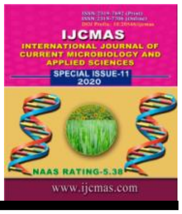
Int.J.Curr.Microbiol.App.Sci (2020) Special Issue-11: 1009-1034

International Journal of Current Microbiology and Applied Sciences
ISSN: 2319-7706 Special Issue-11 pp. 1009-1034
Journal homepage: http://www.ijcmas.com



Review Article

Impact of Water Saturated Soils on Crop and their Effective Crop Reclamation Techniques under Flooded Eco-System

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ABSTRACT

Keywords

Water logging, Climate change, Soil quality, Crop productivity, Technology, Flooded ecosystem

Flooded ecosystems are the major troubleshoots for sustainable farming. Globally, flooding is one of the most damaging abiotic stresses, besides drought, that affects 17 million km^2 of land surface annually. It is the saturation of soil with water. Soil may be regarded as waterlogged when it is nearly saturated with water much of the time such that its air phase is restricted and anaerobic conditions prevail. In extreme condition of prolonged waterlogging, anaerobiosis occurs, the roots of mesophytes suffer, and the subsurface reducing atmosphere leads to such processes as denitrification, methanogenesis, and the reduction of iron and manganese oxides. In agriculture, various crops need air to a greater or lesser depth in the soil. Waterlogging of the soil stops air getting in. How near the water table must be to the surface for the ground to be classed as waterlogged, varies with the purpose in view. Global climate change causes waterlogging events to be more frequent, severe, and unpredictable. Recent research indicates that climate change is resulting in more extreme weather events, such as flooding or soil waterlogging, that negatively affect crop production. Therefore, it is imperative to understand how flooding stress affects crops and to develop improved production practices that make cropping systems more resilient and able to cope with extreme weather events. This paper has been stressed on the current state of knowledge on the effect of flooding or soil waterlogging on crop production losses, nitrogen (N) losses, through runoff, leaching, and denitrification. Potential management practices that can be used to mitigate soil waterlogging stress include the use of waterlogged -tolerant varieties, adjusting management practices, improving drainage, and practicing adaptive nutrient management strategies to improve soil quality and crop productivity through improved ecological and economical flexibility by reducing the need for additional agricultural land. The gaps in current knowledge, technology and farm practices are identified, and recommendations are made for future opportunities to ensure sustainable soil and crop management under waterlogged conditions.

Introduction

Flooding is one of the major abiotic stresses, which affects crop growth (Lone *et al.*, 2018). climate change causes flooded situations to be more frequent, severe, and unpredictable (Intergovernmental Panel on Climate Change [IPCC], 2014). Flooding is also is a hot topic of world wide. Some currently wet areas will become wetter and prolonged waterlogging will also become more prevalent (Intergovernmental Panel on Climate Change [IPCC], 2014). Flooding caused 40–50% wheat yield reduction in a wet year. Flooding is also a matter of worldwide concern affecting 16% of the soils in the United States, 10% of the agricultural lands of Russia and irrigated crop production areas of Southern Asia (Yaduvanshi *et al.*, 2014). Better soil and crop management practices improve soil quality and crop productivity, through improved ecological and economical flexibility by reducing the need for additional agricultural land. Improved soil management can increase infiltration, reduce surface runoff, and additionally provide availability of water and nutrients to plants (Matsunaga and Marques Fong, 2018). Crop management can attribute to higher productivity.

However, N losses due to waterlogging reduce N uptake by plants and nutrient use efficiency and ultimately affects surface and groundwater quality. Therefore, it is important to understand plant responses to waterlogging stress and identify the potential management strategies to reduce the adverse effects of the waterlogging stress. Most previous review studies on soil waterlogging have stressed on the plant responses and adaptions to soil waterlogging. The factors affecting waterlogging injury to crops and plant responses and adaptations in response to flooded stress are briefly discussed. A smart overview and layout of this review paper are depicted in Figure 1.

Current scenario of India

The major waterlogged soils are present in West Bengal, Orissa, Bihar and Uttar Pradesh. Globally, flooding is one of the most damaging abiotic stresses, besides drought, that affects 17 million km^2 of land surface annually.

Effect of saturated or flooded conditions on soil and plant growth and development

Soil saturation in the plant-rooting zone is influenced by several factors including climate, factors that affect the amount of water entering into the soil, the amount of water moving through or over the surface of the soil, and use of soil water by plants and other organisms. A major reason for the increase in flooding or waterlogging is the increase in the frequency of extreme precipitation events and multiple wet days. Precipitation amount, number of precipitation events, event size, and time between events differentiates extreme wet years from dry years (Knapp *et al.*, 2015). In the upper Midwestern United States, the frequency of days with heavy precipitation has increased by 50% during the 20th century. During extreme wet years, precipitation amounts differed from average years by approximately 40% in regions receiving 1,000-mm mean annual precipitation (Knapp *et al.*, 2015) with multiple extreme daily precipitation events occurring as often as twice compared to average or dry years. Human alterations in land use and stream channels, in addition to increased precipitation frequency and intensity, are another reason for increases in flooding.

Soil compaction caused by tractor wheel traffic in the field can decrease infiltration, permeability, and water flow through the soil profile and can cause flooding. Soil compaction also increases impedance to root growth and can influence the seed germination, emergence, and growth of crops. Compaction causes a rearrangement of soil particles, changes bulk density, aggregate stability and/or arrangement, and affects soil structure, which subsequently changes the movement of air in the soil profile. Soil preparation for rice (*Oryza sativa*) cultivation to create flooding conditions for rice in Asian countries results in subsoil compaction, which causes poor drainage and consequently, soil waterlogging problems for the succeeding wheat crop.

Waterlogging hinders the growth of plants by reducing the dispersal of oxygen through the pore spaces in the soil around the root zone with the dispersal of oxygen being 320K times lower than that in non-submerged soils. The plant root needs an adequate supply of oxygen so as to fulfil the water and nutrient requirements of the shoots, and the soil oxygen concentration should be above 10%, where atmospheric molecular oxygen concentration is 21%. Under waterlogging conditions, oxygen demand to the root tip and to the rhizosphere is supplied by forming aerenchyma through removal of some cells of the cortex and these remove excess gases from the root and soil. A number of hydroponic or inert substrate experiments assessed the effect of hypoxia and anoxia on plants in waterlogged conditions, and determined the soil is a vital factor (Morales-Olmedo *et al.,* 2015).

Excessive water percentage in the soil upon waterlogging decreases O_2 diffusion capacity, leading to hypoxic or even anoxic environments that inhibit the activity of nitrifying communities, resulting in depleted soil N availability that will negatively affect N-dependent crop productivity (Jaiswal and Srivastava, 2018) Thus, the rate of nitrification is estimated to decrease in response to waterlogging conditions (Nguyen *et al.*, 2018). Moreover, decreasing molecular oxygen prompts a sequence of changes in the physico-chemical properties of the soil. Many of these also change soil chemical and electro chemicals by decreasing redox potential and excess electron changes, such as Fe^{+3} and Mn^{+4} to Fe^{+2} and Mn^{+2}, correspondingly (Singh and Setter, 2017). Thus, solubility of iron and manganese rises to toxic levels, which are potentially damaging to plant roots (Sharma *et al.,* 2018).

