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Nutrient Management in Conservation Agriculture-based Production Systems

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ABSTRACT

Conservation agriculture (CA) based crop management practices enhance soil health that ultimately improves crop production with low environmental foot prints. Developments of the better nutrient management practices are important to successful implementation of CA. On average, efficiency of fertilizer N in India is only 30-40% in rice and 50-60% in other cereals. Higher nutrient use efficiency (NUE) under CA can be achieved through fine-tuning of nutrient management practices based on local site-specific conditions developed for conventional till-based agriculture. In South Asia systematic research on nutrient dynamics in soils and crop nutrient management requirements in CA systems is limited. Opportunities exist to enhance the yield, profitability, and NUE through site-specific nutrient management (SSNM) in CA. Various tools, techniques and decision support systems (nutrient expert, optical sensors and leaf colour chart) are available for soil- and plant-based precision nutrient management, which offer the potential to enhance NUE in cereals and to mitigate environmental quality risk by avoiding N losses via volatilization, leaching and denitrification. GreenSeeker (GS)-based SSNM saved ~20-30 kg N ha^{-1} without affecting the grain yield under CA-based cereal systems compared to general recommended dose of fertilizers. Nutrient expert® and GS-based nutrient management reduced GHG intensity of rice, wheat and maize production by 5-35 and 0-13%, respectively over farmers' fertilizer practice. There is a need to develop nutrient prescriptions and application strategies in line with the 4R-principles to increase the NUE under CA-based management practices. Future studies should be focused on layering of CA with different novel nutrient management tools and subsurface fertigation for increasing both water and nutrient use efficiency. In CA-based production systems, innovations in machinery are needed for precise band placement at seeding and during crop growth.

Key words: Environmental health, GreenSeeker, nutrient dynamics, nutrient expert, nutrient use efficiency, site-specific nutrient management

Introduction

During the past half century, conventional intensive agriculture practices were successful in achieving goals of production, but simultaneously

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led to degradation of natural resources endangering agricultural productive potential in the future (Kumar *et al*., 2018). In recent years, CA has emerged as an alternative practice of crop production in South Asia. The CA aims to conserve and improve the natural resources through their efficient use and integrated management of available land, water, energy and biological resources combined with external inputs (Jat *et al.*, 2014, 2019c). The success of CA depends on how well the component technologies such as water, weed and nutrient management, are developed and implemented. Fertilizer nutrients play a major role in meeting the plant nutrient demand to sustain yield and quality goals of modern agriculture. Fertilizer best management practices vary from one region to the next and one farm to the next depending on current and historic soil, climate, crop, and management expertise. The CA through its three key principles (zero tillage, leaving crop residues on the soil surface, and diversified crop rotation) influences the soil physical, chemical and biochemical processes and, in turn, modifies the rhizosphere and nutrient dynamics in the soil (Jat *et al.*, 2020). Adequate and plant demand based-nutrient supply is pre-requisite for sustaining crop yields and soil quality under both conventional till (CT) and CA systems. There is a need to combine CA with good agricultural practices (GAPs), such as integrated soil fertility management (ISFM) and the 4Rs (right source, right rate, right time, and right place) to improve fertilizer use efficiency, increase farmer profitability, ensure environmental sustainability, improve food safety and quality, and make farming socially acceptable. Fertilizer misuse produces negative environmental impacts resulting from both overuse and underuse (nutrient mining, loss of topsoil, and land degradation). Soil amendments (lime, manure, rock phosphate, crop residues, leaf litter, etc.) can help ameliorate the negative impacts of fertilizer use and are an important components in ISFM strategies to increase NUE taking changes in seasonal nutrient dynamics into consideration (Jat *et al*., 2016; Parihar *et al*., 2020a). Several studies comparing CT and ZT (zero till) production systems in the Indo-Gangetic plains (IGP) of India suggested that fertilizer efficiency increased by 10–15% in ZT-based rice-wheat system due to better placement of fertilizer with the seed drill compared with broadcasting in the CT system (Hobbs and Gupta, 2004). However, there are also reports of lower NUE when soil microorganisms immobilized mineral N during the decomposition of crop residues (Verhulst *et al*., 2010). There is still a large knowledge gap in understanding of rhizosphere dynamics and nutrient management in CA systems in South Asia where fertilizer recommendation is largely based on the response trials conducted under CT system and based on a wide geographical area. In this paper we attempted to comprehend available information related to nutrient transformations in soil and opportunities for use of precision nutrient management tools for efficient use of fertilizer nutrients on scientifically sound basis in CA with a special reference to India.

Nutrient-Use Efficiency

The objective of nutrient use is to increase the overall performance of cropping systems by providing economically optimum nourishment to the crop while minimizing nutrient losses from the soil-plant system and supporting sustainable agricultural system. Three general management practices that foster the effective and responsible use of fertilizer nutrients are: i) Matching nutrient supply with plant demand and water supply, ii) Optimum rate and method of fertilizer application, and iii) Minimizing nutrient loss, reduce the environmental footprint and groundwater pollution. The nutrient use efficiency (NUE) is an important index that can be used in CA in order to quantify the different nutrient management practices and to determine which is better for increasing the NUE.

