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CLIMATE CHANGE AND SOIL SALINIZATION: IMPACT ON AGRICULTURE, WATER AND FOOD SECURITY

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ABSTRACT

Global climate change (GCC) has the potential of causing sea level rise (SLR) and precipitation changes in vast extents of coastal areas. SLR and precipitation changes will have impact on soil salinization and agriculture production, leading to issues of water and food security. The adverse impact is particularly severe for low lying coastal areas in South and Southeast Asia as well as for regions in the Sub-Sahara Africa that are currently water stressed. Reduced precipitation and SLR will curtail the availability of surface and subsurface water needed to sustain agriculture, human habitation as well as wildlife. Moreover, interaction between coastal vegetation, groundwater salinity, SLR and increased tidal intrusion may induce positive feedback loops to further limit the freshwater lens. Reduced freshwater lens thickness will have adverse consequences for groundwater resources critical to agriculture in many regions. We will use an in-house vegetation-groundwater simulation model MANTRA to demonstrate this dynamic interaction between coastal vegetation and groundwater hydrology in response to SLR in a typical coastal marshland in USA to infer insights on wider impacts of GCC. We then discuss implications on and adaptation to GCC impacts on agriculture, water and food security in several regions, including Malaysia, South Asia, the lower Mekong Delta and China to highlight the potential of catastrophic events of droughts, famine and social-economic crisis.

Key words: Climate change, Soil salinization, Water and food security, Sustainable agro-aquaculture.

Introduction

The eradication of poverty and hunger is one of the United Nations Millennium Development Goals adopted in 2000. There would be, however, substantial reduction in agricultural yields and fresh water resources by the end of the 21st century due to anticipated global temperature increase of 1.4-5.8 °C and Sea Level Rise (SLR) of 1.8-5.9 mm/year as predicted by Global Climate Change (GCC) model. The implied water and food insecurity is a daunting challenge. Worldwide, about 1.5 to 2 billion people rely on groundwater as a main drinking water source. Declining water resources coupled with salinity intrusion into surface and subsurface water will pose threats to water security. Hence, understanding the coupling of surface and subsurface water is crucial in achieving sustainable water resource utilization. Water scarcity, soil degradation and loss of cropland worldwide will have a profound influence on food security. Salinity intrusion and vegetation competition have a pronounced impact on reducing available water and crop yields, directly threatening both water and food security. The threat of SLR on groundwater and vegetation dynamics has been widely reported for wetlands at low-lying coastal plains of South Florida (Willard & Bernhardt, 2011; Pearlstine et al., 2010; Williams et al., 1999), North and South Carolina (Noe et al., 2013; Krauss et al., 2009; Carter et al., 2008) as well as Louisiana (Teal et al., 2012; Baldwin et al., 1996). Wetlands are complex eco-hydrological environments where surface and subsurface water resources interact strongly with vegetation, topography, climate and tidal influence, resulting in dynamic responses on soil salinity and vegetation shifts. Serving as habitat to many important species of plants and animals, wetlands are showing signs of SLR impact with declining freshwater vegetation. Insights and projection of gradual (SLR) or sudden (storm surge) increase in groundwater salinity on vegetation are important in conserving and managing the coastal ecosystem. For this purpose, a coupled vegetation competition and groundwater simulation model named MANTRA was developed. In this paper, we will use the in-house simulation model MANTRA (Teh et al., 2015; 2013) to investigate the dynamic inter-relationship between vegetation growth, groundwater salinity, precipitation and tidal forcing to highlight potential threats to a typical coastal marshland in USA, including regime shifts and loss of crop land due to SLR.

In the following section, we provide a brief overview of how model simulations are used to explain the dynamics of vegetation (marsh, mangrove, hardwood hammock) competition in the presence of groundwater salinity, leading to regime shifts as observed in south Florida. We then report our model simulation results for a typical coastal marshland in USA to indicate potential regime shifts in coastal vegetation from freshwater vegetation towards halophytic vegetation that are adapted to survival in saline water at the expense of crop production, implicating threats to food security. Marshes are complex hydrological environments in which shallow groundwater interact with tidal flows that regulate the temperature and movement of saline groundwater. The salinity gradient in the marsh is generated by the interaction of the tidal flows, topography, climate, and the soil-vegetation factors. In coastal aquifers the estuarine inflow is the main process contributing to the increase in groundwater salinity (Alvarez et al., 2015). This paper then proceeds with a discussion on the development related to water and food security in a broader context, indicating the unsustainability of current rice production systems in some countries including Malaysia and suggesting the wider application of sustainable agro-aquaculture in which crop-fish cultivation in irrigation systems and flooded rice fields can produce more crop per drop of water usage.

