WETLANDS, Vol. 29, No. 2, June 2009, pp. 635–647

ADAPTATION OF FARMING PRACTICES COULD BUFFER EFFECTS OF CLIMATE CHANGE ON NORTHERN PRAIRIE WETLANDS

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Abstract: Wetlands of the Prairie Pothole Region of North America are vulnerable to climate change. Adaptation of farming practices to mitigate adverse impacts of climate change on wetland water levels is a potential watershed management option. We chose a modeling approach (WETSIM 3.2) to examine the effects of changes in climate and watershed cover on the water levels of a semi-permanent wetland in eastern South Dakota. Land-use practices simulated were unmanaged grassland, grassland managed with moderately heavy grazing, and cultivated crops. Climate scenarios were developed by adjusting the historical climate in combinations of 2°C and 4°C air temperature and ±10% precipitation. For these climate change scenarios, simulations of land use that produced water levels equal to or greater than unmanaged grassland under historical climate were judged to have mitigative potential against a drier climate. Water levels in wetlands surrounded by managed grasslands were significantly greater than those surrounded by unmanaged grassland. Management reduced both the proportion of years the wetland went dry and the frequency of dry periods, producing the most dynamic vegetation cycle for this modeled wetland. Both cultivated crops and managed grassland achieved water levels that were equal or greater than unmanaged grassland under historical climate for the 2°C rise in air temperature, and the 2°C rise plus 10% increase in precipitation scenarios. Managed grassland also produced water levels that were equal or greater than unmanaged grassland under historical climate for the 4°C rise plus 10% increase in precipitation scenario. Although these modeling results stand as hypotheses, they indicate that amelioration potential exists for a change in climate up to an increase of 2°C or 4°C with a concomitant 10% increase in precipitation. Few empirical data exist to verify the results of such land-use simulations; however, adaptation of farming practices is one possible mitigation avenue available for prairie wetlands.

Key Words: grassland management, grazing, land use, mitigation, Prairie Pothole Region, wetland modeling

INTRODUCTION

Ecosystem response to climate change is mediated by processes associated with the management of land use and land cover (Asner et al. 2004, Pyke and Marty 2005, Pyke and Andelman 2007). Hence, adapting land use may increase the resilience of ecosystems that are vulnerable to changes in climate (Pyke and Andelman 2007). Voldseth et al. (2007) demonstrated through modeling that conversion of high water use crops and unmanaged grassland to managed grassland produced higher wetland water levels. Van der Kamp et al. (1999, 2003) published a compelling account of reversion from wheat cultivation to unmanaged

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grassland that caused wetlands near Saskatoon, Saskatchewan to dry up, due mostly to increased infiltration of snowmelt, which was then subjected to greater evapotranspiration by the grass cover. In a modeling study of vernal pools in the Central California Valley, Pyke and Marty (2005) found that even with increased periods of inundation due to expected climate change, removal of grazing reduced the maximum annual duration of ponding, which resulted in hydrological conditions that were less supportive of aquatic invertebrates and amphibians.

During the past 200 years there has been a build-up of CO_2 and other greenhouse gases in the atmosphere due to human industry, deforestation, and farming (Ojima et al. 2002, IPCC 2007a). A broad range of climate models are used to make climate projections, not predictions, based on atmospheric emissions scenarios (Ojima et al. 2002, IPCC 2007a, Parry et al. 2007). The Intergovernmental Panel on Climate Change or IPCC (2007a) projected, for a range of atmospheric emission scenarios, that by the year 2100 the globally averaged surface temperature of the Earth will have risen 1.8–4.0°C. General Circulation Model (GCM) projections for the U.S. Great Plains indicate that during the 21st century, the mean annual temperature will increase dramatically, with decreasing precipitation in the west and increasing precipitation in the east (Ojima et al. 1999, National Assessment Synthesis Team 2001, Ojima et al. 2002). The Northern and Central Great Plains warmed by nearly 1.1°C during the 20th century (National Assessment Synthesis Team 2001, Ojima et al. 2002). An analysis of the 20th century climate for the Prairie Pothole Region (PPR, Figure 1) of North America, an 850 000 km^2 matrix of grassland and agriculture, showed that the minimum daily average temperature has warmed by an average of 1°C (Millett et al. 2009). Through regression analysis, Millett et al. (2009) also showed that the east-west precipitation gradient of the PPR steepened during the 20th century, becoming wetter in the east and drier in the west, with an average increase in annual precipitation of 49 mm or 9%. One potential consequence of climate change could be an intensified hydrologic cycle with increased frequency of both droughts and deluges (Ojima et al. 2002, Johnson et al. 2004).

There has been an increased interest in studying the effects of climate change on U.S. agricultural land use and crop production (e.g., Adams et al. 1990, Easterling et al. 1992a, 1992b, Rosenberg 1993, 2005, Rosenzweig et al. 2000, Reilly et al. 2003). These studies utilized GCMs coupled with hydrologic, economic, and crop production models, such as USDA's Erosion Productivity Impact Calculator (EPIC) model (Williams 1995), to demonstrate a range of possible impacts on agriculture due to climate change. These studies reported that the potential economic viability of specific crops in specific regions, given an increase in global mean temperature (GMT), was highly dependent on available moisture and the adaptive capacity of the region. For a GMT increase of 2.5°C with a CO_2 concentration at 365 parts per million, Thomson et al. (2005) demonstrated through modeling that the margins of current dryland corn, soybean, and wheat production regions in the U.S. are more likely to either gain or lose potential for crop production than the central areas of these regions, the gain or loss being highly dependent on the precipitation variability produced by the GCMs. Responses to a warmer climate in the Northern Plains of the U.S. would include increased crop irrigation demand, expansion of fall-seeded small grain crops, and adoption of new crop varieties adapted to longer growing seasons or drier conditions (Adams et al. 1990, Easterling et al. 1992a, Easterling 1996). Agronomic and economic strategies for the adaptation of North American agriculture to climate change are numerous; large adaptive capacity available at minimal costs provides little motivation to divert resources to combat climate change (Easterling 1996).

