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Climate Change Scenarios and Crop Flood Stress in South Africa: A Critical Discussion

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Abstract

In assessing the relationships between crop productivity and future climate change, a combination of climate change scenarios, environmental conditions and resultant crop yields information are utilized. Recent progress in simulating the impacts of future climate change on crops is focused on increased temperature, and little attention is paid to the possibility of flood stress or on the exploration of adaptation options related to flood stress. As part of this review, this relationship is discussed in the context of crop response to predicted flood stress from climate change. Impacts of floods on crop production are reviewed, with a primary focus on climate change scenario in South Africa.

The challenges associated with impacts and adaptation researches related to flood stress are limitless. It is therefore argued that, the generation of knowledge for policy and adaptation in South Africa should be based not only on one aspect of climate change but on a more synergistic and holistic research framework that includes: (i) Reliable quantification of uncertainty in relation to extreme rainfall events, possible flooding and waterlogging conditions; (ii) techniques and approaches for observations that focus on fundamental processes inclusive of flood; and (iii) provision of judicious accounts for the principal drivers of crop productivity, which may well include both biophysical and socio-economic factors. Such a framework will lead to reliable real-world adaptation options in a situation of flood stress.

Keywords: Adaptation climate change; Climate change scenario; Flood stress; Waterlogging

Introduction

There is limited information on the extent of acclimation of crop species to extreme climate events such as floods. With likely long-term changes in the pattern of rainfall, increasing temperatures and shifting in climate zones [1], climate change is projected to increase the frequency of floods, which in turn will impact food security. Anthropogenic climate change is expected to increase the frequency and severity of flooding events globally [2]. With the increased incidence of possible flooding, most cultivated crops and wild plants will be stressed, as the poor gas exchange under excessive soil water conditions would disrupt the energy and carbohydrate economies of crops and wild plants [3,4].

Significant changes in climate have been observed in South Africa over the last five decades [5]. Mean annual temperatures have increased approximately 1.5 times that of the observed global average of 0.65°C and hot and cold extremes have increased and decreased respectively in frequency. Rainfall projections for South Africa predict a change in rainfall intensities characterized by the decreased frequency of low-intensity rains [5]. Climate change modeling in South Africa show that under all four future medium and long term climate scenarios, a higher frequency of flooding and drought extremes is projected, with the range of extremes exacerbated significantly under the unconstrained global emissions scenario [6]. Projections of monthly and seasonal changes in rainfall distribution patterns over South Africa are not uniform. Significant variation will occur in the direction, intensity, as well as spatially in a given month, between different months of the year, and between the intermediate future and the more distant future, suggesting an intensification and acceleration of impacts of climate change over time [6]. This uncertainty calls for intensive adaptation strategies to be carried out on all fronts based on any possible climate change scenario.

Studies on crops in semi-arid and arid environments such as South Africa are subject to multiple climate change stresses [7]. Hence the analysis of only one climate related event provides only a partial view of likely future crop responses to a changing climate. In order to produce robust results of climate change impacts, a range of drivers including flood and waterlogging need to be assessed.

Crops exhibit known responses to weather and climate that can have a severe impact on yield [8]. Evidence indicates that more frequent and more intense extreme weather events, rising sea levels and increasing irregularities in seasonal rainfall patterns are already having an immediate impact on food production [9]. Climate change models predict an increase in the frequency of flooding events globally, making flood stress a major environmental threat for plants [10]. Annually, crop damages due to unseasonal and severe flooding events amount to billions of dollars in yield losses [10].

Crop productivity is heavily dependent on soil available moisture which must be provided in the required amounts and at critical phenological stages of the crop. Flooding and resultant waterlogging which can disrupt soil available water for crop growth thereby limiting productivity has become a major environmental stress in some parts of the World [11]. The soil is considered to be flooded if there is freestanding water on the soil surface or if the available water fraction of the surface

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layer is at least 20% higher than the field capacity [12]. Waterlogging and flooding are common in rain-fed ecosystems, especially in soils with poor drainage [13] and can seriously reduce crop yield [14]. The Food and Agriculture Organization (FAO) and the International Institute for Applied Statistical Research consider flooding and waterlogging as a factor in the calculations of their estimates of global arable land area and global productivity [15] because of its possible effects on food security. The effect of flooding on crop productivity ranges from yield reduction of up to 10% [16] and 40% in severe cases [17]. This is because flooding negatively affects the physiological functioning, vegetative and reproductive growth of plants [18].

There is evidence of a significant variation in plant tolerance to flooding [10]. This could be the result of management techniques coupled with evolved specific strategies by the crops to deal with and even thrive under these conditions. Plants adapted to flood conditions may withstand such conditions better but this many not be applicable to many agricultural systems which are generally grown under well drained soil conditions. Variation in maximum allowable flood duration ranging from a few hours to weeks can be attributed to two primary factors: the increased availability of oxygen to the roots provided by morphological adaptations in tolerant plants and different biochemical responses to anaerobic conditions [19]. Intra-species variation in flood tolerance depends greatly on the plant organs directly affected by flooding; the stage of plant development at which the flood is imposed, and external conditions such as temperature [20]. With the possibility of plant surviving under flood conditions, little has been done in South Africa to make use of this scenario if it thus happens in future.

A recurring feature in climate change projections for South Africa is a slight wetting trend of varying intensity and distribution in the eastern part of the country, a trend which in general could be beneficial to South Africa's agricultural production and to water availability for agriculture, but could also be detrimental due to flood damage [6]. With the possibility of flood stress for crops in South Africa, the question is 'why are there insufficient studies carried out to assess the impacts and possible adaptations for flood occurrences and possible waterlogging scenarios? The bulk of the current literature [21-24], focuses primarily on how crops will survive drought and heat stress and the possible adaptation scenarios thereof. The possibility of crop tolerance to future floods in South Africa is however lacking.

Given the different projections of future climate for South Africa from different emission scenarios, climate models and downscaling techniques, the estimated impacts of climate change on agriculture in South Africa becomes extremely challenging. Due to the current emphasis on temperature and consequent drought, prominence has been placed on research concerning these aspects while some key messages such as frequency of flooding and the resultant possibility of waterlogging are not extracted. This creates a situation where the effects of climate change on agriculture are not looked at holistically thereby allowing very little leeway for an assessment of impact of other parameters such as flooding and possible waterlogging conditions at a regional scale on crops.

This review was therefore conducted to determine the scope of literature that looks at the effects of flood or soil waterlogging on crops in South Africa and what possible directions research on the vulnerability of agriculture to flood can take. The review starts of by examining factors that enhance the possibility of flood/waterlogging to occur; the type of flooding and conditions under which crops can experience flood stress and the consequences of floods on various crops.

Climate Trends in South Africa

Historical trends in climatic variables are of particular interest especially to agriculture and water resource management. As a result, a plethora of studies exist where the climatic trends in South Africa have been investigated. However, most of these studies looked at mean annul precipitation (MAP) which, according to MacKellar, New and Jack [25], are not as vital as the characteristics of how rainfall is distributed throughout the year. These characteristics include the timing of the onset and end of the rainy season, the typical durations of wet and dry periods and the occurrence of extreme heavy rainfall events [25], which will go towards increasing the likelihood of flooding and waterlogging incidences. Various studies have been carried out and show the variability of South African climate.

Historical climate of South Africa

Mason et al. [26] demonstrated increases in the intensity of high rainfall events over 70% of the country in the 1961-1990 periods relative to 1931-1960. Their results indicated that the intensity of the 10-year high rainfall events has increased in excess of 10% over large areas of the country, except for parts of the north-east, north-west and in the winter rainfall region of the south-west. Such percentage increases in the intensity of high rainfall events are said to be largest for the most extreme events.

Easterling et al. [27] found that both southwestern South Africa and the KwaZulu-Natal province in the east experienced significant increases in the average number of days per year with heavy rain, for the period 1926-1997, and 1901-1997 respectively for the two regions. In agreement with these observations, results of a study by Groisman et al. [28] showed a significant increase in the annual frequency of very heavy rainfall events over eastern South Africa from 1906-1997.

Further studies such as that of Kruger [29], as a follow-up study of various others on precipitation trends in the South Africa using data for the for the period 1910-2004, showed increases in extreme rainfall indices over the southern Free State and parts of the Eastern Cape from 1910-2004. New et al. [30] also show some evidence of increased rainfall extremes over parts of South Africa for the 1961–2000 periods.

Mackellar et al. [25] analyzed climatic trends in rainfall and temperature indices for South Africa for the period 1960–2010, using the six hydrological zones (Figure 1), and reflecting boundaries defined by water management areas (WMAs) in the country and grouped them according to their climatic and hydrological characteristics. Analysis were carried out across the four seasons defined as months of March, April and May (MAM)-autumn; June, July and August (JJA)-winter; September, October and November (SON)-Spring and December, January and February (DJF)-summer; This provides updated results on trend analysis in South Africa that will complement previous trend analysis.