Apart from the elemental toxicities to the sensitive root tips, increased concentration of secondary metabolites such as phenolics and volatile fatty acids may become injurious in the low-pH rhizosphere (Coutinho *et al.*, 2018). pH values of waterlogged soil can be further reduced by the accumulation of volatile organic acids as well as the high concentration of CO_2 which reduces root growth. As mentioned, another potential toxic metabolite found in waterlogged soil is ethylene, which suppresses root expansion growth. In addition, with the re-introduction of oxygen at the recovery phase, the remaining ethanol in anoxic cells will be transformed into acetaldehyde which may cause cell injuries. Under abiotic stress conditions, reactive oxygen species (ROS) levels are always elevated compared to pre-stress levels. Excessive production of various ROS such as superoxide radicals, hydroxyl radicals, hydrogen peroxide, and singlet oxygen found in hypoxia-stressed leaf and root tissues can also cause severe damage to plants. All of these lead to restricted root growth, reduced tiller number, premature leaf senescence and production of sterile florets thus affecting the grain yield (Cannarozzi *et al.,* 2018).Even though the accumulation of phytotoxic compounds requires time, the absence of oxygen alone is enough to change the plant metabolic activities to critical levels. O_2 deficiency during waterlogging leads to reduced availability of energy in the roots and, as a result, energy-dependent processes such as nutrient uptake are inhibited. N deficiency is believed to be the other cause of the suppression of growth under waterlogging. Carbohydrate (the energy reserve) production reduced dramatically during complete submergence or subsequent de-submergence due to reduced photosynthetic rate (Perez-Jimenez *et al*., 2018), reduced stomatal conductance, declined root hydraulic conductivity and reduced translocation of photo assimilates.

The stomata closure was attributed to abscisic acid (ABA) transport from older to younger leaves or de novo synthesis of this hormone. Waterlogging also decreases the leaf chlorophyll content. This decrease in chlorophyll directly or indirectly affects the photosynthetic capacity of plants (Yu *et al*., 2019). This decrease in transpiration and photosynthesis is attributed to stomata closure which restricts CO_2 movement (Chu *et al*., 2018). To summarize, waterlogging affects overall plant growth, which leads to a substantial yield loss.

Oxidative damage induced by reactive oxygen species (ROS)

Despite the fact that oxygen is important for life on earth, its reduction by any means could result in the production of ROS perturbing several cellular metabolic processes of plants. Lethal reactive oxygen species include superoxide ($O2^{-}$), hydrogen peroxide (H_2O_2) and the hydroxyl radical (OH). Singlet oxygen generated due to the reaction of oxygen with excited chlorophyll, is also considered as potential ROS. These ROS are extremely reactive in nature and induce damage to a number of cellular molecules and metabolites such as proteins, lipids, pigments, DNA etc. ROS are also produced in plants under normal conditions or nonstresses conditions but their concentration is very low. However, when plants are facing some environmental stress like waterlogging stress, the concentration of ROS is elevated to a level that is damaging for several cellular metabolic reactions of plants such as photosynthesis, efficiency of PS II. For example, elevated cellular levels of hydrogen peroxide result in inhibition of Calvin cycle.

Antioxidant defense mechanism of plants under waterlogged conditions

All the plants have the ability to detoxify the adverse effects of ROS by producing different types of antioxidants. Generally, antioxidants are categorized into enzymatic and non-enzymatic antioxidants. Enzymatic antioxidants include ascorbate peroxidase (APX), superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), glutathione reductase (GR), whereas, ascorbic acid, glutathione, tocopherols and carotenoids are included in non-enzymatic antioxidants.

A marked alteration in the endogenous levels of different enzymatic and non-enzymatic antioxidants has been recorded in a number of studies. For example, when mungbean plants were subjected to waterlogging stress, the activities of various enzymatic antioxidants such as glutathione reductase (GR), superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX) decreased marked. These authors also stated that oxidative damage was not directly involved in the impairment of photosynthetic machinery of plants under waterlogged conditions. In contrast, increase in the activities of different enzymatic antioxidants was recorded in maize seedlings when subjected to varying degree of waterlogging stress. From these, it is amply clear that plants when exposed to waterlogged conditions employ antioxidant defence system to get through the damaging effects of oxidative stress induced by ROS.

Morphological and anatomical variations

Waterlogging stress is also known to cause a number of morphological and anatomical changes in plants. For example, the presence of hypertrophied lenticels is a common anatomical change observed in different woody species under flooding stress. Radical cell division and expansion near stem base results in hypertrophic growth. In addition, it is also believed to be associated with ethylene and auxin production. The lenticels are thought to be involved in the downward diffusion of O_2 as well as, the compounds produced as by-products of anaerobic metabolism (ethanol, CO_2 and CH_4). Although, the actual physiological role of lenticels is still unclear, their presence is often linked to waterlogging tolerance in plants. Moreover, the number of hypertrophied lenticels is more under the water surface that supports the argument stating their involvement in maintenance of plant water homeostasis and deviating from the argument that dictates their role as important facilitators of oxygen entry toward the root system. Their potential role in the plant water homeostasis is evident from their active involvement in partially replacing the decaying roots and facilitating water intake for the shoot. Formation of adventitious roots potentially replacing the basal roots is considered as one of the potential morphological adaptations depicted by plants under waterlogging stress. These specialized roots maintain the continuous supply of water and minerals when the basal root system fails. Another important morphological response of plant is the development of lacunae gas spaces (aerenchyma) in the root cortex. The formation of aerenchyma is considered as an adaptive response of the plant under flooding stress. There are two types of processes involved in the development of aerenchyma. The first is constitutive development of aerenchyma as it is not linked with the abiotic stress. It is formed by the cells separated during tissue development. This type of cell death occurring as a result of cell separation is termed as schizogony, regulated developmentally and independent of external stimulus. It is formed as a result of highly regulated tissue specific pattern of cell separation. The second type of aerenchyma development is known as Isogeny since it is formed due to partial breakdown of the cortex that resembles programmed cell death and its formation depends on the external stimulus like abiotic stress.

Physiological and metabolic changes in plants due to flooding stress

(a) Respiration

Soil waterlogging inhibits plant growth by creating hypoxic (oxygen deficient) or anoxic (complete absence of oxygen) conditions in the soil. The diffusion rate of oxygen in water is approximately 1/10,000th that of air, and the flux of O_2 into soils is approximately 320,000-times less in water-filled soil pores compared to gas-filled soil pores. In plants, respiration is the main metabolic process affected by soil waterlogging. Oxygen is an electron acceptor in the oxidative phosphorylation process generating energy as adenosine triphosphate (ATP) and regenerating NAD^+ from NADH, which is used as a reducing power for biochemical pathways. The NAD^+ and NADH are the oxidized and reduced forms of nicotinamide-adenine dinucleotide (NAD).Lack of oxygen in waterlogged soils for root respiration reduces root growth. Soil phytotoxins also inhibit root formation and promote root decay in flooded soils. Due to the waterlogged conditions, roots are not able to exploit a large soil volume and tend to grow near the soil surface. Flooding also reduces nodulation and nitrogenase activity in soybean due to a reduction in oxygen supply. Mutava *et al.,* (2015) reported that flooding stress significantly increased glucose concentration in the leaves, but decreased sucrose and raffinose concentration in a flood-susceptible soybean cultivar. Alteration in sugar status due to abiotic stresses in plants affects gene expression by down- and up-regulating their expression.

(b) Photosynthesis

The waterlogging injury also reduces photosynthesis (Mutava *et al.*, 2015), possibly due to stomatal closure, abscisic acid (ABA), ethylene, and active oxygen species production. Photosynthesis was CO_2 limited in waterlogged plants. The partial stomatal closure was a response to waterlogging to prevent leaf water deficits and wilting, rather than being a response to low leaf water potential. The stomatal closure also limits CO_2 in plant cells and consequently, results in accumulation of oxygen free radicals. Plants suffer oxidative stress under waterlogged conditions through an increase in reactive oxygen species, such as superoxide ($O2^{-}$), singlet oxygen (1/2 O_2), hydrogen peroxide (H_2O_2), and hydroxyl radicals (OH^{-}) produced in chloroplasts during the electron transport along the electron chain. Waterlogging at the post-anthesis stage significantly reduced wheat root respiratory activity, leaf greenness (SPAD reading), photosynthetic rate, stomatal conductance, transpiration rate, grain number per spike, 1,000-grain weight, grain yield, and increased intercellular CO_2 concentration (Mutava *et al.*, 2015).

