ADÜ ZİRAAT DERG, 2018;15(1):127-133 — doi:10.25308/aduziraat.393466 **Derleme / Review**

Nitrogen Nutrition of Crop Plants: Soil Nitrogen Vis-À-Vis Fertilizer Nitrogen

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Abstract: In unmanaged ecosystems, soil nitrogen (N) released through mineralization of organic matter constitutes the source of N for the plants. In agro-ecosystems, N is applied additionally as mineral or organic fertilizers in order to compensate N which is removed with products. Adequate and timely application of fertilizer N as dictated that by contribution of soil N to crop production is important for minimizing production costs from overuse of N fertilizer and for reducing possible environmental impacts. Using ^{15}N-labelled fertilizers, it has now been convincingly proved that majority of the plant N comes from the soil N. Thus, soil N plays a vital role in supplying N to crop plants and dictates the efficiency of applied fertilizer N. Size of available N pool, though relatively small as compared to total soil N, throughout the crop growth season determines whether crop gets adequate N nutrition or N is lost from the soil-plant system. As fertilizer N contributes directly to available N pool and by N substitution to the soil organic matter pool, N management at that point following the principles of synchrony between crop N need and application of N through soil and fertilizer N can lead to high fertilizer NUE (nitrogen use efficiency). Evaluation of site-based N management in cereals using gadgets like chlorophyll meter, leaf colour chart or optical sensors or OTG (on the go) crop sensing spreaders revealed that same yields can be achieved with less N fertilizer applied but with enhanced fertilizer NUE and diminished losses of N to the environment.

Keywords: soil nitrogen, N use efficiency, fertilizer, environment.

Bitkilerinin Azot Beslenmesi: Toprak Azotu Karşısında Gübre Azotu

Öz: *Yönetilmeyen ekosistemlerde, organik maddenin mineralizasyonu yoluyla salınan toprak azotu (N) bitkiler için N kaynağı oluşturmaktadır. Tarım ekosistemlerinde, topraktan kaldırılan N' u telafi etmek için mineral gübreler veya organik gübreler uygulanmaktadır. N gübresinin uygun bir şekilde ve zamanında uygulanması, üretim maliyetlerini azaltmak, N gübresinin fazla kullanılması ve olası çevresel etkilerin azaltılması için önemlidir. 15N etiketli gübreler kullanılarak yapılmış çalışmalarla, bitki N içeriğinin büyük bir kısmının toprak azotundan geldiği ikna edici bir şekilde kanıtlanmıştır. Böylece, toprak N'u, bitkilerinin N ihtiyacının karşılanmasında hayati bir rol oynamakta ve uygulanan N'lu gübre, verimliliği belirlemektedir. Toprağın toplam N içeriğine kıyasla nispeten çok az olan alınabilir N havuzunun büyüklüğü, bitkinin yeterli N beslenmesini yada toprak- bitki sisteminden N kaybını belirler. Azotlu gübreleme ile doğrudan mevcut alınabilir N havuzuna katkıda bulunulması ve toprak organik madde havuzuna N ikame edilmesi, bitkinin N ihtiyacı ile toprak ve gübrenin N arzı arasındaki senkronizasyon ilkelerini izleyen alana özgü spesifik N yönetimi, yüksek azotlu gübre kullanım etkinliğine neden olabilir. Serin iklim tahıllarında alana özgü spesifik N yönetiminde, klorofil metre, yaprak renk şeması, optik sensörler veya hareketli bitki algılama sensörleri gibi aygıtların kullanılması sonucunda daha az azotlu gübre ile aynı verim değerleri elde edilmiş ancak N kullanım etkinliği artmış ve çevreye karışan N kayıplarının azaldığı tespit edilmiştir.*

Anahtar Kelimeler: *toprak azotu, N kullanım etkinliği, gübre, çevre*

INTRODUCTION

Introduction of industrial sources of nitrogen (N) in the form of mineral fertilizers to farms around the world during the middle of the 20th century was one of the most remarkable transformations in agriculture. Almost half of the alive people live in the world due to N fertilization, which improve crop production. (Erisman et al., 2008). However, only a part of the fertilizer N is used by plants in farm practices (Balasubramanian et al. 2004) and rest of N comes from soil N.