In Zone 1, there is a mixed spatial pattern of rainfall indices in most seasons with a tendency for reduced precipitation (ppt) in the autumn months MAM; fewer rain days in summer DJF. Some stations show reduction in DJF rain days (Figure 2). All but one station show significant increase in maximum temperature (T_{max}), with the strongest warming signal occurring in spring SON. However, Minimum temperature (T_{min}), experienced strongest warming in DJF and winter JJA (Figure3).

There is large temporal variability and no regional mean trends in rainfall indices found in Zone 2 (Figure 2). However, stations suggest

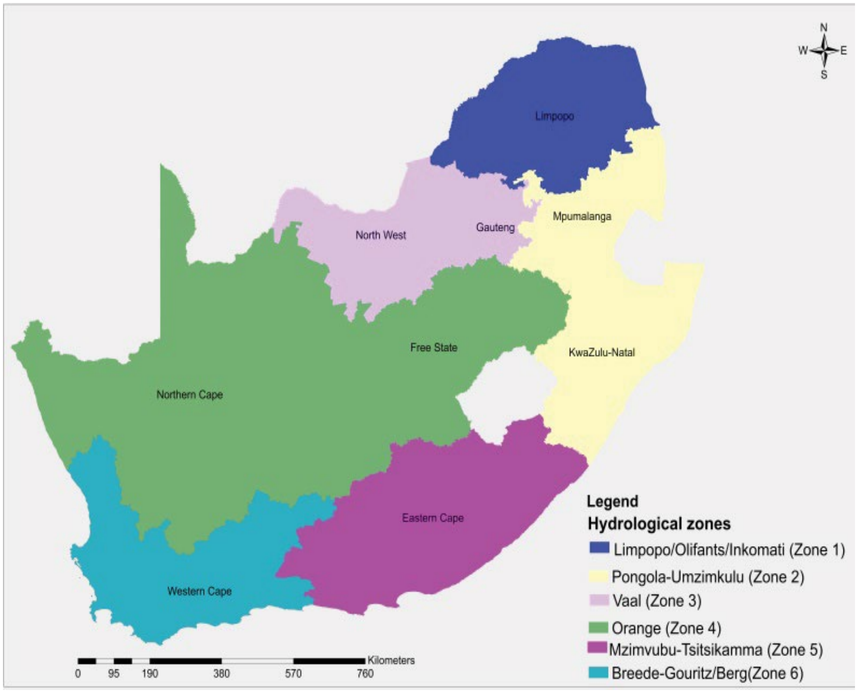

Figure 1: Six hydrological zones of South Africa and Provinces falling in each hydrological zone. Adapted from DEA (2013).

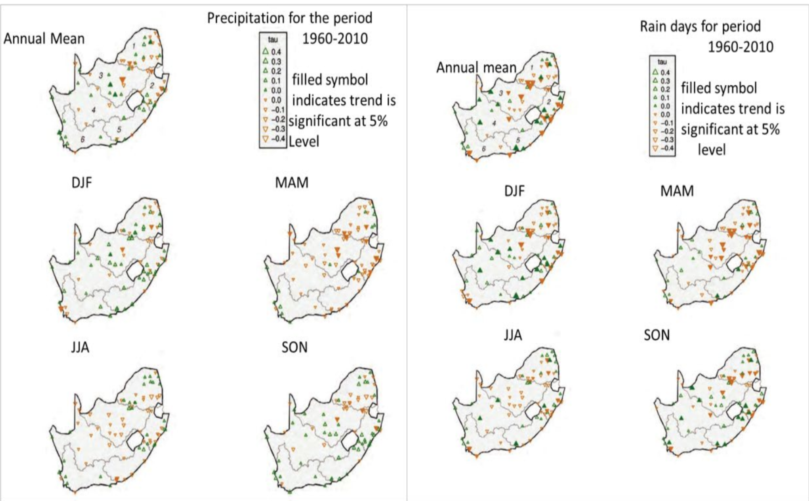

Figure 2: Trends in annual and seasonal precipitation and rain day(s) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map and Figure 1. Source MacKellar, New and Jack (2014).

a spatially-coherent reduction in MAM precipitation with increasing precipitation intensity and rain days. A weak, but spatially coherent pattern of increased precipitation and precipitation intensity in SON and DJF has occurred along with significant increases in rain days in the southern Drakensberg area, which also extends into Zone 5. There is an increased T_{max} and decreased T_{min} for all seasons, but not all are significant (Figure 3).

Opposing signals are shown at individual stations in Zone 3 (northern and central interior) hence no clear region-wide trends are evident. However, there have been significant reductions in precipitation and rain days at some stations in the east in DJF and MAM and some indication of increases in rainfall indices in the west throughout the wet season from spring to autumn (Figure 2). The strongest increases in T_{max} is in JJA, but significant decreases are shown in T_{min}, particularly in JJA.

Zone 4 shows some significant increases in rain days which are apparent in the western part of the region. There are strong increases in T_{max} for all seasons. Increases in T_{min} are generally weaker than those seen in T_{max}.

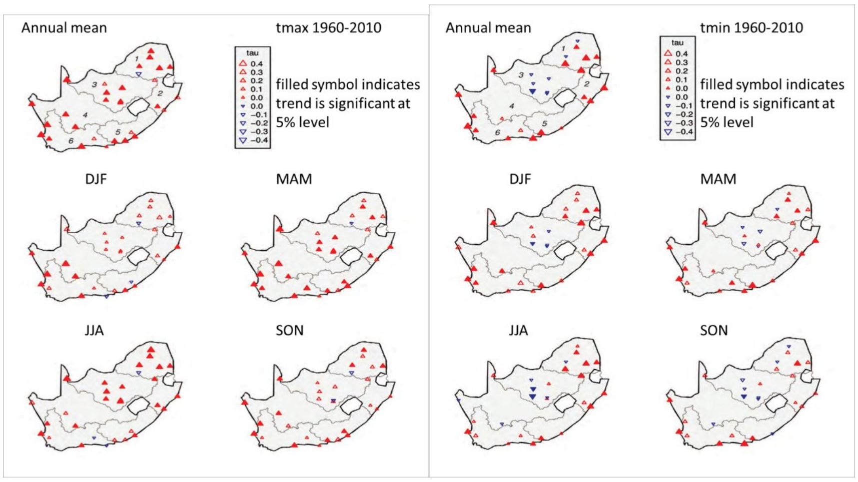

Figure 3: Trends in annual and seasonal mean daily maximum and minimum temperature (T_{max} °C and T_{min} °C) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map and figure 1. Source MacKellar, New and Jack (2014).

In zone 5, there are few significant changes in precipitation but there are some significant increases in rain days across the region (southern Drakensberg and southern coastal areas) in all seasons. Also T_{max} and T_{min} have increased in all seasons, but with a weaker signal in DJF and SON, respectively.

In Zone 6, rainfall trends are generally not significant and show little consistency across the region. Rain days show a fairly consistent decreasing signal along the southern coastal regions with increased tendency for rain days towards the west coast. T_{max} and T_{min} have increased significantly at most stations in all seasons.

Figure 4 shows a multiyear variation in rainfall indices. Results tie in with studies of Kruger et al. [29]; New et al. [30]; Ne W [31] which shows an overall tendency for decreased ppt in MAM and a reduction in rain days over the central and northeastern parts of the country. Mackeller et al. [25] further show a strong and cohesive tendency toward increased rain days, and to a lesser degree ppt, around the southern Drakensberg in DJF and SON. This summer increase is consistent with results previously shown for this location by Ne W [31] and the springtime increase is suggestive of an earlier seasonal onset.

Figure 4 shows that rainfall was above average in the 1970s, the late 1980s, and mid to late 1990s, and below average in the 1960s and in the early 2000s, reverting to average towards 2010. There is a tendency towards an increase in rainfall extreme events, but especially in spring and summer, with a reduction in extremes in autumn (Figure 4 (Zone 3 and 4)). Rainfall trends overall are weak and non-significant, but there is a tendency towards a significant decrease in the number of rain days (Figure 4 (Zone 6)). This would support the observed tendency towards an increase in extreme rainfall events.

For the temperature indices, a significant warming trend in T_{max} is shown for almost all stations (Figure 5), which is in line with recent global and regional warming trends [5]. The central interior is that it experienced a cooling trend in T_{min}, thus resulting in an increased diurnal temperature range.

Results from this long-term analyses collaborated that of Easterling et al. [27] whose results showed that the Free State and most of the Eastern Cape provinces, as well as a part of KwaZulu-Natal experienced extreme daily rainfall while the wetter east and extreme southern and southwestern parts of South Africa will on average experience more days with heavy precipitation.

