Reviews

Management of Flooding Effects on Growth of Vegetable and Selected Field Crops

Renuka Rao and Yuncong Li[1]

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SUMMARY. The review of effects of excessive soil water on performance of various vegetable crops and selected field crops indicates that in areas where temporary flooding hazards are expected during the growing season, crops can be selected on their relative ability to tolerate excessive moisture. Field crops are generally less sensitive than vegetable crops in terms of yield. In addition to the choice of crop species, planting dates could be shifted when possible by delaying dates of sowing or planting to avoid probable periods of flooding during the sensitive growth stages. In most instances, crops are more sensitive at their early developmental phase than at the later stages in terms of yield. Soil management practices like ridging and furrowing or making raised beds before planting is recommended. In addition, amelioration with foliar application of chemicals like nutrients, growth hormones and fungicides is also recommended to overcome nutritional deficiencies, hormonal imbalances and disease infections. Every effort of amelioration should be exerted at the earliest opportunity, since water damage to crops becomes more severe with longer flooding duration.

Department of Soil and Water Sciences, Tropical Research and Education Center, IFAS, University of Florida, 18905 SW 280th St., Homestead, FL 33031-3314.

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[1]Corresponding author.

Plant growth is controlled mainly by too little or too much water in the plant root zone. Temporary or continuous flooding of agricultural soils is very common throughout the world. Soil inundation is caused by overflowing of rivers, storms, over irrigation, poor drainage, impoundment of water by dams, and high water tables.

Flooding of soil induces a series of physical, chemical, and biological processes that can influence the quality of soil as a medium for plant growth (Kozlowski, 1984; Larson et al., 1991). During flooding, gas exchange between soil and air is drastically reduced (Grable, 1966). Soil flooding displaces oxygen (O_2) from soil pores and promotes O_2 depletion by plant roots and microorganisms (Drew, 1990). Anaerobiosis reduces the soil redox potential, changes soil pH, and increases the concentration of toxic ions, metals, fatty acids, phenolic compounds, and ethylene found in soil. After flooding, plants often exhibit changes in metabolism and physiological processes. Plant responses to flooding also include stomatal closure, premature leaf senescence, reduced leaf growth, reduced nutrient uptake, reduced net rates of photosynthesis, reduced root and shoot growth, formation of adventitious roots, aerenchyma, and increased susceptibility to attack by predators and pathogens (Bradford and Hsiao, 1982; Kozlowski, 1977; Núñez et al., 1999).

Although effects of flooding on soils dedicated to growing rice (*Oryza sativa*) and herbaceous and woody plants have been well documented, the responses to flooding of vegetable plants along with changes in chemical properties of soils, excepting rice soils, have received relatively little attention. Our objective, therefore, was to bring together the current knowledge and research findings on the effects of flooding on the growth of vegetable and selected field crops and on management practices to prevent or reduce flooding damage of crops. More information regarding the effects of flood duration and timing on crop growth and yield is required to make proper selection of crops, cultivars, and planting dates to overcome flooding damage.

Legumes

Legumes, a primary food source in many regions of the world, are important as rotational crops that improve soil nitrogen (N) status and help sustain agricultural productivity. Production of beans (*Phaseolus vulgaris*) and other legumes is frequently constrained by flooding of soils with poor drainage (Kahn et al., 1985; Lakitan et al., 1992; Musgrave and Vanhoy, 1989; Umaharan et al., 1997). The degree of crop damage due to water-logging varies with plant species and duration and timing of flooding, and with high water table conditions during the growing season. The timing of flooding relative to plant growth stage during active crop growth seems to play an important role in yield reduction and the extent of injury to plants. Some legume species have been reported to withstand flooding up to 20 d (Heinrich, 1970), but the growth of bean can be significantly suppressed within the first day of flooding (Waldman-van Schravendijk and van Adel, 1985), and growth suppression increases with increasing duration of stress (Kahn et al., 1985; Singh et al., 1991). Root growth is frequently more severely suppressed than shoot growth (Kahn et al., 1985; Waldman-van Schravendijk and van Adel, 1985). Kramer (1951) concluded that plants which produced adventitious roots rapidly under flooded conditions were likely to have less injury and a higher recovery rate than plants which do not produce these roots. Intolerance of peas (*Pisum sativum*) to flooding was associated with failure to form adventitious roots (Jackson, 1979).