Dynamic vegetation-salinity-hydrology modelling

Ross et al. (1999) has documented mangroves inland invasion of up to 3.3 km in the southern Everglades over the past half-century, largely at the expense of freshwater marshes and swamp forest. This is certainly in part due to the effects of both SLR and upstream hydrological degradation, which has reduced the amount of freshwater flow towards the coastal estuaries. Halophytic communities such as mangrove forests and buttonwood hammocks tend to border freshwater plant communities as sharp ecotones. Remote sensing imagery shows the sharp boundaries between freshwater hardwood hammock communities and halophytic communities such as buttonwood and mangroves in southern Florida. The literature documents how transpirations of saltwater and freshwater plants respond differently to vadose zone salinity, thus altering the salinity through feedback. Teh et al. (2008) develop the model MANHAM to explore the possibility of regime shifts from freshwater hardwood hammock (glycophyte) to mangrove (halophyte) that might be triggered by a large storm surge. Our simulations indicate that a significant 1-day storm surge event could initiate a vegetation shift from hardwood hammocks to mangroves in areas initially dominated by the former. In the model, mangroves take over more than half of the higher elevation cells if the storm surge saturates the vadose zone at more than 15 ppt. A light storm surge that saturates the vadose zone by less than 7 ppt will not cause a vegetation shift. The rate of domination by mangroves in the high elevation cells after a significant storm surge depends on the thickness of the vadose zone. A thicker vadose zone will have a larger volume of high salinity water that takes longer to be flushed out by precipitation. Thus, for an extended period of time, the growth of hardwood hammocks will be suppressed while mangroves will continue to grow. This will promote a faster rate of mangroves takeover. On the other hand, a smaller volume of high salinity water will be washed out quickly by precipitation and therefore would allow the hardwood hammocks to recover. Jiang et al. (2014) reported similar conclusion regarding the high dependency of vegetation shift to soil salinization duration and amount. Further, their simulation results indicated sensitivity to the density of mangrove propagules or seedlings transported into the marsh. Using mathematical models, Jiang et al. (2015a, b) show how the self-reinforcing feedback between vegetation and soil salinity, together with physical template consisting of groundwater salinity gradients, tidal flux and topography, control the ecotones between halophytic and freshwater communities. Regions of bistability along salinity gradients have the potential for large-scale vegetation shifts following pulse disturbances induced by hurricane tidal surges in Florida, or tsunamis in other regions. The size of the region of bistability can be large for low lying coastal habitat due to the extensive high saline water table, which extends inland due to salinity intrusion. The implication to water security for low lying coastal region under GCC scenarios is in dire.

The mathematical models used in the above studies does not consider freshwater lens, which typically overlies deeper water salinity levels. To overcome this limitation, the model MANTRA is developed by linking the USGS's Saturated–Unsaturated TRAnsport (SUTRA) groundwater model to the vegetation competition model MANHAM. This is the first known attempt to develop a coupled vegetation-hydrology-salinity model. There exist other studies involving the development of vegetation-hydrology model but notably, the model developed in these studies does not consider groundwater salinity. Chui et al. (2011) developed an eco-hydrological model combining the Richards' equation for characterizing variably saturated groundwater flow, with a vegetation component described by Lotka-Volterra equations tailored for plant growth. Their model for wetland ecosystems characterizes the coupled relationship between variably-saturated groundwater flow and plant growth dynamics. A coupled model that incorporates the effect of soil-water saturation on the plant growth as well as the effect of plant transpiration on groundwater flow in the marsh soil was developed by Xin et al. (2013). The model was applied to simulate marsh plant growth subject to the influence tides. In their study, the plant growth dynamics depend solely on soil-water saturation, with other factors such as soil salinity neglected.

Results: MANTRA Simulation on a typical march in USA

In this paper, we use a newly developed in-house model MANTRA (Teh et al., 2015) to understand and predict zonation of several competing vegetation types along coastal marshes with soil salinity gradients. We integrate a coastal spatially explicit vegetation competition model MANHAM (Sternberg et al. 2007; Teh et al. 2008) with a well-established groundwater hydrology model SUTRA (Voss and Provost, 2002) developed by USGS to form MANTRA to predict coastal habitat changes due to vegetation competition subject to a set of projected precipitation and SLR scenarios under GCC. The modeling takes into account abiotic processes including groundwater salinity and hydrology, precipitation, tidal forcing, as well as salinity pulses derived from episodic storm surges such as hurricane and tsunamis. Biotic processes are incorporated to model plant growth and physiology, evapotranspiration and species competition, subject to the dynamic feedback interaction with soil salinity and hydrology, similar to the approach used by Jiang et al. (2012). To simulate vegetation changes in a tidal swamp habitat exposed to a salinity gradient, our modeling incorporates several vegetation types found along the typical marsh site. Vegetation growth competition dynamics are driven by groundwater hydrology and soil salinity. MANTRA simulates the competition of several vegetation types along a coastal gradient of $N \times N$ grid of spatial cells with cell resolution of about 0.1-1 m. It simulates feedback interaction of vegetation growth with hydrology and salinity dynamics in the vadose zone and groundwater. The meteorology-environmental factors of precipitation and tides are external factors that drive the vegetation competition. MANTRA has been used to examine the impact of SLR on coastal vegetation of southern Florida (Jiang et al., 2015a) and the Rowdy Bend area of the Everglades (Teh et al., 2015).