Nutrient Dynamics and Availability under CA

In general, four important chemical and biochemical processes, often working simultaneously, are involved in influencing the nutrient dynamics in the soil system. These are:

mineralization (release) –immobilization (tie-up), sorption-desorption, dissolution-precipitation and oxidation-reduction. CA, through its three key principles, is expected to influence these processes considerably, and alter nutrient dynamics in the soil throughout the crop growth (Jat *et al.*, 2020). Mineralization and immobilization processes significantly influence the dynamics of mainly N, P, S and the micronutrients. Potassium in crop residues does not need to undergo mineralization and is released easily into soil for absorption by plant roots. Understanding nutrient dynamics under contrasting soil management practices is important for managing nutrients in an efficient way. In a CA-based system, residue placement differences (sub-surface incorporation vs surface retention vs burning/removal) contribute to the effect of tillage on N dynamics in soil. Compared to incorporated crop residues, surface residues in ZT decompose at a much slower rate (Yadvinder-Singh *et al*., 2010). The development of continuous pores between the surface and subsurface (causing high infiltration rate) under CA may lead to more rapid passage of soluble nutrients (e.g. NO_3) deeper into the soil profile than when soil is tilled (Turpin *et al*., 1998).

A combination of high C:N ratio of cereal residues and low soil N is expected to reduce N availability to plants due to immobilization at the initial phases of crop growth and may decline grain yields, particularly during the initial 2-3 years of adoption of CA (Dordas, 2015; Verhulst *et al.*, 2010) and in few cases additional applications of N fertilizer may be required to maintain yield (O'Leary and Connor, 1997). In the years following the adoption of CA, soil microorganisms will significantly increase the N mineralization leading to less need for N fertilizers over time. When N fertilizer is applied as urea after irrigation in the presence of surface residue, N may be lost by ammonia volatilization into the atmosphere. Besides, higher amount of organic C, N substrate (nitrate) and soil moisture together with existence of large aggregates under CA than in CT system may also contribute to higher N loss through denitrification.

The contrasting tillage practices and crop residue as mulch in CA will also have implications on soil moisture regime that in turn will influence soil biota (Choudhary *et al*., 2018b,c; Parihar *et al*., 2017), nutrient availability, nutrient response, and NUE (Majumdar *et al*., 2012). The differences in nutrient dynamics under CT and CA are well illustrated by Majumdar *et al*. (2012) and recorded lower yield in N omission plots under ZT spring maize as compared to CT maize. This is probably due to either greater immobilization of available N, losses of N through leaching and denitrification, lower mineralization of soil organic N, or some combination of these factors that reduced the availability of N to ZT spring maize in the initial growing phase of the crop. However, due to longer duration of winter maize, the mineralization of the immobilized N under ZT system might have supplied more soil N in the later stages thereby increasing the yield over CT maize.

Several researchers have reported significant increases in soil organic carbon (SOC) in surface soil layer under CA-based cropping systems compared to CT systems (Jat *et al*., 2018a, 2019a,b; Parihar *et al*., 2020b; Zahid *et al*., 2020). The improvements in SOC observed in CA systems will have a significant effect on plant nutrient availability due to both changes to the quantity of nutrients available, and their distribution in the soil profile (Jat *et al*., 2020). Continuous addition of crop residues in CA leads to greater input of plant nutrients in soil, resulting in increased storage and availability of macronutrient (Choudhary *et al*., 2018a; Choudhary *et al*., 2020; Nandan *et al.*, 2019; Parihar *et al.*, 2020a; Thind *et al.*, 2019; Yadvinder-Singh *et al.*, 2014b; Jat *et al*., 2018a, 2019d; Das *et al.*, 2020) and micronutrients (Jat *et al*., 2018a; Nandan *et al.*, 2019; Gupta *et al.*, 2007; Zahid *et al*., 2020). CA in most cases improves the availability of P and K in surface soil layer due to reduced mixing of fertilizer with soil causing lower P-fixation and surface retention of crop residues (Franzluebbers and Hons, 1996). Pradhan *et al*. (2011) argued that higher Olsen P contents in CA treatment were due to the formation of stable complexes of P-fixing/ immobilizing ions like Ca^{2+}, Fe^{3+} and Al^{3+}

with soil organic matter. Mycorrhizae, which are obligate symbionts, play an important role in P absorption and translocation to the roots of associated plants under CA. Saikia *et al.* (2019) recorded higher glomalin concentration under ZT due to less soil disturbance compared to CT that accounts for higher activity of arbuscular mycorrhizal hyphae in soil.

After 20 years of ZT, extractable P was 42% greater at 0–5 cm depth, but 8–18% lower at 5–30 cm depth compared with CT treatments in a silt loam soil (Ismail *et al*., 1994). This suggests that there may be less requirement of P starter fertilizer in long-term CA because of high levels of available P in the seeding zone. Govaerts *et al*. (2007) reported 1.65- and 1.43-times higher K concentrations in the 0–5 cm and 5–20 cm layers, respectively, on permanent raised beds than CT raised beds, both with crop residue retention. Thus, retaining crop residue in the field after harvest of previous crops through CA practices can contribute a considerable amount of plant K to the soil and substantially reduces the K fertilizer input requirement (Yadvinder-Singh *et al*., 2010; Singh *et al.*, 2016).

