Environmental Impacts of Nitrogen Use in Agriculture, Nitrate Leaching and Mitigation Strategies

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Abstract Nitrogen (N) fertilization has been found a powerful tool for increasing crop production since the last six decades. Except for legumes, which fix their N biologically by rhizobium, majority of the crops require N for the production of seed and forage. Ammonium (NH_4^+) and nitrate (NO_3^+) are major plant available forms of N in soil, the later having six times higher movement in and is therefore prone to leaching loss. Nitrate leaching down the soil profile results in low N use efficiency and contamination of underground water stream which is a major route of NO_3 entry into food chain. Nitrate related regulations, its health and ecological issues, contribution of food and water to nitrate ingestion and its main mechanisms of movement in soil hve been described for better understanding of the factors affecting NO_3 leaching. Nitrate leaching is governed by a number of factors that affect accumulation and movement of residual NO_3 in soil. These factors including plant characteristics, seasonal fluctuations, climate changes and soil properties are discussed in detail. Management of NO_3 leaching, which has been the main focus of this chapter is categorized into fertilizer, soil and irrigation based management options. Fertilizer management options take into account the balance use of fertilizers, right dose and time of application and controlled release of N through using nitrification inhibitors and slow release fertilizers. Organic agriculture, conservation tillage and growing of crops in high leaching risk associated season are proposed as soil management options. Irrigation management mainly comes around evapotranspiration based irrigation scheduling and wise use of deficit irrigation. In short, the chapter is an effort to make a comprehensive understanding of the reader about NO_3 leaching problem, its possible effect on human health and ecology and measures to manage NO_3 leaching without compromise on crop yields.

Keywords Nitrogen • Nitrogen use efficiency • Nitrate leaching • Evapotranspiration • Soil science

1 Introduction

Nitrogen (N) fertilization has been found a powerful tool for increasing crop production since the last six decades. Since N is a constituent of chlorophyll and many enzymes, it performs a significant part in different growth process of plants. Nitrogen induced increase in yield may be related to increased production of panicles in cereals and pods in legumes (Fageria et al. 2006; Fageria and Baligar 2007). Nitrogen also reduces grain sterility and improves grain or seed weights (Fageria et al. 2006; Fageria and Baligar 2007). Moreover, grain to straw ratio and harvest index of N (N uptake in the grain/N uptake in grain plus straw) which are positively associated with yield in field crops are improved by N application (Fageria et al. 2006; Hakeem et al. 2011).

Depending upon texture, surface soils (upper 15 cm layer) can naturally contain 0.1–0.6 % N (Cameron et al. 2013) representing 2000–12,000 kg N ha^{-1}. Except for legumes which fix their N biologically by rhizobium, majority of the crops require N for the production of seed and forage. Further, the N uptake and assimilation varies among different plant species and their parts. Recovery efficiency of the applied N lies around 30–40 %; the remaining part is lost by leaching as nitrate ($NO_{3)}$, denitrification to gaseous forms, volatilization from surface of high pH soils, surface runoff and immobilization by soil microbes.

Ammonium (NH_4^+) and NO_3 are major plant available forms of N in soil. Owing to its positive charge, NH_4^+ has very poor mobility in negative charged soils of the subtropical climate (Richter and Roelcke 2000). On the other end, NO_3^- movement in soil profile is six times higher than NH^{4+} with flowing water and is therefore prone to leaching loss (Dinnes et al. 2002). In addition to low nutrient use efficiency (NUE), NO_3^- leaching below soil profile results in contamination of underground water stream. Since cereal grains, the most consumed food, contain negligible nitrate, drinking of nitrate polluted water or its use for growing crops is the main route of its entry into food chain. Upon ingestion of NO_3^-, it is acted upon by some bacteria or enzymes in the digestive system that reduces it to nitrite (NO_2^-). Nitrite then absorbs in blood where it oxidizes Fe^{+2} to Fe^{+3} to convert hemoglobin into methemoglobin as a result of which its level increased in blood than normal. Methemoglobin has more affinity for oxygen due to which capacity of red blood cells to release oxygen to tissue decreases. The resultant hypoxic condition is known as methemoglobinemia or blue baby syndrome. At very high concentration, NO_2^- may react with amines and amides and form cancer causing compounds (nitrosamide and nitrosamines). The death rate of gastric cancer patients was found in strong correlation with daily nitrate intake rate in 12 countries of the world (Fine et al. 1982).

There are a number of factors that can affect accumulation and movement of residual NO_3^- in soil. Among these, dose and time of fertilizer application, irrigation schedule and tillage practices are the most important to be considered in order of their significance. Heavy application of N to soil could result in high NO_3^- leaching, low NUE and high risk of water contamination. Dose of applied nitrogen has positive correlation with leaching of NO_3^- away from active root zone (Paramasivam et al. 2002; Jalali 2005). Similarly, high leaching losses of NO_3^- were reported by Fan et al. (2010) at 225–300 kg ha^{-1} N application compared to that below 150 kg ha^{-1} N application. Therefore, it seems that application at optimal level can minimize leaching losses of NO_3^- (Sexton et al. 1996). However, under applying N results in malnourished plants which at later growth stage would not be able to metabolize NO_3^- within their body and efficiently utilize N from well nourished

(NO_3^- sufficient) soil. Application of farmyard manure together with chemical fertilizer can also increase NO_3^- buildup for leaching loss.

In addition to heavy fertilization, problem of NO_3^- abundance in soil profile may also occur when time of application does not synchronize with plant demanding stage. In most of the cereal crops surface distribution of solid fertilizer is difficult at mid-stage because of their tall stature and traffic difficulty. So, presence of high N in soil when there is no crop or when the crop's demand is very low (e.g. before emergence and/or at harvesting) would result in high leaching losses (Shi et al. 2012). Moreover, NO_3^- leaching seems to be higher whenever the abundance of NO_3^- in soil profile coincides with or followed by a period of high rainfall/heavy irrigation. Split application and avoiding fertilizer application during heavy rainfall period (monsoon season) could enhance NUE and reduce NO_3^- leaching losses (Jia et al. 2014). The common practice for N fertilizer application in cereals is to apply half at sowing and remaining half in two or three equal splits at critical growth stages.