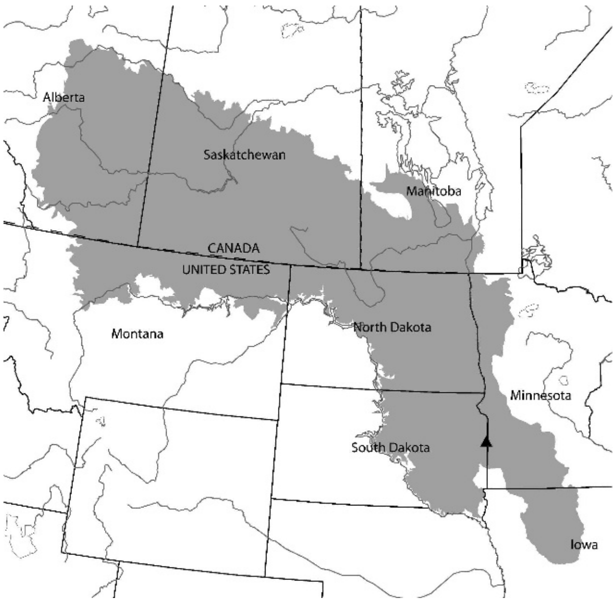

Figure 1. Extent of Prairie Pothole Region in North America. Adapted by combining ecoregion boundaries from sources: Schut (2005) and the U. S. EPA (2006). Triangle indicates the Orchid Meadows research site near Clear Lake, SD, USA.

Watershed hydrology and wetland ecological dynamics are affected by both climate change and land use (e.g., Johnson et al. 2005, Voldseth et al. 2007). Farming practices that cause changes in watershed soil and vegetation conditions can affect how precipitation is routed to wetland basins, thus modifying the wetland water budget (Voldseth et al. 2007). These hydrological factors are affected by land use that alters vegetation cover, surface roughness, and soil macropores in the upland. Climate and watershed hydrologic factors that affect the seasonal and interannual water-level fluctuations of wetlands can change the relative abundance of plant species in wetlands, whereas the longer wet-dry cycles and larger water-level fluctuations found in semi-permanent wetlands can lead to successional changes (van der Valk 2005). Changes in climate or land use that reduce upland habitat (e.g., dense grass for nesting cover) or lower wetland water levels and slow wetland ecological dynamics have negative implications for many ecosystem services including waterbird and other populations, especially those that are less mobile such as aquatic invertebrates and amphibians.

Wetlands of the PPR are particularly sensitive to changes in temperature and precipitation that affect runoff and atmospheric energy fluxes, and as such they are vulnerable to climate change (Poiani and Johnson 1993a, Covich et al. 1997, Winter 2000, Johnson et al. 2005). Climate change may impact the ability of wetland complexes to continue to provide historic ecosystem goods and services (Poiani and Johnson 1991, 1993a, Ojima et al. 1999, Johnson et al. 2005). An effectively drier climate would produce lower water levels and shorter hydroperiods, which in turn would affect goods and services valued by society, including: wetland distribution, structure, function, productivity, biodiversity, water quality, ground-water recharge, recreation, and habitat quality (Clair and Ehrman 1998, Mortsch 1998, Johnson et al. 2005).

Adaptation of watershed farming practices to mitigate negative impacts of climate change on wetland water levels is a potential response strategy available to land managers in the PPR. To explore this we asked two questions: Can adaptation of agricultural land use practices ameliorate effects of climate change on prairie wetlands, and how much climate change can be offset or absorbed through land-use management? To answer these questions, we chose a modeling approach using the single-basin wetland hydrologic and vegetation dynamics model WETSIM 3.2 (Poiani et al. 1995, Voldseth et al. 2007). Earlier applications of WETSIM (versions 1.0 and 2.0) explored the potential impacts of climate change on northern prairie wetlands (Poiani and Johnson 1991, 1993a, Poiani et al. 1995, 1996). In simulations with varied climate scenarios, Johnson et al. (2005) used the WETSIM 3.1 model to explore spatial and temporal dimensions of climate change in the PPR.

METHODS

Field Site

Field data to develop and test the watershed processes component of WETSIM 3.2 were collected at our Orchid Meadows research site in eastern South Dakota (Figure 1). This site is a 65-ha tract of tallgrass prairie that is managed by the U.S. Fish and Wildlife Service as the Severson Waterfowl Production Area. It is located about 16 km east of Clear Lake, South Dakota on the Prairie Coteau (Johnson et al. 2004). The Orchid Meadows database has 18 years of water level data from 10 wetlands and associated wells measured every two weeks during the ice-free season. Wetlands of temporary, seasonal, and semipermanent classes (Stewart and Kantrud 1971) occur throughout the landscape in depressional lows. The Orchid Meadows site is characterized by rolling hills of 4 to 16 slope, although some areas exceed 25 slope. Soils are typically mollisols with calcareous or clay subsoils underlain by glacial till. Uplands are dominated by native grassland with a component of non-native smooth brome *Bromus inermis* L. and bluegrass*Poa pratensis* L., and the site is grazed approximately once every five years. Mean annual precipitation was 663 mm and mean annual temperature was 7.4°C, based on a 41-year (1961–2001) composite data set compiled from the site and the nearest National Oceanic and Atmospheric Administration weather stations at Clear Lake, SD and Canby, MN. Further details on the ecological setting of the Orchid Meadows site can be found in Johnson et al. (2004).