From a long-term study in the IGP of north-west India, Jat *et al.* (2018a) recorded significantly higher available N, P, K, Zn, and Mn contents at 0-15 cm depth under CA based agricultural practices (Table 1). DTPA-extractable (available) Zn concentrations were 51% and 93% higher under CA-based maize-wheat (MW) and rice-wheat (RW) systems compared to CT-RW system, respectively. The build-up of SOC and increases in nutrient availability suggest that, in long–term, the dose of mineral fertilizers may be reduced in CA systems (Thuy *et al.*, 2008; Yadvinder-Singh *et al*., 2009).

In CA system, plant residues decompose and nutrients are released into the soil, with greater levels at the soil surface and lower or similar levels in the deeper soil profile than CT systems. This cycle is repeated each season and is compounded by surface fertilization, creating a soil surface (0-5 or 0-7.5 cm) rich in nutrients (such as P and K) due to lack of soil mixing, but depleted below 0-7.5 cm at depth known as stratification of nutrients (Patra *et al*., 2019). High soil test levels, particularly for P and K in top layers of CA require modification of soil sampling procedure and calibration of fertilizer management and recommendation programmes. Kassam and Friedrich (2009) suggested that conventional soil analysis data might not necessarily be valid for fertilizer recommendations for CA, since the available soil volume and the mobility of nutrients through soil biological activities tend to be higher than in tillage-based systems against which the existing recommendations have been calibrated.

Therefore, in CA systems, fertilizer is the main entry point for nutrient management but has integrated the use of available organic sources as crop residues on soil surface. The synergism between mineral fertilizers and organic sources is utilized to increase the bioavailability of nutrients from organic sources when mineral fertilizer application promotes microbial activity, root growth, and increased rhizosphere activity. Conversely, organic sources improve water and

Table 1. Effect of different CA-based scenarios on total N, available macro and micronutrient contents at 0-15 cm soil depth after 4 years (Jat *et al*., 2018a)

Treatment	Total N	Available macronutrients (kg ha^{-1})				DTPA-extractable micronutrients (mg kg^{-1})			
	(g kg^{-1})	N	P	K	S	Zn	Mn	Fe	Cu
CT-RW	0.14b*	117c	15.7b	183c	20.8a	4.75c	81.3c	132c	2.70a
CA-RW+Mb	0.19a	156b	21.6a	236b	19.1b	9.15a	98.6a	136b	2.70a
CA-MW+Mb	0.19a	197a	19.6a	318a	18.6b	7.17b	87.3b	87.6c	2.55a

Where, CT- conventional tillage, RW- rice-wheat, Mb- mungbean, MW- maize-wheat
*Values within the same column differ significantly at P = 0.05 when not followed by the same small letter (s) according to Duncan Multiple Range Test for separation of mean.

nutrient retention capacity of the soil, resulting in increased fertilizer use efficiency. This leads to improvement of agronomic efficiency in nutrient use and productivity of all types of soils. The ultimate outcome is improved productivity, enhanced soil quality and a more sustainable system through wiser farm investments and field practices with consequent minimal impacts of increased input use on the environment.

Nutrient Management in Conservation Agriculture

Nutrient management is an important aspect of CA for attaining higher productivity so as to motivate farmers for adoption of CA. The aim of nutrient management is to maintain soil nutrient levels, replenishing the nutrients removed by crops and minimizing adverse impact on the environmental quality. Developing effective nutrient management strategies in CA will need: i) better understanding of the nutrient dynamics under altered soil environment due to ZT or permanent beds; ii) proper assessment of the nutrient contribution from retained crop residues to supplement external nutrient inputs; iii) developing scalable precision nutrient management strategies and supporting tools; and iv) quantifying and conveying the economic and environmental benefits of these new tools and techniques of nutrient management to appropriate stakeholders.

The conventional nutrient recommendations for conventional farming systems are not necessarily valid as a basis of fertilizer recommendations for CA. Nutrient management are more complex with CA because of higher residue levels at soil surface and reduced options with regard to method and timing of nutrient applications compared to CT systems. Nutrient management is an important aspect of CA for crop productivity and for its adoption by farmers. Kassam and Friedrich (2009) suggested that nutrient management strategies in CA systems would need to be developed based on the general aspects: i) Improvement in soil organic matter and the soil quality (physical, chemical and biological properties of the soil); ii) Improved soil nutrient stocks through residue recycling and biological nitrogen fixation (when legumes are included) to meet crop needs; and iii) the soil acidity/alkalinity is kept within acceptable range for all key soil chemical and biological processes to function effectively.

