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Forest canopy gap dynamics: quantifying forest gaps and understanding gap – level forest regeneration in Upper Mississippi River floodplain forests

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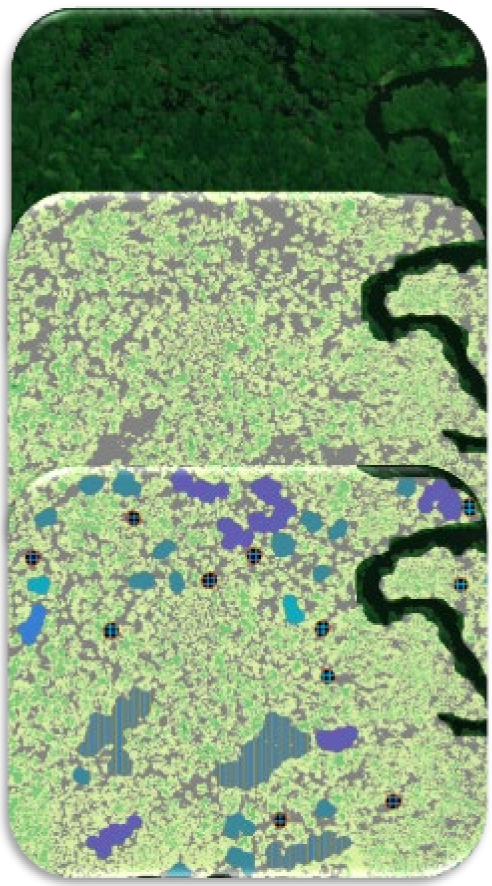

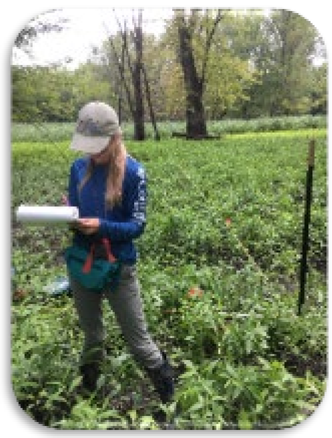

Forest canopy gap dynamics: quantifying forest gaps and understanding gap – level forest regeneration in Upper Mississippi River floodplain forests: Completion Report

Lyle Guyon[1], Andrew Strassman[2], Alexandra Oines[3,4], Andrew Meier[5], Meredith Thomsen[3], Stephanie Sattler[2], Nate De Jager[2], Erin Hoy[2], Ben Vandermyde[6] and Rob Cosgriff[7]

[1] National Great Rivers Research and Education Center, East Alton, IL

[2] USGS Upper Midwest Environmental Sciences Center, La Crosse, WI

[3] University of Wisconsin – La Crosse, Dept. of Biology, La Crosse, WI

[4] Current institution: Winona State University, Dept. of Biology, Winona, MN

[5] U.S. Army Corps of Engineers – St. Paul District, La Crescent, MN

[6] U.S. Army Corps of Engineers – Rock Island District, Pleasant Valley, IA

[7] U.S. Army Corps of Engineers – St. Louis District, West Alton, MO

Abstract

In most forest systems, the dynamics of forest canopy gap development play an important role in the transition from relatively short-lived early successional tree species to longer-lived, late successional tree species. In resilient forest systems, tree seedlings establish within newly created canopy gaps and grow to close the gap within one or two decades of disturbance. However, evidence in portions of the Upper Mississippi River System indicates that floodplain forests do not appear to be following these same trajectories, with canopy gaps instead seeming to fail to recruit new tree seedlings and reverting to non-forested cover types. Because of the heavy dominance of short-lived tree species in current UMRS forests, there is concern that continued failure of canopy gaps to recruit back to forest could be an early indicator of long-term, widespread forest loss as gaps become larger and larger and begin to coalesce into large, non-forested areas. Little research to date has documented either the density and distribution of forest canopy gaps across the UMRS or the vegetative conditions within those gaps to provide an initial assessment of forest dynamics in those areas. The current study utilizes both remotely sensed data and field sampling to assess the conditions of forest canopy gaps within 6 navigation pools on the Upper Mississippi River and one pool on the Illinois River. In general, canopy gap distributions and characteristics are similar across the study, with most pools ranging from 3% to 5% of forest canopy in gaps. Gap sizes are also relatively uniform, with most pools averaging 0.09 to 0.14 ha per gap. The highest proportion of forest cover in canopy gaps at the pool level was driven by the total number of gaps and not gap size, indicating that canopy gap formation in this system is commonly due to individual tree or small clump mortality. Undesirable competing vegetation was dominant in most canopy gaps, with reed canarygrass and native forbs being most prevalent in upper pools and vines most problematic in the lower pools. In the upper pools, very little viable forest regeneration is occurring within canopy gaps. The viability of forest regeneration increases in middle and lower pools, though competing vegetation continues to be a problem. Overall, canopy gaps appear

most likely to recruit back to forest in lower pools, and chronic forest loss facilitated by regeneration failures seems most likely in upper pools. However, competing vegetation in lower pools may still interact with woody regeneration to limit effective re-establishment of forest canopy.

Introduction

The current conditions and future trajectory of extant floodplain forest have received increasing attention from Upper Mississippi River System (UMRS) managers in recent years. A primary concern is the potential for conversion of forest to non-forested systems dominated by herbaceous species, especially the invasive reed canarygrass (*Phalaris arundinacea*). However, forest decline appears to be occurring even in the absence of reed canarygrass as the current overstory ages. There appears to be a pattern of insufficient natural forest regeneration in many areas of the UMRS, potentially resulting in a failure to recruit future cohorts of forest trees. Tree mortality caused by invasive pests, especially Dutch elm disease (*Ophiostoma ulmi* and *O. novo-ulmi*) and emerald ash borer (*Agrilus planipennis*), has and will continue to increase the rate of forest canopy loss.

Forest regeneration is inherently a function of forest disturbance (Runkle 1982, Oliver and Larson 1996), which often increases the availability of resources, such as sunlight and nutrients, for tree seedlings and saplings. Different tree species are adapted to different levels of disturbance, but all require some level of disturbance to establish as seedlings and to grow into the canopy. However, regeneration dynamics are also directly impacted by a wide range of site- and landscape-level factors, including soil moisture, light availability, regeneration substrate, herbivory, historic land use, and seed dispersal (Sousa 1984, Kern et al. 2017). The formation of small gaps in the canopy through the mortality of small clumps of trees are discrete disturbance events that should create the necessary conditions for the establishment of a new cohort of seedlings or the release of already established saplings (Kern et al. 2017). However, in the presence of adverse site- or landscape-level conditions, these gaps may fail to regenerate back to trees, potentially leading to a “demographic disequilibrium” that “triggers forest cover loss” across the landscape (Barrette et al. 2017).

In upland forests, the impact of many of these factors on forest regeneration dynamics are well understood and silvicultural treatments have been designed to promote regeneration of desirable species (Brose et al. 2008, Leak et al. 2014, Poznanovic et al. 2014). In addition, there is a broad literature base describing landscape-level disturbance dynamics in many of these systems (Lorimer 1977, Runkle 1982, Frelich and Graumlich 1994, Oliver and Larson 1996, Seymour et al. 2002). Significant work has also been done on restoration techniques in bottomland forests of the Lower Mississippi Alluvial Valley and elsewhere in the southeastern United States (Hodges 1997, Allen et al. 2004, Stanturf et al. 2009). In contrast, bottomland forest systems in the UMRS have been the subject of only a small amount of basic and applied research, thus limiting the applicability of current ecological understanding and silvicultural tools developed in other systems. Though there are many ecological similarities between southeastern bottomland forests and bottomland forests of the UMRS, southeastern forests differ substantially in tree species composition, hydrology, and land use history from those of the UMRS. Basic research in the UMRS describing bottomland forest spatial pattern (DeJager and Rohweder 2011), forest compositional dynamics in the context of annual inundation duration (DeJager 2012, DeJager et al. 2012), and herbivory and non-native plant invasion (Thomsen et al. 2012, DeJager et al. 2013, Cogger et al. 2014) is available. However, very little information is available related to the extent or frequency of gap formation in floodplain forests and the rate at which forest gaps are converting to non-forested cover types or returning to forest cover. Further, no comprehensive, system-wide field data are available to document gap-scale drivers of regeneration success or failure.

In recent years, multiple Habitat Rehabilitation and Enhancement Projects (HREP) have been proposed or initiated through the Upper Mississippi River Restoration Program with an emphasis on forest rehabilitation at large scales (e.g Reno Bottoms (Pool 9) and Beaver Island (Pool 14)), and future projects promise to place an even greater emphasis on enhancement of existing forest. This study will provide critical information for the selection of project areas and the design of management activities, a quantitative understanding of the drivers of forest loss, indicators of future forest decline, and metrics for assessing the effectiveness of various management actions. At a broad scale, this study will also directly increase our understanding of the relationship between floodplain hydrogeomorphic patterns, forest gap formation, and floodplain forest regeneration in the UMRS.

In particular, this study will ask the following questions:

1. What is the current abundance and distribution of forest canopy gaps in the UMRS, and what proportion of these gaps have been re-colonized by forest tree species relative to herbaceous plants?

2. What site and landscape level variables (e.g., gap size, flood dynamics, soils, surrounding forest) are associated with herbaceous invasion versus forest reestablishment? Is there an association between reestablishment and health and successional dynamics in the surrounding forest?

3. Are there associations between the spatial arrangement of forest gaps and the health of surrounding forests? By integrating geospatial and field-collected data, is it possible to identify forest areas that are most vulnerable to canopy loss in the near-term?

Methods

This study consisted of two primary components: a landscape level geospatial component to assess large-scale forest canopy gap demographics and a site level field-based component to document distribution of vegetation within a subset of those gaps. Canopy gaps for study in both components were identified in a subset of navigation pools within three US Army Corps of Engineers (USACE) UMRS navigation pools: Pools 8, 9 (USACE – St. Paul District (MVP)), 13, 21 (USACE – Rock Island District (MVR)), 24, 26 (through Maple Island just south of L&D 26), and the lower 32 miles of the Illinois River from its confluence with the Mississippi River to Kampsville, IL (USACE – St. Louis District (MVS), Figure 1). All areas within these pools that were classified in the UMRS Long Term Resource Monitoring (LTRM) 2010/11 Land Cover/Use layer (LCU) (US Army Corps of Engineers Long Term Resource Monitoring Program 2017) as forested floodplain vegetation (including lowland, floodplain, and swamp) were included in the analysis.

Geospatial component

For the geospatial analysis, a customized process was developed to identify all gaps within the seven UMRS study pools (Figure 1) and to attribute those gaps with various characteristics related to gap physical characteristics and surrounding landcover. All datasets used for this process covered, at a minimum, the entire pool area as defined in the LTRM datasets, allowing for a landscape level assessment of gap characteristics.

An R script (Sattler 2020) was developed to automate the process of detecting and attributing forest canopy gaps. This R script followed a stepwise analysis of the data for a pool to:

1. Select the analysis area for the pool;
2. Derive a canopy height model (CHM) for the analysis area;
3. Derive a forest gap polygon layer from the CHM;
4. Clean the forest gap polygon layer;
5. Attribute the forest gap polygon layer.

These steps were completed using the following four datasets: Long Term Resource Monitoring 2010/11 Land Cover/Use (U.S. Army Corps of Engineers 2017), a Lidar Digital Terrain Model, a Lidar Digital Surface Model, and the UMRS Floodplain Inundation Attribute Raster (Van Appledorn et al. 2018).

In the first step, the LTRM LCU layer for the pool was used to select polygons of interest for the analysis. Only LCU polygons that were classified as one of the forest landcover types (floodplain forest, lowland forest, *Populus* community, *Salix* community and wooded swamp) and which were classified as having greater than 66% canopy cover and a canopy height of greater than 20 feet (6.096m) in the LCU dataset were used for the analysis. Some forest landcover polygons had a blank cover value but acceptable height values; these were included as well. All other polygons were excluded from the analysis. All polygons meeting the criteria were merged and then exploded to ensure that each polygon was a standalone feature in the shapefile. This formed the analysis polygon layer for the pool.

Next, the script conducted the analysis of the lidar data, but analysis was limited to the areas of interest due to the very large size of the lidar files. This portion of the script clipped the lidar derivatives, the digital terrain model (DTM), and the digital surface model (DSM) to the analysis for the pool to the analysis polygon layer. Next, a canopy height model (CHM) was created by subtracting the DSM from the DTM and saved as a raster TIFF. Following creation of the CHM, a *for* loop was used to take small subsets of the CHM and save polygons of areas that had a height between -0.05m and 10m. Areas below -0.05m were removed to screen out bad lidar data while areas over 10m were removed to exclude forest canopy. The *for* loop began by selecting the first polygon feature per the feature identification number (FID) in the analysis polygons shapefile and clipped the CHM to the extent of that polygon. The CHM subset was then reclassified each cell according to the values listed in Table 1; this step identified cells in the CHM subset that were contained broken forest canopy which potentially could constitute forest gaps. The polygons with a reclassified value of 1 and with an area greater than the 0.026 hectare minimum mapping unit (MMU) were selected; polygons below the MMU or with a value of 0 or 2 were removed from the dataset.

Once the clipped CHM subset was reclassified, it was converted to polygons attributed by the reclassed value and the area of each polygon was calculated. These polygons were then stored in an empty spatial data frame allowing the for loop to move on to the next consecutive FID in the analysis polygon shapefile, repeating the steps until every polygon in the analysis polygon shapefile was analyzed.

Once the for loop finished, the polygons stored in the empty spatial data frame were merged and then exploded to ensure that adjacent polygons became a single polygon and that each polygon was a standalone feature in the spatial data frame. The spatial data frame was then exported in the Esri polygon shapefile format and identified broken forest canopy for the pool. This final layer was referred to as the first pass gap layer.

