.160 Inorg: 7.917	Not reported	INM < Org, Inorg	Org, Inorg < INM
Cai et al. (2013) [51]	China	Maize, winter wheat	Org: 150 MC ‖ Inorg: 150 urea INM: 75 MC + 75 urea (150 total INM)	Control: 22 Org: 166 INM: 118 Inorg: 181	Org: 0.960 INM: 0.640 Inorg: 1.060	8	No significant differences	Not reported
Ding et al. (2013) [19]	China	Maize, winter wheat	Org: 150 MC Inorg: 150 urea INM: 75 MC + 75 kg urea (150 total INM)	Control: 20.4 Org: 117.8 INM: 132.5 Inorg: 142.7	Org: 0.812 INM: 0.934 Inorg: 1.019	8	INM, Org < Inorg	Not reported
Nyamadzawo et al. (2014) [52]	Zimbabwe	Maize, winter wheat	Org: 120 M Inorg: 120 NH_4NO_3 INM: 60 M + 60 NH_4NO_3 (120 total INM)	Control: 32 Org: 27 INM: 35 Inorg: 41	Org: −0.042 INM: 0.025 Inorg: 0.075	Not reported	Org < INM < Inorg	Org < INM, Inorg
Sarkodie-Addo et al. (2003) [53]	United Kingdom	Maize	Org: Inc ¶ rye Inorg: 250 NH_4NO_3 INM: Inc rye + 250 NH_4NO_3 Org: Inc winter wheat Inorg: 200 NH_4NO_3 INM: Inc winter wheat + 200 NH_4NO_3	*Rye* Control: 6.07 Org: 5.27 INM: 9.15 Inorg: 7.72 *Winter Wheat* Control: 2.65 Org: 2.32 INM: 15.4 Inorg: 8.87	N/A	Rye: 13 Wheat: 18	Org, Inorg < INM Rye < winter wheat	Org < INM < Inorg

* Emission Factor (EF) calculated as = $(N_2O_{trt} - N_{ctl})/N_2O$ rate $_{trt} \times 100$; † Organic-only treatment; # Manure compost; ‡ Inorganic-only treatment; § Cattle manure; ¶ Incorporated.

Two field studies in China compared N_2O emissions from inorganic NPK fertilizer, compost, and INM with 50% of N from each source in both wheat and maize. Both studies found that combining inorganic NPK and compost significantly reduced N_2O emissions compared to compost or NPK fertilizer alone at a total N rate of 150 kg N ha^{-1} [19,51]. Cai et al. found that WFPS was significantly correlated with N_2O emissions [51], whereas Ding et al. did not observe this relationship [19]. Both researchers suggested that applying composted organic amendments with C:N lower than 20 would reduce N_2O emissions due to a lower amount of N released during decomposition into the soil [19,51]. Soil pH was also negatively correlated with N_2O emissions in Ding et al. [19], which supports the hypothesis that N_2O emissions may be mitigated in soils with organic N inputs in part due to the effect of organic amendments on soil chemistry. Despite significant differences in N_2O emissions, crop yield did not differ among N input strategies in Cai et al. [51]. Ding et al. [19] did not report yield.

Nyamadzawo et al. [52] measured the effects of INM on N_2O emissions during one growing season for winter wheat and one for maize in Zimbabwe using combinations and rates of cattle manure and ammonium nitrate. The INM treatment increased N_2O emissions compared to the cattle manure treatments, but decreased emissions compared to the inorganic fertilizer treatments. The lower N_2O emissions from the organic amendment treatments were likely due to the slow decomposition of C and N in the manure and the slow release of mineralized N. These authors noted that if the low-quality manure were the only source of N, there would be yield penalties. There was no correlation between N rate and N_2O emissions, which emphasizes the importance of N source in this experiment. Yields from the INM treatments were not different from the inorganic N treatments, but were greater than the manure treatments. These results clearly demonstrate a tradeoff between yield and N_2O emissions and the potential to balance the two with an INM approach.

Sarkodie-Addo et al. [53] compared winter rye and wheat as green manures with added ammonium nitrate and measured subsequent N_2O emissions in one growing season in the U.K. Incorporating green manure with added inorganic N fertilizer significantly increased N_2O emissions compared to inorganic N addition and green manure alone. Sarkodie-Addo et al. [53] suggest that elevated N_2O emissions were due to the supply of C from the incorporated rye and wheat residue, which combined with the added inorganic N provided energy for denitrifying microbes. Crop yields in the INM treatments were greater than in the green manure treatments, but not the inorganic N fertilizer treatments.