To project changes in groundwater and vadose zone salinity subject to SLR of 3.1 mm/year over a 108 year period, we use daily tidal elevations as shown in Figure 1. It should be noted that a SLR of 3.1 mm/year is modest compared to the upper limits of 18 mm/year of SLR predicted more recently. MANTRA is applied to simulate both salinity intrusion in groundwater and the change in vegetation from freshwater vegetation to halophytic vegetation through time, starting from Year zero (Figure 2) through Years 27, 54, 81 and 108 (Figures 3 to 6 respectively). It may be seen from Figure 3 that after a period of 27 years, freshwater vegetation begins to show sign of inland retreat, while groundwater starts to be salinized particularly in the top layer due to salinity intrusion induced by SLR. The inland retreat of freshwater vegetation and salinity intrusion into groundwater continues for the next 27 years, resulting in the initialization of inland invasion of halophytic vegetation (Figure 4). By Year 81, halophytic vegetation has moved inland by some 50 m, while groundwater salinity has reached 30 ppt for about 50 m of the top soil (Figure 5). This salinization of groundwater and inland invasion of halophytic vegetation continue with time, causing the freshwater vegetation to retreat further and with reduced biomass density, as can be seen in Figure 6. This simulated scenario is the consequence of a modest SLR of 3.1 mm/year, without the additional impact of severe salinity top-overs induced by frequent annual hurricanes that are common in Florida. Inland invasion of mangroves could potential reach several km if the SLR is of the order of 10 mm/year or if many severe storm surges occurred that result in salinity in the vadose zone reaching or exceeding 15 ppt. Soil salinization and retreat of freshwater vegetation will have dire implications to agriculture, water and food security, which are the subject of further deliberation in the remaining sections. Preservation and enhancement of our precious water resources and pristine environment that support vibrant ecosystems is crucial in sustaining water and food security, a concept that may be described as sustainable eco-hydrology.

Figure 1: Tidal elevation above MSL (0 m) subject to sea level rise rate of 3.1 mm/year

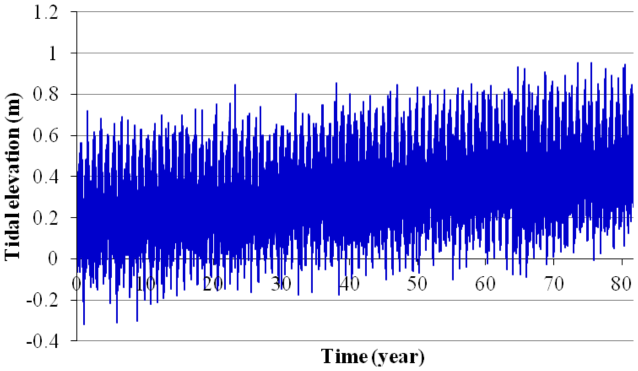


Figure 2: Initial condition before sea level rise scenario. Left panel shows the distribution of halophytic (red) and freshwater (blue) vegetation (g C/m^2) at t = 0 year. Right panel shows the salinity distribution (kg/kg) with ground depth (y-axis) in meters. The x-axis is in meters.

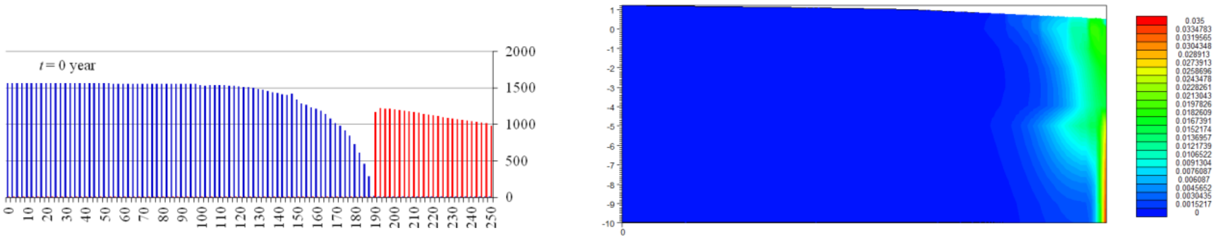


Figure 3: Left panel shows the distribution of halophytic (red) and freshwater (blue) vegetation (g C/m^2) at t = 27 years after sea level rise of 3.1 mm/year. Right panel shows the salinity distribution (kg/kg) with ground depth (y-axis) in meters. The x-axis is in meters.

