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# Management practices to reduce crop production and nitrogen losses from waterlogging

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*Flooded cornfield. Photo courtesy of Gurpreet Kaur.*

Flooding is the most damaging abiotic stress, besides drought, that affects crop production. Waterlogging also promotes soil nitrogen (N) loss through processes such as denitrification, nitrate leaching, and runoff as well as reduces soil N mineralization rates. This article provides potential management strategies to reduce crop production and nitrogen losses from waterlogging.

## Abbreviations:

| | |
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| **BMP** | best management practice; |
| **CDSI** | controlled drainage and subirrigation |
| **EEF** | enhanced-efficiency fertilizer |
| **NUE** | nitrogen use efficiency |
| **PCU** | polymer-coated urea |
| **UAN** | urea ammonium nitrate |
| **UI** | urease inhibitor. |

*Editor's note: The following article is a portion of a review article recently published in Agronomy Journal, titled, "Impacts and Management Strategies for Crop Production in Waterlogged or Flooded Soils: A Review." It has been adapted slightly for publication in this magazine. The References are omitted here due to space constraints but can be viewed in the original article. View the full, open access article online at*

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Flooding is the most damaging abiotic stress, besides drought, that affects crop production. Within the United States, excessive flooding caused monetary losses of $1.6 billion for corn and soybean production in the Midwestern states in 2011 (Bailey-Serres et al., 2012). The NASA simulation models predicted crop production losses worth $3 billion per year by 2030, based on current trends in global climate change characterized by extreme weather events (Rosenzweig et al., 2002). Increases in extreme precipitation events are highly likely in the future as a result of increasing greenhouse gas emissions as assessed by the Intergovernmental Panel on Climate Change (IPCC; Cubasch et al., 2001). Waterlogging also promotes soil nitrogen (N) loss through processes such as denitrification, nitrate leaching, and runoff (Kopyra & Gwó d, 2004) as well as reduces soil N mineralization rates.

Management practices that prevent crop production and/or N losses under waterlogged soil conditions may include adjusting management practices (e.g., early or late planting, use of flood-tolerant crop varieties, and cover crops); adaptive nutrient management practices (e.g., enhanced-efficiency fertilizers and rescue N applications); altering the application rate, timing, and placement (Dawar et al., 2011a); use of adaptive water management practices (e.g., improving drainage, raised bed planting); or use of precision agriculture technology. These practices may be used alone or in combination to synergistically limit N losses and maximize yields.

## Crop Management Practices

## Flood-Tolerant Crop Varieties

One of the approaches for reducing crop production losses is identification, development, and use of crop varieties tolerant to soil waterlogging. Multiple studies have reported genetic variation in many crops for their response to soil waterlogging or flooding (Collaku & Harrison, 2002; Davies & Hillman, 1988; Huang et al., 1994; Torbert et al., 1993; Zaidi et al., 2004; Zaidi et al., 2010). Flood-tolerance mechanisms of plants may include the ability to transport oxygen to anaerobic roots, high capacity for anaerobic respiration and maintaining glycolytic metabolism, their ability to keep stomata open for photosynthesis, and the ability to avoid oxidative damage (Caudle & Maricle, 2012).

Flood-tolerant plants have traits to develop adaptive mechanisms, such as aerenchyma formation, development of adventitious roots, and stem hypertrophy. Traditional breeding programs use wild relatives of cultivated plants as a source of biotic and abiotic stress resistance to improve plant tolerance to stresses. For example, Mano & Omori (2007) used teosinte as a germplasm source for breeding flood-tolerant corn as it can form adventitious roots at the soil surface during extended periods of saturated soils and as well as constitutive aerenchyma in the root cortex under nonflooded conditions and inducible aerenchyma under flooded conditions (Mano & Omori, 2007). Additional traits for flood-tolerant crop varieties that may be considered in breeding programs include an increase in plant N uptake, N use efficiency, and improvement in seed or grain quality parameters. Flooding can occur at any growth stage of the crop, depending upon the location and weather conditions.

