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Assessment of the Efficiency of Nitrogen Slow-Release Fertilizers in Integrated Production of Carrot Depending on Fertilization Strategy

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Received: 2 February 2020; Accepted: 2 March 2020; Published: 5 March 2020

Abstract: Optimization of plant nutrition is a very important part of primary production quality systems. Crop fertilization is the most important agrotechnical measure because it determines the amount and quality of the yield. Moreover, excess fertilization intensifies the eutrophication processes and the greenhouse effect. The study aimed to assess the suitability of slow-release fertilizers in cultivation of carrot subspecies *Daucus carota* L. *ssp. sativus* in the integrated production system. The objective was realized on the basis of a strict field experiment set up on a clay loam soil with low nutrient content. The dose of fertilizer was the experimental factor. The fertilizers were applied during the formation of the ridges. Traditional fertilizers (ammonium phosphate, potassium salt, ammonium nitrate, and a multi-component fertilizer Polifoska 6), as well as a multi-component fertilizer with slow release of nutrients, NPK Mg (18-12-24-4), were used. In individual variants of the experiment, different fertilization strategies were applied: integrated production fertilization, traditional fertilization, and fertilization based on the use of slow-release fertilizers. The control treatment comprised of unfertilized plants. The efficiency of nitrogen fertilization was evaluated based on agronomic efficiency, partial factor productivity, physiological efficiency, and removal efficiency. Fertilization strategy significantly impacted the quantity of obtained yield. In the control sample, prior to mineral fertilization, the crop yield was 33.53 $Mg \cdot ha^{-1}$. The largest yield was 82.30 $Mg \cdot ha^{-1}$.The largest yields were obtained from plants fertilized with a combination of slow-release fertilizers, with nitrogen introduced in the form of ammonium phosphate, and through conventional fertilization. The highest productivity and environmental efficiency were obtained in treatments with fertilization according to the principles of integrated production and with slow-release fertilizers. In terms of environmental efficiency, the best results were obtained through nitrogen fertilization using 400 kg of slow-release fertilizers. The use of slow-release fertilizers in carrot cultivation can significantly improve the efficiency of fertilization, both in terms of production and environmental protection.

Keywords: carrot; integrated production; slow-release fertilizer; fertilization efficiency; management

1. Introduction

At all stages, food production is related to the use of natural resources, such as soil, water, space, or energy. Soil acidification, depletion of organic matter, deterioration of water regime, and chemical contamination of soil and water are the most frequently indicated effects of agriculture. Large-scale plant cultivation with effective weed control significantly reduces the level of biodiversity in agrocenoses and adjacent areas [1,2]. Another consequence of intensification of agricultural production is the deterioration of the quality of produced plant products. This is associated with the increased level of residues of plant protection products [3], as well as excessive content of nitrates and trace elements.

The development and implementation of quality management systems in food production was a sui generis reaction of the consumer market to the unsatisfactory quality of products available in the market [4,5]. Economic growth and the related increase in wealth has impacted consumer awareness of environmental and health effects of overexploitation related to food production in developed countries [6–8]. The consequence of this was the development and implementation of specific rules of production (both animal and vegetable), which were formalized into quality systems. The most popular of them include: Integrated Plant Production (IPP), GLOBAL.G.A.P., and private network systems [9–11].

Fertilization plays an important role in crop production because it affects crop quantity and quality, as well as physical, biological, and physiochemical properties of soil, and the quality of ground- and surface water, as well as the air. From the producer's point of view, fertilization is an important factor impacting production costs. Both excessive and insufficient doses of fertilizers, as well as improper fertilization technologies (techniques used and dates of application), adversely affect the environment and the quantity and quality of crops [12,13]. In addition, the introduction of rational fertilization methods is an effective tool for shaping the image of agriculture in the modern world [14].

Increasing the efficiency of fertilization in modern agriculture is difficult due to the effective production methods that are already in use. Nevertheless, improving the use of fertilizer components by several percent proves profitable on a global scale [15,16]. The effect of optimizing plant fertilization is the production of high quality food, in terms of chemical composition and technological parameters [17–22].

In agricultural practice, various methods are used to increase the use of fertilizer components introduced into agro-ecosystems. To meet the growing needs of agriculture, the fertilizer industry has introduced an ever-growing range of slow-release fertilizers, thanks to which nutrient supplementation of plants is extended over the vegetation period. The use of slow-release fertilizers is one of the methods of fertilization optimization which has increased in importance in recent years [14,23,24]. The purpose of slow-release fertilizers is to reduce both the total amount of plant nutrients introduced into the environment and the amount of energy used for fertilization treatments.

2. Materials and Methods

The aim of the work was to evaluate the effectiveness of different fertilization technologies in the cultivation of carrot subspecies *Daucus carota* L. *ssp. sativus.* For the realization of the project objective, a field experiment was carried out where the fertilization strategy was the experimental factor. The test crop was carrot *Daucus carota* L. *ssp. Sativus*, 'Elegance F1', characterized by 135 days of vegetation. One million two hundred thousand million plants per hectare were planted, spaced at 2.5 cm.

