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Excessive Nitrate Limits the Sustainability of Deep Compost Mulch in Organic Market Gardening

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Abstract: Market gardening is a widespread practice of bio-intensive vegetable production characterized by direct marketing, small-scale farming structures, high crop densities, and innovative cultivation approaches. Currently, deep compost mulch (DCM) is a popular trend among related growing techniques. The combination of no-till and a permanent mulch of compost aims to improve soil fertility, regulate soil temperature, retain soil moisture, and control weeds. To address the problem of perennial weeds in organic no-till, deep mulch layers of typically 150 mm are used. The amount of compost required and the associated N inputs are immense and carry the risk of environmentally harmful N surpluses that can be lost through nitrate leaching or denitrification. The aim of this study is to evaluate the use of compost as mulch and to investigate N dynamics under DCM. For this purpose, a literature review was conducted, and soil inorganic nitrogen (N_{min}-N) was measured under on-farm conditions up to a soil depth of 900 mm in a market garden with DCM in Germany for one year. Furthermore, based on the collected data, the different N pathways were calculated using the N-Expert and NDICEA models and simulated for two additional scenarios. Results from field measurements showed a strongly increased N-surplus not taken up by the crops and a shift of N_{min}-N to deeper soil layers for municipal organic waste compost (MW), with an average accumulation of 466 kg N_{min}-N ha^{-1} at 600–900 mm depth. N inputs from DCM can be significantly reduced by the use of green waste compost (GW) with low bulk density or wood waste compost (WW) with an additional high C/N ratio.

Keywords: organic vegetables; organic mulch; no-dig; no-till; soil mineral N; nitrate leaching; denitrification

Citation: Ruch, B.; Hefner, M.; Sradnick, A. Excessive Nitrate Limits the Sustainability of Deep Compost Mulch in Organic Market Gardening. *Agriculture* **2023**, *13*, 1080. https://doi.org/10.3390/agriculture13051080

Academic Editor: Jose L. Gabriel

Received: 24 March 2023
Revised: 5 May 2023
Accepted: 16 May 2023
Published: 18 May 2023

1. Introduction

Market gardening has established itself as a common farming system within the organic vegetable production sector. Many publications on this subject, e.g., [1–5], have coined it as a term in its own right [6]. Accordingly, market gardening refers to a way of production characterized by small-scale farming structures, direct marketing, and intensive soil and plant cultivation. These management techniques include seasonal extension, high crop densities, optimized timing of transplanting and harvesting, standardized bed sizes, foresighted weed control, new hand tools, and light machinery for rapid and frequent cultivation, as well as high organic fertilizer application [7]. This bio-intensive approach can produce high yields [8,9], which, together with high margins from direct marketing, allow farmers to make a living despite small land holdings [10]. With relatively low investment costs for small acreage and low-level machinery, market gardening is also attractive for start-ups [9]. Consequently, the pertinent literature on market gardening does not only provide information on cultivation methods or small-scale equipment but also picks up the discussion on socio-economic aspects and lifestyles, aiming to demonstrate to (young) people small-scale farming as an attractive option or career change [7]. Motivated by this, many lateral entrants can be found among market gardeners who do not have an agricultural background and are relatively new to vegetable production on a commercial scale [6,7,9,11]. For them, reference books, social media, and peer-to-peer exchanges with other growers are critical elements of their training [6,7,11].

Within the market garden movement, deep compost mulch (DCM) has recently become very popular. The term describes a method that combines no-till with a thick mulch layer of compost, and was pioneered under the name "No-Dig" by Dowding, mainly for use in home gardens [12]. Later, Perkins popularized its use in commercial vegetable production [13], which was then discussed in a more scientific way by Frost, who called it "Deep Compost Mulch" [14]. The authors highlight its benefits, such as increased crop yield, weed suppression, soil temperature regulation, soil water retention, and increased soil fertility through improved physicochemical and biological parameters. While the relationship between these effects and mulching is well known and has been widely used in vegetable production [15–18], compost stands out as a mulching material. Due to its nutrient composition and fine crumb structure, it is also suitable as a germination and growth medium [19]. This allows seeding or planting directly into the compost, which makes it ideal as a permanent mulch cover for a no-till market gardening system [13,14]. Recommendations for compost requirements for the DCM method are given volumetrically and generally correspond to a layer of 150 mm in the first year and 20 mm in subsequent years to maintain the height of the mulch [12–14]. This results in an initial N input of 4300–12,000 kg N ha^{-1}, depending on the bulk density and N content of the compost [20]. Variations occur with different raw materials, composting methods, and maturity [20], which also affect the mineralization rate of the compost through the corresponding C/N ratio and, thus, the N supply [21]. With a N mobilization of 5–15% in the first year [22], 215–1800 kg N_{min}-N ha^{-1} can be compared to an average fertilization requirement of 70–300 kg N_{min} ha^{-1}, depending on the vegetable crop [23]. If these factors are not sufficiently taken into account and compost is only applied volumetrically to achieve a sufficient weed-suppressing mulch thickness, the potential loss of N_{min}-N surpluses escapes control. Against this background, it may be difficult for lateral entrants into market gardening to critically evaluate the usage of compost. However, excess N represents a major environmental risk, e.g., through contamination of ground and surface waters [24], but can also lead to harmful NO_3 accumulation, especially in green leafy vegetables [25,26], or reduced N_2 fixation by legumes in the crop rotation [27]. Consequently, the use of compost in agriculture can be regulated and, depending on country-specific legislation, may hinder the application of DCM due to the amount of compost required [28].

