Effects of Riparian Buffers on Hydrology of Northern Seasonal Ponds

advances in forest hydrology

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Abstract. *Although seasonal ponds are common in northern, glaciated, forested landscapes, forest management guidelines are generally lacking for these systems. The objective of this study was to determine the effect of riparian buffer type on seasonal pond hydrology following harvest of the adjacent upland forest. A replicated block design consisting of four buffer treatments was established in north central Minnesota in 2000. Treatments included an uncut control (i.e., the upland and buffer were uncut) and three treatments in which the upland was clearcut but the buffer was either uncut, partially harvested, or clearcut. Hydrologic characteristics were examined for differences among buffer treatments. One year of pre-harvest data was collected followed by five years of post-harvest data. Regression analysis of water levels indicated that all buffer treatments had significantly higher pond water depth than the uncut control for four years following harvests. The fifth year following harvests showed no difference in water depth between buffer treatments and the uncut control. In the first post-treatment year, the clearcut buffer treatment had the highest mean annual water depth of the three buffer treatments. Changes in evapotranspiration and runoff due to altering upland and riparian vegetation are considered key factors in explaining these hydrological responses. The results of this study indicate that upland harvesting increases water tables in seasonal ponds, and it takes about five years before water tables are similar to predisturbance levels. Our results also suggest that the amount of vegetation harvested within a riparian buffer affects the hydrologic response, especially in the first year following harvest.*

Keywords. *Best management practices, Forest management, Water table, Wetlands.*

Seasonal ponds (Palik et al., 2001), West Coast vernal pools (Jain, 1976; Zedler, 1987; Tiner, 1999), woodland vernal pools (Tiner et al., 2002), and seasonal forest pools (Brooks, 2005) are all similar in function and represent a type of isolated wetland that is common throughout the U.S. and Canada. Regional differences in physiography, including climate and soils, have led to differences in nomenclature. Seasonal ponds often form in depressions due to ponding of snowmelt and/or precipitation. Because these systems are generally geographically and hydrologically isolated, and because they are characterized by an annual or near-annual wet and dry phase, these systems provide valuable habitat and contribute to landscape-level ecological diversity. Yet even though seasonal ponds are recognized as integral components of the ecological landscape, their small size makes them a challenge to manage in a forest setting. An inventory of seasonal ponds in northern Minnesota by Palik et al. (2001, 2003) found their size to range between 0.01 and 0.25 ha. Brooks et al. (1998) found seasonal ponds in central Massachusetts to have a median surface area of 0.07 ha. Because they are generally forested, it is often difficult to identify the presence of seasonal ponds during their dry phase or during winter when most forest harvesting occurs in the northern U.S. Difficulty in identification during the winter often leads to ponds that are mistakenly harvested. As a result of these challenges facing forest managers, it is important to develop a more complete understanding of how seasonal ponds respond to harvesting.

Cole et al. (1997) recognized that the hydrologic regime is a principal factor affecting the structure and function of wetlands. Seasonal ponds have an annual hydroperiod consisting of at least one wet phase and one dry phase (or very nearly dry). The dry phase inhibits fish community development, making seasonal ponds an important habitat for a variety of species including amphibians (Paton, 1999; Karraker and Gibbs, 2009) and invertebrates (Batzer and Sion, 1999; Higgins and Merrit, 1999; Schneider, 1999). Although the hydrology of seasonal ponds is considered important, it is still poorly understood (LaBaugh, 1986; Cole et al., 1997; Boone et al., 2006). Pond hydrology is driven primarily by inputs of precipitation in the form of rain or snow and hydrological losses due to evapotranspiration combined with lesser amounts of infiltration losses to groundwater (Boone et al., 2006; Leibowitz and Brooks, 2008). By altering the vegetation in and around ponds, it is likely that the hydrological balance will be affected, resulting in impacts to the local animal and plant communities. Although there have been a number of studies on other types of isolated wetlands such as southern U.S. pocosins and cypress domes (see Sun et al., 2001, for a review), we are aware of no studies that have assessed the effect of forest harvesting on northern seasonal pond hydrolo-

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gy. In Minnesota, a minimum 15.25 m (50 ft) buffer is prescribed around seasonal ponds where harvesting is allowed, but the soil surface should be less than 5% disturbed (Minnesota Forest Resources Council, 2005). Other states, such as Maine, recommend no harvesting in the pond (vernal pool) itself, a 75% canopy maintained within 30 m of the pool, and 50% of the canopy maintained from 30 to 120 m of the pool (Calhoun and deMaynadier, 2004). Although states are prescribing forest management guidelines for seasonal ponds, little is known regarding the effectiveness of these buffer recommendations for mitigating changes to seasonal pond hydrology.

