ADAPTING TO CLIMATE CHANGE: THE ROLE OF SCIENCE AND DATA IN RESPONDING TO OPPORTUNITIES AND CHALLENGES IN THE WATER-SOIL-WASTE NEXUS

RICHARD LAWFORD

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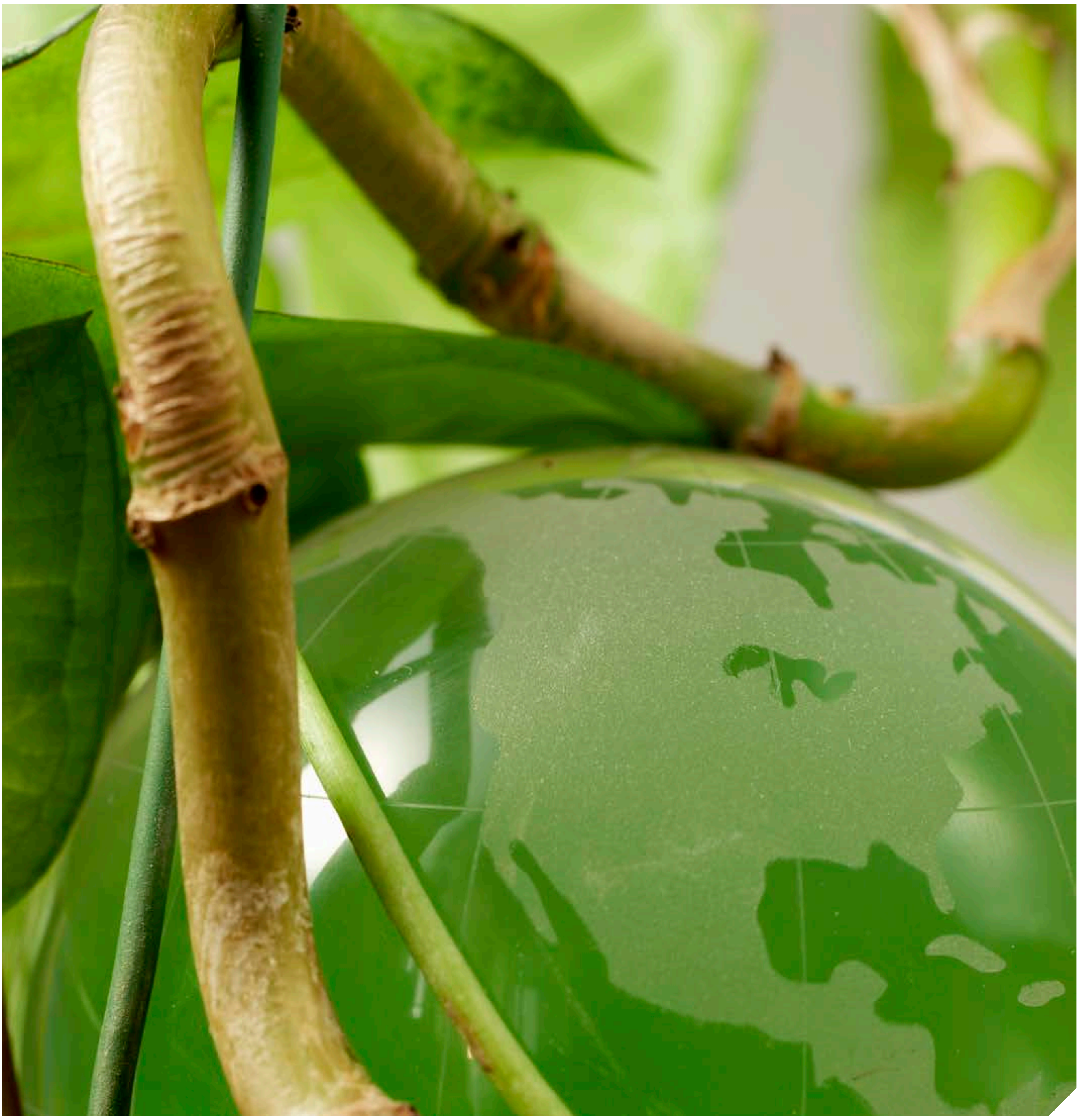

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Adapting to Climate Change: The Role of Science and Data in Responding to Opportunities and Challenges in the Water-Soil-Waste Nexus

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ABSTRACT

The Water-Soil-Waste (W-S-W) Nexus provides a framework for the main factors in food production. This framework, which facilitates the assessment of how policies and activities influence agricultural productivity, is important for all levels of the agricultural industry. It facilitates the assessment of issues that deal with water, soil and waste in a balanced way with full consideration of their impact on the long-term sustainability of the agricultural system and its productivity.

This paper explores the linkages between water, soil, and waste in the context of climate and climate change in order to clarify needs for scientific information and observational data. Climate affects water availability, soil integrity and the production and movement of waste material. As the climate changes, its influences on the W-S-W Nexus will also change and new strategies for coping with climate change will therefore be necessary. This paper describes the types of information needed to select and support these new strategies and reviews the current availability of this information. The paper recommends a more comprehensive study of the effects of climate change on the W-S-W Nexus and an evaluation of the current observational systems and datasets to assess changes in W-S-W variables. The paper also encourages responsible agencies to ensure that their data systems are modernized, their data collection programmes for soil and waste data are enhanced, and their data products and knowledge are made freely available to the world's science community.

1. Introduction

The Water-Soil-Waste (W-S-W) Nexus touches all processes that are important for crop growth. Agricultural production depends on the availability of water as it falls as precipitation and percolates through the soil matrix. In dry soils, irrigation water is frequently added to enable crops to maximize productivity. Water mobilizes nutrients in the soil and transports them to the plant roots, where they can be absorbed by the plant. From the perspective of agricultural productivity alone, water not used by the crop or evaporated and residual plant matter from the crop that is not harvested and removed are considered waste products although evaporated water is important for the water cycle and residual plant material can be valuable for the soil carbon budget. This cycle involving water, soil and waste, which has occurred since the dawn of agriculture, may now be trending to less stability at local and regional scales under climate change.

The interactions outlined above illustrate a few of the interactions in the W-S-W Nexus. Plant growth can be limited by these factors and additionally by the availability of energy and nutrients. Energy limitations are particularly important at higher latitudes where agriculture only occurs in the summer season. Nutrient limitations occur when soils experience carbon and nutrient depletion over the years, especially when soil degradation or desertification become dominant processes.

This paper explores the scientific understanding and on-going data requirements for addressing the W-S-W Nexus and its interaction with the climate. In particular, the role of climate change is discussed and the information needed to develop strategies and responses is identified. The paper closes with a few recommendations on research and data activities required to advance this Nexus.

2. The Water-Soil-Waste Nexus

The W-S-W Nexus is critical for food production. Between 2013 and 2050 the number of people who will need food security will increase by 2 billion, reaching a projected 9.2 billion in 2050 (Lal, 2013). Unless major shifts in dietary patterns occur, water will be needed in larger quantities to support the required increase in production. The loss of land to development and the degradation of soil quality will place further stress on the land base used to produce crops. Agricultural waste is an inevitable product of agricultural production, including livestock production and food processing. By focusing on these three critical factors and developing coherent strategies for responding to climate change, we can reduce our vulnerability to this change and help to mitigate the rate of increase of atmospheric carbon dioxide by absorbing more carbon through farming operations. The emerging focus on sustainable development will enable society to adapt to climate change and, at the same time, mitigate the warming effect by reducing greenhouse gas emissions, increasing carbon sequestration and slowing the rate at which carbon accumulates in the atmosphere.

2.1 Water

It is estimated that 44,500,000 cubic kilometres of water is available in the Earth system (Kotwicki, 2009). Much of this total is locked in glaciers, either inaccessible or hidden in underground aquifers, making it difficult to measure in absolute amounts. The water that arrives in a farmer's field through precipitation runs off, drains from the field into the groundwater system, or is returned to the atmosphere as evapotranspiration. When averaged globally, the amount of precipitation cycled back to the atmosphere through evapotranspiration is much greater than the runoff.

Water is essential for crop production. New plants develop roots first to acquire water and the nutrients dissolved in the soil water. If water is not sufficient in the surface layer of the soil, plants will develop longer roots to tap water from lower soil levels. Irrigation systems that enable plants to have more secure access to water have been developed. Of all the water that is withdrawn and consumed by humans, 70% of it is used for food production (primarily irrigation) and food processing activities (FAO, 2011). In some cases, the use of water in farming operations is facilitated by subsidizing either the infrastructure (such as dams and conveyance systems) needed to store the water, or the energy that is required to pump the water.

Water's property as a near-universal solvent makes it very efficient in absorbing nutrients and transporting them to plants' root systems. Weather systems govern the occurrence of precipitation and represent the primary source of water for the surface hydrologic system. Intense rain events are responsible for soil erosion and, on occasion, the mobilization of pollutants. Given the effects of climate on weather events, it is very important to understand, plan for and manage the effects of climate on the Water-Soil-Waste Nexus.

2.2 Soil

Soil is a critical contributor to crop production. With the exception of hydroponic plants, plants grow roots and, in some cases, fruit in the soil. The World Bank data base indicates that the arable land in the world was 49.3 million square kilometres or 38% of Earth's land surface (excluding glacier covered areas). The composition of this soil is a determining factor for local crop productivity. While most soils have developed over long time spans, their chemical composition can change quite quickly when exposed to intensive agriculture. They are formed and modified by chemical, physical and biological processes. Each of these processes has a strong dependency on climate (long-term) and weather (short-term) conditions.

The composition of soils is very heterogeneous. Soils are generally a mix of clay materials, sand and organic material. Organic materials are very prominent in agricultural soils and play an important role in water retention and in facilitating the uptake of nutrients by plant roots. They are also important for the global carbon cycle since it is believed that there may be two to three times as much carbon in global soils as there is in global plant cover (Brady and Weil, 2008). Building up this soil reserve can help prevent carbon from entering the atmospheric carbon pool. In agricultural soils, organic materials assist in producing nutrients in a form that can be readily used by plants. As Brady and Weil (2008) indicate, organic materials also increase the soil's water holding capacity, support the formation of soil aggregates and control the soil's cation exchange capacity. (Cations and anions are exchanged between soil colloid particles and soil water to influence the chemical properties that change soil composition.) The level of carbon is closely linked with the level of nitrogen in the soil and hence these features and processes that control the provision of nutrients to the crop. Farmers control the amount of organic matter in the soil through soil tillage, residue disposal practices and crop selection. In this sense, organic matter can be considered a manageable soil variable. Farmers can also conserve plant residues and allow them to decay in place to provide more organic matter for soils.

Soil composition also determines the rate at which water moves through the soil. Sandy soils allow water to move very quickly down the gradient or vertically through the soil profile, while clay soils slow the movement of water. In some respects, these soil properties influence irrigation requirements in a particular field.

Soils have a large capacity to absorb and process materials and, in the past, were seen as attractive means for disposing of contaminants. However, these contaminants and their breakdown products in soils may be toxic to humans and animals, especially if they move from the soil to edible plants or are ingested by people through the water supply. Bioremediation uses the soil's biological processes to facilitate soil clean-up. This new technology requires that safe and appropriate sites are found for the storage and clean-up of wastes. Siting and implementing such technologies depends on the availability of accurate soil information. Planning for these activities generally requires extensive soil surveys and the integration of data from satellites, field surveys and laboratory analysis.