There is a potential for large N losses via ammonia volatilization or inefficiency with surface-applied N fertilizers (urea) under CA where residues are retained at surface compared to CT system when residues are burned or removed from the field. For example, Katyal *et al*. (1987) reported that NH_3 volatilization from broadcasted urea in CT wheat can be as high as 42%. Placing nitrogen fertilizer below the soil surface should minimize N immobilization by reducing fertilizer-residue contact and reduce volatilization loss thereby increasing N uptake and the NUE in CA systems. Research conclusively showed that losses from volatilization with urea could be almost eliminated if it is placed in the soil and covered properly. Results from a study by Katyal *et al*. (1987) showed that volatilization loss can also be minimized by the practices that move N into the soil, which include; applying fertilizer N just prior to a rain or irrigation. Splitting of N to match crop demand can also considerably decrease the leaching and denitrification losses of applied N in CA systems.

Determining optimum N fertilization rate and timing is critical to improve yields and economic sustainability for CA-based cropping systems. According to Thuy *et al*. (2008), adjustments in the timing of inorganic fertilizers should be made to synchronize nutrient supply and crop demand under residue retention in ZT system. The increased yields because of the improved soil health and additional soil moisture retained by the crop residue are the factors to be taken into consideration while describing the nutrients recommendation for CA. The grain yield response and N uptake curve showed that whilst yields are less at lower N levels, they are higher as N levels increase under ZT system (Moschler and Martens, 1975). Lower grain yields and N uptake observed with ZT at suboptimal rates of fertilizer N application probably resulted from either greater immobilization of fertilizer N, losses of N from denitrification and leaching, lower mineralization of soil organic N, or some combination of these factors.

Yadvinder-Singh *et al*. (2015) demonstrated that wheat under both CT and CA systems needed similar rates of fertilizer N over short-term when yields were similar for the two systems. However, over the long-term, crops under CA may require less fertilizer to feed the crop (Lafond *et al*. 2008). In another study, Yadvinder-Singh *et al*. (2010) showed that rice straw mulch under ZT released only a small fraction of total N (40 kg ha^{-1}) during the growth cycle of wheat crop (~ 150 days) in rice-wheat system. With small amounts of N released from incorporated residue, a benefit of significant savings in fertilizer N in wheat is unlikely in initial 2-3 years. However, the residue N may contribute to soil N supply for the following rice crop. The banding of P is more advantageous in CA compared to CT system because P movement in the soil is very slow and a zone of high P concentration is formed in the layer where fertilizer is applied. Point or line placement of nitrogen fertilizers in maize and wheat resulted in increased N availability and thereby increased N use efficiency in the CA-based plots (Nayak *et al*., 2019). Site-specific nutrient management (SSNM) captures the spatial and temporal variability in soil fertility and provides an approach to "feeding" crops with all the required nutrients based on crop's needs and thus improving the crop yield.

4R-Nutrient Stewardship

The 4R-Nutrient Stewardship proposed by International Plant Nutrition Institute (IPNI) is an innovative approach centred on four key areas of nutrient management; right rate, right source, right place and right time, for precise fertilizer practice which considers NUE, economic and environmental dimensions of fertilizer management that are important for sustainability of agricultural systems. Managing the 4R- is best accomplished with the right tools for crop-location specific N-management practices. A key scientific principle to select the right fertilizer rate is matching nutrient supply with plant nutrient demand throughout the growing season to avoid nutrient deficiency or excess (see next section on SSNM).

Results from a long-term study on CA-based practices in RW and MW systems showed that to achieve similar yields, wheat required 30% less fertilizer N and 50% less fertilizer K compared to CT-RW system with similar management practices (Jat *et al*., 2018a). By following CA-based practices, we can save precious nutrient resources through building soil quality along with the well-established advantage of higher productivity (yield, water and energy) and profitability in North-West India (Jat *et al*., 2019c; Kumar *et al*., 2018).

Choice of NH_4-based fertilizers may provide opportunities to reduce nutrient losses under CA system. Several additives and treatments are commercialized to modify availability of the N from urea. These include products that break down gradually to release plant available nutrients (e.g. urea formaldehyde), that physically encapsulate fertilizer materials in a protective coating (e.g. sulphur or polymer-coated fertilizers, urea super granules) or that chemically modify the rate of release of the nutrients from the fertilizer materials (e.g. fertilizers stabilized with urease or nitrification inhibitors). Under residue retention in CA, the 100% basal application of coated fertilizer like neem and sulphur coated urea found effective for enhancing NUE and water productivity with INR 3000 to 4000 ha^{-1} more net returns compared to conventional split application of prilled urea in MW system (Jat *et al*., 2014).