We initiated a study in the spring of 2000 in north central Minnesota to investigate the effects of varying seasonal pond riparian buffer treatments on plants, fauna, and hydrology. The objective of the hydrology research was to understand the effect of upland harvesting and various buffer treatments on pond hydrology. To meet this objective, the following hypotheses were tested by analyzing seasonal pond water levels: (1) harvest of adjacent upland forest will impact seasonal pond hydrology, causing an increase of water in the ponds, and (2) the uncut buffer will result in water levels closer to control or undisturbed conditions due to minimal disturbance of buffer vegetation, while the partially cut buffer will mitigate changes to hydrology to a lesser extent. We anticipated that this study would provide valuable insight into whether or not seasonal pond riparian buffers are effective at mitigating adjacent upland harvest impacts on seasonal pond hydrology.

Sites and Methods

In 2000, study sites were established in north central Minnesota (fig. 1). The study consisted of four sites within 35 km (Willow River, Soo Line, Ashebun Lake, and Dog Lakes) with four ponds each. The study areas are characterized by soil parent materials deposited during Wisconsinan-age glaciations that saw the multiple advance and retreat of up to four separate ice lobes: the Wadena Lobe, the Rainy Lobe, the Superior Lobe, and the Des Moines Lobe, which also included the St. Louis Sublobe. Due to these multiple glaciations, this area is composed of a variety of different landforms, such as drumlins, lake plains, moraines, and outwash plains. Generally, the seasonal ponds in this study are elliptical in shape and located on gently rolling ground moraine (Hobbs and Goebel, 1982). Soil parent materials of the study areas include loess, glaciolacustrine deposits, till, and glacial outwash. A layer of loess approximately 20 cm thick overlays outwash material mixed with till at all study areas. Pond soils were similar across blocks, with the general profile of a 10 to 18 cm organic layer over greater than 1 m of loam to silt loam and hydraulic conductivities ranging from 0.002 to 1.33 cm h^{-1} using a constant-head permeameter.

Upland forests of the study areas are dominated by trembling aspen (*Populus tremuloides*) with lesser amounts of northern hardwoods including red oak (*Quercus rubra*), sugar maple (*Acer saccharum*), and basswood (*Tilia americana*). Upland slopes were similar among sites (data not shown). Mean annual precipitation is 71 cm including an average snowfall is 137 cm (Nyberg, 1999; Richardson, 1997). Precipitation is distributed fairly evenly throughout the growing season but is generally highest in June and July. Mean annual air temperature is 4.8°C, and the length of the growing season

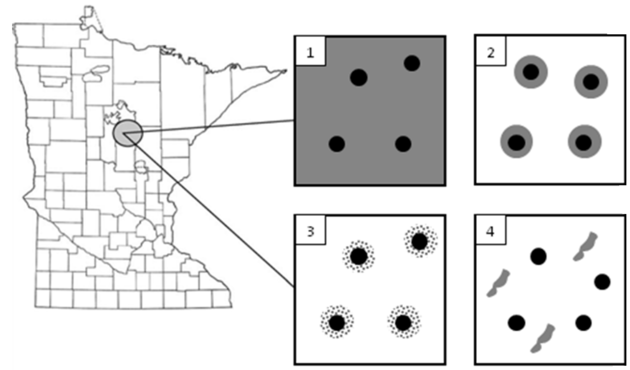

Figure 1. Location of study areas in north central Minnesota and a depiction of buffer treatments applied to study ponds: (1) uncut control; (2) upland clearcut, uncut buffer around pond; (3) upland clearcut, partially cut buffer around pond; and (4) upland clearcut with residual trees in the upland and no buffer around pond.

based on a daily minimum temperature above freezing is approximately 110 days (Nyberg, 1999; Richardson, 1997). Over the period of study, annual precipitation for the years 2000, 2001, and 2005 was 5 to 15 cm above normal, 2004 was 5 cm below normal, and 2003 was 25 cm below normal.

