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Monitoring land cover change in the Lake Superior basin

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Consistent, repeatable and broadly applicable land use, land cover data is needed across the Lake Superior basin to facilitate ecosystem condition assessment and trend analysis. Such a data set collected regularly through time could inform and focus field monitoring efforts, and help prioritize restoration and mitigation efforts. Unfortunately, few data sets exist that are bi-nationally consistent in time, classification method, or resolution. To this end, we integrated land cover data across both the Canadian (Ontario Provincial Land Cover data) and US portions (National Land Cover Data) of the Lake Superior basin for two time steps (approximately 1992 and 2001) roughly one decade apart. After harmonizing landcover classes across the two datasets we compared the explicit amount and relative amount (total hectares and proportion of each area as percents) for each of the common land cover classes that occurred across the two time steps for the entire Lake Superior basin, for the U.S. portion of the Lake Superior basin only, and for the Canadian portion of the Lake Superior basin only. We also compared land cover change for the entire basin within a 1 km and a 10 km buffer of the Great Lakes shoreline. We then summarized and compared these land cover types for each time period across a common set of watersheds derived from elevation data (Hollenhorst et al., 2007) for the entire Lake Superior basin. This allowed us to identify and quantify the types of change occurring generally across the entire basin, more specifically across both the U.S. and Canadian portions of the basin, and more explicitly for near coastal areas and watersheds across the entire basin. Noteworthy changes were detected across the basin, particularly an increase in mixed forest types and a corresponding decrease in coniferous forest types.

Keywords: Great Lakes, land use change, National Land Cover Data, Ontario Provincial Land Cover, Binational Land Cover

Introduction

Lake Superior is the largest freshwater lake in the world by area and the third largest by volume. It is also the most pristine of the Great Lakes (U.S. Environmental Protection Agency, 2006). Even still, Lake Superior is not without its threats, ranging from chemical contaminants, shoreline alteration and development, to atmospheric deposition and climate change. These threats and stresses, whether they are acute or chronic, vary from local to continental and even global scales, and even in these relatively pristine systems, have the potential to push ecosystems and communities to alternative stable states (i.e. monotypic stands of invasive phragmites, or wholesale changes in fish communities)

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(Peckham et al., 2006). At the same time, because of the large size of Lake Superior and its surrounding watershed, it is a difficult system to monitor. This is compounded by the basin's relatively low population, and lack of academic and government institutions available to undertake baseline and monitoring efforts necessary to fully understand and quantify the health and condition of the world's largest freshwater basin.

In view of this, consistent, repeatable, and broadly applicable land use, land cover data are needed across the Lake Superior basin to facilitate ecosystem condition assessment and trend analysis. Such data are instrumental in informing planning and policy analyses, helping to focus intensive monitoring efforts, helping to prioritize restoration and mitigation efforts, and furthering our understanding of landscape - water quality relationships (Morrice et al., 2008). A standardized, bi-national classification of land cover, updated at regular intervals (i.e. every 5 years) has been identified as an important component for assessing the state of Lake Superior and would also provide an international perspective of anthropogenic drivers likely to affect the health of various ecosystems across the Great Lakes basin, including Lake Superior (State of the Great Lakes, 2009).

Although there are several different land cover classification efforts and products available for the Lake Superior region, they are not consistent in time, extent, or resolution, and none are consistent across the U.S./Canadian border. To date there has been little, if any, coordination between the two governments to develop a consistent land cover map designed to detect and quantify land cover change. This is changing as the National Oceanic and Atmospheric Administration (NOAA), in conjunction with the USGS NLCD effort, has begun work developing consistent bi-national land cover change maps for the Great Lakes as part of their Coastal Change Analysis Program (N. Harold, NOAA, Charleston, SC, pers. comm.). The first bi-national land cover classification was developed for a single time step (1985–1987) by the Canadian Forest Service to model breeding bird distribution in the Great Lakes basin (Venier et al., 2004). For this effort, Advanced Very High Resolution Radiometer (AVHRR) and Landsat Multi-spectral Scanner (MSS) data (1-km and 200-m resolution, respectively) were used. Although these classifications were useful for modeling breeding bird distribution, multiple time steps were not available to permit assessment of land use change. Furthermore, the coarse resolution would likely preclude detecting change at a local scale.