Model Description

WETSIM 3.2 (Voldseth et al. 2007) is a single-basin hydrologic and wetland vegetation dynamics model based on earlier model versions 1.0 and 2.0 (Poiani and Johnson 1993a, 1993b, Poiani et al. 1996). WETSIM 3.2 is parameterized and calibrated to semi-permanent wetland SP4 at the Orchid Meadows site (Voldseth et al. 2007). This deterministic model simulates watershed surface processes, watershed ground water, wetland surface processes, and wetland vegetation dynamics (Figure 2). WET-

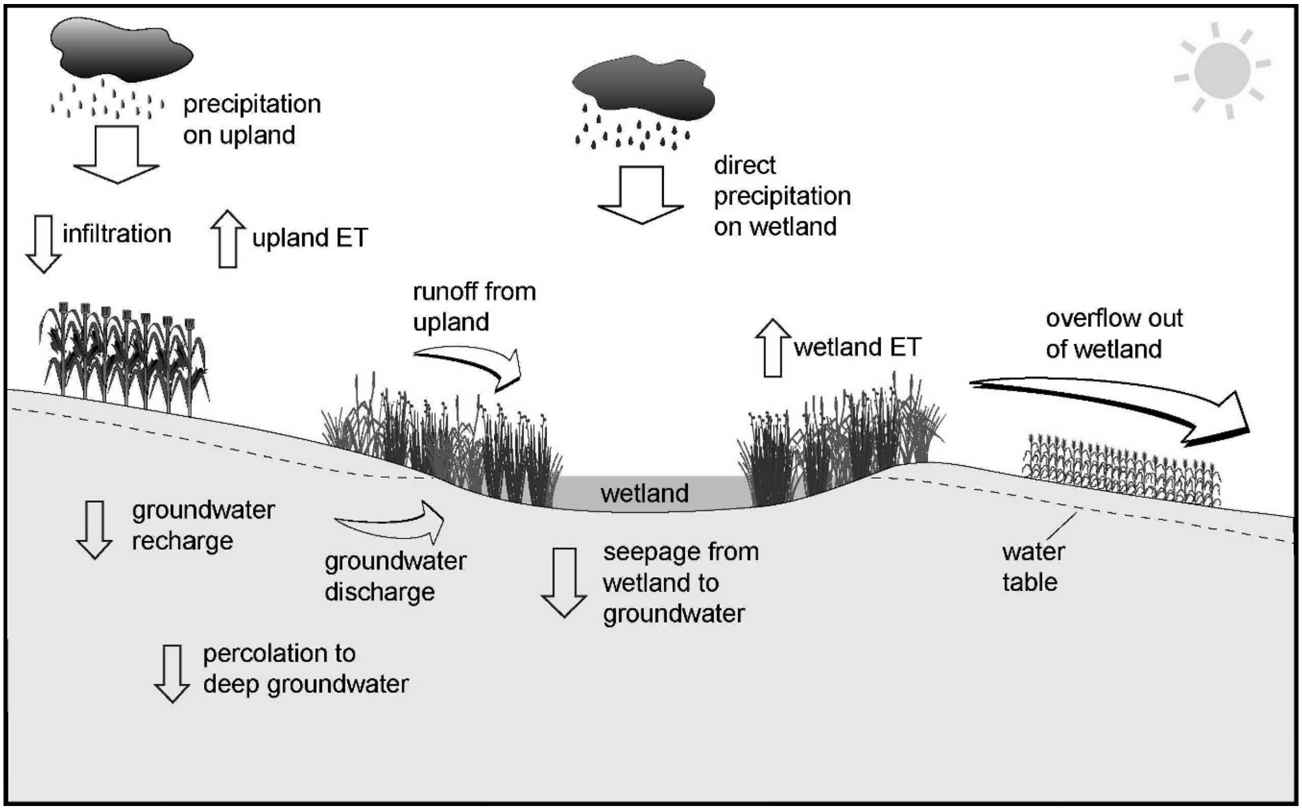

Figure 2. WETSIM 3.2 hydrologic model conceptualization illustrating wetland water budget inputs and outputs. ET = evapotranspiration.

SIM 3.2 calculates several wetland parameters, including water contributions from the upland, water mass balance, and stage (water depth) on a daily basis each year of the simulation. Vegetation cover is determined on a daily basis from May through September for the simulation period using a grid-cell structure, depth and duration of standing water, including lack of water (i.e., drought). Seepage from the wetland to deep ground water is accounted for in a calibrated ground-water flux equation (Carroll et al. 2005). The water table was not tracked below the wetland bottom. The wetland cover types were: open water, bare soil, seedlings, mixed plants, wet meadow/shallow marsh, and deep marsh. Input data required by WETSIM 3.2 were daily precipitation and temperature, total annual precipitation, and elevations representing the topography of the wetland catchment and basin. Observed wetland water levels were used for calibration. The model was programmed in MATHEMATICA (Wolfram 1999).

Effects of different land-use cover types on the three main components of the water budget, namely, runoff, infiltration, and upland evapotranspiration (ET), were simulated using WETSIM 3.2. Runoff was calculated from snowmelt and rainfall based on the Soil Conservation Service (SCS) runoff curve number method (USDA-SCS 1972). Infiltration was the amount of precipitation remaining after subtracting runoff. Evapotranspiration in the upland was calculated with Hargreaves' potential ET (Hargreaves 1994) adapted from the EPIC model (Williams 1995) and was dependent on leaf area index (LAI) and soil moisture. A simple temperature- and precipitation-adjusted LAI growth curve function for determining crop transpiration was developed as a function of the 10-day average temperature, annual precipitation for that year, and a maximum LAI (Voldseth 2004). The maximum LAI value was calculated using the equation: LAI = 0.00698 mean annual precipitation in mm – 2.339 (B. Lauenroth, Colorado State University, personal communication). This equation was developed from grassland sites across the central Great Plains based on data from Lane et al. (2000). Maximum LAI for both grasslands and crops was set not to exceed 4 m^2/m^2 (B. Lauenroth, Colorado State University, personal communication). The range of maximum LAI values used was further supported by Scurlock et al. (2001).

