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Optimizing the N Rate for Maize Forage to Balance Profits and N Ecological Stress

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Abstract: The N application used for the production of forage affects environment stress. The N application rate used for the production of the whole maize (*Zea mays* L.) plant (WMP) affects the produced feed and environment. We carried out a 2-year field experiment aiming to measure how N application rates affect WMP forage production, and estimated the impact on the environment. Five N application treatments (0, 100, 200, 300 and 400 kg N ha^{-1}) were included in our study. The results showed that N application improved forage yield, achieving a higher economic and ecological profit. After reaching a certain optimal rate, however, increasing the N rate further no longer increased the yield and quality of WMP forage, but instead greatly increased estimated N losses, thereby reducing ecological profits. The comprehensive benefit of the optimal N rate was ordered: the optimal N rate that maximized agronomic profit > that maximized economic profit > that maximized ecological benefit. The optimal N rate maximizing ecological profit was lower by 21% and 37% than that maximizing economic profit and forage yield, respectively. N application rates with the highest ecological profit (USD 2478 ha^{-1} in 2017 and USD 2448 ha^{-1} in 2018) were 248 and 245 kg N ha^{-1}, respectively, in 2017 and 2018. The optimized N rate that maximized ecological profit maintained the economic profit while reducing N fertilizer input and associated N losses; it also carried a lower economic and ecological cost due to estimated N losses. Ecological criteria, which combine economic profit and economic losses due to their environmental impact, are more efficient than agronomic or economic criteria when used to provide guidance for WMP forage production. Therefore, in WMP forage production, optimizing N application rate by ecological criteria could maintain a high forage yield and economic profit, but greatly reduce input costs and ecological stress, maximizing ecological profit.

Keywords: maize forage; feeding character; economic profit; N loss; ecological profit

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1. Introduction

Maize is a multi-purpose crop that can be used for the production of human food and livestock forage, as well as raw material for industrial production [1,2]. Because of its high yield, high quality output and relatively low input requirements, maize is used to produce forage worldwide, especially for the dairy industry [3]. Whole maize plant (WMP) forage is a primary source of energy and fiber for dairy cows [4]. In China, the consumption of maize used as forage increased from 85 million tons in 2000 to 157 million tons in 2018 [5], and as a result, improved the efficiency of the forage production process. The forage production process is a major concern for the dairy industry as it affects both farmers' incomes and associated ecological stress [2,6].

The yield of WMP forage can be adjusted by modifying the N application rate. Generally speaking, increasing the N application rate improves maize growth: it enhances the leaf area and chlorophyll content, increases photosynthesis and assimilation rates, and delays senescence, which together have the effect of increasing the accumulation of dry matter and enhancing amino acid, protein, sugar, starch and oil content [7,8]. Therefore, increasing the N application rate is considered to be effective agronomy management for farmers who want to obtain a higher WMP forage yield. Nevertheless, maintaining or even increasing these higher yields over time requires a large investment in agricultural resources, especially in N fertilizer [9,10]. In addition, the yield improvements that are achieved through increasing the N application rate diminish when it surpasses a certain threshold [11]. On top of that, increasing the N input beyond this threshold reduces N use efficiency and increases economic cost, which negatively affects biomass yield and economic profit (income minus production) [12]. Another effect of increasing the N input beyond the rate maximizing yield is that it gives rise to higher N losses, which ultimately lead to contamination of the environment, damage to human health and climate change [9,13,14]. An appropriate N application rate is sought to maximize forage production profits while maintaining an acceptable environmental performance [10,15]. It is difficult, however, to coordinate environmental performance in parallel with economic profits when using the same assessment criteria for both. Notably, the ecological costs of N pollution, which are economic losses due to N pollution, are usually neglected when considering economic profits, or at best seen as separate costs [12,13]. The ecological costs of N pollution should be taken into account when calculating agronomic and economic efficiency. Optimizations based on economic criteria might reduce production cost and increase economic profits from forage production, while ecological criteria might decrease the N pollution level [10,16]. Balancing these two types of criteria is beneficial for both the economy and the ecology, and facilitates optimization of the N application rate as well as maximization of WMP forage productivity. Therefore, we hypothesized whether applying ecological criteria is an efficient way to gauge its efficiency.

To address this issue, we carried out a 2-year field study with the aim to (1) study the effect of the N application rate on the growth and yield of WMP forage, the ecological costs from N losses, and economic and ecological profits, (2) propose an optimized N application rate, and (3) evaluate the efficiency of ecological criteria in WMP forage production.