Leaf conductance and carbon (C) assimilation are usually found to decline following 1 to 3 d of flooding (Lakitan et al., 1992; Moldau, 1973; Singh et al., 1991). High leaf-to-air vapor pressure deficits affect plant water relations and can hasten flooding induced stomatal closure (Lakitan and Wolfe, 1990). A combination of abscisic acid (ABA) accumulation in the leaves and decreased cytokinin supply from the roots was also associated with stomatal closure (Bradford, 1983). Photosynthesis and stomatal conductance were greatly reduced in soybean (*Glycine max*) within the first 2 d of flooding regardless of growth stage (Oosterhuis et al., 1990). This was attributed to stomatal closure, while subsequent reductions were attributed to changes in photosynthetic capacity.

Yield reductions in flooded legumes have been extensively documented (Kahn et al., 1985; Lakitan et al., 1992; Musgrave and Vanhoy, 1989; Tabbada and Flores, 1982; Umaharan et al., 1997; Wein et al., 1979). Larger yield reductions result when flooding is imposed at reproductive stages rather than at vegetative growth stages for soybeans (Griffin and Saxton, 1988; Linkemar et al., 1998; Oosterhuis et al., 1990; Scott et al., 1989), mungbean (*Vigna radiata*) (Trung et al., 1985), snap bean (Lakitan et al., 1992), and cowpea (*Vigna unguiculata*) (Umaharan et al., 1997). The yields of mungbean, peanut (*Arachis hypogaea*), and soybean were reduced by 56%, 49%, and 37% respectively, when flooding occurred 30 d after sowing (DAS) (Herrera and Zandstra, 1979). On the other hand, flooding at 15 DAS and at grain-filling stage had a more severe effect on yield (60% and 64% reduction, for peanut and soybean, respectively). Yield reduction was generally attributed to a decrease in the number of pods caused by peduncle abortion due to the early onset of leaf senescence in addition to a reduction in number of lateral shoots as a result of a shortened reproductive period (Linkemer et al., 1998; Minchin et al., 1978; Nawata et al., 1990; Umaharan et al., 1997). However, it is still unclear whether sensitivity to flooding is directly related to hormonal changes occurring during reproductive development or is due to other factors, such as leaf senescence, a larger leaf area causing an increase in transpiration losses at later growth stages, or restricted root growth resulting from suppression of aerobic respiration. Some studies have concluded that the greatest crop damage and maximum yield reductions occured when plants were flooded during the early stages of plant growth (Herrera and Zandstra, 1979; Kanwar et al., 1988; Sharma and Swarup, 1989). Minchin et al. (1978) reported relatively larger reductions (100%) in yield in response to waterlogging during the vegetative phase than during the reproductive phase, and they attributed this to competition between reproductive and vegetative growth. A summary of results of experiments on selected legumes are reported in Table 1.

Tomato

Tomato (*Lycopersicon esculentum*) typically is considered to be one of the most sensitive vegetable species to excessive soil moisture (Iden, 1956). Water relations and regulation of stomata in the flooded tomato plant have been extensively studied (Bradford and Hsiao, 1982; Else et al., 1995; Jackson et al., 1978; McNamara and Mitchell, 1989). Bradford and Hsiao (1982) have shown that flooding of tomato plants reduces stomatal conductance and translocation of nutrients. In a similar study, when potted tomato plants were subjected to two flooding and recovery cycles imposed at the beginning and at the end of photoperiod, stomatal closure was induced by leaf dehydration linked to a decrease in root hydraulic permeability (Amico et al., 2001). In accordance with the conventional cohesion theory of water movement in plants, this was attributed to the diminished amount of water supplied to the shoot by the roots, which depends on the evaporative demand of the shoot. Thus, under normal conditions, the hydraulic resistance of the roots decreases as rates of transpiration increases. However in a flooded soil, shortages of O_2 and an increase of carbon dioxide (CO_2) in the root system, by interfering with water uptake, induces a temporary depression in conductivity across the membranes, which in turn may cause leaf dehydration (Bradford and Yang, 1981; Kozlowski and Pallardy, 1984). Stomatal closure in tomatoes was also associated with a combination of ABA accumulation in the leaves and decreased cytokinin supply from roots (Bradford, 1983). Effects of flooding duration at various growth stages in tomato are summarized in Table 2.

