Spatial Distribution of Small Water Body Types across Indiana Ecoregions

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Due to their large numbers and biogeochemical activity, small water bodies (SWB), such as ponds and wetlands, can have substantial cumulative effects on hydrologic, biogeochemical, and biological processes; yet the spatial distributions of various SWB types are often unknown, especially in modified landscapes. Using updated National Wetland Inventory data, we compare the spatial distribution of SWB types across various ecoregions and land covers within the state of Indiana. Of 203,942 total SWB, 75% contain a permanent water feature and 80% of those SWB are classified as excavated or impounded ponds. Both underlying geology and human modifications influence SWB distributions. Wetlands are most prevalent in the agricultural Drift Plain and are larger with a greater range of sizes than man-made open water features. Small impoundment ponds dominate the southern forested region of the Interior Plateau. Analysis of variance of slopes from power law distributions confirm differences between SWB distributions in the Drift Plain and the Interior Plateau as well as differences between forested wetlands and diked and excavated open waters across ecoregions. SWB densities are lowest in the Corn Belt regions and in agriculture overall. SWB in urban lands tend to have higher median area than natural or agricultural lands and have intermediate densities. This analysis highlights the presence of hydrological modifications in SWB distributions, namely the potential legacy of wetland removal and pond creation practices in the state. Determining these modified distributions and patterns is the first step in understanding cumulative SWB influences on various ecological processes in modified landscapes.

Key words: agricultural ponds, cumulative effects, density-area curve, impoundments, spatial distribution, wetlands.

Introduction

Water bodies are an integral part of hydrologic, biogeochemical, and biological processes and provide important ecosystem services to society (Brauman et al. 2007, Downing 2010). Natural and constructed water bodies store water, providing water supplies and flood mitigation to communities and agriculture. Nutrient, sediment, and pesticide loads are often reduced within water bodies (Zedler and Kercher 2005). In addition, water bodies are vital to numerous species of both economic and ecological importance. Within the conterminous United States (CONUS), national datasets estimate the number of freshwater open water bodies at 3.5 million, covering 130,800 km^2 (McDonald et al. 2012). Over 99% of these water bodies are smaller than 100 ha and account for 29% of total open water body area in the CONUS (McDonald et al. 2012). Estimates of vegetated water bodies (e.g., emergent or forested wetlands) are incomplete, but freshwater vegetated wetlands in the CONUS are estimated at 394,800 km^2 (Dahl 2011).

Despite the importance and potential extent of water bodies, data on the spatial distributions of small water bodies (SWB) are often incomplete or non-existent (Lehner and Doll 2004). For the purposes of this paper, the definition of SWB includes any freshwater lentic water body, open water or vegetated, with an area less than 100 ha (Renwick et al. 2005, Downing et al. 2006) and would include waters like small lakes, ponds, recreational ponds, retention basins, farm ponds, marshes, and swamps. Broad SWB distributions that are accurate and current are rare due to limitations in remote sensing resolution (Verpoorter et al. 2012) and/or the inability to distinguish vegetated SWB from surrounding spectral signatures (Adam et al. 2010). SWB abundance has been extrapolated using power laws from larger water bodies, but higher resolution imagery has suggested that very small natural water bodies (<0.1 ha) are not well represented by power laws estimations (Seekell and Pace 2011, Muster et al. 2013). Uncertainty of total SWB numbers, their areal extent, and their distribution on the landscape leads to uncertainty in the cumulative importance of SWB in hydrologic and biogeochemical processes and in budgets, such as water storage (Smith et al. 2002, Chaney et al. 2012), sediment retention (Downing et al. 2008), and methane contributions (Tranvik et al. 2009).

Studies which include different SWB types are limited. Past discussions have often focused on the distributions and impacts of open water ponds or impoundments (e.g., Renwick et al. 2005, Downing et al. 2006). However, SWB encompass a large range of water features from seasonal forested wetlands to man-made fishing ponds. These SWB types can differ in their hydrologic and biogeochemical processes; the permanent farm pond likely experiences different rates of biogeochemical processes than the seasonal forested wetland. As different SWB types have varied cumulative impacts on hydrological, biogeochemical and biological processes, it is important to account for major SWB types within regional SWB distribution analyses.

Water body distribution studies have primarily focused on natural open waters in less disturbed systems (Downing et al. 2006, Seekell and Pace 2011, Muster et al. 2013) yet many of our water bodies now reside in heavily modified systems where water bodies are removed, modified or created to better meet human needs. Researchers recently have shown an homogenization of landscapes and water bodies in urban areas (Groffman et al. 2014, Steele et al. 2014). Whether due to the initial selection of urban locations or preferential removal of smaller SWB, urban areas experience a shift towards larger water bodies and less variation in size than in surrounding undeveloped areas (Steele and Heffernan 2014).

An accurate understanding of the spatial and size distributions of various SWB types in agriculture is needed as well. Many agricultural areas have experienced a dramatic historical loss of emergent and forested wetlands while permanent man-made SWB have increased (McCauley and Jenkins 2005, Miller et al. 2012, Dahl 2011, Gallant et al. 2011). Current size and type distributions may reflect the preferential losses of some SWB type sizes like smaller seasonal wetlands (Miller et al. 2012), or the creation of artificial SWB that are intentionally constrained in size or shape to meet intended purposes (Fairchild et al. 2013). The distribution of heavily modified agricultural SWB, such as ponds and wetlands, can have substantial cumulative effects on non-point source pollution including, sediment deposition (Downing et al. 2008, Brainard and Fairchild 2012), nutrient retention (Crumpton 2001, Zedler 2003, Mitsch et al. 2005), and pesticide retention (Reichenberger et al. 2007).

Available datasets within the state of Indiana, USA provide an opportunity to explore the spatial distribution of various SWB types that includes large areas of heavily modified agriculture and large urban areas. An updated National Wetland Inventory (NWI) for Indiana provides the spatial distribution of different SWB types at a high level of resolution (>0.04 ha). This paper explores the size and spatial distribution of SWB in Indiana, differentiating among SWB types across various ecoregions and by land use. We hypothesize that SWB size distributions and densities will differ with SWB type and predominant land use. Specifically, we anticipate that wetlands will be larger in size and have more size variation than artificial SWB. The resulting analysis of these SWB distributions and types is the first step in understanding cumulative SWB influences on ecological processes in agricultural settings.

Methods

Study Area

Indiana is included in the agricultural Corn Belt of the United States and, according to the 2006 National Land Cover Database (Fry et al. 2011), agricultural lands cover 62.1% of the state with 54.7% in crop production (primarily corn and soybeans) and 7.3% in pasture lands. Urban areas cover 10.6% of the state, including the metropolitan areas of Indianapolis, Fort Wayne, Evansville, South Bend, Gary and suburban reaches of the greater Chicago area. Natural areas of forest land and wetlands occupy 22.8% and 1.5% respectively (Figure 1). Human modifications have had a large impact on the state's water resources. Indiana has lost greater than an estimated 87% of its historical wetland acreage (Dahl et al. 1991). In addition, water quality measurements in streams and lakes in the state have recorded high nutrient and pesticide concentrations (Gilliom et al. 2006, Robertson et al. 2009, ISDA 2013). Over 43% of stream/river miles and 41% of lakes in the state are considered impaired (IDEM 2012).

The state has relatively complex surficial geology and includes major portions of 5 ecoregions (Level III) across the state (Omernik 1987, US EPA 2013; Figure 1). The Corn Belt and Drift Plains ecoregions of the northern 2/3 of the state are primarily a result of multiple Pleistocene glacial incursions and irregular retreats ending with the most recent Wisconsinan glaciations (21,000 to 13,600 years ago). Glacial retreats in this northern portion of the state formed the prairies, drift plains, northern moraines and lakes. Glacial till found through the central portion of the state contains much of the state's row crop agriculture. Prior to European settlement, the northern 2/3 of the state was estimated to have had greater than 22,600 km^2 of wetlands (Whitaker and Amlaner 2012). The southern 1/3 of the state contains the Interior Plateau, an area of Mississippian/Pennsylvanian age limestone with distinct escarpments and karst formations. Areas to the west and east of the Plateau were subject to pre-Wisconsinan glacial events and are now a mixture of alluvial deposits, Illinoian glacial till and exposed Paleozoic bedrock (Gray 1989, Whitaker and Amlaner 2012).