The most comprehensive analysis of land cover change in the Great Lakes basin (Wolter et al., 2006), which included the Lake Superior basin, was conducted only for the U.S. portion of the basin and required significant effort to develop comparable land cover maps for 1992 and 2001. Although data from an ongoing national program, the USGS National Land Cover Data (NLCD) set, covered the entire area of interest (the U.S. side of the Great Lakes basin), for the two time steps of interest, due to shifts in the processing protocol, considerable work, and additional datasets were needed to make these two time steps comparable. Nevertheless, this work permitted Wolter et al. to document and quantify U.S. Great Lakes change including detection of a significant increase in low intensity development, with over 38% of that change occurring within 10 km of the Great Lakes coastline. In 2011, USGS updated NLCD 2006 designed for land change analysis, released. This is the first high resolution land cover change product ever produced for the nation at a 30 meter spatial resolution.

Concurrently, the Science and Information Branch, Land Information Ontario, Ontario Ministry of Natural Resources, has developed satellite derived land cover data for similar dates (1992 and 2000 respectively), but only for areas on the Canadian Shield for the later date (Spectranalysis Inc., unpublished data). Thus, data for the year 2000 are available for the entire Lake Superior basin but not for Canadian portions of Lake Ontario or Lake Erie. The objectives of this study were to develop a land use change map for the Lake Superior basin, using existing data products, to highlight the need for consistent land cover maps and to assess the potential for detecting the various types of land cover change using existing maps. Hopefully future data products will include compatible satellite derived circa 2000 land cover maps for the southern Ontario portion of the basin, and new updated 2006 land cover map for the entire Canadian portion of the Great Lakes Basin to match existing maps covering the U.S. portion of the Great Lakes.

Methods

Using the reprocessed 1992 and 2001 U.S. NLCD land cover data from Wolter et al. (2006), and 1992 and 2000 Ontario Ministry of Natural Resources, Provincial Land Cover data (PLO) acquired through the Ontario Geospatial Data Exchange (OGDE), we developed a common land cover classification, cross-walking land cover classes found in each dataset. This was accomplished using ArcGIS version 10 geographic information system software (ESRI, 2010) by aggregating specific land cover classes to a less specific common class (i.e. aggregating the four development classes available in the Wolter et al. classification into only one developed class to match the one development class available in the PLO data) and then standardizing the names for each class. This resulted in the identification of 17 common land cover classes representing open lands, agricultural lands, forest lands, and developed areas (Table 1). Using this common land cover classification (classes are briefly described in Table 2), we compared the explicit amount and relative amount (total hectares and proportion of each area as percents) for each of the common land cover classes that occurred across the two time steps for the entire Lake Superior basin, for the U.S. portion of the Lake Superior basin only, and for the Canadian portion of the Lake Superior basin only. We also compared land cover change for the entire basin within a 1 km and a 10 km buffer of the Great Lakes shoreline. We then summarized and compared these land cover types for each time period across a common set of watersheds derived from elevation data (Hollenhorst et al., 2007) for the entire Lake Superior basin.

The explicit amount (expressed in hectares) and the relative amount (expressed in percent of the total area) was calculated for each common land cover class, for each time step and geographic zone. Change was expressed as the difference in hectares and the difference in percent coverage between the two time steps. We also calculated the percent change for each by dividing the difference in hectares by the original amount and then converting this proportion to a percentage. This allowed us to identify and quantify the relative amount and types of change occurring generally across the entire basin, more specifically across both the U.S. and Canadian portions of the basin, and more explicitly for near coastal areas and watersheds across the entire basin. Such an approach helps contrast the relative amount and types of change expected to vary widely across international borders, proximity to the coast, and explicitly by watersheds in the basin.