One of the primary objectives of right nutrient placement is to ensure that roots access nutrients immediately after application thus reducing the possibility of loss and fertilizer nutrients are used efficiently. Plant type and spacing, tillage practices, soil conditions, characteristics of the fertilizer material being applied, irrigation, and a host of other factors can all affect the placement method. The losses of N may be minimized by either drilling the fertilizer into the soil below the surface residue, applying N just prior to a rain or irrigating after fertilizer application, and/or by delaying the application of N fertilizer when a significant portion of residues have undergone decomposition. Sub-surface banding of P and K with the seed or ideally about 6-10 cm below the seed is highly recommended to promote deeper root growth and avoid stranding these nutrients near the soil surface under the CA system. Similarly, surface application of urea and urea-containing fertilizers results into severe loss of N under ZT system, particularly at the early phases of crop establishment when there is ample moisture and substantial amount of undecomposed organic substrate at the surface of the soil. The subsurface drilling reduces ammonia volatilization losses. Grahmann *et al*. (2016) reported that broadcast fertilizer application compared with drilling of N in between rows of wheat reduced grain yield and N use efficiency. They concluded that N fertilizer management in furrow-irrigated wheat cropping systems should combine splitting the N dose and disking it on the bed pre-planting and in the furrow later in the season, depending on the crop needs at the application time. Results from a two-year study from north-west India showed a saving of 30 kg N ha^{-1} in both maize and wheat with the deep placement of N fertilizer on permanent raised beds compared to uniform broadcast using recommended rate of 120 kg N ha^{-1} to get similar grain yields (Sandhu *et al*., 2019). N use efficiency was significantly higher with deep placement of urea on beds in both wheat and maize compared with broadcast application. Majeed *et al*. (2015) showed that in wheat planting on permanent beds, N application at 120 kg ha^{-1} produced 15% higher grain yield, and 30% higher N use efficiency than flat planting at the same N rate. Planting of wheat on beds with application of 80 kg N ha^{-1} gave yield similar to that of flat planting with 120 kg N ha^{-1}. Nitrogen deep placement in ZT dry seeded rice significantly decreased NH_3 volatilization by 15–45% and increased N recovery efficiency by 26–93% compared with N broadcasting (Liu *et al*., 2015). Split applications of N during the growing season, rather than a single, large application prior to planting, are known to be effective in increasing NUE. The new plant-based diagnostic tools such as chlorophyll meter (SPAD), leaf colour chart (LCC) and GreenSeeker (GS) optical sensor can help in-season estimation of the right time and rate of N application matching the uptake requirement of a crop in a site-specific manner.

Site-Specific Nutrient Management (SSNM)

Traditionally, fertilizers are applied uniformly across large area while ignoring inherent spatial variation in crop needs within crop fields in South Asia. This often results in either reduced yields or low NUE. SSNM is based on a set of nutrient management principles (crop removal adjusting the soil residual nutrients), which aims to supply a crop's nutrient requirements tailored to a particular field or growing environment. Major technologies focused on the adoption of modern diagnostic tools for SSNM for effectively enhancing the NUE, economic profitability with lower environmental footprints include use of SPAD, LCC, GS and Nutrient Expert® (NE) under both CT and CA systems. The plant-based diagnostic tools provide a valuable estimation of the N status of the crop and develop precision N management practices (Bijay-Singh *et al*., 2020). These tools helped in-season estimation of the right time and rate of N application matching the uptake requirement of rice, wheat and maize in a site-specific manner. The SSNM approach does not necessarily aim to either reduce or increase fertilizer use. Instead, it aims to recommend nutrients at optimal rates and times to achieve higher profit for farmers, with higher efficiency of nutrient use by crops across spatial and temporal scale, thereby preventing leakage of excess nutrient to the environment.

Bijay-Singh *et al*. (2002) reported that plant need-based N management through use of SPAD meter or LCC reduced N requirement from 12-25% with no loss in yield in RW system of IGP. The results of GS sensor-based N management resulted into similar (in rice) to higher yield (in wheat) with 10-20% lower N rates compared recommended practice thereby increasing NUE (Bijay-Singh *et al*., 2015, 2020). GS-based precision nutrient management increased partial factor productivity of N in rice by 65% over the farmer's practice in China (Yao *et al*., 2012). As a cost-effective and light weight alternative to original GS, a hand held version of GS has been developed by Trimble's Agriculture Division USA. The precision nutrient prescriptions using SSNM based decision support tools offers a new management paradigm for scaling up of the CA-based cropping systems in India and other countries of South Asia.

Nutrient Expert® (NE), an interactive decision support system is developed by IPNI in collaboration with CIMMYT and national agricultural research systems in India for smallholder production system of South Asia (http:// blog.cimmyt.org/ tag/nutrient-expert/; Pampolino *et al*., 2012; Satyanarayana *et al*., 2014). It can rapidly provide SSNM recommendation for individual farmers' field for maize, wheat, rice and cotton crops in absence of soil testing data. Parihar *et al*. (2017) reported that combination of CA and SSNM increased MW system productivity by ~23% compared with CT using the farmers fertilizers practices, which might be due to optimum supply of nutrients as per crop demand and indigenous soil nutrient supplying capacity. Majumdar *et al*. (2013) reported that NE-based fertilizer recommendations provided higher grain yield, lower fertilizer cost and higher gross returns in maize under CA than the applications based on state recommendation (SR) and farmer's fertilizer practice (Table 2). Better efficiency of nutrients applied according to nutrient expert (NE) recommendations than in farmers' practice indicates that location-specific nutrient application rate and better timing of nutrient application (i.e. a greater number of splits and matching physiological demand of the crops) reduced N losses and enhanced efficiency of nutrient utilization.