In order to assess the phenomenon on the basis of current research, a literature review was conducted on the advantages and disadvantages of mulching with compost. The development of NO_3-N and NH_4-N contents under DCM to a soil depth of 900 mm was measured monthly over a period of one year in a representative market garden farm in North Rhine-Westphalia, Germany. In addition, based on the collected data, relevant N pathways in the soil-plant system were calculated using N-Expert and N losses by denitrification and leaching using NDICEA. While N-Expert simulates the interaction of different plant, soil, and fertilization parameters to provide annual fertilization recommendations [29], NDICEA models the spatial and temporal evolution of different N pathways over an arbitrary observation period [30]. Furthermore, the results were simulated with modified compost properties to evaluate the influence of different composts.

2. Materials and Methods

2.1. Literature Review

For the literature review, the keywords "compost mulch" and "deep compost mulch" were initially searched using the academic search engines Web of Science and Google Scholar. Sources were selected that addressed the use of compost as mulch for agricultural crops, while excluding sources that addressed, for example, orchards, vineyards, or landscaping. The focus was on peer-reviewed articles, but displayed master's theses, dissertations, and conference papers were also reviewed. The most relevant articles were then used for snowballing and forward citation searches. The objective was to evaluate the properties of compost as a mulch material and to assess the current understanding of the associated N dynamics.

2.2. On-Farm Soil Sampling

On-farm soil samples were collected once a month from April 2021 to March 2022 at a market garden farm with DCM in North Rhine-Westphalia, Germany, during ongoing vegetable production. The soil is loam, and annual average temperatures and precipitation are 9.3 °C and 860 mm, respectively. Crops are grown in standardized beds 0.75 m wide and 20 m long. The single beds are separated by 0.3 m paths mulched with wood chips and grouped in units of 10 beds each. Samples were collected from three compost-treated plots and one control plot without compost application, each corresponding to one bed. Beds were not placed in an experimental setup, but followed farm practice design without replicates. The units for Plots 1 and 2 were each established in February 2019, and the unit for Plot 3 in February 2021. The control corresponds to a non-mulched bed in the same unit as Plot 3 that was left fallow and uncultivated during the observation period to illustrate the mineralization potential of the soil at the site. In October 2021, sampling plot 3 had to be moved to the adjacent bed in the same unit. Due to a nest of persistent field bindweed on the initial sampling bed, it was covered with a black plastic tarp for weed control in September 2021 and left in place until spring. Because the cover diverts precipitation from the underlying soil, it would bias the measurement of potential N leaching over the winter. Except for the weed infestation, these two beds did not differ in terms of treatment, crop rotation, or history. All the beds, except the one for the control, were mulched with a 150 mm layer of municipal organic waste compost (MW) [31,32] in the first year and a 20 mm layer in the following years. The nutrient content of the composts used according to the test certificate [33] is shown in Table 1. The crop rotations of each plot are shown in Table 2. For each bed, one representative sample was collected from four subsamples from randomly selected sampling points across the bed at depths of 0–300, 300–600, and 600–900 mm using a hand-driven auger (25 mm diameter). These were analyzed for NO_3-N and NH_4-N content as one composite sample per plot and sampling date by extraction with a 0.0125 M $CaCl_2$ solution [34].

Table 1. Nutrient content in municipal organic waste compost in dry matter (DM) applied to the three sampled plots on the farm.