Following creation of the first pass gap layer, the layer needed to be scrubbed of gaps that did not meet project specifications. Any polygon with a diameter <18.288m was removed from the analysis layer. To locate gaps with an insufficient diameter, the script buffered the polygons in the first pass gap layer by -9.144m and then by 9.144m to remove all polygons with a diameter <18.288m. Some of the lidar used in this project had inconsistent point distribution within the point cloud and included data holes large enough to register as canopy gaps. Because of the fine pixel resolution of the dataset (1 m^2), these data holes produced excessive noise in the initial (first-pass) gap layer by creating very small gaps in intact canopy areas and very small patches of canopy in the interior of gap areas. To resolve this issue and eliminate noise the resulting vector layer was buffered out and then in by 0.6m to close all single-cell or single-cell wide gaps after removing all polygons below the 0.026 hectare MMU. This resulted in a cleaner final gap layer showing all forest canopy gaps that preserved any canopy hole at least $2m^2$ and smoothed jagged gap edges (see Figure 2). A final step removed all areas with more than 180 days of average annual growing season inundation as. This is the upper inundation threshold that is generally expected to support forest using the UMRS floodplain inundation attribute raster layers. The remaining polygons in the spatial data frame were merged and then exploded to ensure that adjacent polygons were considered a single polygon, that overlapping polygons were merged, and that each polygon was a standalone feature in the shapefile.

Finally, the script added attributes to each feature within the polygon. These attributes were placed into two categories. This first category contained attributes examining the forest canopy gap while the second category contained attributes examining the area surrounding the forest canopy gap. The area surrounding the gap was defined as a 150-meter buffer around each gap. Table 2 illustrates the attributes added and their descriptions.

As a last step, the final forest canopy gap layer had an internal accounting field removed before it was exported as an Esri polygon shapefile. Table 2 describes the attributes assigned to each polygon in the final dataset.

After reviewing the polygons created using the automated process, three additional criteria were added to identify the final gap dataset: gaps dominated by polygons classified as *Salix* community, gaps that were in upland forests, and gaps that had <60% forested edge. *Salix* community-dominated gaps were removed because most of these areas are persistent sandbar willow (*Salix interior*) shrublands that follow successional pathways driven primarily by hydrology rather than gap dynamics. Because the maximum height of sandbar willow is just above the minimum height threshold, many areas in these stands were artificially identified as gaps based solely on height variability within the stands. Inclusion of *Salix* community-dominated gaps in the final gap dataset thus introduced thousands of non-gaps and, because other forest community types were of primary interest in this study, it was determined to exclude all of *Salix* community-dominated gaps from the analysis. Upland forest gaps (gaps without yearly flooding) were also identified by utilizing the UMRS flood inundation layers and removed. Finally, many areas identified as “gaps” in the automated process were contiguous with adjacent non-forest types and were thus functionally extensions of adjacent non-forested areas. To account for this, all gaps with less 60% of the gap perimeter classified as a forest cover type were removed from the analysis.

Field component

To assess site-level characteristics of forest gaps, a subset of gaps from each USACE district was selected from the geospatial forest canopy gap layer using a stratified random selection approach. Gaps were binned by three flood inundation classes and three gap size classes to form nine bins (Table 3). Flood inundation classes were defined based on thresholds observed in a qualitative synthesis of multiple datasets describing distribution of tree species and forest community types relative to days of inundation (DeJager et al. 2012, 2018, 2019, Ingvalson et al. 2020). Gap size classes were defined based on specific characteristics of gaps of a certain size. The lower threshold for the smallest gaps (0.0405 ha) was determined to be the minimum size for a single treefall gap in the system. The lower threshold for the medium gaps was based on the distribution of gaps from the geospatial dataset and the biological relevance of a 0.1012 ha gap being approximately equivalent to a gap with the potential for full sunlight at the center. The lower threshold for the largest gaps (0.3035 ha) was approximately 1 standard deviation from the mean gap size, while the upper size threshold for the largest gaps was selected because less than 5% of study gaps were larger than this and it was determined that any gaps significantly larger than this would have been anomalous in the dataset. Following this, all gaps identified in the geospatial component that met study criteria were assigned to one of the nine bins, with the USACE district designated for each gap. The gaps were then sequentially numbered and survey gaps were randomly chosen from each of the nine bins by using a random number generator to select the gaps for the field survey.

Three gaps from each bin were selected for each district, for a total of 27 gaps per district and 81 gaps for the entire project. In some cases where gaps were inundated for the entire growing season in 2019 and could not be sampled or where gap vegetation consisted of more than 50 percent emergent aquatic vegetation, the initially selected gap was dropped for field survey and the next randomly selected gap within the same bin was selected for field survey. However, in MVP and MVR, certain combinations were poorly represented, resulting in a smaller sample size in these two districts (n = 20 in MVP and n = 23 in MVR), resulting in a total of 70 sampled gaps (Table 4). Examples of gap distributions and gap photos from each district can be found in Appendix A.

Field sampling was conducted between June 25, 2019 and September 30, 2019 across all three districts (MVP: 6/25 – 9/30; MVR: 7/3 – 8/14; MVS: 8/27 – 9/30). Gap locations were entered into handheld GPS units and navigated to in the field. If the gap centroid calculated as part of the geospatial component did not accurately reflect the current gap center, the actual gap center was visually determined. Once the gap centroid was located, a metal t-post was placed at that location, a GPS coordinate was recorded and four photos were taken in each cardinal direction from the centroid. The gap was then visually divided into zones: the gap interior, canopy edge, and tree edge (Figure 3). The gap interior was defined as the area from the centroid t-post to the canopy edge, which was defined as the location where the individual walking along the transect first stood beneath continuous tree canopy. The tree edge was defined as the area where large tree trunks of canopy trees were in line with the individual running the transect. The zone beyond the tree edge was considered the surrounding forest, regardless of canopy conditions in that area.

From the centroid t-post, transects were placed along the four cardinal directions (Figure 3) using reel tape measurements and a sighting compass. Six locations for herbaceous layer sampling were temporarily marked along each transect with fluorescent pin flags (Figure 4). Two sampling locations on each transect were placed within the gap interior, one was placed on the canopy edge and another was placed on the tree edge. Two additional sampling locations were placed outside of the gap in the surrounding forest area. The sampling locations within the gap interior were determined by measuring the distance from the centroid to the canopy edge. That distance was divided by three to determine the spacing for the first and second sampling locations along each transect. The two surrounding forest sampling locations were placed relative to the tree edge quadrat, with one location 5m into the surrounding forest and the final location 25m beyond the tree edge along the transect in the surrounding forest. All sampling location distances from the gap center were recorded to the nearest 0.25m. One additional sampling location associated with the gap centroid was placed 2m from the metal t-post at a randomly determined azimuth. Each sampling location was given a unique identifier based on the cardinal direction (N = north, E = east, S = south, W = west, C = centroid) and the location relative to the gap zones (1 = interior nearer centroid, 2 = interior nearer canopy edge, 3 = canopy edge, 4 = tree edge, 5 = surrounding forest 5m from tree edge, 6 = surrounding forest 25m from tree edge). In total, there were 25 vegetation sampling points at each study site.

At each sampling location, a $1m^2$ sampling quadrat, with 0.5m marked in the middle of each side of the quadrat, was placed to assess characteristics of the vegetation. The quadrat edge that was aligned with the marking flag at each location was the edge associated with the azimuth (e.g. the 90° quadrats had the 0.5m mark on the east edge placed at the sampling location marker), with the exception of the centroid sampling location, where the northwest corner of the quadrat was placed at the sampling location designated by the pin flag. When standing or fallen trees were located at the sampling location, quadrats were moved along the transect to a location where no woody debris greater than 15.24cm in diameter was present within the $1m^2$ sampling plot; when quadrats were thus relocated, the northwest corner of the quadrat remained perpendicular to the transect.

Sample points were excluded from data collection if the gap was too narrow to avoid overlap of quadrat placement along the transect or if deep water prevented accurate sampling. Surrounding forest sampling points were excluded or relocated if the transect extended into another canopy gap or marsh area rather than forest. If it was possible to survey closed canopy conditions at the same distance from the gap edge along another azimuth without re-sampling an area that was already sampled on one of the other transects, a substitute azimuth was randomly selected, and a quadrat was placed 25m from the tree edge on the new azimuth. In a few cases, it was impossible to shift the transect location in this way, and a few quadrats were dropped from the sample as a result.

Within each sampling quadrat, all herbaceous vegetation, woody vines and tree seedlings less than 0.5m tall were identified and recorded. The percent cover was recorded for plants within four broad groups: graminoids, forbs, tree seedlings, and non-invasive vines. We also recorded the percent cover for species of forest management concern, including reed canarygrass, wood nettle (*Laportea canadensis*), stinging nettle (*Urtica dioica*), Japanese hops (*Humulus japonicus*), giant ragweed (*Ambrosia trifida*), wild grape (*Vitis vinifera*), oneseed bur cucumber (*Sicyos angulatus*), and trumpet creeper (*Campsis radicans*). For each species or group, the visually estimated cover class (1-6) was recorded (1: > 0-5%, 2: 6-25%, 3: 26-50%, 4: 51-75%, 5: 76-95%, 6: 96-100%). With this method, it was possible for the total percent cover for all species/groups in a quadrat to be greater than 100%.

Additional data identifying all tree seedling species occurring in gap quadrats was recorded in MVP and MVS.

Within each quadrat, if any woody stem greater than 50cm was present, we identified the tallest individual and recorded the species. Height of that individual was measured to the nearest centimeter if the stem was less than 1.5m tall and was measured to the nearest 5cm if the stem was greater than 1.5m tall. We also assessed and recorded a browsing severity index value for the tallest woody stems. Browsing was scored from 0-3 as described in Table 5. For other woody stems present within the quadrat, we recorded the number of individuals present by species and height class (1: 0.5-1.5 m, 2: 1.5-3.0 m, 3: > 3.0 m) for all stems by species.

In addition to surveying the herbaceous layer and woody stems, measurements of canopy cover were taken at each quadrat location. A spherical densiometer was used to determine canopy density above the centroid quadrat and quadrats 3 (canopy edge) and 6 (furthest into interior forest) along each transect. A total of four densiometer readings were recorded per quadrat location; a measurement was taken facing each cardinal direction when standing in the center of the quadrat.

To assess forest conditions in the matrix surrounding selected gaps, and to determine whether any characteristics of the surrounding forest are related to the vegetation inside forest gaps, a combination of remotely sensed LTRM data, the geospatial gap analysis in this study, and previously collected USACE and USFWS forest inventory (FI) data were used to summarize the forested area adjacent to gaps and compare it to gap level vegetation data. FI plots within the same neighborhood were summarized based on field-collected tree basal area, canopy cover, regeneration rating, and presence of invasive species, per the standard USACE FI protocol. If established forest inventory plots were not available in the area surrounding the gap, new pseudo-inventory plots were placed as described immediately below. The new pseudo-inventory plots did not include a full forest inventory sample. Instead, the summary variables described above were recorded for the new plots.

In MVP and MVR, an inventory of forest matrix health was taken at the end each transect. Methods used for this portion were derived from the standard USACE Phase II Forest Inventory Protocol. This procedure was not necessary in MVS as all sampled gaps occurred within areas with current Phase II Forest Inventory data, and that data was used for subsequent analysis. For MVS and MVR, quadrat 6 was used as the temporary center point for a visual 5 radial meter circle representing approximately 0.008ha (Figure 5). From the center point, a regeneration rating was determined by first noting the presence (1 point) or absence (0 points) of trees at least 0.5m tall and less than or equal to 10cm diameter at breast height (DBH, 1.37m). Four 0.0004 hectare plots (1.12 radial m) located at the end of each visual cardinal transect surrounding the center were then assessed and a tally was made (0 to 4 points) of how many of these plots contained trees of at least 0.5m tall and less than or equal to 10cm DBH. To calculate the regeneration rating for the forest location, we summed the scores for the 0.008 and 0.0004 hectare plots and determined a total score between 0 and 5, with 5 being the best possible score.

In addition to calculating the regeneration rating, the three most dominant species of tree regeneration within the 0.008 hectare tree regeneration area that were at least 0.5m tall and less than or equal to 10cm DBH were recorded. The species were recorded in order of dominance, with the first species listed being the most numerous. We also recorded the three most dominant woody invasive species and herbaceous invasive species within the regeneration area, if present. These species were also recorded in order of dominance.

Finally, a 2.3 m^2/ha basal area factor (BAF) variable radius plot sampling tool was used to record density and basal area by species of large, living trees in the surrounding forest area. Variable radius plots were implemented using standard point sampling techniques (USDA-Forest Service 2000).

See Appendix B for a complete description of the field sampling protocol.

Data Analysis

Analysis of the set geospatially-derived gap characteristics consisted primarily of descriptive summaries of physical gap parameters averaged or otherwise aggregated at pool and project-level scales. No formal statistical tests were conducted on this data for this report.

To quantify associations between physical canopy gap characteristics and gap-level floodplain forest vegetation and woody regeneration, we selected gap size and number of growing-season inundation days as the primary analysis variables of interest, using the same thresholds established for stratification of the field plots as described in Table 3. USACE District (MVP, MVR, and MVS) was also used as a variable of interest to assess the degree to which regional (i.e., latitudinal) variability may have had an effect on gap-level vegetation response. Field-level measurements of understory vegetation occurring in canopy gaps (e.g., woody stem densities; herbaceous, graminoid, and seedling percent cover; presence and percent cover of invasive species) were summarized at the gap-level for comparison across gap size, growing season inundation days, and regions. For the purposes of these analyses, all available sample quadrats were aggregated at the gap-level, with no attempt made to differentiate between gap interior, edge, and adjacent forest quadrats.

A multi-response permutation procedure (MMRP) was used to test for significance of vegetation response across the variable groupings described above. MMRP is described by Peck (2016) as a versatile nonparametric tool for conducting one-factor permutation-based (Monte Carlo) significance tests to contrast responses between different treatments, habitats, geographic locations, or other factors. In addition, non-metric multidimensional scaling (NMS) was used to explore vegetation community response across the same grouping variables. NMS is a common multivariate ordination technique used in ecology to look for patterns and structure within typically heterogeneous ecological community datasets (McCune et al. 2002). Statistical analyses were performed using PCORD v.7.08.

Although beyond the scope of the current report, further landscape level analyses are anticipated as part of a future peer-reviewed journal article. These analyses will develop additional landscape-based metrics derived from the geospatial, such as mean patch size, landscape shape index, and landscape cohesion. Such metrics will provide indices of the degree of landscape-scale fragmentation, based on the amount, size, and distribution of individual canopy gaps that exist within the landscape. These metrics will most likely be calculated at the scale of the individual navigation pool and then be related to patch-scale field measurements aggregated at the pool scale.