Waterlogging caused by rainfall events in the fall can delay crop harvesting; therefore, it is important to breed crop varieties for characteristics such as lower susceptibility to diseases or pests, good seed quality, and stem strength. Flooding in early season also exposes plants to cold soil temperature; therefore, it is also necessary to develop varieties with tolerance to both cold and waterlogging stress. However, few seed companies have developed corn hybrids that have tolerance to excessive soil moisture, despite large areas in crop production that experience temporarily saturated soil conditions. In summary, it is important to develop and test new crop varieties that are tolerant or resistant to multiple biotic or abiotic stresses, including waterlogging stress, heat and drought stress, as well as disease pathogens.

*Planting dates can be adjusted to avoid waterlogging conditions during the early spring season. Source: Clint Thompson (UGA CAES/Extension).*

## Adjusting Planting Dates

Planting dates can be adjusted to avoid waterlogging conditions during the early spring season to facilitate good crop emergence and growth, particularly in the Midwestern United States where early spring season precipitation occurrence is common. Planting is usually delayed due to the cool and wet soils that are common to this region. Cool, wet soils can delay crop emergence and early plant vigor. Later planting dates may avoid early-season extreme precipitation events and waterlogged soil conditions, but they may lead to a shorter growing season and exposure to drought later in the growing season that may also result in the lower crop yields.

However, Kucharik (2006) reported that in-season droughts during summer have shifted the planting dates earlier into the spring season. Other factors responsible for early planting dates include the development of varieties tolerant to suboptimal temperatures and diseases, seed treatments, improved planting equipment, and crop protection products and adoption of time-saving crop management practices such as conservation tillage (Kucharik, 2006). Early planting dates allow for a longer growing season, resulting in higher yields through an increase in the time duration for absorption of solar radiation and biomass accumulation (Kucharik, 2006). However, there is a risk of crop damage due to suboptimal soil temperature at early planting dates; therefore, crop varieties used for early planting should also be tolerant to low soil temperatures that occur during or after planting. Shifting planting dates for soil waterlogging abatement depends upon the timing and duration of waterlogging duration.

## Cover Crops

Long-term use of cover crops may not only improve soil health, but also may decrease waterlogging by improving soil structure, reducing compaction, and increasing the water infiltration rate (Blanco-Canqui et al., 2015). Root channels from cover crops can increase macropores, resulting in greater water movement through soil. For example, a cover crop mixture of bromegrass and strawberry clover reduced surface soil strength by 38-41% and increased steady infiltration rate and cumulative water intake by 37–41% and 20–101%, respectively, compared with the no-cover-crop treatments (Folorunso et al., 1992).

Winter cover crops can affect water availability for summer crops by decreasing evaporation while using stored water in the soil for transpiration (Smith et al., 1987). The greater transpiration rate of cover crops during spring can potentially dry soil for early crop planting. Higher water demand of cover crops along with higher temperature during spring can help in removing excess water from the waterlogged soils through greater evapotranspiration (ET) losses.

Multiple studies have reported the effects of cover crops on soil moisture content reduction (Monteiro & Lopes, 2007; Zhang & Schilling, 2006; Zhu et al., 1991). A three-year vineyard study found that volumetric water content under a cover crop mixture (60% nonlegume and 40% legume) was lower compared with no cover crops (Monteiro & Lopes, 2007). Zhang and Schilling (2006) studied the effect of land cover on the water table, soil moisture, and groundwater recharge and reported that reed canary grass had a lower water table and soil moisture content through higher ET losses, which reduced groundwater recharge (Zhang & Schilling, 2006). In the Coastal Plain region of North Carolina, crimson clover reduced soil water content 28–55% before corn planting in the top 15-cm soil depth (Ewing et al., 1991). Zhu et al. (1991) reported that cover crops had the potential to reduce soil water content if they were allowed to bear seed until late April on poorly drained Mexico silt loam soils of central Missouri.

Use of cover crops during the winter fallow period can also be a potential option for managing soil waterlogging. However, the effect of cover crops on the distribution of water in the soil profile can be positive, negative, or neutral, depending upon the soil type, climatic region, and cover crop species used (Blanco-Canqui et al., 2015). Therefore, use of multiple species of cover crops in areas susceptible to flooding or in areas susceptible to drought within a field should be further evaluated.