Total root length, dry matter accumulation, and yield were not significantly affected by the near flooded conditions in a study conducted by

Table 1. Summary of the influence of flooding duration and growth stage on legume response; DAS = days after sowing.

Crop	Duration	Stage flooded	Response	Reference
Bean	4 d	Vegetative growth	Reduced yield, rapid root recovery after termination of flooding.	Nawata et al. (1990)
	16 d		Restricted growth till adventitious roots formed. Retarded post stress growth, drastic reduction in yield.	
	Continuous flooding untill harvest		Maintained active growth; restricted growth until adventitious roots formed.	
Pea	24 h	---	Decreased leaf conductance, transpiration was reduced by 28%.	Jackson and Hall (1987)
	3 d		Increased foliar hydration due to reduced transpiration caused by stomatal closure; 10-fold increase in endogenous abscisic acid concentration.	
Soybean, peanut, mungbean	7 d	15 and 30 DAS	Flooding at 15 DAS resulted in stunted plants, reduced plant stands, delayed maturity. Seed weights reduced when flooded at 30 DAS, especially in peanut.	Herrera and Zandstra (1979)

Table 2. Summary of the influence of flooding duration and growth stage on tomato crop response.

Duration	Stage flooded	Response	Reference
24 h	6–7 leaf stage	Increase in ethylene production rate; leaf water potentials increased, stomatal closure and reduced transpiration, leaf epinasty.	Jackson et al. (1978)
24 h	9 week stage	Pronounced epinastic curvataure of the petioles due to ethylene accumulation and production.	Reid and Railton (1974)
3 d	1 month	Reduced stem growth and leaf chlorophyll content; increase in epinastic curvature of leaf petiole and adventitious roots.	Kuo and Chen (1980)
10 d	Seedling, flowering, fruiting	Greatest sensitivity was at the flowering stage. Overall, reduced plant height, leaf area, chlorophyll, respiration rate, percent survival, fruit set, total yield, seed set and dry weight of the plants. Increased epinastic curvature, stomatal resistance, leaf free praline accumulation.	Lopez and del Rosario (1983)
1 month	1 month	Cessation of leaf elongation, leaf epinasty, formation of adventitious roots, stomatal closure and reduced gaseous exchange.	Aloni and Rosenshtein (1982)
36 h	1 month	Reduced flow of nitrate, hydrogen ions, most protein amino acids, glutamine, and abscisic acid to the shoots.	Jackson et al. (1996)
72 h	Flowering	Decrease in leaf water potentials and increase in adventitious roots.	Perez et al. (1999)
8 d	Fruiting	Induced stomatal closure, hastened fruit maturation, reduced internal fruit firmness and subsequently reduced the storage quality of fruit.	Karlen et al. (1983)
24 h	Flowering	Wilting of 15% of tomato plants (versus 4% for nonwaterlogged plants) and 40% yield reductions.	Hubbell et al. (1979)

Pitts et al. (1990). However, Hubbell et al. (1979) imposed waterlogging on field-grown tomatoes at the second flower cluster stage, which resulted in anaerobic soil conditions to a depth of 0.2 m (8 inches) for 24 h, and which led to wilting of 15% of tomato plants (versus 4% for nonwaterlogged plants) and to 40% yield reductions. Enhanced sensitivity of pot-grown tomato plants to flooding for 10 d at reproductive stages has been reported by Lopez and del Rosario (1983). Respiration was reduced in roots and leaves by 72 and 24%, respectively. Flooding-induced root injury was reduced by adventitious root development, and these roots were important in recovery of shoot growth following flooding (Aloni and Rosenshtein, 1982; Jackson, 1955).

