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Assessing nitrogen flow in production and utilization cycle of wheat and maize as a tool to monitor N loss in Iran

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ABSTRACT. Increasing resource use efficiency is crucial for enhancement of agricultural productions and reducing environmental hazards. For this purpose, improvement of Nitrogen use efficiency is an effective approach. Not only N loss occurs in field but also in processing course of food utilization. The objective of this study was to evaluate N loss and efficiency from production to consumption for wheat and maize. For this purpose, data for the amount of applied nitrogen, acreage, yields, amount of returned residue were collected and a proportion of N allocated to different source of food or feed was also traced. Results showed that total N harvested by wheat and maize were 387 and 81.7 kt and N use efficiency for the same crops were 25 and 60%, respectively. Efficiency of N harvested by the crops was different based on the path used. Total N use efficiency in food production cycle for wheat and maize were 14.2 and 7.6%, respectively. Higher efficiency of N was observed in plant food production compared with animal feed. In general, N use efficiency in plant food production system was about 13 times higher than that of feed. For decreasing N loss in food production system, efficiency should be increased in the field and processing courses.

Keywords: N use efficiency, N loss, nutrient management, fertilizer.

Avaliação do fluxo de nitrogênio na produção e utilização do ciclo do trigo e do milho como uma ferramenta para monitorar as perdas de N em agro-ecossistema iraniano

RESUMO. Aumentar a eficiência na utilização dos recursos é crucial para a valorização das produções agrícolas e reduzir os riscos ambientais. Para este efeito, a melhoria da eficiência de utilização de azoto é um método eficaz. Não apenas perdas de N acontecem em campo, mas também no processamento decurso de utilização dos alimentos. O objetivo deste estudo foi avaliar as perdas de N e eficiência da produção ao consumo de trigo e milho. Para esses dados de propósito para a quantidade de nitrogênio aplicado, a área, o rendimento, a quantidade de resíduos devolvidos foram coletadas e uma proporção de N alocado para outra fonte de alimento ou ração também foi rastreado. Os resultados mostraram que o total de N colhido por trigo e milho foram 387 e 81.7 kte. A eficiência de utilização para as mesmas culturas foram de 25 e 60%, respectivamente. Eficiência de N colhidas pelas culturas foi diferente com base no caminho que foi utilizado. A eficiência total de N utilização no ciclo de produção de alimentos para o trigo e de milho foram 14,2 e 7,6%, respectivamente. Maior eficiência de N foi observada na produção de alimentos planta em comparação com rações para animais. Em geral, N eficiência de utilização em planta do sistema de produção de alimentos foi de cerca de 13 vezes maior do que a de alimentos para animais. Para diminuir as perdas de nitrogênio no sistema de produção de alimentos, a eficiência deve ser aumentada nos cursos de campo e de processamento.

Palavras-chave: eficiência do uso de N, perdas de N, manejo nutricional, fertilizantes.

Introduction

Nitrogen is an important element in food production system and plays the major role in food security (SMIL, 2002). Worldwide, contribution of N in food production system has been reported by authors (SINCLAIR; HORIE, 1989; MASSIGNAM et al., 2009). One of the elements of success in green revolution was the introduction of dwarf varieties of wheat with high N demand. In recent decades, application of chemical fertilizers mainly N has increased significantly in Iran. The average value of fertilizer application in this country was 100×10^3 tons in 1960's, 600×10^3 tons in 1970's and this reached to 2.4 million tons in 2007 (FAO, 2007). Also, plant breeding and improvement of new varieties have grown significantly in the country accompanied by an excessive use of inorganic N fertilizer and irrigation, and were the main driving force in yield enhancement. The same trend has been reported for the world (SINCLAIR; HORIE, 1989; MASSIGNAM et al., 2009).