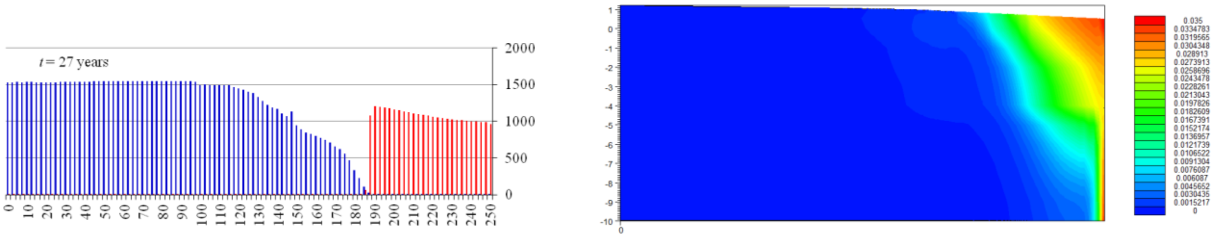


Figure 4: Left panel shows the distribution of halophytic (red) and freshwater (blue) vegetation (g C/m^2) at t = 54 years after sea level rise of 3.1 mm/year. Right panel shows the salinity distribution (kg/kg) with ground depth (y-axis) in meters. The x-axis is in meters.

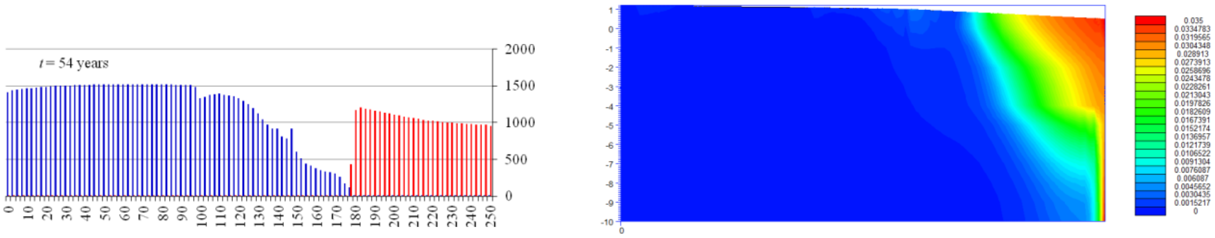


Figure 5: Tidal Left panel shows the distribution of halophytic (red) and freshwater (blue) vegetation (g C/m^2) at t = 81 years after sea level rise of 3.1 mm/year. Right panel shows the salinity distribution (kg/kg) with ground depth (y-axis) in meters. The x-axis is in meters.

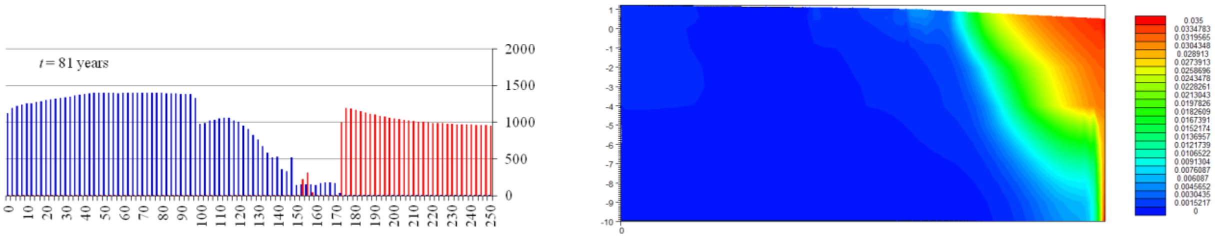
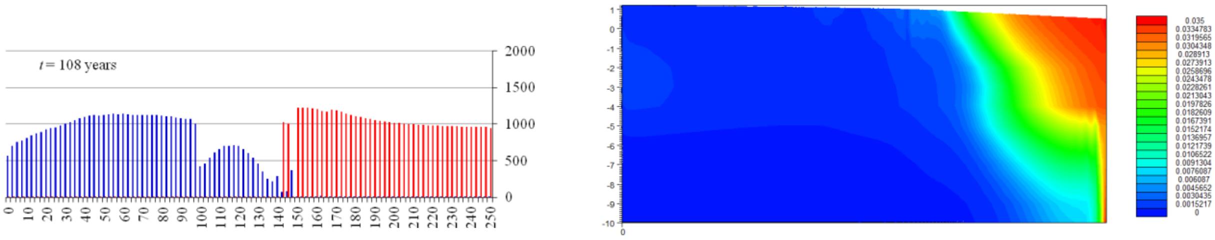


Figure 6: Left panel shows the distribution of halophytic (red) and freshwater (blue) vegetation (g C/m^2) at t = 108 years after sea level rise of 3.1 mm/year. Right panel shows the salinity distribution (kg/kg) with ground depth (y-axis) in meters. The x-axis is in meters.