3.2. Potential for Minimizing N_2O Emissions with INM

We found only six field experiments that fit our criteria for inclusion in this review. Despite the limited data, several key factors appear to be controlling N_2O emissions in INM compared to organic amendment systems. Water-filled pore space and C:N of the organic amendment are likely factors explaining the variability in N_2O emissions from INM systems. Nitrous oxide emissions tend to peak following rainfall events as the soil dries during the transition from high soil moisture to low [22,50]. However, when soil moisture remains high (i.e., with irrigation), the correlation between N_2O emissions and WFPS disappears [18]. Therefore, in the absence of irrigation, a substantial proportion of N_2O emissions will be driven by changes in WFPS and cannot be mitigated via management. Integrated treatments received about half the amount of organic material as the organic-only treatments, which would not be likely to result in short-term changes in soil porosity or soil water holding capacity as discussed above. However, to our knowledge no studies have measured N_2O emissions for more than three years to determine potential long-term effects between organic and INM systems.

For the studies included in this review, C:N of organic amendments in the INM treatments had the greatest potential to control N_2O emissions. N_2O emissions from INM systems using organic amendments with C:N near 8 (composted manures and yard waste compost) were lower or equivalent to the organic amendment treatments in most cases [19,50,51]. Conversely, when the C:N of organic amendments were around 8 which included treatments of fresh cattle manure and freshly incorporated green manure, N_2O emissions from INM increased compared to the organic amendment treatments [52,53]. These results suggest that high C substrate availability relative to the amount of added N is an important contributor to N_2O emissions in INM systems [54]. Differences in C:N of amendments in these studies were typically due to composting, which has been shown to reduce the C:N of organic material [55,56], and limit N_2O emissions when compared to non-composted organic inputs [55]. This preliminary review suggests combining compost with inorganic N fertilizer holds promise for further reducing N_2O emissions compared to either inorganic or organic N inputs alone.

While field studies on N_2O emissions from INM are rare, a number of investigations have assessed the effects of organic amendment C:N on N_2O emissions in lab incubations. As noted above, microbial communities that carry out critical steps of N mineralization, nitrification, and denitrification depend on a supply of available C to function. Considering a context without inorganic N addition, organic amendments with high C:N (>20) tend to result in microbial immobilization of inorganic N, in turn reducing N available for denitrification [57]. Alternatively, amendments with low C:N are more rapidly mineralized by soil microbes [57], releasing C and N which can promote increased microbial activity and increase N_2O emissions. However, microbial activity and resulting N_2O emissions from INM treatments not only depend on C:N, but also the amount of inorganic N in soil from added fertilizer. Application of inorganic N fertilizer with an organic amendment containing large amounts of labile C may further enhance denitrification and therefore increase N_2O emissions [58]. In fine-textured soils, N_2O emissions from both soil fertilized with only inorganic N fertilizer and composted amendments applied in combination with inorganic N application are similar [59]. Moreover, a synthesis of N_2O emission factors for organic N addition recently placed compost and compost plus inorganic N fertilizer application in low- and medium-risk categories, respectively, as compared to the high-risk group containing animal slurries and biosolids [49].

When interpreting results from experiments measuring N_2O emissions using a combination of inorganic N and organic amendments with varying C:N it is critical to consider both the total N rate and type of amendment. Huang et al. [60] found decreasing N_2O emissions in response to increasing C:N of different organic residues in a laboratory experiment, and observed that this relationship became stronger when combined with inorganic N addition. However, in this study, the treatment with the highest N_2O emissions (and lowest C:N) also had the greatest total N rate, which likely accounts for the high emissions. Similarly, results from another laboratory experiment measuring N_2O in response to increasing C:N of crop residue amendments and varying levels of inorganic fertilizer suggest that reductions in N_2O emissions are more likely to occur when lower C:N organic amendments are applied alone or when higher C:N organic amendments are applied in combination with inorganic fertilizer [55]. Differences from our review of field experiments and these laboratory studies can be accounted for by the fact that crop residues were used as organic amendments to provide organic material, and not necessarily an N source, while manure or compost were used as an organic N source in the reviewed field experiments. Moreover, a recent global meta-analysis of fertilizer emission factors for organic amendments concluded that C:N only partially explains the response of N_2O emissions to organic amendments, particularly for C:N lower than 25 where other environmental and management factors appear to become increasingly important [49]. In general, research on the effects of amendment C:N at this lower range of values, including the studies reviewed here, is inconsistent and further field investigations are needed.