*Drainage tile systems at Greenley Research Center in Novelty, MO. The left side of the field is a control with no tile drainage and the right side has a tile system to help with drainage. Photo by Kyle Spradley | © 2014 - Curators of the University of Missouri.*

Agricultural fields do not always have zero grade and can have topography which can influence water and nutrient dynamics within a field and add spatial variability to cover crop biomass production and cash crop yields. Therefore, it is important to further evaluate interaction of topograpghy with cover crops for reducing waterlogging stress in large agricultural fields. The geographic information system (GIS) spatial modeling and remote sensing might be usful for identifying areas susceptible to waterlogging within an agricultural field. Since cover crops generally do not provide direct economic benefits, further research might be needed on the effects of implementing cover crops only on susceptible areas instead of the whole field.

## Adaptive Water Management

### Subsurface Tile Drainage

Drainage can remove excess water from the soil, which improves plant root growth, plant emergence, plant stands, workability of the soil, and consequently, results in higher crop yields (Blevins et al., 1996; Nelson et al., 2012; Nelson et al., 2009; Nelson et al., 2011a). Subsurface drainage technology is used worldwide for improving drainage in the waterlogged soils (Nelson et al., 2012; Sharma et al., 2016). Use of subsurface tile-drain systems with drainage water recycling in the poorly drained soils of the U.S. Midwest is a management option for preventing soil waterlogging that induces N losses through runoff, erosion, or denitrification.

Several studies have examined the interactions of drainage systems with N management (Nelson et al., 2009) and have reported increased crop yields, N uptake, and nitrogen use efficiency (NUE). In the Midwestern United States, free drainage or managed tile drainage systems that use a water table control structure have improved crop yields and reduced fertilizer loss through drainage water flow (Nash et al., 2015a; Nash et al., 2015b). For example, on poorly drained claypan soils, use of integrated subsurface tile-drained systems at 20- and 40-ft spacing between tile lines increased yields by 11–22% compared with nondrained plots (Nelson, 2017). Another study reported that use of tile drainage improved soil moisture conditions and allowed planting of soybean earlier by 17 days as well as increased soybean yields by 9–22% compared with nondrained control plots (Nelson et al., 2011a).

Based on a review on impact of agricultural practices on N management and nitrate loss into the water resources, Dinnes et al. (2002) pointed out that artificial drainage systems negatively affect water quality since they act as shallow direct channels to water bodies from agricultural fields. Factors affecting nitrate loss from the tile-drained agricultural fields include precipitation amount and timing, initial soil moisture content, time of the year, tile depth, and tile spacing (Drury et al., 2009). Subsurface drainage systems that incorporate both controlled drainage and subirrigation (CDSI) can improve crop production, N use efficiency, and reduce possible negative effects on the water quality through reduction of nitrate N entering into surface or groundwater systems (Drury et al., 2009; Fausey et al., 1995; Frankenberger et al., 2006). Use of CDSI allows irrigation of the root zone during in-season drought periods, which may help increase crop growth and nutrient uptake, thereby reducing N losses in the tile drainage water and reducing nitrate N loading up by to 75% (Frankenberger et al., 2006).

Also, nitrate losses through drainage can be reduced by adopting management practices such as improved N application timing, application rates and techniques, use of enhanced-efficiency N fertilizers and soil testing for N application, reducing tillage, utilizing crop rotations, and cover crops (Dinnes et al., 2002). Linking subsurface tile drainage to on-farm irrigation reservoirs is also a promising option to address the water quality issues while simultaneously providing waterlogging and drought resilience to crop production systems. However, this needs to be evaluated further.

## Raised Beds

Raised beds are used to deal with water management issues, such as waterlogging or irrigation application in semi-arid and arid regions (Govaerts et al., 2007). Raised seedbeds can increase crop yields by maintaining a favorable soil moisture content through improved drainage and provide a conduit for irrigation water application (Velmurugan et al., 2016). Raised beds improve soil physical properties via higher macroporosity and infiltration, lower bulk density, and higher aggregate stability by improving soil structure (Hassan et al., 2005; Roth et al., 2005). Restricting traffic in the furrows helps to avoid soil compaction in the beds that further allows better soil infiltration, root growth, and surface and subsurface drainage.