2. Materials and Methods

2.1. Study Site

The field experiments were carried out in 2017 and 2018 at the Shandong Agriculture University Farming Station in Mazhuang, Taian, Shandong Province, China (117°15′82″ E, 36°16′59″ N). Precipitation data were obtained from an automatic meteorological station on site. The total precipitation during the 2017 and 2018 summer maize growing seasons was 400.6 and 461.6 mm, respectively. The soil at the station is a clay loam, classified as fine, montmorillonitic, frigid Mollic Cryoboralf, with a slope of <1%. The soil's physicochemical properties were as follows: the total N concentration was 1.71 g kg^{-1}, the NO_3^--N concentration was 30.01 mg kg^{-1}, the NH_4^+-N concentration was 6.3 mg kg^{-1}, the available P (Olsen) was 8.56 mg kg^{-1}, the available K was 80.72 mg kg^{-1}, the organic matter content was 16.04 g kg^{-1}, and the bulk density was 1.25 g cm^{-3}.

2.2. Experimental Design and Field Management

Forage maize, cv. Siyu 2, was used as the experimental subject. The characteristics of Siyu 2 are as follows: the growing period is 117 d, the plant type is semi-compact, it is harvested at the dent stage, which is when the water content of the whole plant reaches about 66%. The crop grown in the experimental field prior to the experiment was winter wheat (*Triticum aestivum* L.). On the base of our previous research, N application rate exceeding 300 kg N ha^{-1} did not improve maize yield [12]. Therefore, five N application treatments (0, 100, 200, 300 and 400 kg N ha^{-1}) were set in our experiment. The treatments with three replications were performed randomly. The resulting 15 experimental plots were arranged randomly in three blocks. Each plot measured 6 m × 30 m, and was planted with 10 rows of maize at a row spacing of 60 cm. As measured along a row, the plant spacing was 25.5 cm, which corresponds to a planting density of 65,000 plants ha^{-1}. The different

N treatments were realized by applying appropriate amounts of urea fertilizer (46.4% N) before sowing. All plots received 90 kg P_2O_5 ha^{-1} and 100 kg K_2O ha^{-1} before sowing. Plots were kept free of weeds, insects and diseases. In both years, the sowing date was 4 June.

2.3. Sampling and Lab Analysis

Prior to sowing, samples were collected from the soil layer making up the top 20 cm of each plot with an open-faced 6-cm diameter bucket probe (n = 5), and analyzed to obtain the soil physicochemical properties. Before sowing and again at harvest time (about 40 days after silking stage), additional soil samples were collected up to a depth of 100 cm (from 5 consecutive 20-cm sections) using a 3-cm tube probe, and used to determine the soil moisture and NO_3^--N content. Fresh soil samples were used to measure the NO_3^--N content [17]. Air-dried soil samples were sieved (0.5-mm sieve) and used to measure the total N, P and organic matter content. The total N content of the soil was measured using the semimicro-Kjeldahl procedure [18]. The soil-extractable P content was determined using the phosphomolybdate reduction method [19]. The soil extractable K content was determined using an Atomic Absorption Spectrometer (Thermo Fisher Scientific, ICE-3500, Waltham, MA, USA) [20]. The soil organic matter content was determined using the Walkley–Black method [21]. The bulk density was determined by analyzing a 5-cm diameter intact core [22]. The soil moisture was determined by weighing soil samples before and after oven-drying them for 48 h at 105 °C.

When the maize grain reached the dent stage (20 September 2017 and 20 September 2018, or about 40 days after silking) [23], the plant height, ear height, stem diameter, leaf area and leaf area index were measured (n = 10) [24]. To determine relative chlorophyll content, the Spad values of the maize ear leaves (n = 10) were measured using a Spad chlorophyll tester (SPAD502PLUS, Shanghai). Subsequently, 10 consecutive whole plants from plots representing each treatment were sampled, weighed, chopped and mixed evenly. A total of 1 kg of mixed subsample was dried at 105 °C for 30 min and kept in an oven for 7 d at 75 °C.