Therefore, while the number of days with extremely high precipitation has increased, the amount of precipitation during the day of year with highest precipitation has also increased over these areas. There is a tendency towards an increase in rainfall extreme events, but especially in spring and summer, with a reduction in extremes in autumn. Rainfall trends overall are weak and non-significant, but there is a tendency towards a significant decrease in the number of rain days. This would support the observed tendency towards an increase in extreme rainfall events.

From the above studies, an assumption can be made that, although there were no significant changes in annual rainfall during the past century, there is evidence that there were some significant increases in extremes and inter annual variability of precipitation over specific areas in South Africa. With such extremes in rainfall already being experienced in the present day, what will the future climate look like? Besides this, there is little documentation on what the effects of these rainfall intensity and duration have caused food production in South Africa.

Future projections of climate change scenarios for South Africa

Simulation of future climates for South Africa employs both statistical and dynamic downscaling of the output of AR4 (A2 and B1 emissions scenarios) and AR5 (RCPs 8.5 and 4.5) representing unmitigated (A2 and RCP8.5) and mitigated (B1 and RCP4.5) future energy pathways. The scaling method employs 450ppm CO2 stabilization as a mitigated scenario. Projected climate futures for South Africa (2015–2035, 2040–2060 and 2070–2090) show four broad climate scenarios which could represent plausible climate outcomes under unmitigated (unconstrained) and mitigated (constrained) future emissions scenarios [6] as seen in Table 1. These scenarios with different degrees of change and likelihood are:

- Warmer (3°C above 1961-2000) and wetter, with substantially greater frequency of extreme rainfall events;

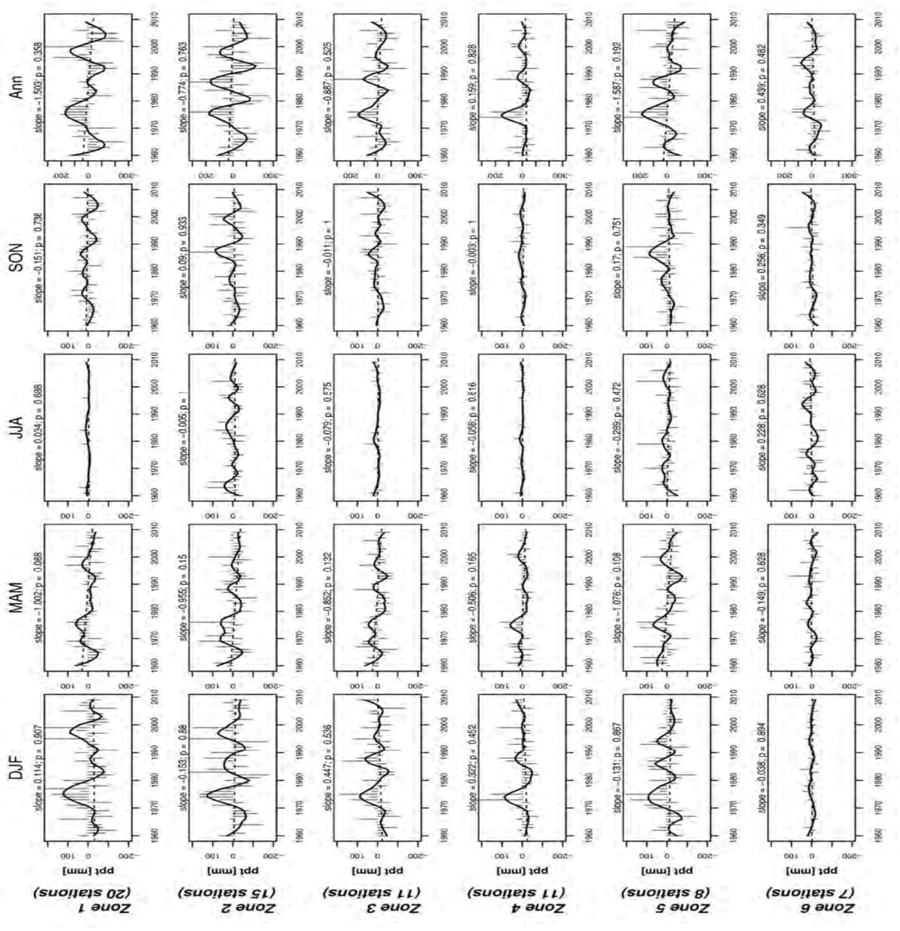

Figure 4: Regional mean time series and trends in total rainfall (ppt) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

Scenario	Limpopo/Olifants/Inkomati	Pongola-Umzimkulu	Vaal	Orange	Mzimvubu-Tsitsikamma	Breede-Gouritz/ Berg
1) Warmer/ wetter	Spring and summer	↑Spring	↑Spring and summer	↑In all seasons	↑In all seasons	↑Autumn, ↓winter and spring
2)Warmer/drier	↓Summer, spring and autumn	↓Spring and Strongly	↓Summer and spring	↓Summer, autumn and spring	↓In all seasons	↓In all seasons
		↓Summer and autumn	↓Strongly autumn		↓Summer and Autumn	↓Strongly in the west
3)Hotter/wetter	↑Strongly	↑Strongly	↑Spring	↑In all seasons	Strongly	↓Autumn
	Spring and summer	Spring	and summer		↑In all seasons	↑Winter and Spring
4) Hotter/ drier	Strongly	↓Spring and strongly	↓Summer and spring	↓Summer, autumn and spring	↓In all seasons	↓In all seasons
	↓Summer and spring and autumn	↓Summer and autumn	↓Strongly autumn		↓Strongly in summer and autumn	↓Strongly in the west

Table 1: Rainfall projections for each of South Africa's six hydrological zones Source DEA (2013)

- Warmer (<3°C above 1961-2000) and drier, with an increase in the frequency of drought events and somewhat greater frequency of extreme rainfall events;
- Hotter (>3°C above 1961-2000) and wetter, with substantially greater frequency of extreme rainfall events;
- Hotter (>3°C above 1961-2000) and drier, with a substantial increase in the frequency of drought events and greater frequency of extreme rainfall events [6] (Table 1).

Under all four future climate scenarios, a higher frequency of flooding and drought extremes is projected, with the range of extremes,

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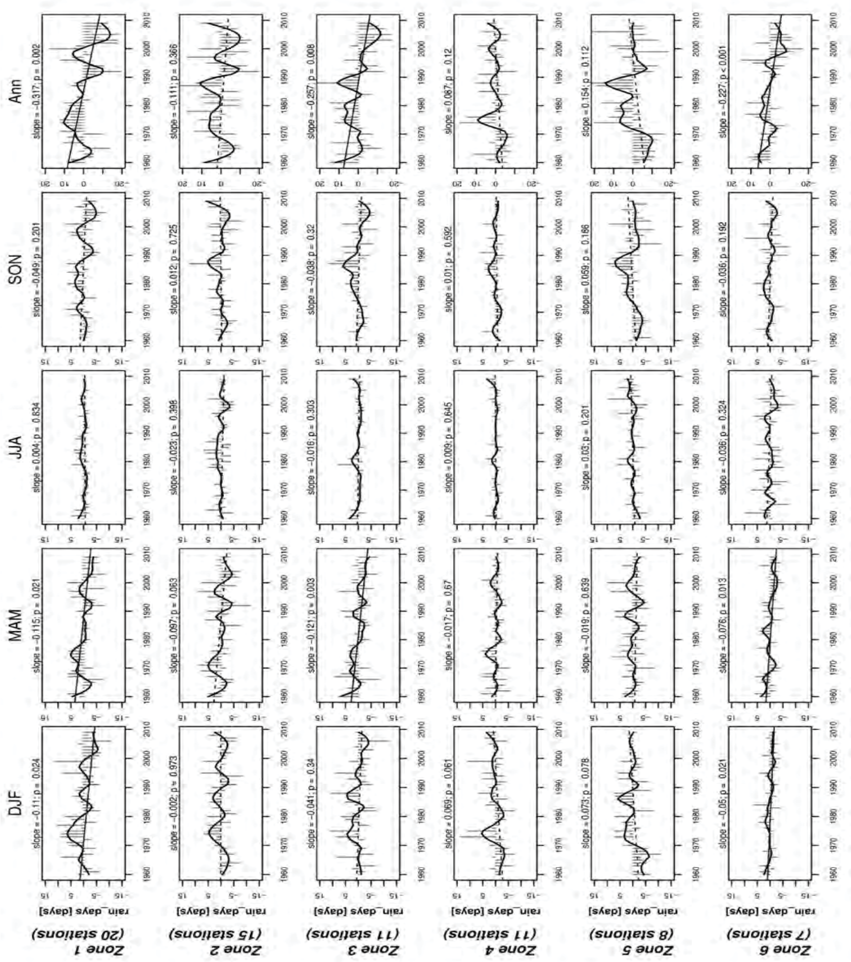

Figure 5: Regional mean time series and trends in number of rain days (days) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

exacerbated significantly under the unconstrained global emissions scenario. Under a wetter future climate scenario, significant increases in runoff would result in increased flooding, human health risks, ecosystem disturbance and aesthetic impacts. Areas showing highest risks in extreme runoff related events (and flooding conditions) include KwaZulu-Natal, parts of southern Mpumalanga and the Eastern Cape [6]. The prospects of flooding and waterlogging conditions should be met with adequate adaptation strategies.