Food security

Water and food security are the key challenges under climate change as both are highly vulnerable to continuously changing climatic patterns, as highlighted in the previous section. Achieving food security is at the top of the international agenda because of a number of compelling factors such as declining freshwater resources, soil salinization, land degradation, population growth, inadequate agricultural infrastructures, plant disease, poor soils and unfavourable climate. The world demand (billion tons) for cereals is predicted to increase from 1.84 in 1997 to 2.50 in 2020. To meet this demand, we need to resort to sustainable eco-hydrology, as conceptualized in the previous section, in achieving aclimate-resilient agriculture intensification, producing more from the same area of land while reducing the environmental impact and negative externalities. Crop response to increased temperatures can reduce grain yield of up to 10 % in rice with every 1 ºC increase in night-time temperature, while most vegetables are relatively sensitive to high temperatures (Lal, 2013). Soil losses from global cropland are currently occurring at a rate of over 6 ton ha^{-1} yr^{-1}, 15 times the average loss rate of 0.4 ton ha^{-1} yr^{-1} over the geological history of the earth. This environmental carnage caused by agriculture intensification needs to be addressed. Otherwise, the improvements in food production will not be sustainable in the long run. Resilient agriculture can benefit all farmers with simple on-site in-field crop residual retention, in addition to water conservation and reduction in soil loss. Corn grain yield with 0 % crop residue retention is 6.3 ton/ha compared to 10.5 ton/ha with 100 % residue retention, a significant 67 % increase. Sustainable management of grassland is important in improving food security in the arid and semiarid regions that covers 37 % of the Earth's terrestrial area. For food security, the four major crops are wheat, rice, maize and soybean, which together account for 85 % of the world cereal exports. Abundant and sustained yields from these four cereals will contribute significantly to balancing regional differences in crop productions, relieving the shortages in the arid and semi-arid grasslands. To assess production of these four cereals subject to various scenarios of Global Climate Change (GCC), a global climate model (HadCM3) has been developed by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES). Global production in the future appears secure and stable with sustainable practices in agriculture; however, regional imbalance in cereal production are likely to persist and widen through time, with major vulnerabilities occurring in low-latitude regions and arid and semi-arid grasslands (Parry et al., 2004). Elevated CO_2 by itself tends to increase growth and yield of most agricultural plants, with an average 4 to 5 % increase in cereal yield for every 100 ppm CO_2 increase. However, the realization of these modeled beneficial effects of CO2 in the field remains uncertain due to the unknown interactions with temperature, nutrients, water, salinity and other stresses (Derner et al., 2003). Generally, SRES scenarios would result in crop yields decreasing in developing countries and yields increasing in developed countries. Decreases are especially significant in Africa and parts of Asia with expected losses of up to 30 %. In these locations, the beneficial direct effects of CO_2 increase are not sufficient to compensate for the adverse effects of temperature rise and precipitation changes on crop yields. Cereal yields dramatically decrease in developing countries as a result of regional decreases in precipitation and large temperature increases. Soil degradation and loss of cropland will have a profound influence on the food security in China in the long run. Simulation results strongly suggest that the present-day production capacity under the current management regime will not be able to sustain the long-term needs of a growing population, which demands a richer diet. Institutional and technological innovations to enhance rural agricultural infrastructure, as well as improvement in land and water management are needed in order to strengthen the integrated utilization of agricultural resources based on local eco-hydrological conditions. Early warning systems are needed, especially in food-insecure regions, so as to alleviate the impact of major catastrophic natural events on local food supplies (Ye & Ranst, 2009).

Water security

Water is the main limiting factor for crop production, culminating in the mantra of more crop per drop. Given the physical limitations of natural resources—primarily water and land—required for food production, understanding the linkage between food security, water security and land use is paramount. New strategies and effective management options are required in order to address water use, land management and food productivity of agricultural systems. Sustainable use of water and other natural resources at various scales (farm, district and region) must be maintained to ensure proper utilization and conservation of both surface water and ground-water. A recent model study in north-west China indicates that a 15 % water saving could be achieved via improved regulation of canal water conveyance and distribution, coupled with improved irrigation scheduling and proper land levelling (Todorovic et al., 2015). China's endowment of land and water resources, on a per capita basis, is notably below the world average. China's annual water supply is equivalent to 1856 m^3 per capita, or 25 % of the world's average, while the internationally accepted definition of water scarcity is set at 1000 m^3 per capita. An estimated 81 % of water resources are found in the south, while most of China's arable land (64 %) is in the arid and semi-arid north. Similarly, the average supply of groundwater is four times greater in the south than in the north. The South-North Water Transfer project could deliver 50 km^3 per year from the Yangtze River Basin to the North China Plain, benefiting 300 to 325 million people. Further, saltwater intrusion and water pollution in heavily polluted cities such as Chongqing has led to reduction of GDP in local areas by about 1.2 %, with damages in agriculture production constituting the largest share (56 %) of the costs (Khan et al., 2009). Hence environmental management is another important dimension in securing water and food security in China, and more so in many other countries located in water stressed regions.