Several studies have reported the beneficial effects of raised bed planting for increasing crop yields under waterlogged soil conditions as compared with flat seedbed planting (Bakker et al., 2005; Blessitt, 2007; Siler et al., 2002). Raised beds lowered the potential for waterlogging by increased runoff rates due to the presence of furrows and improved soil structure as indicated by lower bulk densities and infiltration rates on poorly drained duplex clay soils (Bakker et al., 2005). Raised bed planting reduced waterlogging stress because the top 15 cm of raised bed soils remained unsaturated.

*Raised beds can be used for preventing waterlogging stress in agricultural areas where tillage is used for land preparation but may not be a potential option under no-till cropping systems. Source: Design Pics Inc/Alamy Stock Photo.*

In the United States, raised beds have been evaluated from southern regions to northern areas such as soils of the Red River Valley in in North Dakota, which are highly susceptible to waterlogging upon excessive rainfall events. Hoppe (2013) found that soybean yields in the Red River Valley were not decreased when soybean was planted on the raised seedbed compared with flat seedbeds during a dry year (Hoppe, 2013). In the U.S. Midwest, raised bed planting of corn promoted growth and increased biomass and yields, probably due to a suitable environment for root growth and gas exchange in poorly drained silt loam soil (Siler et al., 2002). In the Mississippi Delta region of the United States, raised bed planting increased plant height, leaf area index by 52–107%, soybean yield by 14–31%, and resulted into 23–45% higher net returns above input costs when compared with soybeans planted on flat seedbeds (Blessitt, 2007). Blessitt (2007) concluded that raised seedbeds can be a feasible option for reducing waterlogging damage on early planted soybeans on poorly drained clay soils in Mississippi River Delta region of the United States.

In summary, raised beds can be used for preventing waterlogging stress in agricultural areas where tillage is used for land preparation but may not be a potential option under no-till cropping systems. However, the use of raised beds along with other management practices such as tile drainage has not yet been evaluated and can be researched to assess the combined effect of these two practices on alleviation of waterlogging stress in areas of high waterlogging risk.

## Adaptive Nutrient Management

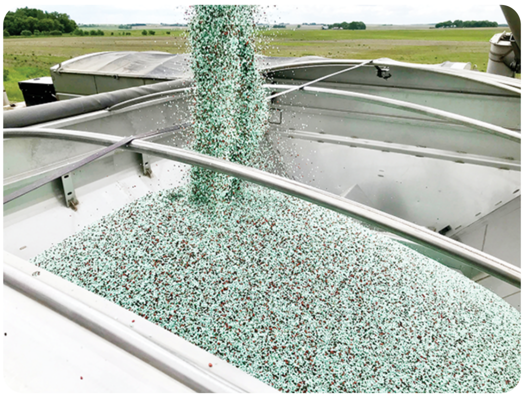
Fertilizer application rate, timing, placement, and sources affect N uptake, losses, and NUE. Synchronization of the N availability with crop N demand and uptake is important for optimum N management to get the maximum benefit from the applied fertilizers through increased crop yields while reducing N losses. Selection of the optimum N source, application rate, and timing is an important management option for N management in poorly drained soils. A single N application may result in N losses if soil waterlogging occurs from early-season extreme precipitation events after pre-plant N application. Corn may need additional N fertilizer applications (known as rescue N) when the preplant-applied N fertilizer is suspected to be lost due to the excessive soil moisture from extreme precipitation events or when wet soil prevented preplant or sidedress N applications (Nelson et al., 2011b). In the Midwestern United States, corn yields were highly responsive to N fertilizer applications as late as the silking stage although full yield potential was not achieved for N application at the silking stage (Scharf et al., 2002). Only about 3% corn yield loss was observed when N applications were delayed until V12–V16 (Scharf et al., 2002).