The issue of flooding and waterlogging are not only dependent on the rainfall characteristics. Another aspect of interest, where the phenomena of floods and waterlogging conditions are examined is the soils.

Soils

One of the predominant functions of a soil is to provide a medium for plant growth. Where there are modifications of a soil's physical and/or chemical characteristics, there is bound to be a great impact on the development of the root biomass and consequently on plant vegetative development [32,33]. According to Morales-Olmedo, et al. [34], the optimal soil composition for plant growth should contain about 50% solid and 50% pore space. The mixture of air and water within the pore space should be close to 50:50; wherein 25% of the soil volume should be occupied by air. Gas diffusion is conditioned by the physical properties of the soil, among which soil porosity is one of the most important, especially the fraction with air [35]. Poorly drained soils such as occur in heavy clays retains moisture over a protracted period unlike sandy soils which are freely drained due to their small particle size. However, if a sandy soil overlay poorly drained clay soils, water logging can occur when rainfall exceed certain amount than can be drained by the soil. In most soils, the microbiological activity and plant growth are extremely inhibited when the porosity with air decreases to less than 20% of the pore space. Soil porosity is related to soil properties such as texture, structure, water content, mineralogy of clays and sodium adsorption relation [36,37]. Sandy soils have less total porosity than clays even though they have larger pores which are well connected. In fine-textured soils, the percentage of space with air tends to decrease when they are poorly structured. Given that clays have many small, discontinuous pores and retain water more easily than soils with coarser texture, plants tend to suffer oxygen limitation more frequently in clay soils in spite of their greater total porosity [38].

Hence when a large amount of water is applied to the soil, greater

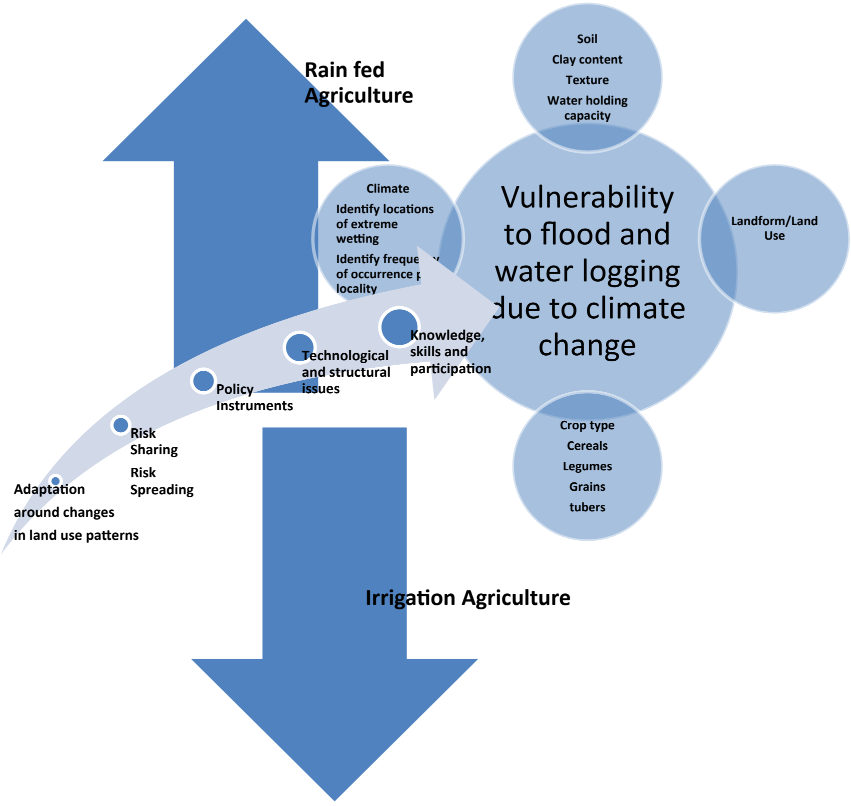

Figure 6: Proposed Approach to resilience of crop tolerance to floods in South Africa.

than its retention capacity, excess water usually drains. However, when the texture is fine with a tendency to compaction or hanging strata that impede drainage, water is retained for a longer time, producing extended saturation of the pore space [34]. Such situation causes the blockage of gas interchange with the atmosphere and extreme slowing of atmospheric interchange with the gases in the water; especially oxygen. Therefore soils should have access to adequate proportions of water and air in the optimal range for the physiological performance of the crops planted in it.

Given the rate of human activities and projected climate change in areas such as South Africa, this balance may be altered and some soils may experience waterlogging. Human-related causes include, amongst others, poor irrigation management and soil compaction, while natural flooding is caused by excessive rain [39]. In both cases soils with high clay content and/or compaction due to agricultural practices are susceptible to soil waterlogging. These effects contribute to limiting water and air movement in the soil, generating oxygen (O2) deficiency and carbon dioxide (CO_2) accumulation [40] as well as changes in the soils chemical properties [41]

In South Africa, the distribution of soils prone to water logging conditions is found in the figure 4. They are the Calcaric Fluvisols, Arenic Fluvisols and Petric Calcisols [42].

The Science of Flooding and Plant Reaction

Excess water produces anoxic soil conditions within a few hours [43]. Surplus water in the soil severely limits the rate of oxygen into the soil because of the lower diffusion ratio of gases into water with respect to air [44,45]. Following a flood, the remnant oxygen is depleted through the process of respiration by plant and microorganisms. This renders the environment hypoxic (i.e. oxygen levels limit mitochondrial respiration) and later anoxic, i.e. respiration is completely inhibited [46,47].

The first constraint for plant growth under flooding is the immediate lack of oxygen necessary to sustain aerobic respiration of submerged tissues [48-50]. As the flooding time increases, a second problem associated with water excesses appears as a result of the progressive decrease in the soil reduction-oxidation potential (redox potential) [51,52]. With the reduction of the soil redox potential, toxic compounds such as sulfides, Soluble iron (Fe) and Manganese (Mn), ethanol, lactic acid, acetaldehyde and acetic and formic acid appear [53,54]. Lack of oxygen and the later accumulation of some potentially toxic compounds are the major constraints that plants suffer under flooding conditions.

Striker [55] sheds more light on the different scenarios under which flooding takes place. Flooding can be viewed from two angles: A situation in which the water excess can range from water saturated soil (waterlogging) to deep water columns causing complete submergence of plants. Waterlogging therefore corresponds to a situation where soil pores are fully saturated with water, with a very thin or even without a layer of water above the soil surface. Therefore under waterlogged conditions, the root system of plant is under the anaerobic conditions imposed by the lack of oxygen, while the shoot is under atmospheric normal conditions.

Contrary to waterlogging, flooding is where there is a water layer above the soil surface. This water layer can either be shallow or deep, thereby provoking partial or complete submergence of plants. Worth noting is the fact that at the same water depth, the degree of plant submergence will depend on the developmental stage (e.g. seedlings *vs* adult plants) and plant growth habit (e.g. creeping plant growth *vs* erect plant growth), among other traits influencing plant height.

Where there is a condition of partial submergence, plants will have a portion of their shoots underwater and their roots completely immersed in water-saturated soil. In a case of complete submergence, plants are confronted with the most stressful scenario because both shoot and root plant compartments are underwater. Under such condition, the chances to capture atmospheric oxygen and to continue with carbon fixation are restricted. This presents a dire situation for the crops because the irradiance available to sustain underwater photosynthesis for survival is drastically reduced [56-58]. According to Colmer & Voesenek [59], this stress can be classified as shallow or deep flood depending on water depth and duration of the submergence. Where the water column is less than 0.5-1 meter and the submerged plants have the chance to surpass the water level by shoot elongation, the stress is referred to as shallow floods [60,61]. Areas with possible shallow submergence can be found in lowland flat areas of the world [62]. Conversely, deep floods are those of more than 1 m of water column, in which the effort of trying to de-submerge the plant shoots is useless, because the chances to surpass the water are non-existent. In these cases, the pursued benefit of developing a shoot elongation response is not outweighed by the incurred cost, because the plant exhausts its carbohydrates reserves, dying before reaching the water surface. In contrast, plants that remain quiescent are able to succeed under deep submergence, surviving by using carbohydrates reserves to maintain a basal metabolism until the flood water subsides [63,64].

