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Monitoring Changes in Minnesota Wetland Area and Type from 2006 to 2014

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INTRODUCTION

It has been estimated that Minnesota has lost approximately half of its original pre-settlement wetlands due to draining and filling for agriculture and development, with some regions of the state having lost more than 90 percent of their original wetlands (Anderson and Craig 1984). Other studies have demonstrated more recent wetland losses for portions of Minnesota. Oslund et al. (2010) reported wetland loss of 4.3% over an approximately 27 year period (circa 1980 to 2007) for southwestern Minnesota.

Concern regarding the loss of the ecosystem services these wetlands provide such as flood attenuation, water quality protection, wildlife habitat, and groundwater recharge (Mitsch and Gosselink 2000), has resulted in national and Minnesota state policy goals of "no net-loss" of wetland quantity and quality (CEQ 2008; Minn. Statutes 103A.201). The Minnesota Wetland Conservation Act (WCA) of 1991 (Laws of Minnesota 1991, Chapter 354) prohibits the draining and filling of protected wetlands unless replaced by restored or created wetlands of equal public value (Forsberg 1992). The WCA is implemented through a network of local government units with oversight from the Minnesota Board of Water and Soil Resources. While the WCA does not preclude wetland loss, any permitted losses should theoretically be replaced by wetlands of equal value. However, there are questions about the overall effectiveness of this program, considering the potential for wetland loss under statutory exemptions or through unreported violations. Assessing whether or not the state is achieving its no net-loss goal requires objective data regarding the quantity and quality of wetlands over time.

There are two broad approaches to assessing wetland gains and losses. One is a programmatic approach, based on aggregating data from state and federal wetland impact permitting programs and governmental and private-sector wetland restoration programs. While useful in obtaining a thorough understanding of general trends and causes of wetland gains and losses, the programmatic approach has deficiencies in obtaining an accurate depiction of actual, on-the-ground change (incomplete reporting and inconsistent terminology and classification issues between programs may reduce accuracy). The other approach is an assessment of wetland land cover, generally involving analysis of aerial or satellite imagery over time to reveal actual changes on the ground.

Within the imagery-based assessment, efforts can be grouped into three methodological categories: 1) comparing existing land cover or wetland inventory data from two different times, 2) updating wetland inventories with new imagery, and 3) probabilistic sampling combined with imagery analysis. These approaches vary in the completeness of the analyses and their applicability for analyzing changes over large geographic areas, as well as in effort and cost.

The first method uses readily available land cover data from different time periods to perform a change analysis for an entire study area. Wright and Wimberly (2013) and Lark et al. (2015) relied on the Cropland Data Layer (CDL) from the National Agricultural Statistics Service (NASS) to assess land cover change for the Western Corn Belt region and the conterminous United States, respectively. Similarly, Johnston (2013) assessed wetland losses for the Prairie Pothole Region of North and South Dakota using a combination of the CDL, the U.S. Geological Survey's National Land Cover Data (NLCD), and the U.S. Fish and Wildlife Service's National Wetlands Inventory (NWI).

The second method is to conduct an inventory-based assessment to report on wetland changes. This effort involves updating a prior wetland inventory using similar survey methods and documenting wetland changes in the process. Changes are detected through manual interpretation of aerial imagery. The NWI program has done this for many specific geographic areas in the northeastern U.S. (e.g., Tiner and Foulis 1992; Tiner and Zinni 1988; Tiner et al. 2012) and for two relatively small states - Delaware and Connecticut (Tiner et al. 2011, 2013).

The third method is a probabilistic approach based on selecting sample plots, acquiring periodic aerial imagery, and then mapping wetland change using manual photo-interpretation. This approach is best for examining changes over large geographic areas as typified by the U.S. Fish and Wildlife Service's (USFWS) national wetland status and trends monitoring program (Dahl and Bergeson 2009). California and Minnesota both have wetland status and trend monitoring programs based on this model (Lackey and Stein 2013; Kloiber 2012). A variation of this approach was used in southern and western Minnesota where investigators selected sample plots and compared the original NWI data (which was photo-interpreted) to an updated wetland photo-interpretation for a later time period (Oslund et al. 2010; Genet and Olsen 2008). There are other approaches to imagery-based wetland change detection, but the majority of the examples found in the literature fall into one of these three categories.

The obvious advantages to a method using existing land cover datasets like the CDL and NLCD are that costs are considerably lower than creating new data and it allows for complete spatial coverage for the change analysis. The principal disadvantage to this method is that datasets like the CDL and NLCD were not designed for this purpose. They typically have very low classification accuracies for wetland land cover. The wetland classes in the CDL are directly derived from the NLCD (NASS 2016) and the reported user's accuracy for woody wetlands and emergent wetland for the 2006 NLCD were 29% and 39%, respectively (Wickham et al. 2013). As a result, wetland change results using CDL or NLCD data will likely have relatively low degree of confidence. In addition, the spatial resolution of the CDL and NLCD are much lower than the typical spatial resolution of most aerial imagery. The NLCD is a raster dataset with a 30-meter spatial resolution. More recent CDL data also have a 30-meter spatial resolution, but for Minnesota CDL data prior to 2010 have a spatial resolution of 56 meters. In addition, these datasets often involve some spatial filtering. As a result, smaller changes in wetland may be under-represented.

Incorporating wetland trends analysis into updates of wetland inventories provides the most comprehensive assessment of change. While this can be done in an efficient manner and works well for areas of limited geographic scope, it is a costly effort for large geographic areas.

