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ORIGINAL PAPER

Wetlands and global climate change: the role of wetland restoration in a changing world

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Abstract Global climate change is recognized as a threat to species survival and the health of natural systems. Scientists worldwide are looking at the ecological and hydrological impacts resulting from climate change. Climate change will make future efforts to restore and manage wetlands more complex. Wetland systems are vulnerable to changes in quantity and quality of their water supply, and it is expected that climate change will have a pronounced effect on wetlands through alterations in hydrological regimes with great global variability. Wetland habitat responses to climate change and the implications for restoration will be realized differently on a regional and mega-watershed level, making it important to recognize that specific restoration and management plans will require examination by habitat. Floodplains, mangroves, seagrasses, saltmarshes, arctic wetlands, peatlands, freshwater marshes and forests are very diverse habitats, with different stressors and hence different management and restoration techniques are needed. The Sundarban (Bangladesh and India), Mekong river delta (Vietnam), and southern Ontario (Canada) are examples of major wetland complexes where the effects of climate change are evolving in different ways. Thus, successful long term restoration and management of these systems will hinge on how we choose to respond to the effects of climate change. How will we choose priorities for restoration and research? Will enough water be available to rehabilitate currently damaged, water-starved wetland ecosystems? This is a policy paper originally produced at the request of the Ramsar Convention on Wetlands and incorporates opinion, interpretation and scientific-based arguments.

Keywords Wetland restoration · Wetland hydrology · Climate change · Wetlands · Mangroves · Seagrasses · Salt marsh · Arctic wetlands · Peatlands · Freshwater marsh and forests · Sundarban · Mekong river delta · Southern Ontario · Carbon sink

Introduction

In the early 1970s, the main obstacle confronting wetland restoration efforts was developing the science for successful wetland restoration projects. Although we have made much progress on that front, the issue of climate change may present greater challenges to wetland conservation and restoration. This is a policy paper originally produced at the request of the Scientific and Technical Review Panel of the Ramsar Convention on Wetlands and incorporates opinion, interpretation and scientific-based arguments. The Ramsar convention is the global intergovernmental treaty which addresses the conservation and wise use

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of wetlands. In this paper, I begin by summarizing the existing science related to the impacts of climate change on wetlands. After examining over 250 articles pertaining to wetlands and climate change, in peer-reviewed journals and gray literature, I found very little discussion of wetland restoration in the climate change literature, only an occasional comment in a very small percentage of the papers. This suggests a substantial and urgent need to determine how to shape future wetland restoration initiatives in light of global climate change. The task is made more difficult in light of the demand for water worldwide that has more than tripled since 1950 and is projected to double again by 2035 (Postel 1997).

Wetlands cover 6% of the world's land surface and contain about 12% of the global carbon pool, playing an important role in the global carbon cycle [International Panel on Climate Change (IPCC) 1996; Sahagian and Melack 1998; Ferrati et al. 2005]. In a world of global climate change, wetlands are considered one of the biggest unknowns of the near future regarding element dynamics and matter fluxes (IPCC 2001; Paul et al. 2006). Nevertheless, restoration practitioners should take climate change into account when implementing restoration projects, and policymakers should promote wetland restoration as part of a climate change adaptation and mitigation strategies.

Climate change and wetlands

Climate change is recognized as a major threat to the survival of species and integrity of ecosystems worldwide (Hulme 2005). The body of literature on the ecological and hydrological impacts expected to result from climate change has grown considerably over the past decade.

Pressures on wetlands are likely to be mediated through changes in hydrology, direct and indirect effects of changes in temperatures, as well as land-use change (Ferrati et al. 2005). Examples of impacts resulting from projected changes in extreme climate events (Ramsar (STRP) 2002) include: change in base flows; altered hydrology (depth and hydroperiod); increased heat stress in wildlife; extended range and activity of some pest and disease vectors; increased flooding, landslide, avalanche, and mudslide damage; increased soil erosion; increased flood runoff resulting in a decrease in recharge of some floodplain aquifers; decreased water resource quantity and quality; increased risk of fires; increased coastal erosion and damage to coastal buildings and infrastructure; increased damage to coastal ecosystems such as coral reefs and mangroves and increased tropical cyclone activity. Under currently predicted future climate scenarios, the spread of exotics will probably be enhanced, which could increase pressure on watersheds and ecosystems (Root et al. 2003).