	2019	**2020**	**2021**
N total [g DM kg^{-1}]	19.21	17.32	19.00
N_{min}-N [g DM kg^{-1}]	1.43	2.19	1.99
P_2O_5 [g DM kg^{-1}]	11.00	15.13	9.50
K_2O [g DM kg^{-1}]	17.71	15.96	16.91
MgO [g DM kg^{-1}]	7.10	6.51	6.50
CaO [g DM kg^{-1}]	54.85	54.55	44.41
pH	8.8	8.7	8.8
C/N ratio	11	11	11
Organic matter [g DM kg^{-1}]	367.65	339.29	375.36
Bulk density [g DM L^{-1}]	493.68	439.82	476.73
Dry matter [%]	68	61.60	69.80

Table 2. Crop rotations of the three mulched plots and the control.

	2020	2021
Plot 1	Radish, spring onion, spinach	Fennel, turnip cabbage
Plot 2	Broad bean, lettuce	Celery
Plot 3	Potato, vetch-rye *	Red cabbage
Control	Potato, vetch-rye	Fallow

* Before compost bed establishment.

2.3. Modeling

The decision support tools N-Expert and NDICEA were used to simulate N dynamics under compost mulch. N-Expert calculates the relevant N pathways in the plant–soil system and is used for field-specific fertilizer recommendations for vegetable crops [29]. The model has been validated on the basis of a large amount of empirical data [35], and it has been shown that its application in practice can lead to a reduction in N surpluses [36]. Mineralization from soil organic matter is calculated according to the potentially mineralizable N in the soil [37], and mineralization or immobilization of N by organic fertilizers is predicted based on the classification into different fertilizer categories and the C to organic N ratio [38]. NDICEA describes the dynamics of N and soil water as a function of weather and crop demand, and allows prediction of denitrification and N leaching throughout the year [30]. Validation was also performed with extensive field data and resulted in a prediction probability in the range of +/− 20 kg N ha^{-1} [39–41].

N-Expert was used to map crop-specific N requirements and N balance during the growing season, and NDICEA was used to calculate potential N losses for each plot throughout the year. The input data regarding climate and soil conditions, compost characteristics and application rate, and crop rotation were consistent with those of the soil samples (Section 3.2). The first N_{min}-N measurements of each plot were also used in the N-Expert calculation as the basis for the predictions. In addition, two scenarios were simulated in which MW was replaced by "Green Compost" and "Woody Compost" [42], while maintaining the other input data, to calculate the influence of different compost compositions on N_{min}-N dynamics under otherwise identical conditions.

3. Results and Discussion

3.1. Literature Review

The literature review identified a total of 29 studies on the use of compost as mulch in agriculture. None of these studies explicitly addressed DCM or the combination of no-till with a permanent, thick layer of compost mulch in bio-intensive vegetable production. Therefore, to the best of the authors' knowledge, there are currently no peer-reviewed articles on this method.

A frequent topic of research has been the effect of compost mulch on yield. With the same fertilizer application in various vegetable crops, the addition of compost mulch resulted in increased yield compared to the unmulched control [43–54]. Compared to other organic mulch materials such as hay, straw, shredded leaves, pine needles, sawdust, wood chips, and corn gluten meal, compost mulch also produced higher yields under otherwise identical conditions [43,47,48,53–55]. Differences were observed with both higher [44], similar [47,52,54], and lower yields [48] when compared to plastic mulches such as polyethylene film or polypropylene fabric. The potential yield-increasing effect of compost mulch can be attributed to factors such as weed suppression, regulation of soil temperature, soil moisture retention, and improvement in soil fertility through nutrient input and microbial stimulation [44,45,47,54,55], which are described in more detail below.

A key criterion for the effectiveness of weed control is the thickness of the mulch cover. Experiments with increasing compost application rates of 0, 50, 100, and 200 mm [56], 0, 38, 75, 113, and 150 mm [57], and 0, 25, 50, 75, and 100 mm [58] show a linear effect on weed suppression with increasing height of the mulch. However, small effects on weed suppression could be achieved with a thin layer of 10–20 mm [51,59]. In two consecutive studies at one site, 50 mm of mulch eliminated the need for weed control [46,47], while under other conditions, a 50 mm layer required a similar weeding effort as the control [60]. A compost mulch thickness of 100 mm resulted in halving the working time for weed control compared to the non-mulched treatment [44]. A 200 mm layer effectively suppressed local perennial weeds but did not completely prevent weed emergence. However, as a rating of weed species showed, this was mainly due to seed contamination from the insufficiently sanitized compost [19]. Some studies compare the weed control of different mulch materials. As might be expected, plastic mulch consistently had a better weed suppression potential than compost. Weed growth was limited to the edges or cutouts of planting holes [44,60]. Comparisons between compost and other organic mulches were less clear, with compost often achieving more effective weed control than the alternatives, including shredded leaves [47], sawdust [43], corn gluten meal [48], and straw [53]. In other studies, hay [60], pine needles [19], and straw [48] performed better than compost, possibly because the coarser texture of hay or straw provides greater resistance to weeds than fine-grained compost [60]. In addition, the fine-crumb texture of compost and the contained nutrients may themselves provide an ideal growing medium for weeds [19]. However, the last two comparisons are clouded by the fact that a 30–50 mm layer of compost mulch was compared to a 100 mm layer of hay [60], and in the other case, the compost used was seed-contaminated [19]. Immature composts were shown to be particularly weed suppressive due to the higher concentration and phytotoxicity of acetic acids [58]. A 75 mm layer of immature compost applied to row alleys between raised soil beds covered with polyethylene completely suppressed weed growth, while significant weed growth occurred in the alleys of the non-mulched control [57]. Although the use of immature compost is limited to such special cases, these results also highlight the importance of ensuring adequate compost maturity to avoid damage to crops. However, it is particularly clear why a mulch height of approximately 150 mm has proven successful with the DCM method. Especially in organic no-till, where perennial weeds can be a problem, only a deep layer of mulch can adequately suppress weeds [61].