The methodology of integrated carrot production was applied. No irrigation was used at the experiment site. The field experiment included five fertilization levels and one control treatment, in four replications. The experiment was conducted on 9 m^2 experimental plots. The fertilization scheme of the experiment is presented in Table 1. In order to determine the optimum level of fertilization, in accordance with the principles of integrated production, the production potential of the habitat was estimated at 70 mg of roots·ha^{-1}.

Table 1. The level of fertilization and fertilizers applied in individual treatments.

Treatment	Triple Superphosphate	Slow-Release Fertilizer	Ammonium Nitrate	Polifoska 6	Potassium salt	N	P_2O_5	K_2O
	kg of Fertilizer·ha^{-1}					kg of Component·ha^{-1}		
Control *								
1	-	-	203	350	92	86	70	160
2	200	-	500	-	400	160	92	240
3	136	200	-	-	233	38	70	160
4	113	400	-	-	200	76	70	160
5	91	600	-	-	167	114	70	160

* Control, without the use of fertilizers;1—- According to the integrated production methodology; 2—-Fertilization used by the producer; 3—-A slow-release fertilizer at 200 kg·ha^{-1}; 4—-A slow-release fertilizer at 400 kg·ha^{-1}; 5—-A slow-release fertilizer at 600 kg·ha^{-1}.

The experiment was established on May 5, 2017, in a vegetable farm in Skorczów (50°15′N 20°25′), in the Świętokrzyskie Province. The plants were harvested on October 17, 2017. The average air temperature during the experiment was 15.2 °C, whereas total precipitation was 419 mm. The soil used for the experiment had a clay loam texture. The forecrop for the test plants was beetroot, grown in the first year after manure application.

Prior to the commencement of the experiment, representative soil samples were collected from the experimental area to determine soil basic parameters (Table 2) and to estimate the yield potential of the site, as well as the fertilizing needs of the plants. The following parameters were determined in the soil: reaction—by potentiometric method in a suspension of water and 1 mol·dm^3 potassium chloride solution; content of available forms of phosphorus and potassium—by Egner-Riehm method; mineral nitrogen—by distillation after extraction with potassium sulfate solution; and available forms of calcium and magnesium—by atomic emission spectrometry after extraction with 1 mol·dm^{-3} ammonium acetate solution. The content of organic carbon and total nitrogen was determined by the elementary analysis method, using an Elementar Vario Max Cube.

Table 2. Properties of the soil on which the experiment was carried out.

pH in H_2O	pH in KCl	N total	C org.	N min.	P	K	Mg	Ca
		[g·kg^{-1}]		[mg·kg^{-1}]				
7.65	7.11	1.135	13.25	28.6	153	181	659.7	19546

After the experiment, the plants were harvested, and the total and marketable yields were determined. A laboratory sample consisting of 10 primary samples was collected from each experimental plot. A primary sample consisted of three adjacent carrot plants from each site. Nitrogen content in the plant biomass was determined in fresh plant matter by the elementary analysis method. The following fertilizers were used in the experiment: a multi-component, slow-release fertilizer (NPK) 19;5;20%, + CaMgS 4;4;19.5%, ammonium nitrate (N) 32%, Potassium salt (K) 60% Polifoska 6 NPK 6;20;30%. The slow-release fertilizers were applied in rows during the formation of ridges. Phosphate and potassium fertilizers were applied at full dose before sowing, while nitrogen fertilizers were applied in partial doses. The dose of organic fertilization was 20 Mg·ha^{-1}. Mineral fertilization of the forecrop was carried out according to its nutritional needs. The assessment of the proposed fertilization systems was based on the size of the marketable yield, the productivity index, the agronomic efficiency index, the removal efficiency index, and the physiological efficiency index.

To determine the Partial Factor Productivity (PFP), the following formula was applied [25]:

$$\text{PFP}\ \left(\text{kg kg}^{-1}\right) = \frac{\text{Y}}{\text{F}}\ , \qquad (1)$$

where:

Y—crop yield per piece (g·pc.$^{-1}$); and
F—N applied per piece (kg N·pc.$^{-1}$).
To determine the Agronomic Efficiency coefficient (AE), the following formula was used [25]:

$$AE\left(\text{kg kg}^{-1}\right) = \frac{Y - Y_0}{F}, \tag{2}$$

where:
Y—yield in treatments with added N fertilizers (Mg·ha^{-1});
Y_0—yield without addition of N fertilizer (control) (Mg·ha^{-1}); and
F—N applied(kg N·ha^{-1}).
Removal efficiency (RE) was determined using the following formula [25]:

$$RE\left(\text{kg kg}^{-1}\right) = \frac{C}{F}, \tag{3}$$

where:
C—N removed with yield (kg N·ha^{-1}); and
F—N applied (kg N·ha^{-1}).
Physiological Efficiency (PE) was determined according to the formula [25]:

$$PE\left(\text{kg kg}^{-1}\right) = \frac{Y - Y_0}{U - U_0}, \tag{4}$$

where:
Y—yield in treatments with added N fertilizers (Mg·ha^{-1});
Y_0—yield without addition of N fertilizer (control) (Mg·ha^{-1}), U—N uptake in aboveground crop in treatments with added N fertilizers (kg N·ha^{-1}); and
U_0—N uptake in aboveground crop in treatments without added fertilizer (control) (kg N·ha^{-1}).