Increasing rate of population, higher demand for food and also higher per capita food consumption due to improvement of lifestyle put pressure on agriculture for food production in the world (POPKIN, 2001; HOWARTH et al., 2002; OENEMA; PIETRZAK, 2002; GALLOWAY et al., 2003). This trend is more apparent in newly developing countries with high economic growth such as India and China. In China, tendency towards consumption of meat has increased and hence more cereal use as animal feed (MA et al., 2009). The same trend is observed in some of countries in the Middle East including Iran. Therefore, demands for cereal production either direct consumption or to be used for animal products have increased in the last decades.

N fertilizer has contributed a great deal to cereal production in the world (MA et al., 2009). Excessive use of N in crop production caused a declining trend in N use efficiency. It has been reported that not more than 33% of N applied is used by the plant and the remaining is lost, causing environmental pollution as well as emission of greenhouse gases (RAUN; JOHNSON, 1999).

Cassman et al. (2002) and Jayasundara et al. (2007) reported that fertilizer N recovery in cereal crops is relatively low (50%) in food production systems. Food production and utilization pathway cause a large amount of N loss. On the other hand, human activities have greatly accelerated the cycle and loss of this nutrient (ANTIKAINEN et al., 2005). The peak of use of chemical fertilizers was obtained in the late 1990's and early 2000's in Iran (MAJ, 2009). Therefore, intensive use of fertilizer has caused a N loss from agricultural field and subsequently has polluted the surface and groundwater resources. N is easily transformed into various reduced and oxidized forms and is readily distributed by water and atmospheric transport processes (CREWS; PEOPLES, 2005). Nitrogen is lost from agricultural farms through soil erosion, runoff, leaching and emissions to the atmosphere. The loss of N through these pathways can potentially cause environmental hazards, such as pollution of both surface and groundwater resources, eutrophication and endangerment of human health (ISERMANN; ISERMANN, 1998; CREWS; PEOPLES, 2004, 2005; VERLOOP et al., 2006).

N flow is an efficient tool for monitoring agro-ecosystem practices and management (BROUWER, 1998). Flows of N across production and utilization chains is an effective tool for better understanding N use efficiency and losses in the long processing system of food production. Monitoring N flow is regarded as a key indicator in food production system from production to processing and utilization.

Several studies show that nitrogen loss is not limited to the agricultural field and there are considerable loss in processing and consumption of crops. For example, Ma et al. (2009) evaluated that N fertilizer use efficiency in crop–animal system for wheat, rice, and maize were 13.4%, 11.3%, and 3.7%, respectively. This means 7.5, 8.9 and 27.1 kg of N fertilizer is required to produce 1 kg N in food via fertilization for these three grains. Also Antikainen et al. (2005) quantified the flows of nitrogen in the Finnish food production and consumption system and reported that approximately 10.3% of total N input to the agricultural field was entered to feeding system of people. They expressed that the per capita nitrogen consumption is 5.5 kg in Finland. This value is 6.6 for the USA while in developing countries such as Bangladesh it is very low (2.6 kg) (FAO, 2007).

Total field crop production was estimated about 74 million tons produced on 13,500,000 ha in Iran. About 73% of total field crop production consists of cereal (wheat, barley, maize and rice) production (MAJ, 2009). Wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) are two important grain crops grown in Iran. Wheat is mostly processed for direct human consumption in Iran. In contrast, maize is mainly consumed by animals as fodder.

This study aimed (1) to monitor the nitrogen flows in wheat and maize production and utilization cycle, (2) to quantify N use efficiency and loss of these crops during production and utilization cycle related to both plant and animal food production, and (3) to propose suitable strategies for reducing N loss and improving N use efficiency in the whole system.

Material and methods

Study area

This study was carried out in Iran. Data were collected from all provinces of the country. In general, Iran has an arid climate where most of the relatively scant annual rainfall falls from October to April. In most of the country, annual rainfall averages are 25 cm or less. Only 12% total land area is under cultivation but less than one-third of the cultivated area is irrigated.