Other benefits of compost mulching are related to soil temperature and moisture. Compost regulates topsoil temperature by reducing the variation around the mean compared to bare soil [46,47,49,54,62]. While Gheshm and Brown report an increase in topsoil temperature under compost compared to the control [47], other studies describe a cooling in the range of 0.5–2 °C [49,54,62]. This involves cooler temperatures in the afternoon but warmer temperatures in the morning [49,54,63]. Compost acts as an insulator, both slowing heat conduction from the atmosphere to the soil and minimizing soil heat loss during the night [54]. As mulch height increases, the effect intensifies, and mean soil temperature decreases [62]. Both the lower variance in topsoil temperatures and a decrease in mean temperature compared to the control can also be observed under other organic mulches such as hay, straw, or wood chips, while the topsoil underneath is generally colder than under compost [47,54,62,63]. The reason given is that black compost warms soil temperature better by absorbing solar radiation and conducting heat than organic mulches of a lighter color [47,54]. Overall, black plastic mulch warms the soil the most [47,54], but lacks the insulating effect, so topsoil temperatures are colder in the morning, and the temperature fluctuates more compared with uncovered soil [47,54,63].

In addition, mulches retain soil moisture by reducing evaporation at the soil surface [54,62,64–66]. This effect is also enhanced by an increasing mulch height [62,65]. By suppressing weeds and the associated transpiration, mulches have a further positive effect on water retention [62]. Soil moisture levels are higher under compost than under wood chips [62,64]. Because plastic mulch diverts much of the rainwater from the underlying soil, higher soil moisture levels have generally been found under compost and other organic mulches when irrigated at the same rate [54,64].

Dowding, Perkins, and Frost particularly highlight the effects of DCM on soil fertility [12–14]. Corresponding assessments of the effects of compost mulch on soil biological and physicochemical parameters are also found in the studies. Organic mulches can increase the occurrence of earthworms compared to the non-mulched control, with the number of individuals under straw and hay being twice as high as under compost [53,67]. Plastic mulch, on the other hand, reduces earthworm abundance, presumably because soil temperatures are too high and soil moisture is too low [67]. Furthermore, a sudden increase in bacterivorous and fungivorous nematodes was observed after compost mulch application, which occurred due to an increase in bacterial and fungal biomass in the course of labile C and N contents released by the compost [45]. Among the physicochemical aspects, an increase in soil organic matter content was mainly observed [43,44,59,67,68]. A single compost mulch application of 100 mm, for example, increased the topsoil organic matter content from 3.9% to 8.6% after three years [44]. An immense annual application of 150 mm of manure compost over seven years in intensively managed permaculture beds increased soil organic C content up to 7.4%, while a neighboring pasture and conventional cropland had 4.9% and 1.1% topsoil organic C, respectively [69]. The high C contents of the permaculture beds are primarily due to an increase in coarse particulate organic matter fractions. This 250–2000 μm labile fraction mineralizes easily and enhances aggregation, but does not interact with clay minerals [69]. Schonbeck and Evanylo investigated the effect of mulch application on aggregate stability as well as soil bulk density and infiltration rate but were unable to measure any significant effects. Since changes in tilth-related soil properties usually occur only in the medium to long term after a management change and the experimental period was only one year, the results were not surprising [67]. An increase in P, K, Ca, and Mg contents [44,67,69], as well as micronutrient contents [44] by compost mulch, could also be demonstrated.