Small Water Body Dataset

The state of Indiana updated their contribution to the NWI in 2010 as part of a Great Lakes state initiative, in collaboration with Ducks Unlimited, Inc. (DU). DU used geographic information system (GIS) technology with spring color infrared (0.5 m) leaf-off imagery from 2005 and summer true color (1 m) National Agriculture Imagery Program 2003 digital orthophotos to: 1) confirm existing wetlands in the NWI, 2) remove wetlands that had been converted to other land uses, and 3) correct or add new wetlands to the dataset. The map scale used to delineate wetlands was 1:10,000 and a conservative minimum mapping unit for the update was set at 0.04 ha, above detectable size limits given the imagery resolution and map scale. DU also performed field verification of delineations for 1% of all wetlands and identified wetlands with 86% accuracy. The same imagery dates, supplementary data, and identification process were used across the entire state for consistency (for more details see Ducks Unlimited 2010). The updated Indiana NWI dataset was downloaded in April 2013 (http://www.fws.gov/wetlands/Data/State-Downloads.html) and consists of over 319,900 polygons representing wetland areas of varying types (i.e., open water, emergent, forested), persistence (i.e., permanent or seasonal), and human alterations (impounded or excavated). All these wetland characteristics are coded in a detailed alphanumeric variable for each wetland polygon (Cowardin et al. 1979). For this study, we selected all polygons with palustrine and lacustrine wetland classes associated with open water, emergent vegetation, or forested vegetation that are designated as seasonal or permanent wetlands (Table 1). All data processing activities were conducted using Environmental Systems Research Institute (Esri® Redlands CA 2010) ArcGIS v.10.0 and 10.1.

Within the NWI, multiple polygons from different wetland types may be adjacent to one another (e.g., an open water polygon surrounded by a seasonal emergent marsh polygon) but in this analysis adjacent polygons are aggregated into a single SWB. Prior to final aggregation, three large lacustrine littoral polygons associated with reservoirs were excluded because examination of the area indicated these polygons represented maximum reservoir fill capacity rather than current water body area. All remaining polygons meeting the wetland type and persistence criteria (Table 1) were selected and adjoining polygons were aggregated into combined SWB. Less than 5% of the SWB dataset are combinations of multiple polygons but as Lane et al. (2012) found, they are typically also the larger SWB, accounting for 40% of total water area in this study. For those SWB derived from multiple polygons, the SWB type with the greatest cumulative area was assigned to the SWB. New areas for each combined SWB were calculated by using the ArcGIS® Calculate Geometry tool. Based on the detection limits accepted in the metadata, SWB with areas less than 0.04 ha are excluded from the dataset. Water bodies larger than 100 ha (excluding Lake Michigan) are included to calculate water area statistics but are excluded from SWB calculations, log-log slope estimations and subsequent statistical analyses. Densities of SWB were calculated and plotted for visual comparison across the state by counting the SWB geographical centroids within each 12-digit Hydrological Unit Code (HUC) catchment. The 12-digit HUCs were downloaded from the Watershed Boundary Dataset (http://nhd.usgs.gov/wbd.html) and clipped to the Indiana NWI extent.

Land use/land cover (LULC) from the 2006 National Land Cover Database (NLCD; Fry et al. 2011) was used to calculate percentages of agricultural (row crop and pasture classes), urban (open, low, moderate, and high density urban classes), and natural lands (forest, shrubland, grassland, and wetland classes). These combined classes were summarized for all National Hydrography Datasets (NHD) catchments from NHDPlus v.2 that intersect the state of Indiana (http://www.horizon-systems.com/nhdplus/NHDPlusV2_data.php). NLCD 2006 was used as it best aligns with the aerial image dates from the updated NWI dataset. The LULC percentages for each NHD catchment were calculated using the Tabulate Area function in ArcGIS v 10.1. The LULC with the greatest percentage was considered the dominant LULC for each NHD catchment. To assign LULC to the SWB, the centroid of each SWB was identified and associated with its corresponding NHD catchment and dominant LULC.

Statistics

Finalized SWB abundance, areal extent, area medians, and 25th and 75th percentiles were summarized across ecoregions, SWB type, and LULC. To compare densities of SWB types, the entire SWB dataset underwent a binning procedure on a log scale and resulting size class bins were preserved when performing statistical analyses into the various ecoregions to produce SWB type density by log-area plots. The inflection point, where the density in log-area plots reverses its direction, was determined as the midpoint value for the area class at the maximum density value. SWB area data were heavily skewed and failed to meet conditions of normality when log-transformed. Due to its skewed nature, means and medians fail to completely capture the size and shape of the distributions. Several authors have used power law log-log linear regressions to compare size distributions, where SWB area and the number of SWB equal to or greater than size A are log transformed (Downing et al. 2006, Seekell and Pace 2011, McDonald et al. 2012, Steele and Heffernan 2014). Resulting slopes can indicate the shape of the distribution; steeper or more negative slopes show more small features of SWB relative to larger features while shallow or less negative slopes indicate greater numbers of larger features. The log-log linear regressions and subsequent analyses of variance were done to compare the size distributions for ecoregions, SWB types, and LULC. All of our statistical analyses were carried on using SAS® (1999).

Results

State and Ecoregion Summaries

A total of 203,942 SWB are found within the five major ecoregions of Indiana, which translates to an overall density of 1.94 SWB/km^2. SWB cover an area of 192,589 ha or 1.8% of total state area (Table 2). SWB account for 99% of all water body abundance and for 74% of the water body area in the state while SWB < 1 ha alone make up 18% of water area. The median size of SWB across the state is 0.24 ha. Overall, 75% of all SWB contain a permanent water feature and 80% of those SWB are classified as excavated or impounded ponds (Supplemental Table 1). The overall spatial distribution of SWB across the state concentrates on the northeast portion of the state, the urban areas surrounding Lake Michigan and Indianapolis, and throughout the non-glaciated southern region (Figure 2).

In the northeast, the Drift Plains have high densities of SWB, 2.33 SWB per km^2 and 4.2% of the ecoregion's total area. Seventy-three percent of Drift Plains SWB are < 1 ha and account for 9% of total water area in the ecoregion (Table 2). High SWB densities are also found in the southern Interior Plateau and Lowlands; respectively, 2.45 and 2.41 SWB per km^2 but only account for 0.9% and 2.4% of their respective ecoregions' areas (Table 2). SWB <1 ha are heavily dominant in the Interior Plateau, making up 31% of total water area. The lowest SWB densities are found in the central agricultural regions; the Central Corn Belt registers densities of 0.99 SWB per km^2 while the Eastern Corn Belt density is 1.65 SWB per km^2 and is dominated by SWB <1 ha, accounting for 34% of SWB area or 28% of total water area. In addition to the predominance of very small water bodies, 76-92% of SWB in the Eastern Corn Belt and the Interior Plateau and Lowlands are permanent waters. This is in contrast to the Drift Plains and Central Corn Belt where only 42% and 59% of SWB include permanent water respectively. The Drift Plains also have more SWB in the 10-100 ha range and the greatest number of large water bodies (>100 ha) which contributes to a larger overall percentage of water coverage than any other ecoregion (Table 2).

This greater proportion of larger water bodies in the northern ecoregions is evident when examining the median values of SWB area; the Drift Plain and the Central Corn belt are 0.36 ha and 0.38 ha, respectively, while the median SWB area for the Eastern Corn Belt, the Interior Lowland and Interior Plateau are 0.25 ha, 0.24 ha and 0.14 ha respectively (Table 2). When comparing ecoregion distributions via the slopes of log-linear regressions, slopes for ecoregions are significantly different (F value = 6.37, p = 0.003) and the negative slope of the SWB distribution in the Interior Plateau (slope = -1.01) is significantly larger (Bonferroni's test stastic: p=0.01) than the slopes of the Drift Plain (-0.75), the Central Corn Belt (-0.75) or the Interior Lowland (-0.74), while the Eastern Corn Belt displays intermediate slopes (-0.89) (Figure 3).

SWB Type Comparisons

Freshwater forested wetlands have higher median SWB area values than other SWB types, especially those of open waters (Figure 4). The range of SWB area are also greatest for forested wetlands, intermediate for emergent wetlands, and smallest for open waters (Figure 4). The slopes for SWB types are significantly different (F value = 3.73, p = 0.025) with forested wetland slopes being significantly more shallow or more dominated by larger SWB (slope = -0.68) than the slope of excavated open waters (slope = -0.91) and diked open waters (slope = -0.90) (Bonferroni's test stastic: p = 0.05; Figure 5).

When combining ecoregions and SWB type via density/log area plots, stark differences become apparent (Figure 6). The high densities in the Interior Plateau are dominated by permanent open water types, especially diked open waters less than 1.0 ha in size which alone account for 60% of all SWB in the Interior Plateau (Supplemental Table 1). Diked and excavated open water are also predominant in the Interior Lowland and in the Eastern Corn Belt, though overall densities are lower than in the Interior Plateau. Diked SWB are very scarce in the Central Corn Belt and in the Drift Plains. The Interior Plateau, Interior Lowland, and Eastern Corn Belt all have relatively low numbers of forested and emergent SWB that range from 10-28% of total SWB (Figure 6, Supplemental Table 1). By contrast, the Drift Plains are dominated by larger forested and emergent SWB types which account for 69% of the SWB types and 79% of SWB area in the ecoregion (Supplemental Tables 1 and 2). These forested and emergent SWB are found across a broader size class range than the diked/impounded SWB. The Central Corn Belt also has 50% forested or emergent SWB, but the overall densities in the Central Corn Belt portion are much lower than in any other region within Indiana. Within the density/log area plots, all ecoregions show very low densities around the minimum detection point of 0.04 ha, increasing SWB numbers with increasing SWB area size up to an inflection point where SWB abundance then decreases with greater SWB area size (Figure 6). The shape of the plot and the inflection point differs between ecoregions as the point of change for the Interior Plateau is 0.11 ha, the Interior Lowland is 0.15 ha, the Eastern Corn Belt is 0.17 ha, the Drift Plain is 0.18 ha, and the Central Corn Belt is 0.29 ha.