Definition of N flow model

In Figure 1, the model of N use in the chain of food and feed production is shown. Wheat is the main cereal crop consumed directly by human and the consumption of wheat in animal feed is negligible. In this model, chemical N fertilizer is the main input in production system. On the other hand, in Iran maize is used mainly as animal feed. However, the residues of crop returned to the soil have been considered another source of N to the system. Due to the lack of available

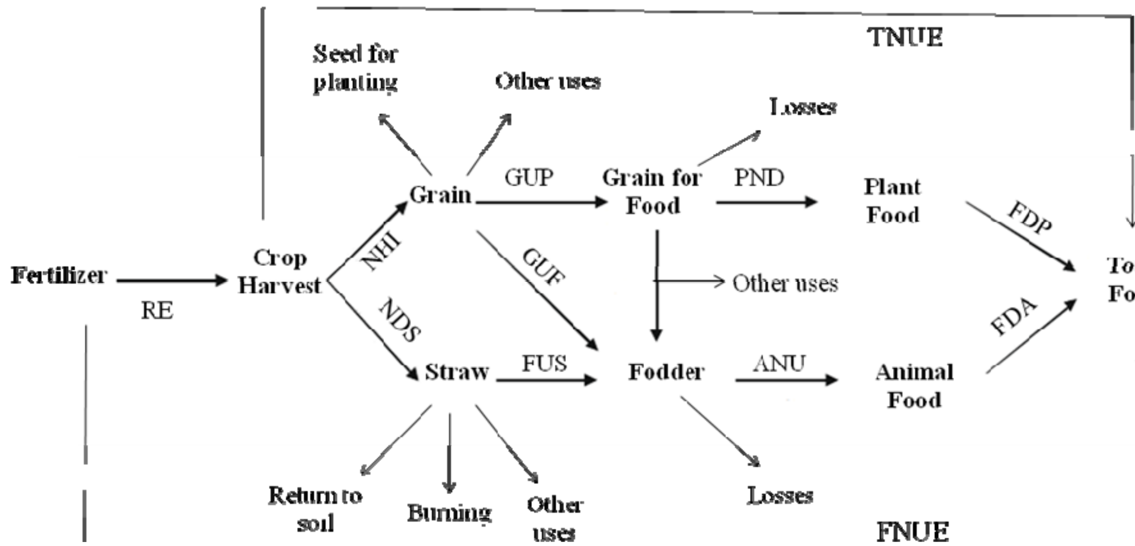

Figure 1. A model of nitrogen flow in food production and utilization system for wheat and maize

data on N fixation by legumes used occasionally in crop production system, this source of N input has not been considered in the model. Generally, N harvested includes two chains of plant food (direct consumption) and animal feed (indirect consumption).

N uptake by the plant for production of grain (wheat) for direct consumption is stored in the grain, part of which is used as seed and a small amount is lost during the process or used for other purpose. Therefore, the main portion of N in the grain enters the processing and consumption cycles. Part of processing N left in the byproduct in the processing stage is used as animal feed. N uptake by the crop which is used as animal feed (maize) is stored in grain and straw, both are used as animal feed.

Several indicators of N use efficiency employed in this study have their definition and abbreviation presented in Table 1. N use efficiency at each stage of production process was estimated based on the amount of N input and output, which indicate the amount of N loss for each stage. Two main indices were used to calculate the N recovery efficiency, TNUE and FNUE. FNUE and TNUE are the N recovery efficiency that N fertilizer and N of crop harvest are N input for calculating of FNUE and TNUE respectively. The N of total food is N output for both the indices. In other words, FNUE and TNUE are the amount of N recovered by total food from fertilizer and crop harvest respectively. Also, indices RE and ANU were used to calculate N use efficiency in plant and animal production system. RE is used to evaluate N use efficiency of fertilizer, which depends on management practices such as fertilizer type, application time, irrigation management, application method, etc. ANU is the N conversion coefficient in animal production system whose value is obtained from Saedi et al. (2002).

Table 1. Abbreviation and definition of used indicators in the context.