Accumulation of N in organic forms in the soil is a typical property in both not controlled and controlled agrosystems. Nitrogen, released mineralization or immobilization process is taken up by plant roots but natural ecosystems often exhibit a high degree of temporal and spatial synchrony and synlocation between N released and N uptake by mixed plant communities. In contrast, agricultural ecosystem are relatively open with respect to N cycling as these produce biomass suitable for consumption outside the system, and N is applied externally as fertilizers and manures to compensate for N removed in exported products. In modern agrosystems, owing to consuming of 300 kg N ha^{-1} by plants, each year mineral and organic fertilizers or biological N fixation is necessary to sustain productivity (Cassman et al., 2002). When adequate amounts of fertilizer N are not applied to the soil, it is mined of N. Intensive cropping in agro-ecosystems shows great N uptake in active but often relatively short growth phase.

The large pool of N in agricultural soils exists in organic combinations. As an integral constituent of soil organic matter, soil N also serves as an index of soil health. Soil N may provide 20 to 80% of the plants N requirement (Broadbent, 1984). To achieve optimum yields, remaining N has to be supplied through fertilizer, but many research have shown that annual fertilizer N inputs exceed N exports in crop harvest by 40% to >100%, and leads to N release to the environment (Galloway and Cowling 2002). Adequate and timely application of fertilizer N as dictated by contribution of soil N to crop production is important for minimizing overuse of N fertilizer and for reducing possible environmental impacts. This paper attempts to provide an understanding of relative contribution of soil and fertilizer in meeting N requirement of cereal crops and how application of fertilizer N can be synchronized with soil N to obtain high fertilizer NUE.

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Nitrogen uptake by crops from soil and ^{15}N-labelled N fertilizers

Tracer studies contain adding a small amount of ^{15}N-enriched (sometimes ^{15}N-depleted) substrates to label a fertilizer source, and tracing the N from the source pool into sinks such as plant biomass and soil. Despite some limitations (Stark, 2000), the use of a ^{15}N tracer permits the detection and quantification of applied N in various sinks, including the crop, soil N pools in agro-ecosystems (Hauck and Bremner, 1976). Indeed, the amount of N in the soil is determining via stable isotope methods even the large backround of soil N (Powlson et al., 1992).

Global assessment of fertilizer NUE in cereal based agricultural systems, Ladha et al. (2005) reported that during the first growing season of maize, rice and wheat, average 15^{N} fertilizer recovery ratios were found 40, 44 and 45%, respectively. Average ratio was found 44% among regions and crops. The International Atomic Energy Agency (IAEA, 2003) reported that the average rate of one time applications of ^{15}N fertilizer recovered in aboveground part of the crop plants in the following 5 cultivation seasons (the crops, applied ^{15}N fertilizer, was excluded) across all locations was 5.7 to 7.1%. After all, the total recovery of ^{15}N fertilizer in the first and the five following crops is approximately 50%, (Ladha et al., 2005). Assuming that amount of ^{15}N (part of N in the roots neglected) in the sixth crop period, most of remaining 50% of the ^{15}N fertilizer would have become part of the large soil N pool and other portions may get lost from the production (Jansson and Persson, 1982).

Table 1. Results of ^{15}N-labeled fertilizers applied to crop fields in some regions of the world

Crop	Region	N applied (kg ha^{-1})	% N in crop	% N in soil	References
Rainfed upland rice	Indonesia	60	19		Sisworo et al. (1990)
Rainfed maize	Nigeria	-	27	15	Vanlauwe et al. (2001)
Rainfed maize	Indonesia	60	33	33	Rowe et al. (2004)
Rainfed wheat	Canada	50	29-40	28-30	Janzen et al. (1990)
Rainfed wheat	Australia	50	46-50	31-34	Ladd and Amato (1986)
Rainfed barley	Sweden	80	36		Bergström and Kirchmann (2004)
Irrigated lowland rice	Philippines	90	42	19	Diekmann et al. (1993)
Irrigated lowland rice	Philippines	60	27	38	Becker et al. (1994)
Irrigated cotton	Australia	100	17		Rochester et al. (2001)
Irrigated lowland rice	India	116	27		Katyal et al. (1985)
Irrigated wheat	India	120	41	19	Bijay-Singh et al. (2001)
Irrigated maize	Japan	150	51		Kanno (2008)
Irrigated wheat	India	120	44		Katyal et al. (1987)