2.4. Estimation of Nitrogen Losses

The N losses were estimated using a new evaluation method proposed by Cui et al. [25], which is specific to summer maize production in the Huanghuaihai area, a region that includes the location of our field study. According to Cui et al. [25], the N losses (N_2O emission, NH_3 volatilization and N leaching) can be estimated using the following equations:

$$N_2O\text{ emissions}\left(\text{kg N ha}^{-1}\right) = 0.99e^{0.0047\times \text{N rate}}, \quad (1)$$

$$NH_3\text{ volatilization}\left(\text{kg N ha}^{-1}\right) = 7.98 + 0.099 \times \text{N rate}, \quad (2)$$

$$\text{N leaching}\left(\text{kg N ha}^{-1}\right) = 10.7e^{0.0060\times \text{N rate}}. \quad (3)$$

2.5. Calculation of the Ecological Profit and Cost

The economic profit from WMP forage can be calculated as follows:

Economic profit (USD ha^{-1}) = WMP forage yield × WMP Forage Price − Cost of inputs.

Where the cost inputs included seeds, seeding, fertilizers, pesticides and herbicides, irrigation, and harvesting. The total costs of seeds, pesticides and herbicides, seeding, irrigation, and harvesting amounted to 97.5, 76.1, 54.36, 19.74 and 347.90 USD ha^{-1}, respectively. Depending on the market survey in the study period, the price of N, P and K fertilizer was 0.651 USD (kg N)$^{-1}$, 1.70 USD (kg P_2O_5)$^{-1}$ and 1.56 USD (kg K_2O)$^{-1}$, respectively, and the average selling price of WMP forage (fresh matter with 60% water content) was 78.28 USD t^{-1}.

The ecological cost can be calculated as follows:

$$\text{Ecological cost (USD ha}^{-1}\text{)} = \quad (4)$$

$$NH_3 \text{ volatilization} \times 1.30 + \text{N leaching} \times 2.71 + N_2O \text{ emission} \times 1.24 \quad (5)$$

where ecological cost is the economic loss due to N pollution in our study; the ecological cost of N leaching (the abatement cost of reducing N from agricultural drainage water), NH_3 emissions (the cost of human health damage) and N_2O (the cost of climate change) are taken to be USD 2.71, 1.30 and 1.24 (kg N)$^{-1}$, respectively [12,26–28].

The ecological profit can be calculated using the following equation:

$$\text{Ecological profit (USD ha}^{-1}\text{)} = \text{Economic profit} - \text{Ecological cost.} \quad (6)$$

2.6. Calculation of the Forage Feeding Characteristics and N Use Efficiency

The following equations relate N productivity, fertilizer-N productivity and $_{\Delta}$Soil NO_3^--N:

$$\text{N productivity (USD kg}^{-1}\text{ N)} = \frac{Y}{NU}, \quad (7)$$

where Y is the ecological profit; NU is the N uptake.

$$\text{Fertilizer} - \text{N productivity} = \frac{Y_x - Y_0}{\text{N rate}}, \quad (8)$$

where Y_x is the ecological profit under application of an N rate of x, and Y_0 is the ecological profit without N application.

$$_{\Delta}\text{Soil } NO_3^- - \text{N (kg ha}^{-1}\text{)} = (C_1 - C_0) \times D \times H \times S, \quad (9)$$

where C_0 is the NO_3 concentration in the soil before planting, C_1 is the NO_3^- concentration at R6, D is the soil bulk density, H is the soil depth (m), and S is the area of 1 ha, or 10,000 m^2.

2.7. Data Analysis

The correlations between the observed data and the N supply were subjected to a One-Way ANOVA analysis that was implemented using the SAS 8.1 software package (SAS Institute). The differences between the treatments were determined using Duncan tests (new method of complex range, $p \leq 0.05$).

3. Results

3.1. Maize Forage Yield

In both years, N application improved the leaf area index, the Spad value, the plant height, the ear height and the stem diameter (Table 1). For applied N rates between 0 and 300 kg N ha^{-1}, the leaf area index, the Spad value and the plant height, as well as the green leaf number, the plant water content, the fresh matter yield and the dry matter yield increased proportionately to the N rate. Increasing the N rate to 400 kg N ha^{-1}, however, did not further improve the values of those plant characteristics.

Table 1. Maize green leaf number, plant height, ear height, stem diameter, leaf area index, Spad value, plant water content and forage yield in 2017 and 2018.