Corn yield response to rescue N application sources and application methods depends upon many factors, such as leaf injury and gaseous N losses from surface-applied N. Nelson et al. (2011b) reported that broadcast application of urea ammonium nitrate or ammonium nitrate on corn at V5–V6, V7–V8 (corn plant with 7–8 leaves), or V9–V10 (corn plant with 9–10 leaves) growth stages reduced corn yields due to the leaf injury caused by broadcast application. They concluded that N source and placement needs

*Nitrogen management in areas prone to soil waterlogging should consider split N application methods to avoid N losses. Photo by L. Kablan.*

to be considered while making decisions for rescue N application when corn is greater than 30-cm tall. Post-flood rescue N application of urea with the urease inhibitor NBPT effectively increased the yield of corn that was waterlogged up to three days (Kaur et al., 2017). Therefore, N management in areas prone to soil waterlogging should consider split N application methods to avoid N losses. However, the final decision about the N application timing and methods can be made only after considering higher net returns from available options for N application methods or timing. In addition, it is also important to evaluate the impact of waterlogging duration and timing in response to N applications and sources on the extent of N leaching and denitrification losses under different soil textures.

### Enhanced-Efficiency Fertilizers



*Use of enhanced-efficiency fertilizers is a management practice that may help prevent crop production and/or N losses under waterlogged soil conditions. Source: Shutterstock/Neil Liesenfeld.*

Increased interest in the use of enhanced-efficiency fertilizers (EEFs) has occurred in recent years due to several factors such as increased cost of fertilizers, higher crop value, greater environmental concerns associated with N application, inefficient crop N uptake, and improved manufacturing technologies (Stewart, 2008). An increased interest in EEFs has grown due to unpredictable precipitation events and more extreme precipitation events that may result in greater fertilizer losses. Enhanced-efficiency fertilizers are fertilizer products that increase plant uptake and decrease the potential of nutrient losses to the environment (e.g., gaseous losses, leaching, and/or runoff) when compared with a conventional fertilizer source (Motavalli et al., 2008). They can include slow- and controlled-release fertilizers, nitrification inhibitors (NI), and urease inhibitors (UI). Benefits of EEFs include their simplicity and ease of use, availability of different types with diverse characteristics, and their potential for N loss reduction (Motavalli et al., 2008). A detailed description of EEFs was reviewed by Chen et al. (2008), Motavalli et al. (2008), Shaviv and Mikkelsen (1993), Trenkel (2010), and Timilsena et al. (2015).

Slow- or controlled-release fertilizers either delay initial nutrient availability or extend nutrient availability for a longer period during the life cycle of a plant by regulating N release in the soil, controlling the availability of ammonium to nitrifying bacteria, and/or reducing nitrate loss through leaching or gaseous losses (Motavalli et al., 2008). The mechanisms responsible for delaying N availability include controlled water solubility of the material by semi-permeable coatings, occlusion, protein materials, or other chemical forms such as slow hydrolysis of water-soluble low molecular weight compounds (Halvorson et al., 2014). Urea-formaldehyde-based fertilizers, sulfur-coated urea, and polymer-coated urea (PCU) are some examples of slow- or controlled-release fertilizers. The term “controlled release” has been generally accepted to refer to coated or encapsulated fertilizers for which the factors determining the rate, pattern, and duration of release are known and regulated during the fabrication, and the term “slow release” is generally used for microbial decomposed N products such as urea–formaldehyde-based fertilizer (Chien et al., 2009; Shaviv, 2001).

Nitrification inhibitors are the chemicals that can either slow, delay, or restrict the nitrification process by affecting the metabolism of *Nitrosomonas* spp. bacteria involved in the nitrification process. Nitrification inhibitors slow nitrate production from ammonium, thereby decreasing leaching of nitrate and denitrification losses from soil. The NIs can inhibit biological oxidation of ammonium N to nitrate N from 4 to 10 weeks (Halvorson et al., 2014). Some commercially available NIs are nitrapyrin, DCD, and DMPP (Huber et al., 1977) and pronitridine (Schwab et al., 2017).