Effects of waterlogging on soil and N_2 availability

Changes in soil due to waterlogging

Oxygen is the most important electron acceptor for microbial decomposition of organic C compounds in soil and sediments due to its ample supply in the atmosphere, easy diffusion into soil pores and ease of reduction. Under anoxic conditions, the reduction of O_2 is followed by NO_3^{-}, Mn^{+4} and Fe^{+3}, SO_2^{-} and CO_2. Microbial activity mainly controls redox reactions in soils. Reducing conditions in the soil can be quantified by measuring redox potential (Eh). Redox potential measurements also help to determine whether chemical compounds, such as NO_3^{-}, are present in their oxidized form or in chemically reduced forms which may affect N losses such as N_20 emissions resulting from denitrification. Soil redox potential normally varies between −300 and +900 mV, whereas Eh of reduced soils can be between −300 mV to +400 mV (Sahrawat, 2015). Soil Eh varies depending upon multiple factors including the amount of organic matter, the nature and content of electron acceptors, temperature, pH, and the duration of submergence.

Nitrogen losses from soil

Soil waterlogging causes reduction in nitrate concentrations in soil (Zurweller *et al.*, 2015). For instance, Zurweller *et al.*, 2015 found a reduction in NO_3–N concentrations following 3–5 week of soil waterlogging. Zurweller *et al.*, (2015) reported a rapid decline in soil NO_3–N concentration with each day of waterlogging amounting to a 61% lower soil NO_3–N concentration in waterlogged treatments than in a nonwaterlogged control.

Denitrification

Denitrification is the process of reduction of NO_3^{-} to molecular N or other gaseous forms of N by both heterotrophic and autotrophic bacteria, known as denitrifies.

$$\mathbf{2NO_3^{-} \rightarrow 2NO_2^{-} \rightarrow 2NO^{-} \rightarrow N_2O \rightarrow N_2}$$

Denitrification process occurs under anaerobic soil conditions caused by waterlogging or flooding. Soil surface N_2O

emissions show positive correlations with soil temperature, water-filled pore space, and mineral N content in soil and are increased by soil waterlogging. Soils with restrictive layers to drainage, such as claypan soils, are more susceptible to N losses via denitrification due to the formation of a perched water table in the surface soil layers because of the low hydraulic conductivity of the claypan subsoil (Mutava *et al*., 2015). Aerobic N transformations in claypan soils are limited by the wet conditions due to combinations of poor drainage and excessive rainfall events, especially in spring season. In poorly drained claypan soils, a study conducted by Zurweller *et al.,* (2015) showed that a major proportion of cumulative surface soil N_2O emissions occurred mostly during and shortly after a soil flooding event. In the same research, the proportion of N fertilizer lost as N_2O–N varied from 0.03 to 0.04% in nonwaterlogged soils and 1.1–2.6% in the waterlogged soils during the 2-yr field experiment.

Nitrate leaching

Nitrate leaching is the process of movement of NO_3–N through the rooting zone. Due to its high solubility and relative lack of surface retention in the soil, NO_3–N is highly susceptible to both lateral and vertical transport by water through the soil profile. Around 10–40% of applied N can be lost through leaching depending upon the application time, fertilizer source, and the crop being fertilized. Restricted water movement due to the lower permeability of argillic horizons reduces NO3–N leaching in soils with subsoil restrictions such as claypan soils. Preferential flow paths developed by biological (e.g., worm burrowing or root growth) or physical processes (e.g., desiccation) are other pathways for rapid movement of N to shallow groundwater. Flooding and waterlogging can result in greater NO_3–N leaching in low cation exchange capacity and sandy texture soils where residual or surplus N concentration are higher after harvesting the cash crop.

Effects of waterlogging on N uptake and assimilation

Reduced root conductance due to waterlogging can lower N absorption and consequently, limit N transport and distribution in the plants, with a reduction in the concentrations of N, P, K, Mg, and Zn in leaves and stems and increased concentrations of these elements in the plant root system. Multiple studies have reported N deficiency symptoms in plants under waterlogging stress. Negative correlation of flood duration with soybean leaf N concentration. Transient N deficiency occurred in wheat due to waterlogging stress, even when the plants were supplied with N at the time of planting. Reduction in N uptake, N recovery, and agronomic efficiency due to waterlogging was also observed in cotton and Bahia grass (Kong chum, 2013). Chlorophyll meter leaf readings were shown to be strongly correlated with leaf chlorophyll concentration or greenness and with leaf N status (Kong chum, 2013).

Use of N fertilization for recovery from waterlogging injury

Plant tolerance to waterlogging stress may increase by N fertilizer applications as they may enhance and accelerate plant adaptive mechanisms to waterlogging, such as adventitious root growth and root regrowth after a flooding event. Under waterlogged conditions, N losses through denitrification and leaching may cause N deficiencies, decrease N availability, and inhibit root function resulting from low oxygen levels under waterlogged conditions that may reduce plant N uptake (Nielsen, 2015). Supplemental N ameliorates root respiration and photosynthetic rate in wheat by promoting synthesis of enzymes for photosynthesis, inhibiting abscisic acid production and stimulating gibberellic and cytokinin synthesis. Greater N rates applied prior to waterlogging promoted root vigour of cotton seedlings after waterlogging stress in a growth chamber study (Zhou and Oosterhuis, 2012).

Crop production losses due to soil water flooding

Based upon previous literature, yield losses ranging from 1 to 100% can occur due to waterlogging stress, depending upon the crop, waterlogging duration, and crop growth stage. However, the impact of soil waterlogging on crop yields can vary in different regions due to the variation in regional climatic and economic conditions, soil types, plant species and age, and management differences. Soil waterlogging resulting from extreme precipitation events is another major contributor to the crop production losses, in addition to floods. Crop production losses due to temporarily saturated soils are a persistent problem in the Midwestern United States. In upland areas excessive rainfall created saturated soil conditions that caused about 70% of the crop losses during the 1993 Mississippi floods. A decrease in corn and soybean yields was also reported by Singh *et al.*, (2016) due to soil waterlogging in low-lying topographic positions (Singh *et al.*, 2016). Soil waterlogging at vegetative and reproductive stages resulted in soybean seed yield reduction of 17–43% and 50–56% respectively. Urban, Roberts, Schlenker, and Lobell (2015) reported that soil waterlogging during the spring season caused 1–3% yield loss for corn and soybean crops in three U.S. states including Illinois, Iowa, and Indiana, over the 62-yr study period from 1950 to 2011.

Another issue with soil waterlogging is the inability to operate machinery in wet conditions which can delay planting or harvesting (Urban *et al.*, 2015), and consequently can reduce crop yields.

Soil management practices under marshy conditions

Soil management practices such as drainage, tillage and traffic control can alter soil structure directly or indirectly. Many of these changes are relatively short term and reversible. Management-induced changes in the quantity and characteristics of soil can also lead to changes in soil structure that are much more persistent. Management practices which are sustainable must maintain the structure of soil, over the long term, in a state that is optimum for a range of processes related to crop production and environmental quality (Belmonte *et al.*,2018).Soil surface biological communities provide critical functions in many ecosystems by controlling infiltration and thus ensure suitable water availability for crop, soil biota, nutrient cycles and vascular vegetation. They increase biodiversity, accelerate soil formation rates, and contribute to the biogeochemical cycling of nutrients by fixing atmospheric carbon (C) and nitrogen (N) (Weber and Hill, 2016). Therefore, a key consideration in designing management practices must be targeting the soil surface.Various soil management practices can mitigate adverse effects of waterlogging stresses. Here, we review some soil management practices emphasizing the system used for waterlogging-prone areas.

Controlled traffic farming (CTF) for flooded stress soils

Controlled traffic farming (CTF) is a management system to control extensive unsystematic trafficking by farm machinery and protect soil structure from indiscriminate change. CTF is a crop production system where the crop area and traffic-lanes are markedly divided. It creates two distinct zones, the crop region which is non-trafficked and traffic region or non-cropped. Consequently, CTF systems always maintain the crop region unaffected by wheel tracks, whereas the traffic zone develops into a compacted zone for machinery draught efficacy.