Submergence can be considered of short duration generally when it is no longer than two weeks and it occurs during flash-flooding events. In the case where, the period of submergence is longer than two weeks (often of a month or more), it can be regarded as of long duration [59]. Although this classification can appear as arbitrary, it is useful in order to understand the strategies used by plants to deal with each combination of water depth and duration of the submergence when carrying out studies and planning for adaptation strategies.

In assessing the effects of flood stress on plant, a crucial aspect that should be taken into account is the duration of flood. Colmer and Voesenek [59] project the steps in recent research which have improved the understanding of mechanisms of flooding tolerance in plants, as dependent upon contrasting flooding regimes in various habitats. For example, temporary floods differ in seasonal timing, and with much variation in durations, depths and frequencies [65]. Disparity in these factors results in a multi-dimensional continuum of flooding regimes in crop lands. This range of environmental conditions determines species distributions and abundances in flood-prone areas [66,67]. As such the diversity in environments, as hypothesized by Darwin [68] would impose specific selection pressures for various traits associated with flooding tolerance, based on the assumption that trait benefits outweigh costs [67].

Response of plants to flood water stress

Early responses of crops to water stress will support immediate survival, whereas acclimation, calling on new metabolic and structural capabilities mediated by altered gene expression, will help in improving plant function under stress conditions [69] such as floods. Responses to the incident of floods can take place either at the leaf level in response to stimuli generated in the leaf itself or elsewhere in the plant. However, it is the integrated response at the whole plant level, including carbon assimilation and the allocation of photo assimilates to different plant parts and reproductive ability that finally dictates survival and persistence under environmental stress [70]. Even though plants can actively adapt to submergence by adaptive growth, their growth is significantly inhibited by incomplete or complete submergence [59,70-73].

Some studies have focused on understanding the response of different crop types such as for cereals, legumes, oilseeds, forage, pastures and grasses to floods and water logging at various growth stages. The major field crops currently cultivated in South Africa is maize, sorghum, wheat, sunflowers, groundnuts, soybean, lucerne, sugarcane and cotton [6]. It is therefore worthwhile to look at responses of certain South African priority crops to flooding and waterlogging.

Soybean response to flood and water logging conditions

Research shows that the effects of waterlogging in soybean rhizosphere are substantial and generally negative. Some studies have looked at various growth stages of soybean and their subsequent response to flooding and water logging.

Early vegetative stages: A decrease in nitrogen accumulation for flooded soybean plants [74,75] has been identified as the limiting factor to growth [76]. Flooding for one week was sufficient to reduce leaf nitrogen concentration levels below deficiency [77]. Reduction in nitrogen has been attributed to decreased nodulation [78-80], increased levels of ethylene [81], and decreased nitrogenase activity [82].

However, after four days of flooding there was no destruction of cellular mitochondria in roots [83]. Maintaining mitochondrial integrity is essential to continued nitrogenase activity. After an initial depression in nitrogenase activity, flooded soybean plants actually recovered to a level of activity comparable to that of the control [82]. Though a reduction in all root growth parameters was observed [79], the development of new nodules at the soil surface and on newly developed adventitious roots offset the loss of original nodule function [79,84] in flooded soybean. Plant nitrogen fixation returned to near normal levels within 15 days after removal of flood treatments of up to 14 days [75,79].

While soybean is generally considered susceptible to flooding, studies carried out by Bacanamwo and Purcell [76,84] and Sullivan et al. [77] showed reductions in growth and yield when flooded for 7 days. Sallam and Scott [79] Oosterhuis et al. [85] evidenced that in comparison to other legumes, soybean has the ability to adapt to soil waterlogging. Studies collaborating this include that of Andreeva et al. [83] who showed soybean to be more flood-tolerant than cowpea. Furthermore, Boru et al. [86] showed no negative effects on survival or leaf greenness of soybean plants grown in nitrogen gas with no detectable oxygen for 14 days, suggesting that soybean is more tolerant to increased levels of water and decreased oxygen than previously thought.

Reproductive stages: Many reports indicated that soybean was more sensitive against the excessive water in soil on the early reproductive than on the vegetative stages [87-89]. Linkemer et al. [90] stated that greatest sensitivity to the water–logging occurred during 7 days in the period starting at R3 stage, and the water–logging reduced the seed yield by 93%, 67% and 30% at the R3, R1 or R5, and V2 stage, respectively. Also, the loss of seed yield under water–logging primarily induced by the decreased pod production which resulted from fewer pods per reproductive nodes in late planting soybean.

Soybeans are generally sensitive to waterlogging [85,91]. A significant reduction in soybeans seed yield in response to floods has been reported [92,93]. Death of the root cortical tissue, reduced vigor, and wilting as a result of hypoxic conditions are some of the reasons of reduced yield in soybean production due to flooding [94]. Flooding has been shown to decrease respiration, causing an increase in membrane permeability, which can result in plant cell death [95].

Russell et al. [93] observed that soybean seedlings had difficulty surviving as little as 48 h of flooding, which is similar to the study Kirkpatrick et al. [96] who reported loss that resulted from flooding at emergence (3- day duration) in their stud. Flooding also has been reported to decrease plant dry weight, with loss in dry weight being greater after a 14-day flood than a 2-day flood [93].

Grasses

Striker et al. [97] in their study assessed the effects of flooding on plant recovery from defoliation on two species: the grass *Paspalum dilatatum*, whose regrowth mainly depends on current assimilation, and the legume *Lotus tenuis*, which can use crown reserves during regrowth. Both plants were subjected to defoliation in combination with 15 days of flooding. Their performance was evaluated during a subsequent 30-day growth period under well-watered conditions. Result showed that flooding plus defoliation did not depress plant recovery from defoliation in the legume species, which showed high sprouting and use of crown biomass during regrowth. However, in the grass species, it negatively affected plant recovery, achieving 32% lower biomass than plants subjected to either flooding or defoliation as single treatments

Imaz et al. [98] showed that flooding episodes during spring and summer, seasons when *Chloris gayana* and *Panicum coloratum* are sown, could constrain their establishment depending on the depth of the flooding water. Evidence showed that seedlings of *Chloris gayana* can tolerate both partial and complete submergence, whereas seedlings of *Panicum coloratum* perform well under partial submergence [98]. However, once established, adult plants of both species might tolerate floods during winter dormancy, spring regrowth, or both periods.

A further study by Imaz et al. [99] assessed the tolerance of adult plants of *Chloris gayana* and *Panicum coloratum* under flood conditions at different times in their growing cycle. Their assessment was related to: (i) late winter flooding for 50 days (WF), (ii) early spring flooding (SF) for 20 days, and (iii) long-term flooding covering both periods (WF + SF, 70 days). A growth period under well-watered conditions was allowed after each flooding event to assess recovery of plant species. Results showed that *Panicum coloratum* had higher tolerance to WF than *Chloris gayana*. The WF Treatment did not affect biomass in *Panicum coloratum*, whereas it reduced biomass of flooded plants by 38% in *Chloris gayana*. Their treatment both registered moderate reduction in their growth (20-30%). Under WF + SF, *Chloris gayana* showed additional reduction in its growth over that observed when subjected separately to either WF or SF, whereas *Panicum coloratum* did not. Both species displayed remarkably fast recovery from flooding when temperatures rose during early summer, attaining biomass equivalent to that of non-flooded plants 1 month after water subsided. It therefore shows that although *Panicum coloratum* appears slightly more tolerant during flooding than *Chloris gayana*, both species are promising for introduction in temperate lowland grasslands.

Maize

Maize requires large amounts of water, but is not resistant to waterlogging. Chen et al. [71] found that when soil moisture reached more than 80% of field capacity, maize growth and development were greatly reduced. Other studies which showed that increased durations of waterlogging decreased maize yield are those of [100-104]. Waterlogging also significantly affects plant morphology, decreasing cell permeability [105-107] reducing root activity and root respiration, and accelerating root senescence [102,108,109].

Vegetative Stages: Van Toai et al. [110] suggested that maize seed can germinate under wet soil conditions in the presence of nominal amounts of oxygen, but that further growth was highly susceptible to excess soil moisture stress. This ties in with the study of Zaidi et al. [111] whose findings showed delay in coleoptile emergence with final germination percentage (>80%) under stress. They further suggested that germinating maize seedlings retain a high tolerance to anoxia in the embryo, but that this tolerance is lost within 2–3 days following germination. Following pre-germination anaerobic stress, the newly emerging leaves showed strong chlorotic symptoms, particularly in susceptible entries which had much delayed emergence indicating poor chlorophyll content. The reduction in the chlorophyll content may have resulted in low current photosynthetic activity, reducing production of photo-assimilates [112], thereby leading to poor seedling growth and development at the early stage [111]. Similar findings were also reported by Loaiza and Ramirez [112], who suggested that reduced growth of seedlings was related to reduce nitrate reeducates activity in root tissues.