In reviewing the literature on the effects of compost mulching, special emphasis was placed on evaluations of N dynamics at high compost application rates. The annual application of a 30 mm layer of municipal solid waste compost to three consecutive winter wheat crops resulted in excess of about 100 kg NO_3-N ha^{-1} in the 0–1000 mm soil layer [68]. However, yields and soil organic matter were not significantly different from a 10 mm compost mulch treatment. Since increases in NO_3-N, soil organic matter, and total plant N could not plausibly explain the fate of applied N at the higher dose, the authors suggest increased denitrification at high compost applications [68]. The application of 30 mm green waste compost (GW) in another study resulted in higher tomato yields compared to the non-mulched control, but did not increase NO3-N levels in the 0–300 mm soil layer [67]. After a three-year experimental period, a single compost application of 100 mm manure compost resulted in 121 kg NO_3-N ha^{-1} in 0–100 mm soil depth after harvest, whereas the unmulched control with otherwise the same fertilization contained only 45 kg NO_3-N ha^{-1} [44]. While more frequent and deeper sampling would have been more informative, the 121 kg NO_3-N ha^{-1} in topsoil measured outside the growing season already indicates an unproductive N surplus. N_{min}-N levels of 39–63 kg ha^{-1} were measured at 0–300 mm depth during the harvest season of blueberries after 200 mm of manure and seafood waste compost application [70]. The relatively low soil N_{min}-N content, measured by the amount of compost and the N it contained, could be related to the high C/N ratio of 22 to 48 of the composts used [70] and thus a possibly low N availability [21]. In addition, seed contamination of the composts resulted in increased weed growth and corresponding N consumption [19]. Relevant immobilization of N_{min}-N present in the soil by composts with a high C/N ratio would not be expected with mulch application compared to incorporation, due to the different degrees of physical contact between soil and compost [67,71]. The highest compost application within the reviewed studies was 150 mm of manure compost annually for seven years. While immense increases in soil organic C and plant-available P, K, Mg, and Ca were demonstrated here, unfortunately, no measured data on N_{min}-N were collected in this study [69].

While the effects on yield, the suitability of compost mulch for weed suppression, and the effects on soil temperature and moisture have been well investigated, there are only a few studies that address N dynamics, especially at high compost application rates. In addition, they provide only an incomplete picture of N dynamics, e.g., due to low sampling frequencies or shallow sampling depths. The reviewed results do not indicate intensive NO_3 leaching so far. Perkins also rules out significant leaching losses by arguing that the interaction of DCM and no-till increases microbial activity and soil organic matter levels to the extent that excess NO_3 is immobilized, allowing high N loads to be maintained in the soil without risk of leaching [13]. The population of microbivorous nematodes was found to correlate with the increased nutrient turnover provided by nutrient-rich mulches [45], supporting Perkins's argument. A comparative analysis of yields, NO_3-N fluxes according to anion exchange resin strips, and foliar N content between treatments with 68 kg N ha^{-1} as urea and 34 kg N ha^{-1} as urea combined with 20.7–27.9 t compost mulch ha^{-1} (DM) suggests that nutrient cycling is generally improved by the mulch application. Although soil NO_3-N levels were at least three times lower in the compost treatment, compost resulted in higher yields, root biomass, and foliar N concentrations, suggesting that soil food web interactions resulted in rapid and tightly coupled nutrient cycling that reduced NO_3-N accumulation but allowed gross mineralization to meet plant N requirements [45]. However, it is questionable which NO_3-N concentrations limit the assimilation by the soil food web. Frost, on the other hand, acknowledges a general leaching risk when applying large amounts of nutrient-rich compost, such as manure compost [14]. Instead, Frost recommends applying them very sparingly to the soil surface and using lower-nutrient composts with a high C/N ratio, such as GW, for the actual mulching layer [14], which is in line with the results of our subsequent investigations.

3.2. On-Farm Soil Sampling

The results of the soil sampling are shown in Figure 1. The highest levels during the study period occurred at the beginning of the sampling in April and May, with a maximum of 680 kg N_{min}-N ha^{-1} in Plot 3. During this period, Plots 1 and 2 showed between 300 and 480 kg N_{min}-N ha^{-1}, with about 100 kg N_{min}-N ha^{-1} in each of the soil layers 300–600 and 600–900 mm, while almost all of the N_{min}-N in Plot 3 was concentrated in the topsoil. The lowest N_{min}-N levels in the mulched plots were measured during the main growing season between July and September and were 60, 70, and 100 kg N_{min}-N ha^{-1} in Plots 1, 3, and 2, respectively. Thereafter, N_{min}-N increased again to 120–170 kg in the mulched plots and to 30–50 kg ha^{-1} in the control outside the growing season from November to February. A further increase was observed in March with values of 160, 180, and 220 kg N_{min}-N ha^{-1} in Plot 1, 3, and 2, respectively.