Year	N Rate kg N ha^{-1}	Green Leaf Number per Plant	Plant Height cm	Leaf Area Index $m^2\ m^{-2}$	Spad Value % $\%^{-1}$	Plant Water Content %	Forage Yield (Fresh Matter) $t\ ha^{-1}$	Forage Yield (Dry Matter) $t\ ha^{-1}$
2017	0	8.9d	288c	3.8c	42.0c	58.6d	34.8d	14.4d
	100	9.7c	299b	4.0b	45.0bc	59.2d	42.0c	17.2c
	200	10.7b	307ab	4.2b	49.1b	60.0c	47.8b	19.1b
	300	12.3a	311a	4.4a	52.6a	61.0b	53.5a	20.8a
	400	12.8a	313a	4.5a	53.5a	62.1a	54.9a	20.8a
2018	0	9.2d	285c	3.9d	40.1d	59.2e	34.5e	14.1e
	100	10.0c	299b	4.0d	45.6bc	59.9d	42.6d	17.1d
	200	11.2b	308ab	4.2c	47.8b	60.5c	48.1c	19.0c
	300	12.3a	314ab	4.5a	54.0a	61.2b	52.9b	20.5a
	400	12.7a	319a	4.6a	54.4a	62.6a	55.1a	20.6a

Note: Values in a column in the same section followed by a letter are not significantly different from the values followed by the same letter at $p < 0.05$ ($n = 3$).

3.2. Estimated N Loss and Ecological Cost

When N application rates increased from 0 to 400 kg N ha^{-1}, estimated N_2O emissions, estimated NH_3 volatilization, estimated N leaching, estimated N loss and measured $_{\Delta}$Soil NO_3^--N increased (Table 2) too. The $_{\Delta}$Soil NO_3^--N from 0 to 100 kg N ha^{-1} was negative while that from 200 to 400 kg N ha^{-1} was positive. Increasing the N application rate resulted in an increased ecological cost from N pollution due to ecological damage caused by N_2O emissions, NH_3 volatilization and N leaching.

Table 2. The estimated N loss, $_{\Delta}$Soil NO_3^--N and ecological cost in 2017 and 2018.

Year	N Rate	Estimated N_2O	Estimated NH_3	Estimated N Leaching kg N ha^{-1}	Estimated N Loss	$_{\Delta}$Soil NO_3^--N	Ecological Cost USD ha^{-1}
2017	0	1.0	8.0	10.7	19.7	−97.4e	40.6
	100	1.6	17.9	19.5	38.9	−47.6d	78.1
	200	2.5	27.8	35.5	65.8	16.9c	135.4
	300	4.1	37.7	64.7	106.5	67.6b	229.4
	400	6.5	47.6	117.9	172.0	104.5a	389.4
2018	0	1.0	8.0	10.7	19.7	−99.1e	40.6
	100	1.6	17.9	19.5	38.9	−36.9d	78.1
	200	2.5	27.8	35.5	65.8	10.6c	135.4
	300	4.1	37.7	64.7	106.5	63.5b	229.4
	400	6.5	47.6	117.9	172.0	94.6a	389.4

Note: Values within a column in the same section followed by a letter are not significantly different from the values followed by the same letter at $p < 0.05$.

3.3. Profits and Nitrogen Use

Varying the N application rate had the same effect on the profit as it had on the forage yield and plant characteristics (Table 3). Initially, applying higher N rates achieved a proportionately higher economic and ecological profit, but the increases peaked at an N rate of 300 kg N ha^{-1}. Increasing the N rate from 300 to 400 kg N ha^{-1} did not improve the economic and ecological profit from forage production. Increasing the N application rate increased the N uptake of plants, but decreased N productivity and the productivity of N from fertilizer.

Table 3. Economic profit, ecological profit, N uptake, N productivity and fertilizer-N productivity in 2017 and 2018.

Year	N Rate kg N ha^{-1}	Economic Profit USD ha^{-1}	Ecological Profit USD ha^{-1}	N Uptake kg N ha^{-1}	N Productivity USD (kg N)$^{-1}$	Fertilizer-N Productivity USD (kg N)$^{-1}$
2017	0	1915.2d	1874.6d	144.2d	13.0a	-
	100	2312.6c	2234.5c	190.0c	11.8b	3.6a
	200	2556.9b	2421.5ab	227.9b	10.6c	2.7b
	300	2748.2a	2518.8a	255.7a	9.9d	2.1b
	400	2605.9b	2216.5bc	264.9a	9.5d	0.9c
2018	0	1848.2d	1807.6c	140.1d	12.9a	-
	100	2296.5c	2218.4b	189.3c	11.7b	4.1a
	200	2531.9b	2396.5a	230.9b	10.4c	2.9b
	300	2688.4a	2459.0a	255.4a	9.6cd	2.2c
	400	2561.8b	2172.4b	266.6a	9.3d	0.9d

Note: Values in a column followed by a letter are not significantly different from the values followed by the same letter at $p < 0.05$ ($n = 3$).