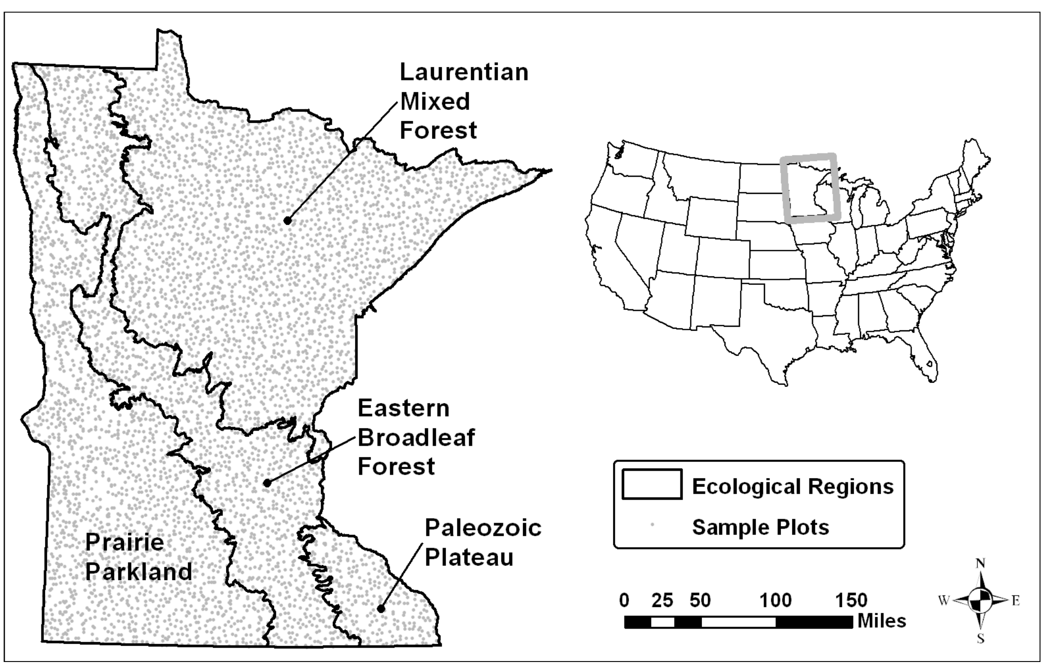
The primary advantages of the probabilistic method using aerial photo-interpretation are that it can detect relatively small changes and, if done properly, it can provide higher wetland classification accuracies than what can be obtained through examining land cover data like the NLCD and CDL. For example, Kloiber (2010) previously reported a wetland-upland classification accuracy of 94% for the Minnesota Wetland Status and Trends Monitoring Program (WSTMP). Similarly, the accuracy of the national wetland status and trends program has an overall accuracy greater than 95% (Mitch Bergeson, pers. comm. 2016). A probability-based wetland status and trend monitoring program for California reported a wetland classification accuracy of 97% (Stein et al. 2016). The disadvantages of this method is that is more expensive and time consuming to implement than the first method, although it is less costly than incorporating wetland trends into updates of wetland inventories.

This paper presents the results of an analysis of wetland areal changes in Minnesota for three monitoring cycles covering the period from 2006 to 2014 using data from the probability-based Minnesota WSTMP (Kloiber et al. 2012).

METHODS

Changes in land cover were mapped for 4,990 randomly-selected, permanent plots located throughout Minnesota (Figure 1). All plots are 2.59 square kilometers (1 mile square) in area except for those that happen to fall on the state boundary, which were clipped to the boundary. Aerial imagery with approximately 0.5 meter resolution was acquired on a repeating three-year cycle: 250 plots were surveyed annually and the remaining 4,740 plots were divided equally into three panels with one panel surveyed each year of the cycle. The baseline imagery was acquired in stereo.

FIGURE 1. Study location includes 4,990 randomly selected 2.59 square kilometer plots distributed across Minnesota, U.S.A. Each grey dot represents a sample plot. The ecological regions shown here are a modified version of the Ecological Classification System of Cleland et al. (1997) modified as described in Kloiber (2010).



Sample plot locations were selected using the generalized random tessellation stratified (GRTS) design (Stevens and Olsen 2004). The GRTS design was used to ensure an adequate spatial distribution of sample plots. Further details of the program design and procedures are described by Kloiber et al. (2012), but are briefly summarized here.

Land cover was mapped and classified (Table 1) with geographical information systems (GIS) software (ArcGIS version 10.2 – ESRI Inc.) using a photo-interpretation approach. GIS polygons were created for each photo-interpreted land cover feature. The baseline data were originally interpreted from stereo imagery and then digitized. Special modifiers were added to the land cover attributes to indicate man-made or modified (m) and artificially flooded (af) features. Extensive field validation was used to measure the accuracy of the baseline land cover classification, which was found to correctly distinguish between wetland and upland 94% of the time and correctly classify the more detailed land cover types 89% of the time (Kloiber 2010). Field validation averaged about 500 sites per year, typically spread across 50 randomly selected primary sampling plots (about 1% of plots per year). The results of the field validation for 2009-2011 were essentially identical to 2006-2008. Consequently, the field work component was suspended in 2013 and is currently being re-designed to focus on different quality control issues.

Land cover polygons from the baseline assessment (2006-08) were overlaid on aerial photography for the second sample cycle (2009-11) to assess changes between these first two cycles. Subsequently, the data from the second cycle was overlaid on aerial photos for the third sample cycle (2012-14) (Figure 2). Changes in wetland extent (gains, losses or change of type) were recorded by splitting land cover polygons as necessary to reflect changes and entering the updated land cover attribute in a second database field. Photo-interpreters also classified the cause of each change as either "direct" when there was direct visual evidence of the cause such as a new road or new drainage structure, or "indirect" when the cause of the change could not be ascertained from the imagery. Analysis of the most recent imagery sometimes reveals classification errors from previous assessment periods, which are corrected and reported as updated results. A previous change analysis reported results for the period from 2006 to 2011 (Kloiber and Norris 2013). Here we also provide updated results for the first change analysis resulting from subsequent data corrections.

Pivot tables and summary statistics were generated using Microsoft Excel (Excel version 2013 – Microsoft Corporation). Hypothesis testing was performed using statistical software (JMP® version 12.0 - SAS Institute). We used the non-parametric Wilcoxon signed rank test (SAS Institute 2012) to assess whether the paired differences in wetland proportion between plots had changed between the first and second cycle as well as between the second and third cycle.