Experimental Design

This experiment was conducted using a randomized block design in which four randomly assigned treatments were replicated in four blocks, resulting in a total of 16 ponds (fig. 1). Each block was greater than 6 ha in size. Isolated seasonal ponds were identified by 1:24,000 leaf-off color infrared aerial photography. A number of seasonal ponds were located within each block. For each site, four ponds were randomly chosen based on the following criteria: (1) the surrounding forest was >50 years old; (2) ponds and surrounding forests showed no evidence of recent disturbance; (3) pond area was between 0.02 and 0.15 ha; (4) ponds had mineral or muck substrates, as opposed to peat; (5) maximum water depth in the ponds at the time of selection in spring of 2000 was >15 cm; and (6) ponds had no inlets or outlets. There was no statistical difference in pond size among treatments (ANOVA p-value = 0.39). Treatments were randomly assigned to blocks, and all four ponds within a block were treated similarly. The treatments were as follows: (1) uncut forest (control); (2) upland clearcut with 15.25 m uncut buffers surrounding pond (uncut buffer); (3) upland clearcut with 15.25 m buffers thinned to 11.5 m^2 ha^{-1} (~50% reduction) surrounding ponds (partial buffer); and (4) upland clearcut with residual patches of tress left in the upland with no buffers around ponds (clearcut buffer) (fig. 1).

Instrumentation and Sampling

Each block was instrumented with standard all-weather rain gauges to record precipitation. Gauges were attached to metal posts and placed in clearings where rainfall catch would not be affected. Trees were removed as they encroached on the gauge so that the clearing for the gauge was defined by a 30° angle from the top of the gauge to the closest tree top (Brooks et al., 2003).

Duplicate metal staff gauges were installed on driven metal posts in each pond. For each pond, a benchmark was established by driving a metal spike into the base of a tree next to the pond. Using a laser level and the benchmark as a reference, the gauges were placed at the lowest points in the pond. After installation of the gauges, the initial elevation difference between the benchmark and the base of the gauge was recorded. This elevation difference was checked annually with a laser level after freeze/thaw activity ceased in the spring. It was found that annual changes (<0.5 cm) in gauge elevation was a minor issue.

Collection of rain and staff gauge data was done weekly to bi-weekly, recording all 16 ponds within two days for each cycle. Rain gauges were read to within 0.03 cm and staff gauges to within 0.30 cm. The sampling period lasted throughout the ice-free season, generally April 1 to October 31.

One season of pre-harvest sampling was conducted at the onset of the study in 2000. Selected treatment stands were marked in the fall of 2000 and harvested that winter, leaving the designated buffer treatment around selected study ponds. Post-harvest sampling began spring 2001 and continued through 2005.

Data Analysis

Water depth measurements were analyzed to determine if significant differences existed among ponds based on treatment effect. For each set of duplicate gauges, data were selected corresponding to the deepest water level reading. Gauge readings for treatments were averaged for each weekly-biweekly measurement period, resulting in a mean depth for each treatment for each period as well as averaged for the year. Using the general linear model (GLM) in SAS 9.1 (SAS, 2003) weekly-biweekly gauge data for the clearcut, partial, and uncut buffer treatments were regressed against the control treatment for the 2000 pre-harvest study season. The pre-harvest relationship was compared to each post-harvest year, and using a paired t-test, we determined if differences in slope and *y*-intercept existed in post-harvest years. Changes in the *y*-intercept are indicative of an inter-annual variability in climate and were generally not significant (data not shown). Positive changes in slope, when comparing the annual pre- and post-harvest treatment relationships, indicate higher water levels when compared to the uncut control.

Additional indictors of pond hydrology including mean annual water depth, maximum water depth, longest wet period, total number of wet days, and most consecutive wet days during the April 1 to October 31 period were also calculated or summed annually for each treatment type. Those data were examined through analysis of variance (ANOVA) using the GLM procedure in SAS 9.1, and least square means were compared to determine any significant difference between buffer treatment types, cumulatively for the years 2001-2004, when treatment differences existed in weekly to biweekly mean water depth.