WETSIM 3.2 Model Simulations and Statistical Analysis

Semipermanent wetland SP4 (2.2 ha) and its surrounding upland catchment were used in all subsequent model simulations. Five land-use cover types lumped into three categories were evaluated: 1) moderately-heavy grazed native grass (Managed Grassland); 2) native grass and 3) smooth brome grass that lacked mowing, haying, burning, grazing or tillage (Unmanaged Grassland); 4) row crops, e.g., corn, and 5) small grains, e.g., spring wheat (Cultivated Crops). Smooth brome was included as a land-use option to compare to native grass, due to its wide-spread planting as hay, pasture, and conservation cover in the past. Climate scenarios were constructed by adjusting the historical climate by combinations of +2°C and 4°C air temperature and ±10% precipitation. One 41-year simulation (1961–2001) was run on a daily time-step for each of the five land-use cover types under the historical climate and six climate scenarios for a total of 35 treatments. Each treatment simulation produced output of daily wetland water levels in meters for 41 years. Daily water levels within each treatment were pooled to calculate 41 observations of mean annual water level for each of the 35 treatments separately. No other data were pooled. Because WETSIM 3.2 is a deterministic model and stochastic effects are not modeled, the model will produce exactly the same output when the same treatment is used as input. The simulation for the native grass (unmanaged grassland) land-use cover type with the historic (1961–2001) climate was used as the reference treatment. To have mitigation potential against a drier future climate, a particular land use change would have to produce water levels under the altered climate that were equal to or greater than water levels for the reference treatment. We assumed that the selected land-use practices would remain viable in this region under the climate scenarios simulated in this study.

The climate by land use by year treatment combination was considered as the experimental unit with 41 mean annual water-level values calculated for each treatment. Treatments were arranged in a factorial design (2 factors – land use and climate) and statistical analyses were conducted as a randomized complete block design with years as blocks. The PROC MIXED procedure in SAS (SAS Institute Inc. 1999) was used with years considered as random effects. The mixed effects model is specified as $Y_{ijk} = \mu_Y + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \rho_k + \epsilon_{ijk}$ where Y_{ijk} is mean annual water level from the j-th climate scenario under the i-th land use, μ_Y is the overall mean of Y_{ijk}, α_i is the fixed effect due to the i-th land use, β_j is the fixed effect due to the j-th climate scenario, $(\alpha\beta)_{ij}$ is the interaction fixed effect due to the j-th climate scenario under the i-th land use, ρ_k is the block or random effect due to the k-th year, and ϵ_{ijk} is the random error due to the k-th year measure from the j-th climate scenario under the i-th land use. Following detection of significant ($P < 0.05$) main effects and treatment interactions a Least Squares Means comparison was conducted on treatments ($P > 0.05$) to test for rejection of the null hypothesis that no differences exist between mean annual water levels for treatments. Comparisons in this statistical analysis are for interactions, thus estimates of standard error can be equal for each treatment. The frequency of dry periods, wetland vegetation cycle conditions, and upland hydrological contributions to the wetland were calculated for each simulation; however, these metrics were not evaluated statistically due to a lack of *a priori* consideration

RESULTS

All six climate scenarios were effectively drier than the historical climate and produced significantly lower wetland water levels compared to the historical climate. For example, unmanaged grassland (native grass and brome grass) produced significantly lower water levels under the climate scenarios than under historical climate (Table 1). For the historical climate and the climate scenarios examined, mean annual wetland stage for both unmanaged smooth brome grassland and unmanaged native grassland were significantly different from all other land-use types, but were not significantly different from each other. Grazed grass, row crop, and small grain with both the +2°C (Celsius) and +2°C+10%P (precipitation), and grazed grass with the +4°C+10%P scenario produced wetland water levels that were significantly greater or equal to the unmanaged native grass land use under the historical climate. These simulations demonstrate the potential for amelioration through changes in land use, by meeting or exceeding water levels produced by the reference historical climate for native grass (e.g., Tables 2 and 3). Hence, these are discussed in more detail below.

Under the historical climate, managed grassland (grazed grass) produced a significantly higher mean wetland water level (Table 1) and a lower frequency of dry periods (Table 2) than both cultivated crops (row crop and small grain) and unmanaged grassland (native grass and smooth brome). Grazed grass experienced a smaller proportion of years that the

Table 1. a) Main effects and interactions of climate scenario and land-use on wetland water level. b) Mean wetland water level for land-use cover by climate scenario treatments. Least-square means with same lower case letters are not significantly different ($P > 0.05$). Reference condition is native grass land-use under historical climate and is underlined. Bolded entries indicate treatment means that are equal to (not significantly different) or exceed the reference condition.

(a)

Effect	Numerator df	Denominator df	F	P
Climate	7	1560	1041.36	< 0.0001
Land-use	4	1560	436.74	< 0.0001
Climate*Land-use	28	1560	3.22	< 0.0001

(b)

	Climate						
Land-Use	Historical	+2°C	+4°C	+2°C+10%P	+2°C−10%P	+4°C+10%P	+4°C−10%P
Native Grass	0.67 gh	0.54 no	0.43 uv	0.62 ij	0.46 st	0.49 qr	0.37 w
Brome Grass	**0.66 h**	0.53 op	0.41 v	0.61 jk	0.45 stu	0.48 rs	0.36 w
Grazed Grass	**0.85 a**	**0.73 f**	0.58 lm	**0.83 b**	0.62 ijk	**0.69 g**	0.49 r
Row Crop	**0.80 bc**	**0.66 gh**	0.52 opq	**0.76 de**	0.56 mn	0.62 ijk	0.44 tu
Small Grain	**0.77 cd**	**0.64 hi**	0.51 pqr	**0.74 ef**	0.54 no	0.59 kl	0.43 uv

Notes: for Table 1. b values are in meters. C = degrees Celsius. P = Precipitation. (SE = 0.028, estimates of SE are equal for treatments because comparisons are for interactions).