Slope analyses for SWB type across ecoregions also show the SWB type distributional differences that exists from the Drift Plain in the north from the Interior Plateau in the south (Figure 7). Both the emergent and forested wetlands deviate from the power law as indicated by lower R^2 values, generally showing a convex curvature in the plots. Open waters, especially dikes open waters, tend to follow the power law more closely with few large open waters and numerous small open waters; some even demonstrate a concave curvature indicating very few large open waters followed by a strong increase in smaller open waters.

Comparison across Land Use/Land Cover

Due to underlying geology, LULC can often closely resemble ecoregions. Such is the case in this study were natural classes are predominately found in the non-glaciated Interior Plateau, while much of the remaining ecoregions are dominated by agricultural land uses. Urban areas are less tied to ecoregions but are more prevalent in the agricultural ecoregions outside of the Interior Plateau (Figure 1). Natural LULC has the highest densities of SWB with 2.57 SWB per km^2 which coincides with the 2.45 SWB per km^2 found in the Interior Plateau (Table 3). Urban LULC has higher densities of SWB 2.08 SWB per km^2 than agricultural LULC which has 1.66 SWB per km^2 (Table 3). Median SWB area values show that urban SWB tend to be larger (0.33 ha) than natural (0.18 ha) and agricultural (0.25 ha) and that trend is consistent across SWB types (Figure 8). However, ANOVA tests for the slopes for the three LULC classes, -0.84 for agriculture, -0.83 for natural, and -0.73 for urban, are not significantly different from each other (F value = 3.65, p=0.07).

Discussion

Natural and Man-made Influences on Distributions

Differences in SWB across the state of Indiana illustrate both the importance of underlying geology that naturally creates variation in water body type distributions and the importance of how humans modify that natural variation to meet their needs. The dual influence of geology and anthropogenic impacts incorporates differences seen between ecoregions, SWB types and LULC. For this discussion, we focus on the strongest SWB contrasts seen in the state: the presence/absence of wetlands in the glaciated agricultural regions and the forested landscape in the Interior Plateau with its numerous modified open waters.

Wetlands in the Agricultural Regions

The upper portion of the Central Corn Belt just east of present day Lake Michigan and the entire Drift Plain contain multiple moraines, kettles, lakes and outwash plains, remnants from the Wisconsinan glaciation. Post-glaciation, the area was historically covered in large swamp forests of beech and maple mixed with oak, so large wetlands are a natural feature of that landscape (Whitaker and Amlaner 2012). We hypothesized that SWB types would differ in size distributions. Indeed, forested wetlands and emergent wetlands within this agricultural region are typically of greater size and have greater variation in size than open waters. One possible contributor to the size difference is that as natural landscapes were converted to agriculture, the smallest forested and emergent wetlands were the first to be modified, drained or converted. It is possible that larger forested wetland complexes were more difficult to convert into other land uses and thus remain a part of the landscape while the smaller areas have been lost. The absence of small wetlands likely includes some of the estimated 87% of historical wetland acreage lost to agricultural and urban areas in Indiana since 1790 (Dahl et al. 1991). Looking at current and historical depression size in northern Iowa wetlands via power law plots, Van Meter and Basu (2015) also suggested a loss of small wetlands and very large wetlands. They described this loss as a homogenization of the agricultural landscape in northern Iowa. Miller et al. (2012) also categorized the large historical wetland losses in Iowa and found that the vast majority of wetlands lost were temporary and seasonal wetlands and those that remain or have been restored are more permanent wetlands. Much of this wetland loss was prior to the signing of the Clean Water Act (CWA) in 1972 which protected remaining wetlands and the Swampbuster provision of the 1985 Food Securities Act which tied wetland protection to farm subsidies (van der Valk and Pederson 2003). Although there is no minimum size for CWA protection, some smaller wetlands have been filled in the past and recent U.S. Supreme Court cases have stripped isolated wetlands of CWA protections, making them more susceptible to loss and degradation (van der Valk and Pederson 2003 Leibowitz et al. 2008).

Agricultural lands in the Corn Belt also include open waters that comprise 63% of agricultural SWB. These open water bodies are increasing in abundance as natural wetlands decrease (Dahl 2011). It may be these types of agricultural open waters that Steele and Heffernan (2014) alluded to when reporting that agricultural SWB were smaller and simpler than undeveloped areas. Agricultural SWB may be disproportionally important to regional and global cycles as pollutant loads and rates may be especially high in agricultural settings. Downing et al. (2008) found high organic carbon burial rates in small agricultural lakes and Crumpton et al. (2006) reported high nitrate inputs and subsequent removal in constructed agricultural wetlands. More discussion on open waters is found below, but both remaining wetlands in Indiana and modified water bodies in agriculture are likely to influence ecological processes and their presence, their historical losses, and historical gains need to be considered in regional analyses of past, current and future cumulative impacts of SWBs (Van Meter and Basu 2015).

Wetlands have typically been minimally represented by hydrography datasets and their omission in discussion of SWB distributions could lead to incomplete or inaccurate understanding of hydrologic processes and biologic connectivity. The inclusion of seasonal and permanent emergent and forested wetlands adds 61,480 SWB or 30% to the total abundance. In the Drift Plains, emergent and forested wetlands account for 69% of SWB. In this ecoregion, densities would have been 0.70 SWB/km^2 instead of the 2.33 SWB/km^2 reported here if wetlands had not been included. Wetland inclusion can have large impacts on spatial connectivity which influences hydrology and biological processes. For example, reproduction, migration, and overwintering for amphibians can depend upon the distance between suitable water bodies; amphibians often use combinations of permanent or seasonal wetlands (Marsh and Trenham 2001). Using a simple nearest neighbor analysis, the average distance between SWB centroids in the Drift Plains is 257 m when wetlands are included and increases to 440 m when only open water bodies are used. Connectivity is not only important to biological and hydrological processes but the presence or absence of wetland connectivity to navigable water bodies has direct implications to wetland protection status (US EPA 2015). Although descriptions and methods of connectivity are beginning to be established, more research is needed to accurately describe and predict wetland connections across the broader landscape (Golden et al. 2014, Ruiz et al. 2014, McDonough et al. 2015)

The importance of wetland inclusion in SWB datasets is also evident when considering cumulative biogeochemical processes. Vegetated wetlands can behave differently than open water areas in nutrient transport and transformations (Saunders and Kalff 2001), carbon cycles (Cole et al. 2007), and pesticide retention (Gregoire et al. 2009). Differences in biogeochemical reactions may be especially pronounced in seasonal wetlands that have periodic drying and oxidation of sediments. If we were to estimate the impact of water bodies in the Drift Plains without considering seasonal and permanent wetlands, we would exclude over 51,000 hectares that have the potential to store water, retain sediments and biogeochemically transform carbon and nutrients.

Open Waters in the Forested Interior Plateau

The Interior Plateau and Lowlands remained to the south of the Wisconsinan glaciation so karst landscapes, greater relief, and greater stream dissection minimize the presence of larger wetlands. In this study, the forested Interior Plateau and Lowland have the highest densities and smallest SWB sizes and ranges. Very small diked or excavated open waters (0.04 to 1.0 ha) account for 69% of all SWB in the regions. Just as preferential loss of wetlands may increase the median size of wetlands in the agricultural regions, preferential open water creation might also help explain why open waters are smaller than natural wetlands. Open waters exhibit a propensity to fall within the range of 0.1 to 1 ha. A similar range has been found in Pennsylvania impoundments (Fairchild et al. 2013) while many regions of Europe report similar distributions below 5 ha (Oertli et al. 2005). Excavated or diked water bodies are often constructed as local water retention or water quality structures, sources of water for livestock or irrigation, or as recreational ponds (Fairchild et al. 2013, Downing 2010). The Natural Resources Conservation Service's (NRCS) conservation practice standard for pond construction (Code 378) and extension literature recommend specific shapes and sizes of SWB that fit functional, aesthetic, and economic purposes (e.g., Carroll and Jones 2008). For example, NRCS recommends a minimum surface area for ponds between 0.06 and 0.1 ha and for ponds larger than 10 ha, rock or concrete spillways should be used (NRCS 1997, Knipp et al. 2008). These recommendations likely contribute to a more select range of pond sizes, potentially leading to the homogenization of the landscape (Groffman et al. 2014, Steele et al. 2014, Van Meter and Basu 2015).

The higher resolution NWI dataset allows for detection of SWB like small retention ponds, excavated farm ponds, and recreational ponds that are typically underestimated in national datasets (Smith et al. 2002, Downing et al. 2006). Many previous studies have used a minimum resolution of 0.1 ha, often relying on satellite data like Landsat imagery which omit or lump SWB smaller than 0.1 ha (Muster et al. 2013). The addition of the smallest size class (0.04 ha – 0.1 ha) in this dataset adds 37,483 SWB or 18% of all SWB though it only adds 1% to total water area.