Sorghum, wheat, and corn

Flooding markedly reduced the growth and delayed maturity in sorghum (*Sorghum* spp.) under waterlogged conditions (Maranville et al., 1986). Grain yield was reduced by about 57% and bloom date was delayed by 5.5 d. The average total plant dry weight was 52% that of nonflooded sorghum. Restrictions in growth were related to low N levels in the leaves.

Many researchers have reported damaging effects of flooding on wheat (*Triticum aestivum*) growth and this has been attributed to low O_2 supply, reduced shoot and root growth (Sharma and Swarup, 1989), and ionic imbalance and/or nutrient stress (Belford et al., 1985; Sharma and Swarup, 1989). Leaf photosynthetic rates in wheat have been shown to decline during waterlogging (Huang et al., 1994; Musgrave, 1994). In a field experiment, yield was reduced by 51% in poorly drained plots compared to well-drained plots (Musgrave, 1994). Reduction in yield was due to reduced kernel number and kernel weight. The effects of single and multiple water-loggings on growth and yield of winter wheat indicated that chlorosis in older leaves was caused by low N concentrations in leaves as a result of restricted N uptake from anaerobic root environment. Also, plants waterlogged before emergence had significantly more grains per spikelet per ear than plants waterlogged at the stem elongation stage (florets differentiation stage). This was due to depressed floret survival resulting from the interruption in N supply caused by waterlogging (Belford et al., 1985).

Corn (*Zea mays*) is highly susceptible to waterlogging damage at the early vegetative stage which results in maximum reductions in plant-canopy height, dry matter production, and grain yield (Mukhtar et al., 1990). An increase in the duration of flooding or a decrease in the age of the crop at the time of flooding increased the severity of yield loss (Mason et al., 1987; Singh et al., 1985). Corn plants can adapt to low O_2 supply by developing aerenchyma in their adventitious root systems (Drew et al., 1979a; Wenkert et al., 1981).

Sweetpotato, yams, squash, capsicum peppers, and asparagus

Serious effects of wet soil on fleshy roots of sweet potato (*Ipomea batatas*) included losses due to rot present at harvest and increased shrinkage in storage (Thompson et al., 1992; Ton and Hernandez, 1978). Other injurious effects were losses in storage carotenoid pigments, dry matter content, and baking quality (Constantin et al., 1974). Flood damage to sweet potatoes depends on the cultivar (Collins and Wilson, 1988) and time of flooding (Kushman et al., 1954; Roberts and Russo, 1991). Midseason flooding caused yield reduction by 36% to 56% and was attributed to the rot of the storage roots (Roberts and Russo, 1991) while the late-season flooding had a detrimental effect on storage quality. The latter may be related to the production of ethanol and its toxic effects (Chang et al., 1981) or to the accumulation of CO_2 (Ahn et al., 1980) or ethylene (Patterson, 1974).

Waterlogging effects on yam (*Dioscorea* spp.) vines for 24, 48, and 72 h was studied by Igwilo and Udeh (1987). Waterlogging caused a progressive degeneration of the leaf starting with the development of fresh lesions on the lower leaves, through necrotic spots, to complete leaf necrosis. The degree of damage increased with the duration of waterlogging and damage was more severe in younger plants compared to the older plants. Waterlogging for 48 and 72 h reduced yield by 32.4% and 43.2%, respectively. Waterlogging vines at early growth stages produced 47.6% less yield than waterlogging at later stages.

Flooding 2 weeks after emergence reduced squash (*Cucurbita pepo*) growth and fruit yield by limiting gas exchange and by reducing water and N uptake (Huang et al., 1995a) Formation of adventitious roots near the stem base close to the more oxygenated soil surface in squash indicates an adaptive response to waterlogging (Huang et al., 1995b). This could explain the full recovery of the squash plants after 7 d of flooding.