Subtracting the N_{min}-N soil stocks corresponding to the control, the compost mulch added about 650 kg N_{min}-N ha^{-1} to the soil of Plot 3 within a short time after spreading. This subsequently decreased to 70 kg N_{min}-N ha^{-1} just before harvest, most likely due to the uptake of red cabbage of up to 250 kg N ha^{-1} [23]. As the soil samples do not indicate any major N_{min}-N shifts into the deeper soil layers during crop growth, it is reasonable to assume that, apart from N immobilization, major losses occur due to denitrification. Corresponding indications with a high application of compost mulch can also be found in the literature [68]. The renewed increase in N_{min}-N in August in Plot 3 can be explained by the absence of a crop and the simultaneously continued mineralization of the compost. In addition, mineralization may have been stimulated by shallow hoeing due to persistent field bindweed, as well as by the application of black film and the associated increase in soil temperature [72]. In contrast, the overall decrease in N_{min}-N in Plots 1 and 2 from spring to harvest can be plausibly explained by the average removal of 210 + 220 kg N ha^{-1} by fennel and kohlrabi and 250 kg N ha^{-1} by celery [23]. After harvest, mineralization from compost continues; N_{min}-N content increases again and gradually shifts to the 300–900 mm soil layer. A further increase in the rate of mineralization can be seen with rising temperatures in March. The trend towards lower N_{min}-N in Plots 1 and 2 in spring 2022 compared to 2021 is due to the fact that the mulch cover was refreshed with 20 mm compost in spring 2021, but not during our sampling in 2022.

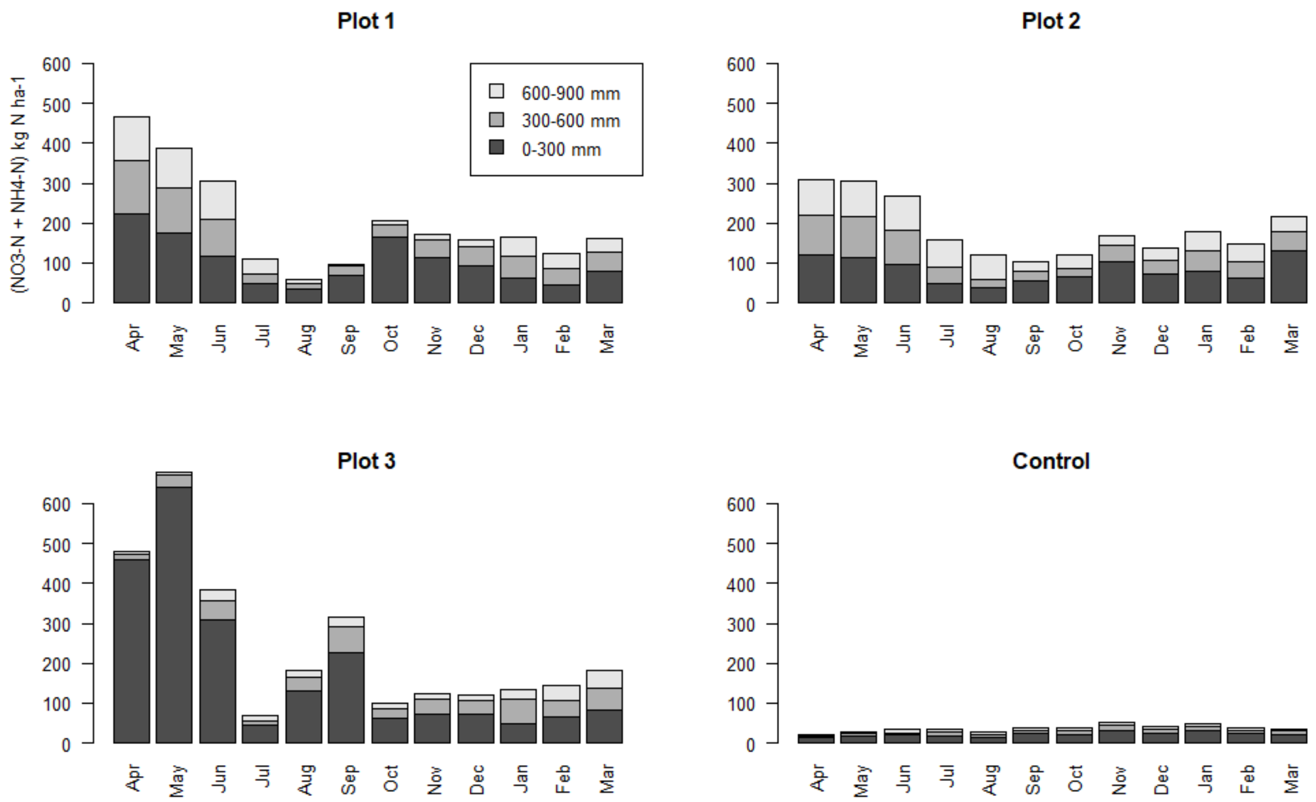

Figure 1. Mineral N content of soil sampled in three soil depths in three mulched and one control plot from April 2021 to March 2022.