Around the globe, surface and sub-surface waters were found to contain NO_3^- at levels exceeding the maximum permissible limit (MCL) recommended by WHO (2004) (Tahir and Rasheed 2008; Iqbal et al. 2013). Some reports say that no tillage (NT) or reduced tillage practices favour the formation of continuous soil macropores which may enhances preferential flow of NO_3. Conversely, lower NO_3^- leaching under NT system than common tillage practice has been reported and found to be associated with decreased mineralization or denitrification of N under the former system (Randall and Iragavarapu 1995; Patni et al. 1998). These reports has begun the debate if intensive agricultural activities like high rates of N fertilizers, repeated application of organic manures, tillage practices and/or high levels of irrigation are responsible for high levels of NO_3^- in water? Due to entirely different climatic condition and management practices at each and every sphere of the world, this review discuss the main causes and management options specific to particular climate and soil. It is also a need of time to identify water saving irrigation practices along with proper rate and time of N application to improve the yield as well as decrease leaching losses of N. Further, it seems necessary to determine the movement and buildup of residual NO_3^- in response to different tillage and fertilization practices under arid to semi-arid climatic conditions.

Optimal N management in agroecosystem is yet a debatable issue. This chapter discuss the fate of N in response to different management strategies like nitrogen source, rate and timing of application, irrigation and tillage systems. Further, this chapter mainly provides a discussion of practical aspects of N management to reduce its surface and subsurface water pollution.

2 Nitrogen in the Environment

Gain and loss of N in the agroecosystem system is associated with many complex and interlinked processes. In agricultural systems, the main routes for N loss are: (a) Gaseous emissions as ammonia volatilization and denitrification (b) leaching (i.e., removal below root zone with percolating water) (c) Plant uptake (d) surface runoff. The N cycle can be easily understood with the help of simple mathematical equation as follows:

$$N_{net} = N[e + bf + c + om + min.] - N[pl + g + i + l + r]$$

The positive sign indicates the addition of N and negative sign indicates the depletion of N from soil. Where, N_{net} is net N added into the soil, e is electrical discharge, bf is biological fixation, c is chemical fertilizer, om is organic manure, min is mineralization, pl is uptake by plants, g is emissions as volatilization or denitrification, i is immobilization, l is leaching and r is surface runoff.

Plant uptake and surface runoff losses are minimal. The losses through volatilization is significant at pH usually above 8.0, high temperature and low CEC soils. Anoxic conditions are favorable for denitrification. Leaching of NO_3^- in ground water make it more detrimental for human health compared to other chemical elements (Garcia et al. 2012).

3 Nitrate Leaching from Soils

Nitrogen fertilizer is a worrisome source of NO_3^- leaching to groundwater. The amount of N leached through the soil profile depends upon the quantity of N present in soil solution and the one that drained over a prescribed period of time (Cameron et al. 2013). Four major forms of N are present in soil, (a) contained in organic matter, (b) part of microbial bodies, (c) NH_4^+ ions bind on the clay surface and organic matter (d) mineral forms of N (NH_4^+, NO_3 and traces of NO_2^-) in soil solution. Because there is no significant adsorption of NO_3 onto the soil surface and the NO_3 is water soluble, it moves downward rapidly with water passing through soil profile which is economically and environmentally undesirable. When it enters in ground water there is a little chance for denitrification. Although, in groundwater there are anaerobic conditions but absence of organic carbon (C) reduces denitrification rate. The problem of NO_3 leaching is more severe in developed countries where N fertilizer and organic wastes are applied at higher rates. In recent years, NO_3 was also detected in ground water of some developing countries including Pakistan due to increased use of fertilizer and raw manure (Tahir and Rasheed 2008).

4 Nitrate Related Regulations

The NO_3 and NO_2 are considered hazardous and legal limits are set for their safe concentration in drinking water and food. The maximum concertation of NO_3 in drinking water set by U.S. Environmental Protection Agency (U.S. EPA 1991) and World Health Organization (WHO 2004) is 50 mg L^{-1} (equivalent to 10 mg N L^{-1}). Moreover, 3.7 mg NO_3 per kg^{-1} of body has been set as the maximum acceptable daily intake (ADI) level of NO_3 by the European Commission's Scientific Committee on Food and The Joint Expert Committee on Food Additives (JECFA) of the Food and Agriculture Organization of the United Nations/World Health Organization. Intake below the above prescribed level is considered as safe for healthy children and adults. Concentration of NO_3 is almost fifty times higher in vegetables than drinking water (US EPA 1991); vegetables often contain >2000–3000 mg NO_3 per kg fresh weight. Intake of dietary NO_3, however, is less likely to increase nitrosation, because of the presence of nitrate reductase enzymes in vegetables.

4.1 Primary Health Issue: Methemoglobinemia

The primary risk of nitrate loaded drinking water is the development of methemoglobinemia from NO_3^- derived NO_2^-. In red blood cells (RBCs), iron (Fe) is usually present in reduced state, i.e. ferrous (Fe^{2+}). The NO_2^- oxidized it to ferric (Fe^{3+}) state which has reduced or negligible capacity to carry oxygen to vital organs of body. The hemoglobin (Hb) containing Fe in Fe^{3+} state is known as methemoglobin (MHb). Although, the production of MHb is a normal process human metabolism but its concentration remains within safe limits. However, when level of MHb is too high not to transfer oxygen to cells, is a condition known as methemoglobinemia. When MHb is 1 and 2 % of the total Hb in adults and infants, respectively, it is considered in safer zone (Denshaw-Burke et al. 2014). The RBCs do contain mechanisms to stop this oxidation process and reverse the reaction to form Hb. However, the RBCs have finite life span and later on are unable to resist against oxidation process. Oxidative stress results in ageing of cells due to production of MHb that is not removed from blood circulation (Denshaw-Burke et al. 2014).

The early manifestation of methemoglobinemia is Cyanosis. It is evident only at 5–10 % conversion of Hb to MHb and is indicated by bluish lips and nails (Denshaw-Burke et al. 2014). The blood color of methemoglobinemia patient is chocolate brown and other indicators include sleepiness, vomiting and diarrhea, and in severe conditions even lead to death due to deprivation of oxygen to body cells.

4.2 Secondary Health Issues

The secondary health problems associated with ingestion of excess NO_3 include acute respiratory infection, thyroid problems, birth defects and colon cancer etc. In addition, the scientific research suggests that the ingestion of NO_3 may cause transmissible changes in the structure of the genetic material of cells that contribute to bladder and ovarian cancers and also to risk of non-Hodgkin's lymphoma. It could also be a reason for the development of thyroid hypertrophy, insulin-dependent diabetes mellitus and respiratory tract infections or causes spontaneous abortions. The NO_3 polluted drinking water causes severe problems in already sick people (malaria and cholera) and develop symptoms of vomiting, pneumonia, nausea, diarrhea, hepatoenteritis, gastroenteritis, muscular cramps, and several poisoning syndromes.