Results

Landscape level gap characteristics

A total of 32,360 gaps were detected in the geospatial analysis across the seven study pools (Table 6). These gaps represent the subset of all the forest openings detected in the project study area that met the project criteria. Following exclusion of all artificial gaps (*Salix* community-dominated gaps and gaps with less than 60% forest edge), the final number of gaps included in the geospatial data summary was 13,782.

From the final dataset, the average number of gaps per ha of forest across all pools was 0.36 with a range of 0.10 – 0.74; the average project gap area was 0.12 ha with a range of 0.0.02 – 0.14 ha. The overall average percent of forest landcover that was in gaps across all pools was 4.3%. However, there was significant variability between pools. Alton Pool on the lower Illinois River has only 0.5% of the total forest area in gaps, while gap area was 10.9% of forest area in Pool 26. The remaining pools had a much narrower range, from 2.4% to 5.2%. Lidar-derived vegetation heights within the gaps averaged 2.45 m with a range of 1.26 – 3.15 m. Vegetation heights were lowest in Alton Pool and the upper three UMR pools (8, 9 and 13) and higher in the lower UMR pools (21, 24 and 26). Average inundation depth and length of inundation for gaps were relatively constant. The average inundation depth was 1.84m with a range of 1.14 – 2.42 m; average inundation length was 23 days with a averages ranging from 18 – 29 days across the study pools. On all pools, excluding Alton Pool on the Illinois River, average inundation depth was less than average vegetation height. The percent forested edge for gaps also showed minimal variability across the system, with an average of 81.5% adjacent forest landcover and a range of 79.3% - 88.1%. There was slightly higher variability in the percent of gap edge that was water; though the overall average was 9.3%, individual pool averages were lowest in the upper pools and highest int the lower pools. Pool 8 in MVP, the northernmost pool, had less than half the average water edge that Pools 24, 26 and the Alton Pool had.

Patterns at the district level were somewhat more pronounced. MVR had the lowest percent of forest cover in gaps, with close to half the area of MVP and MVS (Table 7). The average gap size was remarkably similar across all districts, at just above 0.1 ha. Gap vegetation heights were lowest in MVP, and slightly higher in MVR and MVS. Inundation duration and depth both increased from north to south as did the percent of forest edge that is water. MVR had the highest percentage of gap edge that was forested, and MVP and MVS were similar.

General Compositional and Structural Trends

Vegetation composition and related characteristics were assessed from the 70 discrete floodplain forest canopy gaps across the three USACE districts selected for the field component portion of this study (Table 4).

Several plant functional groups and individual species of management concern were chosen to represent ground layer vegetation; their percent cover and frequency in surveyed UMRS gaps are presented in Table 8. At the broadest level, forbs and tree seedlings (< 50cm in height) had the highest average percent cover and frequency of occurrence system wide, followed by grape vine (*Vitis spp.*), graminoids, and reed canarygrass (*Phalaris arundinacea*). However, regional differences were notable. In MVP, forbs, graminoids, and reed canarygrass were the dominant ground cover occurring in canopy gaps. In MVR, tree seedlings were the dominant ground cover and all other vegetation was relatively sparse. In MVS, forbs, tree seedlings, and a suite of vines species including wild grape, oneseed bur cucumber (*Sicyos angulatus*), trumpet creeper (*Campsis radicans*) and other vines were dominant.

Frequency of occurrence of individual tree seedling species (< 50cm in height) based on additional presence/absence data recorded in MVP and MVS is shown in Table 9; these data were not recorded in MVR. Silver maple (*Acer saccharinum*) was clearly the most common tree seedling species encountered in the study, followed by green ash (*Fraxinus pennsylvanica*). Hackberry (*Celtis occidentalis*), boxelder (*Acer negundo*), and American elm (*Ulmus americana*) were also relatively common systemwide. The only other tree seedling species recorded in MVP were river birch (*Betula nigra*), swamp white oak (*Quercus bicolor*), and the non-native invasive common buckthorn (*Rhamnus cathartica*). Two highly flood tolerant species, eastern swampprivet (*Forestiera acuminata*) and buttonbush (*Cephalanthus occidentalis*), were fairly common in MVS, in addition to honey locust (*Gleditsia triacanthos*), persimmon (*Diospyros virginiana*), and eastern cottonwood (*Populus deltoides*). A handful of other tree seedling species including hickory (*Carya spp.*), American sycamore (*Platanus occidentalis*), pin oak (*Quercus palustris*), and willow (*Salix spp.*) were also recorded in MVS, which overall had twice the tree seedling species richness as MVP.

Green ash was the most common species of large woody regeneration (> 0.5 m in height) occurring in canopy gaps system-wide, followed by silver maple (Table 10). Eastern swampprivet and buttonbush were again common in MVS, as was dogwood (*Cornus spp*.) and northern pin oak (*Quercus ellipsoidalis*) in MVR. Willow and hackberry were of moderate importance system-wide, as was boxelder and American elm to a lesser degree, although woody elm regeneration was only present in MVR and MVS. Total woody regeneration density in canopy gaps was the highest in MVS at 4607.5 stems/ha, followed by MVR (1756.4 stems/ha) and MVP (1080 stems/ha). Diversity of woody regeneration was the lowest in MVP at 7 species, and at 13 species each was nearly twice as high in MVR and MVS. A total of 18 species were recorded in the woody regeneration layer system-wide. The tallest stems encountered in the woody regeneration stratum followed a somewhat similar pattern, with green ash the most common (Table 11). Swampprivet and buttonbush were again common in this category in MVS, and buttonbush also occurred system-wide. Silver maple was also very common throughout, as were hackberry, willow, mulberry, and boxelder to a lesser degree.

Effects of Region, Gap Size, and Flood Regime on Canopy Gap Vegetation

At the system level, average percent cover of plant functional groups and species of management concern by gap size, flood regime, and region are shown in Figure 6. Regional effects were notable and highly significant for all plant functional groups except OW (other woody), as well as several species of management concern including RCG (reed canarygrass), GV (grape vine), and BC (bur cucumber) (see Table 12). For example, reed canarygrass and other graminoid cover was much higher while tree seedling cover was much lower in MVP compared to MVR or MVS. Forb cover was very high in MVP and MVS, but much lower in MVR. Grape vine (GV), bur cucumber (BC), and other vine (OV) cover was much higher in MVS compared to MVP and MVR. Trumpet creeper (TC) cover was much higher in MVS, but this species was not present in MVP and no statistical difference between MVR and MVS was found. The other species surveyed during this effort occurred too infrequently to support statistical analyses. Although some trends with respect to gap size and flood regime are also apparent, most notably with respect to reed canarygrass, none were significant (Table 12).

Figure 7 and Figure 8 explore regional differences in average percent cover of important plant functional groups and management species with respect to gap size and flood regime in more detail. Tree seedling cover decreased somewhat with gap size decrease in MVP and MVR, but was higher in medium and large-sized gaps in MVS. Tree seedling cover was lowest in gaps occurring in moderate flood regimes in MVR and MVS, and although it was relatively low in MVP altogether, actually increased slightly with flood regimes in in that region. Graminoid cover was marginal in MVR and MVS but prominent in MVP, where it was highest in large gaps and increased from low to high flood regimes. Reed canarygrass was also marginal in MVR and MVS but very prominent in MVP, where it increased dramatically with gap size but was actually much lower in moderate and high flood regimes. Interestingly, graminoids appear to have an inverse relationship with reed canarygrass and forbs in MVP, increasing in cover as sites become wetter whereas the latter two decrease. However, it should be noted that reed canarygrass is still the second-most dominant ground cover species occurring in high flood regimes in MVP (Figure 8).

Forb cover was highest in medium-sized gaps in MVP and increased slightly with gap size in MVS. It exhibited opposing trends in MVP and MVS with respect to flood regimes, increasing in MVS and decreasing in MVP as sites became wetter. By contrast, forb cover was very low across gap sizes and flood regimes in MVR. Overall, forbs had the highest percent cover in understory gap environments across gap sizes in MVS, and by far had the highest percent cover in MVS at high flood regimes (Figure 8). Vine species had very low cover in both MVR and MVP, but were of moderate to high importance across gap sizes and flood regimes in MVS. For example, grape vine cover was pronounced in MVS, where it was highest in medium and large-sized gaps and low to moderate flood regimes. Bur cucumber, trumpet creeper, and other vines followed a similar pattern, with highest cover occurring in medium and/or large gaps and moderate flood regimes.

A system-scale non-metric multidimensional scaling (NMS) ordination of plant functional groups and management species cover with gap size, flood regime, and region coded as environmental variables reinforces the significance of regional differences and clarifies important differences in gap-level plant associations between them (Figure 9). With region selected as the grouping variable, individual gaps and group centroids are displayed by region. Species group correlations are also overlayed in the figure. It is apparent from Figure 9 that MVP gaps have a clear positive association with reed canarygrass and graminoids and appear to actually have a negative association with tree seedlings. In addition, most of the other species of management concern, particularly the suite of vine species described above, are associated primarily with MVS gaps. MVR's dissassociation with the other regions is likely related to the fact that most species groups except tree seedlings had very sparse cover in that region compared to the other two. This is likely the most discernable artifact of the record floods occurring in the UMRS in 2019, which had the largest impact in MVR. Record high water and large amounts of residual sediment deposition clearly had the effect of suppressing ground cover vegetation in that region compared to the other two (see example gap phots in Appendxi A for a reference). When gap size and flood regime were selected as the grouping variable (not shown), group centroids were clustered in the center of the 2-dimensional graph and no discernable trends with respect to the gaps themselves were apparent.

Regional differences in tree seedling diversity and woody regeneration diversity and density with respect to gap size and flood regime are shown in more detail in Figure 10. In MVP, tree seedling species richness was slightly higher in small gaps and low flood regimes, while little in the way of discernable trends were apparent for MVS, which in general had moderately but significantly higher tree seedling diversity (Table 12). Interestingly, species richness of larger advance woody regeneration was comparable to tree seedling diversity in MVS, but was much lower in MVP. Finally, while woody regeneration diversity was also relatively low in MVR, woody regeneration density per gap in MVR was notably higher in small gaps and low flood regimes.

Characteristics of Overstory and Understory Vegetation in Gap Neighborhoods

A list of all the plant species documented in this study, including their scientific names, is included in Appendix C, Table C2.

Silver maple was by far the most dominant overstory tree species recorded in forest inventory plots in gap neighborhoods across both districts, delimited by the area in a 150m buffer around study gaps (Table 13). In MVP, the next most dominant species were eastern cottonwood, swamp white oak, green ash, and American elm, respectively. In MVS, the next most dominant species were eastern cottonwood, green ash, boxelder, and willow, respectively. A total of 20 overstory species were recorded, 11 in MVP and 18 in MVS, but most were relatively infrequent in occurrence.

The most common woody regeneration species occurring system-wide in the understory of forest inventory plots in gap neighborhoods were green ash, silver maple, American elm, hackberry, mulberry, and boxelder, although hackberry was not recorded in MVR and mulberry was not recorded in MVP (Table 14). Swampprivet, buttonbush and willow, the three most flood tolerant woody species in the UMRS, were also relatively common in MVS. The remaining 11 species occurring in the regeneration stratum in gap neighborhoods were of relatively minor or local importance. Similar to the overstory, a total of 20 advance regeneration species were recorded, and 15 of those occurred in both the overstory and understory environments. Pecan (*Carya illinionensis*), pin oak, bur oak (*Quercus macrocarpa*), and shellbark hickory (*Carya laciniosa*) were relatively minor mast-producing overstory species that did not occur in the understory. Swampprivet, buttonbush, dogwood, and prickly ash (*Zanthoxylum americanum*) occurred in the understory, but are typically described as small trees or large shrubs that do not attain overstory stature. Finally, vines, invasive species, and other species of management concern that were recorded in the understory of forest inventory plots in gap neighborhoods are shown in Table 15. Wild grape, oneseed bur cucumber, wood nettle, reed canarygrass, and Japanese hops were recorded in both MVP and MVS. Wood nettle was also the only species in these categories documented in gap neighborhoods in MVR. Buckthorn, barberry (*Berberis thunbergii*), and stinging nettle were unique to MVP. Trumpet creeper, bush honeysuckle (*Lonicera maackii*), giant ragweed (*Ambrosia trifida*), garlic mustard (*Alliaria petiolata*), and winter creeper (*Euonymus fortunei*) were unique to MVS in the gap neighborhood understory environment.

A list of the final datasets completed as part of this study is included in Appdendix D.

Discussion

As previously noted, forest regeneration dynamics in forested communities (i.e., seed dispersal, germination, establishment, growth and recruitment into the canopy layer) are a function of a combination of factors including forest disturbance, light availability, soil substrate, water and nutrient availability, and competition, regardless of forest type (Runkle 1982; Oliver and Larson 1996; Sousa

1984; Kern et al. 2017). Canopy gap formation plays an important and well-documented role in the process of establishing future cohorts of overstory trees, particularly in upland systems (e.g., Lorimer 1977; Runkle 1982; Frelich and Graumlich 1994). However, the ecology of canopy gap dynamics, and the importance of canopy gap formation to tree regeneration relative to discrete flood disturbances and general hydrological regimes, is less well understood in floodplain ecosystems such as the UMRS. At the landscape level, of particular interest in these systems is understanding rates and extents of gap formation, and the degree to which individual gaps are returning to forest cover or converting to other non-forest landcover types. At more localized levels, it is also critical to understand the impacts of hydrological regime and competitive exclusion by native and non-native invasive vegetation in driving the success or failure of tree recruitment in floodplain forest canopy gaps.

Forest managers and previous studies have documented concerns regarding sufficient natural regeneration in UMRS floodplain ecosystems (Guyon et al. 2012; Guyon and Battaglia 2018). Combined with the competitive threats posed by invasive species and accelerated canopy gap formation caused in part by the emerald ash borer and greater frequency of severe flood events, the potential for crossing a demographic disequilibrium threshold resulting in forest cover loss in portions of the system cannot be ignored (Barrette et al. 2017). In fact, recent forest successional models have predicted a 5-10% loss of forest cover in the UMRS over the next 50 years (DeJager et al. 2019).

We therefore initiated this study with the goal of answering four questions:

1. assessing the extent of floodplain forest canopy gaps across the UMRS landscape;
2. ascertaining what role of hydrological regime and/or the health or other structural attributes of the surrounding forest play in perpetuating canopy gap formation across the landscape;
3. determining if there are correlations between canopy gap colonization by trees or other competing vegetation and hydrological regime and gap size; and
4. quantifying the extent to which canopy gaps are returning to forest cover or are converting to other landcover types thereby leading to losses of forest cover in the UMRS.