Table 2. Frequency of dry periods experienced by the modeled wetland. Only those climate scenarios that demonstrated potential for amelioration through changes in land use (i.e., meet or exceed water levels for the reference historical climate for native grass) are shown.

	Climate			
Land Use	Historical	+2°C	+2°C+10%P	+4°C+10%P
Native Grass	60	117	90	164
Brome Grass	61	120	91	168
Grazed Grass	18	49	39	73
Row Crop	31	71	48	97
Small Grain	38	75	58	110

Notes: Frequency of dry periods is the number of times the wetland went dry in the 41-year simulation. The wetland can go dry, then rewet and go dry again in the same year. Thus, the frequency of dry periods can exceed 41. C = degrees Celsius, P = Precipitation.

Table 3. Upland hydrological factors by land use for historical climate and climate change scenarios. Climate scenarios shown are those that have potential for amelioration through changes in land use that affect runoff (RO), infiltration (I), and evapotranspiration (ET). Only those climate scenarios that demonstrated potential for amelioration through changes in land use (i.e., meet or exceed water levels for the reference historical climate for native grass) are shown.

	Climate											
	Historical			+2°C			+2°C+10%P			+4°C+10%P		
Land Use	RO	I	ET	RO	I	ET	RO	I	ET	RO	I	ET
Native Grass	79	580	457	58	602	518	69	658	573	50	677	642
Brome Grass	80	580	604	58	602	686	69	657	758	50	677	852
Grazed Grass	124	536	313	100	560	353	121	605	397	101	626	444
Row Crop	115	545	588	91	570	668	110	616	738	89	638	829
Small Grain	107	553	493	84	576	560	101	626	618	81	646	694

Notes: Metrics are mean annual values in mm based on a 41-year simulation. C = degrees Celsius, P = Precipitation.

wetland went dry during the simulation (Figure 3) and a smaller proportion of days in the closed-marsh phase (> 75% of wetland area in emergent cover) compared to unmanaged native or brome grass (Figure 4). Under historical climate, grazing increased runoff, decreased available water for infiltration, and lowered ET when compared to unmanaged native grass (Table 3).

Converting from unmanaged grassland to managed grassland (grazed) or cultivated crops reduced the proportion of years that the wetland went dry by nearly 50% under historical climate and by nearly 40% for the three climate scenarios (Figure 3). Similarly, the frequencies of dry periods experienced by the modeled wetland under these same climate scenarios were reduced by nearly 60% when land use was switched from unmanaged grassland to managed grassland or by nearly 40% when switched to cultivated crops (Table 2).

Changing land use from unmanaged grassland to managed grassland showed the most potential to decrease the proportion of days that the wetland experienced the closed-marsh vegetation phase and increased the amount of time in hemi-marsh conditions (25–75% of wetland area in emergent vegetation cover) under these climate scenarios (Figure 4). The full open-water phase (> 75% open water area) did not occur in this wetland under the historical climate or under these three climate scenarios because depth was limited by the outlet level, meaning that water could not get deep enough to cause widespread drowning of emergent vegetation, thereby creating the open-water phase.

Examination of upland hydrological factors showed that both land-use cover and climate change affected runoff and ET (Table 3). For example, a +2°C increase in air temperature increased ET by 13% for unmanaged native grass land use, which decreased soil moisture and resulted in a 27% decrease in runoff. Switching from unmanaged native grass under the +2°C scenario to managed grazed grass increased runoff by 72% and decreased ET by 32%.

DISCUSSION

Hydrology drives the ecological dynamics of prairie wetlands. Precipitation that falls on the landscape can be intercepted by plant material, occur as runoff that flows into the wetland basin, infiltrate into the soil, evapotranspire, drain to shallow ground water and then seep into the wetland, or percolate to deep ground water. Direct precipitation on the wetland, runoff from snowmelt and rainfall that flows over frozen ground in the early spring are the major sources of water for northern prairie wetland basins (Shjeflo 1968, Eisenlohr 1972, Hubbard et al. 1988, Woo and Rowsell 1993, Hayashi et al. 1998b, Winter 2003). These processes contribute similar proportions to the seasonal water budget (Shjeflo 1968, Eisenlohr 1972, Voldseth et al. 2007). While spring runoff provides the initial rise in wetland water levels, direct precipitation and ground-water inflows (if present) help to maintain wetland hydroperiod, ground water being an important component for the persistence of semi-permanent wetlands (Eisenlohr 1972). Runoff in summer is typically low to non-existent in grassland due to infiltration through soil macropore networks and moisture deficient soils; however, storm intensity, slope steepness, extended drought or deluge, and farming practices can influence runoff capability (Hayashi et al. 1998a, van der Kamp et al. 2003, Winter 2003, Voldseth et al. 2007).

Farming practices that affect runoff can alter the hydrologic and vegetation dynamics of wetlands. van der Kamp et al. (1999, 2003) studied a wetland landscape where 1/3 of wheat fields were converted to grassland. All of the wetlands within the grass reversion area failed to produce surface water after a few years, while all of the wetlands surrounded by cultivation maintained their prior hydroperiods. The development of soil macropores in the grassland soils (van der Kamp et al. 1999, 2003) reduced runoff through increased infiltration of snowpack meltwater.