2.3 Waste

Waste is the most complex aspect of the W-S-W Nexus, because determining what is waste depends on both scientific and political considerations. Waste, which includes the unwanted outputs and by-products of industrial and human activities as well as unwanted natural by-products, comes primarily in liquid and solid forms. Toxic wastes pose a particular problem because they require special handling and treatment because of their adverse effects on humans. The entire life cycle, from generation to collection, transport, treatment and storage must be taken into consideration when addressing waste problems. This paper discusses waste in the context of the W-S-W Nexus, which, in turn, centres on agriculture. As a result, 'waste' is limited here to waste associated with the production and use of agricultural products, including livestock.

Systems are generally put in place for waste collection and treatment in urban environments. In particular, wastewater treatment facilities ensure that wastewater is treated before it enters rivers or surface waters. Solid wastes are often stored in landfill sites, although they are increasingly being recycled and reused. In rural environments, the ability to treat wastes often depends on how that waste is generated. As noted by Cunningham (2011), different types of waste have different implications for the food production system and the environment. Emissions of waste from feedlots and waste disposal sites are clearly defined instances in which contamination, storage and treatment strategies can be implemented. More commonly, emissions in rural areas such as return flows from irrigation systems, runoff and infiltration from feedlot operations as well as other land activities such as construction, logging, wetland drainage and deforestation produce waste materials and also need to be addressed (Cunningham, 2011). These diffuse and diverse sources are often classified as non-point pollution sources, acknowledging that a different strategy is needed to deal with them. In this framework, waste can include chemicals in the runoff from crop management through fertilizer and pesticide applications, from livestock through biological processes, wastes from food production processes, as well as food waste. Waste products are often transported from the point of origin to and concentrated in a particular river or lake.

Primary outputs from agricultural (and food) production include water that has been contaminated by agricultural processes and sludge, both by-products of agricultural activity. Some waste products are chemicals normally found in nature and are, therefore, readily assimilated by the environment. Other waste products contain industrial or synthetic chemicals that require special consideration because the environment cannot absorb or neutralize them easily. While the environment has been effectively dissolving and disposing of natural wastes for millennia, there may have been occasional difficulties coping with large emissions and sudden extreme releases. On the other hand, with the exception of biodegradable products, nature cannot process or break down many synthetic agricultural chemicals. For example, pesticides and herbicides use chemicals that are transported by air and water into the environment and while they can be diffused and diluted, they cannot be easily eliminated. As a result, some of these substances accumulate in the environment and become human and ecosystem health risks, leading to losses in biodiversity and higher levels of cancer risk. Consequently, special steps must be taken to avoid the build-up of these chemicals in the environment.

Chemical fertilizers, which are often used in excess, can lead to high nutrient concentrations in the runoff, streams, and rivers. Excess phosphates and nitrates often produce high nutrient concentrations when they reach lakes and estuaries. In the summer, for example, they contribute to the formation of phytoplankton blooms. The development of these blooms often extracts oxygen from the water, making it harder for aquatic species, including fish, to survive. Also, algal blooms affect lakes' recreational potential and can lower cottage and land values. Other sources of waste can include decreased levels of oxygen in water used by livestock, contaminated water emitted from intensive agriculture and food processing plants, processing inefficiencies and wastewater produced in other steps in the food production chain. Houses and barns on farms are also sources of domestic and animal wastewater that must be stored or removed.

In cases where waste from livestock is used as a natural fertilizer, there are generally high levels of nitrates, including ammonia, in the water and the atmosphere. This loading from non-point sources is very difficult to treat before it enters into streams and rivers. Once it reaches these channels it may mix with pollutants from other sources, such as domestic waste present in water released by towns and villages (or from cities without adequate treatment facilities), and result in even larger nutrient loadings.

Increasingly, wastewater is being recycled and reused in food processing plants. Irrigation water could be of lower quality than drinking water and still be useful. There must be a clear understanding of how the water will move through the soil system and how fitness for purpose will be determined. However, wastewater applications must be evaluated before they go into full production. In one case, wastewater from a potato processing plant was determined unsuitable to irrigate potato fields because it contained very high levels of specific nutrients that would have adversely affected the nutrient balance in the soils in which the potatoes grew. Instead, the wastewater was used to irrigate lower-value forage crops (Smith et al., 1978).

In spite of progress made when dealing with agricultural waste, several issues remain. Among the developing world's most lethal contaminants in water are pathogenic organisms, which lead to 25 million deaths per year (Cunningham, 2011). Detecting and treating these pathogens remains very difficult. In addition, plastic materials used in farming are rarely biodegradable and, in cases in which farmers don't effectively manage their land, they tend to accumulate on farm landscapes.

Having looked at the individual Nexus elements, we will now consider the relationships between these elements and explore the benefits of considering them as an integrated whole within the framework of the W-S-W Nexus.

2.4 Interactions within the Water-Soil-Waste Nexus

The principal interactions in this Nexus involve the role of soil in storing waste, the role of soil and water in removing waste products and providing nutrients to the roots of plants, the role of water in eroding soil, and the role of waste and excessive nutrients in contaminating soils, altering soil chemistries and polluting water. Figure 1 is a schematic representation of these connections. These interactions function as a Nexus because a change in climate, a precipitation anomaly or a new chemical process can produce changes in multiple interactions between the main Nexus elements. Furthermore, planning to maximize the benefits of the Nexus requires many more contributions than just planning for each individual element of the Nexus.

The W-S-W Nexus is a subset of the Water-Energy-Food (WEF) Nexus, which has received considerable attention in recent years. Some authors (Ringler et al., 2013) have raised concerns that land issues are not adequately addressed in the WEF Nexus. The W-S-W Nexus emphasizes physical interactions and the role of agricultural practices and water management in implementing the Nexus approach. While physical interactions between these elements are becoming better known, they have not been fully integrated into management systems; consequently, the most supportive interactive actions have not yet been implemented and, in some cases, have not even been identified. To fully understand the importance of the

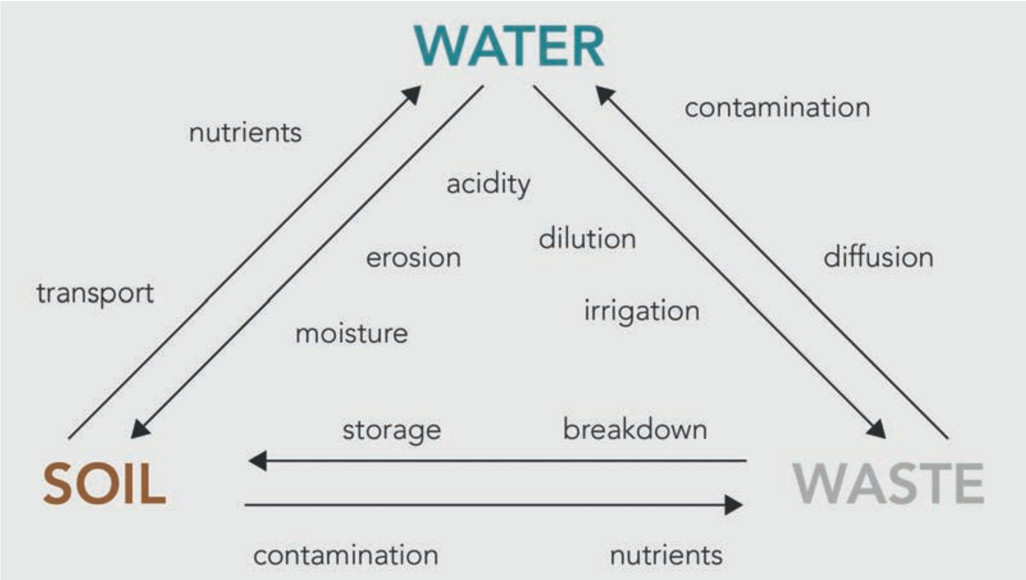

Figure 1: Relationships between water, soil and waste in the W-S-W Nexus. The arrows show the direction of the interaction and the elements next to arrows show the variables and processes connecting the Nexus components. (Design: UNU-FLORES/Claudia Matthias)

W-S-W Nexus in different regions, the influence of the broader WEF Nexus, with its social and economic connections (Lawford et al., 2013), must be considered. This paper focuses on the effects of climate on the physical W-S-W Nexus and the information needed to effectively address them. It is important to consider how the Nexus would respond to actual environmental threats.

3. The Climate Change Challenge

Historically, the climate has been marked by periods of stability and instability. Anthropogenic effects now are forcing the climate into new modes of behaviour. These new modes must be accounted for when managing the W-S-W Nexus. Climate change is most frequently associated with the effects of changing atmospheric composition on the climate, but atmospheric aerosols and land-use and land-cover changes also affect it.

The variability of the climate system is the result of many climate processes operating on a range of time scales. Changes in the sea surface temperatures (SST) have been important in the past and are likely to be associated with future changes (Trenberth and Hoar, 1997). Assessments of long-term climate variability, carried out using paleo records, provide evidence that some regions have been exposed to very dry and very wet periods that lasted several decades over the past millennium (Sauchyn et al., 2002). It is possible that the conditions responsible for these multi-decadal dry periods will reappear and that this natural variability, superimposed on trends associated with climate change, will lead to even more severe meteorological droughts in the future (Dai, 2013).

Given these possibilities, international planners for agriculture should consider how much arable land will still be available for agriculture in coming decades as the climate changes, how much food and fibre will the Earth's arable land be able to produce in the future, and how climate change will affect regional ecosystem services.

Engaging the agricultural community in discussions about adapting to climate change is difficult in some countries. The agricultural community (at least in the United States) has not fully embraced the climate change paradigm. A recent survey study by Prokopy et al. (2015) indicates that there are divergent beliefs between the science and farming communities about the occurrence and causes of climate change. It is necessary to demonstrate that climate change affects the agricultural community so that it can begin to address it. To date, data collection programs have not been adequate for this purpose. Given the agricultural community's reluctance, it is worth reviewing the evidence for climate change in the W-S-W Nexus and the factors forcing that change.

3.1 The Changing Atmospheric Composition

The rising concentrations of atmospheric carbon dioxide and other greenhouse gases drive climate change effects. Carbon dioxide accumulates in the atmosphere because the industrial emissions of carbon dioxide are approximately twice as large as the quantity that lands and oceans can absorb. As the concentrations of atmospheric carbon dioxide increase, more of the outgoing long-wave thermal radiation emitted by Earth is absorbed by the atmosphere, leading to a warming of the near surface layers. Atmospheric concentrations of carbon dioxide have increased by more than 100 ppm (approximately 33%) since they were first measured in 1958 (IPCC, 2007a; Kellogg and Whorf, 2004). Using an earlier baseline of 260 ppt established from ice core analysis, carbon dioxide concentrations have increased by 54% and will continue to increase as long as the population, the use of fossil fuels and product consumption increase. Soil interactions with the atmosphere influence atmospheric composition. Soils tend to give off carbon dioxide, especially when temperatures are high. Decomposing waste as well as wetlands and peatlands give off methane, a very active greenhouse gas. On the other hand, plants absorb carbon dioxide and release oxygen into the atmosphere. Since the Kyoto Protocol was signed in 1997, there has been some slowing in the rate of atmospheric carbon dioxide increase. It remains to be seen whether more effective agreements for controlling greenhouse gas concentrations can be reached through future negotiations.

The increasing atmospheric concentrations of carbon dioxide is likely to result in climate change effects that will last for several future generations. Consequently, climate adaptation strategies must deal with anticipated future changes as well as present conditions. In order to determine the effects of climate change on the W-S-W Nexus, we need to understand water cycle and soil processes, their sensitivities and their role in adaptation strategies.