A third factor possibly explaining trends for N_2O emissions from INM systems is the total N rate when using a combination of organic and inorganic fertilizers. For this review the majority of studies had similar N rates between all treatments, but one study used an additive N approach (i.e., full inorganic N rate plus full organic N amendment rate) for their INM treatment. Increasing N rate generally increases N_2O emissions [26,45]. Not surprisingly, using an additive approach to N application for an INM treatment resulted in higher N_2O emissions compared to the other treatments consisting of either inorganic or organic N inputs alone which had lower total N rates [53]. Studies using a substitutive approach to assess the effects of INM (i.e., half inorganic N rate plus half organic N rate) generally found no differences or decreased N_2O emissions compared to inorganic or organic

N inputs alone [18,19,50,51]. To account for potential differences in N rate for INM treatments across studies, we also calculated fertilizer-induced emission factors (EF) (Table 1). When EFs were averaged across studies, INM resulted in a value of 1.2% compared to 3.9% for organic-only treatments and 2.1% for inorganic-only treatments. While there was a large amount of variability for these means, based on this calculation, INM stands out as a potential management strategy to reduce N_2O emissions. To assess the effect of combining inorganic and organic treatments on N_2O emissions more accurately, it is recommended that consistent total N rates, or consistent levels of different N rates, should be applied for INM, organic, and inorganic treatments in future experiments.

It is important to note that combining inorganic fertilizer and organic amendments is not a guaranteed strategy for reducing N_2O emissions from agricultural soils. However, this review suggests that INM systems employing amendments with medium to low C:N (<8) and a substitutive approach to total N application rates (proportional reduction of N rate from each N source) have the greatest potential to mitigate N_2O emissions. Previous lab experiments provide support for this hypothesis by indicating that integrating inorganic N fertilizer with organic amendments having low to medium C:N may help avoid two important processes contributing to N_2O emissions, namely stimulation of soil microbial communities through addition of excessive carbon substrates (high C:N) and rapid inorganic N mineralization (low C:N).

4. Knowledge Gaps and Additional Considerations

4.1. Knowledge Gaps for Field Research

The challenge of sustainably increasing global food production through appropriate nutrient management practices can also directly be related to soil N_2O emissions. Due to a limited number of available field experiments, definitive conclusions about amendment properties driving N_2O emissions in INM systems cannot be drawn here. To further understand the effect of C:N on N_2O emissions, future INM field experiments should include amendments with a range of C:N paired with inorganic N fertilizer at a constant total N rate (i.e., substitutive N input approach), similar to the laboratory research conducted by Frimpong and Baggs [54]. Moreover, different types of organic amendments (e.g., manure, compost and green manure from different species) with the same C:N should be paired with constant total N rates to explore the effects of other amendment properties aside from C:N on N_2O emissions. While most studies reviewed here used equal portions of organic and inorganic N sources in their INM treatment, there is limited knowledge about the ideal of organic amendment versus inorganic N fertilizer necessary to mitigate N_2O emissions while optimizing crop yield with an INM approach. Our review indicates that additional factors contributing to N_2O emissions in INM systems requiring further study include the duration and method of composting amendments; the method, timing, and location of amendment and fertilizer applications (including whether N sources were incorporated into soil); and local climate and soil characteristics.