Definition of indicators	Abbreviation
N recovery from fodder per animal	ANU
N from animal food to total food	FDA
N from plant food to total food	FDP
Recovery efficiency of fertilizer N in food	FNUE
N in straw used as fodder	FUS
N in grain used as fodder	GUF
N in grain used for food processing	GUP
Distribution ratio of harvested N to straw	NDS
Harvest index to N	NHI
N in processed grain used as food	PND
N use agronomic efficiency	RE
Recovery efficiency of total harvested N in food	TNUE
N used as fodder in by-products from processed grains	UTB

Data source

Data for calculating of N efficiency use and loss at different stages of food production were collected from published evidences and government organization and also by direct interview with farmers (Table 2).

Table 2. Needed data for calculating nitrogen efficiency and loss in production and utilization of wheat and maize.

Reference	Amount	Parameter	Crop
MAJ (2009)	234 kg ha^{-1}	Application of N fertilizer	Wheat
MAJ (2009)	13484465 ton	Production	
MAJ (2009)	6647371 ha	Cultivation area	
Naderi et al. (2000)	46%	HI	
Naderi et al. (2000)	2.07%	Grain N	
Naderi et al. (2000)	0.68%	Straw N	
Satorre and Slafer (2004)	14%	Seed husk	
Saedi et al. (2002)	12.6%	N recovery from fodder per animal	
MAJ (2009)	345 kg ha^{-1}	Application of N fertilizer	Maize
MAJ (2009)	8942656 ton	Production	
MAJ (2009)	395639 ha	Cultivation area	
Tahmasbi et al. (2001)	50%	HI	
Kazempour and Tajbakhsh (2002)	1.2%	Grain N	
Majidian et al. (2008)	0.85%	Straw N	
Saedi et al. (2002)	12.6%	N recovery efficiency in animal production	

Calculation methods

Total N fertilizer applied was calculated by the following equation:

$$Cf = Ac \times Nr \quad (1)$$

where:

Cf is Total fertilizer nitrogen applied to each crop, Ac is planted area and Nr is the application rate per hectare, shown in Table 1. N harvested in grain (Gr) was the product of total grain production (Yc) and N content in grain (Ncg) and also in straw (Sw) was the product of Yc, ratio of straw to grain (Rc) and N content in straw (Ncs). Total N harvested by crop (Ch) was calculated by summing Gr and Sw. Equations 2, 3 and 4 were used to calculate these values.

$$Gr = Yc \times Ncg \quad (2)$$
$$Sw = Yc \times Rc \times Ncs \quad (3)$$
$$Ch = Gr + Sw \quad (4)$$

N efficiency and the amount of N loss were calculated based on N input and output. N use efficiency at each stage was calculated twice. The first is based on initial fertilizer applied and the second is based on previous stage of the process (Equation 5 and 6).

$$NUE_a = \frac{N_i}{N_a} \quad (5)$$

$$NUE_i = \frac{N_i}{N_{i-1}} \quad (6)$$

In this case, NUE_a and NUE_i are the N use efficiency at each stage based on first stage (initial fertilizer applied) and previous stage, respectively. N_i, N_a and N_{i-1} are the N content at each stage, in initial fertilizer applied and at previous stage.

Sensitivity analysis

In order to determine the sensitivity of FNUE and TNUE to various partial indicators of N use efficiency such as RE, NHI, GUP, PND, NDS, FUS and ANU, a sensitivity analysis was performed. For this purpose, to each partial indicator 5% was increased and then new values of FNUE and TNUE were recalculated. Finally, new values were compared to previous values in order to check which partial indicator had more effect on the FNUE and TNUE.

Results

Wheat

N flow in production, processing and utilization cycles of wheat is shown in Figure 2. Total N fertilizer applied in wheat was about 1555 Kt which is mostly used in the form of urea (46% N) and the total harvested N by wheat was 387kt based on this value, N fertilizer use efficiency for wheat production was 25% (RE) and therefore the amount of N loss was 1168 kt in this stage. Based on wheat harvest index of 46% (Table 2), total N in grain and straw were 279 and 108 kt, respectively. In other words, yield of N in straw was 2.5 times lower than N yield in grain. Fertilizer use efficiency for grain on the bases of initial fertilizer applied and for the straw was 18% and 7%, respectively but the corresponding values based on the previous stage (crop harvest) were 72 and 28%, respectively (Figure 3).