While the Intergovernmental Panel on Climate Change's (IPCC) assessments show that the global climate is warming, the projected changes in precipitation and other water cycle variables are less clear because there is less consensus among models on the direction of change. This observation supports the hypothesis that, as a first approximation, the W-S-W variables that are most likely to show the earliest substantial responses to climate change are those associated with thermal changes. According to the IPCC, these changes could be far-reaching: increasing water stress has implications for water-borne disease rates, changing frequencies and magnitudes of extreme events (flood, drought, severe weather) and warmer inland waters, leading to poorer water quality and aquatic ecosystem impacts. Bates et al. (2008) have expanded this list of impacts both in terms of specific changes and the water resources implications for resources management. Regional studies indicate that actual changes are dependent on geographical location (Christensen and Hewitson, 2007).

3.2 Aerosols

Atmospheric aerosols directly affect the radiation budget and indirectly affect cloud formation and rain processes (Ramanathan et al., 2001). Aerosols come from natural sources, such as volcanoes and blowing dust, and from anthropogenic sources, such as emissions from manufacturing and transportation activities. Large dust clouds associated with the wind erosion of dry soils and their transport between continents can affect the atmosphere's radiation budget. The direct effects depend on the aerosols' optical properties and where they are concentrated in the atmosphere. According to Sokolick (2006), in more highly polluted areas climate radiative forcing by atmospheric aerosols can enhance or cancel greenhouse gas warming effects. Large aerosol concentrations in the atmosphere lead to high concentrations of cloud condensation nuclei and higher concentrations of cloud droplets. Rosenfeld (2004) reported that aerosols' indirect effects on precipitation and clouds might also affect cloud system dynamics. Dark aerosols and soot that accumulate on the surface of mountain glaciers may also be partly responsible for their accelerated melt.

3.3 Land-Cover/Land-Use Change

Land cover influences climate because of its role in the carbon cycle and its influence on water cycling in the atmosphere. The conversion of forests into agricultural lands has reduced the area of one of the most effective sinks for carbon. The land surface has important feedbacks to the atmosphere, as indicated by Koster et al.'s modelling study (2004), which examined the effects of soil wetness on precipitation in some regions. During the growing season, vegetation canopies affect surface water and energy budgets because plant canopies that are well supplied with water transpire more moisture into the atmosphere, increasing atmospheric humidity. Changes in land surface characteristics, such as a change from one vegetation type to another, or even from farmland to cities' asphalt surfaces, will affect the surface albedo and latent and sensible heat fluxes. Modelling studies by Hanamean et al. (2003) and Adegoke et al. (2003) have shown that processes like widespread agricultural expansion can raise the annual mean temperature of an area, while large-scale irrigation may have a cooling effect during the growing season.

Humans affect soil formation by removing vegetation cover and making the soil surface vulnerable to erosion processes. Tillage practices can also overturn soil layers, resulting in soil profiles that are continually changing. Water also affects soil formation and structure and is responsible for soil erosion. Deforestation and the construction of forestry roads on slopes can have a significant effect on erosion rates in mountainous areas.

Water management infrastructure affects local water cycling. The rapid expansion in the number of dams and reservoirs in many parts of the world has led to the retention of large quantities of water in storage, resulting in changes in regional evaporation and seasonal streamflow regimes. Water tables are failing in many areas in which farmers and industries withdraw groundwater, causing the land to subside and, thereby, reducing subsurface water availability for local wetlands and streams. This leads to a drying of the landscape, which in time may make it difficult to distinguish between changes attributable to climate change and changes caused by the regional effects of excessive groundwater extraction.

4. How Climate Change is Likely to Force the W-S-W Nexus

Many studies that assess the effects of climate change rely on climate model projections used with hydrologic models to give estimates of the effects of increased carbon dioxide on water resources and river runoff (Hagemann et al., 2013; Gosling and Arnell, 2011). Higher temperatures are expected to lead to more water residing in the atmosphere, which, under certain atmospheric conditions, will be converted into more intense precipitation events. They also cause temporary increases in summer streamflow in mountain rivers due to the more rapid glacier melt, and as already discussed, changes in the runoff seasonality in basins that have a significant snowmelt component (Dettinger and Cayan, 1995; Stewart et al., 2005). Finally, higher temperatures cause changes in the regional water cycle due to the delay in the formation of ice on large lakes and extensive summer melt of the multi-year ice on the Arctic Ocean (IPCC, 2007a).

The effects of climate change have initially been most evident in natural terrestrial ecosystems, which are relatively vulnerable to both slow and rapid changes such as droughts and intense extreme weather. While some types of vegetation can thrive in a wide range of environmental conditions, many do best in relatively narrow ranges of temperature, precipitation, and soil moisture. As surface temperatures rise, biomes are expected to shift poleward. With these shifts the potential for agriculture on the southern edge of boreal forests will increase, while the potential will likely decrease on the Equator side of current agricultural areas (Rhodes, 2012).

Integrated approaches are needed to determine the effects of a changing climate regime on surface hydrology, water resources and water quality. Mimikou et al. (2000) studied the impacts of climate change on water quantity and quality. Using a transient (HadCM2) and equilibrium (UKHI) model, they used the estimated changes in temperature and precipitation as inputs for a hydrological model for a catchment in central Greece. Those changes result in a significant decrease of mean monthly runoff for almost all months with a considerable negative impact on summer drought. They also simulated water quality using the stream (R-Qual) model under current and climatically changed conditions and found adverse effects on monthly concentrations of simulated parameters including BOD, DO, and NH4+.

The UNEP GEO 4 report (UNEP, 2007) notes that approximately 2 billion people depend on drylands for food. Ninety percent of these dryland areas are located in developing countries. Given the changes in water cycle variables and water resource management, Bates et al. (2008) concluded that many areas will be affected by drier conditions. Without changes in local and regional land-use practices, the effects of climate change will accelerate rates of land degradation and desertification.

4.1 The Global Water Cycle and its Sensitivity to Climate Change

The global water cycle links climate and hydrology and plays a critical role in the climate system. IPCC reports (FAR, 2007a; AR5, 2013) affirm that climate change is already taking place, and that its main cause involves human activities. The spectre of climate change raises many concerns about human livelihoods, ecosystem sustainability and even water and food security.

The global water cycle redistributes water from oceans to land through atmospheric circulation and then back to the ocean primarily through precipitation over land, followed by surface and subsurface flow. Evaporation, atmospheric moisture transport and precipitation are key fluxes and processes for the movement of moisture from source to sink regions. The sun provides the energy needed to keep the cycle operating by maintaining atmospheric pressure differentials and providing the energy required for the phase transitions of water among the solid, liquid and gaseous phases.

Water is the medium by which many of the impacts of climate change are transmitted to other sectors such as food production, transportation and health. Unless the effects of climate change on the global water cycle are accurately specified, it is unlikely that accurate predictions of the other impacts can be made. As reported by Trenberth et al. (2007) and Lawford (2011), the maximum amount of water vapour that can be present in the atmosphere is related to the air temperature. A warmer atmosphere has the potential to hold more water vapour and to lead to heavier precipitation events. Furthermore, since water vapour is a greenhouse gas, higher atmospheric concentrations of water vapour contribute to the capture of more outgoing long-wave radiation and further atmospheric warming.

Clouds affect the energy budget because their white surfaces reflect incoming solar radiation back into the atmosphere. The ephemeral nature of clouds makes them very difficult to model or even to measure their distribution and cumulative impact. As a result of the cloud-climate feedback, models that predict lower cloud coverage generally tend to predict larger global temperature increases than those models which project increases in the cloud cover. Cloud cover will also influence the photosynthetically active radiation (PAR) received at the surface for crop production.

The amount of precipitation that falls on an annual basis in a particular country represents the renewable freshwater that is available to that country. Estimates of annual precipitation over Earth's land areas vary from 113,500 to 120,000 cubic kilometres (Shiklomanov and Rodda, 2003). The most significant changes in the global water cycle arising from climate change are likely to be changes in the precipitation regime, with regional effects being significantly greater than changes in the global average. Given the large spatial variability of precipitation and the associated non-uniform supply of freshwater, some nations will have an abundance of water while others will be in a state of near-perpetual water stress. Bates et al. (2008) indicate that there is general consensus among models that precipitation amounts will increase at higher latitudes and decrease at lower latitudes as the climate changes.

Precipitation that falls as snow is particularly sensitive to winter warming. Snow accounts for as much as 40% of the total precipitation that falls at some high-latitude locations. Higher temperatures associated with climate change will have a significant effect on snowfall and runoff patterns, as more of the late fall and spring precipitation at mid and high latitudes will be in the form of rain instead of snow, leading to significant shifts in precipitation type. Furthermore, snow packs will melt earlier in the spring due to higher temperatures (Barnett et al., 2005; Dettinger and Cayan, 1995; Stewart et al., 2005).

Generally, runoff, streamflow and surface water storage will respond to climate change in ways that are similar in direction but different in magnitude than the changes in precipitation. The relationship between runoff and precipitation will be affected by the spatial and temporal characteristics of precipitation, time of year and the changes in evapotranspiration (ET). The amount of water that returns from the land to the ocean is 37,000 cubic kilometres per year. Maurer (2004) reported that long-term stream discharge records show that most stations (but not all) in Africa and Southeast Asia show decreasing flows, while the majority of stations in Europe and North America tend toward increasing discharge. Warmer winters have affected streamflow over the past two decades in watersheds where snowmelt is a significant contributor. Winter flows have increased for many rivers in the western United States and spring peak flows have shifted to earlier in the spring (Stewart et al., 2005).

Soil moisture is critical for crop production and controls the proportion of surface energy that is used in latent heating (evaporation) and sensible heating. In addition to the precipitation that the soil receives, soil moisture is affected by the properties of the soil (such as its porosity) and local climate conditions. Seneviratne et al. (2010) explored the effects of climate change on soil moisture processes. With climate change, soil moisture will tend to increase in areas where increases in precipitation are more significant than the increases in evapotranspiration associated with the trend to higher temperatures. Dry soils are more likely to be subject to wind erosion and to, therefore, be transported to other areas. Periods of drought in China have led to transfers of dust to areas as remote as northeastern Asia and North America.

Groundwater aquifers provide large and important reservoirs of water in the global water system. Estimates of the total amount of groundwater in storage vary widely. Kotwicki's (2009) estimate of 11,000,000 cubic kilometres, approximately 0.8% of the planet's freshwater, is conservative when compared to those of other authors who feel that the groundwater reserve is much larger. The groundwater system consists of areas where recharge (water entering the groundwater system from the surface) occurs and other areas where discharge (water leaving the groundwater system for the surface) dominates. The groundwater - surface water interaction is very important for understanding the integrated effects of climate change on water resources and developing adaptation strategies that account for these interactions. Models, such as the high resolution groundwater model used by Scibek et al. (2007), are important in this regard. On larger scale Döll and Flörke (2005) have provided estimates of the rates of diffuse recharge on a global basis. Döll, (2009) also explored the effects of climate change on renewable groundwater resources. Groundwater is a very important water reserve during drought periods. However, in some dry countries groundwater is being withdrawn so rapidly for daily requirements that the rains cannot replenish the extracted water. In many areas, groundwater aquifers are becoming a principal source of freshwater for irrigation and regional water supplies. As Rodell (2005) has shown, this trend of using groundwater in semi-arid areas leads to the 'mining' of older groundwater reserves in areas such as northern India and the western United States, where groundwater is now the primary source of irrigation water. Future groundwater recharge could be increasingly sensitive to decreases in recharge rates that are associated with higher temperatures, increased evapotranspiration and land-use change. In general, groundwater recharge in a changing climate will increase in those areas where precipitation increases but may not increase as much as precipitation because infiltration rates will be affected by increased evapotranspiration. In areas where precipitation decreases, the decrease in recharge will be even greater because more of the incoming precipitation will be lost to evapotranspiration.