Results and Discussion

The development of a useful common classification that accommodated differences in detail across the four different land cover classifications (Table 1) required us to significantly simplify each classification. For example, the U.S. land cover classification for developed land identifies four different types of developed land, while there is only one class within the Canadian land cover classification. This results in a significant loss of information, especially in light of work by Wolter et al. (2006) who were able to document a significant increase in low intensity development (likely residential) within 10 km of the Great Lakes coastline. Conversely, the Canadian land cover classification had seven forest classes and ten wetland classes compared to only three forest classes and seven wetland classes in the U.S. Finding common classes across data sets required reducing these to just three common wetland classes and three forest classes.

Despite these simplified classes, we detected noteworthy changes across the entire Lake Superior basin. The greatest change was a 4.9% difference (610,811 ha) in area of mixed forest and a corresponding decrease (3.9%; 493,560 ha) in the proportion of coniferous forest types (Table 3) representing a nearly 17% change (increase) in mixed forest and a 22% change (decrease) in coniferous forest types. Land cover changes in the Canadian portion of the basin (Table 4) largely paralleled those of the entire basin. However, the amount of change was greater; a 7.6% difference (increase) in mixed forest and a 5.8% difference (decrease) in coniferous forest cover (−28% and 20% change relatively). Changes in the U.S. portion of the basin were correspondingly smaller (Table 5). The greatest changes found on the U.S. side of the basin were a 0.5% difference (decrease) in deciduous forest types (20,533 ha) and a 0.5% difference (increase) in developed land types (19,147 ha) or a 11% and −1% change relative to the original amount of deciduous forest and developed land cover. When we compared binational land cover change within 1 km and 10 km of the coast we found similar changes. The proportion of coniferous forest decreased by 3.7% within the 1 km buffer and by 2.9% in the 10 km buffer. This was accompanied by a corresponding increase in proportion of mixed forest with an increase in the proportion of cover of 3.5% and 2.7%, respectively. In this analysis the relative amount of bare ground and crop land also increased across the basin (with more

Table 1. Common land use classes across 1990 and 2000 era U.S. and Canadian classifications.

Common Class	Ontario PLC 1990 Land Cover	Wolter et al. 1992	Ontario PLC 2000 Land Cover	Wolter et al. 2001
Background	Background	Background	Background	Background
Open Water	Water	Open Water (non Great Lakes)	Water - deep clear	Open Water (non Great Lakes)
Open Water			Water - shallow/sedimented	
Development	Settlement and Developed Land	Low Intensity Residential	Settlement/Infrastructure	Low Intensity Residential
Development		High Intensity Residential		High Intensity Residential
Development		Tiger Roads (1992)		Tiger Roads (1992)
Development		Commercial/Industrial		Commercial/Industriai
Bare Ground		Bare Rock/Sand/Clay	Bedrock	Bare Rock/Sand/Clay
Quarries/Strip Mines/Gravel Pits	Mine Tailings, Quarries, and Bedrock	Quarries/Strip Mines/Gravel Pits	Sand/Gravel/Mine Tailings	Quarries/Strip Mines/Gravel Pits
Transitional	Recent Cutovers	Transitional	Forest Depletion–cuts	Transitional
Transitional	Recent Burns		Forest Depletion–burns	
Transitional			Forest–regenerating depletion	
Deciduous Forest	Dense Deciduous Forest	Deciduous Forest	Forest–dense deciduous	Deciduous Forest
Deciduous Forest	Sparse Deciduous Forest			
Evergreen Forest	Dense Coniferous Forest	Evergreen Forest	Forest–dense coniferous	Evergreen Forest
Evergreen Forest	Coniferous Plantation			
Evergreen Forest	Sparse Coniferous Forest			
Mixed Forest	Mixed Forest Mainly Deciduous	Mixed Forest	Forest–sparse	Mixed Forest
Mixed Forest	Mixed Forest Mainly Coniferous		Forest–dense mixed	
Shrubland	Old Cuts and Burns	Shrubland		Shrubland
Orchards/Vìneyards/ Other		Orchards/Vineyards/Other		Orchards/Vineyards/Other
Grassland	Alvar	Grasslands/Herbaceous		Grasslands/Herbaceous
Grassland		Urban/Recreational Grasses		Urban/Recreational Grasses