Despite the lack of the smallest impoundments in datasets, there has been a recent focus on the importance of pond distributions and impacts (Downing et al. 2006, Downing et al. 2008, Oertli et al. 2009, Seekell and Pace 2011, McDonald et al. 2012, Winslow et al. 2013). Generally, construction of these open water SWB is thought to be increasing in the U.S. as well as in Europe (Downing et al. 2006, Cereghino et al. 2008, Fairchild et al. 2013). In-stream ponds in southeast Pennsylvania, USA, were shown to alter stream chemistry and reduce nutrient exports (Fairchild and Velinsky 2006) while numerous authors have documented the impacts of small ponds and impoundments on sediment and carbon retention (Smith et al. 2002, Renwick et al. 2005, Downing et al. 2008, Brainard and Fairchild 2012). Pond abundance likely influences hydrologic processes (Vörösmarty and Sahagian 2000) including increasing evapotranspiration rates, potentially reducing peak flows (Chaney et al. 2012) as well as changing the spatial connectivity of the landscape (Freeman et al. 2007, Phillips et al. 2011, Mekonnen et al. 2014). Given that in this study the cumulative area of the smallest SWB is only 1% of the total water area, it is still debatable how much they might influence some large-scale processes like peak flows. However, Winslow et al. (2013) have argued that for many biogeochemical processes, like allochthonous carbon fluxes, denitrification and methane generation, the water to land interface (cumulative perimeter) is more important to rates than cumulative area. Preliminary analysis indicates that SWB <0.1 ha and SWB <1 ha account for 5% and 50% of cumulative perimeter respectively. Likewise, small amounts of total area may not reflect the importance of ponds to spatial connectivity. Increased pond densities have been shown to increase aquatic biodiversity and influence metapopulation dynamics in regions where natural water bodies have been lost (Williams et al. 2004, Cereghino et al. 2008, Brainwood and Burgin 2009, Casas et al. 2012). As constructed SWB numbers increase and our high resolution datasets begin to include these small impoundments, the cumulative impacts of small ponds on biogeochemical, hydrologic, and biological processes need to be quantified.

Urban Settings

Compared to high natural and low agricultural SWB densities, SWB in urban settings have intermediate densities. Higher SWB densities surrounding Indianapolis and the populated region south of Lake Michigan are observed in this study which would indicate that densities may be higher in and around larger cities. In studying cities of various population sizes, Steele and Heffernan (2014) found increasing SWB coverage with increases in city sizes. Conversely, a Pennsylvania study found a negative relationship between pond density and population density in 31 municipalities. It is difficult to compare their population densities with our designation of urban lands and the three city class sizes of Steele and Heffernan (2014) but we suspect larger urban/suburban locations may have increased densities compared with smaller towns and surrounding agricultural lands that have lower densities. Our expectation was that wetlands would be larger and more variable than open water structures, and this was true especially in urban settings where urban forested wetlands were larger than any other SWB type. Though not significant, all urban waters in this study tend to be larger in than agricultural or natural waters. Recent research found increased size and simplicity of urban SWB when compared with nearby SWB of undeveloped areas (Steele and Heffernan 2014). They postulate that increased size in urban areas results from either preferential losses of smaller features, the creation of larger waters to meet designed functions, or the preferential settling of urban areas next to larger bodies of water. Further study should be focused on how these SWB interact with pollutants and hydrology that are unique to urban environments.

Abundance-Area Relationships

In the absence of broad SWB distribution datasets, researchers have attempted to estimate abundance and areal extent of water bodies from smaller datasets through various statistical methods. Downing et al. (2006) used a power law to estimate global open water body abundance and size distributions; this has been supported in regional analyses of natural areas across the globe (reported in Downing et al. 2006) and in the Prairie Pothole Region of South Dakota (Zhang et al. 2009). Numerous authors have suggested that power laws may not represent the lower tail of SWB distributions well and may overestimate the numbers of natural SWB (Seekell and Pace 2011, McDonald et al. 2012). This overestimation is either due to the sensitivity of parameter estimates across logarithmic scales when relying on larger water body datasets

(Seekell and Pace 2011, McDonald et al. 2012) or the apparent plateau of very small water bodies when higher resolution data are used (Seekell and Pace 2011, Muster et al. 2013). Our findings align with the high resolution dataset studies in that very SWB (<0.1 ha) plateau below the expected power law regression. Some of the plateau is necessarily due to errors of omission; it is impossible to determine how much of the plateau is due to error. Yet in light of the high resolution data and the conservative cut off we suggest that the plateau in this hydrologically modified state also reflects the loss of smaller wetlands and the creation of open waters within a preferred size range that are discussed here and in other studies (Van Meter and Basu 2015). Our findings add to the existing literature in that we report abundance-area relationships from multiple SWB types in highly modified landscapes. Wetland SWB tend to have a strong convex shape that indicates larger numbers of moderately sized SWB while diked and excavated open waters trail below the regression line shape (very few large features) and then increase around 1 ha and peak at 0.1 ha. More study is needed in other areas of modified landscapes to see if such patterns of wetlands and man-made structures are consistent.

Conclusion

SWB size distributions and densities differ with ecoregion, SWB type and by predominant land use, reflecting not only the underlying geology but also human alterations to the landscape. Agricultural regions in the glaciated portion of the state are dominated by larger wetlands combined with much smaller open water features, potentially indicating the legacy of selective wetland loss and pond construction constraints. Natural areas located in the Interior Plateau are dominated by very small impoundments that highlight the importance of human modifications and high-resolution data in understanding the true distribution of SWB and its potential effects. Urban areas show increased size and greater densities than agricultural areas. The resulting analysis of these SWB distributions and types is the first step in understanding cumulative SWB influences on ecological processes in agricultural settings.

Future study should focus on SWB distributions in agricultural settings and other disturbed settings. It is in these locations where SWB may have disproportionate impacts on biogeochemical cycles due to their proximity to higher rates of erosion and pollutant loading. To move towards such estimates of effects on biogeochemical cycles, the next steps after determining distributions is to estimate volumes of SWB and delineate catchments to better understand capacities, turnover times and pollutant loads. Research to estimate these parameters continues for the Indiana dataset. Future work should also include the expansion of SWB distributions beyond Indiana. This study uses updated NWI data to determine SWB; NWI data are available for much of the CONUS though its consistency and dates of imagery vary considerably. Several states and non-profit organizations have or are currently updating NWI datasets which could be used to create such distributions in other areas (eg. Van Meter and Basu 2015). Such an effort would greatly increase our understanding of SWB and lead to better estimates of distributions and variability in distributions across a wider area.

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Table 1. Concordance of defined Small Water Bodies types and permanence classes with their associated wetland classes, modifiers and water regimes from the National Wetland Inventory after Cowardin et al. (1979).

SWB type	Wetland Classes[1]	Modifier[3]
Open Water	AB, OW, UB, US	--
Open Water - diked	AB, OW, UB, US	h
Open Water - excavated	AB, OW, UB, US	x
Emergent	EM	--
Forested	FO, SS	--
	Water regime[2]	
Permanent	F,G,H,K	
Seasonal	C,E,J,	

Descriptions are based on Wetlands and Deepwater Habitats Classification (Cowardin et al. 1979*)*. All SWB are lacustrine or palustrine systems, subsystem L1 and L2 (except as noted in text). [1]Class abbreviations: AB = aquatic bed, EM = emergent, FO = forested, OW = open water, SS = scrub-shrub, UB = unconsolidated bottom, US = unconsolidated shore

[2]Water Regime abbreviations: C = seasonally flooded, E = seasonally flooded/saturated, F = semipermanently flooded, G = intermittently exposed, H = permanently flooded, J = intermittently flooded, K = artificially flooded.

[3]Modifier abbreviations: h = diked or impounded, x = excavated or borrow pit

Table 2. Number, total area, densities and median area of SWB for five major ecoregions in the state of Indiana. Density is the total number of SWB per total area for the Ecoregion.

	Drift Plains		Central Corn Belt		Eastern Corn Belt		Interior Plateau		Interior Lowland		All Ecoregions	
Size Class (ha)	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)
0.04-0.1	4081	301	1247	91	10518	780	14342	1040	7295	534	37483	2746
0.1-1	22310	7909	7039	2583	50552	16464	28351	7284	27458	8862	135710	43102
1-10	8199	23721	2584	7519	8847	22063	1960	4623	6244	16466	27834	74391
10-100	1231	33336	378	9471	520	10949	133	3274	653	15319	2915	72349
>100	125	30993	32	6733	26	10818	10	10296	21	8389	214	67229
Total Water (TW)	35946	96260	11280	26398	70463	61075	44796	26517	41671	49568	204156	259818
% SWB of TW	99.7%	67.8%	99.7%	74.5%	100.0%	82.3%	100.0%	61.2%	99.9%	83.1%	99.9%	74.1%
% SWB <1 ha of TW	73.4%	8.5%	73.5%	10.1%	86.7%	28.2%	95.3%	31.4%	83.4%	19.0%	84.8%	17.6%
% SWB with Permanent Water	42.2%	55.2%	59.2%	58.7%	75.9%	67.9%	91.7%	87.8%	86.6%	81.8%	74.7%	67.3%
Ecoregion Area (km^2)	15389		11306		42607		18293		17295		104889	
SWB Density (#/km^2)	2.33	--	0.99	--	1.65	--	2.45	--	2.41	--	1.94	--
% SWB of Total Area	--	4.2%	--	1.7%	--	1.2%	--	0.9%	--	2.4%	--	1.8%
% TW of Total Area	--	6.3%	--	2.3%	--	1.4%	--	1.4%	--	2.9%	--	2.5%
Median area (ha)	--	0.36	--	0.38	--	0.25	--	0.14	--	0.24	--	0.23
25th/75th percentile (ha)	--	0.16/1.07	--	0.17/1.07	--	0.13/0.54	--	0.09/0.26	--	0.12/0.61	--	0.12/0.56

Table 3. Number, area, densities and median area of SWB for three land cover classes in the state of Indiana. Density is the total number of SWB per total land cover area.