As indicated by Mimikou et al. (2000) and Ludwig and Moench (2009), it is also important to understand the effect of climate change on water resources as well as streamflow. To do this, one must consider the integrated effects of these changes on the overall water resource management system, which includes the impacts of physical infrastructure and policies regulating water management.

4.2 Sensitivity of Soils to Climate Change

As reported by Blum (2005), there is a strong connection between soils and climate change through both the carbon and the water cycles. Water is essential for all major chemical-weathering reactions. Water deficiency is a major factor in determining the characteristics of soils in dry regions. Soluble salts are not leached from these soils, and in some cases they build up to levels that curtail plant growth. Soil profiles in arid and semi-arid regions are also apt to accumulate carbonates and certain types of expansive clays, which can reduce crop productivity. Soils in humid areas tend to be acidic and are subject to intense weathering processes such as chemical weathering, leaching and erosion in high and humid regions and areas in which soil does not freeze and deposition of eroded materials occurs in downstream areas (Brady and Weil, 2008).

Climate change could affect soil composition and its ability to provide nutrients to plants. In arid environments where there is little plant cover, the wind moves sand and smaller soil particles, affecting the soil profile's surface layers. The type and amount of precipitation influences soil formation by affecting the movement of ions and particles through the soil and aids in the development of different soil profiles. Soil profiles are more distinct in wet and cool climates, where organic materials may accumulate, than in wet and warm climates, where organic materials are rapidly consumed (Brady and Weil, 2008). The effectiveness of water in weathering parent rock material depends on seasonal and daily temperature fluctuations. Cycles of freezing and thawing constitute an effective mechanism which breaks up rocks and other consolidated materials. Climate also indirectly influences soil formation through the effects of vegetation cover and biological activity, which can modify the rates of chemical reactions in the soil.

Based on this reasoning, we can expect soils to tend to be more acidic at northern latitudes under climate change. Nearer to the equator in areas where drier conditions prevail, this dryness together with higher temperatures could reduce the carbon content of the soil and limit soil fertility (Lal et al., 2004). However, many other factors (such as cropping patterns) also affect the response of soils at a given location to the climate (Gift, 2013). For this reason, long-term monitoring is required to provide data and evidence to validate the inferences of this qualitative reasoning based on climate projections and the rates of change in the soil's carbon content. Only when trends are established by observations can viable adaptation strategies be designed and implemented.

4.3 Extremes

More than a decade ago, Groisman et al. (2004) found trends toward more very heavy rainfall events in precipitation data from the United States and elsewhere. Subsequently, modelling studies reported in IPCC assessments (AIR5 2013, 2007a) showed that climate change is likely to be accompanied by increases in the frequency of extreme events (primarily floods and droughts). For example, Kharin et al. (2007) reported that the return period for heavy precipitation events might be reduced by a factor of two (20-year storms will become 10-year storms). This analysis suggested that many areas with intense rainfall will experience even more intense rainfall rates in the future, while areas with dry conditions will experience even greater water stress, including longer-term droughts (Feyen and Dankers, 2009). Heavy rainfall events cause soil erosion and can have a significant effect on the landscape (including landslides) and river channels, depending on when they occur. Erosion is most significant in areas with sparse vegetation or steep slopes, ploughed agricultural lands and in forests networked with forestry roads and areas cleared of trees. These extremes are often related to the higher water holding capacity of a warmer atmosphere and the associated potential for more severe weather events (Berg et al., 2013; Feldmann et al., 2012).

The spatial variability of water availability will be affected by the trends arising from climate change. These changes will be affected by changing water use patterns, land use changes and modifications to the infrastructure for water management. Although the total quantity of water being cycled through the global water cycle may not change much from year to year, regional changes could be very significant. The measurement of these changes is critical for evaluating the accuracy of climate model projections. Many of the individual components of the global water cycle are monitored as Essential Climate Variables (ECVs) (GCOS, 2013) through a programme coordinated by the Global Climate Observations System (GCOS). However, to develop mitigation strategies such as carbon sequestration, it will be necessary to improve both observational and modelling systems to properly define and characterize the changes associated with the causes of global change.

4.4 Other Global Change Factors

Climate change will affect the ability to achieve the Sustainable Development Goals related to water and food production. However, other effects of human and resource development, operating both together with or separate from climate change, will also affect the ability to support food security. As shown by Vörösmarty et al. (2000), population size and growth has a significant impact on the demand for water (and food). Urbanization, resulting from the movement of people from rural environments to urban environments, is leading to shifts in water use and food demand patterns, and in expectations for water services. Improving economic conditions and changing dietary habits associated with the growth of urban centres puts pressure on the food production system. Finally, pollution from industrial and agricultural processes reduces the safe water availability in areas where wastewater treatment is limited or non-existent. Given the convergence of these impacts with climate change impacts, it is important to develop attribution techniques that will allow us to separate the consequences of societal developments and trends from factors attributable to climate change.

5. Water Quality

Today, water is the base for arguably the world's largest waste disposal mechanism. Water's unusual ability to dissolve many substances has led to its widespread use in the transport and removal of waste and pollution. As noted earlier, wastewater is one of the major outputs from farming operations and includes irrigation water that returns to the soil, water used by livestock directly, water to clean livestock waste and domestic wastewater generated in the farmhouse and on-farm operations. Water quality is diminished by many types of water use, by materials added to the water and by the deposit of pollutants from the atmosphere into the water. Many lakes in agricultural areas around the world are affected by nitrogen and phosphorus pollution from fertilizer applications, which often leads to algal blooms and eutrophication.

Generally, environmental standards and information programs in developed countries have helped change public assumptions that water is the only means of removing waste. However, in some countries where standards are not in place for toxins, carcinogens and pathogens, the degradation of water quality leads to health risks and reduces water's usability and value. Water availability and use in urban areas have their own unique issues since sewage disposal, water treatment and storm sewers are all important factors in maintaining water quality. Another form of pollution is thermal pollution, most frequently arising when hot water from industrial operations is released into bodies of water. Water for agricultural purposes also affect the treatment (or non-treatment) of water in nearby cities and industries through effluent and sewage releases, thermal releases and even pharmaceuticals. In developed countries, the presence of traces of prescription drugs in drinking water shows that a broad collective commitment to environmental wholeness by all society is required to maintain water quality.

Figure 2: Example of a central pivot irrigation system (Courtesy of the Yuma Conservation District).

While it is possible to monitor the chemical content of point-pollution sources and to implement water treatment activities, often the agricultural community is not open to such solutions. Climate change is expected to have negative consequences for water quality, especially in those areas where fresh water availability is reduced and water pollution from urbanization and industrialization take place. Furthermore, according to Peeters et al. (2007), higher air temperatures are leading to higher water temperatures, exacerbating the nutrient pollution problems of lakes in agricultural areas.

Groundwater quality can also be an issue. In many cases, groundwater is treated to remove hardness (generally the result of a calcium deficit) (Randtke, 2012). In some countries such as Bangladesh, groundwater is contaminated by naturally occurring arsenic, while in the US a significant proportion of groundwater is contaminated by naturally occurring iron and manganese (Briggs and Ficke, 1977).

The quality of water is an important consideration in adaptation strategies because there is a growing pressure to use recycled water for many applications that use low quality water. However, the full range of implications of this strategy are not often fully known since water quality is affected by biological factors as well as chemical factors.

6. Water Use

As noted in Section 2, irrigation is the principal user of the world's freshwater supply both in terms of withdrawn and consumed water. If we maintain our current practices, irrigation requirements will be greater because higher temperatures will increase evaporation and losses from inefficient irrigation systems such as the widely used central pivot systems (see Figure 2). McDonald and Girvetz (2013) associate climate change in the US with increasing irrigated areas in wet states and increasing irrigation rates in dry states; two trends that will lead to greater water consumption. The sophistication, design and efficiency of irrigation systems vary widely across the globe. In developing countries where energy is too expensive to be used to pump water, human and/or animal power is used to operate pumps to supply water to crops. A few countries make energy available to farmers at subsidized rates so they can pump groundwater more quickly to irrigate crops. The demand for hydropower as a source of energy is expected to increase. In many areas where hydropower is the major energy source and energy demands are sensitive to temperatures (e.g., air conditioning), the demands for water to generate hydropower will grow. Population density affects water stress, since a high concentration of users in a given area means that local precipitation – or, more frequently, local precipitation plus water imported from elsewhere – must be sufficient to meet local needs. Although the cost of the water supply per capita often is lower in well-managed urban environments, the trend toward urbanization will have consequences for the W-S-W Nexus. Urbanization focuses the growth of water demand in the domestic and industrial sectors, often in geographical regions where needs for expanded access to special supply and treatment capabilities are lagging behind population growth. The growth of urban centres in Mexico and China are examples. Urbanization also concentrates the demand for food and, in turn, increases the demands for water to meet those food requirements. As the demand for water increases, in a future warmer climate, it will lead to increased water stress, especially in those areas where precipitation decreases or remains the same.

7. Assessment Methodologies of Impacts of Climate Change

Given the growing recognition of the need for climate change adaptation, water managers and the agricultural community are increasingly being expected to develop plans for adapting to climate change. Resource managers need to understand how climate change could affect them over appropriate planning horizons. Some managers are beginning to incorporate larger safety margins into their design and operations to accommodate this anticipated change. While some of the potential impacts of climate change have been described in the preceding sections, Bates et al. (2008) identified many other impacts that climate change could have on water management in individual basins. These impacts could be translated into effects on food security by considering the connections between trends in water cycle variables and their influence on food production. Given the wide variation in the level of infrastructure development and watershed management across the globe, it is clear that a basin-based analysis is necessary to determine the local significance of climate change for many applications, including water management and food production.

Some approaches commonly used to address the need for direct inputs to local-scale assessments include:

1. *Statistical tools and dynamic downscaling regional climate models that use values from global climate models to generate small-area estimates that are relevant for impact assessment and the development of adaptation strategies (Fu et al., 2013).* Techniques are required to transform climate model outputs available for large grid squares (e.g., 100 km x 100 km) to point or small-area estimates for use in impact assessments. Regional climate models provide higher-resolution outputs than global models and often reproduce important small-scale processes (e.g., cloud processes) missing for large global climate models. While the credibility of regional models is improving, more development is needed. For example, Otte et al. (2009) have shown that the benefits of regional models for downscaling are greatest when nudging is employed (nudging is a process whereby the outputs are pushed very gently toward some long-term average.) Teutschbein and Seibert (2012) provide guidance on methods for removing biases in regional climate models for use in assessment inputs.

2. *Hydrologic and crop models for use in impact assessments for water applications.* Common approaches include assessing the effects of climate change on hydrologic processes and undertaking a more comprehensive basin-wide approach to estimate changes in water availability and related impacts over entire basins (Laaser et al., 2009). As Zierl and Bugmann (2005) demonstrate, mountain catchments are very complex in terms of the processes which must be modelled. These models need to be extended to include the possible effects of soil processes on crop growth. For these assessments to be reliable, uncertainties in the input data need

to be reduced as much as possible and the remaining uncertainties need to be tracked through each step of the analysis. Impact studies should be supported by analyses of time series of homogenized high-quality observations.

3. *Sensitivity studies involving model runs with and without different processes under climate change conditions to identify the additive effect of climate change on the phenomenon under consideration.* For example, climate change impacts on irrigation can be assessed by carrying out model runs, including only some climate trends, and others that account for both climate and irrigation use trends to assess the effects of climate change on irrigation use. This offers a way to establish baseline conditions with and without the presence of climate change.