CTF is differentiated from conventional traffic practices, known as random traffic farming (RTF) by reducing the trafficked area.Random traffic farming or disorganized traffic causes increases in the soil bulk density resulting in increases in strength limiting soil porosity further leading to soil compact. RTF has an adverse effect on a wide range of soil physical characteristics, including the infiltration and drainage of water, amenability for crop sowing, establishment and nurture, and soil gaseous exchange medium and soil-living organism. Due to random traffic a large amount of soil is adversely affected resulting in soil degradation issues in Australia (4 million ha), Europe (33 million ha), Asia (10 million ha), Africa (18 million ha) (Shahrayini *et al.*, 2018).

The advantages of CTF have been well documented. These include reduced incidence of waterlogging, soil compaction, erosion, tillage, water and nutrient losses and thus increased crop yield.

Effective deep tillage and manuring of subsoil under waterlogged stress situations

Strategic deep tillage (SDT) is a single or occasional practice with a deep ripper, rotary, spader, mouldboard plow or disk plow to help sustain the long-standing productivity of the no-till system (Scanlan and Davies, 2019). Deep tillage or soil cultivation to loosen compact soil layers, particularly the clay subsoil, has been suggested to improve drainage in the subsoil, thus reducing waterlogging. The technique may also incorporate slotting of gypsum to reduce sodicity and improve soil structure, which also reduces waterlogging. Deep ripping loosens hard layers of soil by using sturdy tines to 35–50 cm depth. It is not suitable for all soils and crops, therefore season, timing, soil type, tine spacing, shallow leading tines, soil moisture content, and working depth are all factors that need to be taken into consideration.There are, however, several disadvantages of deep ripping including its short-term nature (especially if traffic is not managed to reduce re-compaction), effectiveness in hostile sub-soils, such as acidity, sodicity or subsoil salinity, and its implementation on a large scale. In this case, amelioration with gypsum or lime may be helpful to stabilize the soil (Matosic *et al.*, 2018). Although yield benefit from SDT has been demonstrated, organic matter, texture and soil nutrients distribution within the root zone need appropriate long-term agronomic management to maximize the benefit.Another way of reducing waterlogging is through a similar practice where large volume of organic matter with high N levels are placed within and above the heavy clay layers. This practice is referred to as sub-soil manuring. In south eastern Australia approximately 80% of the cropping zone of medium annual rainfall (375–500 mm) and high rainfall (>500 mm) are affected by subsoil constraints.

Prominent seepage systems for water filled stress soil conditions

Land drainage is one of the main approaches to improve yields per unit of accessible agricultural area. Reducing soil submergence, salinity control, and making new land accessible for agriculture are the three main objectives of agricultural drainage (Singh, 2018). However, drainage, an efficient agriculture engineering system to combat waterlogging, has not been given equal importance when compared to irrigation by individual farmers and governmental agencies.

A surface drainage systems for high water stressed flooded soils

Surface drainage is defined as the safe removal of excess water through constructed channels from the land surface. Surface drains such as ‘spoon-drains,’ ‘W-drains’ and reverse seepage interceptor banks and interceptor drains have been used to alleviate the conditions of waterlogging in south-western Australia. Surface drainage systems have been shown to be cost effective with cost-benefit ratios being in the range from 1.2 to 3.2, internal return rates from 20 to 58%, and payback periods from 3 to 9 years.

The simplest and cheapest option is to maintain existing surface drains and install extra drains along fence lines or through depressions considering adequate size and proper position. Preventing water flow from upper to lower paddocks with cut-off drains should also be implemented (Palla *et al.*, 2018). However, the success of surface drainage is often limited due to the poor lateral water movement or internal soil drainage properties, which results in poor drainage in the vicinity of the drains. Both surface and subsurface drainage may thus be required to solve these problems.

Conservative raised bed system for waterlogged fields

The use of raised beds is better option for soil management option to improve crop yield, soil structure, and productivity under waterlogged conditions (Hussain *et al.*, 2018). The beds reduce waterlogging and improve the overall soil structure through installing shallow drains or furrows approximately 15–20 cm wide at regular intervals. These are then used for tractors, and sprayers to control traffic movement over the paddock (control traffic farming).The 2–3 m wide and 10–30 cm height bed is formed using soil creating a raised bed allowing water to drain away from the plant root zone and reducing the likelihood of waterlogging damage. Planting on beds also diminishes pesticide applications due to a reduction in fungal and other diseases with improved radiation interception, acquisitive temperature and reduced humidity in the canopy.

When seasonal conditions are appropriate, raised beds can significantly increase grain yield under waterlogged conditions compared with crops grown conventionally on flat ground. The use of raised beds is also prominent in high rainfall areas across Victoria and experiments demonstrated that wheat and barley yield increased by 50% and 30%, respectively (Collis, 2015).While raised beds have had a positive impact on alleviating the effects of waterlogging, they also have a number of disadvantages. These include the cost of adapting and modifying machinery, greater difficulty in controlling sowing depth and seed placement on beds, management of drainage water, limited use where the water table is too high, stubble handling and fodder conservation, firefighting and mustering livestock, the possibility of pesticide contamination into waterways and leaching into the water table and inefficiencies of machinery and weed control in furrows. .

Appropriate subsurface drainage system for waterlogged soils

Poor subsurface water movement occurs due to the inability of water to move through soil as a result of heavy soil texture, compacted layers and naturally created or induced hard pans as well as water moving downhill from upper slopes or from springs, raising the water table (Hussain *et al.,* 2018). Subsurface drainage lowers the water table or perched water and ensures a suitable environment in the root region where waterlogging occurs. About 50% of waterlogged areas in western Europe, 20–35% of total cultivated land in Europe and North America, 5–10% in Asia, Australia, and South America, and 0–3% in Africa have used subsurface drainage measures. Subsurface drainage systems consist of open and pipe drains with variable drain depth and spacing. The systems are more effective in areas where the subsoils are sufficiently stable and not exhibiting characteristics of hostile sub-soils such as sodicity. Subsurface pipe drains are the main forms of subsurface drainage found in the HRZ of Australia. Usually, the type of drain to be installed depends on topography, soil characteristics and rate of drainage required. There has been successful use of sub-surface drainage in areas of Tasmania, Australia and grain growers are willing to invest in drainage as a long-term solution to waterlogging. This is also supported by a study into the economics of drainage, which indicated that subsurface drainage provided crop growers with the confidence to target high potential yields where the cost benefit was positive. Although, subsurface deep drains (depth > 1.75 m) are recommended in India, these deep drains can be economically installed only by mechanical construction practices, and the deeper the drain the higher the installation cost. In some parts of India, several types of subsurface drainage were found to be unsuccessful because they were expensive and failed to control surface water. Managing waterlogging with horizontal tile drainage systems is more beneficial in maintaining the water table within the desirable depths.

Effective subsurface pipe drain system for inundated soil

Horizontal subsurface drainage removes excess water from the crop root zone (Teixeira *et al.,* 2018). Below the ground surface, the drainage structure comprises a grid of perforated pipes connected to control the water table. Tile drainage is a form of horizontal subsurface drainage consisting of small pipes of concrete or burnt clay installed at a certain depth below the ground surface. Tile drainage is used widely in agricultural areas where subsoil surplus water is a common problem. To improve the system gravel is usually used above the tile drains as a backfill material in the areas where there is shallow groundwater and heavy soil conditions. Besides water table control, horizontal drainage controls soil salinity in the root zone of the soil by leaching out the concentrated and harmful salt solutions. This is an established and significantly relevant system for saline land reclamation in India in irrigation areas where excess soil salinity is the prime limitation in agricultural production. However, this method may not be suitable for agricultural lands where the top soils are prone to seasonal waterlogging due to poor hydraulic conductivity and the need to find appropriate outfall for drained water (Prathapar *et al.*, 2018).