Features that did not change and non-target changes were excluded from further analysis. Non-target changes

TABLE 1. Land cover codes for the Minnesota wetland status and trends monitoring program. -

System	Code	Class Name	Description
Deepwater	DW	Deepwater	Lakes, reservoirs, rivers, streams
Wetland	FO	Forested wetland	Forested swamp
	SS	Shrub swamp	Woody shrub or small tree marshland
	EM	Emergent wetlands	Marshes, wet meadows, and bogs
	AB	Aquatic bed	Wetlands with floating and submerged aquatics
	UB	Unconsolidated bottom	Open water wetland, shore beaches and bars
	CW	Cultivated wetland	Wetlands in agricultural fields
Wetland modifiers	*m*	Manmade	DW, UB, AB or EM of artificial origin
	af	Artificially flooded	Aquaculture, sewage treatment, wetland treatment systems, mine tailing ponds
Upland	U	Urban	Cities, incorporated developments
	R	Rural development	Non-urban developed areas, infrastructure
	A	Agricultural	Cultivated lands and managed upland pasture
	N	Natural	All natural upland including forested and wooded land as well as grassland, prairies, and state and federal agricultural set-aside lands.
	O	Other / Transitional	All uplands not otherwise classed

included changes among upland land uses and changes between upland and artificially flooded features (labeled “af”). Artificially flooded features typically serve an industrial or commercial purpose, have little natural wetland function, and usually do not meet the regulatory wetland definition. Examples include mine tailing discharge basins from active mining facilities and wastewater stabilization ponds. These types of features, although they are inundated, commonly lack both hydric soils and hydrophytic vegetation. Conversion of natural wetlands to an artificially flooded feature was considered as a wetland loss, and change from an artificially flooded feature to a wetland without this attribute was regarded as a wetland gain.

As defined by Cowardin et al. (1979), the boundary between deepwater habitat and adjacent wetlands is based on the depth of water or the extent of visible vegetation. However, in practice, it can be difficult to determine this boundary with accuracy from aerial imagery because water turbidity frequently obscures submergent vegetation or other indicators of depth. Therefore, the photo-interpretation convention used in this study is that areas of open water larger than 8.9 ha (20 acres) without visible aquatic vegetation were classified as deepwater habitat, whereas areas of visible aquatic vegetation were classified as aquatic bed. There can be considerable year-to-year variability in the extent of aquatic vegetation. This type of apparent community shift was considered non-target for this analysis. As a result, observed changes between aquatic bed wetland and deepwater habitat were not counted as a wetland gain or loss.

The area of wetland gain, loss and change of type were tabulated for all sample plots. To extrapolate the results statewide, the area of the measured changes in each plot was first normalized by dividing by the plot size. We then calculated the mean of these normalized proportional changes and multiplied this by the area of the state. Wetland changes were also calculated for four ecological regions of the state (Figure 1) based on the Ecological Classification System (Cleland et al. 1997) as modified for this program by the Minnesota Department of Natural Resources (Kloiber 2010). These regions were selected for use in this analysis because the type and abundance of wetland resources in each of them are fairly distinct (Kloiber 2010).

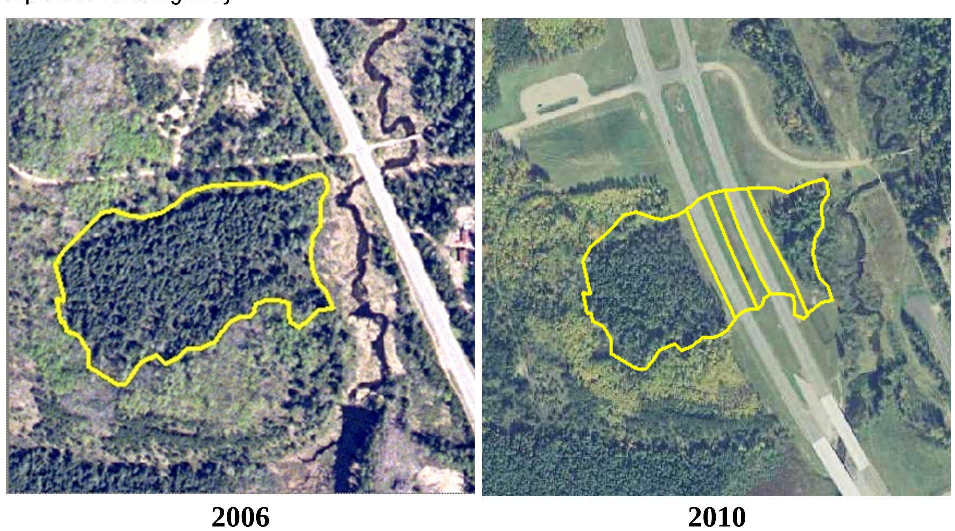
In an effort to understand at least one potential driver of wetland trends, we also evaluated the potential effect of antecedent precipitation on wetland change. We selected twelve common land cover changes of interest, such as change from emergent wetland to upland and change from emergent to cultivated wetland. Plots were then categorized with regard to whether the selected changes occurred within them or not (1 = the selected change occurred, 0 = the selected change did not occur) from the first sample cycle (2006 – 2008) to the third sample cycle (2012-2014). The first and third sample cycles were used for the comparison to maximize the number of plots exhibiting a wetland change and increase the probability of detecting a relationship between precipitation and wetland type change, if one exists. Seasonal precipitation grids were obtained for the trend analysis period from the Minnesota State Climatologist. Precipitation from spring and the preceding winter (December- February) and fall (September-November) were aggregated and joined to the data from the wetland monitoring plots, accounting for the year each plot was monitored. For example, panel 1 was first monitored in 2006, so the data from the wetland monitoring plots were joined to the gridded precipitation data from September 2005 through May 2006. The effect of precipitation differences between the first and third cycle were then evaluated using the Kruskal-Wallis rank sum test.