5 Contribution of Water and Food to NO_3 Ingestion

The occurrence of methemoglobinemia is related with the ingestion of drinking water, with most common cases associated with well water. Most victims of NO_3 were reported with water source having NO_3 level up to 50 mg L^{-1}. However, some reports indicate high level of NO_3 in sterilized/boiled water due to having been concentrated by evaporation (Bruning-Fann and Kaneene 1993). Bacterial contamination of high NO_3 water also causes more conversion of NO_3 to NO_2 before its entry to stomach and poses serious risks.

In humans, the intake of NO_3 through food often do not cause toxicity. This might be due to the reason that ascorbic acid like compounds present in foods chelate the NO_3 and minimizes its reduction to NO_2 in the gut. The most common food related NO_3 toxicity was reported in infants consuming formula milk prepared in well water (Bruning-Fann and Kaneene 1993). Moreover, grains can accumulate negligible amount of NO_3 which is even useful to fulfill human protein needs. Many vegetables like spinach, lettuce and root vegetables contain high levels of nitrates. Further, the processing and handling of these vegetables may also increase the risk to consumer. For example, spinach and carrots stored at room temperature contained more NO_3 as compared to fresh spinach (Fomon 1993).

6 Nitrate Related Ecological Issues in Aquatic Ecosystems

Leaching of NO_3 into surface and ground waters is one of the pathways by which it enters into aquatic ecosystems. This inorganic N can disturb the aquatic ecosystems by three ways: First, it can decreases the pH of fresh water by increasing the concentration of H^+ ions which ultimately reduces the acid-neutralizing capacity of lakes. Second, it can result in eutrophication of lakes by enhancing growth and proliferation of primary producers. Third, high concentration may be too toxic to impair the ability of aquatic life to survive and reproduce.

The decrease in pH of water could results in the production of mobile aluminum (Al^{3+}) and other heavy metals like cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn) (Nelson and Campbell 1991). This dissolved Al^{3+} then reduced the availability of orthophosphate and disturbs the P cycling in water system. A pH range of 5.5–6.0 is considered as a threshold limit below which organisms cannot survive. Some nutrients like silicon (Si) and iron (Fe) can significantly increase the mass of algae; however, according to recent literature NO_3^- is considered the primary cause of cultural eutrophication of aquatic ecosystems (Anderson et al. 2002; Smith 2003). Human activities which according to estimates have increased N fluxes into the coastal waters of the Gulf of Mexico by 4- to 5-fold, into the coastal waters of the northeastern USA by 6- to 8-fold, and into the European rivers draining to the North Sea region by 6- to 20-fold are the main cause of NO_3 linked eutrophication (Smith 2003).

The regular monitoring of aquatic ecosystems to prevent the eutrophication problem has been previously based on P and chlorophyll-a concentrations; in recent criteria, N has also been involved. The upper limits of N suggested for eutrophic temperate lakes and streams are 1260 and 1500 μg/L, respectively (Smith 2003). The well-known cases of hypoxic (or anoxic) water bodies due to cultural eutrophication are the Baltic and Black Seas, Chesapeake Bay and the northern Gulf of Mexico (Anderson et al. 2002; Smith 2003). In these water bodies, suitable habitat for food, growth and reproduction of both invertebrates and fishes (sensitive benthic species, particularly) significantly reduced and their excessive deaths were recorded (Anderson et al. 2002). This adverse effect of hypoxic condition on aquatic animals could further be aggravated by the formation of reduced ionic species, such as hydrogen sulphide (H_2S) (Breitburg 2002). Hydrogen sulphide affects the nervous system even at very low concentrations, leading to mortalities in aquatic animals.

7 Physical Transport Mechanisms of NO_3

The movement of any dissolved ion like NO_3 in the field is governed by the following physical mechanisms:

7.1 Convective/Mass Flow

This occurs because of the movement of NO_3 along with the actual movement of water through the soil during drainage events. Under saturated zone, the convective flux of NO_3 is in steady state and hence can be described by Darcy's law as follows:

$$Jc = J_w C = -K_s \ dH/dz \tag{1}$$

Where, J_c is the mass of NO_3 per unit area per unit time transported by convection, C is the nitrate concentration in mass per solution volume, J_w is the water flux, K_s is the saturated hydraulic conductivity and dH/dz is the hydraulic gradient. The distance transported per unit time by convection depends on the average pore water velocity, v, where:

$v = q/\theta_v$ and θ_v is the volumetric water content.

Under unsaturated conditions, the transient flow of NO_3 along with water can be explained by Richards's equation:

$$\partial\theta / \partial t = \partial / \partial z [K_h (\partial h / \partial z + 1)] \tag{2}$$

Here, Kh is unsaturated hydraulic conductivity, $\partial\theta/\partial t$ is change in water contents with time and $\partial h/\partial z$ is change in matric potential with space. As such this equation is not solved because of two variables h and θ.

Convective transport implies uniform displacement of the pulse of NO_3 just like a piston which is true only for structureless soils. But, in reality, processes of diffusion and hydrodynamic dispersion tends to spread the NO_3 pulse throughout soil profile. In field, the convective flow paths of the solution are never estimated exactly, another volume-averaged expression is used to describe convective flow. A separate solute transport mechanism, called hydrodynamic dispersion is included as an average of three dimensional convection.

7.2 *Diffusion*

Dissolved/water soluble NO_3 spread out as a result of random thermal motion of ions/molecules, a process known as molecular diffusion. This net movement of NO_3 is generally proportional to concentration gradient, the cross-sectional area for diffusion and the time available for diffusion. In one dimension, Fick's first law for steady state transport is explained as:

$$J_{NO3} = -D\partial C / \partial z \tag{3}$$

Where, J is NO_3 flux density (kg/m^2.s), D is molecular diffusion coefficient of solute in solution (m^2/s) and dC/dz is the concentration gradient. When value of concentration gradient becomes one, the value of D and solute moved will be more. Diffusion coefficient depends upon soil texture, physical and chemical properties of ion/molecule, temperature, salt and water content. In actual field conditions, the expression must be modified due to decreased cross-sectional area and increased actual path length by solid and air spaces. The modified form of Fick's law is:

$$J = -\text{€}\,(\theta)\,D\partial C/\partial z \tag{4}$$

Here, € is the tortuosity factor whose value is <1 and according to studies tend to decrease in non-linear fashion with decreasing θ

7.3 Hydro-dynamic Dispersion

The NO_3 not only moves with the flowing water as shown in Eq. 1, but also mixes with the soil solution of different chemical composition. Being non-adsorbing solute NO_3 has no interaction with the soil surfaces (no sorption) and produces solute concentration an "S shape curve" that varies with time. The process of dispersion can easily be visualized with the help of simple cylindrical column which is already filled with water. By the law of water conservation, each segment of the column must have same one dimensional flux density in steady state conditions. The NO_3 which is introduced from the inlet end not only diffuses and be convicted with Jw, but also spread out around the solid barriers. This velocity distribution is three dimensional due to three boundary effects: one boundary effect is due to more velocity of solute at the center of pores than along the edges, second is due to the pore size distribution and the third boundary effect occurs when actual flow path of solute fluctuates with respect to mean direction of flow. The mathematical equation for hydrodynamic dispersion is as follows:

$$J_h = -D_h \partial C_l / \partial z$$

7.4 Sorption

Sorption of anions (negatively-charged ions) like halides and NO_3 is less likely to occur in groundwater but most commonly noted in soils that contain allophone, imogolite and other poorly-crystallized oxide or hydroxide materials.