Results

Regression relationships in mean weekly to biweekly water levels in the pre-harvest year among treatment and uncut control ponds were all significant at $p < 0.01$ ($R^2 = 0.93$ between control and uncut buffer, $R^2 = 0.83$ between control and partial buffer, and $R^2 = 0.90$ between control and clearcut buffer). Prior to treatment installation in 2000, no differences existed in weekly to biweekly water level among treatments (fig. 2). Following the upland harvest in winter 2000, mean weekly to biweekly water level of all buffer treatments significantly differed from that of the control for the years 2001, 2002, 2003, and 2004 (table 1, fig. 2). By 2005, the fifth year following upland harvest, water levels in all buffer treatment ponds were similar to pre-harvest conditions (fig. 2). The first year following harvest (2001), all buffer treatments yielded significantly higher mean water depth than the control, with the clearcut buffer having the largest response, followed by the uncut buffer and the partial buffer (fig. 2). The second year following harvest, the partial buffer had the highest mean water depth, with the uncut buffer and control having similar depths and the clearcut buffer having the lowest mean water depth (fig. 2). The third year after harvest, the partial buffer continued to have the highest mean water depth, fol–

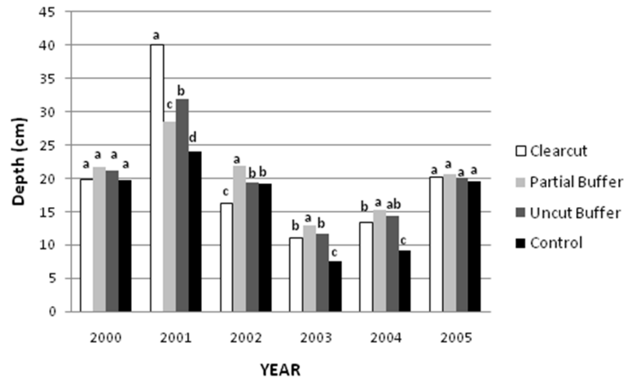

Figure 2. Comparison of seasonal pond mean annual water depth among buffer treatments and years. Year 2000 was pre-harvest and years 2001-2005 are post-harvest. Different letters indicate significant differences within years ($p < 0.05$).

Table 1. Regression analyses of weekly/biweekly water levels comparing the slope of the pre-harvest calibration regression (year 2000) to the slope of the post-harvest regression (years 2001-2005). All pre-harvest regressions were significant at the 0.01 level with R^2 ranging from 0.83 to 0.93 when comparing the three buffer treatments to the control. The post-harvest regressions shown below for individual years include the R^2 value between the control and the treatment for each year, the difference in slope and standard error (SE) of the slope between the pre-harvest and post-harvest regressions, and the likelihood (t and p values) that the post-harvest slope is different from the pre-harvest slope.

Buffer Treatment	Year	R^2	Difference in Slope[a]	SE	Paired t-Value	p-Value
Uncut	2001	0.95	7.0	2.7	2.58	0.01
	2002	0.93	18.3	3.4	5.63	<0.01
	2003	0.93	24.7	3.4	7.41	<0.01
	2004	0.91	21.6	4.0	5.66	<0.01
	2005	0.97	-10.1	2.4	-0.39	0.70
Partial	2001	0.96	7.6	3.7	2.08	0.04
	2002	0.88	21.6	4.6	4.61	<0.01
	2003	0.88	27.7	4.9	5.74	<0.01
	2004	0.78	24.4	5.5	4.42	<0.01
	2005	0.99	6.7	4.0	1.68	0.09
Clearcut	2001	0.96	10.1	3.7	2.73	0.01
	2002	0.82	16.2	4.6	3.46	<0.01
	2003	0.93	20.1	4.9	4.15	<0.01
	2004	0.83	11.3	5.5	2.05	0.04
	2005	0.95	2.4	4.0	0.64	0.52

[a] Between pre-harvest and post-harvest regressions.

Table 2. Comparison of hydrologic variables among buffer treatments when statistical differences in mean annual water tables showed differences among treatments (2001-2004). No significant differences ($p < 0.05$) were found in these parameters during pre-treatment (2000) or at five years post-treatment (2005).