In Table 1 shows some examples of the fate of 15^{N}-labeled fertilizers applied to field studies. These experiments clearly refute the premise for application of fertilizer N to crops that fertilizer N rather than the soil N supply is the major source for crop uptake. In a field study with a wheat-wheat cropping sequence, Ichir and Ismaili (2003) applied 85 kg ^{15}N ha^{-1} in a three-split application and recorded 33.1% fertilizer N recovery by wheat in the first year. At harvest, fertilizer N was found 64.8% rate in the 0-80 cm soil profile; 2.1% of N could not be accounted for. The recovery of the residual labelled fertilizer N by the subsequent wheat crop was 6.4%.

Apparent recovery efficiency of applied N (RE$_{N}$) values obtained with ^{15}N are often slightly lower than those predicted by the difference method because of confusing effects caused by pool exchange, immobilization of ^{15}N fertilizer and initial release of microbial-derived 14N (Cassman et al., 2002).

Dourado-Neto et al. (2010) reported that crop N uptake minimum 7% and maximum 58%, average of 21% (mean 147±6 kg N ha^{-1}) was provided from fertilizer during the first growing season. On average, 79% of crop N was derived from the soil (Table 2). At the end of first growth season ^{15}N-labeled fertilizer and residue recoveries in crops were 33 and 7%, respectively. Final recoveries ratio in the soil were 38 and 71%. At the end of five growth seasons, more residue N (40%) than fertilizer N (18%) were recovered in the soil, better preserved the soil organic matter N content. Gardner and Drinkwater (2009) examined the fate of ^{15}N additions to temperate grain agro-ecosystems using a meta-analysis of 217 field-scale studies and inferred that despite application of high levels of fertilizers, majority of plant N (60%) for maize, spring small grains, and winter small grains) came from soil N. The meta-analysis conducted by Gardner and Drinkwater (2009) further revealed that practices that aimed to higher efficiency by commercial fertilizer (inorganic N form, nitrification inhibitor, reduced N rate, management history, proximity to roots and timing- fall versus spring) had a lower action on total ^{15}N recovery (3–21% increase) than practices (crop rotation and organic N sources) that re-coupled C and N cycling (30–42% increase). It also suggests that plant cover, short time periods, reduces the N sinks and the ability for N to cycle internally thereby creating the need for much practices of fertilizer N in intensively cultivated farms (Drinkwater and Snapp 2007).

Table 2. Total N accumulation and fertilizer N contribution and soil N content as estimated by applying ^{15}N labelled fertilizer for different crops under various soil and climatic conditions

Country	Soil Class	Crop	N applied ($kg\ N\ ha^{-1}$)	Total crop N ($kg\ N\ ha^{-1}$)	Derived from fertilizer N (%)	Derived from soil-N (%)
Bangladesh	Haplaquepts	Wheat	60	60 ± 3	43 ± 1	57 ± 1
Brazil	Ultisol	Sugarcane	63	251 ± 7	16 ± 1	84 ± 1
Chile	Andisol	Maize	300	178 ± 7	31 ± 2	69 ± 2
Chile	Andisol	Wheat	160	124 ± 4	16 ± 2	84 ± 2
China	Inceptisol	Rice	60	292 ± 7	7 ± <1	93 ± <1
Egypt	Entisol	Wheat	60	80 ± 6	20 ± 1	80 ± 1
Malaysia	Ultisol	Maize	60	53 ± 2	23 ± 1	77 ± 1
Morocco	Aridisol	Wheat	42	161 ± 7	18 ± 1	82 ± 1
Morocco	Inceptisol	Sunflower	35	129 ± 7	7 ± <1	93 ± <1
Morocco	Inceptisol	Bean	85	225 ± 6	7 ± <1	93 ± <1
Sri Lanka	Ultisol	Maize	60	139 ± 6	11 ± <1	89 ± <1
Sri Lanka	Ultisol	maize	60	139 ± 6	18 ± 1	92 ± 1
Vietnam	Ultisol	maize	120	92 ± 3	58 ± 1	42 ± 1
Mean				147 ± 6	21 ± 1	79 ± 1

Modified from Dourado-Neto et al. (2010)