Climate change can be expected to act in conjunction with a range of other pressures, many of which, depending on the region, may pose far greater immediate concern for wetlands and their water resources in the short to medium term (Table 1; STRP 2002). Wetland systems are vulnerable and particularly susceptible to changes in quantity and quality of water supply. It appears that climate change may have its most pronounced effect on wetlands through alterations in hydrological regimes: specifically, the nature and variability of the hydroperiod and the number and severity of extreme events. However, other variables related to climate may play important roles in determining regional and local impacts, including increased temperature and altered evapotranspiration, altered biogeochemistry, altered amounts and patterns of suspended sediment loadings, fire, oxidation of organic sediments and the physical effects of wave energy (IPCC 1998; Burkett and Kusler 2000; USGCRP 2000).

Climate change will affect the hydrology of individual wetland ecosystems mostly through changes in precipitation and temperature regimes with great global variability. From the perspective of assessment of climate variability and the effect on wetlands, these ecosystems need to be viewed in the broader context of their spatial location in a watershed within a specific region. Given the diversity of wetland types and their individual characteristics, the impacts resulting from climate change will be somewhat customized and so will the restoration remedies. It will be critically important to determine specific expected future changes in climate by region and conduct adequate monitoring to ascertain how actual conditions track with the specific climate change model for a region. This may prove to be difficult and will take a considerable educational effort to convince governments and organizations to spend money on monitoring.

Table 1 Projected impacts in some key water-based systems and water resources under temperature and precipitation changes approximating those of the special report of emission scenarios (SRES, modified from STRP 2002)

Indicators	2025	2100
Corals	Increase in frequency of coral bleaching and death of corals	More extensive coral bleaching and death Reduced species biodiversity and fish yields from reefs
Coastal wetlands and shorelines	Loss of some coastal wetlands to sea level rise. Increased erosion of shorelines	More extensive loss of coastal wetlands Further erosion of shorelines
Freshwater wetlands	Widespread stress on many marshes, swamps, vernal pools, etc. Some will disappear	Most systems will be changed significantly, many such as prairie potholes and vernal pools will disappear with some spatial drifting
Ice environments	Retreat of glaciers, decreased sea ice extent, thawing of some permafrost, longer ice free seasons on rivers and lakes	Extensive Arctic sea ice reduction, benefiting shipping but harming wildlife (e.g., seals, polar bears, walrus) Ground subsidence leading to changes in some ecosystems. Substantial loss of ice volume from glaciers, particularly tropical glaciers
Seagrasses	Some reduction in cover and distribution due to changing salinities	More extensive loss of seagrasses
Water supply	Peak river flow shifts from spring toward winter in basins where snowfall is an important source of water	Water supply decreased in many water-stressed countries, increased in some other water-stressed countries
Water quality	Water quality degraded by higher temperatures, changes in flow regimes and increase in salt-water intrusion into coastal aquifers due to sea level rise	Water quality effects amplified
Water demand	Water demand for irrigation will respond to changes in climate; higher temperatures will tend to increase demand	Water demand effects amplified
Floods and droughts	Increased flood damage due to more intense precipitation events. Increased drought frequency	Flood damage several fold higher than “no climate change scenarios”. Further increase in drought events and their impacts

An important management strategy to ensure wetland sustainability is the prevention or reduction of additional stress that can reduce the ability of wetlands to respond to climate change. Maintaining hydrology, reducing pollution, controlling exotic vegetation, and protecting wetland biological diversity and integrity are important activities to maintain and improve the resiliency of wetland ecosystems so that they continue to provide important services under changed climatic conditions (Kusler et al. 1999; Ferrati et al. 2005).

The predicted hydrologic changes associated with climate change will potentially affect the performance of the infrastructure (e.g., surface water management systems) and thereby will affect the different uses of water in many areas. An increase in extreme droughts and floods will heavily stress organisms and add to human-induced stress factors.

Future climate changes will affect wetlands in two fundamental ways: the number of functioning wetlands (and their functional capacity) within most eco-regions will decline and the geographic location of certain types of wetlands will shift. Simulations in a recent study on North American prairie wetlands indicate that the northern short grasslands were the most vulnerable portion of the prairie pothole region to increases in temperature. Semi-permanent wetlands in this eco-region have historically functioned on the margin, and any increased temperature would result in decreased water levels and increased vegetation cover (Johnson et al. 2005).

Although the ecological effects of climate change are increasingly apparent (Root et al. 2003), the evidence is unbalanced across ecosystems. The IPCC predicts that global temperatures will rise from 1 to 5°C during the 21st century. This increase in temperature will affect coastal biota directly and lead to changes in precipitation and an acceleration of sea level rise. It is predicted that as the tropics gain more heat, there will be a greater transport of water vapor towards higher latitudes. Thus, it is likely that, in general, lower latitudes will experience a decrease in precipitation and higher latitudes will experience an increase in rainfall (Day et al. 2005).