	Agriculture		Natural		Urban	
Size Class (ha)	Number	Area (ha)	Number	Area (ha)	Number	Area (ha)
0.04-0.1	20832	1536	15071	1094	1580	115
0.1-1	87783	28589	39253	11394	8674	3119
1.0-10.0	19696	52588	5729	15169	2409	6634
10-100	1881	45585	718	19315	316	7449
Total SWB	130192	128299	60771	46973	12979	17317
Land Cover Area (km^2)	78281		23644		6214	
SWB Density (#/km^2)	1.66	--	2.57	--	2.09	--
% SWB of Land Cover Area	--	0.02	--	0.02	--	0.03
Median Area (ha)	--	0.25	--	0.18	--	0.33
25th/75th percentile (ha)	--	0.13/0.62	--	0.10/0.40	--	0.16/0.82

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Figure 1. National Land Cover Database 2006 and major urban centers for the state of Indiana (state boundary in blue). Black lines and associated labels denote major ecoregions (level III). The red line denoted the southern limit of the Wisconsinan Glacial extent.

Figure 2. Density of SWB (total#SWB/catchment area km^2 in Hydrologic Unit Code (HUC) 12-digit) catchments across five major ecoregions (level III) in the state of Indiana. HUC-12 catchments clipped from the Natural Resources Conservation Service's Watershed Boundary Dataset.

Figure 3. Mean and standard error for slope values for each ecoregion, using the power law log-linear regressions for SWB type within each ecoregion. Letters signify significance at $p=0.05$, Bonferroni's test for multiple comparison of means.

Figure 4. SWB median area (ha) and 25th and 75th percentiles for each SWB type in each ecoregion. DP=Drift Plain, CCB=Central Corn Belt, ECB=Eastern Corn Belt, IP=Interior Plateau, IL=Interior Lowland. FEM=freshwater emergent wetland, FFOR=freshwater forested wetland, OW=open water, OWd=open water diked, OWe=open water excavated.

Figure 5. Mean and standard error for slope values for each SWB type, using the power law log-linear regressions for SWB type within each ecoregion. Letters signify significance at $p=0.05$, Bonferroni's test for multiple comparison of means. FEM=freshwater emergent wetland, FFOR=freshwater forested wetland, OW=open water, OWd=open water diked, OWe=open water excavated.

Figure 6. Density/log-area classes for five major ecoregions of Indiana. Density is the number of SWBs within a given size class per total hectares land area in the ecoregion. Vertical dashed lines denote 0.1, 1.0, and 10.0 hectare SWB size class divisions. FEM=freshwater emergent wetland, FFOR=freshwater forested wetland, OW=open water, OWd=open water diked, OWe=open water excavated.

Figure 7. Number of SWB of greater area per SWB area on log-log scale for individual SWB types for three ecoregions: the Drift Plains ecoregion, the Eastern Corn Belt ecoregion and the Interior Plateau ecoregion in the state of Indiana. The fitted regression line for each SWB type as well as resulting slope value and R^2 value are shown. FEM=freshwater emergent wetland, FFOR=freshwater forested wetland, OW=open water, OWd=open water diked, OWe=open water excavated.

Figure 8. SWB median area (ha) and 25th and 75th percentiles for each SWB type within each land use/land cover class. Ag=Agriculture, Nat=Natural, Urb=Urban. FEM=freshwater emergent wetland, FFOR=freshwater forested wetland, OW=open water, OWd=open water diked, OWe=open water excavated.

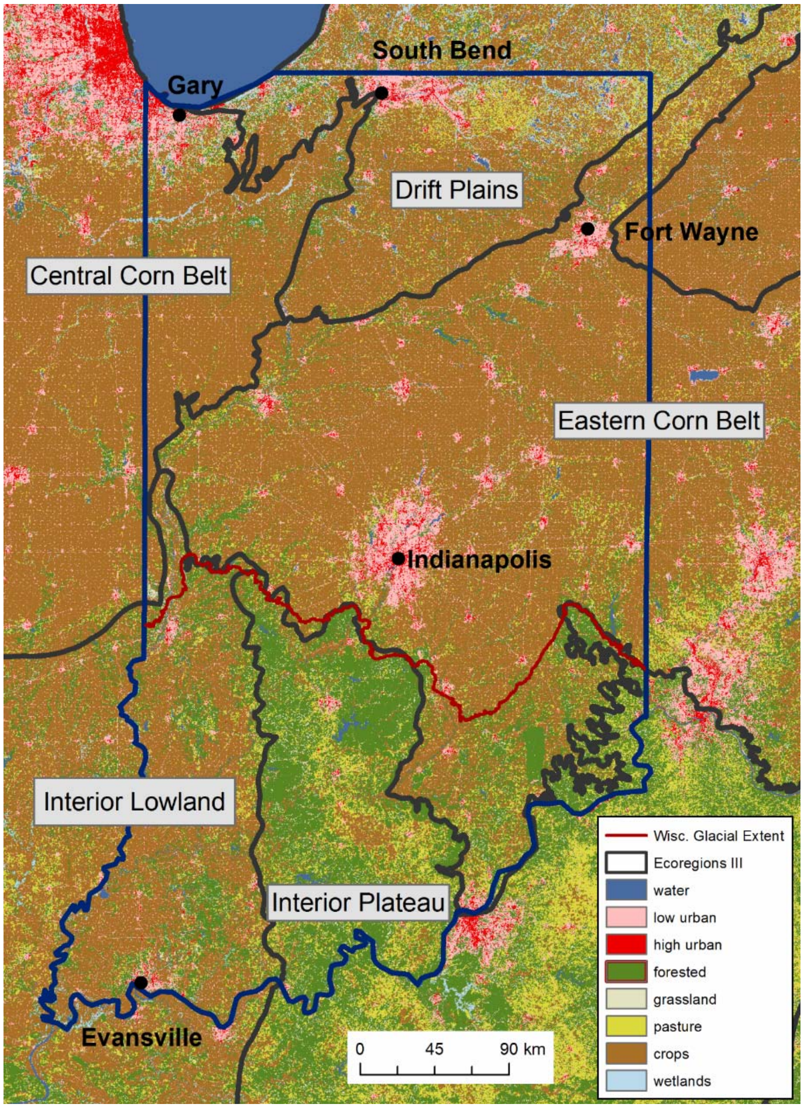

South Bend
Gary
Drift Plains
Fort Wayne
Central Corn Belt
Eastern Corn Belt
Indianapolis
Interior Lowland
Interior Plateau
Evansville
0
45
90 km
Wisc. Glacial Extent
Ecoregions III
water
low urban
high urban
forested
grassland
pasture
crops
wetlands