Productive vertical subsurface drainage system for submerged soil

Vertical drainage (VD) is used for controlling rising groundwater levels in some parts of Australia such as Burdekin, Kerrang, and Shepperton. Recent results showed that installing VD can reduce the duration of seasonal waterlogging in Bihar, India (Prathapar *et al.,* 2018). Various types of vertical drains have been used to consolidate the soil, such as prefabricated vertical drains (PVDs), sand compaction piles, sand drains, gravel piles and stone columns.

The VD system has some advantages over other subsurface drainage systems. For example, VDs are often preferred because of relative low capital cost and the length of open surface drains is less with VD when compared with other types of drainage. VDs also allow the groundwater level to be lowered to a greater depth than other drainage systems. However, the maintenance and operational costs are higher than horizontal drainage systems as it involves high energy to operate a network of tube wells (Prathapar *et al.*, 2018). The effectiveness of the VD system is demonstrated by the drop in the groundwater level; therefore, the system is more suitable for an area with fluctuating high levels of groundwater.

Operative mole drains system for inundated soil

Mole drainage is another form of subsurface drainage. Its effects on reducing waterlogging have been shown in Victoria, Australia. Mole drain systems were found to improve performance in terms of growth parameters, yield attributes and economic parameters of soybean (*Glycine max*) and wheat (*Triticum aestivum*) in Madhya Pradesh, India (Dhakad *et al.*, 2018). Mole drains are a semi-permanent system from a layout and operational point of view and are similar to tile drainage. Although costing less than tile drainage, they do require more maintenance (Tuohy *et al.*, 2018). This drainage system is generally installed to manage rising groundwater levels and land salinization problems. it relies on closely spaced channels and subsoil cracks to quickly send surplus soil water to the tile or agricultural (ag) pipe drainage system throughout the season. They are installed in close proximity to tile drains and are most suitable for low-permeability heavy soils such as clay. These drains should be installed at less than 600 mm from the ground surface and form 40–50 mm diameter circle of drainage. A mole drain can be formed by dragging a metal object through the soil which creates an open channel. Combined drainage systems (mole and tile drainage) can be used efficiently to simulate water balance and drainage network system over a watershed, and to aid drainage management in a floodplain landscape (Tuohy *et al.*, 2018).

Agronomic management practices for crop plants

There are a large and diverse number of crop management practices used by grain growers to alleviate the effects of waterlogging. These include: crop choice, waterlogging tolerant crop varieties, bio-drainage, and different agronomic practices such as sowing time, nutrient application and plant growth regulators (PGRs).

Early planting and vigorous plants

Crop management options to increase crop water use and decrease the incidence of waterlogging include early sowing and higher sowing rates. Early sowing of wheat varieties showed better performance (Ali *et al*., 2018) due to reduced risk of waterlogging damage through de-watering of the soil profile and avoiding waterlogging at vulnerable early growth stages. Wheat, barley and rapeseed plants were less affected by early waterlogging (vegetative stages) than late (reproductive stages). It can be another important trait for waterlogging tolerance in the field. Tillering and reproductive stages are crucial for waterlogging tolerance in crops such as wheat and barley. Reduced nitrogen uptake is one of the main effects of waterlogging stress in crops (Jaiswal and Srivastava, 2018). It may be linked with increased uptake of nitrogen. However, under normal conditions seedling growth rates can also vary with genotypic differences. Further research may provide more insight into the interactions and possible use of early vigour to mitigate the effects of waterlogging.

Plant adaptations to waterlogging stress

Plants have several adaptive mechanisms to cope with waterlogging or flooding stress, such as the formation of airspace (aerenchyma) in the root cortex, stem enlargement (hypertrophy), radial root oxygen barrier, adventitious root formation (especially near the soil surface), and early root tip death. Aerenchyma is the term used for plant tissues containing enlarged gas spaces to provide a low resistance internal pathway for gas exchange between aerobic shoots and anaerobic roots. Aerenchyma helps the plant in delivering oxygen to the root tip and rhizosphere as well as remove gases (CO_2, ethylene, and methane) from the root and soil (Colmer and Flowers, 2018)Adventitious roots are formed from the submerged part of the stem in flooded plants and grow horizontally close to the surface so that oxygen is more available to these roots compared to belowground roots.Diffusion of gases between shoots and roots is facilitated by the presence of large airspaces in the adventitious roots. Adventitious roots often contain more aerenchyma compared to the primary lateral roots and thus are less affected by the anaerobic conditions caused by waterlogging. Studies have also shown an increased contribution of the apo plastic bypass to water flow and reduced dependence of roots on the hypoxia-sensitive aquaporin-mediated water transport in the adventitious roots.

Genetic variation for waterlogging tolerance

Plants under waterlogged conditions exhibit marked up and/or down-regulation of a number of genes. By investigating the induced expression of these genes in low oxygen environment, it is possible to identify certain gene products. Then these potential genes involved in conferring waterlogging tolerance can be isolated and introduced into the transgenic plants in order to identify their possible contribution in stress tolerance. Early studies performed by isotopic labelling of maize roots with 35S-methionine clearly indicated the synthesis of anaerobic polypeptides when plants were subjected to low oxygen environment. The anaerobic polypeptides include the enzymes involved in fermentation, that is, pyruvate decarboxylate, alcohol dehydrogenase and lactate dehydrogenase.

Use of tolerant varieties and suitable genotype cultivars

One of the key economical approaches for reducing the loss caused by waterlogging is to introduce waterlogging tolerance into existing plant varieties. Genetic differences exist for tolerance to waterlogging in different crops which include barley and wheat (Nguyen, *et al.*, 2018). However, waterlogging tolerance is a complex trait which is controlled by many different mechanisms, such as aerenchyma formation in roots (Luan *et al.*, 2018) under waterlogging stress, tolerance to secondary metabolites ion toxicities (Huang *et al.*, 2018), the maintenance of membrane potential and control of ROS production under stress, with many QTL being reported to control these traits. The success of a breeding program relies on the discovery of genes and linked markers to various tolerance mechanisms, which enable breeders to pyramid tolerance genes. 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. 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. These 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. Waterlogging caused by rainfall events in fall season can delay crop harvesting and 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 and therefore, it is also necessary to develop varieties with tolerance to both cold and waterlogging stress. 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.

Bio-drainage / bio- plantations

The incorporation of herbaceous perennial legumes such as lucerne, clovers and Messina (*Melilotus siculus*) adapted to waterlogging and inundation into cropping systems has been suggested to reduce waterlogging (Nichols, 2018). Usually these deep-rooted pasture plants can extract water and dry the soil to greater depths than most annual crops. However, there is significant variation in tolerance to waterlogging between different pasture species, and their suitability for grain production systems and how they would be integrated to provide maximum benefit has been identified as a gap in knowledge and warrants further investigation.Bio-drainage or bio-pumping is the VD of soil water using specific types of fast-growing tree vegetation with high evapotranspiration demand and is considered an economically viable option in dealing with the drainage congestion and environment hazards (Singh and Lal, 2018). Bio-drainage vegetation has been demonstrated to lower the rising water table around the root zone of adjacent cultivated crops in waterlogged areas through drainage.Lowering of the rising water table is apparent within 5–10 years of growing vegetation and trees (Singh and Lal, 2018). If trees tolerant to waterlogging are introduced into the prone areas, these can easily assist in controlling water stagnation and rising water table. The right choice of plant species with optimum plant population and suitable plant geometry will help to control the elevated groundwater table in waterlogged areas and thus maintain the desired soil moisture regime for timely cultivation.Prevention and remediation are the two stages of bio-drainage where the trees planted could provide a benefit to agriculture as well as resolving other issues such as waterlogging, salinity and shelter. Therefore, incorporation of a bio-drainage system with a conventional agriculture farming system could improve land and water productivity as well as the environment. Combining of bio-drainage with conventional drainage measures is an option to consider with the possibility of integration of silviculture and aquaculture with conventional agriculture to improve land and water productivity.