In a modeling study of land use and wetland water levels in eastern South Dakota, Voldseth et al. (2007) found that certain crops in watersheds can affect wetland drought. They demonstrated that by shifting from unmanaged native grass to grazed grass or row crops under the historical climate, runoff increased and wetland water levels raised significantly. Changes in the amount of water reaching the wetland affected spring rise, summer draw-down, frequency and length of dry periods, and reproduction, establishment, and mortality of wetland vegetation. The degree to which this would occur is dependent on the wetland type and climatic region. The number of years the modeled wetland went dry during the growing season was approximately 1 of 2 for unmanaged native grass, 1 of 3 for small grain, 1 of 4 for row crop, and 1 of 5 for grazed grass. Voldseth et al. (2007) also suggested that management of land-use cover types in grassland-wetland landscapes can have tradeoffs in terms of benefits to waterfowl. Landscapes with low abundance of grass provide little nesting habitat and lower reproductive success of waterfowl, whereas

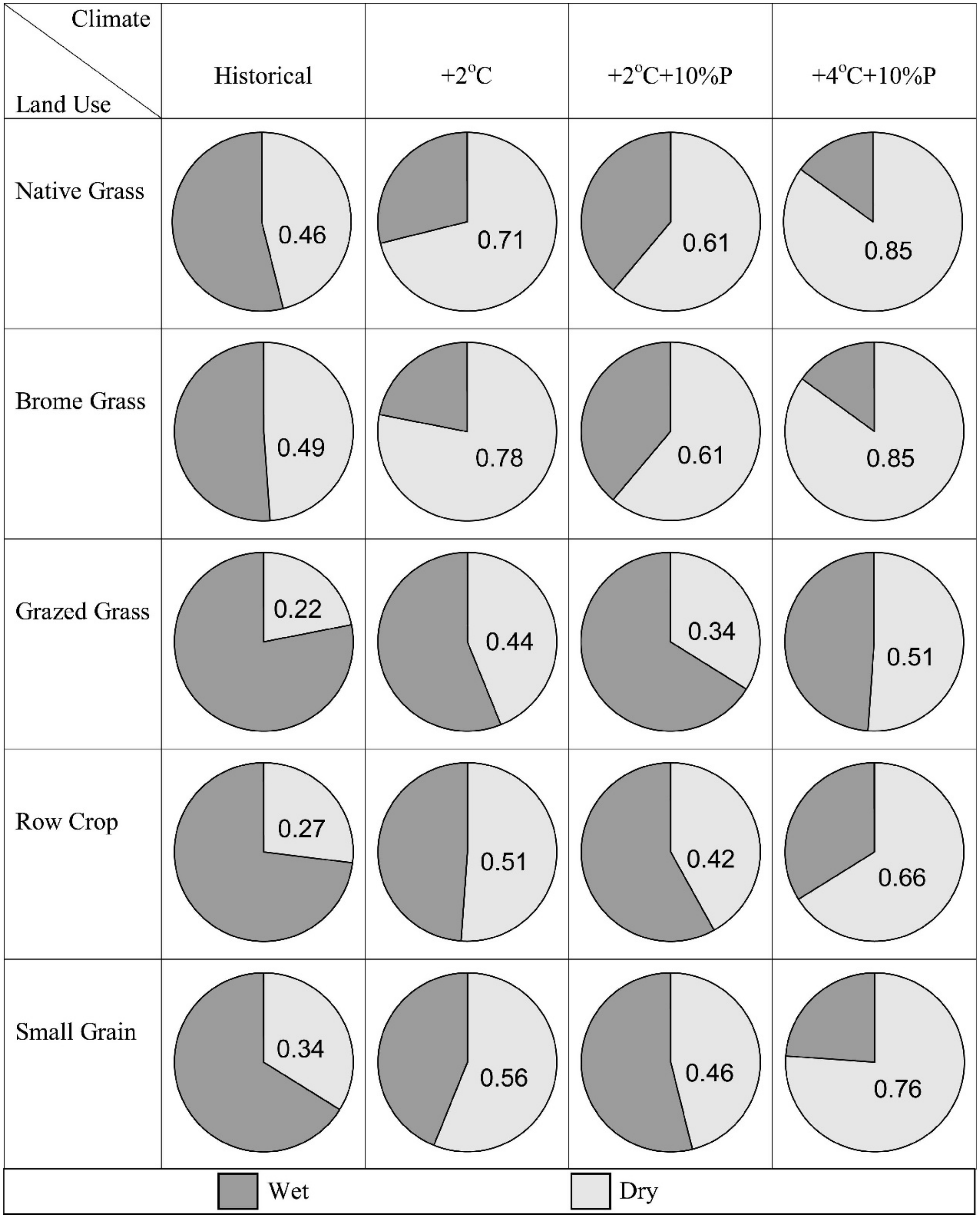

Figure 3. Proportion of years simulated that the wetland went dry (light gray) during the growing season. Values are mean annual values based on a 41-year simulation. C = degrees Celsius, P = Precipitation. Only those climate scenarios that demonstrated potential for amelioration through changes in land use (i.e., meet or exceed water levels for the reference historical climate for native grass) are shown.