4. *Ensembles for a range of simulations developed by running models many times with different initial conditions and climate change scenarios, usually producing averages that are closer to reality than any single model run.*

Climate change can have negative impacts on many regions and at times positive impacts for people in some regions. Pressures such as higher temperatures and more aridity will affect land areas in the tropics and semi tropics, leading to decreased crop productivity and, in some cases, economic hardship. In contrast increased crop production is possible at higher latitudes in North America and Europe.

Studies on the linkages between climate change, precipitation extremes and floods have been carried out (Min et al., 2011). More work is needed to assess the effects of climate change on extremes and their consequences for intense precipitation events and changes in the frequency of floods and droughts and in turn their effects on soils and crop production.

The following tables provide a preliminary listing of some of the impacts that are expected to occur with two aspects of climate change (Table 1: more intense rainfalls; Table 2: higher temperatures) along with some suggestions for how one could adopt to these strategies.

8. Adaptation Strategies

In order to reduce the range of impacts, it is important for society to have proposals for changes in technology and financing that will allow the agricultural community to adapt to these changes. Adger et al. (2007) have carried out a comprehensive assessment of the adaptation practices and options for dealing with climate change. Black et al. (2013) summarize a number of strategies for adaptation in the USA – a large country with many different climate conditions. Many adaptation techniques are region-specific. For the Netherlands where climate change is a major concern, de Bruin et al (2009) have carried out extensive planning studies to assess the need for adaptive measures to address climate change in the context of their country’s unique situation.

Table 1: Impacts of changes in heavy rainfall events and examples of adaptation strategies that could deal with the impacts.

Heavy but more variable rainfall	Impacts	Possible Adaption Strategy
Greater rain intensity	More soil erosion	Creation of buffers to minimize erosion and sediment transport in erosion prone areas.
More total rain	Increased flood frequency and severity	Early detection and warning systems to protect life and property. More use of the landscape depressions to store water during floods.
Increased variability of the climate	Longer dry periods and more intense droughts	Implement strategies for storing more water in reservoirs and on the landscape.

Table 2: Impacts of changes in heavy rainfall events and examples of adaptation strategies that could deal with the impacts.

Higher Temper-ature Effect	Impacts	Possible Adaption Strategy
Desertification of agricultural lands at lower latitudes	Farms may become less productive	Find alternative employment options for people who will be displaced by desertification
Longer growing season at northern latitudes	Increase areas for northern agriculture Increased shipping on the Arctic Ocean	Develop policy for opening northern farm areas Develop marine infrastructure along the Arctic coast
Heat waves	Prolonged periods of extreme heat Heat strokes, power outages, etc.	Through biotechnology develop plants that are resistant to heat and drought Develop an emergency response team to deal with heat stroke victims

In developing the sustainability of the food production system, FAO (2014) advocates specific principles to balance the social, economic and environmental conditions necessary for sustainability in the food sector. These principles include improving efficiency in the use of resources; developing actions to convey, protect and enhance natural resources; protecting rural livelihoods and improving equity and social well-being; enhancing the resilience of people, communities and ecosystems, especially with respect to climate change and market volatility; and promoting good governance for the sustainability of both the natural and human systems. These principles could also serve as the basis for dialogue regarding strategies to deal with climate effects on the W-S-W Nexus.

8.1 Addressing Direct Climate Change Impacts

Given the large spatial variability of the important variables in the W-S-W Nexus, strategies for adapting to expected climate change impacts on water resources and soils need to be place-based. Strategies also need to recognize that different cultures have different perceptions of the role and management of food and water. In some free enterprise economies, the maximization of immediate economic returns from soil and water resources is often promoted. On the other hand, there is a very strong case for ensuring that all adaptations related to water and soil should advance sustainable development. The guarantee of ongoing reliable water supplies for human needs and minimum environmental flows, and the maintenance of the integrity of the soils and ecosystems must be priorities.

One long-standing assumption in planning flood response and designing water infrastructure involves the concept of a stationary climate where the design statistics of the past are assumed to be valid for the future. However, as shown by Milly et al. (2008), changes show that the climate can no longer be considered stationary. As non-stationarity becomes more evident, with increases in intense rainfalls, soil erosion, flooding and the inadvertent releases of stored pollutants, agricultural practices will need to be adjusted to decrease the sector’s vulnerabilities to climate change. This should include the development of best practices for farming to minimize erosion such as continuous cropping, and more careful stewardship of the basic soil and water resources. Observations of the occurrence and magnitudes of these phenomena will be an important basis for changing opinions in the farming community about the significance of climate change and the importance of their actions.

Current water management practices could have difficulty coping with the full range of climate impacts on water services, such as water supply, flood prevention, mitigation of drought impacts, irrigation services, health and energy production. Adaptive capacity has been defined as ‘the ability of a system to adjust to, cope with, and take advantage of climate changes’ (IPCC, 2007b). Adaptation actions should include analyses to determine what should be done and strategies to develop public support for implementing the necessary changes. Adaptive measures could include improved water supply efficiency (water storage and delivery networks), more efficient/integrated management of water demand, increasing water productivity ('more crop per drop'), land-use management, recycling treated wastewater and cropping with low water consumption crops. The best strategies are those that have social and economic benefits whether or not climate change impacts are the major factor. Given the uncertainties in current projections of key water cycle variables, there is a need to understand the extent to which uncertainties must be reduced before society should change its practices (Kundzewicz and Stakhiv, 2010). Both direct and indirect approaches are needed to provide a basis for incorporating climate change considerations into decision-making. This is true for many rural environments where urban services are not available. For example, in a rural environment water used to wash animal wastes from a barn should be treated before entering domestic water supply chains or it should be fully separated from the clean water supply stream.

Direct approaches use climate change information taken directly from climate change models to assist decision-making. There are numerous examples of studies and assessments being used to screen various possible actions to determine which would be most desirable. Two European examples were assessments of both the hydrological impacts and the options for adaptation were carried out by Lehner at al. (2001) and Leipprand et al. (2008). In addition, the SimCLIM model, another integrated modelling system for assessing climate change impacts and adaptation (http://www.climsystems.com/site/home/), has been used by climate scientists and partnering utilities to find space and timescales appropriate for adaptations focused on reducing the risk of climate extremes (Warrick, 2009). The model provides an economic framework for estimating the costs and benefits of adaptation. Models are needed to provide similar economic assessments for planning agricultural operations and making crop yield projections under various adaptation scenarios.

8.2 Climate Change and Policy Considerations

Scientists must learn how to communicate with policymakers and the agricultural community. During the past decade, the focus has been on mitigation, specifically reducing carbon dioxide emissions to the atmosphere. While mitigation remains a priority, adaptation is now recognized as an essential component of society's response to climate change. Due to the present accumulation of atmospheric carbon dioxide, questions related to climate change have moved from 'what?' and 'when?' to 'how much?' and 'how long into the future?' as more of the expected trends begin to be observed. As part of this adaptation approach, the links between climate change and water at the science-policy level should be strengthened. The interface could identify needs for research to support policy decisions, communicate research results to the policy community and make best possible use of available research resources to ensure these problems are addressed and the benefits are available to all. These issues would be most effectively discussed in a sustainable development framework where other pressures on water (e.g., land use, water use, etc.) are also considered. Policy support tools (models, dialogue/participatory processes) could be part of this approach, because they can be used to identify adaptation (coping) strategies even though the climate scenarios may still contain uncertainties.

In some areas it may be most appropriate to use qualitative information when informing policymakers of the implications of climate change. Indices, expressed as departures from average conditions, or as desirable or undesirable with respect to some target or threshold, are more effective for some audiences. Specific win-win strategies for adapting to climate change – in which the benefits of the action are shared with society in the present and protect the future resource base – are those likely to gain the widest acceptance. Examples of these approaches are discussed below for each part of the W-S-W Nexus.

8.3 Non-climate Trends that Affect the Water-Soil-Waste Nexus

In addition to climate, other trends affect the way in which the W-S-W Nexus will have to be managed in the future. In the policy area, some experts are:

- Advocating the use of the water footprint or virtual water as a policy instrument to promote diets with low water inputs. Although these arguments are unlikely to make more water available, since much of the water use in question is for dryland farming (including rangelands), a shift away from beef farming could impact soils and on-farm biological waste production.

- In the private sector, technology is being used by large corporations to grow food using genetically modified and patented crop forms. Diversity has been an unquantified strength of the agriculture sector in the past. Through crop rotation and mixed farming practices, small farmers could develop fertile soils and minimize pests so that crops would grow with remarkable consistency year after year (Fick, 2008). The growth of GMO foods may place serious constraints on the management of the W-S-W Nexus.

8.4 Water Management Strategies for Responding to Climate Change and W-S-W Issues

As noted by Vrtis (2011), farmers can take steps to reduce the amount of water needed by growing drought-resistant crops that require less water over the growing season. They can also adopt more efficient irrigation systems so that evaporation losses are greatly reduced. Farmers can implement good land management practices to support the provision of good quality water supplies. For example, the cost of water supply for New York City has generally been reduced by combining a wise use of forecast information and good watershed protection practices by a number of farmers and rural dwellers in the Catskill Mountains, where water that infiltrates the soils of the watershed is used as a source of New York's drinking water.

Some of the lessons learned from examples like that of New York City and the Catskill Mountains could be promoted as part of an effort to improve catchment management. In addition to protecting recharge areas and source regions for water, water conservation can be supported by using more efficient irrigation, using low water intensity facilities (e.g., ultra-low flush toilets) in homes and by implementing farming operations and other practical steps that can greatly reduce the amount of water used in agriculture so that more water can be available for other sectors.

8.5 Soil Management Strategies

Erosion is one of the greatest challenges for soil management. In areas with high wind and water erosion potential, strip farming and buffer zones help reduce erosion. Over the past century, agricultural practices such as continuous cropping have been helpful in conserving moisture and reducing the probability of soil erosion by wind (Brady and Weil, 2008; Hatfield et al., 2001). To some extent, responding to climate change would mean increasing the applications of these tools in appropriate areas. There is an urgent need to assess different options available to determine the benefits of different soil treatments and their effects on soil carbon. The use of a carbon management index, such as the one described by Viera et al. (2007) may be one way to track progress to determine if specific actions are improving the soil carbon in a given field.

Steps should be taken to reduce the vulnerability of soils and water supplies to precipitation variability. Municipalities could provide support during droughts by providing farmers with access to community pastures in which cattle could forage. A similar response to that which occurred in the severe 2001 and 2002 drought in western Canada (Wheaton et al., 2005) could be an effective adaptation strategy for range lands. The use of community pastures helped to maintain healthy cattle herds and distributed the impacts of the severe water stress produced by the drought.

8.6 Waste Management Strategies

As time progresses, there is an increasing amount of agricultural waste generated. As noted by Fridgen (2011), there are several lines of defence against this growth, including:

1. Reduction: Reduce the amount of waste material produced in the first place. This can be done by promoting the use of biodegradable products so that the waste can be readily assimilated into the soils.

2. Reuse: Making the materials available for reuse. This recycling approach has been very successful in urban environments but requires commitment by people in rural environments where wastewater transport services are not available.

3. Composting: w Accelerating waste decomposition by breaking down organic materials under anaerobic conditions. This approach can turn potentially harmful products such as manure into effective fertilizers.

4. Controlled interaction can also be a useful approach when products of the combustion process (e.g., heat, nutrients in the ash) are recycled. An excellent example has been developed by the International Institute for Sustainable Development (IISD), which promotes water distribution on the landscape using wetlands as storage for excess flood waters. IISD developed an experimental program in which cattails that grow on the wetlands are harvested and processed into fuel pellets. Since these pellets

are a substitute for coal they are burnt in a closed environment and the ash is collected and reused as fertilizer because of its high phosphorus content (Grosshans et al., 2015).