Hydrologic Variable Comparison	F-Value	p-Value
Maximum depth	6.64	0.0009
Clearcut > Control		0.0084
Number of wet days	14.31	<0.0001
Partial buffer > Control		0.0032
Uncut buffer > Control		0.0119
Partial buffer > Clearcut		0.0062
Uncut buffer>Clearcut		0.0225
Longest wet period	19.54	<0.0001
Partial buffer > Control		0.0028
Uncut buffer > Control		0.0044
Partial buffer > Clearcut		0.0193
Uncut buffer >Clearcut		0.0297
Consecutive wet days	15.50	<0.0001
Partial buffer > Control		0.0032
Uncut buffer > Control		0.0047
Partial buffer > Clearcut		0.0397

lowed by the clearcut and uncut buffers, which were not different, and the control had the lowest mean water depth (fig. 2). The fourth year after harvest, the partial buffer was again the greatest, followed closely by the uncut and clearcut buffers, and again the control treatment had the lowest pond water levels (fig. 2).

Over the period when weekly to biweekly water level treatment differences existed (2001-2004), the maximum water depth was greatest in the clearcut treatment, which was significantly higher than in the control treatment (table 2). The partial and uncut buffer had a greater number of wet days, a longer wet period, and a greater number of consecutive wet days than the control treatment, and the partial and uncut buffers also had a greater number of wet days and longer wet period than the clearcut buffer, with the partial buffer also having a greater number of consecutive wet days than the clearcut buffer (table 2). No other treatment differences existed for maximum water depth, number of wet days, longest wet period, and consecutive wet days (data not shown).

Discussion

Although a number of studies have investigated northern seasonal pond hydrology (e.g., Brooks and Hayashi, 2002; Brooks, 2004; Boone et al., 2006; O'Driscoll and Parizek, 2008) and in some cases related hydroperiod to amphibian populations (e.g., Skidds and Golet, 2005; Baldwin et al., 2006; Karraker and Gibbs, 2009), few have attempted to relate hydrology to pond and upland vegetation communities (Palik et al., 2001; Palik et al., 2007), and no study has conducted an upland harvest with varying pond riparian buffer treatments as in this study. Following a characterization of biotic and abiotic variables across a chronosequence of adjacent forest ages in Minnesota, Palik et al. (2001) found only limited evidence that forest age influenced biophysical pond characteristics, including hydroperiod and water depth. However, because the youngest surrounding stands were seven years post-harvest in that study, it was not possible to understand the short-term harvesting effects on pond hydrology.

Our results indicate that the harvest of upland forest surrounding seasonal ponds does impact short-term pond hydrology, and that buffer treatments influence this impact. Mean annual water depth increased following harvesting, most dramatically in the first year, with recovery appearing to begin already in the second year after harvest (fig. 2). These results suggest that the pond water depth difference between buffer and control treatments recovers to pre-harvest conditions within five years following upland harvest. Several studies have shown that, following a wetland timber harvest, the usual response is an increase in the water table due to reduced evapotranspiration (e.g., Sun et al., 2001). The recovery of the water table (i.e., return to pre-harvest level) has been studied for a variety of wetland ecosystems. Marcotte et al. (2008) reported a ten-year recovery period for boreal forested wetlands and noted that Pothier et al. (2003) did not detect complete recovery for a northern forested wetland five years after harvesting a wet mineral site.

In the first year following harvest, the buffer treatments influenced pond hydrology with some large increases in pond depth relative to the control treatment. The clearcut buffer responded with the highest mean water levels but then dropped to levels comparable to the other treatments in following years (fig. 2). In the second year after harvest (2002), the clearcut buffer actually had lower mean water depths than the control (and other treatments). Following clearcutting of aspen-dominated forests, leaf area recovers rapidly (Kull and Tulva, 2000), such that transpiration in the clearcut treatment likely already exceeded that of the other treatments by the second year.

Following the first year after harvest, the partial buffer treatment consistently had the highest mean water levels (fig. 2), until no differences were found in the fifth year. The partial buffer likely provided some shading that limited both evaporation and understory regrowth. The latter, combined with harvesting in the upper portions of the pond watershed, likely resulted in reduced leaf area and transpiration, relative to the control. Both factors could lead to higher water levels.

Except in 2002, the uncut buffer had consistently higher water levels than the control and was generally most similar in response to the partial buffer treatment (fig. 2). Similar to the partial buffer, shading of the uncut buffer lessened evaporation. Moreover, with little understory response and harvesting in the upper portion of the pond watershed, leaf area and transpiration was likely reduced relative to the control, again leading to higher water levels.