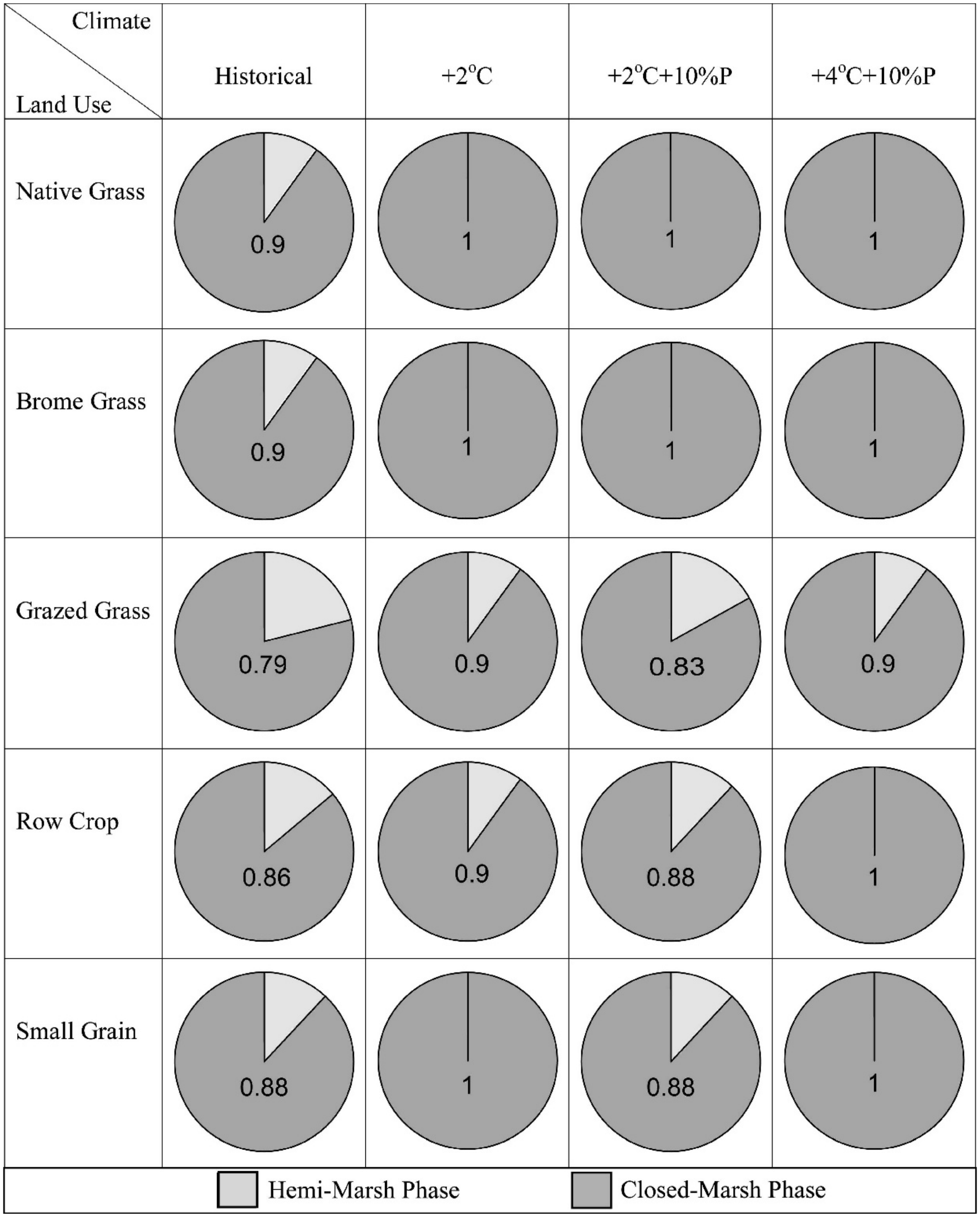

Figure 4. Proportion of days simulated that wetland was in either the Hemi-marsh phase (light gray) or Closed-marsh phase (dark gray) of the vegetation cycle. The Open-marsh phase did not occur in this wetland under the modeled climates as water depth was limited by the outlet level. Values are mean annual values based on a 41-year simulation. C = degrees Celsius and P = precipitation. Only those climate scenarios that demonstrated potential for amelioration through changes in land use (i.e., meet or exceed water levels for the reference historical climate for native grass) are shown.

those with high abundance of grass may experience reduced wetland water levels, depending on geographic location, management and associated climate. Wetlands with reduced water levels and slower vegetation dynamics may experience a greater frequency of dry periods or could become ''stuck'' in a closed-marsh phase for long periods, thus becoming less favorable as waterfowl habitat (Swanson and Duebbert 1989). Reduced wetland water levels and dynamics can lead to autogenic processes that decrease habitat heterogeneity through establishment of monotypic stands of emergent vegetation, causing changes in water temperature, decomposers, submergent vegetation, and invertebrate productivity that tend to be undesirable to waterfowl (Kantrud 1990). Given that planting dense stands of grass to increase nesting cover in the wetland watershed can dry up wetlands, it is important for land managers to ensure that sufficient wetlands of all permanence types remain in the landscape after reversion to satisfy habitat needs of wetland-dependent organisms.

Our simulations with WETSIM 3.2 showed that both land use and changes in climate can alter wetland water levels. Farming practices and climate scenarios that reduced runoff to the wetland caused reduced water levels, dampened water-level fluctuations, and increased the incidence of wetland drought — the same processes that drive wetland ecological functions. Correspondingly, wetland cover cycles were affected and resulted in an increase in the closed-marsh phase, indicating ecologically significant changes in wetland conditions. Because land use in the upland affects the amount and routing of precipitation that reaches the wetland, it follows that the type of farming practices employed can be used to further shift wetland water levels toward drier or wetter conditions in response to climate change. However, land managers would need to consider the impacts that a particular land use (e.g., cultivation vs. unmanaged grassland) can have on soil compaction, surface litter loss, yield of sediment to the wetland, and alterations to water chemistry and geochemical cycling. In addition, long-term influences of land-use practices on soil moisture should be considered.

Adaptation to changes in socio-economic conditions and weather has been an integral part of North American agriculture (Field et al. 2007, Rosenzweig and Tubiello 2007). Adaptation, in the context of this paper, is a choice or deliberate management strategy to enhance the resilience of vulnerable ecosystems and to minimize the adverse impacts of climate change (IUCN 2001). Can adaptation of land use practices mitigate climate change impacts on wetlands? Land use can have significant effects on wetland water levels in the PPR (Voldseth et al. 2007). Our modeling suggests that adaptation of farming practices by converting to certain land-use cover types can lessen the impacts of changes in climate on wetland water levels and vegetation dynamics. Converting unmanaged grassland to managed grassland could mitigate for a drier climate by increasing water received in the wetland through overland flow. Converting unmanaged grassland to row crops also increased overland flow to the wetland; however, the loss of grassland habitat and the potential for increased sedimentation and pollution in the wetland are likely to offset many of the benefits of increased water levels. Of the land uses examined in this study, managed grassland demonstrated the greatest capacity to mitigate against negative effects of a drier climate. However, much depends on how a drier climate is manifested or expressed. Seasonal changes in precipitation could result in different responses than changes applied uniformly over the entire year. The climate scenarios tested in this study were applied uniformly across seasons.