Fertilizer nitrogen use efficiency and soil nitrogen

Nitrogen use efficiency (NUE) is a complicated term based on many factors amongst which a great degree of compensation takes place. Moll et al. (1982) reported that nitrogen efficiency is defined as the ratio of grain weight to N supply. Where N is the amount of plant available N present in the soil. Since it is difficult to measure the nitrogen that can be taken by the pant, many researchers changed it with applied fertilizer N to calculate the efficiency of N. Not all applied fertilizer N is available, nor are applied fertilizer N as the sole N source of the plant. This description of "nitrogen use efficiency" mostly referred to like partial factor productivity (PFP_N), provide an integrative index of the total economic output concerning to use of total sources of N in the system including fertilizer N and indigenous soil N.

Along with PFP_N, most widely used measures of N use efficiency include:

(1) Agronomic Efficiency (AE_N): the ratio of net grain weight to total fertilizer amount of N fertilized and untreated plants.

(2) Recovery Efficiency (RE_N): the ratio of net increased total N uptake by N fertilized and untreated plants to total amount of fertilizer N.

(3) Physiological Efficiency (PE_N) or Internal Efficiency: the ratio of net increased grain weight to net increased N uptake with and without application of fertilizer N (Novoa and Loomis, 1981).

PFP_N can be symbolize mathematically, as the ratio of grain yield (Y) to the amount of applied fertilizer N (NF): $PFP_N = Y/NF$

As grain yield at a given fertilizer N level expresses the total of yield without fertilizer N (Y0) plus the incremental increase in grain yield due to fertilizer N application (YF), the PFP_N may be written as: $PFP_N = (Y0 + YF)/NF = Y0/NF + YF/NF$

As YF/NF is the rate of net increased grain weight with and without N fertilization to total amount of fertilizer N (or the benefit-cost ratio from purchased N inputs), it is equivalent to agronomic efficiency (AE_N), which also represents the product of recovery efficiency (RE_N) and physiological efficiency (PE_N) from applied N. Thus, PFP_N may be written as: $PFP_N = Y0/NF + AE_N = Y0/NF + RE_N * PE_N$

A total efficiency index that includes contributions to crop yield of N derived from soil N, fertilizer N uptake efficiency (RE_N) is the partial factor productivity, and the efficiency with which N acquired by the plant is converted to grain yield (PE_N) is the partial factor productivity. While biological significance of AE_N, RE_N and PE_N are very well understood, the term Y0/NF helps to identify whether limitations to increased PFP_N in farmers' fields include low Y0, poor AE or both (Cassman et al., 1998). Fertilizer N use efficiency as measured in terms of PFP_N can be enhanced by increasing the efficiency with which applied N is taken up by the crop and utilized to produce grain besides by increasing uptake and utilization of soil N. As changes in Y0 have a huge impact on PFP_N, adjusting the timing and rate of fertilizer N in response to Y0 is crucial for optimizing AE_N. The part of the fertilizer N kept in soil as residual inorganic N or in different organic N pools (including microbial biomass and soil organic matter) should be considered a positive contribution to N input efficiency only once there is a net increase in total soil N content. There is an additional loss of N from the cropping system above that from applied N fertilizer if soil organic matter is declining day by day, and it leads to reduction in PFP_N so that larger amounts of fertilizer N are required to maintain optimum yield levels.

Not only soil N but also applied fertilizer N contribute to plant available N pool consisting of NO_3^- and NH_4^+ ions from where N is take up by plants or it may get lost from the soil-plant system. At any time during the cropping season, available N pool remarks a very small fraction of the soil and fertilizer N (Fig. 1); even total N removed by crop plants constitutes a small fraction of the soil N. For example, a typical soil under wheat in Asia includes more than 2,500 kg N ha^{-1} in the top 30 cm. Application of 120 kg N ha^{-1} to irrigated wheat with RE_N of 40% will lead to total uptake of 110 kg N ha^{-1} of which 48 kg N ha^{-1} is the addition of fertilizer and 62 kg N ha^{-1} comes from the soil. Thus, N contributions from the indigenous soil resources can greatly alter RE_N. The amount of N derived from indigenous soil resources during a single cropping cycle typically ranges from 30 to 80 kg N ha^{-1} that represents only 1.2 to 3.6 % of total soil N. Although small in size the indigenous N supply has a very high fertilizer N substitution value because of the relatively low RE_N.