Saline groundwater

Most of the freshwater resources are depleting at a fast rate due to unprecedented escalation in water demand from domestic, irrigation and industrial sectors. It is important to search for additional sustainable water resources including wetlands and marshes. Water scarcity is a particularly serious problem for agricultural production in arid and semi-arid areas. Majority of the arid and semiarid countries are not able to fulfill the required demand for water and food under the scenarios of climate change. Shallow groundwater is potentially a valuable source of additional water supply to partially meet crop water requirements in these arid and semi-arid regions. Saline groundwater is often found at shallow depth in irrigated areas of arid and semi-arid regions and is associated with problems of soil salinization and land degradation. This shallow groundwater, via capillary rise, is a valuable resource that can be utilized directly. In this way, it is possible to meet part of the crop water requirement, even where the groundwater is mildly saline, thus reducing the demand for irrigation water and alleviating the burden of disposal of saline drainage effluent (Gowing et al., 2009). However, this is accomplished at the expense of reduced yields. In Iran, where groundwater contributes more than 50 % of the total water requirement, groundwater with salinity levels of 2.9 dS/m or higher results in pronounced yield losses (Talebnejad & Sepaskhah, 2015). With limited major source of water, Arabic countries depend on natural precipitation, water conservation and groundwater to fulfill their water needs, resulting in continuous unsustainable drawdown of aquifers (Misra, 2014). Artificial recharge of the dried aquifer systems with partially treated water may be one solution. The unsaturated lithology (vadose zone) acts as a natural filter to remove essentially all pollutants before the water reaches the freshwater lens if the vadose zone has the desirable quality. Rain fed agriculture systems can be upgraded through enhanced rainwater harvesting and augmented by artificial recharge systems. Being one of the world's driest continents, Africa continues to face a severe water crisis. Climate change will directly affect African countries, in particular, the Sub Sahara, with declining crop yield and escalating water demand. It is clear that to fulfill water demand from arid and semi-arid regions requires substantial and sustained investments in technology and innovations.

Health impact of salinity in drinking water

For drinking water, the USEPA stipulates that the maximum allowable salinity concentration is 250 mg/L. SLR-induced salinity intrusion into coastal rivers and aquifers may result in salinity in drinking water far exceeding this safety limit. For example, the IPCC study indicates that marine and coastal ecosystems in South and South-East Asia (SSA) will be affected by SLR, imparting severe impact on water security in those developing countries located along deltaic regions. The impacts are particularly severe for the regions which are subjected to frequent large storm surges from the sea that can intrude up to 100 km inland. While the global SLR rate is estimated to be in the range of 1.8 to 5.9 mm/year (IPCC); for Bangladesh, the rate is higher (4.6-7.8 mm/year). SLR-induced salinity intrusion in Bangladesh will pose immense pressure on existing water resources. Salinity intrusion into surface and subsurface water is determined by a combination of factors, including rainfall, river flow, tidal elevations and groundwater extraction, as well as the influence of SLR and other climatic variables. A combination of reduced rainfall and river flows, increased tidal elevations, and elevated groundwater extraction will contribute to vastly increased salinity intrusion along coastal regions, as indicated by several model simulation studies. In addition, large-scale shrimp farms have contributed significantly to increased groundwater salinity, soil degradation, and a lower yield and lower acreage of rice in Bangladesh. Of critical concern is the salinity during the dry seasons. To provide perspective, the average level of river salinity in the Passur River in Khulna (a coastal area), is estimated at 8210 mg/L in the dry season, resulting in an average human salt intake of up to 16 g/day from river water alone, which is 10 times higher than recommended daily salt intake (Vineis et al., 2011). Similarly, in the critically dry 1991 water year, electrical conductivity at Sacramento and San Joaquin rivers averaged 589 µS/cm, corresponding to 920 mg/L, posing dire medical consequences with regard to blood pressure. A study in Massachusetts, USA, reported that systolic and diastolic blood pressures of high-school pupils from towns with a high-sodium content (272 mg/L) in public drinking water were significantly higher than those in matched cohorts in the lower-sodium towns (20 mg/L) by 3 to 5 mmHg after controlling dietary salt intake (Calabrese & Tuthill, 1981). The problem of saline intrusion due to climate change and SLR can potentially affect 11 Asian mega-deltas, and other large deltas or estuaries elsewhere, such as the Nile and the Mississippi.