8 Factors Affecting NO_3 Leaching in NO_3 Leaching Environments

8.1 Plant Characteristics

Root systems play a very important role in NO_3 leaching. Root length and surface area are the two most important parameters indicative of nutrient acquisition (Thorup-Kristensen 2001). If the rooting zone is small and shallow, the highly mobile NO_3 ion can easily search the way to groundwater. However, on the basis of diffusion theory NO_3 uptake is more even in low rooting density crops. But, it does not account for the ease with which NO_3 can escape low rooting density crops. The difference is only due to root density distributions in the top soil and subsoil. Generally, the rooting densities are more in top soil as compared to sub soil. The increase of rooting density in this region may enhance water and NO_3 uptake, reduces the chances of leaching. It was found true for field-grown maize having direct relationship with subsoil root growth and NO_3 uptake (Wiesler and Horst 1994). Catch crop species showed a strong correlation with NO_3 depletion from that zone and subsoil root proliferation (Thorup-Kristensen 2001). Habib and La Folie (1991) findings contradicted to that of above scientists and concluded that the top soil rooting densities have pivot role in reducing NO_3 leaching because N source is in the surface layer. The plants having more rooting densities along with deep tap roots exploit more the mineralization zone, reduce the downward displacement of water. This type of root architecture helps the plants to store water and NO_3 and reduce the risk of drought stress and nitrate pollution. The root length of a specific plant depends upon its genetic makeup and temporal and spatial distribution of nutrients. Further, in non-homogenous field situations less branched rooting pattern is optimal for nutrient acquisition in one environment; but more branched pattern for second environment. Model root architecture is required for ions of different mobility over a wide range of environments and soil textures.

The thinner roots are more efficient to capture NO_3 compared to coarse roots because of infinitely small diameter and more reactive surface area. But, the finer roots have some disadvantages too; they are more susceptible to herbivore attack, less capable of exploring compact soils and limited growth potential and transport capacity.

8.2 Seasonal Fluctuations

Seasonal fluctuations in climatic conditions along with the drainage events are one of the promising factors affecting NO_3 leaching. The greatest NO_3 leaching losses were recorded during autumn, early winter and late summer months because of slower plant N uptake due to cooler weather conditions with high amounts of drainage (Wild and Cameron 1980). In autumn and winter, drainage is high because of slower evapotranspiration. The autumn applied N fertilizer had nitrate leaching losses between 15 and 19 % than spring applied fertilizer (8–11 %). Autumn rainfall after crop harvest can also cause mineralization of organic N and leaching of residual soil NO_3 (Cameron et al. 2013). So, the efficiency of autumn applied N (NUE) is low than spring applied.

But in tropical regions like Pakistan, where summers are not dry and 60–70 % rains are concentrated in monsoon season, the leaching of NO_3 is often higher in the summer than the winter. Cameron et al. (2013) concluded that there were greater leaching of NO_3 in summer monsoon (400–500 mm rainfall) than winter (100 mm rainfall).

8.3 Climate Change

Climate change is also a contributing factor towards the leaching of NO_3 down into ground water by modifying key soil processes that control crop growth (MAFF 2000). Increased CO_2 enhances rate of photosynthesis and it can demand application of additional fertilizers, however, rainfall and temperature can be both detrimental and beneficial. The factors governing the rate of mineralization of organic N are nature and abundance of the organic matter, humidity, temperature, pH and faunal activity. According to Leiros et al. (1999), increased ambient temperature is expected to decrease soil organic matter content which in turn will affect its hydraulic properties. Nitrate build up in soil are linearly affected by temperature and soil organic matter content (Leiros et al. 1999) leading to an increased risk of leaching (Olesen et al. 2002).

Although the mineralization and nitrification are directly related to temperature and indirectly to rainfall (Emmett et al. 2004). However, the changes in soil moisture during the summer season (Leiros et al. 1999) and uptake of NO_3 uptake by vegetation (Ineson et al. 1998) determine the extent of overall effects caused by these agents. Generally, microbial and enzyme activities are low when the soil is either too dry or saturated (Sardans et al. 2008). While reviewing the effects of wetting and drying cycles on mineralization, Borken and Matzner (2009) concluded that increasing summer precipitation could enhance N and C fluxes whereas increasing summer droughts will reduce them. The commonly observed pulse in net mineralization of N and C following wetting of dry soil is short-lived because it is derived from release of solutes and exposure of hidden organic matter, accumulated plant necromass and microbial cell lysates. To simulate the effect of increasing temperature on mineralization of organic N in soil, Rustad et al. (2001) simulated the effect of increased temperature on net N mineralization rate and plant productivity and reported increased of 46 and 19 %, respectively as a result of artificial warming in the range 0.3–6 °C over a period of 2–9 years. Overall, climate change scenarios is appearing to enhance mineralization of N in soil.

Proportioning between run-off and infiltration is an important control on N leaching to groundwater. Changes in rainfall intensity and hydraulic properties will lead to change in partitioning of NO_3 between run off and recharge. In a test farm of Netherlands, weather-induced fluctuations in NO_3 are found to be in the range of 55–153 % of average field concentration (Rozemeijer et al. 2009). Callesen et al. (2007) showed that periods of frost results in large losses of NO_3 and attributed this change to increased mineralization and ammonification. Contrarily, Matzner and Borken (2008) suggested that post-frost changes in NO_3 pulse are more likely to be associated with reduced uptake rather than increased mineralization. Under alpine, arctic and forest vegetation elevated nitrate losses from soils occurred only in the year following exceptional soil frost. Decrease in losses with short-term repeated events evidenced that pool of N susceptible to freeze-thaw events is rather limited. Different attempts undertaken to model the impact of climate change on N leaching and crop has generated variable results. For example, Eckersten et al. (2001) simulated the possible consequences of both elevated atmospheric CO_2 and temperature using two linked process-oriented models (SOIL/SOILN). The model predicted an increase of 10–20 % in present value of winter wheat production by the year 2050. Precipitation and drainage was expected to increase with the consequent increased in N leaching flux by 10 kg ha^{-1} year^{-1}. However, Ulen and Johansson (2009), based upon the simulation using tile drain and piezometer, reported this value to be only 0.06 kg ha^{-1} year^{-1} due to an increased temperature of 2 °C during the growing season from 1993 to 2005 (April to September). They also predicted an increase in precipitation by 16 mm, mainly in June. The projected increased frequency of droughts and decrease in summer recharge will lead to an increased requirement for agricultural irrigation.