4.2. Yield-Scaled Emissions and INM

Recent reports have highlighted the importance of considering crop yield response when measuring the environmental impact of N_2O mitigation strategies for agriculture. For example, the concept of yield-scaled emissions (expressed as mass of N_2O emissions per unit yield) has gained recognition as a practical assessment tool [61]. Importantly, if fertilizer N input strategies aimed at N_2O mitigation decrease yield in addition to reducing N_2O emissions, they may not be considered as an effective strategy for addressing both food security and environmental goals. With a focus on yield, research demonstrates that management of crop nutrients through INM can increase crop productivity compared to fields managed with inorganic N fertilizer alone [11]. Similarly, based on the few studies in this review that reported yield, INM holds the potential to increase yields compared to organic amendments alone [18,52,53]. A general consideration is that promising yield-scaled N_2O mitigation strategies either decrease emissions while maintaining yield, or maintain emissions while increasing yield. On a yield-scaled basis, soils receiving only organic amendments have been found to emit more N_2O than soils receiving inorganic N fertilizer [24,25,62]. However, this comparison is confounded by other factors that often limit yield in systems primarily managed with organic N inputs (e.g., pests [28,63]), which may not accurately represent N_2O emission potential based on soil nutrient management alone. Two studies measuring yield in this review [18,52] also calculated yield-scaled emissions and found that INM treatments generally reduced yield-scaled emissions compared to organic amendment and inorganic N fertilizer treatments. Future field experiments should evaluate yield-scaled emissions when assessing the potential environmental and agronomic benefits of INM, as this metric is likely to become increasingly important due to the ongoing challenge of achieving global food security.

4.3. Net Global Warming Potential

This review focused on direct soil N_2O emissions, but the net global warming potential (GWP) of cropping system greenhouse gas (GHG) emissions is determined by changes in soil N_2O, CO_2, and CH_4 emissions as well as changes in soil C [64]. Addition of organic amendments can be expected to increase soil CO_2 emissions, while also contributing to short- and long-term pools of soil C [65]. Increases in soil C are particularly important because they can offset higher soil CO_2 emissions due to respiration of organic C added to the field through organic amendments, as well direct N_2O emissions and embodied CO_2 costs related to organic or inorganic N inputs [34,66]. At the same time, when assessing the combined addition of inorganic N fertilizer with organic amendments, cycling of soil C and N is tightly coupled and N fertilizer addition has been shown to influence microbial activity and the breakdown of C and N substrates compared to organic amendments alone [65]. Future work is thus needed under field conditions to determine whether INM increases or decreases the buildup of soil C relative to addition of organic amendments alone, while also simultaneously monitoring for potential changes in N_2O fluxes. Finally, there are upstream environmental impacts beyond the field boundary related to inorganic and organic N sources that need to be considered. Large amounts of energy are consumed to produce and transport N fertilizer and this is associated with significant embodied CO_2 costs, which can be large enough to negate changes in soil C discussed above [67]. Likewise, organic N amendments derived from manure or compost have CO_2, N_2O, and CH_4 emissions associated with their processing and transport [34]. Therefore, to fully determine the net impact of INM practices on GWP, changes in soil C and the embodied GHG costs associated with inorganic N fertilizer and organic amendments need to be quantified and weighed against any increase or decrease in soil N_2O emissions discussed in this review.

5. Conclusions

Increasing nutrient use efficiency and reducing nutrient loss in agricultural systems while simultaneously improving crop yields is a critical sustainability challenge facing humanity. The concept of using all available sources of N inputs (organic, inorganic or biological) has been gaining momentum under the umbrella term Integrated Nutrient Management (INM) to help address this challenge. While INM is considered a sustainable approach offering a number of potential cropping system benefits, there is limited research on the effects of this management strategy on air quality and climate change, particularly N_2O emissions. Soil N_2O emissions result from microbial nitrification and denitrification processes which are affected by a number of soil properties including moisture content, texture, pH, source of organic amendments and the C and N contents of amendments. In this paper, available field studies were reviewed to identify promising INM strategies for reducing N_2O emissions compared to organic N inputs. Despite considerable variability in results and the complexity of potential mechanisms controlling N_2O emissions, INM treatments having low C:N (<8) tended to reduce emissions compared to organic amendments alone, while INM treatments with higher C:N resulted in no change or increased N_2O emissions. To further understand the effect of C:N on N_2O emissions, future INM field experiments should include amendments with a range of C:N paired with inorganic

N fertilizer at a constant total N rate (i.e., substitutive N input approach). Moreover, different types of organic amendments (e.g., manure, compost and green manure from different species) with the same C:N should be paired with constant total N rates, or levels of N rates, to explore the effects of other amendment properties aside from C:N on N_2O emissions.