From the total N in grain, 89% (248 kt) enters flour making processes (GUP) and only 2.1% (5.9 kt) is used for animal feed (GUF), 7% for seed and 1.9% for other purposes such as industrial products (Figure 2 and 3). Therefore, fertilizer efficiency for wheat in the processing stage was 16% and hence for the total amount of N used as animal feed, seed and industrial purposes was 2% of the total fertilizer applied (Figure 3).

Wheat straw contained 108 kt N of which only 9% (9.7 Kt) was returned to the field, which is about 0.6% of the total applied fertilizer. Most of N in wheat straw was used as animal fodder (FUS) hence, 79% N in straw is consumed by animal. Based on our calculation, 3.2 kt N was lost by burning straw and 9.7 kt N (9%) was used for other applications such as compost production and animal bed.

Since the husk is 14% of the total grain, about 34.8 kt N in flour processing stage enters seed husk of which 89% (31 kt) is consumed as animal feed (UTB) and 11% (3.8 kt) was used for other purposes. There were N losses in bread making, therefore N loss from flour to bread making (PND) is 3.3% (8.2 kt) and about 82.7% N (205 t) enters to bread. Therefore, it can be concluded that N fertilizer efficiency of wheat for direct consumption by human was 13% (Figure 3). In this process the total amount of N used by animal in straw was 85 kt, in seed husk 31 kt and in whole grain 5.9 kt. Therefore, only 7.8% N in fertilizer enters the fodder (Figure 3). Based on N conversion coefficient in animal production systems (ANU = 12.6%), the amount of N in animal production was 15.6 kt and therefore N fertilizer efficiency for animal production was only 1% (Figures 2 and 3).

N harvested in food production (plant + animal products) was 221 kt and N fertilizer efficiency for food production (FNUE) was 14.2% of which 92.8% (205 Kt) was contributed by plant food production (FDP) and 7.2% (15.6 Kt) was related to animal food (FDA). N efficiency for food production based on N harvested by the crop (TNUE) was 57% (Figure 3).

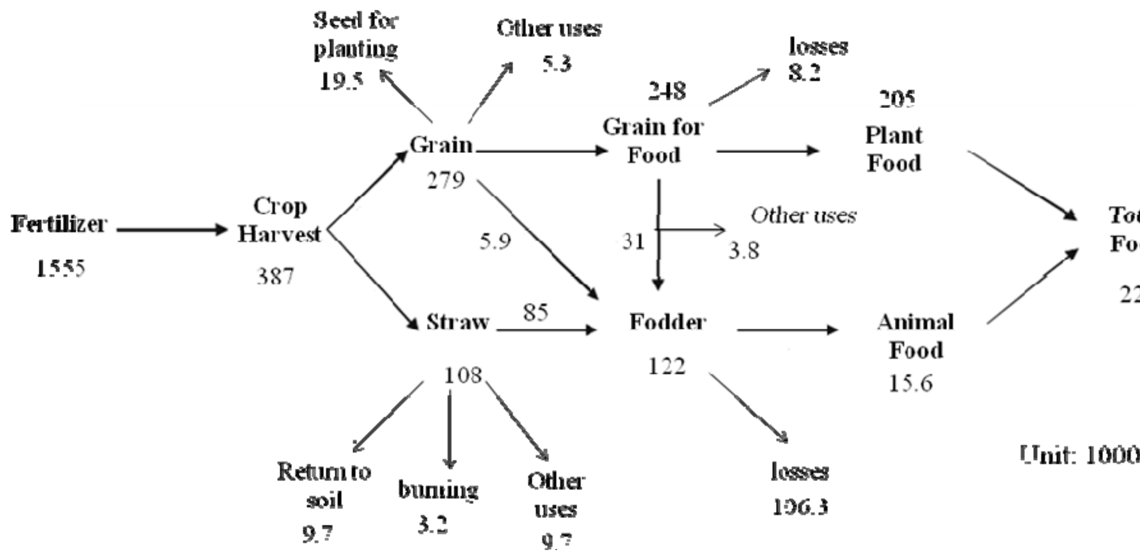

Figure 2. N flow in food production system from wheat in Iran (unit: 1000 ton).