Overall, the application of DCM resulted in a high N_{min}-N content in the soil. Reliable statements about actual N losses can only be made on the basis of appropriate measurements [73,74]. However, based on the data collected, it seems likely that excess N_{min}-N was released on the farm during the monitoring period. In particular, the shift of N_{min}-N from topsoil to subsoil over time and the resulting potential leaching is evident when comparing Plot 3, established in spring 2021, with Plots 1 and 2, which already received the initial compost layer of 150 mm in 2019. Furthermore, the relatively high N_{min}-N levels throughout the main growth period indicate an excess supply compared to crop demand. Especially during the winter months, leaching losses are likely due to the high N_{min}-N contents and the increasing proportion in the 600–900 mm soil horizon. The MW applied has very high N_{total} and N_{min}-N contents with a low C/N ratio and a high bulk density (Table 1). As a result, the already high N supply is increased by a comparatively high mass of compost when applied in volumetric dosage. Therefore, the use of MW should be avoided when using the DCM method to reduce N surpluses. Furthermore, the low-intensity crop rotation is noticeable (Table 2), since high crop intensities with up to four crops per season are actually more common in market gardening [9,75] and would have allowed better utilization of the N_{min}-N supply.

3.3. Modeling

The models were used to calculate the N pathways in the plant–soil system and the expected N losses due to denitrification and leaching (Table 3). For all plots, N-Expert outputs for MW are in line with field measurements (Figure 1). Except for a small negative balance in spinach and celery, N supply exceeded demand in all crops, with an average surplus of 81 kg N ha^{-1} a^{-1} during the growing season at depths of 0–300 and 0–600 mm, respectively, depending on the rooting depth of the crop [23]. The N balance for the whole year was calculated using NDICEA. It defines leaching losses as the cumulative N_{min}-N sum below 600 mm soil depth. Compared to the field data, where the annual totals at 600–900 mm soil depth were 518, 637, and 244 kg N_{min}-N ha^{-1} in Plots 1, 2, and 3, respectively, these were overestimated by the model. Replacing MW with GW and wood waste compost (WW) reduced predicted N losses due to leaching and denitrification by 44.7 and 68.5%, respectively. Because compost amounts were measured volumetrically at 150 mm mulch height, significantly lower amounts of GW and WW were required than MW due to the lower bulk density [42]. While GW and MW differed only slightly in g N_{total} kg DM^{-1} and C/N ratio, WW was also characterized by low N content and high C/N ratio [42]. N_{min}-N supply was always higher than crop removal in the NDICEA simulations. N-Expert, on the other hand, does not calculate sufficient coverage of crop N demand for the GW and WW scenarios. However, if N-Expert is not adjusted to the N_{min}-N level based on soil samples, as in the calculation for MW, only the N input in the calculated year is taken into account, and an accumulated N_{min}-N soil stock, as in DCM, cannot be considered.

Table 3. Model predictions in kg N ha^{-1}. MW = municipal organic waste compost, GW = green waste compost, WW = wood waste compost, N_{min}-N = inorganic N, Min OM = mineralization from soil organic matter, and Min/Im OF = mineralization or immobilization from organic fertilizer N.