Figure 1

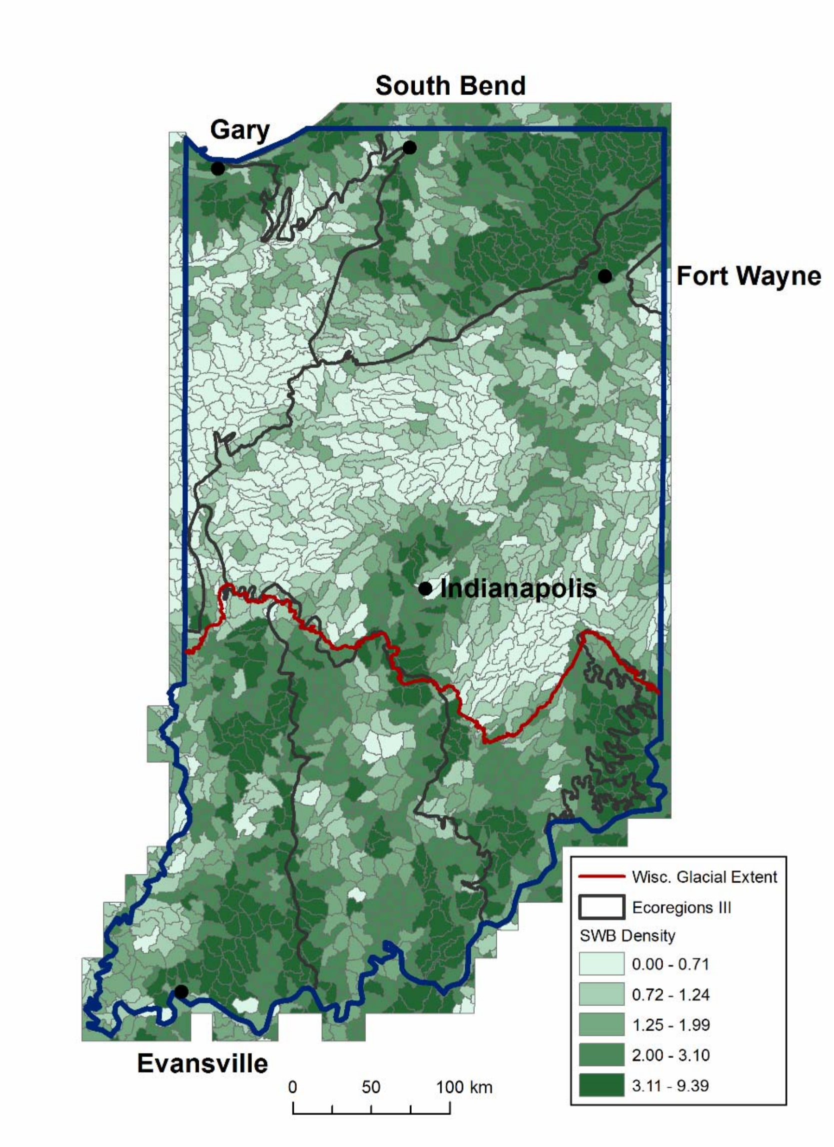
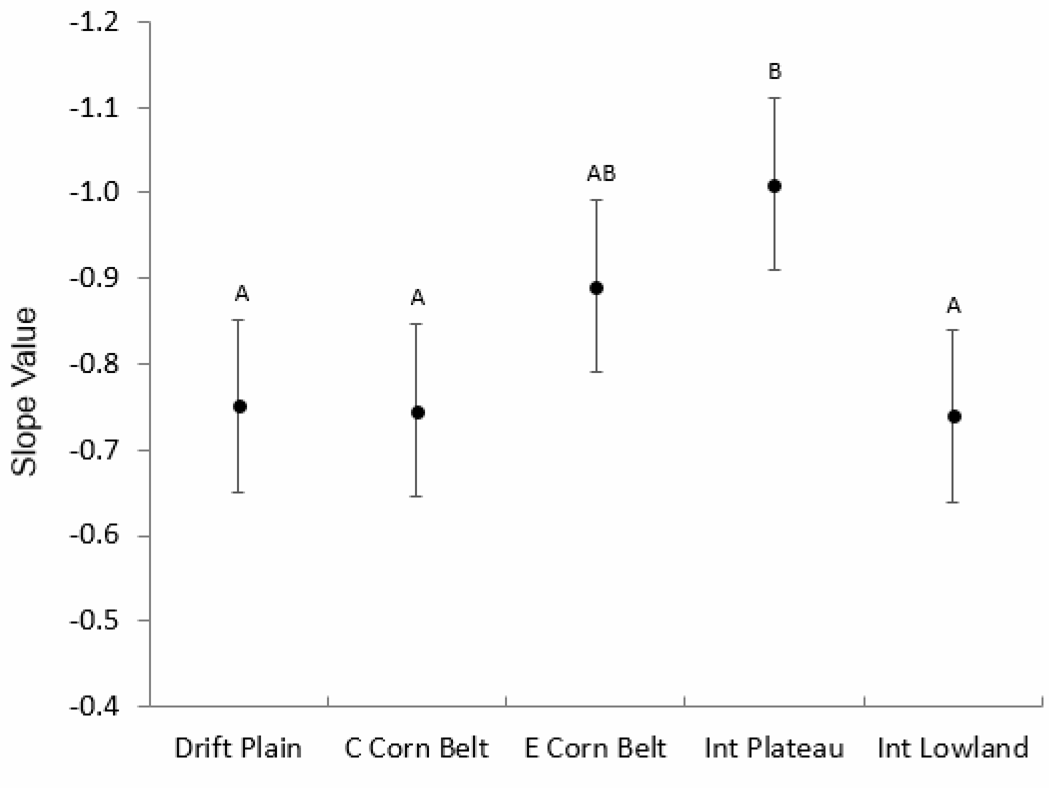

South Bend
Gary
Fort Wayne
Indianapolis
Evansville
0
50
100 km
Wisc. Glacial Extent
Ecoregions III
SWB Density
0.00 - 0.71
0.72 - 1.24
1.25 - 1.99
2.00 - 3.10
3.11 - 9.39

Figure 2



Slope Value
-1.2
-1.1
-1.0
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
A
A
AB
B
A
Drift Plain
C Corn Belt
E Corn Belt
Int Plateau
Int Lowland

Figure 3

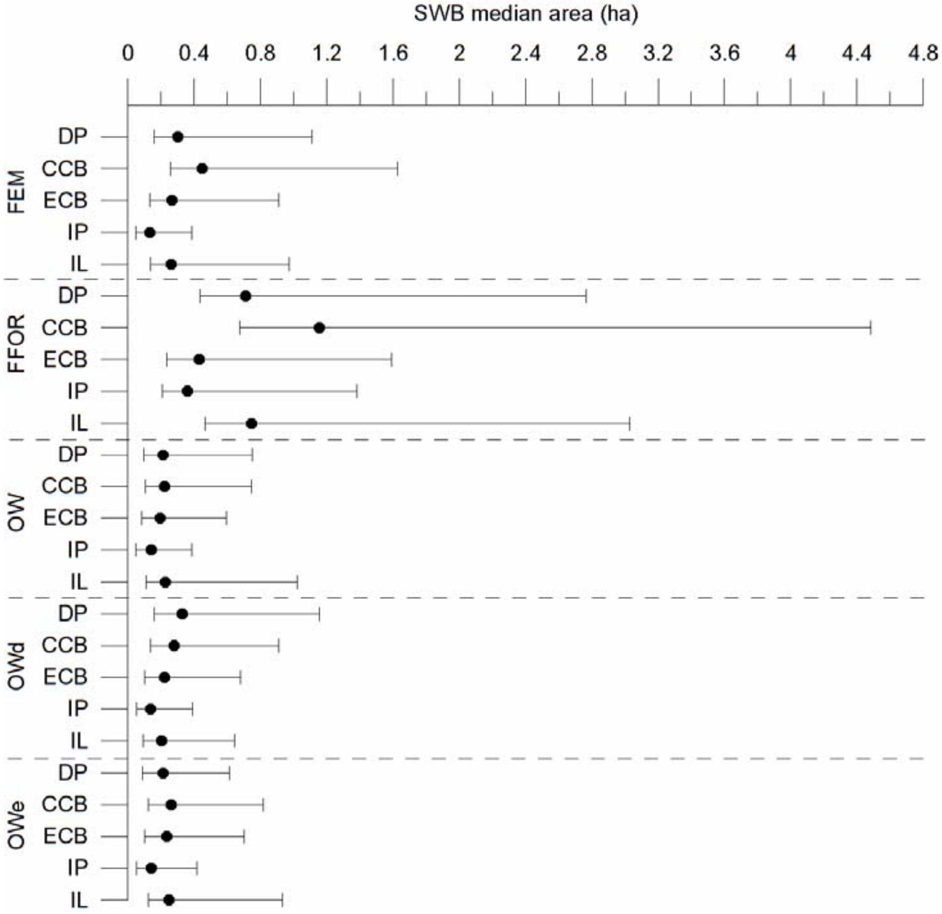

SWB median area (ha)
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
4.4
4.8
FEM
FFOR
OW
OWd
OWe
DP
CCB
ECB
IP
IL