Bio-drainage systems may be established under both rainfed and irrigated conditions. When established under rainfed conditions, the plant roots reduce the soil bulk density and enhance groundwater recharge capacity. The roots also draw subsurface flow to reduce the water load. It is particularly useful when there is a perched water table and the water cannot easily move down the soil profile due to the presence of an impermeable layer. In HRZs, application of vegetative buffer strips is also effective for controlling runoff quantity and quality. Vegetative buffer strips have also been proposed as one of the best management or conservation practices to protect water bodies from nutrients, antibiotics, bacteria and pesticides applied on adjacent agricultural fields. Tree species with high transpiration rates are selected to mitigate waterlogging from canal seepage in irrigated areas. Water quality in supply canals is suitable and can be effectively intercepted and used by the trees planted along the canals (Singh and Lal, 2018).

However, the efficiency of bio-drainage plantations needs to be verified in HRZs where permanent stagnant water is a real problem. Lack of proper knowledge, plantation techniques, expertise, motivation as well as maintenance are issues that need to be addressed to derive the real benefit of this system. In addition, the land under bio-drainage cannot be utilized for growing other crops, as in the case of conventional drainage (Sarkar *et al.*, 2018). Therefore, an economic analysis of the bio-drainage endeavour is required on a case by case basis.

Cover cropping

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. Root channels from cover crops can increase macropores resulting in greater water movement through soil. For example, a cover crop mixture of bromegrass (*Bromus inermis Leyss*.) and strawberry clover (*Trifolium fragiferum* L.) reduced surface soil strength by 38–41% and increased steady infiltration rate and cumulative water intake by 37–41% and 20–101%, respectively, compared to the no-cover crop treatments. Winter cover crops can affect water availability for summer crops by decreasing evaporation while using stored water in the soil for transpiration. 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. However, the effect of cover crops on the distribution of water in soil profile can be positive, negative, or neutral, depending upon the soil type, climatic region, and cover crop species used. 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.

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 topography with cover crops for reducing waterlogging stress in large agricultural fields. The geographic information system (GIS) spatial modeling and remote sensing might be useful 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.

Nutrient management

Nutrient deficiency is one of the major effects of waterlogging on plants, resulting in reduced photosynthesis and net carbon fixation ultimately leading to a reduction in growth and therefore yield. Application of essential nutrients will assist in mitigating the negative effects of abiotic stresses like waterlogging leading to increased productivity. The use of enhanced-efficiency N fertilizers such as slow-release or controlled-release (SR/CR) fertilizers play an important role in improving plant growth and development under waterlogged conditions. Slow-release fertilizer can release nitrogen over a prolonged period during crop growth, thus maximize nitrogen-use efficiency (NUE) by synchronizing nitrogen release according to the crop demand. Waterlogging reduces the endogenous levels of nutrient in different parts of plants. Oxygen deficiency in the root zone causes a marked decline in the selectivity of K+ /Na+ uptake and impedes the transport of K+ to the shoots. Generally, waterlogging causes acute deficiencies of essential nutrients such as nitrogen, phosphorous, potassium, magnesium and calcium. In Australia, research under both controlled-environments and field conditions have shown that additional CR urea application can mitigate waterlogging effects of wheat and increase growth (Kisaakye *et al.*, 2017) and grain yield by approximately 20%. Similar findings reported by Mondal *et al.*, (2018) showed that increased rates of top-dressed urea significantly increased wheat grain yield on flooded sodic soils in India. Likewise, the use of polyolefin coated urea (a controlled-release fertilizer) resulted in a total N recovery of 66% in flood irrigated barley grown in north eastern Colorado, United States. Fertilizer application also increases canopy duration and accelerates the production of photo-assimilates translocated to the grain compared with the straw thus increasing the harvest index (Kisaakye *et al.*, 2017).Potassium fertilizer has also been reported to ameliorate the detrimental effects of waterlogging in several crops including. Exogenous application of various phosphorus (P) sources such as dairy cow manure (DCM) and meat and bone meal (MBM) is effective for producing optimum yields in P-deficient conditions during a wet growing season.

Application of farmyard manure also significantly increased grain Fe, Zn, Cu concentration of paddy under flooded conditions (Matsunaga and Marques Fong, 2018). Similarly, foliar application of boron has been reported to increase overall plant growth and alleviate deleterious effect of waterlogging of maize.The use of fertilizers to alleviate waterlogging damage in broadacre cropping, even with high value crops, has been limited by lack of research and availability of information on their potential use in improving crop performance under waterlogged conditions. Appropriate application methods, nutrient types, timing and rate should be considered to avoid the negative effect of tissue toxicities (e.g., manganese) (Huang *et al.*, 2018) and nutrient imbalance on soil ecology. The ability to predict waterlogging events (variable seasons) and therefore the crops' nitrogen demand also limits the effectiveness of SR/CR fertilizers and therefore raises the question of whether highly available N applications would be preferable when waterlogging limits growth suggested that pre-waterlogging application of N fertilizer might not be effective on wheat at the tillering stage. Application of nitrogen fertilizer during or immediately following waterlogging was less effective than pre-waterlogging due to inefficient nutrient ion absorption capacity of impaired roots, high leaching risks in the wet soils and at the late growth phase additional fertilizer applied could cause excessive vegetative growth and harvesting problems of cotton plant. Therefore, this strategy has limitations on a large-scale as the damaging effects of waterlogging can only be partially alleviated by the addition of fertilizers because of the reduced capability of roots to absorb nutrients (Kisaakye *et al.*, 2017). For example, a drop in root membrane potential by 60 mV, often observed under hypoxic conditions will require a 10-fold increase in cation (e.g., K^+ or NH_4^+) concentration.

Growth regulators for plants under saturated soils

Plant growth regulators may mitigate waterlogging damage of plants by applying at the appropriate growth stage (Nguyen H.C. *et al.,* 2018). The application of PGRs such as auxins and cytokinin's has been reported to improve plant growth under waterlogged condition. The two hormones act in concert to promote stomatal conductance and photosynthetic capacity of waterlogged plants. Synthetic auxin 1-naphthaleneacetic acid (1-NAA), was reported to promote the growth of adventitious roots in waterlogged barley plants and; exogenous application of a cytokinin, 6-benzyladenine (6-BA) can alleviate waterlogging injuries and increase yield of maize. Pre-waterlogging foliar application of ABA increased tolerance to successive waterlogging-induced injury in cotton plant by improving photosynthesis of leaf (Kim *et al*., 2018). Triazoles are known as fungitoxic and also have plant-growth regulatory effects and protect plants against various stresses. For example, paclobutrazol mitigates waterlogging induced damage in canola and sweet potato plants. Uniconazole can also increase the chlorophyll content and the activity of antioxidant enzymes in canola. Under waterlogging condition, the application of tricyclazole [5-methyl-1,2,4-triazole(3,4-b) benzothiazole] also mitigates the damage in plants. However, due to inconsistent results there has been little commercial use of PGRs to alleviate waterlogging damage.

Integrated supplementation of growth regulators and fertilizers

Integrated application of fertilizers and growth regulators can provide another option for ameliorating detrimental effects of waterlogging in crops, with the fertilizers acting as a nutrient supplier, while the PGRs assist with recovery from physiological injury .1% urea + 0.5% potassium chloride and growth regulators [brass in (0.02 mg/L) + diethyl aminoethyl hexanoate (10 mg/L)] improved growth and yield of waterlogged cotton (Li *et al.,* 2013). Both foliar nutrient and PGRs application provide opportunities for future research.