Statistical Analysis

ANOVA was applied to analyze the results. The significance of mean differences among the treatments was tested by multiple comparison, and Tukey's range test was applied at a significance level of $\alpha = 0.05$. The analysis was performed using the statistical software package Statistica v. 12.0 (StatSoft Inc., Tulsa, OK, USA).

3. Results and Discussion

From the economic point of view, the amount of yield is the most important indicator of plant production efficiency. Based on data on soil properties and field history, the production potential of the soil used for the experiment was estimated at 70 Mg·ha^{-1}. The average yield in the control area was established at 33.53 Mg·ha^{-1} (Table 3). After fertilization with conventional fertilizers in the amount consistent with the principles of integrated production, marketable yield was similar to the production potential of the habitat and amounted to 67.8 Mg·ha^{-1}.

Fertilization according to production practices used at the experiment site led to an increase in the yield of plants by almost 30%, as compared to fertilization according to the principles of integrated production. In this variant of the experiment, the amount of nitrogen fertilizer was approximately 80% higher than data estimated according to integrated carrot production methodology. Application of slow-release fertilizers to plant roots prior to forming the beds resulted in a marketable carrot root yield of 84.7 Mg·ha^{-1}. The nitrogen dose was 76 kg, according to the principles of integrated production. Carrot is a plant that reacts strongly to nitrogen fertilization by increasing the amount of biomass and accumulating nitrates [26]. Therefore, in terms of quality management, it is very important to develop a fertilization technology that would guarantee safe nitrate content in the produced yield [27]. In the case of this plant, intended both for consumption and for processing, the most important aspect in selecting the production technology is quality, not quantity, of the yield. Due to the high level of intensification, carrot production has a strong environmental impact due to the emission of greenhouse gases and a large amount of nitrates dispersed to the environment. Medeiros and Kiperstok [28] point to the possibility of optimizing carrot cultivation by up to 70% with a proper fertilization and irrigation management policy. Assessment of the agricultural systems in question was carried out based on the technological quality of the product, with weight of the produce being a very important factor. For all experiment sites, the unit weight of carrot was 56.16 g and ranged from 24.21 to 79.49 g·pc. $^{-1}$. The highest variability of the parameter was identified in the control site (Table 3). In other sites, the variability ranged from about 11 to 15%, and no effect of the applied fertilization strategy on this parameter was found. Niemiec et al. [29] found that increasing the dose of slow-release fertilizers applied to roots in the cultivation of Chinese cabbage (nappa cabbage) resulted in an increased difference in unit weight of individual plants. Similar results were obtained by Niemiec et al. [29]. From the producer's perspective, the most important indicator of the efficiency of an agricultural system is its productivity rate, i.e., the increase in the yield per 1 kg of nitrogen fertilizer. The value of this parameter depends not only on the applied fertilization strategy but also on the plants' growth conditions, soil fertility, climatic conditions, and the productive potential of a given plant variety. Thus, the value of the productivity coefficient allows assessing the efficiency of fertilization under specific production conditions [30]. Depending on the fertilization technology used, the value of the productivity coefficient ranged from 63.88 to 152.23 kg d.m.·kg N^{-1} (Table 4).

Table 3. Marketable yield of carrot and unit mass of roots in particular variants of the experiment.

Treatment	Mean Marketable Yield	Range	Mean Weight of the Carrot Root	Range
Unit	Mg·ha^{-1}		g·pc.$^{-1}$	
Control	33.53a *	30.25–34.52	28.44a	24.21–33.80
1	67.80c	64.52–69.31	56.82c	49.88–65.44
2	86.40d	84.29–88.44	73.62d	66.51–79.49
3	48.90b	46.92–50.43	38.93b	36.29–46.82
4	84.70d	81.45–87.22	71.09d	65.21–72.46
5	82.30d	76.58–85.49	68.11cd	64.29–78.14

* Different letters indicate statistically significant differences at the significance level p = 0.05.

Table 4. Values of efficiency coefficients in particular experimental treatments.

Variant of Experiment	Physiological Efficiency	Partial Factor Productivity	Agronomic Efficiency	Removal Efficiency
Unit	g·pc.$^{-1}$	kg f.m.·kg N^{-1}	kg d.m.·kg fertilizer^{1}	kg N kg·N^{-1} applied
Control			-	-
1	6.284	89.12	45.05	0.717a *
2	5.766	63.88	39.09	0.678a
3	4.646	152.23	47.85	1.030b
4	6.650	131.84	79.65	1.198b
5	5.538	85.40	50.61	0.914ab

* Different letters indicate statistically significant differences at the significance level p = 0.05.