Figure 4

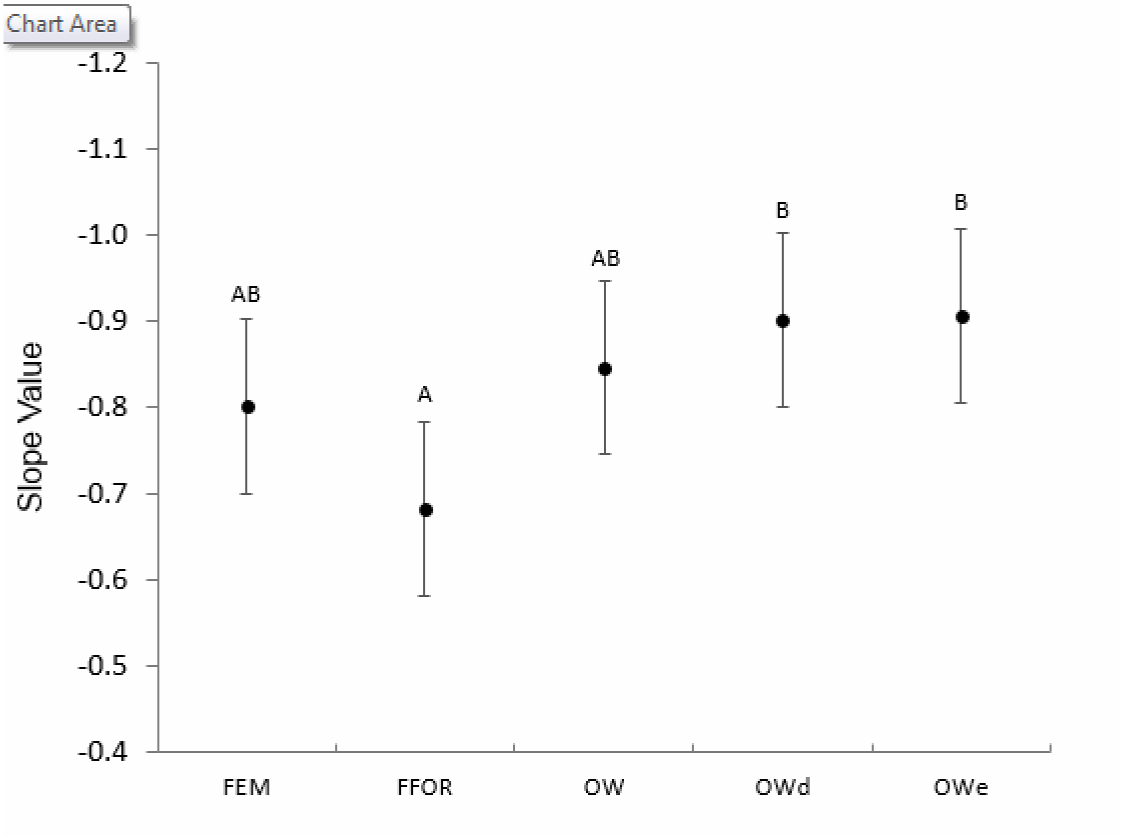


Chart Area
Slope Value
-1.2
-1.1
-1.0
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
AB
A
AB
B
B
FEM
FFOR
OW
OWd
OWe

Figure 5

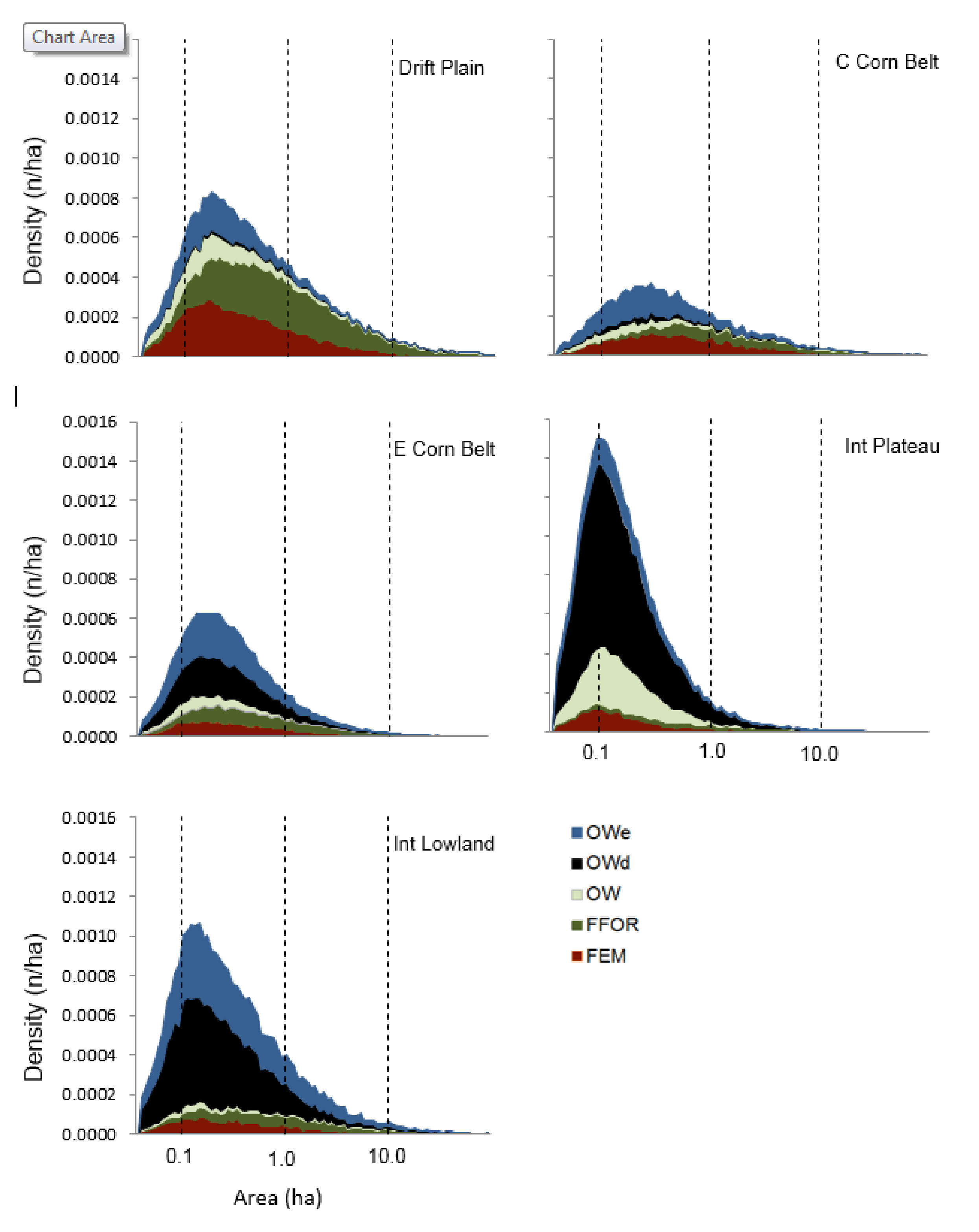
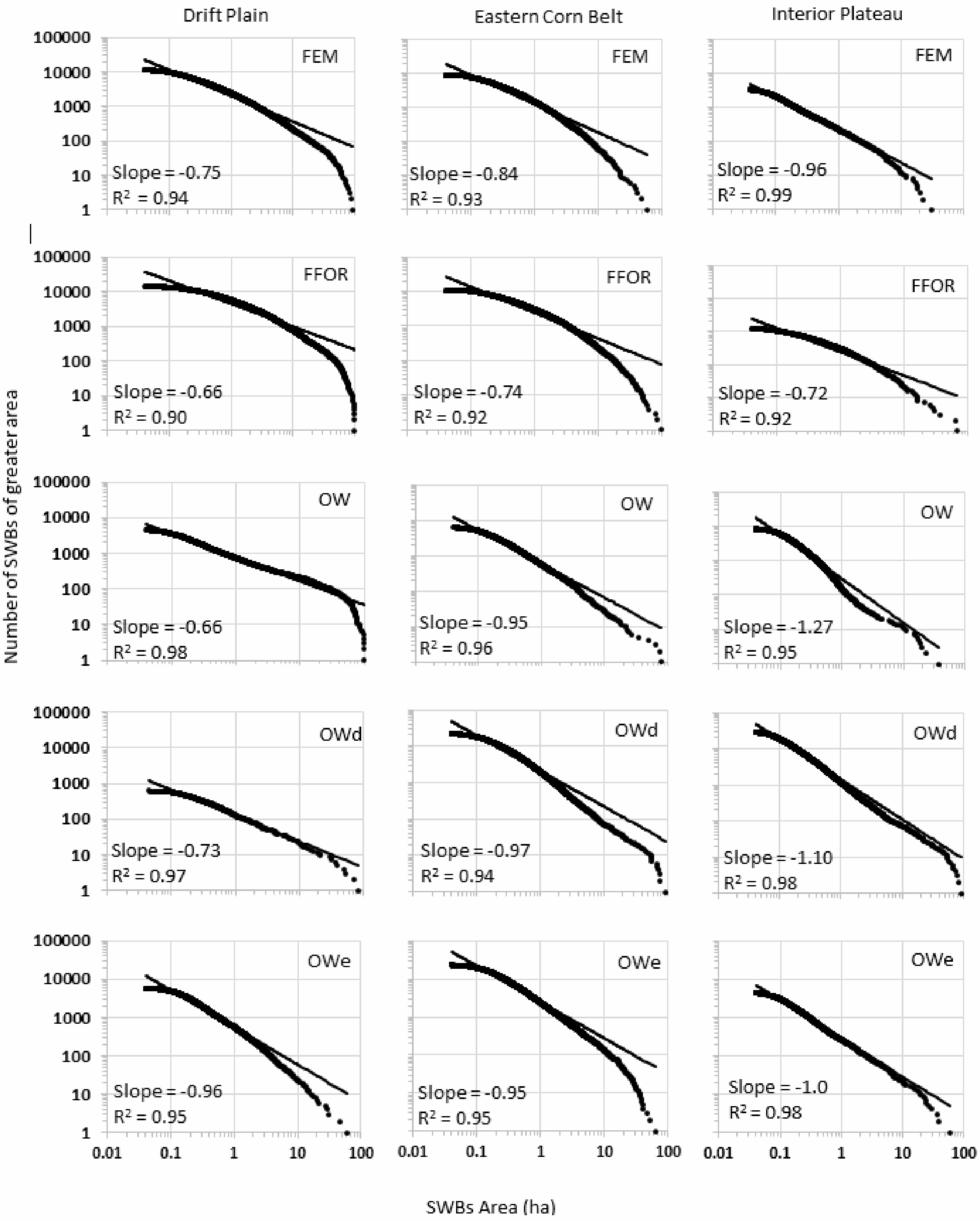