Remotely-sensed Datasets

The analysis of the available GIS data showed that substantial customization is required to utilize existing data created with other research objectives. While the same analytical process was used for the initial analysis on each pool, the resulting canopy gaps were widely different. These differences primarily resulted from one or more of the following issues: 1) Lidar with a point cloud of insufficient resolution; 2) Lidar data collected during periods of high water that masks the land surface; 3) Lidar data that was temporally out-of-sync with the 2010 LCU data; 3) Misclassified vegetation data in the 2010 LCU.

Lidar data collected during flooded periods is particularly problematic. Because the lidar registers the water surface as the ground, lidar collected during a flood presents the appearance of an elevated ground surface elevation. This creates a collective and false shortening of the canopy height. Additionally, topography and vegetation below the water surface is not recorded in the dataset. In this study, the use of lidar data collected during flood events prevented a reliable estimate of the height of vegetation within gaps with high water lidar and may have led to inclusion of gaps within the dataset that should not have been included in the analysis because actual canopy height was taller than the lidar dataset indicated. These issues cannot be reliably corrected for and this study has inherent error due to the quality of the lidar data.

A final complicating factor is the difference between the MMU of the 2010 LCU map and the MMU of this project. The 2010 LCU map MMU was 0.405 ha while the MMU for this project was 0.0263 ha. This becomes important along the border of areas mapped as forest in the 2010 LCU where the mappers had to make choices of where to split different habitat types. In instances where the terrestrial areas went quickly from floodplain forest over a narrow band of herbaceous habitat into aquatic habitat with area less than the MMU, the mapper almost always mapped the terrestrial herbaceous areas with the terrestrial floodplain forest. The R script analysis saw this area not as the interface between the floodplain forest and aquatic habitat, but as a forest gap. This created many gaps along the edge of forest polygons. However, gap edge criteria used in this study were able to remedy this by limiting areas considered to be gaps to those with greater than sixty percent of the surrounding landcover being forest.

Though there were challenges with using the currently available lidar datasets, the methods developed for this study to account for variability will be highly repeatable and reliable. With the high-degree of automation now built into the process these datasets could be expanded to cover the entire UMRS using the existing lidar datasets and, as new lidar data is collected, used to monitor for systemic changes in forest canopy cover and structure across the basin. This study could also provide more refined parameters for timing of lidar data collection to provide greater usefulness.

Landscape Level Gap Patterns

With the exception of Pool 26, landscape level gap patterns were similar across the pools (Table 7), indicating that gap formation dynamics are likely being driven at least in part by processes at the local scale. This is not surprising, as the criteria used for this study results in a gap size that is generally smaller than what would be created by large scale, stand replacing disturbances caused by regional events such as flooding. Instead, the gaps in this study most likely represent individual tree mortality from wind, pests (like emerald ash borer), or local changes in hydrology. Pool 26 had nearly twice as many gaps per forest hectare as the mean, while each of those gaps was significantly smaller in total area than the average. Even with the relatively small size of the gaps, however, almost 11% of the total forest area in Pool 26 was in gaps, which is more than twice the amount of other pools and almost three times the mean. However, Pool 26 was also one of only two pools where the average vegetation height within the gap was over three meters tall. Only woody vegetation, or vines growing on woody vegetation, are able to reach this height, so this is an indication that gaps in Pool 26 are more likely to contain woody vegetation than in other pools.

Differences in gap distributions and characteristics were more evident at the district level (Table 8), which may indicate that regional drivers are also important. The most evident difference in gap characteristics at the district level are the differences in overall gap area, gap vegetation height and inundation characteristics. One important result is the indication that overall gap area relative to total forest area is a function of the number of gaps rather than the size of those gaps. Average gap size across the three districts varied by only 0.03 ha, yet MVR had half the relative area in gaps of MVP and MVS. Pool 26 had the highest relative forest gap area of all the pools, yet it had the lowest average gap size.

Given that the average gap size was consistently small when summarized at the pool or the district level, it seems most likely that gap dynamics in this system are being driven by individual tree mortality or mortality of individual clumps. This suggests that gap formation is probably not being vectored by large events like blowdowns but instead by internal stand processes and forest health issues, especially emerald ash borer and Dutch elm disease. However, the MMU used in this project and the associated MMUs in the LTRM LCU dataset may have artificially excluded gaps formed by large-scale disturbance events or may have artificially truncated gaps where small clumps of trees remained within the gap. Substantial mortality has been observed in these pools, especially the upper pools, following multiple years of growing season flooding in the late 2010s; these patches of dead trees will most likely not be classified as forest in future landcover datasets and, thus, similar trends over the past few decades would not have been captured in this study. Higher elevation areas in this study are much less likely to be subject to catastrophic flooding, and the gap distributions evidenced by the geospatial analysis in this study probably more accurately represent canopy gap dynamics in those areas than in lower elevation areas.

Vegetation Composition in UMRS Floodplain Forest Canopy Gaps

Strong regional effects clearly overshadowed the impacts of hydrological regime and/or canopy gap size with respect to vegetation composition in the UMRS floodplain forest canopy gaps randomly selected for field data collection (Figure 6, Figure 9 and Table 12). For example, at the system level forbs were the dominant plant functional group cover occurring in canopy gaps, even though forbs and most other plant cover appeared to be suppressed in MVR canopy gaps in 2019, most likely due to record flooding that season (Figure 11). Similarly, small tree seedlings (<50 cm in height) were the second-most dominant plant cover system-wide even though they were poorly represented in MVP canopy gaps. Aside from forbs and tree seedlings, relatively high system-wide averages for any individual plant group were largely driven by high percent cover in just one of the three UMRS USACE Districts in the study. For example, reed canarygrass and other graminoid cover were dominant in MVP, but very low in MVR and MVS. A suite of vine species (wild grape, bur cucumber, trumpet creeper, and other vines) were individually (and collectively) dominant in MVS, but low in the other two. As previously noted, tree seedling cover was relatively high in MVR, but all other plant functional groups had very low cover.

Although not discernable at a system level, interactions between several plant functional groups, hydrological regime, and gap size were apparent at within-district spatial scales, most notably within MVP canopy gaps (see Figure 7). In MVP, forb cover was more pronounced in small and medium-sized gaps occurring in areas with fewer days of annual inundation. Reed canarygrass and other graminoids were both dominant in larger gaps, but reed canarygrass cover was much more pronounced in low flood regimes while other graminoids increased in dominance in areas with longer average annual inundation periods. Generally speaking, this suggests that grasses dominate the understory environment in MVP floodplain forests. Competitive exclusionary effects therefore likely contribute to correspondingly low tree seedling and advance regeneration density and diversity in northern reaches, but the role of competition versus hydrology in suppressing tree regeneration remains unclear given the lack of apparent trends in MVP tree seedling cover across hydrological regimes in this study. A more in-depth analysis of field data collected in St. Paul District over the course of this study (Oines 2020) found that tree seedling percent cover declined significantly with increasing gap size and reed canarygrass cover. An interesting and significant 3-way interaction between gap size, flood regime, and percent forest buffer was also found for reed canarygrass, graminoid, and forb cover by Oines. Patterns of reed canarygrass cover may have also been influenced by periods of high water and sedimentation in the growing seasons prior to the study; it has been noted by anecdotal observation that many areas in MVP previously dominated by reed canarygrass shifted to dominance by rice cutgrass (*Leersia oryzoides*) following these recurrent floods. It is also interesting to note that, though reed canarygrass is often considered to become more dominant as sites get wetter, in this study, reed canarygrass was most dominant in the low flood duration gaps, and declined in gaps with longer inundation periods. This may be a function of sediment deposition in the initial 2019 flood on the lower elevation sites with subsequent colonization by more ruderal graminoids and reed canarygrass may become more dominant on the wetter sites over the next few years. However, an alternative explanation could be that reed canarygrass, rather than exploiting changes in hydrology, is actually exploiting regeneration failures in declining forests and, when canopy gaps are created, with no viable woody regeneration, reed canarygrass instead captures those gaps, regardless of inundation regime.

In MVS, the only obvious trend in plant functional group cover or regeneration diversity with respect to gap size or hydrological regime was that forb cover increased dramatically at higher flood regimes relative to other species groups. Vine cover appeared to peak at moderate flood regimes and gap sizes, but was relatively high throughout. Vine cover clearly plays an important role in the canopy gap understory environment in southern reaches, and invasive species like Japanese hops have been noted to suppress native species as well as tree regeneration. Species with similar growth habits like bur cucumber and trumpet creeper have also been noted to have inhibitory effects, but the competitive effects of other species like wild grape, while less well quantified, are also likely significant. Field observations suggest that wild grape vine forms thickets that overtop and, in some cases, effectively arrest the development of other woody vegetation in canopy gaps (Figure 12). For example, some older gaps were noted to have thickets of heavy grape vine in and atop stands of small mulberry and other tree species that appeared to be persisting around 3-6 m in height. Furthermore, some of these gaps were noted to be increasing in size as edge trees snapped due to windthrow or otherwise died.

In MVR the only discernable trend with respect to gap size and flood regime was that tree seedling cover and woody regeneration density and diversity were higher in smaller gaps and low flood regimes. It should be noted that record flooding in the summer of 2019 had an impact on the field data collected, and MVR (the Rock Island District) suffered the worst impacts that season (see Figure 11), which is reflected in the relative scarcity of other ground-level understory vegetation recorded in that region. Persistent standing water well into the growing season combined with fresh layers of sediment deposition delayed and reduced seasonal plant establishment and development. However, significant sediment deposition may have also increased new seedling germination and establishment by providing exposed mineral soil across large swaths of floodplain forest understories. Similar effects were also noted in MVS and MVP, where dense patches of silver maple seedlings were sometimes coincident with dense patches of eastern cottonwood seedlings (Figure 12). Seasonal flushes of silver maple seedlings occur regularly throughout the system, but widespread flushes of cottonwood seedlings, which require exposed mineral soil for successful germination and establishment, are highly unusual except in recently abandoned agricultural inholdings. This suggests there may be linkages between large-scale flood events and cyclical patterns of cottonwood establishment and recruitment in the impounded reaches of the UMRS worth further exploration (see for example Yin 1998).

The high tree seedling cover observed in the MVR and MVS may seem counterintuitive given the many concerns expressed by UMRS forest managers and others regarding tree regeneration throughout the system. However, previous studies (e.g., Guyon and Battaglia 2018) and a wealth of observation-driven anecdotal evidence by practitioners have commonly reported dense numbers of first-year seedlings (most commonly silver maple) accompanied by a subsequent lack of recruitment into larger sapling and small tree cohorts. This phenomenon was also generally observed in the current study, although strong regional differences with respect to larger woody regeneration are again apparent. Generally speaking, both density and diversity of woody regeneration increased along a latitudinal gradient from north to south in the UMRS. Interestingly, at gap-level spatial scales, diversity of regeneration was even comparable to tree seedling diversity in MVS, suggesting that recruitment issues are likely much more pronounced in northern reaches than more southerly ones.

Linking Landscape and Gap Level Patterns

If individual tree or small patch mortality is the primary mechanism for gap formation in this system, at least in areas not subject to catastrophic flooding, then re-establishment of forest cover in these canopy gaps would almost certainly be dependent either on the establishment of advance regeneration in the understory prior to canopy mortality or the establishment of new cohorts of more shade tolerant species in the canopy openings after gap creation. Gaps identified in this study are, on average, likely far too small for shade intolerant species like eastern cottonwood or river birch to establish, survive, and grow into larger size classes (although patches of new cottonwood seedlings were observed in MVS, both of these species were nearly absent from the dataset across all study gaps, see Table 10), so maintenance of forest cover likely depends on the ability of other species to naturally regenerate. Two lines of evidence from this study indicate that establishment of advance regeneration, and subsequent recruitment into canopy gaps, varies across the UMRS.

The first indicator comes from the field collected data. The frequency of the smallest size class of tree seedlings is very high across all districts, but the average percent cover was almost four times greater than MVP in MVR and almost 5 times greater in MVS. Additionally, large woody regeneration is almost twice as common in MVR than MVP and over four times as common in MVS relative to MVP. Of the large woody regeneration in MVP, half was green ash which is no longer a viable species due to the emerald ash borer beetle. MVP averaged only 99 stems per ha of tree species other than green ash, which is far below the number necessary for re-establishment of a forest stand. Total stems per hectare in MVR and MVS are closer to the minimum amount needed to retain forest canopy.

Though it is much harder to interpret whether gaps have been recaptured by trees in the landscape level dataset, and interpretations are further limited by the issues with the underlying lidar data, average canopy heights from the geospatial dataset provide a second indicator of the variability in the establishment of regeneration. The average canopy heights across the landscape are potentially indicative of the patterns shown in the field collected data. Average canopy heights are higher in MVR and MVS than in MVP; MVP average heights are roughly equivalent to the maximum height of common herbaceous vegetation, while MVR and MVS heights are higher, potentially indicating that woody vegetation is established in those gaps. This pattern is more pronounced at the pool level where the three northern Mississippi River pools have vegetation heights all under two meters, with the lower Mississippi River pools all above two meters (and Pools 21 and 26 both above three meters). The implications of these patterns are significant. While MVS, and, to some extent, MVR, likely have adequate regeneration established in a large number of canopy gaps that will be sufficient to re-establish forest in those gaps, both datasets in this study indicate that in MVP particularly, forest regeneration is not occurring in canopy gaps. It therefore seems likely that, over time, individual tree mortality in MVP will continue to increase the number of small canopy gaps, leading to a larger and larger percentage of forest area in non-forest conditions, while new gap creation from individual tree mortality in the lower pools will likely be offset by re-establishment of forest in older canopy gaps, leading to a relatively stable density of forest canopy gaps over time.