Pasture/Hay	Pasture and Abandoned Fields	Pasture/Hay	Agriculture–Pasture/ abandoned fields	Pasture/Hay
Cropland	Cropland	Row Crops	Agriculture–cropland	Row Crops
Cropland		Small Grains		Small Grains
Emergent Herbaceous Wetlands	Intertidal Marsh	Emergent Herbaceous Wetlands	Marsh–intertidal	Emergent Herbaceous Wetlands
Emergent Herbaceous Wetlands	Supertidal Marsh	Lowland Grasses	Fen–open	Lowland Grasses
Emergent Herbaceous Wetlands	Freshwater Coastal Marsh/Inland Marsh		Bog–open	
Emergent Herbaceous Wetlands	Open Fen			
Emergent Herbaceous Wetlands	Open Bog			
Emergent Herbaceous Wetlands	Tundra Heath		Tundra Heath	
Exposed Shore		Unconsolidated Shore		Uimconsolidated Shore
Exposed Shore	Coastal Mudflats			
Woody wetland		Lowland Scrub/Shrub	Fen–treed	Lowland Scrub/Shrub
Woody wetland	Deciduous Swamp	Lowland Conifers	Bog–treed	Lowland Conifers
Woody wetland	Conifer Swamp	Lowland Mixed Forest		Lowland Mixed Forest
Woody wetland	Treed Fen	Lowland Hardwoods		Lowland Hardwoods
Woody wetland	Treed Bog			

Table 2. Common land cover class descriptions.

Common class	Description
Background	Outside the area of interest
Bare Ground	Bare Rock, Sand or Clay
Cropland	Agriculture cropland and small grains
Deciduous Forest	Sparse or dense deciduous Forest
Development	All residential, commercial and industrial areas, including roads and highways.
Emergent Herbaceous Wetlands	All marsh areas, fens, bogs and lowland grasses.
Evergreen Forest	Sparse or dense coniferous forest inluding coniferous plantations
Exposed Shore	Unconsolidated shore and coastal mudflats
Grassland	Grassland, urban recreational grasses and alvar areas
Mixed Forest	Mixed forest decidous or coniferous
Open Water	Shallow or deep open water areas
Orchards/Vineyards/Other	orchards and vineyards
Pasture/Hay	Pasture, hay and abandoned Fields
Quarries/Strip Mines/Gravel Pits	Quarries, strip mines, gravel pits and mine tallings
Shrubland	Shrublands, old cuts and burns
Transitional	Recent cuts and burns, depletion cuts and burns and regenerating areas
Woody wetland	Treed fens, bogs and swamps, lowland scrub and forest

than 10 times as much bare ground and more than 4 times as much crop land available across the basin in 2001), but these are relatively rare land cover types (less than 1% of the total area) and changes in their amount could be due simply to classification error etc. The proportion of developed lands in the 1 km buffer increased by 0.5% and in the 10 km buffer by 0.2%. But like bare ground and cropland these are also relatively rare cover types more likely to be affected by classification errors.

Table 3. Land cover change across the entire Lake Superior basin.