Chart Area
Drift Plain
C Corn Belt
E Corn Belt
Int Plateau
Int Lowland
Density (n/ha)
0.0016
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
0.1
1.0
10.0
Area (ha)
OWe
OWd
OW
FFOR
FEM

Figure 6



Drift Plain
Eastern Corn Belt
Interior Plateau
Number of SWBs of greater area
SWBs Area (ha)
100000
10000
1000
100
10
1
0.01
0.1
1
10
100
FEM
Slope = -0.75
R² = 0.94
FEM
Slope = -0.84
R² = 0.93
FEM
Slope = -0.96
R² = 0.99
FFOR
Slope = -0.66
R² = 0.90
FFOR
Slope = -0.74
R² = 0.92
FFOR
Slope = -0.72
R² = 0.92
OW
Slope = -0.66
R² = 0.98
OW
Slope = -0.95
R² = 0.96
OW
Slope = -1.27
R² = 0.95
OWd
Slope = -0.73
R² = 0.97
OWd
Slope = -0.97
R² = 0.94
OWd
Slope = -1.10
R² = 0.98
OWe
Slope = -0.96
R² = 0.95
OWe
Slope = -0.95
R² = 0.95
OWe
Slope = -1.0
R² = 0.98

Figure 7

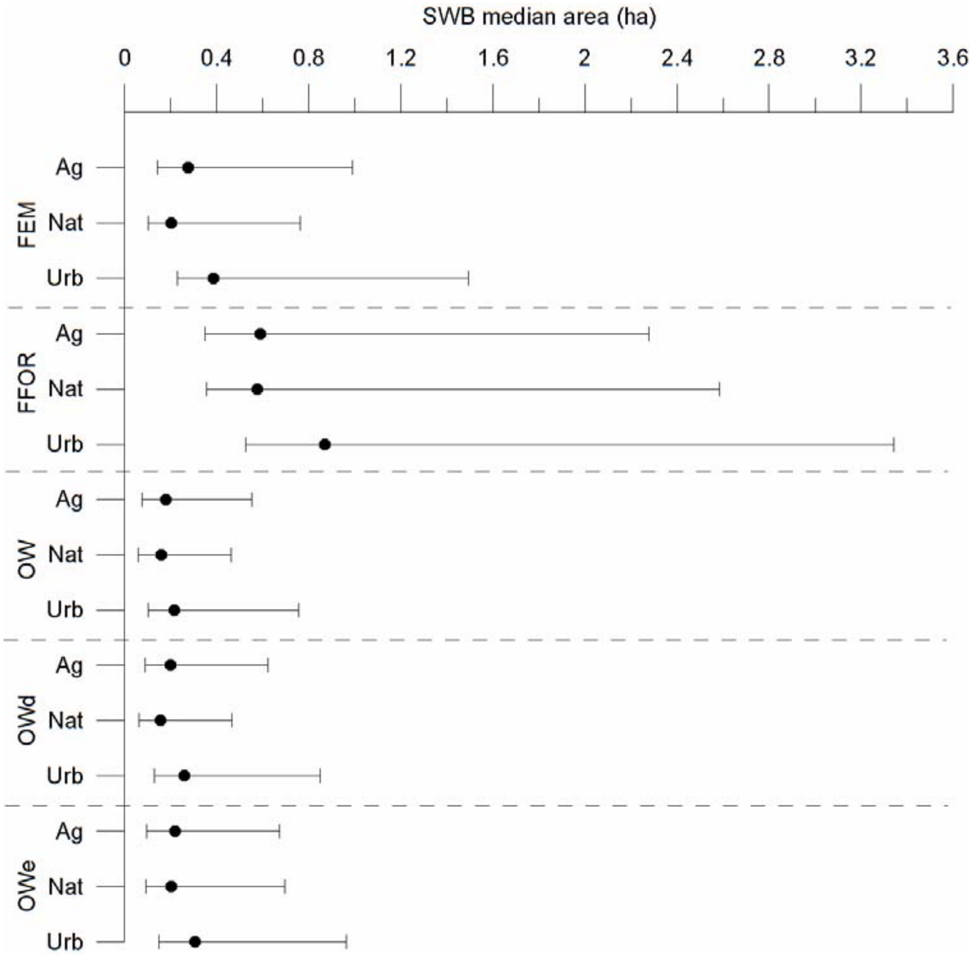

SWB median area (ha)
0
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
FEM
Ag
Nat
Urb
FFOR
Ag
Nat
Urb
OW
Ag
Nat
Urb
OWd
Ag
Nat
Urb
OWe
Ag
Nat
Urb

Figure 8

Supplemental Table 1. Number of SWB by size class by ecoregion. OW=open water, OWd=open water diked, OWe=open water excavated, FEM=freshwater emergent wetland, FFOR=freshwater forested wetland.

Ecoregion		0.04-0.1 ha	0.1-1 ha	1-10 ha	10-100 ha	Total	# permanent
All	Total	37483	135710	27834	2915	203942	152342
	OW	4963	14197	1536	327	21023	20864
	OWd	17107	47625	4998	276	70006	69964
	OWe	8740	36288	6010	395	51433	51358
	FEM	4978	19739	5251	456	30424	5567
	FFOR	1695	17861	10039	1461	31056	4589
Drift Plains	Total	4081	22310	8199	1231	35821	
	OW	867	2794	523	205	4389	
	OWd	47	437	108	21	613	
	OWe	1030	4220	538	22	5810	
	FEM	1523	7335	2168	216	11242	
	FFOR	614	7524	4862	767	13767	
Central Corn Belt	Total	1247	7039	2584	378	11248	
	OW	235	725	143	33	1136	
	OWd	86	498	101	11	696	
	OWe	551	2725	517	37	3830	
	FEM	346	2192	911	115	3564	
	FFOR	29	899	912	182	2022	
Eastern Corn Belt	Total	10518	50552	8847	520	70437	
	OW	1278	4366	526	27	6197	
	OWd	3705	15766	1897	70	21438	
	OWe	3449	17274	2251	132	23106	
	FEM	1360	6243	1393	59	9055	
	FFOR	726	6903	2780	232	10641	
Interior Plateau	Total	14342	28351	1960	133	44786	
	OW	2354	5641	134	11	8140	
	OWd	9329	17340	1088	69	27826	
	OWe	1348	2790	242	21	4401	
	FEM	1151	1850	215	11	3227	
	FFOR	160	730	281	21	1192	
Interior Lowland	Total	7295	27458	6244	653	41650	
	OW	229	671	210	51	1161	
	OWd	3940	13584	1804	105	19433	
	OWe	2362	9279	2462	183	14286	
	FEM	598	2119	564	55	3336	
	FFOR	166	1805	1204	259	3434	

Supplemental Table 2. Total area of SWB by size class by ecoregion. OW=open water, OWd=open water diked, OWe=open water excavated, FEM=freshwater emergent wetland, FFOR=freshwater forested wetland.

Ecoregion		0.04-0.1 ha	0.1-1 ha	1-10 ha	10-100 ha	Total
All	Total	2746	43102	74391	72349	192588
	OW	364	3954	4112	10207	18637
	OWd	1246	13967	11289	7391	33894
	OWe	638	11299	15085	7473	34495
	FEM	368	6679	13905	10430	31382
	FFOR	130	7203	30000	36848	74180
Drift Plains	Total	301	7909	23721	33336	65267
	OW	63	837	1469	7344	9714
	OWd	3	154	310	605	1073
	OWe	75	1238	1253	445	3010
	FEM	113	2522	5865	5306	13805
	FFOR	47	3158	14824	19636	37664
Central Corn Belt	Total	91	2583	7519	9471	19664
	OW	17	230	401	830	1478
	OWd	6	167	280	437	891
	OWe	40	892	1425	721	3078
	FEM	25	853	2541	2657	6077
	FFOR	2	441	2871	4827	8141
Eastern Corn Belt	Total	780	16464	22063	10949	50257
	OW	94	1298	1258	659	3309
	OWd	274	5004	4136	1930	11343
	OWe	254	5456	5338	2504	13552
	FEM	103	2117	3474	1081	6775
	FFOR	56	2589	7858	4776	15278
Interior Plateau	Total	1040	7284	4623	3274	16221
	OW	174	1388	263	193	2018
	OWd	675	4449	2376	1971	9471
	OWe	96	707	621	453	1877
	FEM	83	473	585	194	1335
	FFOR	12	267	777	464	1519
Interior Lowland	Total	534	8862	16466	15319	41180
	OW	16	200	720	1182	2119
	OWd	287	4193	4187	2448	11116
	OWe	174	3005	6448	3351	12978
	FEM	43	714	1440	1192	3390
	FFOR	13	749	3670	7145	11577