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References

1. Galloway, J.; Aber, J.D.; Erisman, J.W.; Seitzinger, S.P.; Howarth, R.W.; Cowling, E.B.; Cosby, B.J. The Nitrogen Cascade. *Bioscience* **2003**, *53*, 341–356. [CrossRef]
2. Bouwman, A.F.; Boumans, L.J.M.; Batjes, N.H. Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. *Glob. Biogeochem. Cycles* **2002**, *16*. [CrossRef]
3. Snyder, C.S.; Bruulsema, T.W.; Jensen, T.L.; Fixen, P.E. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agric. Ecosyst. Environ.* **2009**, *133*, 247–266. [CrossRef]
4. Davidson, E.A.; Kanter, D. Inventories and scenarios of nitrous oxide emissions. *Environ. Res. Lett.* **2014**, *9*, 105012. [CrossRef]
5. Ravishankara, A.R.; Daniel, J.S.; Portmann, R.W. Nitrous Oxide (N_2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. *Science* **2009**, *326*, 123–125. [CrossRef] [PubMed]
6. U.S. Environmental Protection Agency (US EPA). *Draft Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2010*; U.S. Environmental Protection Agency: Washington, DC, USA, 2012.
7. Birkhofer, K.; Bezemer, T.M.; Bloem, J.; Bonkowski, M.; Christensen, S.; Dubois, D.; Ekelund, F.; Fließbach, A.; Gunst, L.; Hedlund, K.; et al. Long-term organic farming fosters below and aboveground biota: Implications for soil quality, biological control and productivity. *Soil Biol. Biochem.* **2008**, *40*, 2297–2308. [CrossRef]
8. Wortman, S.E.; Drijber, R.A.; Francis, C.A.; Lindquist, J.L. Arable weeds, cover crops, and tillage drive soil microbial community composition in organic cropping systems. *Appl. Soil Ecol.* **2013**, *72*, 232–241. [CrossRef]
9. Wortman, S.E.; Galusha, T.D.; Mason, S.C.; Francis, C.A. Soil fertility and crop yields in long-term organic and conventional cropping systems in Eastern Nebraska. *Renew. Agric. Food Syst.* **2012**, *27*, 200–216. [CrossRef]
10. Janssen, B.H. Integrated nutrient management: The use of organic and mineral fertilizers. In *The Role of Plant Nutrients for Sustainable Food Crop Production in Sub-Saharan Africa*; van Reuler, H., Prins, W.H., Eds.; VKP: Leidschendam, The Netherlands, 1993; pp. 89–105.
11. Wu, W.; Ma, B. Integrated nutrient management (INM) for sustaining crop productivity and reducing environmental impact: A review. *Sci. Total Environ.* **2015**, *512–513*, 415–427. [CrossRef] [PubMed]
12. Vanlauwe, B.; Kihara, J.; Chivenge, P.; Pypers, P.; Coe, R.; Six, J. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil* **2011**, *339*, 35–50. [CrossRef]
13. Chivenge, P.; Vanlauwe, B.; Six, J. Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. *Plant Soil* **2011**, *342*, 1–30. [CrossRef]
14. Mondal, S.; Mallikarjun, M.; Ghosh, M.; Ghosh, D.C.; Timsina, J. Influence of integrated nutrient management (INM) on nutrient use efficiency, soil fertility and productivity of hybrid rice. *Arch. Agron. Soil Sci.* **2016**, *62*, 1521–1529. [CrossRef]
15. Javaria, S.; Khan, M.Q. Impact of integrated nutrient management on tomato yield quality and soil environment. *J. Plant Nutr.* **2010**, *34*, 140–149. [CrossRef]
16. Roberts, T.L. Improving nutrient use efficiency. *Turk. J. Agric. For.* **2008**, *32*, 177–182.
17. Vitousek, P.M.; Naylor, R.; Crews, T.; David, M.B.; Drinkwater, L.E.; Holland, E.; Johnes, P.J.; Katzenberger, J.; Martinelli, L.A.; Matson, P.A.; et al. Nutrient imbalances in agricultural development. *Science* **2009**, *324*, 1519–1520. [CrossRef] [PubMed]
18. Nyamadzawo, G.; Wuta, M.; Nyamangara, J.; Smith, J.L.; Rees, R.M. Nitrous oxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic and integrated nutrient management. *Nutr. Cycl. Agroecosyst.* **2014**, *100*, 161–175. [CrossRef]