There is abundant literature predicting the effects of climate change on species' ranges, but climate change models are rarely incorporated into restoration and conservation plans. The spatial and temporal scales of climate models are disconnected from the scales of land parcels and actions that managers must work within. Some research results demonstrate that extreme drought can cause sudden and dramatic changes in the abundance and spatial arrangement of dominant plants, and that site characteristics will differentially affect the dominant species that characterize many vegetation types. They suggest that the key to maintaining resilient populations of dominant plants will be to conserve areas that are subject to a wide variety of environmental extremes, including sites that are under stress, while restoring habitat structure to increase rare habitat abundance and reduce water stress on dominant plant populations (Gitlin et al. 2005).

A number of case studies recently undertaken by The Wildlife Society revealed the complexity and potential effects of climate change, while also demonstrating the uncertainty. For example, one case study suggested that waterfowl would be susceptible to changes in precipitation and temperature, both of which affect shallow seasonal wetlands with which the species are associated. The effects will vary by species and even within species depending upon geographic location. The annual migration of neotropical migrant birds exposes them to climate changes in both their wintering and breeding habitats, as well as in migration corridors. The breeding range of many species is closely tied to climatic conditions, suggesting significant breeding range shifts are likely as climate continues to change. The adverse effects of climate change on wildlife and their habitats may be minimized or prevented in some cases through management actions initiated now (The Wildlife Society 2004). To do so, we must understand the nature of climatic and ecological changes that are likely to occur regionally in order to properly design wetland management and restoration plans.

Wetland habitat responses to climate change and the implications for restoration

Climate change will most likely impact wetland habitats differently on a regional and mega-watershed level; therefore it is important to recognize that specific management and restoration issues will require examination by habitat. A mega-watershed is a landscape comprised of multiple watersheds.

Floodplains

Floodplain is a broad term used to refer to one or more wetland types. Some examples of floodplain wetlands are seasonally inundated grassland (including natural wet meadows), shrublands, woodlands and forests (Ramsar Classification System for Wetland Type 1971).

Globally, riverine floodplains cover $>2 \times 10^6$ km^2; however, they are among the most biologically diverse and threatened ecosystems due to the pervasiveness of dams, levee systems, and other modifications to rivers, all of which makes them excellent candidates for restoration.

Floodplain degradation is closely linked to the rapid decline in freshwater biodiversity; the main reasons for the latter being habitat alteration, flow and flood control, species invasion and pollution. In North America, up to 90% of floodplains are already 'cultivated' and therefore functionally extinct. In the developing world, the remaining natural flood plains are disappearing at an accelerating rate, primarily as a result of changing hydrology. In the near future, the most threatened floodplains will be those in China, south-east Asia, Sahelian Africa and North America. There is an urgent need to preserve existing, intact floodplain rivers as strategic global resources and to begin to restore hydrologic dynamics, sediment transport and riparian vegetation to those rivers that retain some level of ecological integrity. Otherwise, dramatic extinctions of aquatic and riparian species and of ecosystem services are faced within the next few decades (Tockner and Stanford 2002).

Mangroves/intertidal forested wetlands

Climate change will significantly alter many of the world's coastal and wetland ecosystems (Poff and Hart 2002). Historically, mangroves have been able to respond to relatively small changes in sea level (<8–9 mm/year in the Caribbean) through landward or seaward migration (Parkinson 1989; Parkinson et al. 1994) mediated by local topography (Bacon 1994), while larger changes in sea level have led to mangrove ecosystem collapse (Ellison and Stoddart 1991; Ellison 1993). In the future, landward migration of fringing mangrove species, such as *Rhizospora mangle*, will likely be limited both by in situ differences in growth and by coastal development and associated anthropogenic barriers (Parkinson et al. 1994; Ellison and Farnsworth 1996). As with other wetland species, interspecific variation in physiological responses of different mangrove species to factors associated with climate change would be expected to lead to changes in species composition and community structure following predicted changes in sea level and atmospheric CO_2 levels (Ellison and Farnsworth 1997).

In the short term, protecting and restoring vast amounts of mangrove habitat is important to mitigate some climate change impacts such as attenuating increased incidences of floods and catastrophic tropical cyclones. In the long term, thought should be given to establishing new zones of mangrove habitat where there is no conflict with human development so that as sea level rises and mangroves die-back they are replenishing themselves at the landward extent of the intertidal zone. If this is not done, in the future, the substantial areas of mangrove forest will be gone and with it the huge engine that provides the carbon base of the tropical marine ecosystem.