These are easy-to-use, interactive computer-based decision tool that can rapidly provide nutrient recommendation for individual farmers' field even in the absence of soil testing. Few studies have evaluated NE-based fertilizer recommendation with farmers' fertilizer practice in terms of NUE, yield and environmental footprint from cereal production (Sapkota *et al*., 2014; Jat *et al*., 2018b; Parihar *et al*., 2017). Sapkota *et al*. (2014) evaluated three different approaches to SSNM based on recommendations from the NE and GS in ZT wheat. The SSNM strategies increased yield, NUE as well as net return compared to state recommendation and farmers' fertilization practice in MW system (Jat *et al*., 2018b). The estimated total carbon footprint, *i.e.*, GWP (kg CO_2 equivalent per Mg of wheat grain production) was lower for NE-based strategies (NE + GS) than other nutrient management strategies. NE-based fertilizer management reduced N application in rice and wheat crop by 5-25% but increased other major nutrient (P and K) input. NE also increased rice and wheat yield by 2-2.5%, in western IGP and 9-25% in Eastern IGP compared to farmers' practice. Besides, NE lowered global warming potential (GWP) by about 2.5% in rice and between 12-20% in wheat (Sapkota *et al*., 2020). Similarly, results from another study showed that NE + GS based N-application improved the

Table 2. Agronomic and economic performance of farmer fertilizer practice (FFP), state recommendation (SR), and nutrient expert (NE)-based nutrient prescriptions in wheat across sites (n=27) under conservation agriculture practice in IGP, India (Majumdar *et al*., 2013)

Parameter	Unit	FFP	SR	NE	P>F†
Grain yield	Mg ha^{-1}	4.4	4.7	5.2	<.001
Fertilizer N	kg ha^{-1}	157	139	165	<.001
Fertilizer P	kg ha^{-1}	24	27	25	0.387
Fertilizer K	Kg ha^{-1}	0.9	39.0	69.7	<.001
Fertilizer cost	USD ha^{-1}	57	62	73	-
Gross profit	USD ha^{-1}	1034	1102	1214	<.001

Table 3. Precision nutrient management in wheat under conservation agriculture-based maize-wheat system (RK Jat, BISA, Pusa, Bihar, unpublished)

Nutrient Management	Grain yield (Mg ha^{-1})	Additional cost (INR ha^{-1})	Additional income (INR ha^{-1})
FFP (BC)-CT	4.61	0	-
State recommendation (BC)-PB	4.89	0	8795
State recommendation (D)-PB	5.31	1000	12350
Nutrient Expert based NPK rates (BC)-PB	4.90	658	8364
Nutrient Expert based NPK rates (D)-PB	5.52	1658	16018

Where, FFP- Farmers' fertilizer practice; BC- Broadcast; D- Drilling; CT—conventional till; PB- Permanent raised beds.

partial factor productivity of N by 34 and 59% in rice and wheat, respectively, as compared to farmers' practice (Kakraliya *et al*., 2018). Oyeogbe *et al*. (2018) reported that fertilizer N application guided by the optical sensor increased mean grain yields of CA-based maize and wheat up to 20 and 14%, saved up to 45 and 30 kg N ha^{-1}, respectively, over whole quantity of recommended N application at sowing. Results from a study conducted by BISA, Pusa (Bihar) showed that combination of fertilizer drilling and NE-based fertilizer application increased the mean productivity of wheat in MW system by 13 and 20% compared to state blanket recommendation and farmer practice, respectively. Both drilling of fertilizers and NE based fertilizer management provided the maximum profitability (Table 3).

Similar findings of higher productivity of ZT maize with SSNM (using NE) compared with recommended fertilizer dose or farmer practice were reported by different researchers (Singh *et al*., 2015; Kumar *et al*., 2014; Parihar *et al*., 2017, 2020a) and in wheat (Parihar *et al*., 2017, 2020a). Better efficiency of nutrients applied according to NE recommendations than in farmers' practice indicates that location-specific nutrient application rate and better timing of nutrient application (a greater number of splits and matching nutrient demand of the crop) reduced N losses and enhanced nutrient utilization.

International Rice Research Institute (IRRI), together with its partners, has developed Crop Manager for rice, maize and wheat (http://cropmanager.irri.org/home) which can also be used by extension workers, crop advisors, and service providers to give advice to farmers specific to their growing condition. Studies have shown comparative advantage of using Rice Crop Manager as a tool for providing site-specific nutrient and crop management advisory to the farmers. However, sufficient information on the evaluation of crop manager for nutrient management under CA system is not available.