Applications of anti – ethylene compounds and substances

Plant hypoxia-induced growth and yield losses could be the consequence of increased accumulation of ethylene (Najeeb *et al.,* 2018). Use of anti-ethylene agents such as 1-methylcyclopropene (1-MCP), amino ethoxy vinyl glycine (AVG), 1-aminocyclopropane-1-carboxylic acid (ACC), amino ethoxy acetic acid (AOA), silver and cobalt ions have been reported to inhibit the synthesis or accumulation of ethylene through blocking the biosynthetic pathway (Vwioko *et al.,* 2017) of ethylene. Application of 1-MCP and AVG has been shown to diminish crop loss induced by ethylene accumulation (Najeeb *et al.,* 2018).Vwioko *et al.,* (2017) reported a positive effect of 1-MCP and AVG on cotton seed and lint yield. They determined that the initial reproductive phase is the best time for AVG application for improving cotton yield under waterlogging condition. In cotton, waterlogging prompts ethylene accumulation leading to young fruit abscission (Najee *et al.,* 2018). During waterlogging conditions, an inverse link between ethylene production and cotton yield has also been found, therefore the application of AVG can regulate ethylene production and increase both photosynthesis and fruit retention of cotton. Likewise, the positive effect of 1-MCP has been studied on hypoxia cotton plants, where it also blocked ethylene action and enhanced physiological processes, such as antioxidant enzyme activity and stomatal resistance. Utilizing an ethylene-insensitive cotton mutant (eliminating ethylene sensitivity) may be another option for waterlogged areas, where the mutant plant showed a remarkably improved yield of cotton. There is further research required to fully understand the ethylene mediated pathways in other crops such as grains.

Chemical treatment with H_2O_2

Pre-treatment of crops with an agent may be an effective way to increase tolerance to different stresses. For example, pre-treatment with H_2O_2 can protect crops from oxidative damage caused by waterlogging, high light intensity, low temperature, salt stress, drought and exposure to heavy metals (Andrade *et al.*, 2018). Priming seeds with H_2O_2 generated seedlings exhibiting elevated activity of antioxidant enzymes, low H_2O_2 and $O_{2.}$ content, and low cell membrane damage under waterlogged conditions. H_2O_2 pre-treatment also resulted in increases in net photosynthetic rate and photosynthetic pigments, root volume, high biomass accumulation, and stem diameter (Andrade *et al.*, 2018). Despite much research being conducted on priming with agents against biotic and abiotic stresses, pre-treatment with H_2O_2 tolerant to waterlogging still in its infancy.

Precision farming with smart technologies

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 foot slope slopes of terraced fields in Missouri due to waterlogged conditions prevailing in the channel and foot slopes. 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 reduces soil solution nitrate-N at foot slope positions possibly due to N loss through denitrification, which further contributed to lower corn and soybean yields at foots lope land scape positions. Smart 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. 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. 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 on farm scale 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 modelling approach and decision supporting system tools

There are many models that can simulate crop growth and yield in response to soil waterlogging such as SWAGMAN Destiny, DRAINMOD and the Agricultural Production Systems Simulator. 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. However, adequacy of the process representations in these simulation models determines their success for use in estimating waterlogging stress. 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 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.

Table.1 Current scenario of India

States	Waterlogged soil(ha)	States	Waterlogged soil (ha)
Andhra Pradesh	10654	Maharastra	0
Arunachal Pradesh	0	Manipur	8517
Assam	46021	Meghalaya	1606
Bihar	188070	Mizoram	0
Chhattisgarh	521	Nagaland	0
Goa	0	Orrisa	242838
Gujrat	0	Panjab	0
Haryana and Delhi	0	Sikkim	0
Himachal Pradesh	0	Rajasthan	4108
Jammu&kasmir	0	TamilNadu	0
Jharkhand	3321	Tripura	14721
Karnataka	0	Utter Pradesh	131428
Kerala	0	Uttaranchal	0
Madhya Pradesh	333	West Bengal	240480

Figure.1 Outline of flooding causes, crop production and nitrogen losses, and potential management practices