Tri et al. (1998) quantified in a preliminary fashion, various economic benefits of mangrove restoration tied to sea defense systems in three coastal districts in northern Vietnam. The results from the economic model show that mangrove restoration is desirable from an economic perspective based solely on the direct benefits of use by local communities. The restoration scenarios have even higher cost-benefit ratios when the indirect benefits of the avoided maintenance cost of the sea dike system, protected from coastal storm surges by the mangroves, are included. A strong case for mangrove rehabilitation can be made as an important component of a sustainable coastal management strategy (Tri et al. 1998). The correlation between those coastal communities not protected by mangrove forests and the resulting high loss of life and property as a result of the 2005 tsunami was significant, and has led to accelerating the restoration of mangrove habitat along some Indian Ocean shorelines.

Seagrasses/marine subtidal aquatic beds

The long-term sustainability of seagrasses, particularly in the subtropics and tropics, depend on their ability to adapt to shifts in salinity regimes influenced by anthropogenic modifications of upstream hydrology, as well as predicted long-term temperature increases (Short and Neckles 1999). Tropical species are living at the edge of their upper physiological limits of salinity (Walker 1985; Walker et al. 1988) and temperature (Zieman 1975; Koch et al. 2007), so further increases in salinity as a result of climate change and freshwater extraction may have significant consequences for tropical seagrasses particularly in estuaries with restricted circulation and high rates of evaporation such as Shark Bay, Baffin Bay and Florida Bay in the USA (Koch et al. 2007). In other areas higher rainfall may increase freshwater runoff and reduce salinity levels causing reduction in seagrass cover. Seagrass restoration has been conducted at various scales for more than 30 years with limited success. Like mangroves, they may be "squeezed out" of existence in some coastal areas because the continued stress of human activities such as pollution have reduced the resiliency of these habitats.

Salt marshes/intertidal marshes

Climate change can affect salt marshes in a number of ways, including through sea-level rise, particularly when sea walls prevent marsh vegetation from moving upward and inland. However, evidence from southeast England and elsewhere indicates that sea-level rise does not necessarily lead to the loss of marsh area because some marshes may accrete vertically and maintain their elevation with respect to sea-level where the supply of sediment is sufficient. However, organogenic marshes and those in areas where sediment may be more limiting may be more susceptible to coastal squeeze, as may other marshes, if some extreme predictions of accelerated rates of sea level rise are realized (Hughes 2004).

McKee et al. (2004) suggests that increases in temperature and decreases in rainfall associated with climate change may dramatically affect tidal marshes. Increased temperature may interact with other stressors to damage coastal marshes. For example, during the spring to fall period of 2000 in the Mississippi delta, there were large areas of salt marsh that were stressed and dying (Day et al. 2005). This appears to be the result of combination of effects related to a strong La Niña event, which resulted in sustained low water levels, prolonged and extreme drought, and high air temperatures. This combination of factors apparently raised soil salinities to stressful and even toxic levels.

An important result of increasing temperature along the northern Gulf of Mexico will likely be a northward migration of mangroves replacing salt marshes. Mangroves are tropical coastal forests that are freeze-intolerant. Chen and Twilley (1998) developed a model of mangrove response to freeze frequency. They found that when freezes occurred more often than once every 8 years, mangrove forests could not survive. At a freeze frequency of 12 years, mangroves replaced salt marsh. Along the Louisiana coast, freezes historically occurred about every 4 years. By the spring of 2004, however, a killing freeze had not occurred for 15 years and small mangroves occur over a large area near the coast. If this trend continues, mangroves will probably spread over much of the northern Gulf and part of the south Atlantic coast. In fact, mangroves are already becoming established and more widespread due to warming (Day et al. 2005).

Arctic wetlands/Tundra wetlands

Climate models generally agree that the greatest warming due to the enhanced greenhouse effect may occur at northern high latitudes and in particular in the winter season. In addition, the precipitation over high latitude regions is mostly expected to increase, both in summer and in winter (Houghton et al. 2001). For water resources, all climate scenarios lead (with high confidence) to the large-scale loss of snowpack at moderate elevations by mid-century, bringing large reductions in summer flow in all streams and rivers that depend on snowmelt (Mote et al. 2003). Where reliable water supply is available during most of the thawed season that exceeds the demands of evaporation and outflow losses, the soil remains saturated and a high water table is maintained. (Woo and Young 2006). However, a continued warming trend under climatic change will eliminate these lingering snow banks. Then, many meltwater-fed wetlands will diminish or disappear. Although the combined effect of higher temperatures and precipitation is still uncertain, it seems likely that snow cover in these areas will decrease, and evapotranspiration will increase (Everett and Fitzharris 1998, Dankers and Christensen 2005). These phenomena will require significant changes to be made in the management and restoration of wetlands in this region.