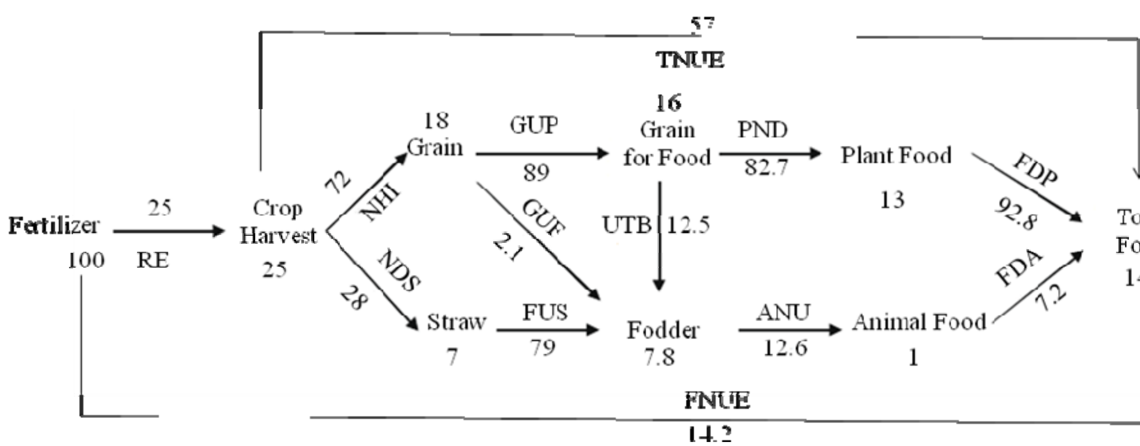

Figure 3. N use efficiency in wheat production and utilization cycle in Iran (unit: %).

Maize

Figure 4 shows that the amount of N fertilizer applied to maize was 136 kt. N agronomic efficiency by maize (RE) was 60%, and about 81.7 kt N was accumulated in maize biomass (Figure 4). As stated before, maize is used mainly as animal feed in Iran in the form of silage and maize silage contains 76% of total harvested N (NDS) which is 62 kt of N. About 4% N in maize silage (2.48 kt) is returned to the field as crop residues and 91% of this (56.42 kt) is consumed by animal (FUS) and therefore 5% is lost. A great proportion of N in maize seed (92.15%) is consumed as animal feed (GUF) and only 4% (800 t) is consumed as human food (PND).

Total N provided as animal feed was 74.57 kt. Based on N conversion coefficient in animal production systems (ANU), 9.54 kt N was available for animal production. This means that animals consumed 12.6% N in fodder and 87.2% N is lost at this stage. N harvested in food production by corn was 10.34 kt, of which animal product (FDA) contribution was 93% and plant product was 7% (Figures 4 and 5).

N fertilizer efficiency for maize seed was 14.5% and for maize silage was 46% (Figure 5) and this value for plant and animal food production were 0.6% and 7%, respectively (Figure 5). N fertilizer efficiency for the total plant and animal food products (FNUE) was provided by 7.6% and N fertilizer efficiency on the base of crop harvest for plant plus animal products was 12.6% (TNUE). In other words, human consume 7.6% and 12.6% N in fertilizer and maize biomass, respectively.

Sensitivity analysis

The range of increase for FNUE and TNUE were 0 - 36.6% which was due to 5% increase in partial indicators for both crops (Table 3). RE has contributed