Management Implications

Hydrology is generally considered to be the single most important driving factor related to floodplain vegetation community development and differentiation across large river floodplain ecosystems. While that is not in dispute, results from this study, such as a lack of significant findings correlating relative plant functional group cover in canopy gaps with hydrology at a system level, reiterate that when it comes to plant functional group interactions and tree regeneration establishment, growth and maturity, other important factors need to be accounted for when developing both regional forest management plans and local-scale silvicultural prescriptions. From a management perspective, the significant regional differences in vegetation establishment and development in floodplain forest canopy gaps emphasizes that there is no “one size fits all” approach to sustainable forest management in the UMRS. Specifically, competitive interactions between woody regeneration and other plant functional groups (e.g., reed canarygrass, graminoids, and vine species) likely play a major role in tree seedling establishment, survival, and growth throughout the system, but the specific species and pathways involved differ substantially between regions. This in turn means different approaches or at least modifications to management and reforestation efforts will also be required in different management districts.

For example, reed canarygrass and other graminoids dominate ground cover across large areas in northern reaches and have been noted to significantly inhibit tree establishment and regeneration. Similarly, wild grape and other vine species, both native and invasive (e.g., Japanese hops) can easily smother canopy gaps and other openings and are known to suppress natural and artificial (planted) regeneration. However, while vegetative competition is a common challenge to reforestation efforts across regions, the different species guilds involved means specific management techniques will need to be tailored to regional and possibly even more local conditions. As another example, greater amounts of naturally occurring tree regeneration in southern reaches suggest that it might be worthwhile to focus tree planting efforts on mast producing or other less common species to increase overall floodplain forest diversity in that region. In northern reaches, extremely low levels of tree seedling establishment and regeneration coupled with widespread and increasing dominance of reed canarygrass suggests that management should be focused on maintaining the distribution of current forest types, including cottonwood and silver maple, with less focus on species composition.

Forest management prescriptions often call for the creation of canopy openings to allow for the development of a new cohort of trees, and this study may provide some insight into optimal sizes for silviculturally created gaps though, again, these recommendations likely vary by region. In MVP and MVR, tree seedlings were most prevalent in the smallest gaps, while in MVP forbs were most dominant in medium-sized gaps and reed canarygrass was most dominant in the largest gaps. In MVP, and potentially MVR, it appears that smaller gaps may be necessary to prevent dominance by non-woody species upon gap creation. However, in MVS, tree cover was higher in medium and large gaps, with only minor variability in the cover of competing species in larger gap sizes. It may be possible, therefore, in MVS, to create larger gaps which allow for a wider range of potential tree species and more rapid growth.

However, especially in MVP, this study indicates that silvicultural gap creation without established regeneration is likely to accelerate the transition to non-forest canopy by increasing the number of small gaps on the landscape. Without a better understanding of regeneration dynamics and how to reliably establish regeneration, active gap creation should be undertaken with extreme caution in the upper pools.

Next Steps

The information contained in this summary report primarily reflects summary results from the geospatial component that defined, identified, and mapped discrete floodplain forest canopy gaps occurring in seven selected pools of the UMRS, and preliminary investigative results from an analysis of field level vegetation data collected in a random sample of those canopy gaps. The next phase of analyses will involve a more detailed landscape-level analysis of geospatially derived gap metrics to further explore possible correlations between floodplain forest landscape features, hydrology, and vegetation trends associated with canopy gap formation and persistence in the floodplain landscape, and more clearly define the ecological role of canopy gaps as they relate to competitive interactions between plant functional groups and overall floodplain forest health, diversity, sustainable self-replacement, and loss of forest cover and conversion to other landcover types. Additional analyses of the geospatial dataset should leverage the robust and widespread USACE forest inventory datasets and, where the two datasets overlap, relationships should be developed between local level gap distributions (density per ha, gap size, overall canopy density) and field-collected forest inventory data (tree species, forest community types, average tree density, average tree size) to determine whether there are any characteristics in the geospatial dataset that can be related to on the ground forest health and whether any remotely sensed canopy characteristics are predictive of on the ground forest decline. Such metrics would be very useful in prioritizing areas for management activity based on a quantitative assessment of forest stand level forest viability.

The field component of this study has also highlighted significant differences in regeneration dynamics among UMR pools, confirming that complete regeneration failures in the upper pools are a significant concern, and that in lower pools, viable forest regeneration remains difficult to achieve due to competition from undesirable vegetation, particularly vines. Future studies should focus on developing a stronger understanding of the factors associated with the recruitment of natural regeneration in MVP, and methods to manage competing vegetation in all districts, as well as the potential role of herbivory in limiting seedling recruitment in the upper pools.

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Tables and Figures

Table 1. Reclassed values for the canopy height model in meters.

Reclassed Value	Original Lower Value	Original Upper Value
0	Layer Minimum	< −0.05
1	−0.05	10.00
2	> 10.00	Layer Maximum

Table 2. Attributes added to the final forest canopy gap shapefile and their descriptions.

Attribute Name	Description
G_Area	Area of the canopy gap (ha)
G_Perim	Perimeter of the canopy gap in (m)
G_APR	Canopy gap area/perimeter ratio
G_Dom	Dominant landcover/use within the canopy gap derived from the 31-class LTRM LCU layer
G_ICT	Canopy gap interior vegetation cover type derived from image interpretation
G_AvgHt	Canopy gap average canopy height as derived from the CHM (m)
G_MinHt	Canopy gap minimum canopy height as derived from the CHM (m)
G_MaxHt	Canopy gap maximum height as derived from the CHM (m)
G_NFP	Percentage of the canopy gap perimeter that is non-forest as derived from the 31-class LTRM LCU Layer
S_MjFCT	Majority forest type within a 150-meter buffer surrounding the canopy gap as derived from the 31-class LTRM LCU layer
S_PFA	Percentage of the 150-meter buffer area surrounding the canopy gap that is forest as derived from the 31-class LTRM LCU layer
S_PWA	Percentage of the 150-meter buffer area surrounding the canopy gap that is water as derived from the 31-class LTRM LCU layer
S_PNwNf	Percentage of the 150-meter buffer area surrounding the canopy gap is neither forest nor water as derived from the 31-class LTRM LCU layer
S_PFpg	Percentage of the first pass gap layer that falls within the 150-meter buffer surrounding the canopy gap
G_AvGsFd	Average flood inundation length within the canopy gap in days as derived from the UMRS Floodplain Inundation Attribute Raster (days per growing season)
G_AvgDep	Average flood inundation depth within the canopy gap in feet as derived from the UMRS Floodplain Inundation Attribute Raster (days per growing season)
S_MdJPK	Median Julian day of maximum flood inundation depth for the 150-meter buffer area surrounding the canopy gap as derived from the UMRS Floodplain Inundation Attribute Raster (days per growing season)

Table 3. Bins for field study gap selection. Attributes are defined in Table 2.

Gap size (G_Area)	**Flood Regime (G_AvGsFd)**		
	≤ 20 days per year (LOW)	**>20 AND ≤ 40 days per year (MOD)**	**> 40 AND ≤ 100 days per year (HIGH)**
> 0.0405 ha (0.1 ac) AND ≤0.1012 ha (0.25 ac) (**SM**)	SM-LOW	SM-MOD	SM-HIGH
> 0.1012 ha (0.25 ac) AND ≤ 0.3035 ha (0.75 ac) (**MED**)	MED-LOW	MED-MOD	MED-HIGH
> 0.3035 ha (0.75 ac) AND ≤ 0.8093 ha (2.0 ac) (**LG**)	LG-LOW	LG-MOD	LG-HIGH

Table 4. Gap characteristics matrix for gaps sampled in the field component of this study.

Region	**Flood Regime**	**Gap Size**			***Total***
		SM	**MED**	**LG**	
MVP (Pools 8 & 9)	LOW	3	2	3	*8*
	MOD	3	3	3	*9*
	HIGH	2	1	0	*3*
	Total	*8*	*6*	*6*	*20*
MVR (Pools 13 & 21)	LOW	4	3	3	*10*
	MOD	2	3	3	*8*
	HIGH	1	2	2	*5*
	Total	*7*	*8*	*8*	*23*
MVS (Pools 24, 26, & Alton Pool)	LOW	3	3	3	*9*
	MOD	3	3	3	*9*
	HIGH	3	3	3	*9*
	Total	*9*	*9*	*9*	*27*
UMRS (Combined)	LOW	10	8	9	*27*
	MOD	8	9	9	*26*
	HIGH	6	6	5	*17*
	Total	*24*	*23*	*23*	*70*

Table 5. Description of browse severity index.

Severity	Description
0	No browsing or girdling
1	Some browsing and/or girdling but > 25% of available forage or stem circumference has been browsed and plant growth is unaffected
2	25-75% of available forage has been browsed and/or 25-75% of circumference has been girdled and plant growth if affected
3	> 75% of available forage has been browsed and/or >75% of stem circumference has been girdled and growth has been affected enough that plant survival is questionable)

Table 6. General project gap characteristics and summary statistics from the geospatial dataset, summarized by navigation pool.

USACE district			MVP		MVR		MVS		
	Pool	All	8	9	13	21	24	26	Alton
Pool Forest Cover (ha)[1]		38,677.3	2,525.2	4,536.5	5,128.1	7,880.4	4,081.7	7,236.5	7,288.8
First-pass gaps	Count	32,360	2,881	4,749	4,156	2,620	4,819	10,309	2,826
	Gaps per ha forest by pool	0.84	1.14	1.05	0.81	0.33	1.18	1.42	0.39
Final study gaps	Count	13,782	920	2,239	1,381	1,703	1,556	5,323	698
	Gaps per ha forest by pool	0.36	0.36	0.49	0.27	0.22	0.38	0.74	0.10
	Gap total area (ha)	1,675.6	84.2	251.1	142.8	187.5	213.2	789.2	34.7
	Gap avg area (ha)	0.12	0.09	0.11	0.10	0.11	0.14	0.02	0.05
	Gap avg veg ht (m)	2.45	1.80	1.58	1.65	3.05	2.30	3.15	1.26
	Gap avg inundation depth (m)	1.84	1.14	1.56	1.58	1.87	2.05	1.99	2.42
	Gap avg inundation (days)	23	18	24	21	26	28	21	29
	Pct of forest that is gap	4.3%	3.3%	5.5%	2.8%	2.4%	5.2%	10.9%	0.5%
	Avg % gap edge that is forest	81.5%	79.9%	79.8%	80.4%	88.1%	82.4%	80.7%	79.3%
	Avg % gap edge that is water	9.3%	5.2%	6.8%	8.0%	7.9%	11.7%	11.0%	11.0%

[1] Pool Forest Cover is the total cover of all floodplain forest map classes within the UMRS Pool Study area boundary

Table 7. General project gap characteristics and summary statistics from the geospatial dataset, summarized by navigation pool.

	District	All	MVP	MVR	MVS
	Pool Forest Cover (ha)[1]	38,677.3	7,061.7	13,008.5	18,607.0
First-pass gaps	**First-pass gap count**	32,360	7,630	6,776	17,954
	First-pass gaps per ha forest in pool	0.84	1.08	0.52	0.96
Final study gaps	**Final gap count**	13,782	3,159	3,084	7,577
	Final gaps per ha forest in pool	0.36	0.45	0.24	0.41
	Final gap total area (ha)	1,675.6	335.3	330.3	1,037.1
	Gap average area (ha)	0.12	0.11	0.11	0.14
	Gap average vegetation height (m)[2]	2.45	1.69	2.35	2.24
	Gap avg inundation depth (m)[2]	1.84	1.35	1.73	2.15
	Gap avg inundation (days)[2]	23	21	24	26
	Percent of forest that is gap	4.3%	4.7%	2.5%	5.6%
	Average % gap edge that is forest[2]	81.5%	79.9%	84.3%	80.8%
	Average % gap edge that is water[2]	9.3%	6.0%	8.0%	11.2%

[1] Pool Forest Cover is the total cover of all floodplain forest map classes within the UMRS Pool Study area boundary

[2] Averages calculated from overall pool averages by district rather than individual gap values

Table 8. Plant functional groups and management species of concern from the field survey – average percent cover and frequency of occurrence

Species Groups[1]	MVP		MVR		MVS		UMRS (Combined)	
	% Cover	Freq (%)	% Cover	Freq (%)	% Cover	Freq (%)	% Cover	Freq (%)
TS (< 50cm)	3.81	100.0%	11.23	87.0%	14.26	100.0%	10.45	95.7%
G	14.77	95.0%	1.79	52.2%	1.27	51.9%	5.26	64.3%
F	19.40	100.0%	2.10	56.5%	21.14	100.0%	14.58	85.7%
OV	1.27	45.0%	0.33	56.5%	8.04	88.9%	3.64	65.7%
OW	0.01	5.0%	0.20	21.7%	0.00	0.0%	0.07	8.6%
BC	0.06	20.0%	0.20	30.4%	9.55	59.3%	3.87	38.6%
GRW	0.38	10.0%	0.01	4.3%	0.73	11.1%	0.39	8.6%
GV	0.24	25.0%	0.41	47.8%	14.90	96.3%	6.10	60.0%
NS	0.23	10.0%	0.69	4.3%	5.09	51.9%	2.30	24.3%
NW	2.55	30.0%	2.60	52.2%	0.06	3.7%	1.60	27.1%
TC	0.00	0.0%	0.65	30.4%	5.07	74.1%	2.22	38.6%
RCG	14.70	85.0%	0.12	8.7%	0.05	11.1%	4.21	31.4%
H	0.49	5.0%	0.00	0.0%	1.61	18.5%	0.76	8.6%

[1] TS = Tree Seedlings; G = Graminoid; F = Forbs; OV = Other Vines; OW = Other Woody; BC = Oneseed Bur cucumber; GRW = Giant Ragweed; GV = Grape Vine; NS = Stinging Nettle; NW = Wood Nettle; TC = Trumpet Creeper; RCG = Reed Canarygrass; H = Japanese hops

Table 9. Woody seedlings (< 50cm in height): frequency of occurrence of woody seedlings < 50cm in height by species in canopy gaps.[1,2] Species listed in ***bold*** *are tree species, underlined species are woody shrubs. Young willow are difficult to identify to species, so may represent either tree willows (e.g Salix nigra, S. amygdaloides) or shrub willows (e.g. Salix interior).*