Layering CA with Drip Irrigation Systems for Increasing Nutrient Use Efficiency

Water is becoming increasingly scarce worldwide and more than one-third of the world population would face absolute water scarcity by the year 2025 (Rosegrant *et al*., 2002; Yadvinder-Singh *et al*., 2014a). Wide scale adoption of RW in north-west India has resulted in decline in water level at an alarming rate. So, for the sustainable food production, the irrigation water productivity needs to be increased significantly in the near future by adoption of innovative micro-irrigation (fertigation) practices. Subsurface drip irrigation (SDI) system allows simultaneous delivery of water and nutrients directly to the crop root zone, while minimizing nutrient (N) losses. Integration of CA with drip irrigation system has potential to improve water productivity and nutrient use efficiency. The SDI system is considered economically viable option for row crops, such as maize, rice and wheat under CA (Sidhu *et al*., 2019; Patra *et al*., 2020; Jat *et al*., 2019c). Integrating CA, decision tools/sensors and fertigation can boost the NUE significantly. Field experiment conducted at BISA, Ladhowal, Punjab showed that fertigation using SDI in in CA-based RW system significantly increased N use efficiency in both rice and wheat compared to both flood irrigated ZT and CT (Sidhu *et al*., 2019). Results from another study by Jat *et al*. (2019c) showed that SDI system resulted in 25% saving of fertilized N in rice, maize and wheat without any yield penalty. On system basis SDI system saved 47 (C.M. Parihar personal communication) and 41% irrigation water in rice and maize respectively under CA-based RW-mungbean and MW-mungbean systems compared to their respective flood irrigated CA-based systems. Above-mentioned these studies showed that SDI system provided tangible benefits for substantial saving in irrigation water and energy and increasing NUE and net income for CA-based RW and MW systems in NW India.

SDI layered with CA-based RW and MW systems has potential to save both irrigation water and fertilizer use with significant reduction in GHGs while producing same or even higher yields of major cereals. The CA layered with SDI in rice (ScV) and maize (ScVI) improved the partial factor productivity of nitrogen (PFP_N) by 20 and 33% compared to farmers' practice (ScI) (Jat *et al*., 2019c). Like rice and maize, the PFP_N of wheat was significantly higher with the SDI compared to the flood irrigation in both partial CA (ScII) and CT (ScI) (Table 4). The CA + SDI system in wheat improved the PFP_N by 46% compared to the CT in rice (37.8 kg grain kg^{-1} N applied). The CA-based RW-mungbean (ScV) and MW-mungbean (ScVI) recorded 45 and 50% higher PFP_N compared to those of ScI and ~31% higher compared to their respective CA-based systems (ScIII and IV), respectively.

Table 4. Partial factor productivity of nitrogen (PFP_N) under different CA-based RW and MW systems (Jat *et al.*, 2019c)

Scenarios	PFP_N (kg grain kg^{-1} N applied)		
	Rice/Maize	Wheat	System
ScI	40.2	37.9	41.1
ScII	47.5	39.3	52.1
ScIII	36.7	43.1	45.2
ScIV	40.7	43.4	47.2
ScV	48.4	56.8	59.4
ScVI	53.4	54.9	61.5

Where; ScI: conventional-till (CT) rice-CT wheat (farmers' practice); ScII: CT rice-Zero tillage (ZT) wheat-ZT mungbean with flood irrigation; ScIII: ZT rice-ZT wheat-ZT mungbean with flood irrigation; ScIV: ZT maize-ZT wheat-ZT mungbean with flood irrigation; ScV: ZT rice-ZT wheat-ZT mungbean with SDI; and ScVI: ZT maize-ZT wheat-ZT mungbean with SDI.

Mechanization for Precision N Application in CA

As discussed earlier, surface application of fertilizers under CA leads to more loss of nutrients (*e.g.* volatilization losses of N) and plant roots are unable to take up fertilizers present on the soil surface thereby resulting into poor NUE. This is particularly more important P being less mobile. At planting, nutrients can be banded with the seed, below the seed and to the side of the seed. Placement near the seed-row will increase access of crops to the nutrient early in the growing season and provide a 'starter' effect that improves early growth. Fertilizer N precisely placed the N near root zone will reduce the volatilization losses. After planting, application is usually restricted to N and its placement can be as a top dress or a subsurface side dress.

Application of fertilizers in a localized band allows for more efficient use of N and as a result, lower application rates can be used than would be needed if the urea was broadcast on the surface and not incorporated. In a RW system, fertilizer efficiency increased by 10–15% due to better placement of fertilizer using fertilizer cum seed drill compared with broadcasting in the CT system (Hobbs and Gupta, 2004). With the development of straw management machine called Turbo Happy Seeder (THS), band placement became possible allowing ammonium-based fertilizers like urea to be used effectively (Sidhu *et al*., 2015). With THS, fertilizer P (DAP) and K can be drilled directly through the residues at appropriate depth at 1-2 cm below the seed placement. Study by Yadvinder-Singh *et al*.