For extensive wetlands, a change in the water balance in favor of enhanced evaporation (due to warmer and longer summer season than the present) will not only lead to greater water loss from the wetland patches themselves, but will also reduce the water inputs from their catchments. Therefore, many wetland patches will then be adversely affected. Enhanced thawing of permafrost due to climatic warming may lower the water table, which is unfavorable to most existing wetlands, but increased thermokarst activities can cause flooding in some areas to create new wetlands, or to switch from bogs to fens (Grossman and Taylor 1996; Woo and Young 2006).

Peatlands/non-forested peatlands/forested peatlands

Peatlands are important natural ecosystems with high value for biodiversity conservation, climate regulation and human welfare. Peatlands are those wetland ecosystems characterized by the accumulation of organic matter (peat) derived from dead and decaying plant material under conditions of permanent water saturation. They cover over 4 million km^2 worldwide (3% of the world's land area), contain 30% of all global soil carbon, occur in over 180 countries and represent at least a third of the global wetland resource (Parish et al. 2008).

Peatland dynamics are extremely sensitive to changes in the hydrological cycle, which in turn respond to variations in the climate and carbon cycle (Briggs et al. 2007). The response of peatlands to change in the climatic water budget is crucial to predicting potential feedbacks on the global carbon cycle (Belyea and Malmer 2004). Changes in peatland ecosystem functions may be mediated through land-use change and/or climatic warming. In both cases, lowering of the water level may be the key factor. Logically, lowered water levels with the consequent increase in oxygen availability in the surface soil may be assumed to result in accelerated rates of organic matter decomposition (Laiho 2006). Climate change impacts are already visible through the melting of permafrost peatlands and desertification of steppe peatlands. In the future, impacts of climate change on peatlands are predicted to significantly increase. Coastal, tropical and mountain peatlands are all expected to be particularly vulnerable (Parish et al. 2008). There are several gaps in our knowledge of the carbon cycle in peatlands under change, such as: how the amounts and quality parameters of litter inputs change in different peatland sites after short- and long-term change in the water level; and how the litters produced by the successional vegetation communities decompose under the changed environmental conditions following persistent lowering of the water level in the long term (Laiho 2006). Protecting and restoring peatlands is also critical to maintaining the biodiversity and hydrological functions they provide.

Freshwater marshes and forests/freshwater, tree-dominated wetlands

These classifications encompass a broad diversity of habitat types, with great ranges of hydroperiod and depth of inundation, including vernal pools and wet prairies with a wet season water table at or barely above the surface for a very brief duration, to cypress swamps, hardwood swamps, sawgrass and bulrush marshes inundated by nearly a meter of water for many months. Most of these habitats respond specifically to slight changes in hydrology and water quality. There is a significant wealth of literature stemming from many decades of research on the functions and management of these wetland systems, including restoration, but not climate change.

Based on the synergistic effect of multiple stressors, the management and restoration of these habitats may be more difficult in the future due to the present availability of many more efficient colonizer species such as *Phragmites*, *Melaleuca quinquenervia*, *Lygodium microphyllum*, and *Imperata cylindrical*.

Given the individualistic responses of the numerous endemic species supported by these habitats, a wide range of subtle environmental changes could reduce their sustainability and increase the risk of species extinction. These factors will need to be considered as we review new policies and guidelines for wetland management and restoration.

Case studies

The following examples are of areas where the impacts of climate change are evolving in different ways illustrating the science and management options that need to be applied. Such case studies may assist with the development of future wetland management and restoration policies and guidelines both at the habitat and regional ecosystem levels.

Sundarban

The Sundarban, one of the world's largest coastal wetlands, covers about one million hectares in the delta of the rivers Ganga, Brahmaputra, and Meghna and is shared between Bangladesh (~60%) and India (~40%). Large areas of the Sundarban mangroves have been converted into paddy fields over the past two centuries and more recently into shrimp farms. The regulation of river flows by a series of dams, barrages and embankments for diverting water upstream for various human needs and for flood control has caused large reduction in freshwater inflow and seriously affected the biodiversity. Two major factors will determine the future of the Sundarban mangroves and their biological diversity. The first is the demand on freshwater resources from growing human populations in both countries (Gopal and Chauhan 2006). Second, climate change is expected to increase the average temperature and spatio-temporal variability in precipitation, as well as cause a rise in sea level (Ellison 1994). The increase in temperature and variability in rainfall will put further pressure on freshwater resources and hence alter the freshwater inflows to the mangroves.

Some models of climate change also present an increased frequency of tropical cyclones and storm surges, which may cause further changes in freshwater-seawater interactions, thereby affecting the mangroves (Ali 1995; Ali et al. 1997). Ultimately, the future of the Sundarban mangroves hinges upon the efficiency of managing the limited freshwater resources for meeting both human and environmental needs, coupled with effective adaptive responses to the added threats from climate change (Gopal and Chauhan 2006). Changed hydrological extremes due to climate change will have important implications for the design of future hydraulic structures, floodplain development, and water resource management (Cunderlik and Simonovic 2005).