	LC 1990 Merge		LC 2000 Merge				
Common Class	ha	Percent	ha	Percent	change (ha)	change (%)	percent change
Open Water	1156347	9.22	1294009	10.33	137662	1.11	11.9
Development	222542	1.78	219621	1.75	−2921	−0.02	−1.3
Bare Ground	1846	0.01	22580	0.18	20735	0.17	1123.4
Quarries/Strip Mines/Gravel Pits	39836	0.32	20758	0.17	−19078	−0.15	−47.9
Transitional	598429	4.77	509894	4.07	−88535	−0.70	−14.8
Deciduous Forest	2975165	23.73	3102975	24.78	127810	1.04	4.3
Evergreen Forest	2253269	17.98	1759709	14.05	−493560	−3.92	−21.9
Mixed Forest	3627237	28.94	4238048	33.84	610811	4.91	16.8
Shrubland	311013	2.48	34416	0.27	−276597	−2.21	−88.9
Grassland	77409	0.62	94643	0.76	17233	0.14	22.3
Pasture/Hay	208474	1.66	173719	1.39	−34755	−0.28	−16.7
Cropland	1025	0.01	5397	0.04	4372	0.03	426.7
Emergent Wetlands	207870	1.66	209220	1.67	1350	0.01	0.6
Exposed Shore	6050	0.05	298	0.00	−5752	−0.05	−95.1
Woody wetland	848692	6.77	837100	6.68	−11593	−0.09	−1.4

Table 4. Land cover changes across the Canadian portion of the Lake Superior basin.

	PLC90		PLC2000				
Common Class	ha	Percent	ha	Percent	change (ha)	change (%)	percent change
Open Water	1031649	12.47	1165447	14.11	133798	1.64	13.0
Development	54834	0.66	32759	0.40	−22075	−0.27	−40.3
Bare Ground	0	0.00	13906	0.17	13906	0.17	
Quarries/Strip Mines/Gravel Pits	21921	0.27	3511	0.04	−18410	−0.22	−84.0
Transitional	577008	6.98	500601	6.06	−76407	−0.91	−13.2
Deciduous Forest	1340995	16.21	1489442	18.03	148447	1.82	11.1
Evergreen Forest	1700564	20.56	1217643	14.74	−482921	−5.82	−28.4
Mixed Forest	3035086	36.69	3655370	44.26	620284	7.57	20.4
Shrubland	291787	3.53	8	0.00	−291779	−3.53	−100.0
Grassland	1	0.00	0	0.00	−1	0.00	−100.0
Pasture/Hay	32401	0.39	4413	0.05	−27988	−0.34	−86.4
Cropland	84	0.00	4478	0.05	4394	0.05	5215.5
Emergent Wetlands	25067	0.30	26721	0.32	1653	0.02	6.6
Exposed Shore	5752	0.07	0	0.00	−5752	−0.07	−100.0
Woody wetland	154415	1.87	144587	1.75	−9828	−0.12	−6.4

When we considered more spatially explicit land cover change (change within watersheds), the most striking change was the loss of coniferous forest types, particularly within watersheds on the Canadian side of the basin (Figure 1). This change is particularly noticeable near Lake Nipigon where large amounts of timber harvest have likely occurred. Without additional time steps of land cover we cannot yet assess whether these harvested areas will regenerate back to coniferous forest types, but there clearly has been significant change in these watersheds in the 10 years between 1991 and 2001.

Table 5. Land cover changes across the U.S. portion of the Lake Superior basin.