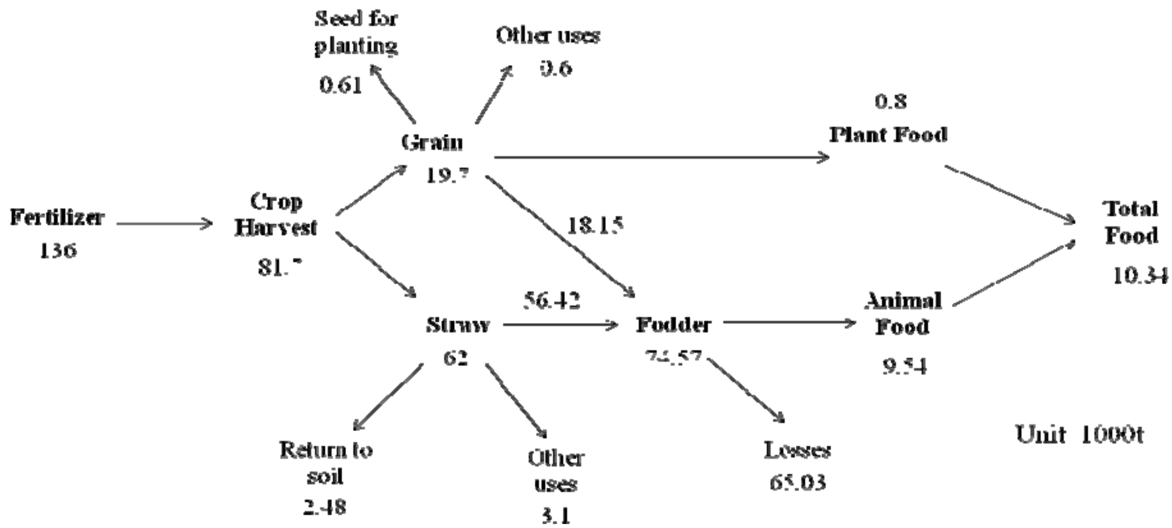

Figure 4. N flow in food production system from maize in Iran (unit: 1000 ton).

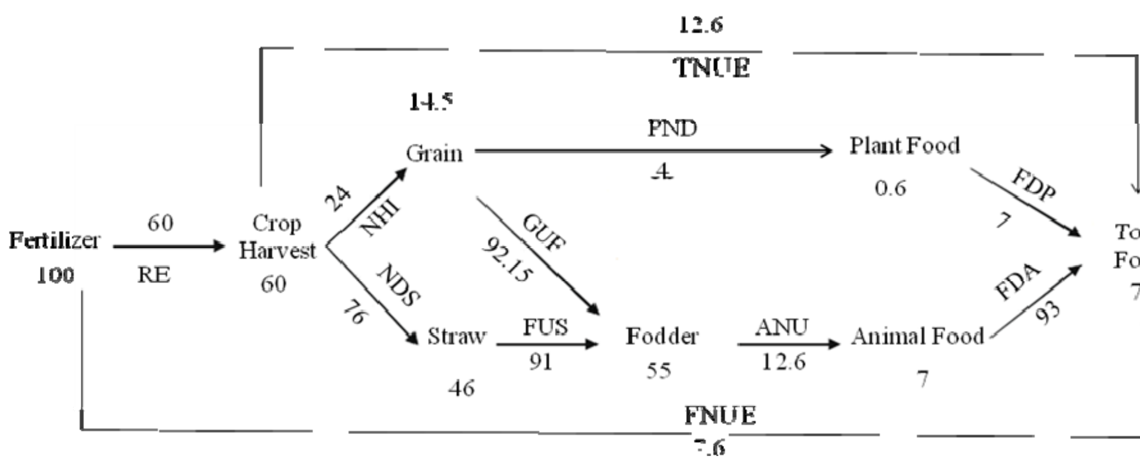

Figure 5. N use efficiency in maize production and utilization cycle in Iran (unit: %).

with most effect in FNUE for wheat so that an increase of 5% in RE increased FNUE by 20.5%. This indicates that, in order to enhance efficiency of N fertilizer (FNUE) in wheat, RE should be improved by management practices in the field. The trend of the effect of other partial indicators on FNUE and TNUE was NHI ≥ PND ≥ GUP > ANU > FUS > NDS.

For maize, FNUE and TNUE were most affected by ANU than other partial indicators. Therefore, an increase of 5% in ANU led to 35.8 and 36.6% increase in FNUE and TNUE, respectively. The effect of RE on FNUE for maize was lower compared with wheat. The relative increase of coefficients declined in the order of ANU > PND > FUS > NHI > NDS. An increase of 5% in NDS caused a negative effect on both crops and indices. This means that more N moved towards animal food production chain, which is associated with low efficiency of animal food production.