Scientific Name	Common Name	MVP	MVS	UMRS (Combined)
Acer saccharinum	**Silver maple**	90.0%	96.3%	93.6%
Fraxinus pennsylvanica	**Green ash**	50.0%	66.7%	59.6%
Celtis occidentalis	**Hackberry**	15.0%	44.4%	31.9%
Acer negundo	**Boxelder**	15.0%	29.6%	23.4%
Ulmus americana	**American elm**	35.0%	14.8%	23.4%
Forestiera acuminata	Eastern swampprivet	0.0%	37.0%	21.3%
Cephalanthus occidentalis	Buttonbush	0.0%	29.6%	17.0%
Betula nigra	**River birch**	20.0%	0.0%	8.5%
Gleditsia triacanthos	**Honeylocust**	0.0%	14.8%	8.5%
Diospyros virginana	**Persimmon**	0.0%	11.1%	6.4%
Populus deltoides	**Eastern cottonwood**	0.0%	11.1%	6.4%
Quercus bicolor	**Swamp white oak**	15.0%	0.0%	6.4%
Carya spp.	**Hickory**	0.0%	3.7%	2.1%
Rhamnus cathartica	Buckthorn	5.0%	0.0%	2.1%
Lindera benzoin	Spicebush	0.0%	3.7%	2.1%
Morus spp.	**Mulberry**	0.0%	3.7%	2.1%
Platanus occidentalis	**American sycamore**	0.0%	3.7%	2.1%
Quercus palustris	**Pin oak**	0.0%	3.7%	2.1%
Salix spp.	**Willow**	0.0%	3.7%	2.1%

[1] Based on presence/absence data at the whole-gap level; [2] Data not available for MVR

Table 10. Woody regeneration (> 0.5m in height; average stems/ha) in UMRS canopy gaps.[1] *Species listed in* ***bold*** *are tree species,* *underlined* *species are woody shrubs.*

Species	MVP	MVR	MVS	UMRS
Green ash	540.0	17.4	1185.2	617.1
Silver maple	20.0	243.5	770.4	382.8
Eastern swampprivet	0.0	0.0	918.5	354.3
buttonbush	60.0	34.8	607.4	262.8
Willow	380.0	17.4	385.2	262.8
Dogwood spp.	0.0	747.8	0.0	245.7
Hackberry	20.0	69.6	325.9	154.3
Northern pin oak	0.0	295.6	0.0	97.1
Boxelder	20.0	17.4	118.5	57.1
Mulberry	0.0	52.2	88.9	51.4
American elm	0.0	69.6	59.3	45.7
Pricklyash	0.0	121.7	0.0	40.0
Hickory	0.0	34.8	29.6	22.9
Honeylocust	0.0	0.0	59.3	22.9
Spicebush	0.0	0.0	44.4	17.1
Buckthorn	40.0	0.0	0.0	11.4
Bush honeysuckle	0.0	34.8	0.0	11.4
Eastern cottonwood	0.0	0.0	14.8	5.7
Total	*1080.0*	*1756.4*	*4607.5*	*2662.7*

[1] Includes tallest woody stems.

*Table 11. Average height (cm) of tallest woody stems by species. Species listed in **bold** are tree species, underlined species are woody shrubs.*

Species	MVP		MVR		MVS		UMRS (Combined)	
	Count	Ht (cm)	Count	Ht (cm)	Count	Ht (cm)	Count	Ht (cm)
Green ash	16	90.3	1	100.0	34	166.5	51	141.3
Swampprivet					31	205.3	31	205.3
Buttonbush	3	143.3	2	176.0	24	199.6	29	192.1
Silver maple	1	130.0	3	195.0	23	278.7	27	263.9
Hackberry	1	65.0	1	200.0	17	282.1	19	266.3
Willow	6	235.8	1	181.0	6	276.7	13	250.5
Mulberry			3	108.3	4	260.0	7	195.0
Boxelder	1	400.0	1	200.0	4	242.5	6	261.7
Dogwood			5	238.2			5	238.2
American elm			2	170.0	3	225.0	5	203.0
Hickory			2	180.0	1	350.0	3	236.7
Pricklyash			3	108.0			3	108.0
Buckthorn	2	280.0					2	280.0
Honeylocust					2	200.0	2	200.0
Spicebush					2	300.0	2	300.0
Cottonwood					1	150.0	1	150.0
Northern pin oak			1	580.0			1	580.0

Table 12. MRPP (Multi-Response Permutation Procedure) significance tests of plant functional group differences across regions, gap sizes, and flood regimes (based on gap-level average % cover).

Plant Group	Region (Pairwise)	(T) stat.	A value	*p*-value	Gap Size (T) stat.	A value	*p*-value	Flood Regime (T) stat.	A value	*p*-value
Combined		-21.710	0.146	< 0.0001	2.058	-0.014	0.9997	0.284	-0.002	0.5609
	MVP v. MVR	-12.524	0.107	< 0.0001						
	MVP v. MVS	-15.576	0.120	< 0.0001						
	MVR v. MVS	-15.861	0.114	< 0.0001						
TS		-4.691	0.063	0.0013	0.795	-0.011	0.7784	-0.775	0.010	0.1894
	MVP v. MVR	-1.431	0.021	0.0896						
	MVP v. MVS	-7.261	0.098	0.0002						
	MVR v. MVS	-0.942	0.013	0.1469						
G		-2.313	0.046	0.0298	-0.326	0.007	0.3075	1.131	-0.023	0.9142
	MVP v. MVR	-1.994	0.039	0.0474						
	MVP v. MVS	-3.233	0.060	0.0120						
	MVR v. MVS	0.432	0.013	0.5636						
F		-6.553	0.103	< 0.0001	1.291	-0.020	0.9636	1.460	-0.023	0.9921
	MVP v. MVR	-7.111	0.146	0.0002						
	MVP v. MVS	0.718	-0.011	0.7580						
	MVR v. MVS	-7.838	0.133	< 0.0001						
OV		-4.415	0.100	0.0020	0.703	-0.016	0.7339	0.379	-0.009	0.5777
	MVP v. MVR	0.289	-0.100	0.4985						
	MVP v. MVS	1.609	0.036	0.0738						
	MVR v. MVS	-6.507	0.128	0.0004						
RCG		-2.096	0.110	0.0341	0.890	-0.039	0.8187	0.221	-0.011	0.5336
	MVP v. MVR	-1.514	0.070	0.0786						
	MVP v. MVS	-1.576	0.059	0.0759						
	MVR v. MVS			N/A						
GV		-8.564	0.215	< 0.0001	0.614	-0.015	0.6882	0.662	-0.016	0.7130
	MVP v. MVR	0.750	-0.042	0.7679						
	MVP v. MVS	-4.810	0.115	0.0022						
	MVR v. MVS	-10.774	0.215	< 0.0001						

Plant Group	Region (Pairwise)	(T) stat.	A value	*p*-value	Gap Size (T) stat.	A value	*p*-value	Flood Regime (T) stat.	A value	*p*-value
BC		-6.721	0.258	< 0.0001	0.116	0.004	0.4686	-1.140	0.043	0.1272
	MVP v. MVR	0.608	-0.057	0.6758						
	MVP v. MVS	-6.626	0.221	0.0001						
	MVR v. MVS	-7.426	0.218	< 0.0001						
TC[1]		-0.823	0.022	0.1688	-0.867	0.032	0.1721	1.188	-0.045	0.9344
Woody		-6.315	0.193	0.0002	0.965	-0.029	0.8773	0.690	-0.021	0.7264
Regen	MVP v. MVR	0.616	-0.037	0.6815						
(>0.5m)	MVP v. MVS	-7.027	0.181	0.0003						
	MVR v. MVS	-5.890	0.146	0.0011						
Tree Seedlings[2] (<0.5m)		-7.873	0.138	0.0001	0.324	-0.008	0.5512	0.178	-0.000	0.4207

[1] Trumpet Creeper did not occur in MVP and there were no significant differences between MVR and MVS.

[2] Tree seedling species richness data was only available for MVP & MVS

Distance measure: Sorensen (Bray-Curtis); Weighting option: C(I) = n(I)/sum(n(I)); (Analyses performed using PCORD v. 7.08)

Table 13. Average tree basal area in squarem per hectare in forest inventory plots in gap neighborhoods for the field survey gaps.[1]

Scientific Name	Common Name	MVP	MVS	UMRS (Combined)
Acer saccharinum	Silver maple	81.3	47.3	58.6
Populus deltoides	Eastern cottonwood	7.3	15.2	12.6
Fraxinus pennsylvanica	Green ash	3.6	11.7	9.0
Acer negundo	Boxelder	1.9	6.6	5.0
Ulmus americana	American elm	3.0	4.8	4.2
Salix spp.	Willow	0.9	5.8	4.2
Platanus occidentalis	American sycamore		3.0	2.0
Quercus bicolor	Swamp white oak	5.6		1.8
---	Dead tree[2]		2.7	1.8
Carya illinoinensis	Pecan		2.0	1.3
Celtis occidentalis	Hackberry	2.1	0.6	1.1
Morus rubra	Red mulberry		1.4	0.9
Carya cordiformis	Bitternut hickory	2.1		0.7
Betula nigra	River birch	1.3	0.1	0.5
Quercus rubra	N. red oak	1.1		0.4
Gleditsia triacanthos	Honey locust		0.4	0.2
Gymnocladus dioicus	Kentucky coffeetree		0.3	0.2
Quercus palustris	Pin oak		0.3	0.2
Quercus macrocarpa	Bur oak		0.2	0.1
Carya laciniosa	Shellbark hickory		0.1	0.1
Maclura pomifera	Osage-orange		0.1	0.1
	Total	*110.1*	*102.6*	*105.1*

[1] Data not available for MVR; [2] Species not recorded for dead trees

Table 14. Frequency of occurrence of woody regeneration in forest inventory plots in gap neighborhoods for field survey gaps. Species listed in ***bold*** *are tree species, underlined species are woody shrubs.*

	MVP		MVR		MVS		UMRS (Combined)	
Species	**Plots (%)**	**Gaps (%)**	**Plots (%)**	**Gaps (%)**	**Plots (%)**	**Gaps (%)**	**Plots (%)**	**Gaps (%)**
Green ash	31.4%	70.0%	12.0%	34.8%	29.8%	70.4%	24.8%	58.6%
Silver maple	12.9%	35.0%	21.7%	47.8%	28.4%	74.1%	22.8%	54.3%
American elm	12.9%	20.0%	16.3%	43.5%	26.2%	66.7%	20.1%	45.7%
Hackberry	1.4%	5.0%			26.2%	55.6%	12.5%	22.9%
Mulberry			14.1%	30.4%	17.0%	40.7%	12.2%	25.7%
Boxelder	2.9%	10.0%	2.2%	8.7%	14.2%	48.1%	7.9%	24.3%
Swampprivet					16.3%	51.9%	7.6%	20.0%
Willow	1.4%	5.0%			6.4%	25.9%	3.3%	11.4%
Buttonbush	2.9%	5.0%			4.3%	37.0%	2.6%	15.7%
Kentucky coffeetree					3.5%	11.1%	1.7%	4.3%
Am. sycamore			1.1%	4.3%	2.8%	11.1%	1.7%	5.7%
Dogwood			4.3%	8.7%			1.3%	2.9%
Honeylocust					2.8%	7.4%	1.3%	2.9%
Northern pin oak			4.3%	8.7%			1.3%	2.9%
Bitternut hickory	2.9%	5.0%					0.7%	1.4%
E. cottonwood					1.4%	7.4%	0.7%	2.9%
Pricklyash	1.4%	5.0%	1.1%	4.3%			0.7%	2.9%
River birch	1.4%	5.0%					0.3%	1.4%
Swamp white oak	1.4%	5.0%					0.3%	1.4%
Northern red oak (*Quercus rubra*)			1.1%	4.3%			0.3%	1.4%

Table 15. Frequency of occurrence of invasive woody species, vines, and herbaceous species in forest inventory plots in gap neighborhoods for field survey gaps. Species in italics are non-native species.

Species	MVP		MVR		MVS		UMRS (Combined)	
Vines	**Plots**	**Gaps**	**Plots**	**Gaps**	**Plots**	**Gaps**	**Plots**	**Gaps**
Wild grape	15.7%	35.0%			56.0%	85.2%	29.7%	42.9%
Japanese hops	1.4%	5.0%			9.9%	25.9%	5.0%	11.4%
Trumpet Creeper					9.2%	25.9%	4.3%	10.0%
Bur cucumber	4.3%	10.0%			2.8%	14.8%	2.3%	8.6%
Winter creeper					0.7%	3.7%	0.3%	1.4%
Woody Shrubs								
Buckthorn	4.3%	15.0%					1.0%	4.3%
Barberry	1.4%	5.0%					0.3%	1.4%
Bush Honeysuckle					0.7%	3.7%	0.3%	1.4%
Herbaceous								
Wood nettle	21.4%	35.0%	4.3%	8.7%	7.1%	22.2%	9.6%	21.4%
Reed Canarygrass	34.3%	50.0%			2.8%	11.1%	9.2%	18.6%
Giant Ragweed					4.3%	14.8%	2.0%	5.7%
Stinging nettle	5.7%	10.0%					1.3%	2.9%
Garlic mustard					0.7%	3.7%	0.3%	1.4%