8.4 Soil Properties

Soil parameters such as soil texture, hydraulic conductivity, residual water content, porosity and cation exchange capacity (CEC), predict leaching potential of soil (Vachaud and Chen 2002). Most of the alkaline and calcareous soils having pH around 8 are negatively charged, NO_3 cannot be retained in these soil. The mean content of N differs among the soil texture; heavy soils have good water holding capacity due to high porosity which resulted in low leaching. So, because of slower drainage and the greater potential for denitrification, fine texture soils exhibit less NO_3 leaching than coarse textured ones (Di and Cameron 2002; Fan et al. 2010). On the same grounds, Liu et al. (1998) reported higher NO_3 leaching in sandy soil (200 cm depth) compared to clayey soil (100 cm depth) in Loess Plateau of northern China. The extremes of NO_3 loss in one growing season on coarse textured soil reported by Tong et al. (2005) might be due to excess N supply beyond the crop needs for optimum growth/yield.

There is a great variability in pore-size and continuity in spatial distribution of pores that will contribute to irregular movement of water down to the soil profile. For example, macropores created by wetting and drying cycle and activity of roots/earth worms can allow NO_3 to leach down into deeper soil layers (Silva et al. 2000). When there is a heavy rainfall after a long dry spell, residual N present in soil can be washed through large soil cracks or channels by irrigation water or rainfall, by-passing through the fine pores. While macropores may only constitute 5 % of the total porosity of a soil, they allow ready movement of water, NO_3 and other solutes (Bouma et al. 1981). This transport phenomenon is very difficult to explain because of its high spatial and temporal variability.

pH, organic C, potentially available N, NO_3-N, sand content and hydraulic conductivity has significant positive correlations with NO_3 concentration in soil water, while bulk density and clay content had significant negative correlation. The soils having negative charges on their exchange sites have high potential to loose NO_3 than positively charged acid tropical soils. High N and organic C load and low clay content in soil profiles with high hydraulic conductivity would ensure NO_3 in ground water. The type of soil govern the rate of water infiltration and hence the processes of nitrification and denitrification.

9 Management Options to Minimize NO_3 Leaching

As seen in the above discussions, the NO_3 leaching is multifaceted problem and there is no single magical cure that can solve it. An integrated approach is required to minimize leaching losses and increase. In broader sense, options to minimize NO_3 leaching are fertilizer, soil and irrigation based management strategies which are discussed in detail as follows;

9.1 Fertilizer Based Management Options

9.1.1 Balanced Fertilization

The pressing need to feed the growing population propelled the farmers to apply N fertilizer at higher rates, which is a root cause of NO_3 accumulation in soil. To increase crop yield while keeping NO_3 at minimum, balanced fertilization is an effective method. For example, the application of P fertilizer along with N may decrease nitrate leaching (Fan et al. 2003). Zhang et al. (2004) reported NO_3 accumulation in soil in a wheat-maize cropping system over 9-years period in the following order: N>NK>NPK>NP>CK>PK. Yuan et al. (2000a) reported much lower accumulation of NO_3 with NP where N was applied at 220 kg ha^{-1} compared to NK or N alone with N application at 1171 and 1075 kg ha^{-1}, respectively. The most probable reason of low NO_3 accumulation in soil was much higher N uptake (1360 kg N ha^{-1}) by plants in NP treatment compared to NK and N alone resulting in uptake of 720 and 800 kg of N ha^{-1}. Alone applied N resulted in not only high concentration of soil NO_3, but also in its movement to deeper layers in the soil profile (100–180 cm) compared with NP treatment (80–120 cm layer). Manure along with NPK further decreases NO_3 leaching. But, manure applied at higher rates can enhance nitrate leaching e.g., by applying poultry manure which contain higher proportion of N, 40–75 % of accumulated N leached to 200 cm depth and NO_3-N concentration in water of 50 % wells exceeded 10 mg N L^{-1}. Therefore, manure should be applied at lower rates to minimize its negative impacts on the environment. In short, balanced fertilization at proper rates may decrease NO_3 accumulation in the soil profile and further its water contamination.

9.1.2 Right Dose of N Fertilizer Application

Due to rising food demand, grain yield goal is currently considered as the sole independent variable for determining plant N recommendations all over the world. The realistic yield goal should not be more than 10 % of the current or recent average yield of the farm. It has enforced the agriculturists to adopt intensive agriculture, including increased application of water and fertilizer (Rong and Xuefeng 2011). It is believed that if the Haber-Bosch process for industrial fixation of N had not been invented, 40 % of the current human population would not be alive. However, the increase N fertilizer inputs and crop yields are not concomitant; low nitrogen use efficiency resulting from leaching potential of NO_3 might be the reason. The fertilizer N applied in excess of crop demands may happen when residual soil inorganic N content is not properly considered or when estimated yield goals are larger than the expected yields under particular soil types and climate (Keeney 1997).

Worldwide, dominant and main source of N input in the crop production systems is the application of chemical fertilizers. About 60 % of global N fertilizer is used for producing the world's three major cereals viz. rice, wheat and maize contributing to reliance of 50 % of the human population on N fertilizer for food production. The extent of quantity N loss and its depth varies with soil, crop and experimental conditions. Abbasi et al. (2011) concluding from a field experiment on maize that there was non-significant difference between 60 and 80 % of fertilizer level regarding NO_3 losses but, 80 % treatment was better when considering crop yield along with NO_3 losses. At 100 % application of N (400 kg ha^{-1}), NO_3 losses were maximum. In a sandy farmland of North-West China, application of 225, 300 and 375 kg N ha^{-1} caused higher NO_3-N accumulation in soil compared to 0 and 150 kg N ha^{-1} (Rong and Xuefeng 2011). No NO_3 leaching was observed when N fertilizer was applied below 150 kg N ha^{-1} whereas, the N rate above 400 kg ha^{-1} caused NO_3 leaching and decreases fertilizer use efficiency (Barraclough et al. 1992. Although rate of N varied with crop, application at higher than the recommended for wheat and maize resulted in increased residual NO_3 in soil and its leaching below soil profile at the later growth stages with the movement of water (Wang et al. 2010; Jia et al. 2014).