3.4. Calculation of the N Application Rate That Achieves Maximum Productivity

The observed data (Tables 1 and 3) were fitted to a regression equation, which was used to evaluate the effect of the N rate on the WMP forage yield, the profit, the ecological profit, and the $_{\Delta}$Soil $NO_3{}^{-}$-N (Table S1). The optimized N rate maximized the agronomic efficiency (the WMP forage yield), economic profit and ecological profit (Table 4). We compared the optimized N rate that maximized economic profit with that which maximized forage yield. We found that the former required 22% less N inputs than the latter, while it achieved a 2% lower yield. The estimated N loss, $_{\Delta}$Soil $NO_3{}^{-}$-N, ecological cost from N pollution, however, was 33%, 41% and 36% lower, respectively, and the economic profit and ecological profit had improved by 2% and 8%, respectively (Table 4). A similar comparison between the optimized N rate that maximized ecological profit and that which maximized economic profit, showed that the former required 20% less N inputs, and achieved a 3% lower yield, and a 1% lower economic profit (Table 4). The N loss, $_{\Delta}$Soil $NO_3{}^{-}$-N, ecological cost from N pollution was 25%, 50% and 27% lower, while the ecological profit had been improved by 2%. When comparing the optimized N rate that maximized ecological profit with that with soil N balance, we found that the former achieved a 4% lower economic profit and a 1% lower ecological profit, while it required a greatly decreased N input (by 25%) and N loss (by 26%), and carried an 28% lower ecological cost from N pollution (Table 4).

Table 4. The optimal N rate, forage yield, economic profit, estimated N loss, $_{\Delta}$Soil $NO_3{}^{-}$-N, ecological profit, ecological cost when the forage yield, economic profit or ecological profit is optimized or when soil N is in balance.

Parameter	Year	Optimized N Rate kg N ha^{-1}	Forage Yield *t* ha^{-1}	Economic Profit USD ha^{-1}	Estimated N Loss kg N ha^{-1}	$_{\Delta}$Soil $NO_3{}^{-}$-N kg N ha^{-1}	Ecological Cost USD ha^{-1}	Ecological Profit USD ha^{-1}
Forage yield	2017	400.1	21.0	2629.3	172.1	112.7	389.8	2244.3
	2018	383.9	20.7	2598.7	159.1	96.2	357.4	2240.3
Economic profit	2017	312.3	20.6	2691.6	112.9	67.1	244.8	2436.5
	2018	303.6	20.4	2655.2	108.3	57.1	233.8	2411.3

Table 4. *Cont.*

Parameter	Year	Optimized N Rate kg N ha^{-1}	Forage Yield *t* ha^{-1}	Economic Profit USD ha^{-1}	Estimated N Loss kg N ha^{-1}	ΔSoil NO_3^--N kg N ha^{-1}	Ecological Cost USD ha^{-1}	Ecological Profit USD ha^{-1}
Ecological profit	2017	247.9	20.0	2658.1	83.1	33.7	174.6	2478.4
	2018	245.0	19.8	2625.0	81.9	28.5	171.9	2448.4
Soil N balance *	2017	183.1	19.0	2556.5	60.5	0.0	123.8	2435.9
	2018	186.6	18.9	2535.0	61.6	0.0	126.2	2411.7

Note: * indicates the absence of N residual in the soil after the maize-growing season. The total costs of seeds, pesticides and herbicides, seeding, irrigation and harvesting amounted to USD 97.5, 76.1, 54.36, 19.74 and 347.90 ha^{-1}, respectively. Depending on the market survey in the study period, the price of N, P and K fertilizer was USD 0.651 (kg N)$^{-1}$, USD 1.70 (kg P_2O_5)$^{-1}$ and USD 1.56 (kg K_2O)$^{-1}$, respectively, and the average selling price of WMP forage (fresh matter with 60% water content) was USD 78.28 t^{-1}. The ecological cost of N leaching (the abatement cost of reducing N from agricultural drainage water), NH_3 emissions (the cost of human health damage) and N_2O (the cost of climate change) are taken to be USD 2.71, 1.3 and 1.24 (kg N)$^{-1}$, respectively.