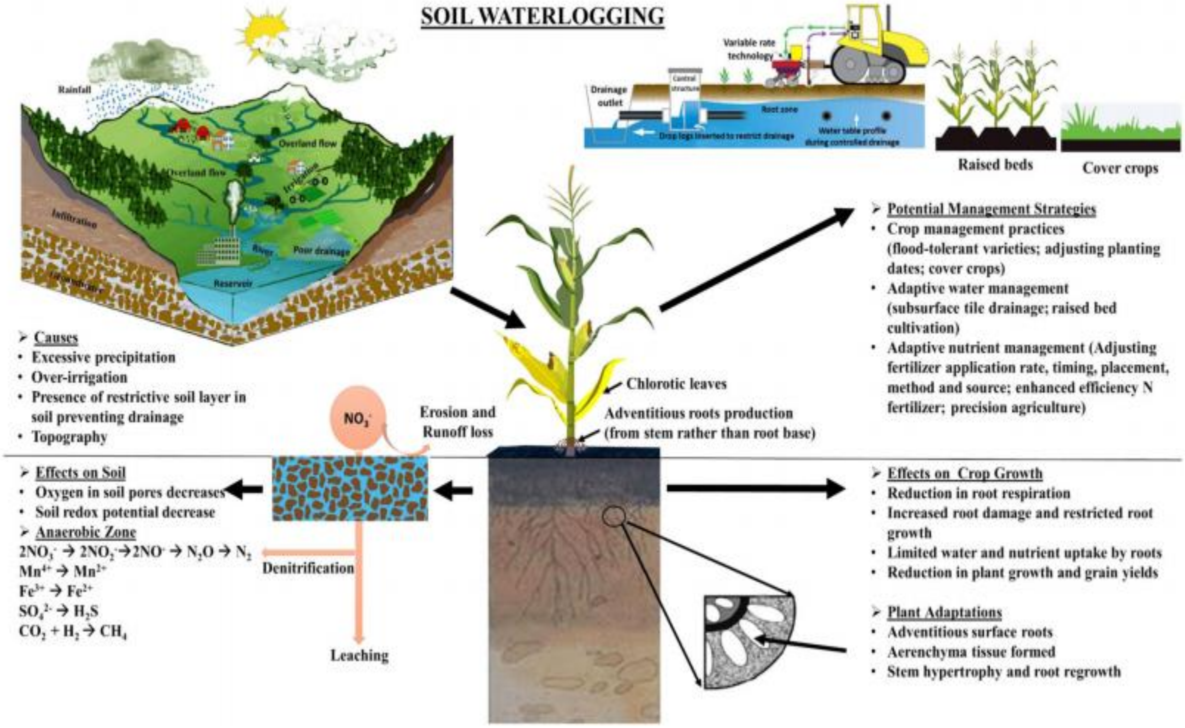


Fig.2 Effect of waterlogging on soil properties

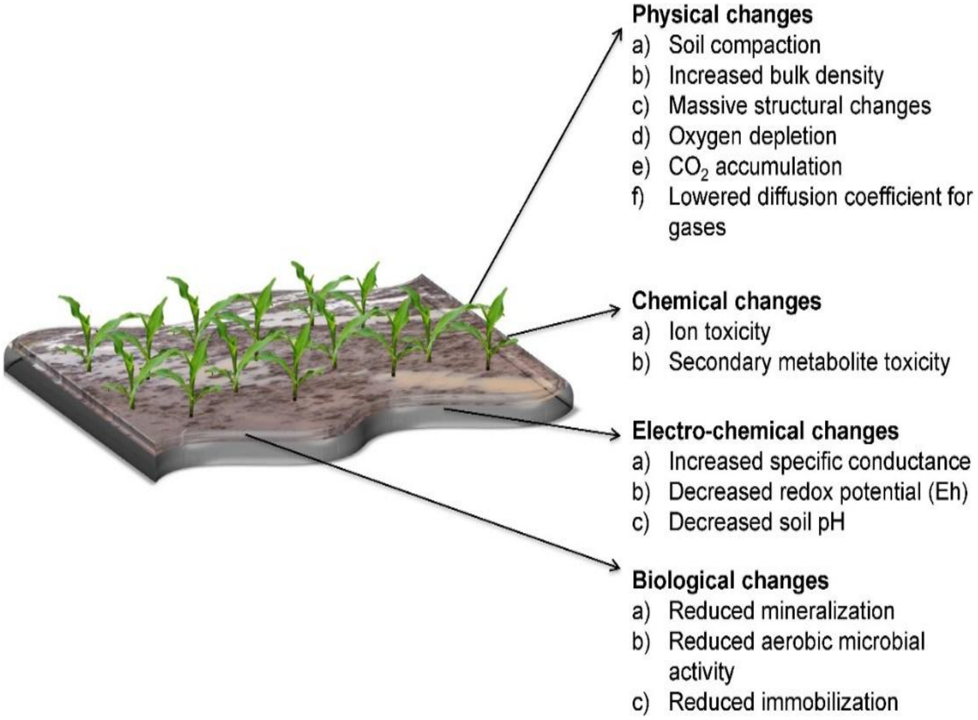


Fig.3 Impact of flooding stress on Plant growth

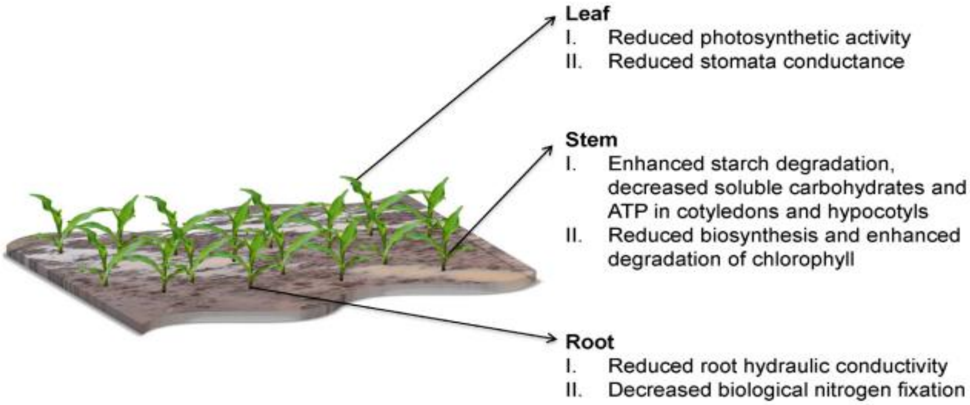


Fig.4 Raised bed system

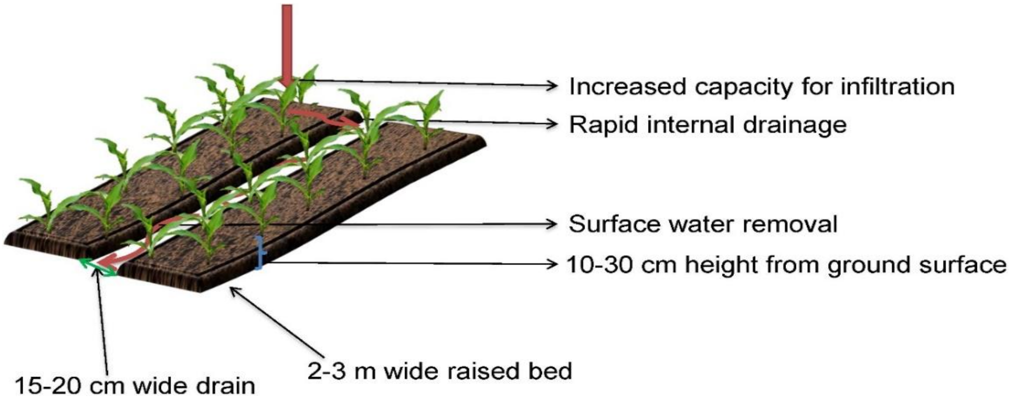


Fig.4 Vertical drainage

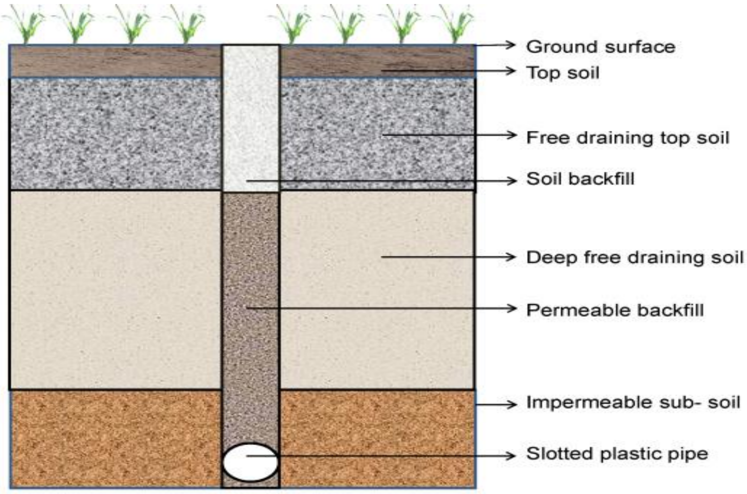
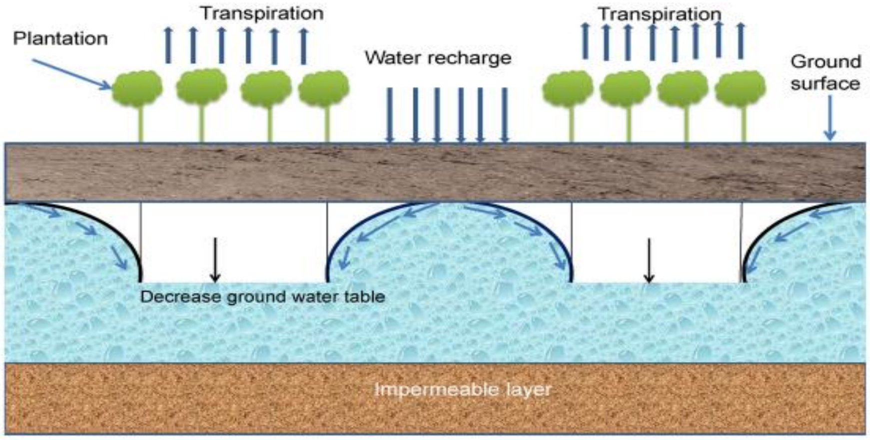


Fig.5 Bio drainage system



Merriman, Daggubati, Srinivasan, and Hayhurst (2019) used Water Assessment Tool (SWAT) model to evaluate the effectiveness of use of multiple agricultural Best Management Practices (BMPs) either as single BMP or combination of BMPs on nutrient losses from an agricultural field. Although these decision support tools are evaluated for determining BMPs for water quality improvement, they have not yet tested for assessing 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 review 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.

Many soil and crop management practices have been employed to alleviate waterlogging in crop production systems as summarized. For severe waterlogging, combinations of drainage and crop management will be the foremost step. For minor waterlogging, choosing tolerant varieties or applying appropriate agronomic practices can be effective. There are still significant knowledge gaps in our understanding of the advantages or disadvantages of relevant management measures under different soil types or different crops, management of other macro- and micronutrients; and the genetic basis of plants' adaptation to hypoxia and elemental toxicities in waterlogged soils.

While many tolerance mechanisms and related quantitative trait loci (QTL) have been reported, most of them are focused around oxygen availability and largely ignore other constraints imposed by waterlogged soils.

For improved mitigation strategies, further research should be focused on the following aspects:

Comparison of the cost/benefit analyses of different drainage strategies;

Understanding the mechanisms of nutrient loss during waterlogging and quantifying the benefits of nutrient application;

Increasing soil profile de-watering through soil improvement and agronomic strategies;

Increased specificity of the interaction between different management practices and environment (soil types, severity of waterlogging, etc.) as well as among management practices.

Discovering new (non-oxygen-associated) QTLs; the effectiveness of these mechanisms/QTL (and combined) on improving waterlogging tolerance in paddocks with soils with multiple constraints; the effect of these QTL on other agronomic, yield and quality traits, as well as management packages for varieties with diverse waterlogging tolerance genes.

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