Table 3. Sensitivity of FNUE and TNUE to the increase of partial indicators in wheat and maize

	Wheat		Maize	
	Relative increase of FNUE (%)	Relative increase of TNUE (%)	Relative increase of FNUE (%)	Relative increase of TNUE (%)
RE+5%	20.51	-	8.13	-
NHI+5%	6.16	5.80	1.45	1.98
GUP+5%	5.61	5.24	-	-
PND+5%	6.07	5.69	8.07	8.64
NDS+5%	-6.39	-6.65	-1.93	-1.41
FUS+5%	0.75	0.39	3.65	4.20
ANU+5%	1.15	0.79	35.85	36.56

Discussion

The aims of sustainable agriculture with respect to population growth are: increasing food production, considering environmental and economy issues. Increasing input efficiency, resource replacement and design of agro-ecosystem are three steps for achieving sustainable agriculture (GLIESSMAN, 2001). Therefore, input efficiency seems to be the most important step towards sustainable food production (COG, 2005).

In the present investigation, low efficiency of N fertilizer use in wheat (25%) compared with worldwide (33%) is an indicator of high loss of N in the field level. There are effective ways to improve FNUE in various levels of food production. In our study, it was shown that by increasing RE it can be enhanced FNUE according to sensitivity analysis for wheat production system. There is a strong relationship between management practices in agro-ecosystems and improving of RE, so field management practices are determinant to the efficiency at field level. Some management options have proven useful including optimizing the rate and timing of nitrogen application and deep placement of fertilizer nitrogen into soil (MOSIER et al., 2004; XIONG et al., 2008), intercropping systems, management of fertilizer application with respect to the irrigation, use of legumes and cover crops and conservation tillage practices (JAYASUNDARA et al., 2007).

The loss of N is not limited to the agricultural field level and there are significant losses in other levels of food production system, and increasing losses are associated to reduction efficiency at each level (MA et al., 2009). Based on our findings FNUE and TNUE were 25% and 57% for wheat and 12.6% and 7.6% for maize, indicating that the loss rate in the field level is approximately 2 times higher than in next levels (especially for wheat). In attention to the higher loss of N in the field level, it seems that reducing losses in the field affect more N use efficiency. Results showed that maize harvested N more effectively than wheat and this could be associated with different photosynthetic pathways of this crop (maize is C4 and wheat is C3).

There are evidences in the literature (SAGE; PEARCY, 1987) that indicate better NUE of C4 plants compared with C3. It must be noticed that part of this high efficiency of maize in our study could be due to the lack of adequate data on inputs such as animal and green manure to this crop.

The value of ANU depends on animal breed and type, animal feed composition and nutrient management strategies (ZHANG et al., 2005). The ratio of used N fertilizer to N content in meat was 20 for wheat in Norway (BLEKEN; BAKKEN, 1997).

The negligible amount of returned residues of wheat (0.6 %) and maize (1.8 %) to soil is an important contributing factor to low organic matter in the soil and hence higher dependence of system to chemical fertilizer application in next years. This subject can be affected by carbon sequestration in agro-ecosystems, since, cereal production in Iran is based on intensive monoculture and rotation practices have been replaced by application of chemical fertilizers. It appears that including a proper rotation of cereal with N fixing legumes is necessary to reduce the high rate of chemical fertilizer use.

Conclusion

Our results evidenced that 100 and 7.7 kg N fertilizer were required to produce 1 kg N in animal and plant food product, respectively. We can conclude that fertilizer use efficiency in plant food production system is about 13 times of animal food production. More is needed to fodder production, which is associated to the lower N use efficiency. With the calculation of sensitivity analysis in maize, the improvement of ANU is the best way to increase FNUE and TNUE.

In other words, for producing 1 kg N in meat, 20 kg N fertilizer is required and this value is 3 for plant products.

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