Mekong river delta

The Mekong river delta plays an important role in the Vietnamese economy and it has been severely impacted during this century by a series of unusually large floods. In the dry season the delta is also impacted by saline intrusion. These effects have caused severe human hardship. Recent modeling (Hoa et al. 2007) predicts that sea-level rise will enhance flooding in the Mekong river delta, which may worsen in the long term as a result of estuarine siltation caused by dam construction.

While comprehensive flood control measures will reduce flooding, planned high embankments may be more prone to catastrophic failures from increased flow velocities in the rivers. Also, the high embankments obstruct the fine-sediment flow into agricultural lands. Extensive estuarine siltation and increased flooding, together with increased coastal erosion and the loss of coastal wetlands, are likely to occur if dam construction decreases riverine sediment inflow to the sea (Hoa et al. 2007). This situation is similar to coastal Louisiana and the Mississippi River delta. The activities required to restore and maintain basic functions in these systems are not what we usually think of when we define the term wetland restoration; however, they need to be a fundamental part of any meaningful plan for maintaining global wetland ecosystems in the long term.

Southern Ontario

Because of its location, Canada is projected to experience greater rates of warming than many other regions of the world. According to Lemmen and Warren (2004), changes in the Canadian climate will be variable across the country, with the arctic and the southern and central prairies expected to warm the most. Canada has a relative abundance of water, but its resources are not evenly distributed across the country. As a result, most regions of Canada experience water-related problems, such as floods, droughts, and water quality deterioration (Cunderlik and Simonovic 2005).

Southern Canada is expected to experience higher temperatures (Mooney and Arthur 1990; Poiani and Johnson 1991). This would lead to drier conditions, more frequent and more severe droughts (Lenihan and Neilson 1995), reduced river and stream flows, and higher rates of wildfire (Suffling 1995). These problems are exacerbated by the fact that extensive areas of southern Ontario are where Canada's most valuable farmland exists. This part of the province has lost the vast majority of their wetlands, as much as a 70–90% loss in some regions. While climate impacts may be severe, they are likely to be intensified by current land and wetland management practices, such as the construction of drainage systems that remove water from the landscape, lowering water levels, increasing flood flows and reducing base flows. Climate change may result in even less water being available to maintain groundwater supplies, provide baseflow to streams and provide adequate soil moisture to farmers during the growing season. This is a situation common throughout the world in areas such as south Florida and sub-Saharan Africa.

Agricultural landscapes are more sensitive to climatic variability than natural landscapes because the drainage, tillage, and grazing will typically reduce water infiltration and increase rates and magnitudes of surface runoff and pollutant loading. High-resolution floodplain stratigraphy of the last two centuries show that accelerated runoff associated with agricultural land use has increased the magnitudes of floods across a wide range of recurrence frequencies (Knox 2001).

Restoring degraded wetland soils

Vast areas of hydric soils have been impacted by agricultural conversion and drainage. Restoring degraded hydric soils and ecosystems has a high potential for sequestrating soil carbon. Most degraded soils have lost a large fraction of the antecedent SOC pool, which can be restored through adopting judicious land use practices. Cultivation has been suggested to be the most important factor in soil carbon loss (Lal et al. 2004). However, the restoration of wetland hydrology (e.g., plugging drains) also is a critical component of restoration. The fact that carbon storage is enhanced under anoxic conditions is important because flooded wetlands provide optimal conditions for accretion of organic matter (Euliss et al. 2006).

To dike or not to dike

How we choose to respond to the effects of climate change has everything to do with the future wetland management and restoration programs we develop. For example, in maritime Canada there are the many stretches of dikes that provide protection to agricultural land, infrastructure, homes and communities. These dikes also inhibit salt marshes from naturally shifting with the level of the sea, and absorbing and dispersing the impacts of intense wave action. There are three adaptation strategies for society to consider: raising and reinforcing the dikes, realigning the dikes, or restoring diked lands to natural salt marsh (Marlin et al. 2007).

Salt marsh restoration can be a good adaptation strategy to sea level rise (Government of Canada and Government of Nova Scotia 2002). However, this response requires a certain adaptive capacity. Some communities have more adaptive capacity than others due to the strength of their social, economic and environmental systems, equitable resource allocation, high skill levels, and the ability to disseminate useful information. Each community is unique and each has different vulnerabilities and strengths which contribute to its adaptive capacity. A community may choose to restore a salt marsh for its ecosystem, economic and/or social values, or for other reasons (Marlin et al. 2007).