The lowest value of this parameter was found in the conventionally fertilized treatment, according to the production practice applied in the experiment area. Applying the principles of integrated production to the use of conventional fertilizers increased the value of the productivity coefficient to 89.12 kg d.m.·kg N^{-1}. The most favorable value of the productivity coefficient was determined with slow-release fertilizers, at 76 kg N·kg^{-1}. However, the assessment of the agricultural system based on the value of the productivity coefficient must be carried out in relation to the yield value, taking into account the production potential of the site [31]. With the optimization of maize fertilization technology, the value of the discussed parameter increased from 37 kg N·kg-1 to 59 kg N·kg^{-1} under nitrogen fertilization at 140 kg N·kg^{-1} [24]. Niemiec et al. [32] reported values of the efficiency coefficient of celery from 19.35 to 151.76 kg, depending on the fertilization variant, under intensive production conditions on a soil with high agronomic suitability. Amanullah and Almas [33] determined the value of this parameter at 28 to 55 kg·kg^{-1} of grain, depending on the applied fertilization strategy, while Li et al. [34] achieved a more than double increase in the value of the productivity coefficient when introducing nitrogen fertilizers through the root. Zhang et al. [35] reported the values of the productivity coefficient at 17.3 kg N·kg^{-1} under conventional fertilization, while the optimization of fertilization associated with the addition of biochar resulted in an increase in this parameter to 29.19 kg N·kg^{-1}. Biochar introduced with mineral fertilizers gives them the characteristic of slow-release fertilizers [36]. The high value of the coefficient does not necessarily prove high production efficiency. Under intensive cultivation, the most common values of this parameter range from 40 to 80 kg·kg^{-1} per dry matter of the yield [25]. Values above 60 are found in well-managed systems with low nitrogen content in soil.

Depending on the fertilization technology used, the value of the efficiency coefficient ranged from 39.09 to 79.65 kg d.m.·kg N^{-1} (Table 4). The lowest value of this parameter was found in the conventionally fertilized treatment, and a slightly higher value was determined for fertilization with conventional fertilizers according to the principles of integrated production. The highest value of the efficiency coefficient was determined for slow-release fertilizers, at 76 kg N·kg^{-1}, and this fertilization strategy proved to be the most advantageous in terms of plant production economics. Kafesu et al. [31] reported agronomic yields of corn at approximately 20 kg d.m.·kg N^{-1} for soils with low agricultural suitability. The authors did not find any significant differences in shaping of this parameter between nutrient rich soils and nutrient poor soils. On the other hand, Xu et al. [37] estimated the value of this parameter for rice production in developing countries, and it was about 13 kg of produce·kg^{-1}, while Niemiec et al. [32] reported the value of this parameter for the conventional production of root celery to be about. 20 kg·kg^{-1}. As a result of optimization of fertilization using a combination of slow-release and conventional fertilizers, the authors achieved the value of agronomic efficiency coefficient at about 90 kg of produce·kg^{-1} d.m. At the current level of global agriculture development, it is possible to increase the efficiency of fertilization in many areas through optimization of fertilizer application techniques, selection of appropriate agrotechnical measures, or by providing plants with the right amount of water and micro- and macro-elements. An et al. [38] reported that implementing simple methods of optimizing rice fertilization allowed an improvement in agronomic efficiency by 38%. In our own research, the use of integrated fertilization methods resulted in increasing the value of agronomic efficiency coefficient by 15%, as compared to traditional fertilization methods, while a treatment fertilized with slow-release fertilizers demonstrated an increase in the agronomic performance index by approximately 100% (Table 4).

Nitrogen removal efficiency is the most important indicator for assessing the environmental impact of fertilization. Cassman et al. [39] studied the efficiency of wheat, rice, and maize fertilization in Asia and the USA, based on the nitrogen removal coefficient. These authors reported the values of this parameter in the experiment area at 0.18 to 0.49 kg N·kg^{-1} of nitrogen used in the form of mineral fertilizers. On the other hand, Vinzent et al. [40] reported the values of nitrogen removal coefficient in the production of rape at 0.45 to 0.54 kg N·kg^{-1} of nitrogen used in the form of mineral fertilizers, depending on the addition of urease inhibitors. These authors draw attention to the major potential of slow-release fertilizers in the process of reducing water eutrophication and greenhouse gas emissions to the atmosphere. The increase in the potential of using nitrogen in the form of slow-release fertilizers was also observed by Niemiec et al. [29,32] and Purnomo et al. [41]. The results of our own research also indicate the suitability of slow-release fertilizers in the process of optimizing nitrogen fertilization. In carrot production, introduction of a fertilization strategy based on the use of slow-release fertilizers at 76 kg N·ha^{-1} allowed achievement of a nitrogen removal coefficient at 1.198 kg N·kg^{-1} (Table 4). Further increase in the dose of slow-release fertilizers applied to plant roots resulted in a decrease in the use of nitrogen introduced with fertilizers. In the treatment fertilized in accordance with the integrated carrot production methodology, the value of nitrogen removal coefficient was 0.717 kg N·kg^{-1}, while in fertilization according to the production practice, 0.678 kg N·kg^{-1} of nitrogen used in the form of mineral fertilizers. High values of this parameter indicate good use of nitrogen from fertilizers and soil resources. In the case of obtaining yield significantly below the production potential of the site, the high value of nitrogen removal coefficient may indicate insufficient fertilization with this element. The results obtained in the treatments fertilized with slow-release fertilizers were high, characteristic for well-managed farm systems. Significantly lower values of the nitrogen removal coefficient were obtained by Shan et al. [42] in the production of Chinese cabbage (nappa cabbage).