Submergence during germination and seedling stages can lead to poor seedling establishment, stunted growth, and delayed development [113]. An experiment to assess the response of maize genotypes to excess soil moisture (ESM) at different stages of life cycle revealed that there was significant and detrimental effect of ESM on maize seedlings in the earlier stages [114]. Zaidi et al. [113] on their part, showed that amongst the four crop stages *viz*; early seedling, knee-high, tasseling and milk stage, early seedling was found to be highly susceptible, followed by knee high stage. Similar studies to assess the response of maize genotypes to excess soil moisture at different stages of life cycle revealed that there was significant and detrimental effect of excess soil moisture on maize seedlings in the earlier stages [115]. The effect of pre-germination anaerobic stress due to excessive soil moisture showed that pre-germination anaerobic conditions are highly detrimental for maize seed germination and emergence [111]. It was noticed that at 36 hours of stress exposure, > 50% genotypes showed significant decrease in germination and at 72 hours, the germination of most of the entries was significantly reduced and emergence was delayed by more than 5 days. Similar findings were reported in previous studies on temperate maize germ plasm, where it was observed that 48–96 hours of pre-emergence flooding at 25°C soil temperature [116] or seed soaking for 48 hours at 35°C [117] resulted in a significant inhibition of germination in maize inbred lines. Pre-germination anaerobic stress (due to excessive moisture) may inhibit seed germination by restricting the seed respiratory metabolic processes essential for germination.

Reproductive stages: Zhang et al. [118] looked at the effects of different waterlogging durations (three and six days) on the yield and growth of summer maize. They assessed the response of maize plant during the three-leaf stage (V3) (see appendix 1), six leaf stage (V6), and the 10th day after the tasseling stage (10VT). Their results showed that maize development and grain yield responses to waterlogging depended on both stress severity (intensity and duration) and different growth stage. From their study, Zhang et al. [118] reported that waterlogging affected the grain-filling characteristics of maize and at V3-V6 the grain-filling parameters were lowest. Days of maximum grain filling (D_{max}), maximum grain filling (G_{max}), weight of maximum grain filling rate (W_{max}), and active grain filling period (P) of V3-6 decreased by 25, 18, 48, and 36%, respectively. After waterlogging, D_{max}, G_{max}, W_{max}, and P of grains decreased as waterlogging duration increased. The greatest losses from waterlogging occurred at V3, followed by V6 and 10VT. Furthermore, their study showed that waterlogging affected the ear length of summer maize. Ear characteristics (grains per ear and 1000-grain weight) and plant morphology (plant height, ear height, and leaf area index) decreased, whereas the bald tip length increased significantly. The maximum grain-filling rate decreased under waterlogging. Additionally, the dry matter accumulation decreased and dry matter distribution proportions of the stem and leaf increased. However, the distribution proportion of grain decreased. Maize was most susceptible to waterlogging damage at V3, followed by V6 and 10VT, with damage increasing with increasing waterlogging duration.

Root growth and development: With regards to root and growth development, Ren et al [119] showed that waterlogging significantly decreased root length, root length density, and number of root tips. It also reduced significantly the total absorption area and active absorption area with the most significant reduction in treatment at V3. The active absorption area of roots at V6, tasseling (VT), milking (R3), and physiological maturity (R6) stages decreased by 68, 67, 57, and 67%, respectively, due to waterlogging at V3. In addition, waterlogged plants generally had much lower root bleeding rates, which were significantly decreased by 46, 28 at V3, V6, and 10VT stages, respectively. The negative effects of waterlogging on root growth and development led to abnormal development of the aboveground biomass, resulting in significant reductions in dry matter, leaf area, net photosynthetic rate, and yield. Summer maize was most susceptible to waterlogging damage at V3 stage, followed by V6 and 10VT stages. Waterlogging reduced grain yield of summer maize, as a result of the delayed of root growth.

On their part, Li et al. [120] found that waterlogging for one day had little effect on maize production. However, waterlogging for more than 3 days decreased yield by over 40% at V6; and total loss of summer maize for waterlogging for 57 days, as well as 7 days at VT. These results however differed from those of Chen et al. (1989), who reported that waterlogging at V6 had the greatest impact on summer maize yield findings from previous studies in which waterlogging for more than 3 d decreased summer maize production by 40 to 100% [109,121].

According to Lone et al [114], the effects of excess soil moisture are highly unpredictable and the intensity of stress may also vary from location to location and year to year. Maize plants are injured more and greater yield losses occur when flooded at early stages. Furthermore, maize plants have no ventilating system for transport of oxygen between upper organs and roots. Plant growth in the field is not affected immediately after the flooding virtually, despite the speed with which the soil is saturated, but the after effects result in substantial reduction in the final yield [122].

Studies on excessive moisture/water-logging stress tolerance in maize during the seedling or vegetative stages found that the stress adversely affects maize at every growth stage, but susceptibility varied at different growth stages. These studies concluded that maize is highly susceptible to excess soil moisture stress before tassel emergence [123-125].

Sunflower

Stress caused by waterlogging impairs the crop growth and yield of sunflower.

Vegetative Stage: A study was carried out by Lose et al. [126] to determine the response of sunflower plants to long periods of water excess during initial development stages. Water excess treatments were applied at the initial development of these plants at the sowing day, three days after sowing, at plant emergence, and at V2 and V4 stages. The treatments had different duration periods 0, 48, 96, 144, 192, and 240 hours. Treatments were applied at three sowing dates. Plant emergence, leaf area, plant height, shoot dry mass, maximum root length, main root length and root dry mass were herein assessed. It was found that excess water is more harmful to sunflower plants during the sowing-emergence period. It substantially reduces emergence, plant density, shoot and root growth, even after 48-hour stress. The water excess led to severe losses in plant emergence in all sowing dates.

Similar results were found by Sung [127] in a study with soybeans wherein excess water to the plants for periods longer than 24 and 48 hours result in reduced emergence by 50% and 100%, respectively. Hence, waterlogging conditions during sunflower crops germination might be harmful right after sowing, as already seen for soybean seedlings [128]. The reduction in the rate of emergence can be explained by an increase in respiration rate and enzyme activity after the first seed imbibition peak, causing a high demand for O2 which potentiates seed damages [129].

Leaf area: Sung [127] showed that with regards to leaf Area (LA), adverse effects of excess water on leaf area in Sunflower were more evident when such stress occurred right after sowing and after onset of germination and this can lead to emergence failures and plant density reduction. The LA values dropped down to almost zero after 48 hours of water excess on all sowing dates except for the first sowing date due to lower air temperatures.

Such negative effect of water excess on LA has also been observed in other crops such as maize [115], sorghum [129], wheat [130] and soybeans [105,131]. According to Orchard & Jessop [129], sunflower leaf expansion is strongly reduced due to water excess at V3 and V6 stages. Moreover, significant reductions in the photosynthetic rate took place after 48 hours of water excess application [131]. Yasumoto et al. [132] described treatments using water excess in the establishment phase (V2 stage) and found sunflower growth suppression. Their results corroborated the observations of Loose et al. [126], which showed a large reduction of LA due to water excess occurrence. Leaf wilting was observed few hours after water excess treatment for all three sowing dates. Furthermore, plant leaves showed photo oxidative damage, mainly for V4-stage.

According to Vartapetian and Jackson [133,134], stomatal closure is an early plant response to water stress. Roots are unable to meet the water demand of plant leaves due to cell anoxia. Furthermore, photo oxidative damages were visually observed in the leaves, mainly for water excess applied at V4 stage. Photo oxidative damages under water excess were also observed in eggplants, tomatoes [49], and in pigeon pea [135].

Plant Height: Water excess had greater adverse effect on plant height when treatment was applied before emergence since it led to major reductions [136]. This effect was mostly severe during the first 2 to 4 days, especially at higher temperatures). Orchard & Jessop [129] reported significant reductions in plant height for sunflower (V6 stage) and sorghum (V5 stage) plants caused by water excess. Likewise, Shimono et al. [131] observed plant height reductions of nearly 23-30% under water excess for soybean plants.

Exposure to excess water right after sowing and after germination is mostly harmful to sunflower plants than it is in later stages since it affects emergence, plant density, leaf area, as well as shoot and root dry matter contents. Sunflower seedling emergence is negatively affected even under periods shorter than 48 hours of water excess application. Yasumoto, et al. [137] found out besides the negative effects of excess water on plant growth, it also affected seed yield and oil quality. Seed yield, the major yield components, the oleic acid content and the total oil content were negatively affected. In addition, waterlogging during the flowering and maturation stages tended to decrease the oleic acid content and to increase the linoleic acid content.