The role of modeling in wetland restoration and adaptive management

Integrated groundwater and surface water modeling of watersheds should become a very important part of the wetland restoration and management process. The modeling can be used to predict the effects of climate change on watersheds and wetland systems, and ultimately be used to design a wetland more resilient to climate change. There will need to be a shift from applying two-dimensional event-based models, which cannot accurately simulate the complex behavior of the system, to three-dimensional models such as MikeShe. Others (Carroll et al. 2005) have found that a simpler model could simulate general trends in the system. However, my experience is that a three-dimensional model is required to appropriately simulate integrated surface and groundwater characteristics using land use, topography, hydrological and ecological data for model calibration.

With increasing concerns surrounding global climate change, there has been growing interest in the potential impacts to aquifers; however, relatively little research has been undertaken to determine the sensitivity of groundwater systems to changes in critical climate change parameters. It is expected that changes in temperature and precipitation will alter groundwater recharge to aquifers, causing shifts in water table levels in unconfined aquifers as a first response to climate trends (Changnon et al. 1988; Zektser and Loaiciga 1993). This activity may have a considerable impact on wetland systems that are groundwater driven where a change of less than one foot in the surficial water table elevation can significantly impact a wetland.

Undertaking a climate change impact assessment on a groundwater system is complicated because, ultimately, atmospheric change drives hydrologic change, which, in turn, drives hydrogeologic change. The latter requires detailed information about the subsurface; information that is traditionally difficult to obtain (Scibek and Allen 2006). Additionally, as a consequence of reduced groundwater levels, streams in upland areas, can expected to have lower seasonal flows, thus having significant adverse impacts on large headwater wetland systems. The ability of a groundwater flow model to predict changes to groundwater levels, as forced by climate change, depends on the locations and types of model boundary conditions, the success of model calibration and model scale (Scibek and Allen 2006). We must collect data through monitoring, which unfortunately is rarely done at the individual wetland complex level, let alone at the watershed level. This type of evaluation would also prove invaluable to those evaluating the existing and potential impacts of mining and flood control.

The carbon sink function

The capacity of some wetlands to act as a carbon sink is an important function that may provide additional impetus for undertaking the large scale restoration of wetlands. Research in Canada by Waddington and Price (2000) and Waddington and Warner (2001) reported a reduction in the magnitude of CO_2 losses when the peatland was restored and vegetation became re-established. Komulainen et al. (1999) and Tuittila et al. (1999) observed that the carbon balance of Finnish peatlands became a new sink within a few years of restoration. While studies of the CO_2 dynamics in restored cutaway peatlands have concentrated either on boreal or continental peatlands, there is a dearth of information regarding dynamics of restored cutaway peatlands within many regions such as the temperate maritime zone. For example, in Ireland peatland formation is influenced by the proximity of the North Atlantic Ocean cool summers (Keane and Sheridan 2004). Under such optimal conditions for peat formation, restoration in temperate, maritime regions could be accelerated, with the ecosystem quickly becoming a CO_2 sink (Wilson et al. 2006).

Setting priorities

In the future how will we make priority determinations for research and restoration? Maintaining biodiversity in regional ecosystems may be an appropriate high priority goal since this issue involves so many other conditions and responses of ecosystem health. The major ecological consequences that we may expect by 2025 for wetlands systems, like floodplains, are similar to those predicted for most aquatic systems (Naiman and Turner 2000; Malmqvist and Rundle 2002). The projected changes will be manifest as what has been termed the 'distress syndrome' (sensu Rapport and Whitford 1999), indicated by reduced biodiversity, altered primary and secondary productivity, reduced nutrient cycling, increased prevalence of diseases, increased dominance of invaders and a predominance of shorter-lived opportunistic species.

By 2025, an area equivalent to the size of the entire Great Lakes basin in North America, and water courses equivalent to the combined lengths of the Rhone and Rhine rivers, were expected to be restored to full health throughout the world according to an IUCN 2000 report. These predictions are probably over-optimistic. For example, although 15,000 km of streams and rivers in Switzerland have been identified for restoration programs, the annual rate of river-floodplain restoration is only 11 km compared to the 70 km lost during the same period due to development. In 2025, the most water-stressed countries will be in Africa and Asia. When considering the present state of floodplains their future appears dismal, despite recognition of the vital functions provided by these ecosystems. Perhaps the only hope for sustaining functional floodplains over the long term lies with highly enlightened management and restoration efforts (BUWAL 1993; Tockner and Stanford 2002).

Non-governmental organizations and multinational institutions such as IUCN, UNEP, UNESCO, Worldwatch Institute, World Resource Institute, WWF, Ramsar Secretariat, The Nature Conservancy, Wetlands International, and Birdlife International, among many others, play a leading role in transferring basic research information to the public and to decision makers and in securing protection for biodiversity hot spots. Their role in conserving and restoring flood plains and wetlands must increase in the near future in relation to the fast growing scientific knowledge about the strategic importance of floodplains to healthy rivers that parallels the accelerating deterioration of remaining systems (Tockner and Stanford 2002). These institutions will need to partner with governments on multinational restoration efforts.