Pepper (*Capsicum annum*) is sensitive to prolonged flooding. Continuous flooding of pepper plants for 4 weeks resulted in poor growth, yellowing of leaves, blackening of the root tips, and a distinct swelling at the junction of the shoot and the roots (Hasnain and Sheik, 1976) caused by decreased O_2 supply, decreased N uptake by roots, and development of cortical cells. Also, 24-h flooding periods at 7, 17, and 27 d after transplanting increased the mortality of pepper plants infested with *Phytophthora capsici* by 20%, 53%, and 100%, respectively (Bowers and Mitchell, 1990). This was attributed to increased zoospore release associated with high soil moisture.

Flooding asparagus (*Asparagus officinalis*) plants continuously for 48 h after 2 and 3 weeks after transplanting delayed growth and reduced survival of the transplanted seedlings when compared to two 8-h flooding separated by a 16-h period of drainage (Falloon et al., 1991).

Amelioration by application of chemicals

The effects of waterlogging have often been partially or entirely counteracted by addition of N fertilizer to overcome N deficiency (Haq and Mallarino, 2000; Hodgson and MacLeod, 1987), addition of natural or synthetic hormones to correct hormone imbalances (Drew et al., 1979b), and addition of fungicides to control soil-borne pathogens (Mason et al., 1987).

Nitrogen fertilizers. Waterlogging causes a significant decrease in N content and rate of N accumulation in plants because of reduced root activity. Yellowing of leaves due to loss of chlorophyll within 2 to 3 d of waterlogging is attributed to N deficiency. Thus, a strategic use of N fertilizer before flooding may alleviate N deficiency.

While the deleterious effects of waterlogging have often been partially counteracted by the addition of N fertilizer to pots or nutrient solution (Drew et al., 1979b; Watson et al., 1976) and in the field (Hodgson, 1982; Singh et al., 1985), plants do not fully overcome those effects. This may be due to the reduced ability of roots to accumulate nitrate at low O_2 levels (Meyer et al., 1987; Spek, 1981).

Foliar and soil application of N as an ameliorant has been reported in cotton (*Gossypium hirsutum*), corn, barley (*Hordeum vulgare*), and soybean (Drew et al., 1979b; Haq and Mallarino, 2000; Hodgson, 1984; Hodgson and MacLeod, 1988). Submerged barley plants subjected to daily applications of calcium nitrate showed no water-logging damage (Drew et al., 1979b). Leaf extension, shoot weight, emergence of tillers, chlorophyll concentrations and accumulation of shoots were similar to those plants in nonwaterlogged soil. Additions of nitrate to the soil surface allowed superficial roots to continue to absorb nitrate, as well as other nutrients. Nitrate provides a substrate for the N metabolism of growing shoot tissues. Nitrate is necessary in roots for the synthesis of cytokinins and their transport to shoots and for the delay of premature leaf senescence (Yoshida and Oritani, 1974). Foliar application of 3N–8P–15K at a rate of 28.1 $L\cdot ha^{-1}$ (3 gal/acre), corresponding to 1.2, 3.1, and 5.9 $kg\cdot ha^{-1}$ (1.07, 2.77, and 5.26 lb/acre) of N, P, and K, was successful in increasing soybean yields without causing any leaf injury (Haq and Mallarino, 2000). Foliar application of potassium nitrate and urea caused an increase in net accumulation of N and in shoot concentrations of N and a slower decline in chlorophyll, thereby alleviating leaf chlorosis (Trought and Drew, 1981). Amelioration of flooding effects in cotton by foliar application of N also has been well documented (Hodgson, 1984; Hodgson and MacLeod, 1987; Hodgson and MacLeod, 1988).