Urease inhibitors (UI) reduce the urea hydrolyzation rate and its conversion to ammonium by restricting the activity of urease enzyme in the soil. By delaying this hydrolysis, volatility losses of ammonia, which occur primarily at the soil surface,. can be lowered by delaying the urea hydrolysis process through the use of UIs (Motavalli et al., 2008). However, reduction of urease activity by use of UIs may also cause phytotoxicity by an accumulation of excess urea in plant parts (Krogmeier et al., 1989). Globally, more than 14,000 compounds or mixtures have been tested and patented as UIs (Chien et al., 2009). However, NBPT is the most commercially available UI with relatively high efficiency in inhibiting urease at low concentrations in a wide variety of soils compared with other UIs (Kawakami et al., 2012; Rawluk et al., 2001). In soil, NBPT converts to its oxon analog NBPTO, which is the actual inhibitor of urease activity (Creason et al., 1990; Krogmeier et al., 1989). These chemical forms, NBPT and NBPTO, compete with urea molecules for the enzyme Ni receptor sites in the structure of the urease molecule and inhibits its activity (Kolodziej, 1994). Delaying urea hydrolysis by NBPT allows more time for rainfall or irrigation to move the urea of the soil surface into subsoil layers near the plant rooting zone where it is less susceptible to ammonia volatilization losses (Dawar et al., 2011b).

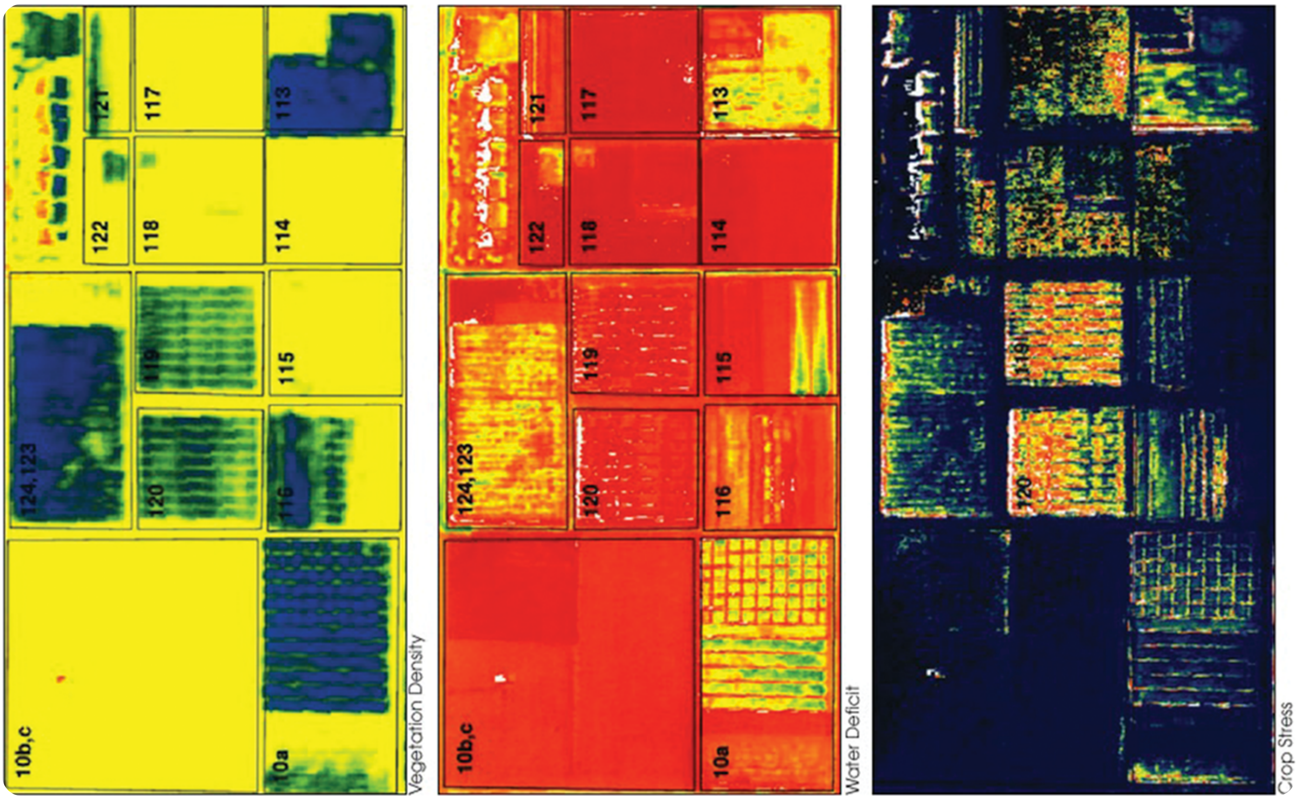
Many studies have reported that use of EEFs resulted in greater crop yields and lower N losses. Corn yields increased 15.9 to 19.1 bu/ac by pre-plant application of anhydrous ammonia with nitrapyrin and PCU compared with noncoated urea (Nash et al., 2013). In eastern Canada, PCU and urea with NI resulted in greater corn yield during wet years compared with urea applied without NI but showed no differences between yields among fertilizer sources during dry years (Gagnon et al., 2012). Economic analysis revealed that, despite 30% higher costs, PCU gave comparable net returns at an equivalent N rate than urea ammonium nitrate (UAN) in wet years. Anhydrous ammonia and PCU applications increased corn yields by approximately 23–29 bu/ac and gross profits $20–260/ac compared with urea in the low-lying field positions compared with the summit and side-slope positions in a poorly drained claypan soil landscape (Noellsch et al., 2009). The PCU-treated soil had 51–63% lower soil $NO_3$–N concentration than urea 59 days after application in water samples collected by suction lysimeters, and thus, reduced nitrate leaching early in the season (Nelson et al., 2009). In the United States, the NBPT evaluation from 78 trials showed that it increased corn grain yields by 4.3 bu/ac when applied with urea and by 1.6 bu/ac when applied with UAN when averaged over N and NBPT rates for all locations and years of the study (Hendrickson, 1992). Similarly, Dawar et al. (2010) reported that use of NBPT with urea increased ryegrass herbage dry matter yield and N uptake more than urea alone or other forms of N fertilizers used in the study through improved N availability. Further research should be conducted to evaluate the use of EEFs under varying waterlogging durations, either under continuous or intermittent waterlogging conditions, as well as assessing their N losses under such conditions.