RESULTS

MEASURED GAINS FROM AND LOSSES TO UPLAND

Within the sample plots, we observed a gain of 219.2 hectares of wetland from upland for the second to the third monitoring cycle (2009-11 vs 2012-14) and a concurrent loss of 65.5 hectares (Table 2), producing a net increase of 153.7 hectares. About two-thirds of the gains from upland

FIGURE 2. An example of wetland mapping is shown. The image on the left shows a forested wetland dominated by black spruce in the spring of 2006, while the image on the right shows the same site in the summer of 2010. In the later image, the wetland has been split by a relocated and expanded rural highway.



and almost 90% of the losses to upland were classified as direct, indicating that there is usually visual evidence of human intervention in most of the observed changes. The revised analysis for the first trend reporting period (2006-2011) shows a gain of 104.4 hectares of wetland along with a concurrent loss of 46.5 hectares, producing an overall net increase of 57.9 hectares. This is a slightly larger net gain than the previously reported increase of 50 hectares within the sample (Kloiber and Norris 2013), but the difference is within the margin of uncertainty.

Much of the wetland change observed was associated with agricultural land (Table 3). Over half (60%) of the wetland gains and a high proportion (76%) of the wetland losses in the period from 2009 to 2014 occurred on agricultural land. For the previous assessment period, agricultural land was involved in about half of the gains and half of the losses (Kloiber and Norris 2013). Rural developed land and natural land made up most of the remainder of wetland losses and gains between the second and third monitoring cycle. Wetland changes were observed for urban lands, but these contributed less than 1% of the gain and less than 3% of the loss.

For 2009-2014, the wetland type with the largest gross gain from upland for the most recent reporting period was emergent wetland with a gross increase of 90.9 hectares (including man-made emergent wetlands), accounting for 41% of the total gain (Table 4). However, 44.3 hectares of emergent wetland were lost to upland during this same period. The changes for emergent wetlands for this reporting period stand somewhat in contrast to the changes observed between the first and second cycle for which there was a gross gain from upland of 35.3 hectares and a concurrent loss of 30.5 hectares.

The largest net gains from upland for the 2009-2014 reporting period were seen in the unconsolidated bottom wetland class (i.e., ponds) with a gross gain of 71.7 hectares (33% of the total gains) and a loss of only 2.2 hectares. The changes for unconsolidated bottom wetlands for this reporting period are generally consistent with the change observed from the first to the second monitoring cycle, in which there was a gain of 60.6 hectares and a concurrent loss of 8.1 hectares.

Cultivated wetlands show a gross gain of 46.8 hectares between cycles two and three, which is larger than the gross gain of 6.9 hectares shown in the previous assessment. Forested and scrub shrub wetlands both showed small gains and losses in both trend assessment periods.

TABLE 2. Observed wetland gains from upland, losses to upland, and net change in hectares. -

Reporting Period	Direct Gain (ha)	Indirect Gain (ha)	Direct Loss (ha)	Indirect Loss (ha)	Net Change (ha)
2009-2014	149.1	70.1	57.9	7.6	153.7
2006-2011	65.9	38.5	44.8	1.7	57.9

TABLE 3. Upland and non-wetland land cover role in observed wetland change in hectares. -

	Wetland Change 2006-2011		Wetland Change 2009-2014	
Cover Code (see Table 1)	**Gain from (ha)**	**Loss to (ha)**	**Gain from (ha)**	**Loss to (ha)**
A	56.4	27.8	130.8	49.7
ABmaf	0.0	0.0	0.0	0.0
EMmaf	0.0	0.0	0.0	0.0
N	27.1	1.8	44.4	3.9
O	0.0	4.4	0.0	0.0
R	18.4	12.3	40.4	10.2
S	0.0	0.0	0.0	0.0
U	2.1	0.3	1.3	1.8
UBmaf	0.4	0.0	2.3	0.0
Total	**104.4**	**46.5**	**219.2**	**65.5**

MEASURED TYPE CHANGES

Changes between wetland types are frequently larger than the wetland gains and losses to and from upland. For example, there appears to be a dynamic relationship among wetlands shifting back and forth between aquatic bed wetlands and unconsolidated bottom wetlands or deepwater habitat. For the first trend assessment period, 209 hectares of aquatic bed wetland shifted to unconsolidated bottom wetland and 233 hectares of wetland shifted in the opposite direction. At the same time, 295 hectares of aquatic bed wetland shifted to deepwater habitat, while 123 hectares shifted the opposite direction. The results for the second trend assessment period were roughly similar with respect to these shifts for these three types. Some of this apparent shift between aquatic bed and unconsolidated bottom may reflect difficulties in detecting submerged vegetation using photo-interpretation.

Also, in the first trend assessment period we observed a net shift of 102 hectares from emergent wetlands to cultivated wetlands. However, in the most recent assessment period we observed a net shift of 15.4 hectares from cultivated wetland to emergent wetland. In another notable change for the most recent reporting period, we observed a shift of 368 hectares of forested wetland to scrub shrub wetland, possibly due to timber harvesting.

HYPOTHESIS TESTING FOR NO-NET-LOSS

Given that the data do not follow a normal probability distribution (Kloiber and Norris 2013), we used the non-parametric Wilcoxon signed rank test (SAS Institute 2012) to determine if the paired differences of wetland proportion for each plot between time periods are statistically different from zero, indicating a change in wetland area. This test indicated that the observed direct, indirect, and total wetland change were significantly different from zero for both the 2006-08 to 2009-11 comparison and the 2009-11 to 2010-12 comparison. All comparison results were significant at $p<0.001$. Thus, we conclude that we did observe a slight net increase in wetlands for both assessment periods.

GEOGRAPHIC DISTRIBUTION OF GAINS AND LOSSES

The occurrence of observed changes in wetland is distributed across the state (Figure 3). However, slightly more wetland change was observed in the Prairie Parkland and Eastern Broadleaf Forest ecological regions in terms of both the number of plots showing changes and the mean size of the change. In addition, most of the plots exhibiting wetland loss tend to fall along the vegetation tension zone from the northwest to the southeast, while plots exhibiting wetland gains are more broadly distributed.

In terms of the number of plots exhibiting wetland change, approximately 2% of the sample plots in the Laurentian Mixed Forest and Paleozoic Plateau were found to exhibit wetland gains or losses from 2009 to 2014, whereas wetland gains or losses were observed for approximately 5% and 6% of the sample plots in the Prairie Parkland and Eastern Broadleaf Forest regions. In terms of the area of wetland change for the 2006-11 assessment period, the net gain

TABLE 4. Observed wetland gains and losses by wetland type (conversions from and to non-wetland) in hectares.