Will enough water be available?

Many of our watersheds and their related wetland ecosystems are currently damaged, water-starved and often marginally functional. We may have to manage for a reduced carrying capacity based upon those stresses modified by what we can restore or modify and how much water we think will be available. The competition between man and wetland ecosystems where minimum flows and levels must be maintained will become elevated and at times political much like the water management of the Kississimee-Lake Okeechobee-Everglades (KLOE) ecosystem in south Florida. At least temporarily during drought periods, many regions like the KLOE ecosystem, sub-Saharan

Africa, China and peat areas in central Europe will have a great demand for water. This is an important subject that needs to be considered in the design and implementation of sustainable restoration/conservation practices for wetlands, particularly with regard to the predictions of climate change (Schwarzel et al. 2006).

Recommendations

There is no doubt that globally there is a great need to reverse certain significant human-induced stressors to ecosystems including drainage, flood control, and unsustainable development. We can do this by undertaking wetland restoration programs and implementing sustainable ecosystem management plans now as we continue to work on the task of reducing CO_2 emissions and reversing existing climate change trends.

The following global recommendations are offered to scientists, practitioners and policymakers to provide some perspective as well as a stimulus for discussion with a goal toward developing a new direction for global wetland conservation in a changing world.

1. One of our goals should be to significantly reduce non-climate stressors on ecosystems: The reduction of stressors causes by human activities will increase the resiliency of habitats and species to the effects of climate change and variability. In essence, this situation is what good management already seeks to accomplish. However, a changing climate amplifies the need for managers to minimize effects these stressors have on wildlife populations.
2. Protect coastal wetlands and accommodate sea level change. Impacts of sea level rise can be ameliorated with acquisition of inland buffer zones to provide an opportunity for habitats and wildlife to migrate inland. Setback lines for coastal development can be effective at establishing zones for natural coastal migration based on projected sea level rise. Storm surge should be considered in establishing buffer zones and setback boundaries. In other cases, restoration of natural hydrology could facilitate sediment accretion and building of deltaic coastal wetlands.
3. Monitoring is an essential element of ecosystem management, in that it is in intended to detect long-term ecosystem change, provide insights to the potential ecological consequences of the change, and help decision makers determine how management practices should be implemented. Monitoring may be used as a starting point to define baseline conditions, understand the range of current variability in certain parameters and detect desirable and undesirable changes over time within reserve areas and adjacent ecosystems.
4. We need to quickly train restoration scientists and practitioners. There will be a great need to monitor, design and implement wetland restoration and management projects globally on a large scale. Currently we have no global plan for improving expertise in these areas.
5. Rapidly changing climates and habitats may increase opportunities for invasive species to spread because of their adaptability to disturbance. Invasive species control efforts will be essential, including extensive monitoring and targeted control to preclude larger impacts.
6. Wetland restoration and management must incorporate known climatic oscillations. Short-term periodic weather phenomena, such as El Niño, should be closely monitored and predictable. By understanding effects of periodic oscillations on habitats and wildlife, management options can be fine-tuned. For example, restoration of native plants during the wet phase of oscillations, avoiding the drought phase, could make the difference between success and failure.
7. Conduct medium- and long-range planning that incorporates climate change and variability. This planning should also apply to institutions and governments alike. If climate change and variability are not proactively taken into account, the potential for conservation plans to succeed will likely be much reduced.
8. We must develop a strategy for selecting and managing restoration areas appropriately. As wildlife and habitats have declined across North America, the establishment of refuges, parks, and reserves has been used as a conservation strategy. However, placement of conservation

areas has rarely taken into account potential climate change and variability. For example, in highly fragmented habitats, the placement of conservation areas on a north–south axis may enhance movements of habitats and wildlife by in essence providing northward migration corridors. Efforts to conserve habitats for single, or small numbers of species, should be concentrated in northern portions of their range(s), where suitable climate is more likely to be sustained.

9. We need to educate the public and private sectors to redefine the way that we now think of the protection, management and restoration of wetlands around the world. The impacts of climate change will differ regionally. Within some regions a number of wetlands will disappear from the landscape, especially those drier end systems and systems that are already under stress and their resiliency has been compromised. Many wetlands may ‘drift’ spatially within the region due to changes in precipitation and PET rates depending upon future land use, topography and hydro-patterns.
10. We must understand the nature of climatic and ecological changes that are likely to occur regionally in order to properly design wetland management and restoration plans at the mega-watershed level.

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