Pearl millet and Sorghum

Grains such as pearl millet and sorghum which are dry land-adapted food crops with high yield potential even under limited rainfall conditions have been used as food by many [137]. They are widely cultivated grain crops in the semi-arid regions of Asia and Africa. They account for over 70% of all cereals grown in the Sahel of Africa [138]. Although pearl millet is one of the most drought-resistant food crops, it is extremely susceptible to conditions caused by waterlogged soil [139].

A study by Awala et al. [140] evaluated the survival, growth and grain yields on pearl millet and sorghum with rice under controlled field flooding. Five cropping systems; single-stand pearl millet, single-stand sorghum, single-stand rice, pearl millet mix-planted with rice and sorghum mix-planted with rice were tested. The seedlings were exposed to flood stress for 22, 11 or 15 days at a mean water level of 9cm and 5–7 cm respectively. The survival rates of flood-stressed experiments showed that pearl millet was generally unaffected by flood stress for nearly 5 days after flooding (DAF) irrespective of the cropping treatments. However, after this period the survival rate tended to decline rapidly though it remained relatively higher in the mixed plants than in the single-stand plants. At 13 DAF, the survival rates in the single-stand treatments were 40%, 3% and 20% compared with 57%, 23% and 33% in the corresponding mixed plant treatments. Nonetheless, in all of these experiments, the survival rate generally dropped fast, all the plants were killed at 18 DAF. Moreover, the plants in the experiment remained alive for only about 11 days after flooding.

With regards to sorghum, plant survival rate patterns were almost similar to pearl millet. In most cases, the survival rate was much higher in the mixed than in the single-stand plants. At 13 DAF, the survival rate of the sorghum mixed plants was 87%, 56% and 63% as compared with 60%, 40% and 13% of their single-stand counterparts. These results indicated that the impact of flood stress was much higher in pearl millet than in sorghum.

Looking at grain yield, their results demonstrated that the grain yields of pearl millet, sorghum and rice, in the 2014/2015a experiment, where the plants were exposed to 3 weeks flood stress, no yield was obtained from pearl millet because all of the plants were killed by flood stress and for sorghum no yield was obtained from the single-stand plants due to poor filling. In the 2014/2015b experiment with two weeks of flood stress, pearl millet and sorghum in the mixed plant treatments produced 26% and 18% greater yields, respectively, than in the corresponding single-stand treatments. However, the yields of pearl millet were affected by flooding much more than that of sorghum, irrespective of the cropping treatments.

In the 2015/16 experiment, the effects of flooding were significant ($P < 0.01$) on the grain yields of pearl millet, sorghum and rice. Cropping systems did not have a significant ($P > 0.05$) influence on grain production in all the crops. However, the interaction between the flood treatments and cropping systems was significant ($P < 0.05$) on the sorghum grain yields. Overall, flooding decreased the dry land cereal yields, but increased the rice yields.

Grain yields of pearl millet and sorghum were reduced by flooding in both the single-stand and mixed plant treatments, relative to the non-flooded upland yields. However the reduction was lower in the mixed plant treatments than the single stand. None the less, worth noting is the reduction in yield on all treatments on the pearl millet and sorghum due to the flood treatment. Soil flooding reduces tillering, plant height and dry matter in pearl millet [141,142].

Cow pea

In cowpea, waterlogging has been reported to reduce nodule production, accelerate senescence of the lower most leaves and delay branch formation [143].

Pea

Four days of waterlogging on pea resulted in chlorosis of foliage, lower rates of transpiration, reduced number of fruiting nodes and extension of internodes [144]. The effect of waterlogging varies with plant age. Studies by Jackson [144] on pea indicated that flowering plants at the 9 to 10 leaf stages were more severely damaged than young vegetative plants bearing only two to three leaves.

Groundnut

A study by Zaharah [145] sought to identify the sensitivity stages of groundnut to flooding as well as the quantification of plant performance and yields. Results showed that groundnut plants exposed to flood experienced stunted growth beginning at 28 and 35 days after sowing (DAS). At a later stage, the plants leaves turned yellow followed by wilting. The wilting was most severe when flooding began at 49 DAS, resulting in the death of most of the plants. This was further reflected by the significantly lower number of plants at harvest. The reduced groundnut seed yield of the flooded plants was related to the low number of pods and seeds, a result of poor plant performance. In the growth stages of up to 49 DAS, the reduction in yield was probably due to reduced pod production as seen from the number of rotten pods. A similar effect of waterlogging in reducing the number of fruiting nodes was also reported [144]. At later stages, yield reduction might be due partly to the result of a large number of rotten pods. There was also a higher incidence of germinated seeds in the pods if flooding occurred at the later stages as was reflected by the high number of seedlings at harvest.

Flooding groundnut plants around 49 and 56 DAS and 54 DAS affected the leaf, stem and root dry weights significantly. There was a significant reduction in total plant dry weight. The effect of waterlogging in reducing the dry weights of vegetative parts had also been reported in pea [145]. Results from the study showed that the final fresh and dry weights of both the pods and vegetative parts of the pea were reduced severely after two days of waterlogging.

With regards to the effects of flooding on plant, pod and seed dry weights, the number of pods and seeds, floods caused a reduction in these variables. Flooding for seven or more days at any stage between 28 and 77 DAS could reduce the seed yield by more than 50%. Between 42 and 70 DAS a reduction of up to 70% in seed yield by was experience. The effects of waterlogging in reducing crop yield were also reported by Kawase [146].

It was proven that groundnut, at any growth stage, was sensitive to flooding. The effects, however, varied with the phases of plant development. They were most serious between 42 and 78 DAS (a period which partly coincided with the rapid pod-filling stage), and were less before and after this period.

Cotton

With regards to other crops such as cotton, the effect of waterlogging on vegetative growth and yield of cotton depends flood duration and the developmental stage [147]. Prior studies showed that an inundation period of 4-32 hours significantly limits the yield of cotton yield [103]. Waterlogging sensitivity in cotton is strongly associated with growth stage [148]. In a series of test-pit experiments during early reproductive stage, Wu et al. [149] observed 27–30 % decline in yield output after 4–9 days of waterlogging. At 10-day exposure, there was significantly increased young boll and square abscission, leading to a 42% reduction in yield [150]. This is similar to the study of de Brito et al. [151], where higher waterlogging sensitivity during early reproductive growth in cotton was notionally linked to the hormone-dependent shedding of young squares observed during abiotic stress. Likewise, Bange et al. [152] reported larger yield losses in cotton waterlogged at early squaring stage (65 DAS) compared with a later growth stage (112 DAS).

Given that the reduction in yield in waterlogged cotton crops is a function of lower fruiting number, fruit abscission after waterlogging has been directly implicated in yield losses [152]. Waterlogging significantly suppressed plant growth and reproductive node development, reducing the total number of fruiting sites. Waterlogging-induced damage to cotton during later growth, as observed by McLeod [15] due to inhibited nutrient uptake.

Inspite of the tolerance of some crops to flooding, most cited literature shows the detrimental effects of floods. Flooding is a major problem in many areas of the world, and most crop species are susceptible to flooding stress. Dudal [152] estimated that 12% of the world's soils are likely to suffer from excess water at some time.

Sugarcane

There has been reported decrease in sugar cane yield under flood conditions as a result of a reduction in photosynthesis, root development, leaf area (LA), LA index, tiller production, stalk height, and sucrose yield [153]. It was found that the application of periodic flooding every month leads to a 50% reduction in the photosynthesis rate [154] and reduced plant growth as a result of a decrease in the metabolic activity of the roots due to hypoxia [155]. Furthermore, Gilbert [156] found that flooding sugarcane in the summer caused sequentially greater yield reductions throughout the harvest season in plant cane.

Flood and temperature interplay

Worth noting here is the effect of the air temperature during the sowing-emergence sub period. Temperature led to differences in seed germination among sowing dates [157]. Air temperature influenced the sunflower seedling emergence under water excess. Recent findings have evidenced the effects of water excess on seed germination of both soybeans [158] and maize [114]. Here, it was noted that emergence reduction was more harmful at 25 °C than at 15 °C and 10 °C. According to Orchard & Jessop [129], high air temperatures lead to increased enzymatic activity and metabolism in sunflower seeds. This must occur because the seeds under stress of excess water lack oxygen for metabolic activities [159]. This therefore means that flood stress in plants will be exacerbated by increased temperatures (Appendix 1).