## Precision Agriculture

Different soil moisture regimes may exist within a field due to the spatial variability caused by slope, topography, or soil heterogeneity. Within the same field, low-lying areas may become waterlogged under excessive rainfall events while the upland areas may suffer from droughts in the dry years. For example, Singh et al. (2016) reported that topography resulted in excess soil moisture at the depositional position and reduced corn and soybean yields in southern Illinois. Similarly, Adler et al. (2019)

reported that corn, soybean, and cover crop biomass yields were consistently low in the channel and footslopes of terraced fields in Missouri due to waterlogged conditions prevailing in the channel and footslopes. Furthermore, N availability and losses also vary with the soil moisture content, which may result in variable crop responses to N fertilizer applications across agricultural landscapes. Anaerobic conditions due to waterlogging conditions reduces soil solution nitrate N at footslope positions possibly due to N loss through denitrification, which further contributed to lower corn and soybean yields at footslope landscape positions (Singh, 2018; Singh et al., 2019). Precision agriculture technology can be utilized for identifying management zones based on yield maps, soil productivity maps, high-resolution digital elevation models from LIDAR (Light Detection and Ranging), flow accumulation, and soil electrical conductivity maps for site-specific management to increase crop productivity (King et al., 2005).

The pairing of flood-tolerant crop varieties with or without optimum N fertilizer rates and/or sources with the low productivity areas within a field that are susceptible to occasional waterlogging can be a potential management option for reducing yield and N losses due to land constraints and needs to be further researched. Also, waterlogging in the low productive zone can be can be managed by the introduction of tile drainage in the targeted areas and should be supplemented with control structures to manage water table depth in the field in order to reduce N loss and increase crop production. Variable-rate N fertilizer application for improving N recovery, increasing crop yields, and reducing environmental N losses has been used extensively using information from grid sampling, site-specific management zones based on previous yield maps, or optical sensors. Noellsch et al. (2009) reported that PCU resulted in higher corn yields compared with conventional urea in low-lying areas due to lower N loss from PCU during saturated soil conditions in the early spring. Therefore, a variable-source N-fertilizer strategy for targeted application of EEFs and conventional N fertilizer can increase crop production and N recovery efficiency and is a feasible management option for reducing N losses due to the waterlogging stress in poorly drained soils (Motavalli et al., 2003).