9.1.3 Right Time of Fertilizer N Application

Usually, too much N is applied at early developmental stages where crop needs are minimal. The limited N application at the end of crop growing season and before the next crop favors the establishment of extensive rooting system and reduces losses (Al-Kaisi and Yin 2003). N application in four splits either in the urea or manure form resulted in less nitrate leaching than that in two splits. According to Isidoro et al. (2006) and Claret et al. (2011), application of N with first irrigation shows highest leaching losses (35–43 %) which could be attributed to less biomass at seedling stage, poorly developed root systems and less assimilation by plants. That's why, higher agronomic efficiency of applied N with winter wheat as obtained when the first N dose was applied 90 days after seeding. Reported that when total application of 102 N ha^{-1} was splitted in ten equal doses, only 6 % of the applied urea-N lost by leaching while corresponding value for single dose applied at transplanting was 13 %. Hence, single dose application can reduce NUE by 50 % and ultimately results in reduced yield which was also witnessed by Dunbabin et al. 2009.

The ill-timed application may disturb N balance of soil resulting in increased residual N build up directly proportional to the rate applied of fertilizer. No doubt, this is a positive sign of soil fertility gain for the upcoming crop, but farmers again apply N to the next crop irrespective of the current status of the soil. (Claret et al. 2011). When the sowing of winter-autumn crop is delayed, then topdressing of N fertilizer should be preferred than fertilization at the time of sowing to minimize NO_3 loss. It has been shown that recovery of N was more when fertilizer was applied at tillering rather than at emergence under similar agro-environmental conditions (Kirda et al. 2001; López-Bellido et al. 2005). Reported that optimum ratio of base to topdressing was 50:50 and suitable top-dress developmental stages were jointing and anthesis. Shi et al. (2007) concluded from their study that irrespective of rate and type of fertilizer applied, increased topdressing of N clearly elevates NUE by reducing NO_3-N losses and shows no difference in nitrate accumulation in plants. The sound management to reduce NO_3 leaching in corn was to side-dress N at six and twelve leaf stage but delayed application at sixteen leaf stage minimized yield benefits (Jaynes 2013).

9.1.4 Nitrification Inhibitors and Controlled-Release Fertilizers

The NH_4^+ has the ability to be sorbed on high CEC soils but NO^{3-} can be leached down. This leaching process can be slowed down by lowering the population and activity of *Nitrosomonas* bacteria in the first step of nitrification process. The N fertilizers are used along with different chemicals like nitropyrene. However, the most practiced technique is to retard entry of water into the fertilizer particle and exit of N out by coating of water soluble N fertilizer with less soluble materials. Generally, three types of materials have been used for the purpose: (1) Encapsulated urea; coating of urea with impermeable material to allow slow entry of water and exit of soluble N, (2) Encapsulated urea needing disintegration; coating of urea with impermeable material that needs to be broken physically, chemically, or biologically before the N is dissolved, and (3) Semi-permeable coated urea: By diffusion, water get inside creating sufficient internal pressure that destroy coating.

Sulfur and neem-extract coated urea (SCU) has been recommended as a promised technique with characteristics of slow-N release. Elemental sulfur (S) was preferred because of its relatively low cost and easy handling. Now a days, variety of polyolefin resin coated slow-release N fertilizer are available in the market. The strength of coatings can be adjusted to provide a range of N release rates that are suitable for a variety of cropping systems. However, it needs further research to optimize the application of these newer materials for different crops and soil types.

9.2 Soil Based Management Options

9.2.1 Shift to Organic Agriculture (Merits vs Demerits)

The solid wastes contain large amount of N and usually applied to the soil in their present form without going to any preparation procedure like conversion in to composting, biochar etc. As we are already aware, in these manures N is present in organic form and converted to inorganic form through mineralization process which ultimately is a serious risk to environment.

It is evident from literature that mineralization can release up to 50 % of manure based organic-N (Power and Doran 1984). After a period of 3 months, about 13 % of the N mineralized is from non-composted aged cattle manure (Hartz et al. 2000). Klausner et al. (1994) recorded that decomposition of organic N form dairy manure was 21, 9, 3 and 2 % over a 4-year period. In another study, it was concluded that over an application period of 21-year, mineralization rate of cattle manure was 56 % (Chang and Janzen 1996). This uncertainty and variability of organic N mineralization increases the risk of over and under application. In nitrate vulnerable zones, the maximum permissible limit of N from manure is 170 kg ha^{-1} year^{-1} (Mantovi et al. 2006).

The soils in arid zone of world are deficient in organic matter which enforce the farmers to add high inputs of external fertilizers (either organic or inorganic) into nutrient poor drylands. Organic matter is a main pool of N which it is released from organic matter by mineralization. There is a growing interest in organic agriculture as an environmentally friendly alternative to conventional agriculture because it is a practice of choice around the dynamic world. But, along with benefits there are some demerits if the organic wastes when not applied without proper evaluation.

Manure from dairy production can serve as a valuable source of N for agricultural fields but, efficient use of animal manure is a greater challenge than mineral fertilizer. From environmental point of view, repeated and heavy application of manure in agriculture is questionable. Mostly, the solid manure is spread over the surface of soil in fields just before planting and is either left on the surface or incorporated (Tarkalson et al. 2006) without considering the soil and manure specifications regarding N. The large proportion of N in cattle manure collected from dairy farms is organic fraction. However, the proportion of organic N that can be absorbed by plant roots during the first and subsequent growing periods is called as plant available N (Tarkalson et al. 2006). Mineralization of organic material as a result of microbial activity is influenced by several factors like type of manure (age, feed and sex of animal), C/N ratios, water soluble and recalcitrant compounds, soil moisture, temperature, pH and oxygen availability (Sistani et al. 2008). These factors may differ both spatially and temporally making it difficult to determine exact availability factor from site to site and through years.

The effects of independent application of mineral fertilizer and manure at agronomically optimum rates are highly discordant (Diacono and Montemurro 2010). One group of researchers thought that manure is considered the root of all evil. It is metaphorical for environmental degradation. For example, Basso and Ritchie (2005) observed that the total amount of NO_3 leached was 681 kg ha^{-1} in the manure treatment followed by the compost and then chemical fertilizer with values of 390 and 348 kg ha^{-1}, respectively. Because, in manure whole of the N is applied at the one time, so more leaching occur as compared to chemical fertilizer (mostly urea) which is normally applied in three splits. Dividing application of fertilizer in more splits causes more adaptation between plant and fertilizer. This management helps to use fertilizer when plant needs fertilizer. When half of the total fertilizer is applied before planting and field is repeatedly irrigate, large fraction of N is leached as plant uptake is low at this stage.