Both land use and climate change can influence wetland water levels and function, wetland dependent organisms and upland wildlife. Degradation or loss of upland and wetland habitat can strongly affect waterfowl populations (Inkley et al. 2004). Row crops are largely incompatible with upland waterfowl nesting, while conversion of annual cropland to grassland or spring-seeded row crops to fall-seeded small grain crops provide more attractive and secure nesting habitat for waterfowl (Duebbert and Kantrud 1987, Inkley et al. 2004). Improvement of wetland water levels and function, in the face of climate change that results in drier wetlands, is not incompatible with production of upland nesting habitat for waterfowl or agricultural production of small grains, grazing pasture, or even hay. In a drier climate, conversion of spring-seeded row crops to fall-seeded small grains or to grassland that is appropriately managed can improve wetland water levels and function while ensuring favorable upland nesting habitat. In the event that environmental limitations brought by climate change do not necessitate such changes in land-use practices, adaptations of agricultural land-use practices may require incentives to achieve conservation goals, as is often the case today.

The ability to adapt farming practices to mitigate for negative effects of climate change on wetlands is dependent on the types of cropping and conservation alternatives available to farmers across the PPR. Except for managed grassland, the western portion of the PPR may already be somewhat limited in its adaptive capacity to ameliorate effects of a drier climate on wetlands, due to few alternative cropping options for this area. For example, due to the temperature and precipitation gradient across the PPR, conditions for growing row crops tend to be more favorable in the southeastern portion of the PPR and are rather limited along the western boundary, and an even drier climate may limit this capacity further. The potential for adaptation may also be limited by the existing land-use cover type. For example, if wetlands existed in a row crop matrix and the climate became drier causing wetland water levels to drop significantly, it may not be possible to employ a different land-use cover type in that location that could supply enough runoff to restore original water levels. However, if these same wetlands had existed in an unmanaged grassland matrix prior to a drier climate change, it might be possible to lessen the severity of reduced water levels by grazing the grassland at an appropriate intensity.

The adaptive capacity in the agricultural sector of the U.S. Northern Plains is quite large (Easterling 1996). Both the development of more pest- and drought-resistant crop varieties or varieties adapted to longer growing seasons may increase the adaptive capacity of this region in the future. In addition, employing irrigation to offset a drier climate is an adaptation that will likely occur (Adams et al. 1990, Easterling 1996). In general, if future climate becomes warmer and drier in the PPR then conversion to grassland or expansion of fall-seeded small grains could occur, while if trends toward a warmer wetter climate occur then the potential for row crop expansion could increase (Inkley 2004, Thomson et al. 2005). For moderate warming scenarios, adaptations that include new cultivars and adjusted planting times can allow low- and mid- to high-latitude cereal yields to be maintained (IPCC 2007b). Given a modest warming of the climate, it would seem reasonable to expect that row crop and small grain production will continue to be land-use options for producers in the PPR.

How much climate change could managed grasslands mitigate? In this study, mean wetland water levels in wetlands surrounded by managed grassland (grazed) equaled or exceeded those in unmanaged native grass under historical climate for the +2°C, +2°C+10%P, and the +4°C+10%P scenarios. This suggests that with managed grassland, amelioration potential exists for climate change on the order of a 2°C rise in air temperature alone, and up to a 4°C rise in air temperature with a concomitant increase in precipitation on the order of 10%. In the event of a drier climate, wetland water levels could be augmented by converting row crops or unmanaged grassland to managed grassland, thus providing additional spring runoff to the wetland. The challenge would be to optimize farming practices with conservation efforts; that is, to maximize the return of a more favorable wetland water level regime without significantly increasing sedimentation or introducing biocides and fertilizers, while also maintaining some level of suitable upland habitat.

Historically, wetland acreage has significantly decreased across the PPR (Dahl 2000), and now wetland complexes in this region continue to be subject to potentially adverse land-use changes brought by economic pressures (e.g., reductions in federal funding for grassland and wetland conservation programs and increased corn acreage to produce ethanol fuel) that can continue to promote drainage and conversion of grassland to grain production. To understand the implications for current and future ecosystem goods and services and to utilize or maintain adaptive capabilities, land management requires the careful consideration of these land-use issues and their potential interactions with changes in climate. Adaptation of farming practices to offset reduced water levels due to climate change is one possible mitigation avenue available for northern prairie wetlands; however, consideration of possible deleterious impacts such as increased sedimentation or inputs of fertilizers and biocides is necessary.

CONCLUSIONS

Model simulations and some empirical data suggest that farming practices and changes in climate both affect wetland water levels through changes in water routing to the wetland, particularly runoff. Model simulations with WETSIM 3.2 indicated that under a drier climate, conversion of unmanaged grasslands to managed (grazed) grassland has potential to produce more favorable wetland conditions. Mitigation of climate change impacts on northern prairie wetlands through adaptation of farming practices is a concept that scientists and land managers should consider and explore further. In addition, studies are needed that explore the economics, including potential policy incentives, for land-use options that maintain wetland function under climate change. The results of this modeling study stand as hypotheses. Few empirical data exist for validation of land-use simulations and their role in the potential amelioration of climate change impacts on wetlands.

ACKNOWLEDGMENTS

This project was funded by the USGS – Biological Resources Division's Global Change Research Program. Additional funding was provided through the US-EPA STAR Grant Program. We would like to thank South Dakota State University and the USDA – Forest Service for providing additional support. We also thank the USFWS for access to the Orchid Meadows field site. Our appreciation is extended to Karen Poiani, Tom Winter, Jim Lynch, Brett Werner, Tor Johnson, and Susan Boettcher for their assistance. We also thank the anonymous reviewers and subject-matter editor for their insight and direction.

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Manuscript received 28 December 2007; accepted 21 October 2008.