	2020									2021					
	MW	GW	WW	MW	GW	WW	MW	GW	WW	MW	GW	WW	MW	GW	WW
	Plot 1									Plot 1					
	Radish			Onion			Spinach			Fennel			Kohlrabi		
Whole plant N uptake		70			157			100			170			178	
N_{min}-N Start 0–30/ 0–60	218	44	26	132	18	16	74	25	25	225	59	40	135	33	33
Min OM		20			112			45			90			94	
Min/Im OF	−17	−8	−19	−8	−1	−1	0	0	0	−42	−10	−23	−1	0	0
N losses		−19			−25			−24			−33			−40	
N-balance	132	−33	−62	54	−53	−55	−5	−54	−54	70	−64	−96	10	−91	−91
Sum							181	−140	−171				80	−155	−187
Denitrification							471	153	96				292	90	46
Leaching							1230	974	580				795	567	279
	Plot 2									Plot 2			Plot 3		
	Broad Bean			Lettuce						Celery			Red Cabbage		
Whole plant N uptake		187			86						200			230	
N_{min}-N Start 0–30/ 0–60	231	59	41	147	36	36				99	47	22	341	10	10
Min OM		60			37						156			137	
Min/Im OF	−38	−11	−25	0	0	0				−32	−6	−13	−164	−39	−90
N losses		−26			−22						−40			−38	
N-balance	40	−105	−137	76	−35	−35				−17	−43	−75	46	−160	−211
Sum				116	−140	−172				−17	−43	−75	46	−160	−211
Denitrification				441	158	79				342	107	60	764	182	118
Leaching				1024	757	389				897	635	354	1653	749	487

Overfertilization of N is a common and widespread problem in vegetable production [76]. For example, many vegetable crops have a low N-use efficiency [77], and deliberately high N fertilization is often used as insurance against yield loss [78]. The problem is exacerbated by intensive irrigation, which has the potential to leach significant amounts of soluble N [79]. Many vegetables are harvested during full vegetative growth, and N-rich crop residues can result in significant NO_3 leaching and N_2O emissions outside the growing season [80,81]. Sustainable vegetable production requires efficient and environmentally friendly measures, and precise and adapted fertilization can have a large leverage effect [82]. The use of compost as a mulch material is particularly challenging in this context, as it has a low N fertilization effect in the year of application, and uncontrolled N mineralization makes it difficult to synchronize with crop demand [83]. However, with DCM, the low N release of the compost is overcompensated by the exceptionally high application rate, which further complicates the adjustment. Since the method is based on a high compost volume that allows integration of no-till and permanent mulch cover with adequate weed suppression, the adaptation of nutrient loads must be made through the choice of the compost and its nutrient composition. As the simulations show, N losses due to denitrification and leaching decrease strongly in the order MW, GW, and WW. Compared to the measured data, reliable quantification of the actual N fluxes by NDICEA and N-Expert seems unlikely, but both models illustrate the leverage of different compost qualities on N turnover. While absolute N inputs decrease with decreasing bulk density and N concentration for the same compost volume, N mineralization rates decrease with increasing C/N ratio [21]. The corresponding N inputs by MW, GW, and WW for 150 mm mulch were 10,159, 5609, and 3588 kg N ha^{-1}, respectively. Therefore, light, woody, nutrient-poor composts are particularly suitable for realizing high compost volumes through DCM. As they are also recommended as a bulk substitute for peat-free growing media [42], they can also meet the requirement for permanent mulch cover as a growing medium. The comparatively low P content [42] also reduces the risk of problematic P accumulation in the soil, which can occur in composts with low N/P ratios [84]. To meet a possible N_{min}-N demand of individual crops beyond the release of the compost, the targeted use of rapidly available organic N fertilizers is recommended [38], depending on the N_{min}-N content of the soil and the expected uptake by the crop [23].

4. Conclusions

The advantages and disadvantages of compost as mulch were revealed in the literature review. Compared to common organic mulch materials such as hay, straw, or wood chips, compost has similar mulching properties but may contain higher nutrient concentrations. Since compost is a good germination and growth medium, it can remain on the site as permanent mulch. It is, therefore, well suited for no-till market gardening systems, but must be piled high enough to provide adequate weed suppression. Although the existing literature does not provide an understanding of the N dynamics in DCM, results from on-farm soil sampling suggest that nutrient-rich composts such as MW can lead to substantial accumulations of N_{min}-N. These accumulations pose a risk of leaching into surface and groundwater. To reduce the risk of environmentally harmful N_{min}-N surpluses, woody composts with low nutrient concentration, low bulk density, and high C/N ratio are recommended, as they are associated with lower N inputs and mineralization rates. However, according to model predictions, this may lead to the undersupply of individual crops in the rotation. In this case, additional applications of readily available organic N fertilizers may be appropriate for targeted supplementation of crop N_{min}-N demand. Decision support tools such as N-Expert can assist with application rates when calibrated to fertilizer and soil analyses. More field data under different compost types and site conditions are needed to accurately assess N dynamics, N losses, and the contribution of DCM to plant nutrition.

Author Contributions: Conceptualization, B.R.; methodology, B.R.; software, A.S. and B.R.; validation, A.S.; formal analysis, A.S.; investigation, B.R.; resources, B.R.; writing—original draft preparation, B.R. and A.S.; writing—review and editing, B.R., M.H. and A.S.; visualization, B.R.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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