A major consideration for waste is the need to maintain the nutrient balance in the soils. Brady and Weil (2008) report on Phosphorus (P) data collected by Beegle et al. (2002) for the State of Delaware. The P added to the crop from chemical fertilizers and poultry manure are estimated to be approximately triple the amounts needed for the soils. Needless to say, this results in a significant build-up of P in the soil and a loss of P to the runoff, which contributes to the eutrophication in the receiving waters along the Chesapeake Bay. The nutrient balance of the soil over time is also affected and must be considered in planning wastewater recycling.

In some cases, it may be necessary to move beyond voluntary actions by farmers and adopt policy options that would encourage or constrain farmers and water managers to take specific actions to protect the W-S-W Nexus. Before government intervention occurs, however, it is very important to have a strong scientific basis for the proposed action in terms of model results and observational evidence of the changes that are taking place. At present this information and data loss is not adequate.

9. Observational Needs

In addition to models, observations are critical for the future of the W-S-W Nexus. Observations are important for identifying the occurrence of trends that require action. While models may project trends which are often borne out in reality, some results may be an artefact of the model structure or overlook some critical process or threshold that affects the use of the results.

Observations are essential inputs for the scientific analysis of the causes of trends and the assessment of the relevance and functioning of the processes that are responsible for these same trends. Observations and data are needed to assess the adaptation techniques that should be put in place to deal with changes and to identify the locations and the times when priority should be given to the implementation of certain adaptation processes. Global-scale observations provide a framework for assessing regional developments. Within these global frameworks, regional, national and local data processing capabilities must be developed to ensure each country has access to the information needed to support decision-making related to climate change adaptation.

Observations are also an important element in convincing the public that action is needed. Many governments are reluctant to act upon scientific theories that they may find difficult to understand or which seem to be controversial due to the variety of opinions expressed by different media and information sources. Observations of change bear much more authority because they indicate that something is happening and they provide a strong basis for action, especially when interpreted and placed in the hands of public opinion-makers. Although there are many possible variables to measure, it is important to focus on the critical variables needed to assess trends and conditions in the W-S-W Nexus. Some of the factors to be considered in an observational program are coverage/extent, temporal resolution (frequency), spatial resolution (vertical and horizontal, as relevant), timeliness (availability of measurement), accuracy/precision and data latency (the delay between actual observation and when it is available for analysis or input into models). In addition, the information must be quality-checked and formulated in ways that are meaningful to decision makers. Many changes are expected to occur over coming decades, so it is important to maintain continuous measurement programmes and to make clear linkages to extreme events when these are associated with changes in climate. The use of data is also critical in developing the rationale and the authority to argue for new investments in adaptations to climate change and to the mitigation of the causes of climate change.

The Global Climate Observing System (GCOS) programme coordinates diverse national and regional observing activities and directly addresses the needs of the UN Framework Convention for Climate Change (UNFCCC). The UNFCCC asked GCOS to provide routine reports on the status of the climate observing system. As part of this effort, GCOS and supporting agencies specified Essential Climate Variables (ECVs) and the observing systems needed to provide them. They elaborated these variables in the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (GCOS, 2004). Listings of the climate variables needed to track climate change have also been included in documents such as assessments by the Intergovernmental Panel on Climate Change (IPCC) of the UNFCCC. In a similar way, essential measurements (variables) need to be monitored to assess the impacts of year-by-year change.

The Group on Earth Observations (GEO) has undertaken an analysis of the needs for information in each of its nine Societal Benefit Areas, including climate, agriculture and water. In this context, 'Earth observations' are used to refer to variables (e.g., physical, geophysical, chemical, biological) sensed or measured with in-situ sensors and space-based remote sensing as well as derived parameters and products, and related parameters from model outputs, using a bibliographic approach to determine the overall critical Earth observation priorities. Based on similarities between W-S-W data users and other water data users considered in the GEO study, we can infer that W-S-W information is most likely needed for modelling and scenario development; applications of the projections of models and scenarios; planning future agricultural policies and cropping scenarios; and resource management and investment decisions by agribusiness and economic users (modified from Unninayar et al., 2010).

To meet observational needs, very diverse systems have been developed for the different components of the W-S-W Nexus. The variables are wide-ranging, vary over different time and space scales and require different observational techniques.

9.1 Water and Climate Data

On short timescales water is very dynamic: substantial changes occur on an hourly basis for precipitation and on a daily basis for soil moisture. While the W-S-W resources responds to these hourly and daily changes, it is their integrated effect over a longer period of time that constitutes the sensitivity of the W-S-W Nexus to climate variability and the response of soil to climate change. In many respects, satellite remote sensing can best provide those types of data since it provides global data on a routine basis and that information can be integrated with in-situ surface measurements through the use of data assimilation systems. Gaps exist in observational programs, especially for streamflow (where national hydrometric networks have been reduced), for soil moisture (where a systematic global observational network has never been developed), and for groundwater (where observational networks are not well developed and where data are not always shared freely among nations).

Climate data are central to understanding changes in the global water cycle and the effects on soils and waste. Temperature is the main controlling factor since it determines when water will be a vapour, liquid, or solid. Modified temperature, precipitation, and streamflows arising from climate change will be critical for planning strategies for adapting the W-S-W Nexus to future changes. Some of the variables that are important for the water component of the W-S-W Nexus are identified as either ECVs or Essential Water Variables (EWVs) by GEO. While ECVs have been the basis for planning measurement programmes for the past decade, EWVs have only recently been defined as part of the GEOSS Water Strategy Report (GEO, 2014).
While water data acquisition, archiving and dissemination are quite mature for some water variables (precipitation, streamflow), they are less developed for other variables (groundwater, water quality). Special needs exist in the area of soil moisture. Soil moisture is an important water cycle variable that involves both soil and water. Climate modellers are interested in the moisture in a shallow surface layer of soil that evaporates water into the atmosphere. The agricultural community is interested in the soil water throughout the root zone. Although efforts have been undertaken to globally coordinate in-situ soil moisture measurements, it has proven difficult to gain consensus on a single international standard. However, the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) mission and the National Aeronautics and Space Agency's Soil Moisture Active Passive (SMAP) mission now produce global maps of soil moisture which address a number of data needs including those related to the distribution of ground frost.

9.2 Soil Data

Soils are dynamic on longer timescales and their texture and chemical composition often change in response to environmental conditions influenced by climate. A fundamental dataset for understanding the role of soils in the W-S-W Nexus, and indeed in Earth system processes, should include the information needed to answer questions about stores and fluxes of water, carbon and nutrients on different spatial scales. Satellites can provide global maps of land cover. However, scale issues in data collection can make it difficult to provide land data at the farm scale. Soil data and information are also needed for global hydrological and biogeochemical modelling.

To meet the needs for reliable information, datasets must be regularly updated. While this can be done to some extent through remote sensing, it is not possible to provide the necessary information without developing updated profiles of the soil through in-situ sampling. FAO maintains an extensive global soils database that is the reference for most global studies. After the data have been assembled, efforts are needed to reconcile the data between countries. For example, the Harmonized World Soil Database (HWSD), including the FAO/UNESCO Soil Map of the World (from 1980), is widely used. However, some soil experts suggest that there may be sufficient changes in the soil profiles in some areas that the national and global databases should be updated.

No soil monitoring frameworks are available at the global level, although national frameworks do exist. To meet this need, a database including information about soil family, carbon content, soil and land resources should be developed. Considering the importance of food security, climate change adaptation and mitigation, and provision of ecosystem services, the soil science community should clearly respond to the need for improved, up-to-date, quantitative and applied soil data and information.

9.3 Wastewater Data for the Nexus

Data on waste is even more difficult to obtain than data on water or even soils. Information on waste production is needed to plan waste storage and water treatment facilities. The storage and transportation of waste can be a critical activity when hazardous wastes are involved. Some data can be made available through waste collection systems. However, in rural areas a source of data does not exist except where farmers are sufficiently motivated to maintain the statistics themselves. Governments responsible for waste clean-up usually monitor waste more actively than those who produce it.

Wastewater data are collected in several international archives but none of them are fully satisfactory because much of the data is submitted by countries on a voluntary basis (EOTT, 2015). The AQUASTAT database (ww.fao.org/nr/water/aquastat/data), maintained by FAO, is considered to be the most complete database on agricultural waste. It consists of annual reports submitted voluntarily by nations that contain nation-scale information of wastewater production, wastewater treatment, use of treated wastewater, amount of recycle wastewater and so on. Many developed countries have their own wastewater databases because they tend to monitor data by state or province and maintain a wide range of data types.

In addition to the data types discussed above, it will also be important for the W-S-W community to have access to a broad range of contextual environmental data, including climate change effects. Management of the W-S-W Nexus would benefit from access to data that were collected in a more rigorous fashion and complete records for data from all countries.

10. Summary

In this paper we have reviewed the role of climate change for the W-S-W Nexus and the information that will be needed to manage the Nexus in the future. While the thermal aspects of climate change are widely accepted and confirmed by recently observed trends, uncertainty still surrounds other variables, such as precipitation, the most important input to the W-S-W Nexus. Temperature trends lead to predictable changes in the water cycle where snow or ice are present because the warming will lead to more rain and less snow, changing ground frost patterns and changes in the seasonality of runoff.

This review assessed the importance of climate for the Water-Soil-Waste Nexus. While general preliminary strategies exist for addressing specific problems with regards to water, soils and wastewater, the priorities may change as a Nexus Approach is adopted and the effects of climate change become more clearly delineated.

In terms of the information needed to assess the effects of climate change on the W-S-W Nexus, the following variables will be priorities for data collection programmes:

- Water: precipitation, precipitation extremes, soil moisture, runoff and streamflow, snow water equivalent, groundwater

- Soils: soil moisture, soil profiles, porosity, vegetation types supported by the soil

- Waste: wastewater production, irrigation use, human and livestock population density, reuse of treated waste water

In order to advance the understanding of processes governing the W-S-W Nexus and to relate this understanding to improved crop productivity, it is recommended that the following steps be taken:

1. An assessment of the possible implications of climate change for the W-S-W Nexus to provide a basis for a comprehensive strategy for adapting to climate change and to establish a comprehensive set of essential variables.

2. The databases needed to support the information requirements of the W-S-W Nexus, including information on basic water cycle variables, and updated and modernized soil information, including soil carbon, and data on waste and wastewater production, wastewater emission and treatment and reuse, should be developed. As a first step, the adequacy of current databases needs to be reviewed in the context of climate change to ensure that the impacts of climate change can be accurately monitored and the success of adaptation techniques can be tracked. Among others, known data gaps include data for monitoring trends in soil carbon and soil acidity.

3. A new approach to waste management should be developed. This could include a waste production allocation system, whereby waste producers would be required to keep their waste production within a pre-approved limit and would have to register when waste was produced. Furthermore, this new approach could also include an end-to-end tracking system to determine where wastes are transported, the extent to which they are recycled and the amounts and ways in which they are disposed. This monitoring system would allow users to identify when waste was lost in the system so they could take appropriate action.

A number of research needs were also identified throughout this paper. Some of these included better tools for producing reliable, high-resolution climate change projections. Others involved identifying when more rapid rates of change may occur as critical tipping points were passed. While the concept of tipping points has become popular in the sustainable development community, those aspects of climate change that may produce sudden changes must be defined. We must then begin to monitor those variables in detail. Merging socioeconomic data related to the W-S-W Nexus together with climate data is another issue that requires attention.