The physiological efficiency index is an indicator of the conditions of plant growth, including the parameters of soil fertility, climate elements, and plant production potential, as well as the policies of fertilization and plant protection. Its low values indicate the occurrence of a stress factor that limits the plant growth [43–46]. The cause of the problem cannot be indicated based on the value of the physiological efficiency index. Nevertheless, it is a reliable source of information on the efficiency of an agricultural system. The values of the physiological efficiency index in the individual fertilization variants did not vary significantly. The physiological efficiency factor in subsequent variants of the experiment ranged from 4.646 to 6.65 kg d.m. of root·kg of nitrogen assimilated by plants^{-1}, as shown in Table 4. The lowest value of the coefficient was obtained using fertilization with slow-release fertilizers at 38 kg·ha^{-1}, whereas the highest value of this parameter was obtained with the use of a slow-release fertilizer at 76 kg N·kg^{-1}. From the point of view of the discussed parameter, no statistically significant differences were found in individual research sites.

The development of modern agriculture is contingent on increasing the efficiency of fertilization. Scientific literature offers more and more information regarding the possibilities of using slow-release fertilizers in the context of improving the efficiency, production, and economic and environmental aspects of this part of the production process [47–53]. The results of the research indicate the potential of slow-release fertilizers in the context of increasing the efficiency of fertilization. Therefore, the share of slow-release fertilizers applied in the vicinity of the root zone is expected to increase in the future. As a result, from the point of view of science and production practice, it is important to conduct further research aimed at developing fertilization technologies based on slow-release fertilizers, to limit the amount of elements released to the soil ecosystem and at the same time achieve high yields of good quality.

4. Conclusions

Fertilization of carrot according to the principles of integrated production using conventional fertilizers produced lower yields than traditional fertilization. The use of slow-release fertilizers in the amount consistent with the principles of integrated production allowed the yield obtained to be comparable with that found in conventionally fertilized sites.

The most favorable value of agronomic efficiency and nitrogen removal coefficients was obtained in the variant with the use of a slow-release fertilizer at 76 kg N·ha^{-1} applied at the root of plants. In that treatment, the obtained value of the agronomic efficiency index was 79.65 kg d.m.·kg fertilizer.

The lowest values of the agronomic efficiency index and productivity index were obtained in the fertilization variant compliant with the production practice used at the research area.

The use of mineral nitrogen in the form of slow-release fertilizers at over 76 kg N·ha^{-1} resulted in a decrease in the size of biomass and deterioration of all fertilization efficiency coefficients.

Author Contributions: Conceptualization, M.N.; M.K. (Maciej Kuboń), J.S.; methodology M.T.; M.K. (Maciej Kuboń), A.S.-S., Z.G.-S. formal analysis, M.N., M.T., M.K. (Maciej Kuboń); investigation, J.S., M.N.; resources, Z.G.-S., M.K. (Monika Komorowska.); A.S.-S.; writing—Z.G.-S., M.T.; A.S.-S.; visualization, M.K. (Maciej Kuboń), J.S., M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