A long duration study (135 years) was carried out to check the effect of farm yard manure compared to N fertilizer at Rothamsted Experimental Station (Powlson et al. 1989). The continued use of FYM equivalent to 238 kg N ha^{-1} increased the total soil N content (0–23 cm) to 7680 kg N ha^{-1} compared with 2570 kg N ha^{-1} for the N fertilizer treatment equivalent to 144 kg N ha^{-1}. The NO_3 leaching losses were five times greater in FYM treatment compared with fertilizer treatment leading to conclusion that mineralization of organic N would have contributed a significant part to the NO_3 loss. Stoddard et al. (2005) also recorded significant increase in NO_3 concentration in manured soils as compared to inorganic treatment. The leaching was greater in winter as compared to summer which was mainly due to late fall and early spring mineralization of organic N resulting in excess of crop N uptake in summer and also in the fall leading to elevated levels of NO_3 in leachate during winter. Long term studies show that up to 50 % more NO_3 leaching occurs due to annual manuring relative to control soils, because of the gradual buildup of mineralizable N in manured soils and the loss of soil organic matter in un-manured soils (Shepherd and Newell-Price 2013; Pang and Letey 2000). This occurs only when soils are manured both in winter and summer annually without considering its residual effect. Continued manure applied organic N that is not mineralized in the first year is added into cumulative organic N pool that raises future N availability. This is most commonly experienced in sandy soils than clayey soils (Hassink 1995). Shepherd and Withers (1999) suggested that manure should be applied in rotation, for example, once in every 3 years because manure application may increase NO_3 loss if there is no synchronicity between N mineralization and crop N uptake. Chadwick et al. (2000) did not recorded extra leaching of NO_3 in the first year after manure application, but significant leaching in the following years. The manure based nitrate-N leaching could also be increased if a large amount of N is supplied to crop from manure without adjusting subsequent inorganic fertilizer application resulting in post-harvest residue of soil mineral N. Taking into consideration of all the above discussion, one solution to slow the build-up of N in the soil is to apply manure at low rates and more frequently.

9.2.2 Conservation Tillage

Tillage systems significantly affect dynamics of N in soil through their effect on N pools in the soil system. Tillage increases soil aeration, porosity and hydraulic conductivity which can increase residue decomposition. This process can lead to build up of high quantity of readily plant available N in soil (Dinnes et al. 2002) which increases its potential for leaching into shallow water tables. Halvorson et al. (1999) reported more accumulation of soil NO_3 down to 150 cm depth with conventional tillage compared with no-tillage system in spring wheat (Triticum aestivum L.) - fallow cropping system. They found it to be associated with the higher mineralization of N at the soil surface induced by soil disturbance. However, no tillage is rarely practiced because of sudden attack of weeds during growth phase of crop. However, Randall and Iragavarapu (1995) reported that 11-year average of NO_3 losses for moldboard plowing and no tillage were 43 and 41 kg ha^{-1}, respectively under continuous corn. The greater length of the study, which caused greater variability in the soil and environmental conditions, was attributed as the cause of the narrow difference in NO_3–N loss.

Stoddard et al. (2005) reported a lack of difference in NO_3 leaching between no tillage and minimum tillage (chisel plough + discing) which might be due to insufficient disturbance of the soil to affect physical and biological properties. It suggests that minimum tillage could be adopted to avoid disadvantages of both conventional tillage and notillage. Contrarily, Mkhabela et al. (2008) suggested that denitrification is significantly lower under conventional tillage than no tillage which in part, could be the reason of lower NO_3 concentrations observed under no tilled corn field. Evaluated the effect of no tillage, minimum tillage and deep tillage on nitrate leaching on silt loam soil at Lincoln, Canterbury, New Zealand. The average cumulative NO_3-N leached from winter cover crops was 208, 192 and 200 kg ha^{-1} for deep tilled, the minimum and no tillage treatments, respectively. Patni et al. (1998) also reported no significant difference between no tillage and conventional tillage, but, reported lower NO_3 concentrations under former practice. Usman et al. (2013) attributed low NO_3 leaching under no tillage system to more evenly distributed mineralization throughout the crop life span, while under conventional tillage there is rapid mineralization after cultivation and more chances of leaching than its availability to crop. In case of no tillage, crop residues present on soil surface has less plant available N because of its wider C:N ratio. Bellido et al. (2013) concluded from an 18-year field study on Vertisol that during most of the years NO_3 concentration was higher under conventionally tilled plots as compared to non-tilled plots. They supported their results by suggesting that under un-ploughed soil there was less decomposition of crop residues which was responsible for low net N mineralization and more N immobilization and nitrification differences.

9.2.3 Growing of Cover Crops in High Leaching Season

The growing of cover crops is the best option to minimize NO_3 losses in post-harvest seasons. In most of the areas after one crop harvest there is a gap or fallow period for next crop to grow. If some cover crops are not grown then prairies become the part of that land. The function of the cover crops, between the main crop seasons, is to accumulate inorganic N and thus reduce the chance of leaching. The N is then slowly released for the next growing season after residue decomposition. The other beneficial aspects of cover crops are to prevent soil erosion, enhance SOM and act as herbicide. Cover crops must have the ability to grow on less fertile, cool weather without inhibiting the growth of row crops. It not only reduces the NO_3 concentration in soil but also increase the growth of row and or following crops (Mei-singer and Delgado 2002). The crops which are more effective in reducing NO_3 leaching are grasses and brassicas than legumes. The plant species that can be used as cover crops vary from region to region depending upon climatic conditions. Rye was successfully used as a cover crop but the major drawbacks to grow rye as a cover crop are; it overwinters early, consumes more water and immobilize more N. Reported that the growing of cover crops like forages in winter decreased 25 kg N ha^{-1} $year^{-1}$ NO_3 leaching. Reported that after maize harvest covering of land with rye decreased 80 % NO_3 leaching losses as compared to winter fallow.

9.3 Irrigation Based Management Strategies

9.3.1 Significance of Evapotranspiration (ET) Based Irrigation Scheduling

Evapotranspiration (ET), the main mode of water loss from agricultural lands, is a critical component of hydrologic cycle. Across the hydrosphere, biosphere and atmosphere, ET is a form of continuous energy flow (Wang et al. 2012), and every aspect of productivity of the ecosystem is virtually influenced by it. Thus, sustainable management of water resources and balanced water supply among industrial, domestic, ecological and agricultural sectors necessitates having adequate knowledge on ET (Wang et al. 2012).

According to ET is extremely important for accurate predictions of crop productivity in dynamic resource environments. However, heterogeneity of vegetation and difficulties in measuring hydrological processes at comparable scales make the estimation of ET usually complicated. The most investigated variables of ET are evaporation and transpiration (Wang et al. 2012), however the contributions of precipitation, irrigation and soil factors remains relatively less investigated aspects. Thus, partitioning ET into its fractions could improve our understandings not only on the management of water resources, but also on recent global climatic variations (Fig. 1).