References

Adegoke, J.O., R.A. Pielke Sr., J. Eastman, R. Mahmood, and K. Hubbard. 2003. "Impact of Irrigation on Midsummer Surface Fluxes and Temperature under Dry Synoptic Conditions: A Regional Atmospheric Model Study of the U.S. High Plains." Monthly Weather Review 131: 556-64.

Adger, W.N., S. Agrawala, and M. Monirul Qader Mirza. "Assessment of Adaptation Practices, Options, Constraints and Capacity." 2007. In Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. 717-43. Cambridge: Cambridge University Press

Barnett, T., J. Adam, and D. Lettenmaier. 2005. "Potential Impacts of a Warming Climate on Water Availability in Snow-dominated Regions." Nature 438: 303-09.

Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof, eds. 2008. Climate Change and Water. Intergovernmental Panel on Climate Change (IPCC) Technical Paper VI, IPCC Secretariat, Geneva, Switzerland.

Beegle, D.B., L.E. Lanyon, and J.T. Simms. 2002. "Nutrient Balances." In Agriculture, Hydrology and Water Quality, edited by Haygart, M. and C.S. Jarvis. 171-193. Wallingford, U.K.: CAB International.

Berg, P., C. Moseley, and J.O. Haerter. 2013. "Strong Increase in Convective Precipitation in Response to Higher Temperatures." Nature Geoscience 6: 181-85.

Black, B.C., D.M. Hassennahl, J.C. Stephens, G. Weisel and N. Gift. 2013. "Agriculture and Adaptation in the United States." Climate Change: An Encyclopedia of Science and History. 1: 33-45.

Blum, W.H.E. 2005. "Soils and Climate Change." Journal of Soils and Sediments, 5 (2): 67-68.

Brady, N.C., and R.R. Weil. 2008. The Nature and Properties of Soils. 14th ed. Upper Saddle River: Pearson Prentice Hall.

Briggs, J.C., and Ficke, J.F. 1977. Quality of Rivers of the United States, 1975 Water Year -- Based on the National Stream Quality Accounting Network (NASQAN). U.S. Geological Survey Open-File Report. 78-200

Colwell, R.N., Agriculture. 2012. In McGraw-Hill Encyclopedia of Science and Technology, 11 edition, Vol. 1. 258-265. McGraw Hill, New York.

Christensen, J. H., and B. Hewitson. 2007. "Regional Climate Projections: Climate Change 2007: The Physical Science Basis." In Contribution of Working Group I to the Fourth Assessment Report of IPCC, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller. 847-940. Geneva: IPCC.

Considine, G.D. and P.H. Kurlik. 2008. "Wastes and Pollution." In Van Norstand's Scientific Encyclopedia, 10th Edition, Vol.3. 5773-5781. New Jersey: Wiley-Intescience.

Cunningham, W.P. 2011. "Water Pollution." In Environmental Encyclopedia, 4th Edition. 1731-34. Detroit: Gale Cengage Learning.

Dai, A. 2013. "Increasing drought under global warming in observations and models." Nature Climate Change, 3: 52-58.

de Bruin, K., R.B. Dellink, A. Ruijs, L. Bolwidt, A. van Buuren, J. Graveland, R.S. de Groot, P.J. Kuikman, S. Reinhard, R.P. Roetter, V.C. Tassone, A. Verhagen, and E.C. van Ierland. 2009. "Adapting to Climate Change in The Netherlands: An Inventory of Climate Adaptation Options and Ranking of Alternatives." Climatic Change, 95: 23-45.

Dettinger, M.D., and D.R. Cayan. 1995. "Large-scale Atmospheric Forcing of Recent Trends Toward Early Snowmelt in California." Journal of Climate, 8: 606-23.

Döll, P. 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. Environmental Research Letters, 4 (3): 035006, doi:10.1088/1748-9326/4/3/035006.

Döll, P., and M. Flörke. 2005. "Global-Scale Estimation of Diffuse Groundwater Recharge." Frankfurt Hydrology paper presented at the Institute of Physical Geography. Frankfurt, Germany: Frankfurt University.

EOTT (Earth Observation Task Team). 2015. Final Report on Monitoring for the Water Sustainable Development Goal Prepared for the UN Water GEMI Project Team, Edited by R. Hossain and R. Lawford. World Health Organization.

FAO. 2014. Building a Common Vision for Sustainable Food and Agriculture: Principles and Approaches. FAO: Rome.

FAO. 2011. The state of the world's land and water resources for food and agriculture (SOLAW): managing systems at risk. FAO: Rome.

Feldmann, H., G. Schädler, H.-J. Panitz, and C. Kottmeier. 2012. "Near Future Changes of Extreme Precipitation Over Complex Terrain in Central Europe Derived from High Resolution RCM Ensemble Simulations." International Journal of Climatology, 33 (8): 1964-77.

Feyen, L., and R. Dankers. 2009. "Impact of Global Warming on Streamflow Drought in Europe." Journal Geophysical Research 114 (D7): 2156-2202.

Fick, G.W. Food, Farming and Faith. Albany: State University of New York Press, 2008.

Fridgen, C. 2011. "Waste Management." In Environmental Encyclopedia, 4th Edition. 1718-20. Detroit: Gale Cengage Learning.

Fu, G., S.P. Charles, F.H.S. Chiew, J. Teng, H. Zheng, A.J. Frost, W. Liu, and S. Kirshner, 2013. "Modelling runoff with statistically downscaled daily site, gridded and catchment rainfall series." Journal of Hydrology 492:254-265.

GCOS (Global Climate Observing System). 2004. Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC. Geneva: WMO.

———. 2013. "GCOS Essential Climate Variables." Last modified January 28, 2013. http://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables

GEO. 2014. The GEOSS Water Strategy: From Observations to Decisions. Tokyo: JAXA.

Gift, N. 2013. "Agriculture and Adaptation in the UNITED States." In Climate Change: An Encyclopedia of Science and History, Vol. 1. Edited by C. Black Gen. 33-45. Santa Barbara, CA: ABC-CLI0, LLC.

Gosling, S.N., and N.W. Arnell. 2011. "Simulating Current Global River Runoff with a Global Hydrological Model: Model Revisions, Validation, and Sensitivity Analysis." Hydrological Processes 25: 1129-45.

Groisman, P., R.W. Knight, and T.R. Karl. 2004. "Contemporary Changes of the Hydrological Cycle over the Contiguous United States: Trends Derived from In-Situ Observations." Journal of Hydrometeorology 5: 64-85.

Grosshans, R., L. Grieger, J. Ackerman, S. Gauthier, K. Swystun, P. Gass, and D. Roy. 2015. Cattail Biomass in a Watershed-Based Bioeconomy: Commercial-scale harvesting and processing for nutrient capture, biocarbon and high-value bioproducts. Winnipeg, Manitoba: IISD Publication.

Hagemann, S., C. Chen, D.B. Clark, S. Folwell, S.N. Gosling, I. Haddeland, N. Hanasaki, J. Heinke, F. Ludwig, F. Voss, and A.J. Wiltshire. 2013. "Climate Change Impact on Available Water Resources Obtained Using Multiple Global Climate and Hydrology Models." Earth System Dynamics 4: 129-44.

Hanamean, J.R., R.A. Pielke Sr., C.L. Castro, D.S. Ojima, B.C. Reed, and Z. Gao. 2003. "Vegetation Impacts on Maximum and Minimum Temperatures in Northeast Colorado." Meteorological Applications 10: 203-15.

Hatfield, J.L., T.J. Sauer, and J.H. Prueger. 2001. "Managing Soils to Achieve Greater Water Use Efficiency: A Review." Agronomy Journal 93: 271-80.

IPCC. 2007a. Climate Change 2007. The Physical Science Basis: Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC.

———. 2007b. "Glossary." In Climate Change: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson. Cambridge: Cambridge University Press.

———. 2013. "Summary for Policymakers." In Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. Cambridge: Cambridge University Press.

———. 2014. "Climate Change 2014, Synthesis Report, Summary for Policy Makers" In Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core writing team: R.K. Pachauri and L.A. Myere. 151 p.. Geneva, Switzerland : IPCC.

Keeling, C.D., and T.P. Whorf. 2004. Atmospheric CO2 from Continuous Air Samples at Mauna Loa Observatory, Hawaii, U.S.A. La Jolla: Carbon Dioxide Research Group, Scripps Institution of Oceanography, University of California.

Kharin, V.V., F.W. Zwiers, X. Zhang, and G.C. Hegerl. 2007. "Changes in Temperature and Precipitation Extremes in the IPCC Ensemble of Global Coupled Model Simulations." Journal of Climate, 20: 1419-44.

Koster, R.D., P.A. Dirmeyer, Z. Guo, G. Bonan, E. Chan, P. Cox, C.T. Gordon, S. Kanae, E. Kowalczyk, D. Lawrence, P. Liu, C. Lu, S. Malyshev, B. McAvaney, K. Mitchell, D. Mocko, T. Oki, K. Oleson, A. Pitman, Y. C. Sud, C.M. Taylor, D. Verseghy, R. Vasic, Y. Xue, and T. Yamada. 2004. "Regions of Strong Coupling between Soil Moisture and Precipita¬tion." Science 305: 1138-40.

Kotwicki, V. 2009. "Water Balance of Earth." Hydrological Sciences Journal, 54 (5):829-40. doi 10.1623/hysj.54.5.829

Kundzewicz, Z.W., and E.Z. Stakhiv. 2010. "Are Climate Models 'Ready for Prime Time' in Water Resources Management Applications, or is More Research Needed?" Hydrological Sciences Journal, 55 (7):1085-89.

Lal, R. 2013. "Climate-strategic Agriculture and the Water-Soil-Waste Nexus." Journal of Plant Nutrition and Soil Science 176: 479-93.

Lal, R., R.F. Follett, B.A.Stewart, and J.M. Kimble. 2004. "Soil Carbon Sequestration to Mitigate Clmate Change and Advance Food Security." Soil Science Society of America Journal 172:943-956.

Laaser, C., A. Leipprand, C. de Roo, and R. Vidaurre. 2009. Report on Good Practice Measures for Climate Change Adaptation in River Basin Management Plans. Copenhagen: EEA

Lawford, R. 2011. "Climate Change and the Global Water Cycle." In Water Resources Planning and Management. Edited by Q. Grafton and K. Hussey. 3-22. Cambridge: Cambridge University Press.

Lawford, R., J. Bogardi, S. Marx, S. Jain, C. Pahl Wostl, K. Knupe, C. Ringler, F. Lansigan, F. Meza. 2013. "Basin Perspectives on the Water-Energy-Food Security Nexus." COSUST 5:607-16.

Lehner, B., T. Henrichs, P. Döll, and J. Alcamo. 2001. "EuroWasser: Model-based Assessment of European Water Resources and Hydrology in the Face of Global Change." International Watershed Technology 56 (6):1407-17.

Leipprand, A., T. Dworak, M. Benzie, and M. Berglund. 2008. Impacts of Climate Change on Water Resources – Adaption Strategies for Europe. Dessau-Roßlau: FEA.

Ludwig, F., and M. Moench. 2009. "The Impacts of Climate Change on Water." In Climate Change Adaptation in the Water Sector. Edited by. F. Ludwig, P. Kabat, H. van Schaik, and M. van der Valk. 35-50. London: Earthscan.

Maurer, T. 2004. "Detection of Change in World-wide Hydrological Time Series of Maximum Annual Flow and Trends in Flood and Low Flow Series Based on Peak-Over-Threshold (POT) Methods." Paper presented at the IGWCO/GEWEX/UNESCO workshop on global water cycle trends, Paris, France.