References

1. Dwivedi, S.L.; Lammerts Van Bueren, E.T.; Ceccarelli, S.; Grando, S.; Upadhyaya, H.D.; Ortiz, R. Diversifying food systems in the pursuit of sustainable food production and healthy diets. *Trends Plant Sci.* **2017**, *10*, 842–856. [CrossRef] [PubMed]
2. Forleo, M.B.; Palmieri, N.; Suardi, A.; Coalo, D.; Pari, L. The eco-efficiency of rapeseed and sunflower cultivation in Italy. Joining environmental and economic assessment. *J. Clean. Prod.* **2018**, *172*, 3138–3153. [CrossRef]
3. Jiao, X.; Nyamdavaa, M.; Zhang, F. The transformation of agriculture in China: Looking back and looking forward. *J. Integr. Agric.* **2018**, *17*, 755–764. [CrossRef]
4. Alluvione, F.; Moretti, B.; Sacco, D.; Grignani, C. EUE (energy use efficiency) of cropping systems for a sustainable agriculture. *Energy* **2011**, *36*, 4468–4481. [CrossRef]
5. Lorenz, K.; Lal, R. Environmental Impact of Organic Agriculture. *Adv. Agron.* **2016**, *139*, 99–152.
6. Conacher, A. Resource development and environmentalstress: Environmental impact assessment and beyond in Australia and Canada. *Geoforum* **1988**, *19*, 339–352. [CrossRef]
7. Sassenrath, G.F.; Halloran, J.M.; Archer, D.; Raper, R.L.; Hendrıckson, J.; Vadas, P.; Hanson, J. Drivers impacting the adoption of sustainableagricultural management practices and productionsystems of the northeast and southeast United State. *J. Sustain. Agric.* **2010**, *34*, 680–702. [CrossRef]
8. Cole, D.C.; Levin, C.; Loechl, C.; Thiele, G.; Grant, F.; Girard, A.W.; Sindi, K.; Low, J. Planning an integrated agriculture and health program and designing its evaluation: Experience from Western Kenya. *Eval. Program Plan.* **2016**, *56*, 11–22. [CrossRef]
9. Wongprawmas, R.; Canavari, M.; Waisarayutt, C. A multi-stakeholder perspective on the adoption of good agricultural practices in the Thai fresh produce industry. *Br. Food J.* **2015**, *117*, 2234–2249. [CrossRef]
10. Ariyawardana, A.; Ganegodageb, K.; Mortlock, M.Y. Consumers' trust in vegetable supply chain members and their behavioral responses: A study based in Queensland, Australia. *Food Control* **2017**, *73*, 193–201. [CrossRef]
11. Rajkovic, A.; Smigic, N.; Djekic, I.; Popovic, D.; Tomic, N.; Krupezevic, N.; Uyttendaele, M.; Jacxsens, L. The performance of food safety management systems in the raspberries chain. *Food Control* **2017**, *80*, 151–161. [CrossRef]
12. Pypers, P.; Sanginga, J.M.; Kasereka, B.; Walangululu, M.; Vanlauwe, B. Increased productivity through integrated soil fertility management in cassava–legume intercropping systems in the highlands of Sud-Kivu, DR Congo. *Field Crop. Res.* **2011**, *120*, 76–85. [CrossRef]
13. Bailey, A.P.; Basford, W.D.; Penlington, N.; Park, J.R.; Keatinge, J.D.H.; Rehman, T. A comparison of energy use in conventional and integrated arable farming systems in the UK. *Agric. Ecosyst. Environ.* **2003**, *97*, 241–253. [CrossRef]
14. Nardi, P.; Neri, U.; Di Matteo, G.; Trinchera, A.; Napoli, R.; Farina, R.; Subbaravo, G.V.; Benedetti, A. Nitrogen release from slow-release fertilizers in soils with different microbial activity. *Pedosphere* **2018**, *28*, 332–340. [CrossRef]
15. Oenema, O.; Witzke, H.; Klimont, Z.; Lesschen, J.P.; Velthof, G.L. Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27. *Agric. Ecosyst. Environ.* **2009**, *133*, 280–288. [CrossRef]
16. He, J.; Wang, J.; He, D.; Dong, J.; Wang, Y. The design and implementation of an integrated optimal fertilization decision support system. *Math. Comput. Model.* **2011**, *54*, 1167–1174. [CrossRef]
17. Tuomisto, H.L.; Hodge, I.D.; Riordan, P.; Macdonald, D.W. Exploring a safe operating approach to weighting in life cycle impact assessment e a case study of organic, conventional and integrated farming systems. *J. Clean. Prod.* **2012**, *37*, 147–153. [CrossRef]
18. Papadopoulos, S.; Markopoulos, T. Factors Affecting the Implementation of Integrated Agriculture in Greece. *Proc. Econ. Financ.* **2015**, *33*, 269–276. [CrossRef]
19. Craheix, D.; Angevin, F.; Doré, T.; De Tourdonnet, S. Using a multicriteria assessment model to evaluate the sustainability of conservation agriculture at the cropping system level in France. *Eur. J. Agron.* **2016**, *76*, 75–86. [CrossRef]
20. Bedano, C.; Domínguez, A.; Arolfo, R.; Wall, L.G. Effect of Good Agricultural Practice sunder no-till on litter and soil invertebrates in areas with different soil types. *Soil Tillage Res.* **2016**, *158*, 100–109. [CrossRef]