	2006-2011		2009-2014	
Cover Code (see Table 1)	**Gain (ha)**	**Loss (ha)**	**Gain (ha)**	**Loss (ha)**
A	0.0	0.1	1.1	0.2
ABm	1.1	0.0	0.0	0.0
CW	6.9	2.0	46.8	12.7
EM	34.8	30.2	86.0	39.5
EMm	0.5	0.3	4.9	4.8
FO	0.2	1.7	5.7	1.1
SS	0.2	4.1	3.0	5.0
UB	15.9	0.7	37.4	0.0
UBm	44.7	7.4	34.3	2.2
Total	**104.4**	**46.5**	**219.2**	**65.5**

TABLE 5. Summary statistics and hypothesis testing for proportional wetland change from 2009-2011 to 2012-2014.

	Net Direct Change	Net Indirect Change	Net All Change
Mean	+0.00684%	+0.00507%	+0.01191%
Standard Deviation	0.17428%	0.10801%	0.20585%
Standard Error of the Mean	0.00247%	0.00153%	0.00291%
Upper 95% Mean	0.01167%	0.00807%	0.01762%
Lower 95% Mean	0.00200%	0.00207%	0.00620%
N	4990	4990	4990
Signed Rank Test Statistic	234253	180538	385131
Signed Rank Test Prob > |t|	<0.0001	<0.0001	<0.0001

TABLE 6. Summary statistics and hypothesis testing for proportional wetland change from 2006-2008 to 2009-2011.

	Net Direct Change	Net Indirect Change	Net All Change
Mean	+0.00140%	+0.00289%	+0.00429%
Standard Deviation	0.10844%	0.04777%	0.11918%
Standard Error of the Mean	0.00154%	0.00068%	0.00169%
Upper 95% Mean	0.00441%	0.00422%	0.00760%
Lower 95% Mean	-0.00161%	0.00157%	0.00099%
N	4990	4990	4990
Signed Rank Test Statistic	145289	121621	250114
Signed Rank Test Prob > |t|	<0.0001	<0.0001	<0.0001

in wetlands for the Eastern Broadleaf Forest and Prairie Parkland regions were +0.012% and +0.0087% (Figure 4). For the same period, the Laurentian Mixed Forest showed a very small net loss of wetlands of -0.0023%. The Paleozoic Plateau had a net increase in wetlands for this period of +0.0027%, but this change was not statistically significant. For the 2009-14 assessment period, the net increase in wetland area for the Eastern Broadleaf Forest and Prairie Parkland were about 50-60% larger than they were for the previous assessment period. For the Laurentian Mixed Forest region, the 2009-14 wetland change reversed from the previous period with a net change of +0.0085%. Using the Wilcoxon signed rank test, we found that all of the regional net wetland change results were statistically significant (P<0.01), except for within the Paleozoic Plateau.

STATEWIDE WETLAND GAINS AND LOSSES

Using the mean proportional changes observed in our random sample, we extrapolated the wetland changes for the entire state by multiplying the mean proportional changes by the total state area of 218,550 square kilometers (Table 7). The updated wetland change results from 2006 to 2011 show an estimated net gain of 980 hectares (a gain of 0.023% as a percentage of all wetlands), which is slightly larger than the previously reported net gain of 842 hectares (Kloiber and Norris 2013). The difference is due to corrections made to the GIS data subsequent to the original analysis. For the assessment period from 2009 to 2014, the statewide estimate of wetland change shows a net gain of 2,610 hectares (a gain of 0.060% as a percentage of all wetlands). The results between the two assessment periods are not strictly additive because occasionally wetland features gained in one assessment period can become losses in the subsequent period and vice versa. The overall statewide net change calculated from 2006 to 2014 is a gain of 3,600 hectares.

STATEWIDE WETLAND TYPE CHANGES

In addition to outright wetland gains and losses, we also extrapolated statewide wetland type changes. There are many potential wetland type changes, but one subset of these is of particular interest. Changes between emergent, cultivated, and unconsolidated bottom wetlands (Figure 5) are of particular interest because they may result in changes for important wetland functions. This subset of wetland type changes may also have an important human-induced component. The baseline assessment indicates that

FIGURE 3. Net wetland change in area from 2009 to 2014 by sample plot. Plots are symbolized according to the magnitude and direction of wetland change with larger triangles for larger changes. Plots with net wetland gains are symbolized with green triangles that points up, whereas plots with net losses are symbolized with red triangles that point down.

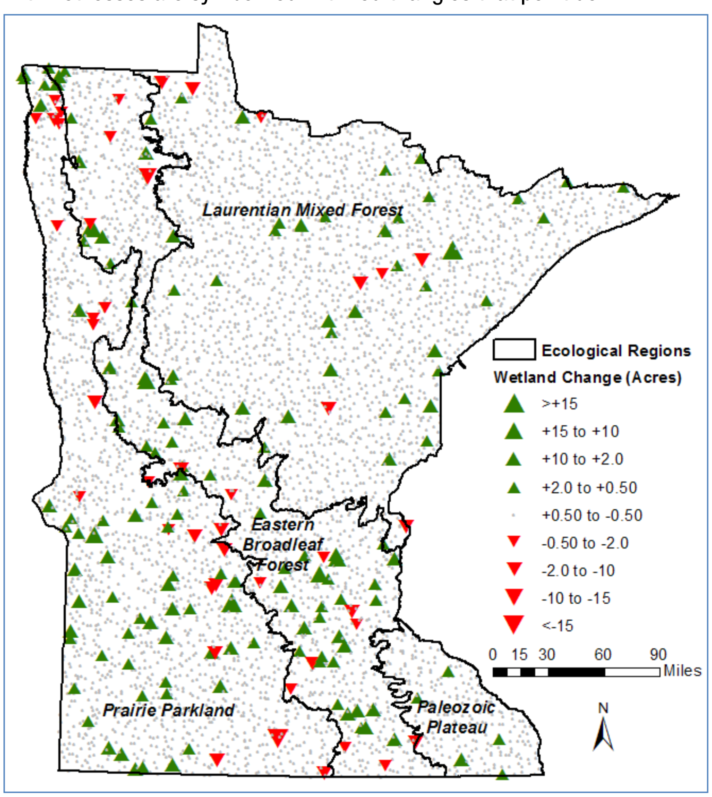


FIGURE 4. Estimated net wetland change for each of the four ecological regions for the two assessment periods; 2006-11 and 2009-14.