Salinity impact on crop yield

A crop yield model has been developed to predict crop yields subject to the interactions and feedback mechanisms in the plant-water-nitrogen-salinity regime. Model results clearly indicate that salinity can increase nitrogen leaching from soil and can decrease corn yields. For this study, available nitrogen is fixed at 200 kg/ha, while salinity levels are kept at three levels (EC = 0.2, 2, and 10 dS/m), where EC denotes electrical conductivity. It investigates the impact of available water (cm) on corn relative yield (%) and on nitrate leaching. For each of the three salinity levels, the corn relative yield gradually increases with increasing water availability, following a sigmoid S curve, up to a maximum, which is achieved at 50-60 cm of available water. The relative yield subsequently declines with further increase in water availability exceeding 60 cm, implicating nitrate leaching with excess available water. The maximum relative yield decreases with increasing salinity levels (70 % at 0.2, 65 % at 2, and 50 % at 10 dS/m). For each of the three salinity levels, nitrate leaching does not occur below 80 cm of available water, at which point available water balances the plant uptake capacity. Beyond 80 cm of available water, nitrate leaching then sharply increases with increasing available water, following a sigmoid S curve, eventually reaching a maximum when available water exceeds 100 cm. The maximum level of nitrate leaching is 18 kg/ha at EC = 0.2 dS/m, increases to 20 kg/ha at EC = 2 dS/m and peaks at 30 kg/ha at EC = 10 dS/m. It is clear from this study that salinity stress increases nitrogen leaching and decreases corn yields (Wang & Baerenklau, 2014), implicating the dire consequences of SLR. This finding is highly relevant to food production as over 800 million hectares of land worldwide are affected by salinity (Alvarez et al., 2015) via a so-called ‘primary salinization’, where salts are transported by capillary flow of brackish water from groundwater into the root zone. The underlying mechanisms of salinity stress on plants are well explained by Pang & Letey (1998) as follows: “Salinity leads to reduced plant growth, which leads to reduced evapotranspiration, which leads to more leaching, which leads to removal of N from the root zone. Reduced N leads to reduced plant growth, which leads to less evapotranspiration, which leads to more leaching, which leads to even less N in the root zone” (p. 1426).

Non-sustainable rice production in Malaysia

At 3817 kg/ha, the national average productivity level for rice in Malaysia is low, as compared to the world average of 4527 kg/ha. In 2013, the total paddy production in Malaysia was 2.63 million tons cultivated from 688,207 ha of farmland. However, the potential is vast for improving rice productivity in Malaysia. In a recent study, (Muazu et al., 2015) report that the average paddy yield in their study area, consisting of 40 farms, is 7625 kg/ha, which is well above the national average. This yield is close to the average rice yield in America (7616 kg/ha), although it is less than the rice productivity levels in Australia (9896 kg/ha) and in China (8098 kg/ha). The rice productivity level in the study area is, incidentally, higher than that in India (3800 kg/ha), in Bangladesh (4870 kg/ha), and in Japan (4650 kg/ha). The vast discrepancy in regional rice yields carries the implication that rice productivity worldwide has the potential of vast improvement if the appropriate cultural, institutional and technological innovations are implemented in the regions with low rice productivity. Farmers in the study area reap merely 7.76 times the energy they invested, with a minute monetary benefit-cost ratio of 1.37. This low level of rice productivity deserves close attention. Further, 84 % of the total energy input used by the farmers for the entire cultivation period is derived from fossil-based non-renewable resources. This high level of fossil non-renewable fuel input and low benefit-cost ratio is detrimental to the sustainability of paddy cultivation in Malaysia in the long run. The government should devise policies supportive of sustainable paddy cultivation by channeling incentives to farmers that adopt best sustainable cultivation practices that promote environment health.