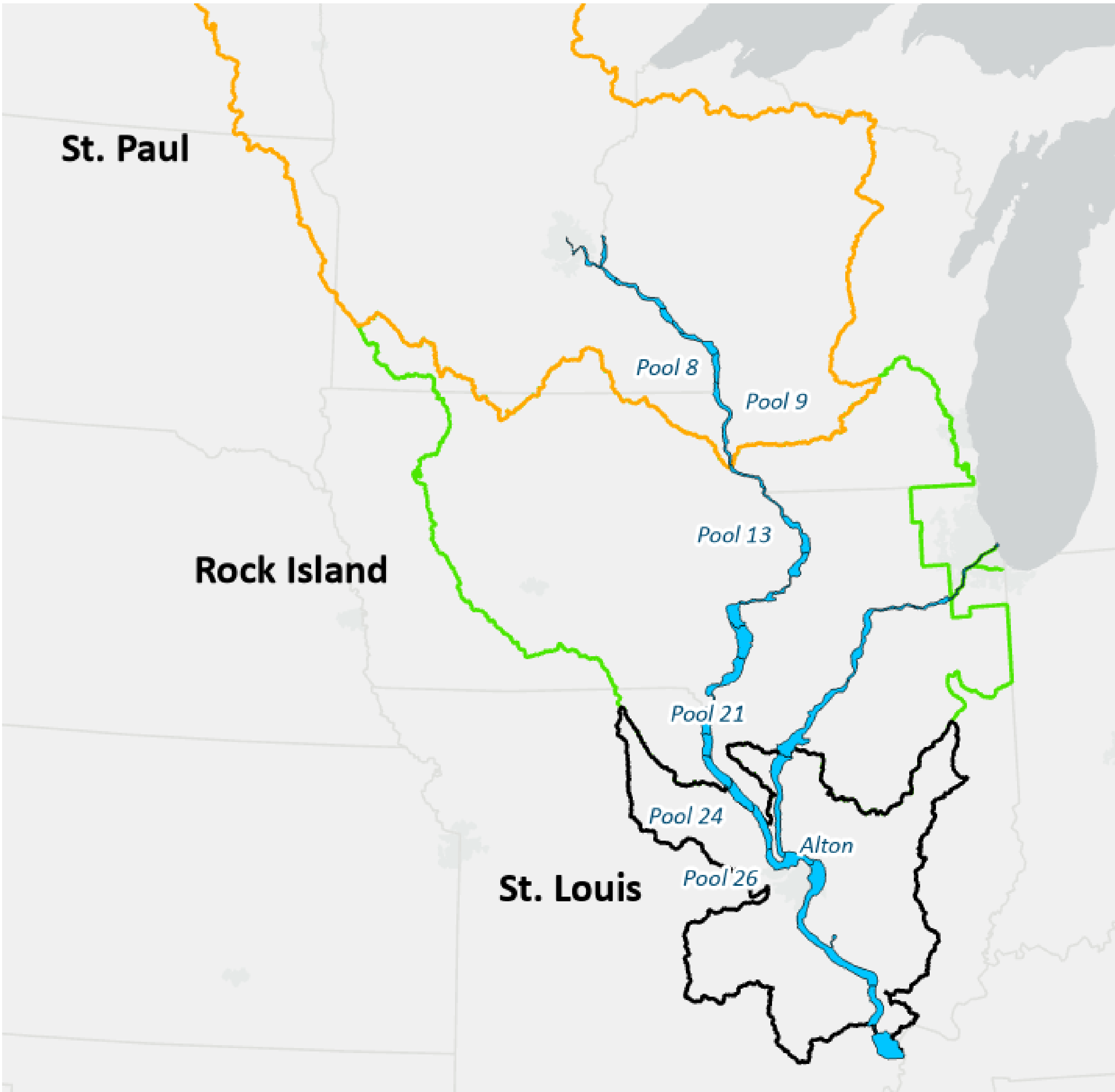


Figure 1. Study area for the current project showing USACE districts and the Upper Mississippi River navigation pools included in the study.

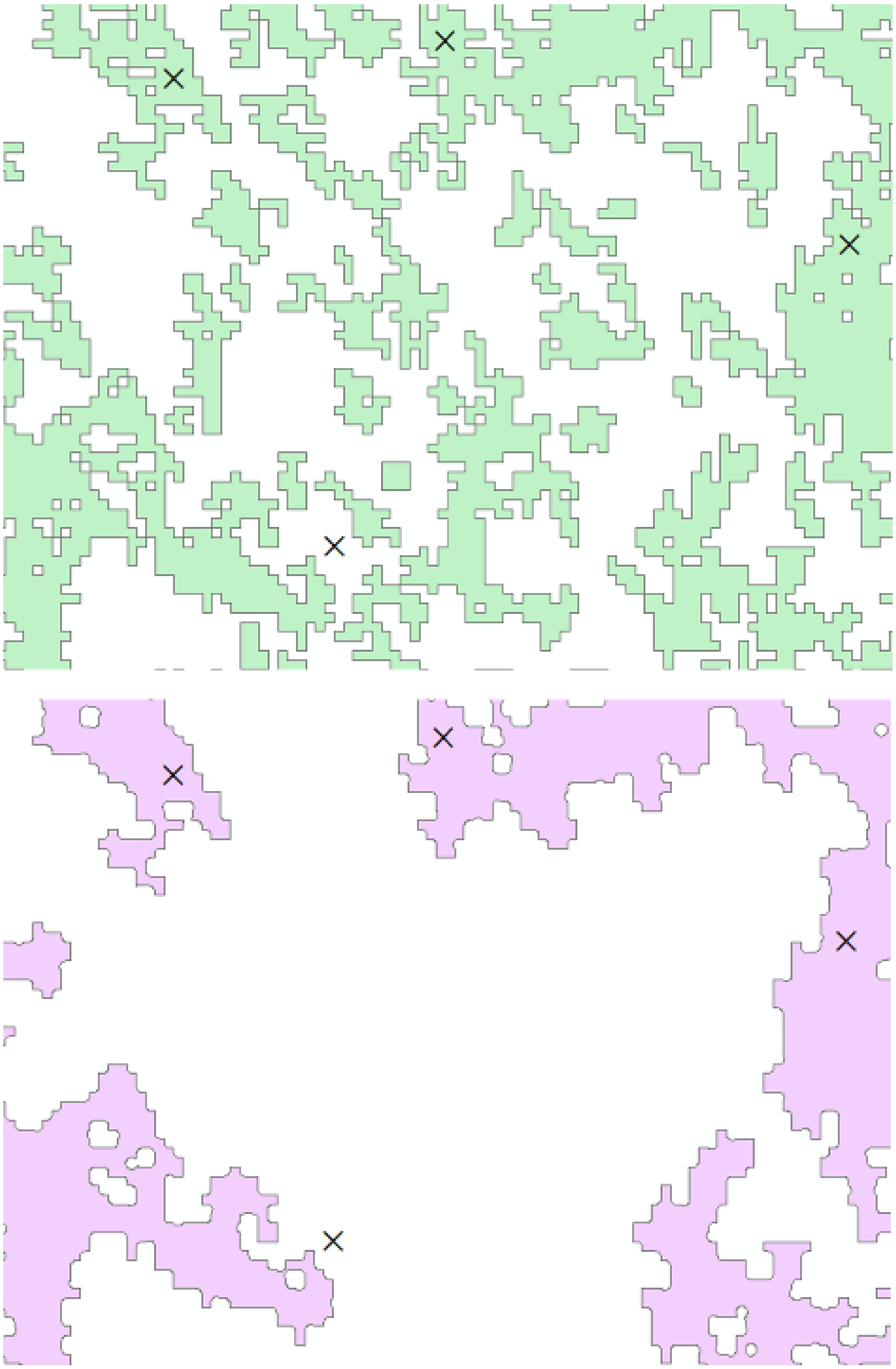


Figure 2. Comparison of first-pass gap layer before (top) and after (bottom) cleaning to remove 1) all gaps below the minimum mapping unit of 0.026ha and 2) close all holes if gaps less than 2 x 2 m. Each image has “X” placed to compare images.

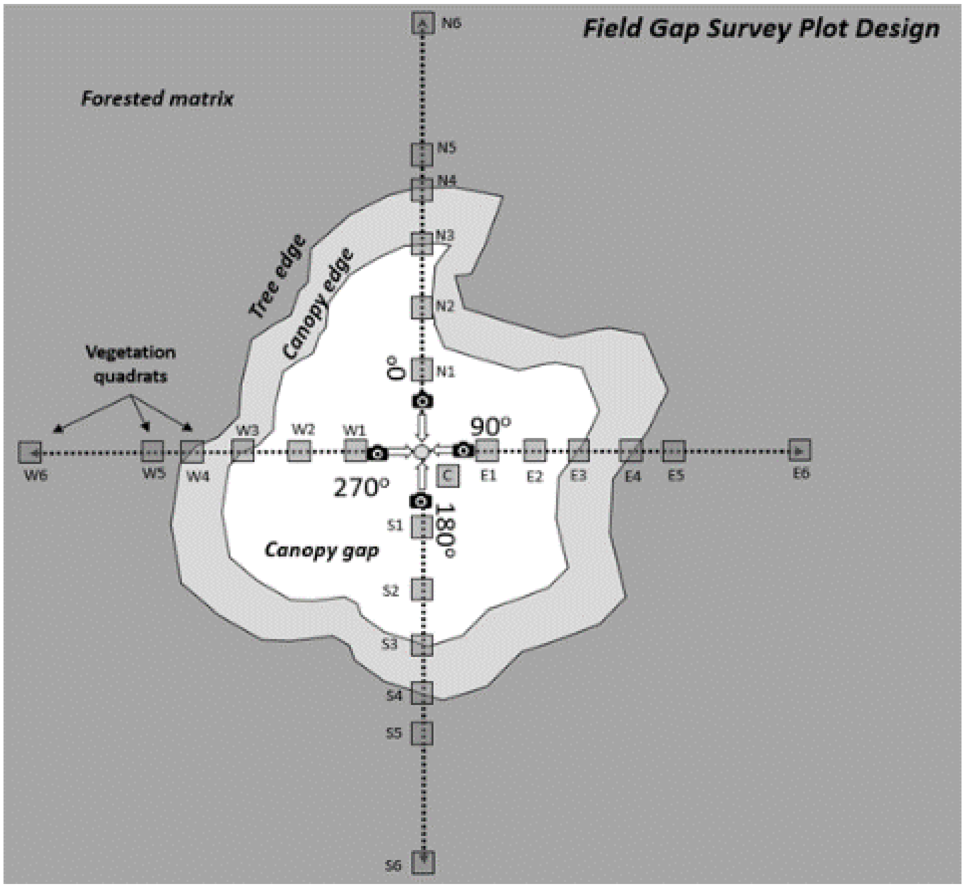


Figure 3. Layout of transects (dotted lines), quadrats (squares) and photo points in a hypothetical gap.

Figure 4. Field layout of canopy gap transects. Locations are: a) t-post placed at gap centroid; b) pin flags marking quadrat locations; c) tape marking out transect location and distances between quadrats

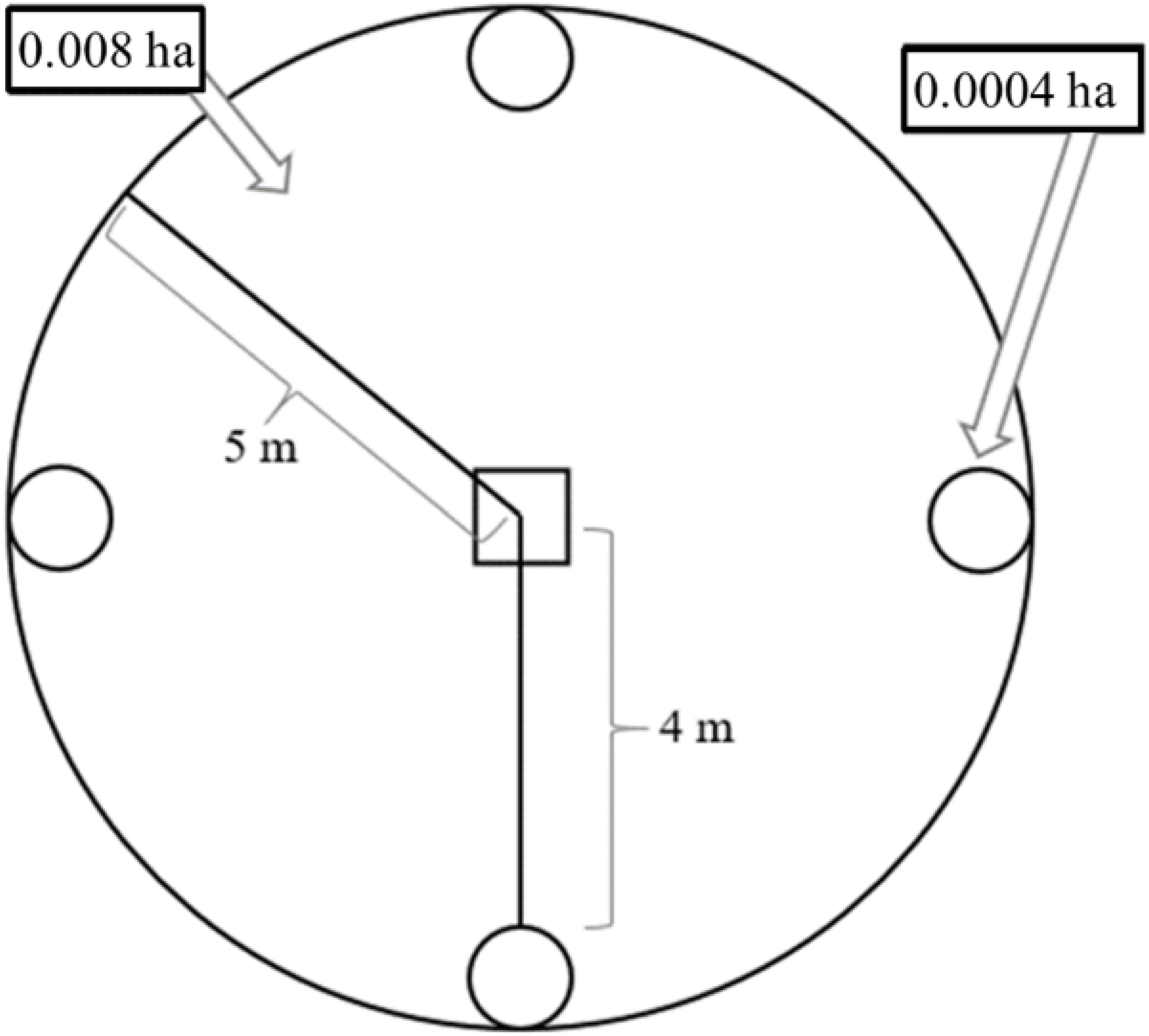


Figure 5. Layout of the forest inventory point surrounding quadrat #6 (square). Adapted rom Oines (2020).