19. Ding, W.; Luo, J.; Li, J.; Yu, H.; Fan, J.; Liu, D. Effect of long-term compost and inorganic fertilizer application on background N2O and fertilizer-induced N_2O emissions from an intensively cultivated soil. *Sci. Total Environ.* **2013**, *465*, 115–124. [CrossRef] [PubMed]
20. Abalos, D.; Jeffery, S.; Drury, C.F.; Wagner-Riddle, C. Improving fertilizer management in the U.S. and Canada for N_2O mitigation: Understanding potential positive and negative side-effects on corn yields. *Agric. Ecosyst. Environ.* **2016**, *221*, 214–221. [CrossRef]
21. Decock, C. Mitigating Nitrous Oxide Emissions from Corn Cropping Systems in the Midwestern U.S.: Potential and Data Gaps. *Environ. Sci. Technol.* **2014**, *48*, 4247–4256. [CrossRef] [PubMed]
22. Aguilera, E.; Lassaletta, L.; Sanz-Cobena, A.; Garnier, J.; Vallejo, A. The potential of organic fertilizers and water management to reduce N_2O emissions in Mediterranean climate cropping systems. A review. *Agric. Ecosyst. Environ.* **2013**, *164*, 32–52. [CrossRef]
23. Tuomisto, H.L.; Hodge, I.D.; Riordan, P.; Macdonald, D.W. Does organic farming reduce environmental impacts?—A meta-analysis of European research. *J. Environ. Manag.* **2012**, *112*, 309–320. [CrossRef] [PubMed]
24. Skinner, C.; Gattinger, A.; Muller, A.; Mäder, P.; Flieβbach, A.; Stolze, M.; Ruser, R.; Niggli, U. Greenhouse gas fluxes from agricultural soils under organic and non-organic management—A global meta-analysis. *Sci. Total Environ.* **2014**, *468–469*, 553–563. [CrossRef] [PubMed]
25. Mader, P. Soil Fertility and Biodiversity in Organic Farming. *Science* **2002**, *296*, 1694–1697. [CrossRef] [PubMed]
26. Shcherbak, I.; Millar, N.; Robertson, G.P. Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 9199–9204. [CrossRef] [PubMed]
27. Millar, N.; Robertson, G.P.; Grace, P.R.; Gehl, R.J.; Hoben, J.P. Nitrogen fertilizer management for nitrous oxide (N_2O) mitigation in intensive corn (Maize) production: An emissions reduction protocol for US Midwest agriculture. *Mitig. Adapt. Strateg. Glob. Chang.* **2010**, *15*, 185–204. [CrossRef]
28. Seufert, V.; Ramankutty, N.; Foley, J.A. Comparing the yields of organic and conventional agriculture. *Nature* **2012**, *485*, 229–232. [CrossRef] [PubMed]
29. Snyder, C.; Davidson, E.; Smith, P.; Venterea, R. Agriculture: Sustainable crop and animal production to help mitigate nitrous oxide emissions. *Curr. Opin. Environ. Sustain.* **2014**, *9–10*, 46–54. [CrossRef]
30. Venterea, R.T.; Coulter, J.A.; Dolan, M.S. Evaluation of Intensive "4R" Strategies for Decreasing Nitrous Oxide Emissions and Nitrogen Surplus in Rainfed Corn. *J. Environ. Qual.* **2016**, *45*, 1186. [CrossRef] [PubMed]
31. Bouwman, A.F. Land use related sources of greenhouse gases: Present emissions and possible future trends. *Land Use Policy* **1990**, *7*, 154–164. [CrossRef]
32. Hu, H.-W.; Chen, D.; He, J.-Z. Microbial regulation of terrestrial nitrous oxide formation: Understanding the biological pathways for prediction of emission rates. *FEMS Microbiol. Rev.* **2015**, *39*, 729–749. [CrossRef] [PubMed]
33. Hatfield, J.L.; Chatterjee, A.; Clay, D. Soil and Nitrogen Management to Reduce Nitrous Oxide Emissions. In *ACSESS Publications*; American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Inc.: Madison, WI, USA, 2016.
34. Thangarajan, R.; Bolan, N.S.; Tian, G.; Naidu, R.; Kunhikrishnan, A. Role of organic amendment application on greenhouse gas emission from soil. *Sci. Total Environ.* **2013**, *465*, 72–96. [CrossRef] [PubMed]
35. Baggs, E.M. Soil microbial sources of nitrous oxide: Recent advances in knowledge, emerging challenges and future direction. *Curr. Opin. Environ. Sustain.* **2011**, *3*, 321–327. [CrossRef]
36. Butterbach-Bahl, K.; Baggs, E.M.; Dannenmann, M.; Kiese, R.; Zechmeister-Boltenstern, S. Nitrous oxide emissions from soils: How well do we understand the processes and their controls? *Philos. Trans. R. Soc. B Biol. Sci.* **2013**, *368*, 20130122. [CrossRef] [PubMed]
37. Thomson, A.J.; Giannopoulos, G.; Pretty, J.; Baggs, E.M.; Richardson, D.J. Biological sources and sinks of nitrous oxide and strategies to mitigate emissions. *Philos. Trans. R. Soc. B Biol. Sci.* **2012**, *367*, 1157–1168. [CrossRef] [PubMed]
38. Weier, K.L.; Doran, J.W.; Power, J.F.; Walters, D.T. Denitrification and the Dinitrogen/Nitrous Oxide Ratio as Affected by Soil Water, Available Carbon, and Nitrate. *Soil Sci. Soc. Am. J.* **1993**, *57*, 66–72. [CrossRef]
39. Jäger, N.; Stange, C.F.; Ludwig, B.; Flessa, H. Emission rates of N_2O and CO_2 from soils with different organic matter content from three long-term fertilization experiments—A laboratory study. *Biol. Fertil. Soils* **2011**, *47*, 483–494. [CrossRef]