21. Gori, M.A.; Eusebio, G.S.; Silveira, R.L. Impact of Microcredit on Small-Farm Agricultural Production: Evidence from Brazil. Available online: https://ideas.repec.org/p/ags/saeana/46747.html (accessed on 3 March 2020).
22. Walters, J.P.; Archer, D.W.; Sassenrath, G.F.; Hendrickson, J.R.; Hanson, J.D.; John, M.; Halloran, J.M.; Vadas, P.; Vladimir, J.; Alarcon, V.J. Exploring agricultural production systems and their fundamental components with system dynamics modeling. *Ecol. Model.* **2016**, *333*, 51–65. [CrossRef]
23. Gaetano, M.; Polinori, P.; Tei, F.; Benincasa, P.; Turchetti, L. An economic analysis of the efficiency and sustainability of fertilization programs at level of operational systems of soft wheat in Umbria. *Agric. Agric. Sci. Proc.* **2016**, *8*, 298–306.
24. Chen, X.P.; Cui, Z.L.; Fan, M.S.; Vitousek, P.; Zhao, M.; Ma, W.; Wang, Z.; Zhang, W.; Yan, X.; Yang, J. Producing more grain with lower environmental costs. *Nature* **2014**, *514*, 486–489. [CrossRef] [PubMed]
25. IFA. Sustainable Management of the Nitrogen Cycle in Agriculture and Mitigation of Reactive Nitrogen Side Effects. Available online: https://www.semanticscholar.org/paper/Sustainable-Management-of-the-Nitrogen-Cycle-in-and/599c908a1e75dbd409ca10d3b7f164355e61abd1 (accessed on 3 March 2020).
26. Krejčová, A.; Návesník, J.; Jičínská, J.; Černohorský, T. An element analysis of conventionally, organically and self-grown carrots. *Food Chem.* **2016**, *192*, 242–249. [CrossRef]
27. Quijano, L.; Yusà, V.; Font, G.; McAllister, C.; Torres, C.; Pardo, O. Risk assessment and monitoring programme of nitrates through vegetables in the Region of Valencia (Spain). *Food Chem. Toxicol.* **2017**, *100*, 42–49. [CrossRef]
28. Medeiros, D.L.; Kiperstok, A. Combining cleaner production and life cycle assessment for reducing the environmental impacts of irrigated carrot production in Brazilian semi-arid region. *J. Clean. Prod.* **2018**, *170*, 924–939.
29. Niemiec, M.; Tabak, M.; Paluch, Ł.; Komorowska, M. Assessment of productive and environmental efficiency of slow-release fertilizers in integrated production of napa cabbage depending on application method. In Proceedings of the 8th International Scientific Conference Rural Development, Kaunas, Lithuania, 23–24 November 2017.
30. Mucheru-Muna, M.; Pypers, P.; Mugendi, D.; Kung'u, J.; Mugwe, J.; Merckx, R.; Vanlauwe, B. A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the highlands of Central Kenya. *Field Crop. Res.* **2010**, *115*, 132–139. [CrossRef]
31. Kafesu, N.; Chikowo, R.; Mazaruraa, U.; Gwenzi, W.; Snapp, S.; Zingored, S. Comparative fertilization effects on maize productivity under conservation and conventional tillage on sandy soils in a small holder cropping system in Zimbabwe. *Field Crop. Res.* **2018**, *218*, 106–114. [CrossRef]
32. Niemiec, M.; Cupiał, M.; Szeląg-Sikora, A. Evaluation of the efficiency of celeriac fertilization with the use of slow-acting fertilizers. *Agric. Agric. Sci. Proc.* **2015**, *7*, 177–183. [CrossRef]
33. Amanullah, A.L.K. Partial factor productivity, agronomic efficiency, and economic analyses of maize in wheat-maize cropping system in Pakistan. In Proceedings of the Selected Paper Prepared for Presentationat the Southern Agricultural Economics Association Annual Meetings, Atlanta, Georgia, 31 January–3 February 2009.
34. Li, L.P.; Liu, Y.Y.; Lou, S.G.; Peng, X.L. Effects of nitrogen management on the yield of winter wheat in cold area of northeastern China. *J. Integr. Agric.* **2012**, *11*, 1020–1025. [CrossRef]
35. Zhang, D.; Pan, G.; Wu, G.; Kibue, G.W.; Li, L.; Zhang, X.; Zheng, J.; Zheng, J.; Cheng, K.; Joseph, S. Biochar helps enhance maize productivity and reduce greenhouse gas emissions under balanced fertilization in a rain fed low fertility inceptisol. *Chemosphere* **2016**, *142*, 106–113. [CrossRef] [PubMed]
36. Maucieri, C.; Zhang, Y.; McDaniel, M.D.; Borin, M.; Adams, M.A. Short-term effects of biochar and salinity on soil greenhouse gas emissions from a semi-arid Australian soil after re-wetting. *Geoderma* **2017**, *307*, 267–276. [CrossRef]
37. Xu, X.; He, P.; Yang, F.; Ma, J.; Pampolino, M.F.; Johnston, A.M.; Zhou, W. Methodology of fertilizer recommendation based on yield response and agronomic efficiency for rice in China. *Field Crop. Res.* **2017**, *206*, 33–42. [CrossRef]
38. An, N.; Wei, W.; Qiao, L.; Zhang, F.; Christie, P.; Jiang, R.; Dobermann, A.; Goulding, K.W.T.; Fand, J.; Fan, M. Agronomic and environmental causes of yield and nitrogen use efficiency gaps in Chinese rice farming systems. *Eur. J. Agron.* **2018**, *93*, 40–49. [CrossRef]
39. Cassman, K.G.; Dobermann, A.R.; Walters, D.T. Agroecosystems, nitrogen-use efficiency, and nitrogen managment. *J. Hum. Environ.* **2002**, *31*, 132–140. [CrossRef]