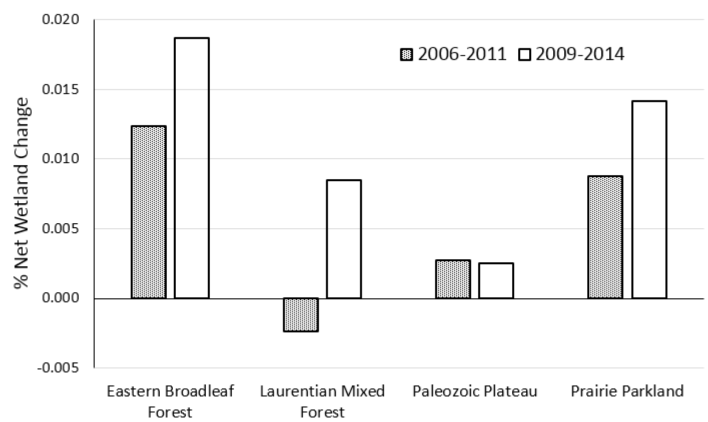


TABLE 7. Summary statistics and hypothesis testing for proportional wetland change from 2009-2011 to 2012-2014.

	Statewide Wetland Change (2006-2011) (%)	Statewide Wetland Change (2009-2014) (%)
Gross Gain	+0.00289%	+0.00429%
Gross Loss	0.04777%	0.11918%
Net Change	0.00068%	0.00169%

there were an estimated 1.27 million hectares of emergent wetland in the state, compared to 174,000 hectares of unconsolidated bottom wetlands and 58,700 hectares of cultivated wetland. There was an estimated net shift of 1,630 hectares of emergent wetland to cultivated wetland from 2006 to 2014 (Figure 6). There was also a net shift of 700 hectares of emergent wetland to unconsolidated bottom wetlands. These changes were partly offset by a net gain of 860 hectares of emergent wetland created from upland. Overall, this still represents a net loss of 1,470 hectares of emergent wetland from 2006 to 2014. Shifts from emergent to cultivated wetland were largely (95%) attributed to direct human causes. Shifts in the reverse direction were mostly (77%) attributed to indirect (undetermined) causes (Table 8). Shifts between emergent and unconsolidated bottom wetlands in either direction were largely (>90%) attributed to indirect causes.

EFFECT OF ANTECEDENT PRECIPITATION

In many cases, the influence of human actions on wetland change is directly visible in the aerial imagery. In other cases, the source of change is not readily apparent. In an effort to better understand the source of these indirect changes, we evaluated the potential effect of differences in antecedent precipitation for twelve possible wetland change scenarios involving emergent, unconsolidated bottom, and cultivated wetlands as well as upland.

On average, statewide wetland plots were generally slightly drier in the third cycle compared to the first cycle with a grand mean of 1.5 centimeters less precipitation for the previous 9-month period. Significant differences in antecedent precipitation ($p<0.05$) between the first and third sample cycles were observed for five out of the twelve wetland change scenarios evaluated (Table 9). The seven wetland changes that were not associated with significant precipitation differences had generally lower occurrence frequencies.

Wetland plots that exhibited shifts from emergent to cultivated wetlands were significantly drier in the third sample cycle compared to the first cycle than the average plot (-5.4 cm instead of -1.4 cm). While this observation seems to support the hypothesis that the conversion of emergent wetlands is potentially facilitated by drier conditions, the converse shift from cultivated to emergent wetland was also correlated with significantly drier antecedent precipitation (-9.5 cm instead of -1.4 cm). However, if the shifts from cultivated wetlands to emergent wetlands are part of an intentional restoration effort, these would occur regardless of the precipitation patterns.

Shifts from emergent to unconsolidated bottom wetlands and the converse shift were also both correlated with drier than average conditions for the antecedent 9-month period. Emergent wetlands are usually associated with lower water levels than unconsolidated bottom wetlands, so we might expect less precipitation to potentially favor the development of emergent vegetation, but the fact that we also observed lower antecedent precipitation for wetlands that shift the opposite direction suggests that precipitation patterns alone do not adequately explain these shifts. It is important to recognize that even wetlands of the same type can vary widely with respect to their relative dependence on various source water mechanisms (e.g., runoff, stream flow, groundwater, and precipitation). Therefore, we cannot necessarily expect a simple relationship between the variability of a single hydrologic driver such as precipitation and changes in wetland type. Importantly, there are also human effects that are not readily discernable by simply examining aerial imagery, such as the potential impact of agricultural tile drainage and local water table drawdown from water appropriations.

We also saw a significant correlation between wetter conditions and apparent cultivated wetland gain from upland. We hypothesize that this may be an artifact of

FIGURE 5. Examples of photo signatures for cultivated, unconsolidated bottom, and emergent wetlands. -

Cultivated **Unconsolidated bottom** **Emergent**

the climate conditions for the baseline assessment period of this monitoring program. If these sites were drier than normal for the initial period, they may have been classified as upland due to the lack of a wetland signature. However, in subsequent monitoring cycles, the wetter conditions may have revealed a wetland signature of the cultivated wetland. Over time, as we build a longer record of aerial imagery for these sites, we should improve our ability to distinguish these cultivated wetlands.