40. Bhogal, A.; Nicholson, F.A.; Young, I.; Sturrock, C.; Whitmore, A.P.; Chambers, B.J. Effects of recent and accumulated livestock manure carbon additions on soil fertility and quality. *Eur. J. Soil Sci.* **2011**, *62*, 174–181. [CrossRef]
41. Graham, C.J.; van Es, H.M.; Melkonian, J.J. Nitrous oxide emissions are greater in silt loam soils with a legacy of manure application than without. *Biol. Fertil. Soils* **2013**, *49*, 1123–1129. [CrossRef]
42. Fontaine, S.; Mariotti, A.; Abbadie, L. The priming effect of organic matter: A question of microbial competition? *Soil Biol. Biochem.* **2003**, *35*, 837–843. [CrossRef]
43. Mikha, M.M.; Rice, C.W.; Milliken, G.A. Carbon and nitrogen mineralization as affected by drying and wetting cycles. *Soil Biol. Biochem.* **2005**, *37*, 339–347. [CrossRef]
44. Cheng, Y.; Zhang, J.-B.; Wang, J.; Cai, Z.-C.; Wang, S.-Q. Soil pH is a good predictor of the dominating N_2O production processes under aerobic conditions. *J. Plant Nutr. Soil Sci.* **2015**, *178*, 370–373. [CrossRef]
45. McSwiney, C.P.; Robertson, G.P. Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. *Glob. Chang. Biol.* **2005**, *11*, 1712–1719. [CrossRef]
46. Mulvaney, R.L.; Khan, S.A.; Mulvaney, C.S. Nitrogen fertilizers promote denitrification. *Biol. Fertil. Soils* **1997**, *24*, 211–220. [CrossRef]
47. Doran, J.W.; Fraser, D.G.; Culik, M.N.; Liebhardt, W.C. Influence of alternative and conventional agricultural management on soil microbial processes and nitrogen availability. *Am. J. Altern. Agric.* **1987**, *2*, 99. [CrossRef]
48. Poudel, D.D.; Horwath, W.R.; Mitchell, J.P.; Temple, S.R. Impacts of cropping systems on soil nitrogen storage and loss. *Agric. Syst.* **2001**, *68*, 253–268. [CrossRef]
49. Charles, A.; Rochette, P.; Whalen, J.K.; Angers, D.A.; Chantigny, M.H.; Bertrand, N. Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. *Agric. Ecosyst. Environ.* **2017**, *236*, 88–98. [CrossRef]
50. Meng, L.; Ding, W.; Cai, Z. Long-term application of organic manure and nitrogen fertilizer on N_2O emissions, soil quality and crop production in a sandy loam soil. *Soil Biol. Biochem.* **2005**, *37*, 2037–2045. [CrossRef]
51. Cai, Y.; Ding, W.; Luo, J. Nitrous oxide emissions from Chinese maize-wheat rotation systems: A 3-year field measurement. *Atmos. Environ.* **2013**, *65*, 112–122. [CrossRef]
52. Nyamadzawo, G.; Shi, Y.; Chirinda, N.; Olesen, J.E.; Mapanda, F.; Wuta, M.; Wu, W.; Meng, F.; Oelofse, M.; de Neergaard, A.; et al. Combining organic and inorganic nitrogen fertilisation reduces N_2O emissions from cereal crops: A comparative analysis of China and Zimbabwe. *Mitig. Adapt. Strateg. Glob. Chang.* **2014**, *22*, 233–245. [CrossRef]
53. Sarkodie-Addo, J.; Lee, H.G.; Braggs, E.M. Nitrous oxide emissions after application of inorganic fertilizer and incorporation of green manure residues. *Soil Use Manag.* **2003**, *19*, 331–339. [CrossRef]