Discussions

By analyzing crop performances under different flooding scenarios throughout the year, it is possible to assess short- and long-term effects of flood stress on various crops species grown in South Africa. It has been shown that legumes are sensitive to waterlogging [159-162]. Legumes are a very important component in South Africa dietary component. By generating information on flood stress, management practices can be developed to reduce flooding impact on crop production in South Africa. Considerable transient and persistent flooding of the soil and deeper submergence of crops occurs in much rain fed farmlands [163] and the majority of farmlands in South Africa are rain fed. Plant emergence of sensitive species such as wheat, soybeans, and maize is strongly affected by water excess [115,127,128,131]. Even though high air temperatures have a major effect on seed germination of these species [115,128,158], however, few species have evolved to germinate and grow in anoxic environments [128].

Information about flooding tolerance of crops in South Africa is scarce. Most experiments that have been conducted are under tropical conditions [164-166] and not in semi-arid conditions such as South Africa where this agro-ecological condition prevails in most part of the country. Furthermore, most often than not, the recovery period after the water subsides has often been overlooked in flooding experiments, even though it is regarded as crucial when aiming to determine true plant tolerance to this stress [167-170].

There is limited information on the acclimation of various crops species to the specific production environments and its performance under a frequent flood scenario in South Africa. Concurrently there has been limited research done in relation to extreme weather conditions and increase in the frequency of floods as projected by climate change scenarios. Due to the projection of increase temperature, most of the research and consequent crop production has been with species that are tolerant to drought.

Relevant literature shows that many crops are sensitive to waterlogging and complete submergence. Just a few days of flooding can damage plants and will result in significant agricultural losses. It is therefore highly relevant to understand strategies that can improve flood tolerance. Owing to the global nature of flooding and the serious threat that floods will occur more often in the near future in South Africa, it is to be expected that good understanding on flood tolerance will strongly facilitate the development of flood tolerant crop varieties that can grow and yield on marginal, flood-prone land, thereby working towards food sustainability.

Towards a practical approach in forecasting and planning adaptation to climate change in the South African flooded croplands

The approach suggested in this paper is to develop science-informed strategies and plans of action to adapt to incidences of flood and waterlogging conditions brought about by climate change in South Africa. An integrated approach, where land use, soil characteristics and climate are used as the cornerstone to establishing effective resilience to projected flood impacts of climate change on crops is of essence. Figure 6 shows a possible approach to projecting the incidence of flooding and waterlogging conditions. The main parameters considered are soil characteristics and climatic variables. The parameters suggested are not exhaustive but can form a solid foundation for such analysis. Using the soil characteristics, clay content, textural class and water holding capacity, it is possible to classify which soils will be tolerant to incidence of flood. Using such classification, crop suitability maps are produced depend ending on their degree of tolerance to flood and waterlogging conditions.

Using climate variables, mainly rainfall and temperature and their frequency of occurrence, it is possible to extract parameters and timeframes which can be used as baselines or indicators for such frequencies and magnitude of extreme rainfall conditions. Other parameters of importance in developing baseline for susceptibility of flood on production fields of farmers include land use, crop type, knowledge and managerial skills of the farmer, as well as policy framework within the country. The interactive effect of these factors will determine the extent of vulnerability to flood and water logging within a locality.

Landforms and present land use can be used to indicate land use patterns.

Taking into consideration all these parameters, field or greenhouse experiments can be run to give a quantitative impact of the flood stress to crops. The degree of impact will depend on the crop type and their degrees of tolerance to flood as well the measures taken during the period of flood to alleviate the level of stress to the plants.

The slope could play a role here. Report on that, flat terrains in combinations with heavy soils will be more susceptible to floods.

For any process of adaptation to take place, there must first of all be a process of recognizing the factor(s) that are vulnerable and what the causes of the stress are (Figure 6). Building on the study by Schulze [170] in the case of flood stress, the approach is to identify:

The major categories in which adaptive capacity can be enhanced in relation to flood stress and the crops cultivated.

Important and vulnerable sectors within the broader environment in South Africa which are likely to be impacted by flood stress.

The range of foreseen changes the various sectors would have to cope with, and adapting to, in regard to projected climate change and resultant flooding and waterlogging.

Five broad categories of enhancing adaptive capacity are identified [171] as seen in figure 1:

- Technological and structural issues
- Knowledge, skills and participation
- Policy instruments
- Risk-sharing and risk-spreading
- Adaptation around changes in uses of land, activities on the land and the location of activities

Putting the measures of enhancing adaptive capacity in the context of flood stress is of paramount importance. With regards to technological and structural issues, there should be appropriate structures in place for putting in place early warning systems. If areas that are risked are being supplied relevant information in time, advised on possible methods of draining flood prone fields, their adaptive capacity will increase.

Knowledge, skills and participation should involve creating risk maps, communicating such results to relevant stakeholders, training of relevant personnel and involve the farmers in the process of formulating adaptation measures. This is because adaptation should be site specific.

A relook on various policies at national to municipal and district levels will help shape future adaptation measures. Existing policies may not be in accordance with methods that will alleviate flood stress because maybe at the time of the development, the issue of flood stress was not taken into consideration.

Where the burden of exposure to flooding and consequent waterlogging is shared, the vulnerability is reduced and adaptive capacity increased. In terms of risk sharing and spreading, adaptation is enhanced where there is the participation of both the private and public sector. Establishing relief fund, making it easier to access insurance, development and micro lenders will take most of the burden off affected persons.

Adaptation around changes in uses of land, activities on the land and the location of activities should be assessed and changed accordingly. This could be in terms of changes in land use, changes in the types of crops cultivated (e.g. flood resistant crops), practice of conservation agriculture or change in tillage practices. It therefore involves adaptive spatial planning.

It is worth noting that for each of these five categories of enhancing adaptive capacity do not work in isolation but interterm with each other [172] (Figure 6). Also, even with this approach established, it should be noted that the degree of adaptation available to each area will vary. It is only with proper methods and research that steps can be taken to build resilience of the rain fed agricultural system to the impacts of flood stress.

No major limitations were encountered during the review of the paper on crop susceptibility to floods and water logging in South Africa. However, the paper was reviewed based on published articles and the authors' personal experiences and informal communications with farmers and relevant stakeholders in the agricultural sector. The lack of published data on work that might have been carried out in this field could limit the overall conclusion of the report to some extent in totality.

Recommendations

Further field and controlled experiments are required to generate data that will assist in modeling future impacts of floods on crop growth and development.

Conclusion

Granting that much of southern Africa, South Africa inclusive, lie within the arid to semi-arid climatic regions, extreme rainfall events in the region are relatively frequent [173]. Long-term implications of such increases in the magnitude and frequency of high rainfall events for flood impacts on crops is therefore of serious concern. The longer that excessive water is present the more likely that damage to plants will be fatal. Even once the flood waters recede it can take weeks for the soil to dry out while the plants continue to suffer damages in the meantime. It would be valuable for the agriculture sector to conduct a holistic assessment of future research needs relating to flooding impacts and possible adaptation scenarios. Such an assessment could distinguish needs at a range of scales of implementation and identify adaptation needs for specific crops at local scale. The feasibility of an approach for assessing activity-specific adaptation options needs to be explored. This should include defining the appropriate level of intervention and prioritizing of research. Assessments of the relationships between crop productivity and climate change rely upon a combination of modeling and measurement.

Developing an appropriate method of responses to address and prevent flood stress requires a reliable flood/waterlogging risk analysis including hazard, vulnerability and exposure and the possible adaptive responses. This paper explores the possibility of flooding and water logging due to climate change, the vulnerability of different kind of crops to flood/waterlogging prevention capacity and adaptation, particularly with regards to soils, climate, and land use in South Africa. A baseline framework was established that could be used to assess crop risk to flood and waterlogging and reduction of crop risk to flood/waterlogging. The following conclusions were reached:

1. In order to address the impact of crop flood stress, information on land uses, climate, crop types, soils are required. These factors can be used to model future impacts of crop flood stress. It is recommended that this framework be tested and evaluated for more place specific events to enhance the reliability of the framework.

2. The crop flood stress may be enhanced by elevation, land uses, farming practices, soils present in the area. These indices should be easily adopted by the administrative department for effective management. These will be consistent with the indicators developed for the area.

3. Within a conceptual and theoretical ground, the framework operates well. Structural measures are taken as the main resistance strategies, which are aimed at flood/waterlogging prevention. The non-structural measures are taken as the main resilience strategies to minimize the flood/waterlogging impacts and enhance the recovery of crops and farmlands from the impacts of floods and waterlogging conditions. Under the impact of climate change, flood/waterlogging risk increases and the flood mitigation become more difficult, complex and long-term. More emphasis should be put on flood forecasting, emergency planning and response on flooded and waterlogged farmlands as well as post-flood recovery. A reasonable flood/waterlogging risk analysis for farmlands is important, which can be utilized for spatial land use planning, for flood control works design, and for emergency response decision making.

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