	NLCD92		NLCD01				
Common Class	ha	Percent	ha	Percent	change (ha)	change (%)	percent change
Open Water	126132	2.96	129839	3.04	3708	0.09	2.9
Development	167723	3.93	186871	4.38	19147	0.45	11.4
Bare Ground	1850	0.04	8681	0.20	6832	0.16	369.4
Quarries/Strip Mines/Gravel Pits	17915	0.42	17247	0.40	−668	−0.02	−3.7
Transitional	21529	0.50	9313	0.22	−12216	−0.29	−56.7
Deciduous Forest	1634960	38.32	1614427	37.84	−20533	−0.48	−1.3
Evergreen Forest	552882	12.96	542310	12.71	−10572	−0.25	−1.9
Mixed Forest	592367	13.88	583110	13.67	−9256	−0.22	−1.6
Shrubland	19227	0.45	34409	0.81	15181	0.36	79.0
Grassland	77408	1.81	94644	2.22	17235	0.40	22.3
Pasture/Hay	176073	4.13	169305	3.97	−6768	−0.16	−3.8
Cropland	940	0.02	919	0.02	−22	0.00	−2.3
Emergent Wetlands	182804	4.28	182500	4.28	−303	−0.01	−0.2
Exposed Shore	298	0.01	298	0.01	0	0.00	−0.1
Woody wetland	694278	16.27	692512	16.23	−1766	−0.04	−0.3

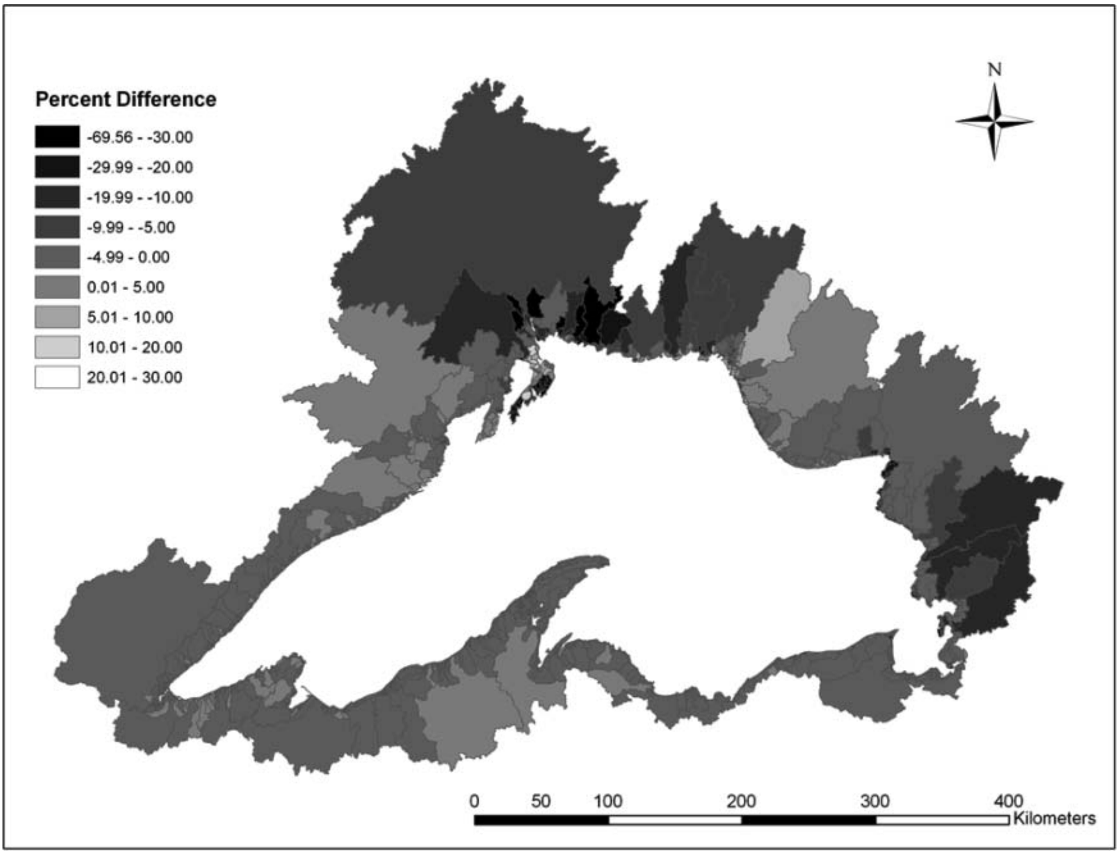

Figure 1. Difference in the percentage of coniferous forest (1992–2001) for tributary watersheds in the Lake Superior basin.