54. Frimpong, K.A.; Baggs, E.M. Do combined applications of crop residues and inorganic fertilizer lower emission of N2O from soil?: N_2O from combined residue and fertilizer application. *Soil Use Manag.* **2010**, *26*, 412–424. [CrossRef]
55. Dittert, K.; Lampe, C.; Gasche, R.; Butterbach-Bahl, K.; Wachendorf, M.; Papen, H.; Sattelmacher, B.; Taube, F. Short-term effects of single or combined application of mineral N fertilizer and cattle slurry on the fluxes of radiatively active trace gases from grassland soil. *Soil Biol. Biochem.* **2005**, *37*, 1665–1674. [CrossRef]
56. Tang, J.-C.; Maie, N.; Tada, Y.; Katayama, A. Characterization of the maturing process of cattle manure compost. *Process Biochem.* **2006**, *41*, 380–389. [CrossRef]
57. Hoge, A.; Robinson, D.; Fitter, A. Are microorganisms more effective than plants at competing for nitrogen? *Trends Plant Sci.* **2000**, *5*, 304–308. [CrossRef]
58. Senbayram, M.; Chen, R.; Budai, A.; Bakken, L.; Dittert, K. N_2O emission and the $N_2O/(N_2O + N_2)$ product ratio of denitrification as controlled by available carbon substrates and nitrate concentrations. *Agric. Ecosyst. Environ.* **2012**, *147*, 4–12. [CrossRef]
59. Zhu-Barker, X.; Doane, T.A.; Horwath, W.R. Role of green waste compost in the production of N_2O from agricultural soils. *Soil Biol. Biochem.* **2015**, *83*, 57–65. [CrossRef]
60. Huang, Y.; Zou, J.; Zheng, X.; Wang, Y.; Xu, X. Nitrous oxide emissions as influenced by amendment of plant residues with different C:N ratios. *Soil Biol. Biochem.* **2004**, *36*, 973–981. [CrossRef]
61. Van Groenigen, J.W.; Velthof, G.L.; Oenema, O.; Van Groenigen, K.J.; Van Kessel, C. Towards an agronomic assessment of N_2O emissions: A case study for arable crops. *Eur. J. Soil Sci.* **2010**, *61*, 903–913. [CrossRef]
62. Mondelaers, K.; Aertsens, J.; Van Huylenbroeck, G. A meta-analysis of the differences in environmental impacts between organic and conventional farming. *Br. Food J.* **2009**, *111*, 1098–1119. [CrossRef]

63. De Ponti, T.; Rijk, B.; van Ittersum, M.K. The crop yield gap between organic and conventional agriculture. *Agric. Syst.* **2012**, *108*, 1–9. [CrossRef]
64. Robertson, G.P. Greenhouse Gases in Intensive Agriculture: Contributions of Individual Gases to the Radiative Forcing of the Atmosphere. *Science* **2000**, *289*, 1922–1925. [CrossRef] [PubMed]
65. Liang, L.L.; Eberwein, J.R.; Allsman, L.A.; Grantz, D.A.; Jenerette, G.D. Regulation of CO_2 and N_2O fluxes by coupled carbon and nitrogen availability. *Environ. Res. Lett.* **2015**, *10*, 34008. [CrossRef]
66. Gan, Y.; Liang, C.; Chai, Q.; Lemke, R.L.; Campbell, C.A.; Zentner, R.P. Improving farming practices reduces the carbon footprint of spring wheat production. *Nat. Commun.* **2014**, *5*, 5012. [CrossRef] [PubMed]
67. Schlesinger, W.H. On fertilizer-induced soil carbon sequestration in China's croplands. *Glob. Chang. Biol.* **2010**, *16*, 849–850. [CrossRef]