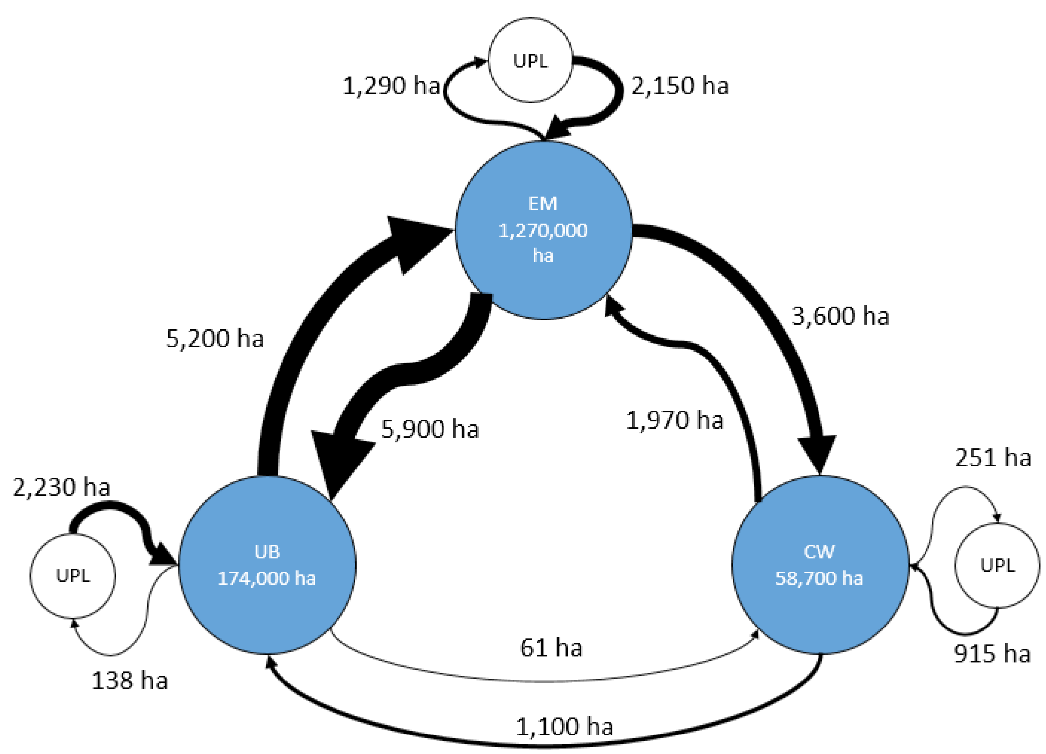
DISCUSSION

The 1991 Minnesota Wetland Conservation Act established a statewide policy calling for no-net-loss in the quantity, quality, and biological diversity of the state's wetlands (Minn. Statute 103A.201). The results from the first three sample cycles of the wetlands status and trends monitoring program, covering the period 2006 to 2014, indicate an overall net gain of wetlands for the state. For the most recently analyzed assessment period (2009-14), there was an estimated statewide net gain of 2,610 hectares, which was larger than the net gain of 980 hectares for the first trend assessment period (2006-11). These gains are relatively small compared to the overall area of wetlands in the state. Nonetheless, these statistically significant gains suggest that the no-net-loss goal was nominally met with respect to wetland quantity, but not necessarily quality, for the study period.

There are reasons to be cautious about declaring that the overall policy objective of no-net-loss has been met. The first caveat is that there may be important ongoing losses of wetland quality and function. The national wetland status and trends program has reported that most wetland gains in the conterminous United States were due to gains in un-vegetated wetland "ponds" (Dahl 2006; Dahl 2011), which agrees with the results of the WSTMP that the largest net gains in Minnesota come from unconsolidated bottom wetlands. An assessment of depressional wetlands in Minnesota found that man-made basins, which are predominantly classified as unconsolidated bottom, were in worse biological condition than natural basins that are typically a mosaic of emergent, aquatic bed, and unconsolidated bottom wetland types (Genet 2015). In addition, our results show that gains in emergent wetland from upland are offset by type changes from emergent to other wetland types with potentially lower quality and function, specifically shifts to unconsolidated bottom wetlands and cultivated wetlands. Unconsolidated bottom and cultivated wetlands are characterized by a lack of hydrophytic vegetation implying a loss of wetland function for fish and wildlife habitat. Furthermore, a statewide wetland condition assessment of all wetland types using floristic quality assessment showed that while many of Minnesota's wetlands are of high quality, there is a stark regional difference with most of the high quality wetland located in the northeastern part of the state, while wetlands in the southwestern part of the state are largely degraded (Bourdaghs 2015). Taken together, these results suggest that while there may be small net gains in wetland quantity, there are potential ongoing loses of wetland function.

The second reason for caution about the nominal net gain observed by the WSTMP is that other stud-

FIGURE 6. Wetland changes involving emergent (EM), cultivated (CW), and unconsolidated bottom (UB) wetlands from 2006 to 2014. The line weight reflects the magnitude of the type change and the arrow shows the direction of the change. This figure shows a net shift from emergent wetlands to cultivated and unconsolidated bottom wetlands.



ies have shown different results. In particular, Dahl (2014), using a similar probabilistic sampling approach, showed significant wetland losses for the Prairie Pothole Region (PPR), which includes southern and western Minnesota as well as North and South Dakota. He reported an overall loss of 30,080 hectares for all wetland types within the PPR or 2,509 hectares/year from 1997 to 2009; whereas, the Minnesota WSTMP reported a statewide gain of 870 hectares/year from 2009 to 2014 (net gain of 2,610 hectares divided by the three year cycle). Furthermore, Dahl reported a loss of 38,582 hectares of emergent wetlands in the PPR with most of that occurring in Minnesota. This appears to conflict with the results presented here. However, there are some potentially important differences between the Minnesota WSTMP and Dahl's study of the PPR which may explain this apparent discrepancy.