The differences seen between the uncut buffer and the control also indicate that the harvested upland is influencing the impacts of the larger landscape (i.e., the watershed) on pond hydrology. Independent of riparian buffer type, for the first four years after harvest (with the exception of the clearcut and uncut buffer in 2002), pond water levels in the areas that were harvested increased relative to the control, providing support for our first hypothesis that harvest of adjacent upland forest impacted seasonal pond hydrology, causing an increase of water in the ponds. However, our second hypothesis, postulating that the uncut buffer would result in water levels closer to control conditions and that the partial cut buffer would mitigate changes to a lesser extent, was not shown. For the years 2003 and 2004, water levels in the clearcut buffer exhibited more similar pond water levels to the control than the uncut or partial buffer (fig. 2). The rejection of the second hypothesis may reflect changes in the hydrologic cycle near the ponds as a result of the buffer treatments. The amount of total evapotranspiration (ET) likely dictates the differences in the buffer effects. Beginning in the second year after harvest, the partial harvest appeared to have the lowest ET, followed by the uncut and clearcut buffers.

For other parameters such as the number of wet days, longest wet period, and consecutive wet days, the partial and uncut buffer treatments were similar to each other and exhibited the highest number of significant differences from the control treatment (table 2). Additionally, the clearcut buffer treatment differed the least from the control treatments based on these variables and was more similar to the control treatment than to the partial and uncut buffer treatments. These data support the results of the mean annual water level data.

Interestingly, the clearcut buffer ponds did have higher annual maximum water table depths than the control ponds during 2001-2004 (table 2). Because differences in annual water levels were small beginning in the second year after harvesting, the variation in water depth in the clearcut ponds must be high to balance the high maximum depths. The standard deviation in the clearcut pond water depth was the highest among the four treatments from 2001 to 2004, with the control treatment having the lowest standard deviation (data not shown). Together, these data indicate that the clearcut ponds filled to the greatest depth following snowmelt, but also dried the quickest with the onset of transpiration from plant growth and evaporation from warmer growing season temperatures. Although we did not measure snowpack depth, the clearcut treatment probably led to a deeper snowpack in the buffer area surrounding the pond, leading to greater pond water depths upon melting, similar to what other researchers have found when comparing clearcut and unharvested northern hardwood forests in the region (Murray and Buttle, 2003).

Conclusions

The objective of this study was to gain a better understanding of seasonal pond hydrology and determine the influence that different types of riparian buffer treatments have on hydrological variables following harvest of the adjacent upland forest. We confirmed our first hypothesis that water depth significantly increased in all buffer treatment ponds for a period of four years following upland harvest. This difference was not seen in the fifth year, suggesting that the water levels of buffer treatments had reestablished to pre-harvest conditions.

The effect of the pond buffer treatments was most apparent in the first year following harvest, with those effects decreasing thereafter. The clearcut buffer showed the greatest increase in pond water level in the first year after harvest, with the partial buffer showing the greatest increases in the second, third, and fourth years after harvest. Contrary to our second hypothesis, the clearcut buffer mitigated hydrologic changes to the greatest extent beginning in the second year after harvest.

Examination of additional hydrologic variables indicated that the partial and uncut buffer treatments had similar hydrological responses, including significantly more wet days, longer wet periods, and more consecutive wet days than the control treatment and in some cases the clearcut treatment. In addition, the clearcut buffer treatment had higher maximum water depth than the control treatment. The relationships among treatment types and the responses of these hydrological variables can be explained by examining the inputs and outputs to the water budget for seasonal ponds. Beginning in the second year after harvest, the partial and uncut control treatments may have had lower ET than the other treatments, leading to the highest mean annual pond levels and more wet periods. The higher maximum water table depth in the clearcut buffer treatment likely resulted from greater snowpack accumulation, and hence snowmelt, compared to the control treatment.

This study suggests that it is possible to manipulate the length of saturation and average depth of water in seasonal ponds by altering the vegetation communities within riparian buffers between the ponds and adjacent upland clearcuts. Such information is valuable to forest managers who may be concerned with providing a certain type of seasonal pond habitat following harvest of adjacent uplands or for ameliorating the effects of climate change (Brooks, 2009).

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