Growth regulators. Various plant growth regulators have been associated with alleviation of waterlogging damage, but there is a void in the information available on their effects on waterlogged crops (Drew et al., 1979b; Jackson and Campbell, 1979; Zhou et al., 1997). Spraying shoots with a synthetic cytokinin [6-benzylaminopurine (BAP)] reduced injury to shoots of dicotelydons in waterlogged soil by improving leaf extension and retarding premature loss of chlorophyll in older leaves (Drew et al., 1979b). This was related to BAP compensating for the restricted transport of natural cytokinin from the root system (Even-Chen and Itai, 1975), which affects metabolism of gibberellins (Reid and Railton, 1974), and adversely affects the inhibitory action of abscisic acid (ABA) on growth (Millborrow, 1974). Foliar application of BAP together with gibberellic acid (GA) can be effective in partially offsetting the inhibitory influence of poor aeration in roots on stem elongation, transpiration, and the increase of fresh and dry weight in leaves and stem of peas (Jackson and Campbell, 1979) and of tomato (Selman and Sandanam, 1972). Soaking soybean seeds in kinetin solution alleviated the flooding damage by overcoming deficiency of natural cytokinin (Vorobeikov and Anikina, 1977). Pretreating of corn seedlings to a hypoxic environment with ABA acclimatized plants to anoxic conditions, thereby improving the flooding survival of plants 10-fold (VanToai, 1993). Seedling treatments with the synthetic cytokinin like uniconazole helped delay waterlogging-induced chlorosis and senescence by modification of GA, zeatin, ABA, and ethylene levels in the plants (Leul and Zhou, 1998). Foliar sprays of urea and mixtalol [a mixture of a spectrum of aliphatic alcohols with chain lengths C-24 to C-34 (Menon and Srivastava 1984)] at flowering stage in winter rape (*Brassica napus*) and rice alleviated plant damage by waterlogging by retarding chlorophyll and N degradation, increasing superoxide dismutase and catalase activities and root oxidizability, and improving yield components and seed yield (Ni et al., 1995; Zhou et al., 1997).

Fungicides. Flooding increases the severity of some diseases (De Siva et al., 1999; Falloon et al. 1991; Jacobs and Johnson, 1996; Wilcox and Mircetich, 1985). The susceptibility of waterlogged plants to disease, particularly root-rotting fungi, depends on the relative abilities of the microorganisms and plants to grow in anaerobic conditions. Moisture is critical for many fungi to complete many stages of their life cycle, such as production of zoospores and to ensure their mobility (Duniway, 1979; Schaffer et al., 1992). The abiotic environment influences the three-way interaction involving the pathogens, microbial competitors of the pathogen on or within the roots, and the roots (Baker and Cook, 1983). The symptoms of diseased roots are discoloration, rotting of the root, and the premature death of the plant. Damage roots reduce the ability of the root systems to obtain mineral nutrients or perform other functions essential to the shoot (Cook, 1984). Fungi in the genera *Phytophthora* and *Pythium* cause the greatest damage to roots in poorly drained soil (Stolzy et al., 1965).

Application of fungicides may reduce the incidence of plant disease in waterlogged soils and thereby increases plant tolerance to flooding. Growth in bean was less affected by low oxygen levels when soil pathogens were controlled (Miller and Burke, 1975). Establishment of *Phytophthora* infested asparagus (*Asparagus officinalis*) under flooded conditions was improved by application of metalaxyl immediately after transplanting (Falloon et al., 1991). However, application of fungicides (benomyl and metalaxyl for control of *Pythium* and *Fusarium*, respectively) on corn did not mitigate the waterlogging effects (Mason et al., 1987). Lack of literature in relation to recovery of flood stressed vegetable plants from disease by fungicide application mandates the need for additional studies.

In conclusion, waterlogging, or flooding of soil, can cause considerable injury, reduced growth rate, and even death in crop plants. Thus, flooding is a problem of considerable economic importance in many parts of the world. The lack of oxygen in the root zone and uptake of nutrients is the major cause of limited plant growth in waterlogged soils. Flooding also causes adverse changes in the hormone content of the plant. In addition, waterlogging increases susceptibility of plants to disease organisms, particularly root rotting fungi. These changes adversely affect the growth and development of plants resulting in poor quality and reduced yield. Soil and foliar applications of certain inorganic nutrients, growth regulators and fungicides have been associated with substantial alleviation or prevention of flooding injuries in plants. Evidently, amelioration should be done at the earliest opportunity considering that flooding injury to crops becomes more severe with longer flooding duration.

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