40. Vinzent, B.; Fuß, R.; Maidl, F.X.; Hülsbergen, K.J. N_2O emissions and nitrogen dynamics of winter rapeseed fertilized with different N forms and a nitrification inhibitor. *Agric. Ecosyst. Environ.* **2018**, *259*, 86–97. [CrossRef]
41. Purnomo, C.W.; Respitoa, A.; Sitanggang, E.P.; Mulyono, P. Slow release fertilizer preparation from sugar cane industrial waste. *Environ. Technol. Innov.* **2018**, *10*, 275–280. [CrossRef]
42. Shan, L.; He, Y.; Chen, J.; Huang, Q.; Lian, X.; Wang, H.; Liu, Y. Nitrogen surface runoff losses from a Chinese cabbage field under different nitrogen treatments in the Taihu Lake Basin, China. *Agric. Water Manag.* **2015**, *159*, 255–263. [CrossRef]
43. Gródek-Szostak, Z.; Malik, G.; Kajrunajtys, D.; Szeląg-Sikora, A.; Sikora, J.; Kuboń, M.; Niemiec, M.; Kapusta-Duch, J. Modeling the Dependency between Extreme Prices of Selected Agricultural Products on the Derivatives Market Using the Linkage Function. *Sustainability* **2019**, *11*, 4144. [CrossRef]
44. Niemiec, M.; Komorowska, M.; Szeląg-Sikora, A.; Sikora, J.; Kuboń, M.; Gródek-Szostak, Z.; Kapusta-Duch, J. Risk Assessment for Social Practices in Small Vegetable farms in Poland as a Tool for the Optimization of Quality Management Systems. *Sustainability* **2019**, *11*, 3913. [CrossRef]
45. Kapusta-Duch, J.; Szeląg-Sikora, A.; Sikora, J.; Niemiec, M.; Gródek-Szostak, Z.; Kuboń, M.; Leszczyńska, T.; Borczak, B. Health-Promoting Properties of Fresh and Processed Purple Cauliflower. *Sustainability* **2019**, *11*, 4008. [CrossRef]
46. Szeląg-Sikora, A.; Sikora, J.; Niemiec, M.; Gródek-Szostak, Z.; Kapusta-Duch, J.; Kuboń, M.; Komorowska, M.; Karcz, J. Impact of Integrated and Conventional Plant Production on Selected Soil Parameters in Carrot Production. *Sustainability* **2019**, *11*, 5612. [CrossRef]
47. Gródek-Szostak, Z.; Szeląg-Sikora, A.; Sikora, J.; Korenko, M. Prerequisites for the cooperation between enterprises and business supportinstitutions for technological development. *Bus. Non Profit Organ. Facing Increased Compet. Grow. Cust. Demand.* **2017**, *16*, 427–439.
48. Niemiec, M.; Komorowska, M.; Szeląg-Sikora, A.; Sikora, J.; Kuzminova, N. Content of Ba, B, Sr and As in water and fish larvae of the genus Atherinidae L. sampled in three bays in the Sevastopol coastal area. *J. Elem.* **2018**, *23*, 1009–1020. [CrossRef]
49. Kasprzak, K.; Wojtunik-Kulesza, K.A.; Oniszczuk, T.; Kuboń, M.; Oniszczuk, A. Secondary metabolites, dietary fiber and conjugated fatty acids as functional food ingredients against overweight and obesity. *Nat. Prod. Commun.* **2018**, *13*, 1073–1082. [CrossRef]
50. Kuźnia, M.; Wojciech, J.; Łyko, P.; Sikora, J. Analysis of the combustion products of biogas produced from organic municipal waste. *J. Power Technol.* **2015**, *95*, 158–165.
51. Sikora, J.; Niemiec, M.; Szeląg-Sikora, A.; Kuboń, M.; Olech, E.; Marczuk, A. Zgazowanie odpadów z przemysłowego przetwórstwa karpia. *Przem. Chem.* **2017**, *96*, 2275–2278. [CrossRef]
52. Szeląg-Sikora, A.; Niemiec, M.; Sikora, J.; Chowaniak, M. Possibilities of Designating Swards of Grasses and Small-Seed Legumes From Selected Organic Farms in Poland for Feed. In Proceedings of the IX International Scientific Symposium Farm Machinery and Processes Management in Sustainable Agriculture, Lublin, Poland, 22–24 November 2017.
53. Cupiał, M.; Szeląg-Sikora, A.; Niemiec, M. Farm Machinery and Processes Management in Sustainable Agriculture Location. In Proceedings of the 7th International Scientific Symposium on Farm Machinery and Processes Management in Sustainable Agricul, Gembloux, Belgium, 25–27 November 2015.