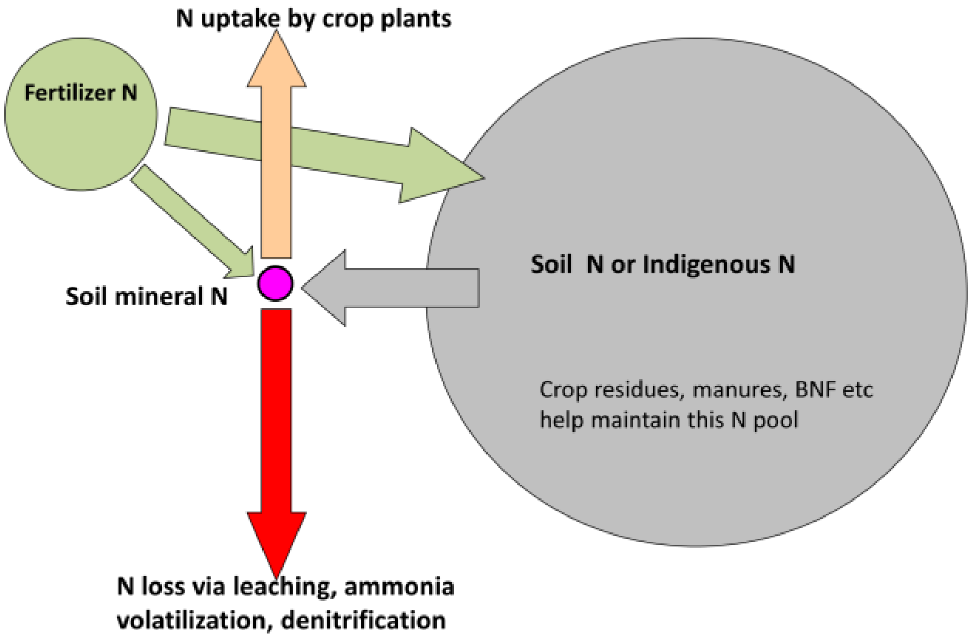

Figure 1. Relative contribution of soil and fertilizer N to the plant available N pool and uptake of N by crop plants

If the contribution of soil N decreases from 62 to 50 kg N ha^{-1} (about 19% reduction), to achieve the same yield of wheat fertilizer N requirement increases by 25% to 150 kg N ha^{-1}, assuming RE_N remains 40% even at the high fertilizer N rate. Recovery efficiency typically decreases as the fertilizer N application rate increases (Reddy and Reddy, 1993). Since C:N ratio of soil organic matter is relatively constant, changes in soil C introduced by management practices including fertilizer use affect the soil N balance. Thus, when there is improvement in soil health, soil N content increases and it makes contribution to higher NUE. Increase in the amount of soil N due to fertilizer N substitution further makes contribution to a higher RE_N. Conversely, any decrease in soil N stocks will reduce overall N use efficiency and RE_N. A decrease in soil N supply naturally harmful for productivity. Crop yields might be sustained or even increased by using improved varieties or higher fertilizer application; however, soil degradation can lead to yield decline or stagnation in yield.

Synchrony between crop N demand and N supply from soil and fertilizer – A case for site-specific nitrogen management

Synchrony defined as a close balance between demand of N by crop and its supply from soil, environment and fertilizer suggests that there exists potential for two types of asynchrony. When N supply exceeds N requirement of the crop, it is called “excess-asynchrony” but when N supply is insufficient to meet plant needs at certain times it is referred to as ‘insufficient-asynchrony’ (Crews and Peoples, 2005). When farmers started using N fertilizers, excess-asynchrony was observed but it has been due to farmers trying to avoid periods of insufficient-asynchrony. Farmers all over the world aim to sustain crop yields by avoiding or reducing periods of N deficiency. Until recently, N use efficiency used to be of minor consideration for application of fertilizer N to agricultural lands and there was a trend which applied additional 'insurance N' against the possibility of not guaranteeing income loss at yield (Dobermann and Cassman 2004). It resulted in excess-asynchrony and substantial losses of N from the soil-plant system.

Recently, some farmers have been able to reduce N related environmental problems simply by applying less fertilizer N as it leads to a scenario of improved synchrony as well as increased N use efficiency.