Clearly, one difference is the time period of the two studies; from 2006-2014 for our study as opposed to 1997-2009 for the Dahl study. So one possible explanation is that there was a real change in the wetland trend between the two time periods, although it is not clear what might be causing any such trend, if it really exists. Another difference is the sampling intensity which likely to be an important factor. Dahl had 156 plots in the portion of the PPR in Minnesota whereas we had nearly 10 times that number (1,475 plots) within the Prairie Parkland Province of Minnesota. Even accounting for Dahl's larger plot size (10.36 square kilometers), the total sampled area for the WSTMP in the Prairie Parkland Province was more than double that of Dahl's. The smaller sample size of Dahl's study will result in larger uncertainty in the estimated wetland change. Finally, there are likely differences pertaining to the treatment of cultivated wetlands. We previously reported an estimate of 27,393 hectares of cultivated wetland for the Prairie Parkland Province in Minnesota (Kloiber 2010), whereas Dahl (2014) reported 20,878 hectares of cultivated wetland for the entire PPR. Cultivated wetlands exist at a rather uncertain boundary between features that are clearly wetland and features that have clearly been converted to effectively-drained agricultural land. Differences between these two studies in classifying cultivated wetlands may have an effect on the trend results. Overall, the differences in geographic scope, time period, sampling design and intensity, and classification methodology makes a direct comparison of results between these two studies difficult.

Other wetland change studies have also shown varied results, but all of these also cover the different geographic areas and time periods. Nationally, the U.S. Fish and Wildlife Service reported annual percentage change in wetlands of -0.055%, +0.030%, and -0.012% for the reporting periods 1986-1997, 1998-2004, and 2004-2009, respectively (Dahl 2011). The net change in Minnesota wetlands from this study are +0.018% and +0.049% for the reporting periods 2006-2011 and 2009-2014. We have previously compared our results to other regional estimates of wetland change for southwestern Minnesota (Kloiber and Norris 2013). In these studies, both Oslund (2010) and Genet and Olsen (2008) reported net wetland losses for southwestern Minnesota. However, both of these studies used the National Wetlands Inventory as the baseline for their studies, which dates from circa 1980. The difference in the respective study periods between these various efforts may account for much of the difference in results. This not only substantially predates the study period for the WSTMP, but importantly, it also predates the 1985 implementation of the Swampbuster provision of the federal farm program, which has been shown to have substantially slowed the loss of wetlands on agricultural lands (Dahl 2000; Haufler 2005).

Finally, in attempting to explain certain results of our study, we hypothesized that observed shifts between emergent, cultivated, and unconsolidated bottom wetlands and uplands (Figure 6) may be influenced by climate patterns. Under drier conditions, emergent wetlands may be more susceptible to conversion to cultivated wetlands. Minnesota state and federal regulations all contain provisions that potentially allow wetland vegetation to be cleared and crops to be planted if conditions are dry enough to allow farm equipment to operate. If wetter conditions return, sites that previously appeared as cultivated wetland (or they might even appear to be cultivated upland) may revert to unconsolidated bottom wetlands as precipitation and water tables rebound. The precipitation analysis presented here provides

TABLE 8. Proportion of selected wetland changes with directly human causes and indirect causes

Change Category	%Direct	%Indirect
EM-CW	95%	5%
CW-EM	23%	77%
UB-CW	17%	83%
CW-UB	76%	24%
EM-UB	9%	91%
UB-EM	8%	92%
EM-UPL	92%	8%
UPL-EM	66%	34%
CW-UPL	79%	21%
UPL-CW	62%	38%
UB-UPL	88%	12%
UPL-UB	27%	73%

mixed evidence, with some results supporting and other results contradicting this hypothesis. Additional information on the geographic distribution of agricultural tile drainage and groundwater appropriation could also be incorporated into this analysis, where it is available. Over time, using the data from this ongoing monitoring program and additional analysis, we should be able to better resolve the potential effect that climate variability and other factors may have on wetland changes.

SUMMARY

The State of Minnesota has been operating a wetland status and trends monitoring program (WSTMP) since 2006. Wetland change is monitored using remote sensing data for 4,990 random plots, with each plot being 2.59 square kilometers (one square mile) in size, and conducted over repeating 3-year sampling cycles. The analysis presented here includes the results from three complete sampling cycles; 2006–2008, 2009–2011, and 2012–2014. We found small, but statistically significant net gains in wetland area. Extrapolating the results statewide indicates that Minnesota had a net gain of 980 hectares (+0.023%) of wetland from 2006 to 2011 and a net gain of 2,610 hectares (+0.060%) from 2009 to 2014. In spite of nominally achieving the State's no-net-loss goal with respect to wetland quantity, the data suggest important reasons to be concerned about the state of wetlands in Minnesota. First, much of the observed gains were unconsolidated bottom type wetlands (ponds) that typically have limited wildlife habitat value. Second, there are conversions between wetland types, such as emergent wetlands converted to cultivated wetlands or to unconsolidated bottom wetlands that, while not a loss of wetland area, undoubtedly represent a loss of wetland function. To fully achieve the no-net-loss policy, we will have to gain a more complete understanding of the drivers of these observed wetland changes. Given the diversity of wetlands and the complexity of teasing out the potential influence of multiple drivers, this will be a challenging effort. ■

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TABLE 9. Antecedent 9-month precipitation differences associated with select observed wetland changes from 2006-2011 to 2012-2014. -

Change Category	Probability	Mean Precipitation Difference for Plots without Specified Wetland Change (cm)	Mean Precipitation Difference for Plots with Specified Wetland Change (cm)	Count of the Plots with Specified Wetland Change
EM -> CW	0.0137*	-1.4	-5.4	73
CW -> EM	0.0011*	-1.4	-9.5	22
UB -> CW	0.0911	-1.5	-11.0	4
CW -> UB	0.8939	-1.5	-1.1	4
EM -> UB	0.0203*	-1.4	-3.1	230
UB -> EM	<0.0001*	-1.2	-5.9	261
EM -> UPL	0.1256	-1.5	-3.6	64
UPL -> EM	0.1352	-1.5	0.6	115
CW -> UPL	0.5389	-1.5	-2.3	12
UPL -> CW	0.0294*	-1.5	3.2	54
UB -> UPL	0.1983	-1.5	6.6	6
UPL -> UB	0.9495	-1.5	-1.6	55

* Statistically significant at the $p<0.05$ level using the Kruskal-Wallis rank sum test with a one-way Chi-squared approximation.

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