Table 5. Effect of method and time of N application on yield and nitrogen use efficiency of applied nitrogen in zero-till wheat sown into rice residues (Adapted from Yadvinder-Singh *et al.*, 2015)

	N applied (kg ha^{-1}) at		Grain yield	Recovery efficiency
Sowing	Before 1st irrigation	Before 2nd irrigation	(Mg ha^{-1})	of N (%)
25*D +35	60	0	4.42	45.0
25D+35B	30	30	4.29	44.1
25D+65B	0	30	4.27	41.9
25D+95B-0	0	0	4.02	39.1
25D	48	48	4.79	56.7

Where, D- drill, B-broadcast at sowing, PSI, before pre-sowing irrigation

(2015) showed that better fertilizer N management strategy in terms of achieving higher grain yield and NUE for ZT wheat sown into rice residue was drilling of 24 kg N ha^{-1} as di-ammonium phosphate (DAP) into the soil at seeding followed by two top dressings of 48 kg N ha^{-1} each just prior to first and second irrigations compared to the presently recommended N fertilizer recommendation for CT wheat; applying 60 kg N ha^{-1} at sowing and the remaining 60 kg N ha^{-1} with first post-sowing irrigation (Table 5).

One-pass seeding and drilling fertilizer (as side band, or mid-row band) in ZT system are regarded as a highly efficient way of managing small doses of fertilizers for achieving higher NUE by minimizing the nutrient loss and immobilization so common with broadcast application under dryland conditions (Malhi *et al.*, 2001). However, management of high doses of fertilizers, especially N, often discourages farmers from adopting a one-pass production system. This has prompted considerable research to determine how much fertilizer can be safely applied with the seed in ZT-wheat. Seeding openers' adjustment was made in the THS that allows placement of fertilizer in a separate band between two rows of wheat to avoid seed germination and emergence problems (Yadvinder-Singh *et al.*, 2015). Results from field evaluation of these openers' showed that up to 75% of recommended fertilizer N dose for ZT wheat (120 kg N ha^{-1}) along with P and K fertilizers can be drilled at seeding with significant increase in grain yield over the recommended practice of broadcast application in two equal splits in medium to fine-textured soils. On the coarse-textured soil (sandy loam), drilling more than 50% of the recommended fertilizer N at sowing significantly reduced grain yield and N use efficiency.

For increasing NUE, development of new drilling equipment is also needed for deep placement of fertilizer N for first and second top dressing in standing row crops. This machinery can be used for drilling fertilizer N in ZT and surface residue conditions either during planting or post-emergence in rice, maize and wheat. Studies showed band placement of fertilizers in standing crops of maize and wheat on permanent raised beds covered with crop residue resulted in higher grain yield and partial factor productivity of N in side-drill method using seed cum fertilizer drills with double disc openers compared to broadcast application in maize-wheat system (Jat *et al.*, 2016; Parihar *et al.*, 2020a).

Conclusions and Way Forward

Conservation agriculture (CA) is increasingly advocated as a management strategy for saving production resources, and improving farm profitability, soil health and environment on a sustainable basis. The three components of CA substantially influence nutrient dynamics in soil thereby requiring paradigm shift in nutrient management strategies for increasing NUE with minimal environmental footprints. ZT and residue in CA system means the timing and method of fertilizer application are very important. For example, deep placement of N-fertilizer in CA system reduces immobilization (as it separates fertilizer and residue) and volatilization loss. Similarly, sub-surface banding of P and K in the seed row below seed promotes deeper root growth and avoids stranding these nutrients near the soil surface. Optimal nutrient management under CA with varied levels of surface residues are poorly understood. The current fertilizer application practices under CA need revision with a thrust on nutrient management research to improve NUE, crop productivity and reducing environment pollution. Few researchers claim likelihood of more immobilization, denitrification or leaching of applied N in CA systems requiring higher N fertilizer application during initial 1-2 years. The research findings from India and other parts of the world showed that in CA systems over long-term, nutrient requirements are generally lower and nutrient efficiencies are higher due to increase in nutrient cycling. Optimal nutrient management practices for different cropping systems with varied levels of surface residues under CA are poorly understood. New scientific thinking and research are needed in the area of nutrient dynamics and nutrient management under medium to long-term studies, to fill the knowledge gap that currently exists about CA in different agro-ecological conditions. Mechanisms and pathways of nutrient losses under CA are poorly understood. Opportunities exist to fine-tune in-season nutrient management to increase the NUE in CA systems through SSNM using various tools, techniques and decision support systems. Limited studies suggest that fertilizer management practices employing SSNM, GS and Nutrient Expert tools increased crop yields, NUE and profitability. There is a need to refine fertilizer prescriptions and application strategies in line with the 4R principles to increase NUE under CA. Improved mechanization is needed for deep placement of fertilizers under residue retained conditions both for basal and split application at later crop growth stages. More studies on new modified (coated) fertilizer sources and subsurface drip fertigation are needed to increase NUE in CA-based systems. Tailoring of higher nutrient use-efficient cultivars of different crops for CA should to be accelerated. Soil sampling depth also needs modification for CA-systems as it results in a highly concentrated layer of soil test extractable nutrients (e.g. P and K) in the surface (0-7.5 cm) layer. To harness the impact of SSNM tools and technologies on improved nutrient management in CA-based systems and there is a need to formulate enabling policy and institutional framework for wide-scale adoption of best fertilizer management practices.

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