*Precision agriculture technology can be utilized for identifying management zones. Source: Susan Moran, Landsat 7 Science Team and USDA-ARS.*

As with variable-rate N application, multi-hybrid planting is becoming increasingly possible in many of the main agricultural areas of the United States. Multi-hybrid planting allows producers to place hybrids with traits that match particular areas of a field. For example, planting flood-tolerant hybrids in low landscape positions in South Dakota that are prone to waterlogging and planting drought-tolerant hybrids at the upper landscape positions resulted in an increase in yields (Sexton et al., 2013; Sexton et al., 2014). However, there is very limited information available on the use of multiple-hybrid planting for agricultural fields prone to abiotic stresses such as flooding or drought. Further research is needed in the use of multiple-hybrid planting in agricultural fields of variable soil characteristics and to evaluate the economic benefit of using this practice at the farm scale. Delin and Berglund (2005) concluded that poor-performing areas in agricultural landscapes, including areas that are susceptible to waterlogging during wet years, can be better managed with precision agriculture techniques utilizing variable-rate and/or source N application in conjunction with variable hybrid and plant population plantings. Additionally, the decision making of the split application of N to the crop can be based on the remote-sensing imagery obtained from unmanned aerial vehicles in season, and targeted areas can be aerial-sprayed with fertilizer mixes to enhance yields.

## Crop Modeling and Decision Support Systems

There are many models that can simulate crop growth and yield in response to soil waterlogging such as SWAGMAN Destiny (Meyer et al., 1996), DRAINMOD (Skaggs, 2008), and the Agricultural Production Systems Simulator (APSIM; Asseng et al., 1997). These models can be used to assess the impact of changes in management practices on alleviation of waterlogging stress on crop plants and identifying areas or conditions that will cause yield reduction. For example, Bassu et al. (2009) used APSIM-Wheat to predict waterlogging effect on wheat at multiple planting dates and found that an early planting date could increase crop yield only in areas having low-to-moderate waterlogging risk but did not increase crop yield in frequently waterlogged areas. However, adequacy of the process representations in these simulation models determines their success for use in estimating waterlogging stress (Shaw et al., 2013). In addition, GIS and remote sensing can be used for identifying areas in field that are vulnerable to soil waterlogging or drought conditions and can help in precision placement of any crop or nutrient management practice to reduce waterlogging stress. For example, using cover crops only in areas of maximum nutrient losses might result in reducing the cost of cover crop planting and saving money for farmers. There is need for decision support tools for producers for decision making about the implementation of precision placement of different crop management practices for alleviation of soil waterlogging stress. McLellan et al. (2018) described the Right Practice, Right Place (RPRP) Toolbox, which includes a set of online conservation-planning tools that can link the "right conservation practice" to "right place" at the regional, watershed, and field scale to help increase the efficiency and effectiveness of water quality improvement efforts. Merriman et al. (2019) used the Soil and Water Assessment Tool (SWAT) model to evaluate the effectiveness of multiple agricultural best management practices (BMPs) either as a single BMP or combination of BMPs on nutrient losses from agricultural fields. Although these decision support tools are evaluated for determining BMPs for water quality improvement, they have not yet been tested for assessing the effectiveness of BMPs for mitigating waterlogging stress in different soil and environmental conditions. Such models can act as tools for crop producers to make informed decisions about adoption of any crop management practice in areas vulnerable to waterlogging stress. However, there is limited knowledge on use of decision support tools for site-specific stationing of management practices discussed in this article in response to soil waterlogging, and future research efforts should consider further the development of crop models along with decision support tools for soil waterlogging conditions.

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