Discussion and Conclusions

Detecting landscape change is a complex endeavor, confused by changing data sources, varying data resolution and differential spatial extents, and finally, land cover classifications. Sources of error include errors (which are not yet well documented) associated with each land cover classification, registration errors and the ambiguity associated with each land cover class definition and temporal differences in the imagery used for the classification. For this analysis we worked with the best available datasets and don't intend this analysis to be the definitive enumeration of land cover change in the Lake Superior basin. Rather, we hope to highlight the need for, and provide a first step towards a consistent and repeatable bi-national land cover change analysis and eventual trend analysis for the Lake Superior basin. We were able to document changes across the entire Lake Superior basin for the decade between the early 1990s and early 2000 using existing land cover data from the U.S. and Canada. Although this effort was complicated by differences in classification schemes (and slightly different dates), we were able to develop a common set of land cover classes both across the basin and across the time steps available. Most notably, we detected a general loss of coniferous forest cover types in the basin, and a trend towards a mixed forest type. This was particularly evident on the Canadian side of the basin and within watersheds near Lake Nipigon. It is beyond the scope of this effort to comprehensively assess mechanisms for this change, but it was visually evident, using Google Earth and Bing Maps imagery, that timber harvesting has occurred proximate to areas with the greatest amount of coniferous forest change. It's possible, and perhaps likely, that these areas will regenerate back to coniferous forest types, but with a changing climate, it's not guaranteed. Irrespective of the mechanism for change, an understanding of forest composition and change will be necessary to anticipate and mitigate climate change effects (i.e. carbon sequestration, nutrient cycling, and changes in ecosystem services in general).

Although we did detect a slight increase in the amount of developed land, particularly closer to the coast, this change was not as large as we might have expected. This is probably generally due to the low human population levels particularly on the Canadian side of the basin. It might also be partially due to the coarse classification resolution for developed lands within the cross-walked classification scheme, with only one land cover class representing the many different types of developed land, and therefore no possibility of assessing intensification of land use (i.e. transition from low density development to high density development). This potential for ambiguity, stemming from the amalgamation of dissimilar land cover classifications, underscores the need for a concerted bi-national effort to consistently document and quantify land cover change across all of the Great Lakes. The effectiveness and potential uses of this effort would be maximized by maintaining the highest possible level of resolution within the land cover classification scheme so that significant types of land cover change can be detected (e.g. transformation from coniferous forest to mixed or deciduous types, or changes from low intensity development to high density development). In fact, documenting and understanding such subtle changes in land cover, including forest age, structure, and fragmentation as well as changes within particular land cover classes, will likely be as important as more obvious types of land cover change. Verry (2000) demonstrated the importance of stand age in influencing stream flow peak discharge. Young forests (less than 16 years of age) exhibited the same increases in discharge at the watershed scale as open land. Consequently, the amount of young forest (< 16 years) has been combined with the area of open land as part of standard hydrologic assessments within Wisconsin Great Lakes watersheds (WI Lake Superior Basin Partner Team 2007). Also, marked effects of forest fragmentation on bird communities have been well documented (Andren, 1994; Hagan et al., 1996), yet we still have few tools or programs to effectively measure changes in habitat fragmentation over time or changes in forest age and structure over large extents (Jaeger, 2000; Jaeger et al., 2008; Riiters et al., 2004; Wickham et al., 2007). In light of the rapidly changing climate in this region (reflected in changing ice cover and water temperatures in Lake Superior (Austin and Colman, 2007), forest fragmentation may be an especially important metric for predicting impacts on wildlife species as they move to new habitat. In summary, we recommend a bi-nationally consistent classification of land cover collected at regular intervals (i.e. every 5 years) that would provide an international perspective of the natural and anthropogenic drivers likely to affect the condition of the key components of the ecosystem across the Lake Superior basin.

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