4. Discussion

In our study, we found that applying more N fertilizer improved maize growth with respect to increasing the plant height, leaf area index, Spad value and N uptake. Increasing the N input improved their light interception and photosynthesis rates, strengthened senescence resistance of maize, and as a result, achieved a higher yield and improved feeding characteristics of WMP forage [7,8,29,30]. The improvements in agronomic benefits discussed above diminish when an excessive amount of N is applied, because applying N rates that exceed the optimal rate do not further improve maize growth, which agreed with our research [11,12,31].

Economic profit is considered as a more important indicator for evaluating agricultural production, as compared to agronomic benefits (yield) [12]. However, ecological profit, in which economic profit subtracts ecological cost from N pollution, should be considered together with agronomic benefits and economic profits in the quest to maintain high economic profits while simultaneously reducing environmental pollution. Unfortunately, many researchers before us who attempted to optimize agricultural production compromised agronomic benefits in favor of economic profits, while ignoring ecological profits or, at best, separating them from agronomic benefits and economic profits [10,15,32,33]. In our study, the ecological costs of N pollution and inputs of agricultural resources were taken into account for evaluating the efficiency of WMP forage production. Increasing N rates resulted in more N losses, and then increased the ecological costs from N pollution, decreasing ecological profits. N application improved ecological profit, and the maximum ecological profit was realized at 200 kg N ha^{-1}. However, increasing the N supply beyond the optimal rate, i.e., 400 kg N ha^{-1}, reduced economic and ecological profit, instead increasing estimated N losses and ecological cost, which decreased N productivity and the productivity of fertilizer N. This means that the practice of using high N rates is associated with a high ecological cost, and underachieving economic and ecological profits [12]. Therefore, optimizing application rate is necessary for evaluating the benefits of WMP forage production.

The regression equation, based on measurement data from the field experiment, was then used to estimate the optimal N rates for maximizing various sets of benefits from WMP forage. The N rate maximizing economic profit reduced N input, N loss and its ecological cost, and increased economic and ecological profits, as compared to the N rate maximizing forage yield. The N rate that maximized ecological profit reduced N input, N loss and its ecological cost, and increased ecological profits, but maintained economic profit, compared to the N rate that maximized economic profit. Therefore, the comprehensive benefit of the optimal N rate was ordered thus: the N rate maximizing agronomic profit > that maximizing economic profit > that maximizing ecological benefit. The N rate that maximized ecological profit was 21% lower and 37% lower than that which maximized economic profit and forage yield, respectively. Han et al. [12] and Li et al. [10] stated that reducing N input to an appropriate rate resulted in slightly lower agronomic benefits, but decreased economic or ecological cost, which maximized economic and ecological benefits. Ecological criteria are better to gauge the efficiency of WMP forage, compared to agronomic and economic criteria. Therefore, using the ecological criteria, the recommended N application rate in our study was 248 and 245 kg N ha^{-1}, respectively, in 2017 and 2018.

We also addressed ecological criteria by optimizing the soil ecological benefits of applying N. The soil in N balance exhibited zero N residual, which indicated that the N load from fertilizer was minimized [12]. Compared to the N rate that maximized ecological profit, that with zero N residual greatly reduced N input, N loss and ecological cost, but caused a 4% lower economic profit and 1% lower ecological profit. This means that if a 4% reduction in economic profits is acceptable to farmers, the recommended N application rate in the current study—183 and 187 kg N ha^{-1}, respectively, in 2017 and 2018—would further reduce the ecological cost from N pollution and increase the efficiency of the production process.

5. Conclusions

Using an appropriate N application rate during WMP forage production improves and maximizes its yield as well as its economic and ecological profits. Applying excessive N inputs of 400 kg N ha^{-1} or higher achieves the same yield, but is associated with higher estimated N losses through N_2O emissions, NH_3 volatilization and N leaching, which ultimately results in reduced N productivity, and lower economic and ecological profits. When comparing them with economic or agronomic criteria, we found that ecological criteria which maximize ecological profit were more efficient for optimization of the WMP forage production process. In the current study, the recommended N application rates for efficient and clean production in 2017 and 2018 were 248 and 245 kg N ha^{-1}, respectively. The recommend rates maximized the ecological profit and maintained the highest economic profit, while reducing the required N inputs and the associated N pollution and its ecological costs. If a 4% reduction in economic profits was acceptable to farmers, the recommended N application rate in the current study would have been 183 and 187 kg N ha^{-1}, respectively, for 2017 and 2018, further reducing the ecological cost and increasing the efficiency of the production process.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12030718/s1. Table S1: The regression equations of forage yield, economic profit, ecological profit, $_{\Delta}$Soil (NO_3^--N) based on the two-year measured data.

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