McDonald, R.I. and E.H. Girvetz. 2013. "Two challenges for U. S. irrigation due to climate change: increasing irrigated area in wet states and increasing irrigation rates in dry states." Plos One 8 (6):e65589, doi:10.1371/journal.pone.0065589.

Milly, P.C.D, J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. "Stationarity Is Dead: Whither Water Management." Science 319:573-74.

Mimikou, M.A., E. Baltas, E. Varanou, and K. Pantazis. 2000. "Regional Impacts of Climate Change on Water Resources Quantity and Quality Indicators." Journal of Hydrology, 234 (1-2):95-109.

Min, S., X. Zhang, F.W. Zwiers, and G.C. Hegerl. 2011. Human contribution to more-intense precipitation extremes. Nature 470 (7334):378-381

Otte, T.L., J. H. Bowden, J. A. Herwehe, C. G. Nolte, G. Faluvegi, 2009. Dynamical Downscaling of NASA/GISS ModelE Using WRF, Presented at 2009 CMAS Users' Conference, Chapel Hill, NC, October 20, 2009.

Peeters, F., D. Straile, A. Lorke, and D.M. Livingstone. 2007. "Earlier Onset of the Spring Phytoplankton Bloom in Lakes of the Temperate Zone in a Warmer Climate." Global Change Biology 13:1898-909.

Prokopy, L.S., L.W. Morton, J.G. Arbuckle Jr., A.S. Mase and A.K. Wilke. 2015. "Agricultural Stakeholder Views on Climate Change." Bulletin of the American Meteorological Society 96: 181-190.

Ramanathan, V., P.J. Crutzan, J.T. Kiehl, and D. Rosenfeld. 2001. "Aerosols, Climate and the Hydrological Cycle." Science 294:2119-24.

Randtke, S.J. 2012. "Water Treatment." In Environmental Encyclopaedia, 4th Edition. 1741-44. Detroit: Gale Cengage Learning.

Rhodes, S.L. 2012. "Climate Change Impacts." In Encyclopaedia of Science and Technology, Vol. 4. 254-55. New York: McGraw Hill.

Ringler, C., A. Bhaduri, and R. Lawford. 2013. "The Nexus across Water, Energy, Land and Food (WELF): Potential for Improved Resource Use Efficiency." COSUST 5:617-24.

Rodell, M. 2005. India's Water Economy: Bracing for a Turbulent Future. Washington, DC: World Bank.

Rosenfeld, D. 2004. "Anthropogenic Aerosols Impacts on Precipitation Trends through Suppression of Precipitation Forming Processes in Clouds." Paper presented at the IGWCO/GEWEX/UNESCO workshop on global water cycle trends, Paris, France, 2004.

Sauchyn, D.J., A. Beriault, and J. Stroich. 2002. "A Paleoclimatic Context for the Drought of 1999-2001 in the Northern Great Plains." Geographical Journal 169 (2): 1-18.

Scibek, J., D.M. Allen, A. Cannon, and P.H. Whitfield. 2007. "Groundwater- surface Water Interaction under Scenarios of Climate Change using a High-resolution Transient Groundwater Model." Journal of Hydrology 333 (2-4):165-81.

Seneviratne, S.I., T. Corti, E.L. Davin, M. Hirschi, E.B. Jaeger, I. Lehner, B. Orlowsky, and A.J. Teuling. 2010. "Investigating soil moisture-climate interactions in a changing climate: A review." Earth-Science Reviews 99 (3-4): 125-161.

Shiklomanov, I.A., and J.C. Rodda. 2003. World Water Resources at the Beginning of the 21st Century. Cambridge: Cambridge University Press.

Smith, J.H., C. W. Robbins, J. A. Bondurant, and C. W. Hayden. 1978. Treatment and Disposal of Potato Processing Waste Water by Irrigation. U.S. Department of Agriculture Conservation Research Report 22, 37 pp.

Sokolick, I.N. 2006. "NEESPI Focus Research Center on Atmospheric Aerosol and Air Pollution." Paper presented at the NEESPI planning workshop, Vienna, Austria, 2006.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2005. "Changes toward Earlier Streamflow Timing across Western North America." Journal of Climate, 18:1136-55.

Teutschbein, C. and J. Seibert. 2012. "Bias correction of regional climate model simulations for hydrological climate-change impact studies: review and evaluation of different methods." Journal of Hydrology 456:12-29.

Trenberth. K.E., and T.J. Hoar. 2007. "El Niño and Climate Change." Geophysical Research Letters 24:3057-60.

Trenberth, K.E., L. Smith, T. Qian, A. Dal, and J. Fasullo. 2007. "Estimates of the Global Water Budget and its Annual Cycle using Observational and Model Data." Journal of Hydrometeorology 8:758-69.

UNEP. 2007. Global Environmental Outlooks. Calietta: Progress.

UNFCCC. 2011. Water and Climate Change Impacts and Adaptation Strategies. Geneva: FCCC.

Unninayar, S., et al. 2010. GEO Task US-09-01a: Critical Earth Observations Priorities. Geneva: GEO.

Viera, F.C.P., C. Bayer, J.A. Zanatta, J. Diekow, J.Mielniczuk, and Z.L. He. 2007. Carbon Management Index based on Physical Fractionation of Soil Organic Matter in a Acrisolunder Long-Term No-Til Cropping Systems. Soil and Tilth Research V (96):195-204.

Vörösmarty, C.J., P. Green, J. Salisbury, and R.B. Lammers. 2000. "Global Water Resources: Vulnerability from Climate Change and Population Growth." Science, 289:284-88.

Vrtis, N. 2011. "Water Allocation." In Environmental Encyclopedia, 4th Edition. 1718-20. Detroit: Gale Cengage Learning.

Warrick, K.E. 2009. "Using SimCLIM for Modelling the Impacts of Climate Extremes in a Changing Climate: A Preliminary Case Study of Household Water Harvesting in Southeast Queensland." Presented at 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation, Cairns, Australia July 2009, 2583-89.

Wheaton, E., S. Kulshreshrtha, and V. Whittrock, Eds. 2005. Canadian Droughts of 2001 and 2002: Climatological Impacts and Adaptations. Vol. 1 and 2. Saskatchewan Research Council.

Zierl, B., and H. Bugmann. 2005. "Global Change Impacts on Hydrological Processes in Alpine Catchments." Water Resources Research 41:1-13.

ABOUT UNU-FLORES

MISSION

"Advancing the Nexus Approach to the sustainable management of environmental resources"

In line with the general mission of UNU to foster sustainable development, UNU-FLORES aims to contribute to the resolution of pressing challenges to the sustainable use and integrated management of environmental resources, such as water, soil and waste. UNU-FLORES strives to advance the development of integrated management strategies that take into consideration the impact of global change on the sustainable use of the environmental resources. To this end, the Institute engages in research, teaching, advanced training, capacity development and dissemination of knowledge.

VISION

UNU-FLORES acts at the forefront of initiatives promoting a Nexus Approach to the sustainable management of water, soil and waste. The Institute supports the overall mission of UNU as a think tank for the United Nations and its member states, in particular addressing the needs of developing countries and emerging economies. In this role, UNU-FLORES aspires to become an internationally recognized hub and intellectual focal point promoting integrated management strategies.

Additionally, UNU-FLORES engages in policy-relevant research, postgraduate education and capacity development in a broad sense. The Institute attracts high-calibre students for postgraduate study and research programmes in cooperation with other research institutions. Furthermore, UNU-FLORES builds the capacity of future leaders in the area of environmental resources management and develops innovative concepts for target- and region-specific knowledge transfer.

ORGANIZATIONAL STRUCTURE

In developing its functional structure, UNU-FLORES has positioned itself well to consolidate the scientific foundation of the Nexus Approach. The institutional arrangement is a direct response to critical knowledge gaps relating to integrated management of the environmental resources water, soil and waste. The organization of UNU-FLORES into five academic units – three core scientific units (Water Resources Management (WRM), Waste Management (WM) and Soil and Land Use Management (SLM)) supported by two cross-cutting units (System Flux Analysis Considering Global Change Assessment (SFA) and Capacity Development and Governance (CDG)) – supports the think tank function of the Institute. All scientific units are supported by the operational support units, which consist of the Office of the Director, Finance and Administration, Communications and Advocacy, and Computing and ICT.

OUR DEFINITION OF THE NEXUS APPROACH TO ENVIRONMENTAL RESOURCE MANAGEMENT

"The Nexus Approach to environmental resources' management examines the inter-relatedness and interdependencies of environmental resources and their transitions and fluxes across spatial scales and between compartments. Instead of just looking at individual components, the functioning, productivity and management of a complex system is taken into consideration."

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ABOUT THE DRESDEN NEXUS CONFERENCE

As a hub for initiatives on the Nexus Approach, UNU-FLORES is not only committed to strengthening its own network but also to providing an international platform to foster cooperation and networking amongst all actors working on or with the Nexus Approach to managing environmental resources. That platform is the **Dresden Nexus Conference (DNC)**.

Every two years UNU-FLORES will organize a DNC, welcoming scholars, politicians, and practitioners from all regions of the world to meet and discuss the most recent and innovative initiatives on a Nexus Approach to the management of environmental resources.

DNC2015: GLOBAL CHANGE, SUSTAINABLE DEVELOPMENT GOALS AND NEXUS APPROACH

Building on the outcomes of the 2013 "International Kick-Off Workshop on Advancing a Nexus Approach to the Sustainable Management of Water, Soil and Waste", UNU-FLORES organized the inaugural Dresden Nexus Conference (DNC). From 25 to 27 March 2015 representatives from academia, politics and civil society assembled in Dresden under the theme "Global Change, Sustainable Development Goals and Nexus Approach". Working together with co-organizers, TU Dresden and IOER, in 2014 UNU-FLORES solicited applications from numerous renowned academic institutions from around the world. Categorized under three key themes – climate change, urbanization and population growth – 18 sessions were selected for the first DNC. Compromising a comprehensive selection of the diverse initiatives on the Nexus Approach, sessions will be convened by UN entities, international research organizations, universities and non-governmental organizations. Besides these 18 sessions, the organizers have arranged for six keynote speeches and concluding talks by renowned scholars as well as panel discussions with senior officials from UN Member States. During the entire conference academic initiatives will be on display in the poster and exhibition halls.

In parallel to the organizational activities of the DNC2015, UNU-FLORES arranged for the drafting and distribution of nine position papers to help build and consolidate the background knowledge of the three topics covered during the conference: climate change, urbanization and population growth and the increasing demand for environmental resources. This working paper has emerged from one of those position papers.

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Institute for Integrated Management
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The United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES) was established in Dresden, Germany in 2012 with the support of the Federal Ministry of Education and Research (BMBF) and the Ministry for Higher Education, Research and the Arts (SMWK) of the Free State of Saxony, Germany. As part of the United Nations University (UNU), the Institute helps build a bridge between the academic world and the United Nations. UNU encompasses 13 research and training institutes and programmes located in 12 countries around the world. UNU as a whole aims to develop sustainable solutions for pressing global problems of human survival and development.

UNU-FLORES develops strategies to resolve pressing challenges in the area of sustainable use and integrated management of environmental resources such as soil, water and waste. Focusing on the needs of the UN and its member states, particularly developing countries and emerging economies, the Institute engages in research, capacity development, advanced teaching and training as well as dissemination of knowledge. In all activities, UNU-FLORES advances a nexus approach to the sustainable management of environmental resources.

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ADVANCING A NEXUS APPROACH TO THE SUSTAINABLE MANAGEMENT OF ENVIRONMENTAL RESOURCES

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