Sustainable agro-aquaculture: adaptation to GCC

Producing one-third of the world’s food from 240 million ha, irrigated agriculture is the largest user of the world’s fresh water (Dugan et al., 2006). To improve food security, efforts should be devoted to enhancing water productivity in irrigated agriculture, by improving crop yield per drop of water used and by the harvest of fish, both cultured and catch, from irrigation systems. Out of the 240 million ha irrigated agriculture, an estimated 600,000 km of large channels and 2.4 million km of small channels are potentially available for fish culture. Fish culture in flooded rice fields can increase water productivity substantially. Culture fish production can achieve 600 kg/ha/year in shallow-flooded areas and up to 1500 kg/ha/year in deep-flooded areas, without reduction in rice yield and wild fish catch. Culture-based fisheries in small reservoirs can further augment fish yield in a substantial way as they do in China (743 kg/ha/year), in Sri Lanka (300 kg/ha/year) and in Cuba (125 kg/ha/year). In Asia, potential yields from small reservoir fisheries are estimated to be 500 to 2000 kg/ha/year. In these enhanced agro-aquaculture ecosystems, the opportunity exists to build large fence-in areas, up to several hectares, by creating enclosed water bodies and stocking them with fish. Substantial additional benefits can be obtained by combining intensive aquaculture with irrigated crop production in this way. At national, community and family levels, these systems of agro-aquaculture are critically important in sustaining food security by improving efficiency of water utilization in food production. This improvement in water productivity by crop-fish agro-aquaculture mediated via cultural, technological and institutional innovations will benefit large numbers of low-income families in Africa, Asia and Latin America, where freshwater fisheries are a crucially important resource for poor rural families (Dugan et al., 2006). Rich in protein and minerals, these fish are high value food, which can be and are harvested using a range of simple, low-cost technologies. Rivers and their associated floodplains are particularly important in sustaining these low-cost fish harvests. For example in Cambodia, fish harvested primarily from the Mekong river system constitute 65-75 % of total protein in the diet. The total direct use value of the fishery resources of the Lower Mekong Basin has been estimated as USD 1478 million (Sverdrup-Jensen, 1999). Studies in Vietnam and Bangladesh show that socially and financially viable approaches for integrating fish into rice culture systems are possible, with potential extension to the Sub-Saharan Africa (Delgado et al., 2003). Agro-aquaculture is widely regarded as playing a crucial role in meeting regional food requirements over the coming decades. Unfortunately, a growing number of rivers run dry along parts of their course for part of the year, including the Colorado (USA) and the Huang Ho (China). Restoring a vibrant hydrology of these river systems is critical in sustaining food and fish production. Critical to a sustained fishery in rivers and flood plains are water level and river flow, the timing, duration and regulation of the floods, characteristics of the flooded zones, fish migration routes and dry season refuges. Sufficient investment in research and development will go a long way towards achieving food security in these local regions. Salinization in the lower reaches of river systems as well as reduced flows at the mouth of many big rivers, as in the Lower Mekong, is of grave concern. In addition to the adverse effects on agriculture, this salinization drives a change in the natural vegetation structure, leading to reduced bio-diversity, impacting subsequently the livelihood of local populations. Higher salinity in estuaries encourage the invasion of many marine predators whose presence would decimate the safe nursery for fishery.

Conclusion

The simulation model MANTRA is capable of providing insights on the future effect of saltwater intrusion due to sea level rise and storm surge-induced inundation on coastal vegetation subject to the influence of various stochastic and deterministic factors. This study is performed by means of a two-dimensional cross-section model. Future work will include the use of a three-dimensional model capable of representing the landscape spatial heterogeneity to allow a better understanding on the spatial distribution of the vegetation. This paper has outlined the risk of soil salinization, soil degradation and loss of arable land due to climate change and population growth. The implications on water and food security are then discussed. We conclude this paper with the following remarks. We must produce more from less per capita land and water resources through sustainable intensification in order to feed a growing population that is projected to reach 9 billion by 2050. Integrating hydrology and agro-ecosystems to optimize on the relationship between soil, water, nutrients and crops is important to ensure food security. By the judicious choice of efficient management systems that minimize losses of water by surface runoff and evaporation and maximize storage of soil-water in the root zone, we can significantly reduce water scarcity. High soil erosion exacerbates pollution and reduces soil organic carbon, leading to diminished yield. This must be controlled. Adaptation of agricultural, water and food systems to climate change necessitate appropriate economic and policy interventions at the national and international levels. Accelerated soil erosion by water and wind, and salinization are the dominant processes that reduce the global per capita arable land area from 0.42 ha in 1960 to 0.22 ha in 2004 (Lal, 2013). Restoration of degraded and desertified soils is therefore a high priority, particularly in SSA and densely populated Asia. An increasing preference for a meat-based diet by large populations of developed and emerging economies exert a strongly demand on grain consumption. Energy and water consumed and greenhouse gas emitted in animal-based food are 10-20 times more than that based on grains and plants. Adoption of plant foods will therefore go a long way towards water and food security. The high yield gap between the global average yield and the maximum attainable yield and the wide range of variations in rice yield in Asia and in wheat yields in Europe must be reduced by use-efficiency of resources. Ample opportunities exist to vastly improve productivity in mixed water-crop-livestock systems practiced worldwide by small-scale farmers who collectively produce half of the world food. Producing more from less per capita land and water resources through sustainable intensification is not a promise. It is a mandatory necessity.

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