Increased depletion of ground water with intensifying irrigation is severely limiting crop productivity, food security, social stability and economic growth. In arid/semi-arid regions, soil water gained from precipitation and irrigation could easily be depleted by ET due to high temperatures. In developing countries, water productivity is far below than that in the developed world. This is particularly true for Pakistan, a developing country with over approximately 190 million people, where flood irrigation with pumped groundwater drive crop production and the scientific method for irrigation scheduling of crops are not followed. Flood irrigation may cause

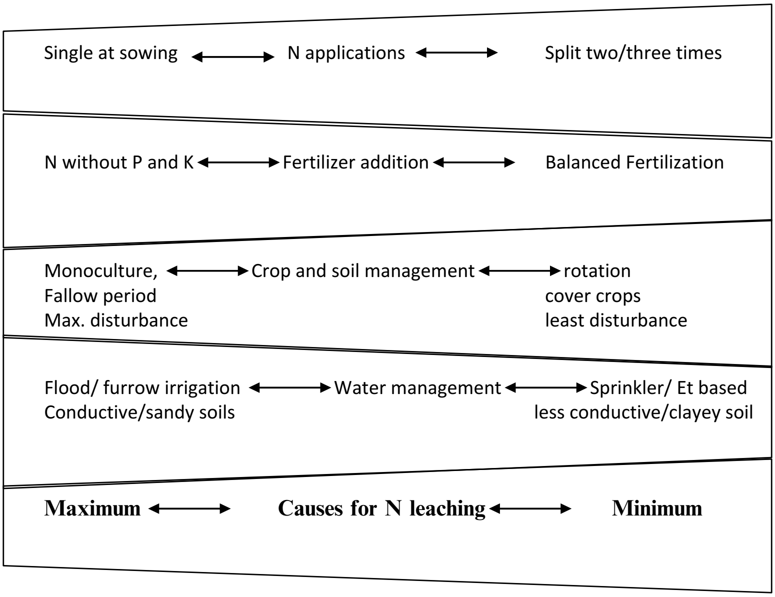

Fig. 1 Effect of N fertilizer, soil, crop and water management practices on N leaching

uneven distribution of nutrients, high rate of nutrient loss due to leaching and in some cases injurious to crops at early stages. The continuous pumping of ground water due to irrigation has resulted in the lowering of water table in several regions of Pakistan and many other countries.

Model data collection and simulation processes are exposed to errors by the current hydro-agronomic model parameters. Therefore, more efficient ways of accounting for the component fractions of the water budget are needed. In this regard, computer based softwares like CROPWAT 8.0 which use baseline meteorological data and specific crop coefficients to estimates parameters like ET are highly important (Hogue et al. 2005). In this way, water productivity could be enhanced by quantifying the contributions of precipitation, irrigation and soil water fractions to ET (Fig. 2).

9.3.2 Deficit Irrigation

In the past, NO_3 leaching has been paid a very little attention in arid and semi-arid regions. Although total annual rainfall is very low in these regions, but 60–70 % of the precipitation is generally concentrated in monsoon season (July–September). Heavy rainfall in monsoon season transports surface NO_3 deep into the soil profile. This phenomenon is more prevalent in areas where summer fallow procedure is

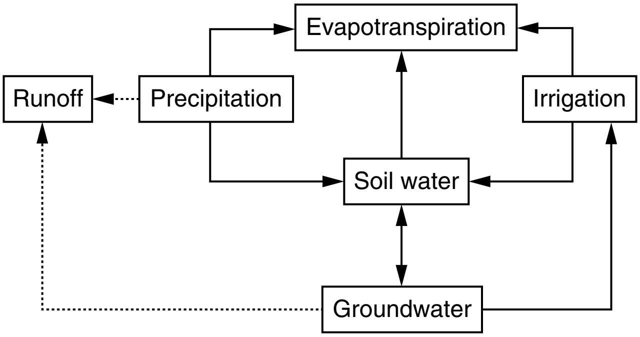

Fig. 2 Flow diagram of the soil water balance model

practiced. Additionally, flood irrigation being the common farming practice could also cause NO_3 transport to deeper soil layers (Cameron et al. 2013).

Over irrigation in case of maize crop caused 47 % increase in NO_3 leaching as compared to optimum irrigation (Gheysari et al. 2009). Heavy rainfall or irrigation immediate to N fertilizer application is likely to aggravate NO_3 leaching due to possible bypass flow through macropores as well as lower ammonia volatilization (Di and Cameron 2002). Yuan et al. (2000a, b) reported 64 % higher accumulation of NO_3 in 0–400 cm layer over a period of 8 years under irrigated than dryland conditions. The leakage of NO_3 may also occur below 400 cm depth. So, soil analysis further to 100 cm depth, the most emphasized depth previously, is needed. Wang et al. (2010) evaluated that higher rates of irrigation drastically increased drainage and NO_3 in drainage water. On the other hand, deficit irrigation seems an efficient irrigation management practice to reduce NO_3 leaching without compromising on crop yield. There are different modern ways to regulate deficit moisture conditions in the soil like furrow irrigation system, partial root zone drying irrigation. Djman et al. (2013) found less residual N with 50 % of full irrigation treatment than rainfed condition. Abbasi et al. (2011) irrigated corn fields at 60, 80, 100 and 120 % of crop water requirement (CWR) and observed 15, 29 and 35 % of NO_3 leaching, respectively. Wang et al. (2012) studied the effect of deficit irrigation i.e. 0.6, 0.8 and 1.0 of ET_c on NO_3 distribution in soil and concluded that no NO_3 accumulation was recorded in medium (0.8 ET_c) and low irrigation (0.6 ET_c) levels up to 200 cm soil profile. Skinner et al. (1999) recorded increased N uptake in furrow irrigation system which resulted in less NO_3 leaching. Similarly, Kirda et al. (2005) reported improved RE_N and lower buildup of N in the soil profile with partial root zone drying as compared to full and deficit irrigation that might be due to increased surface area of roots for water and nutrient uptake through lateral branching under the former irrigation practice (Mingo et al. 2004). Tafteh and Sepaskhah (2012) used three irrigation techniques viz., ordinary furrow irrigation, variable alternate furrow irrigation and fixed alternate furrow irrigation for maize. They observed that less water was required in variable alternate furrow irrigation causing less drainage water and NO_3 concentration in soil. However, high application of manure may dilute or completely nullify the beneficial effect of deficit irrigation in reducing leaching losses of NO_3, reported by Tarkalson et al. (2006) from an experiment on maize crop. The preferential flow of water from macropores after precipitation and irrigation are the main reasons for losses of N under limited water conditions.

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