In the last two decades, a large amount of information has been available to improve the NUE by providing a balance between N demand and supply of N (Witt et al., 2007; Diacono et al., 2013; Bijay-Singh and Singh, 2017). This approach clearly recognizes the need to efficiently utilize both soil N and fertilizer N because losses of N via different mechanisms increase in proportion to the size of available N pool present in the soil profile at any given time (Fig. 1). Too little N in the plant available pool reduces yields and profit while too much N is vulnerable to losses (Cassman et al., 2002). High degree of variability and very small size of the available N pool relative to much larger background of total soil N makes the prediction of soil N supply as one the key challenges for enhancing fertiliser N use efficiency. Also, it is important to know the amount and temporal variations of the indigenous N supply during crop growth for determining the optimal timing and amount of fertilizer N applications (Liu et al., 2017). The field to field variability in nutrient levels is found even on similar soil types and is in part due to historical differences in management. Fertilizer management strategies to improve N use efficiency through better harmony of crop N demand with N supply from soil and fertilizer N are focussed on providing (i) better N prescription through improved split application schemes or by managing spatial variability through precision farming, and (ii) by managing the dynamics of soil N supply and crop N demand through site-based real-time N management, modified fertilizer sources, inhibitors or placement techniques that do not allow excessive accumulation of N in the soil (Dobermann and Cassman, 2004).

Site-specific N management strategies are now becoming available but for their wide scale implementation these should be simple, involve little extra time, provide consistent gains in N use efficiency and yield, and are cost effective. Precision farming with variable-rate N fertilizer application could significantly reduce N rate required to achieve yields similar to those obtained with standard management (Dobermann et al. 2004).

The principles and objectives of the site-based N management are similar no mechanization conditions or small fields in developing countries and precision of spectral reflection in developed countries (Buresh and Witt, 2007). There are several studies about in-season N management using simple leaf colour chart (Yang et al., 2003) or chlorophyll meter (Peng et al. 1996) after establishing local calibrations. During the growing season, fertilizer N is applied whenever the leaf N status as revealed through relative greenness of leaves falls below an empirically calibrated threshold. Evaluation of site-specific leaf colour chart or chlorophyll meter based N management in rice had indicated that the similar rice yield can be succeed with significantly more less N fertilizer applied, while enhances in yield appear to be rare or are relatively small (Bijay-Singh and Singh, 2017). The leaf colour chart is now being used for site-specific management of fertiliser N in wheat and maize as well (Bijay-Singh, 2014). High fertiliser N use efficiency has also been recorded when fertiliser N was managed following leaf colour chart based fixed-time variable rate approach in rice (Witt et al., 2007; Bijay-Singh et al., 2012). Some modifications in the amount and times of application of fertiliser N doses at different critical stages during the crop growth season have been made to suit farmers in different regions. Recently, optical sensors, have been used to manage fertilizer N in crops like wheat and rice as per need of the crop and availability of N in the soil which measure visible and near-infrared spectral response from plant canopies to detect N stress. (Raun et al., 2002; Li et al., 2009; Xue et al., 2014; Bijay-Singh et al., 2015, 2017).

CONCLUSIONS

The available N pool of NO_3^- and NH_4^+ in the soil is relatively very small as compared to total N pool and is continuously being replenished through mineralization of soil organic matter. Size of available N pool if at any time becomes smaller than adequate, crop plants may not be able to meet their N requirement. But if its size becomes more than adequate, N in the pool may be lost via different mechanisms. Fortunately, all of fertilizer N when applied to the soil does not end up in the available N pool; rather a large part of it becomes a part of the big total soil N pool via N substitution. As a result, crop plants meet their N requirement more from the soil N rather than fertilizer N and the fertilizer N use efficiency is also influenced by the availability pattern of soil N. The appropriate management of fertilizer N thus revolves around conservation of the available N pool at the minimum size required to meet crop N requirements throughout the growing season of the crop. It can be considered for the best result, crop N demand and supply could be synchronized with the N mineralization of the organic matter and fertilizer N contents. Precision site-specific management of fertilizer N can help achieve this synchrony and can ensure production of optimum yield of cereals with high fertilizer N use efficiency. Site-specific N management both takes care on productivity and profitableness of food production systems. It also helps in the decision-making on environmental consequences of modern farming and cropping systems.

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