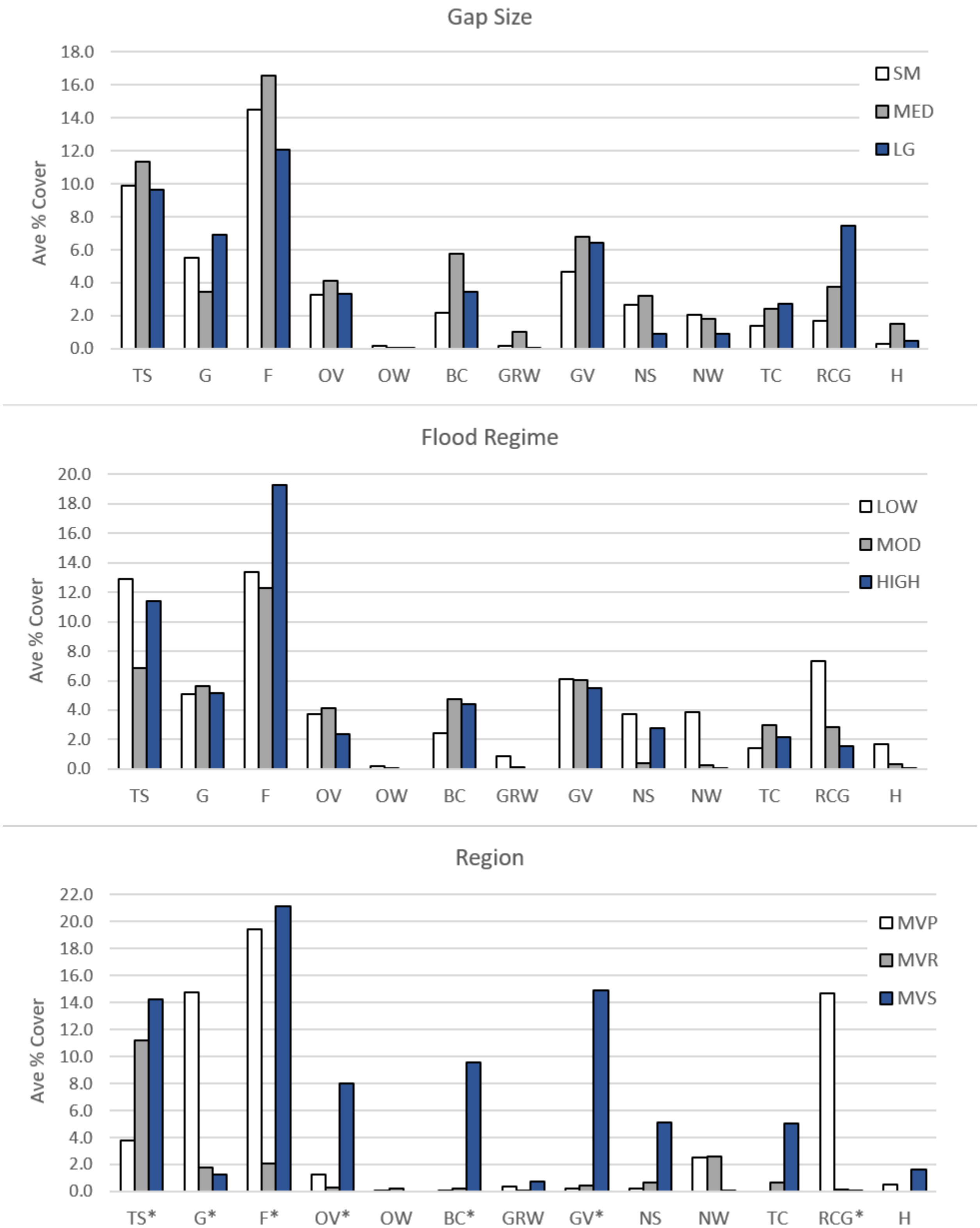


*Figure 6. Effects of gap size, flood regime, and region on percent cover of the focal plant functional groups in field quadrats. * indicates statistical significance (p<0.05)*

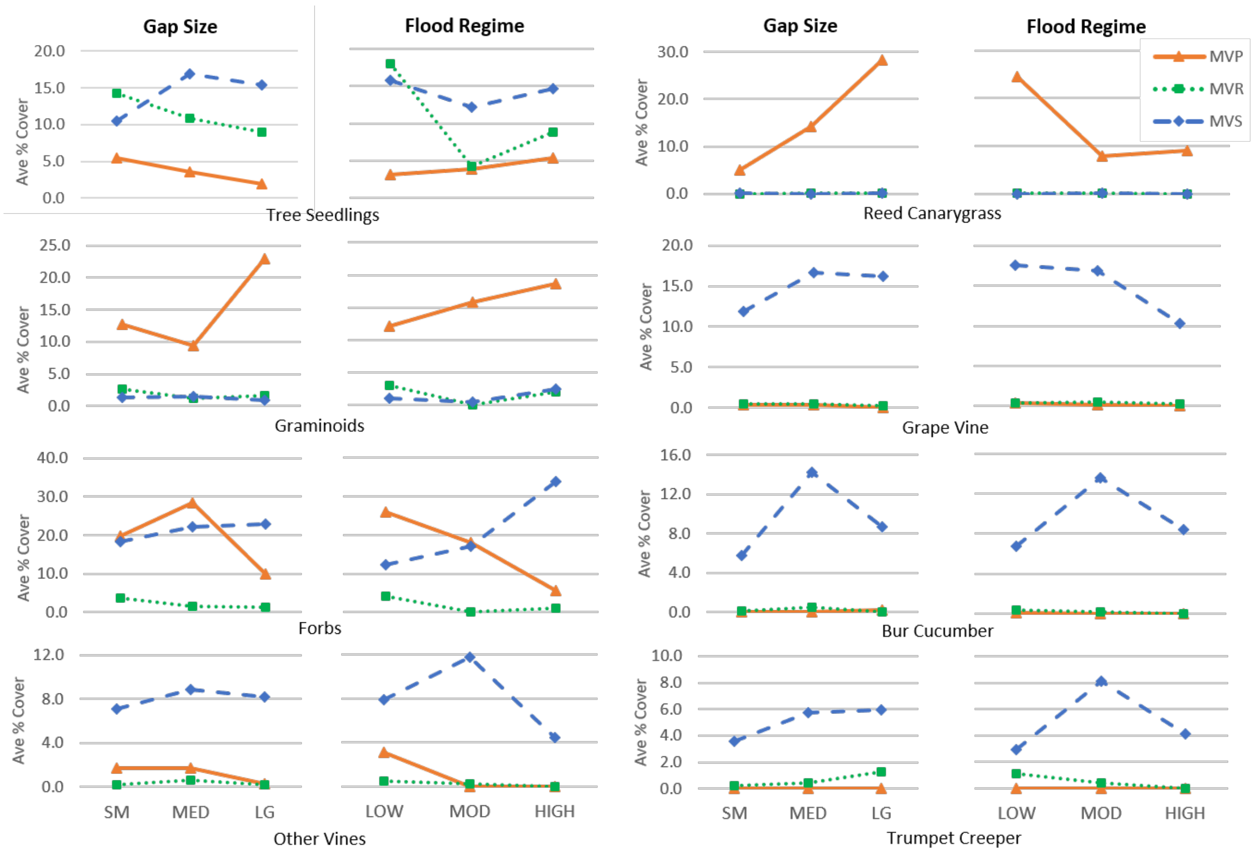


Figure 7. Plant functional groups: effects of gap size and flood regime by region for the field survey gaps.

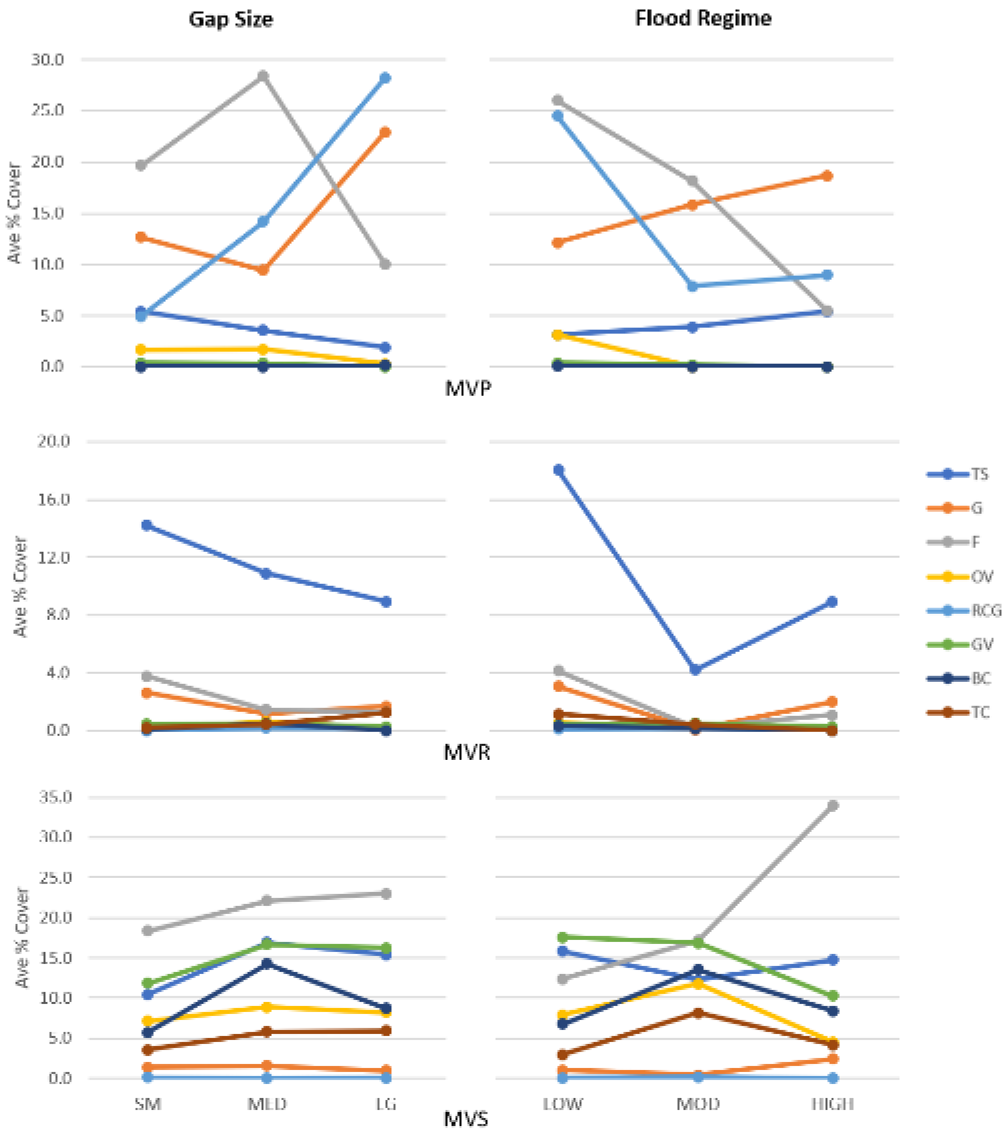
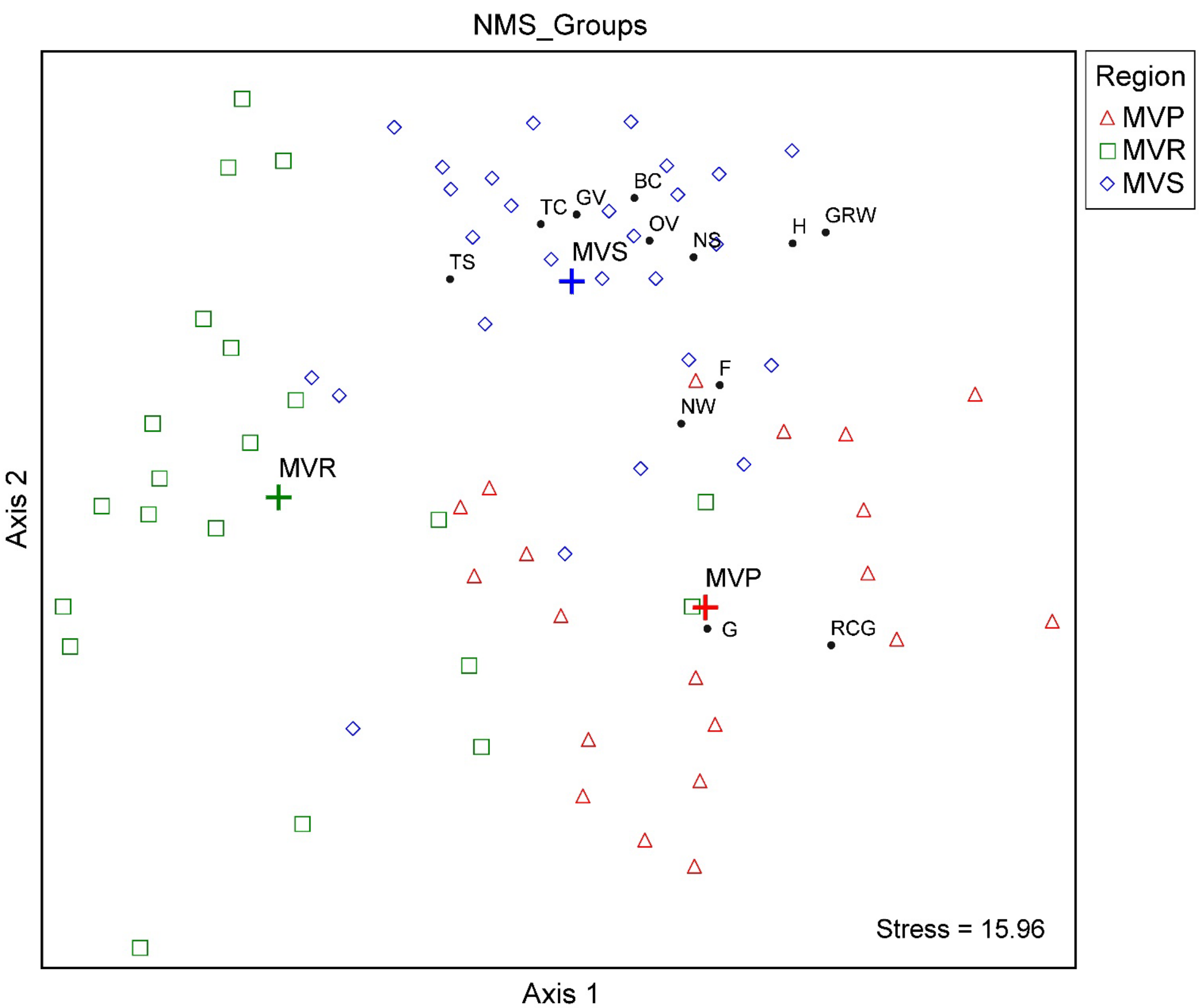


Figure 8. Plant groups & management species: within-region effects of gap size and flood regime for the field study gaps.

Figure 9. Non-Metric Multidimensional Scaling (NMS) ordination of plant groups & management species by region, gap size, & flood regime for the field survey gaps. Symbols represent individual gaps color-coded by region. Cross points represent group centroids with region as the grouping variable. Plant functional group correlations are also overlayed on the graph.



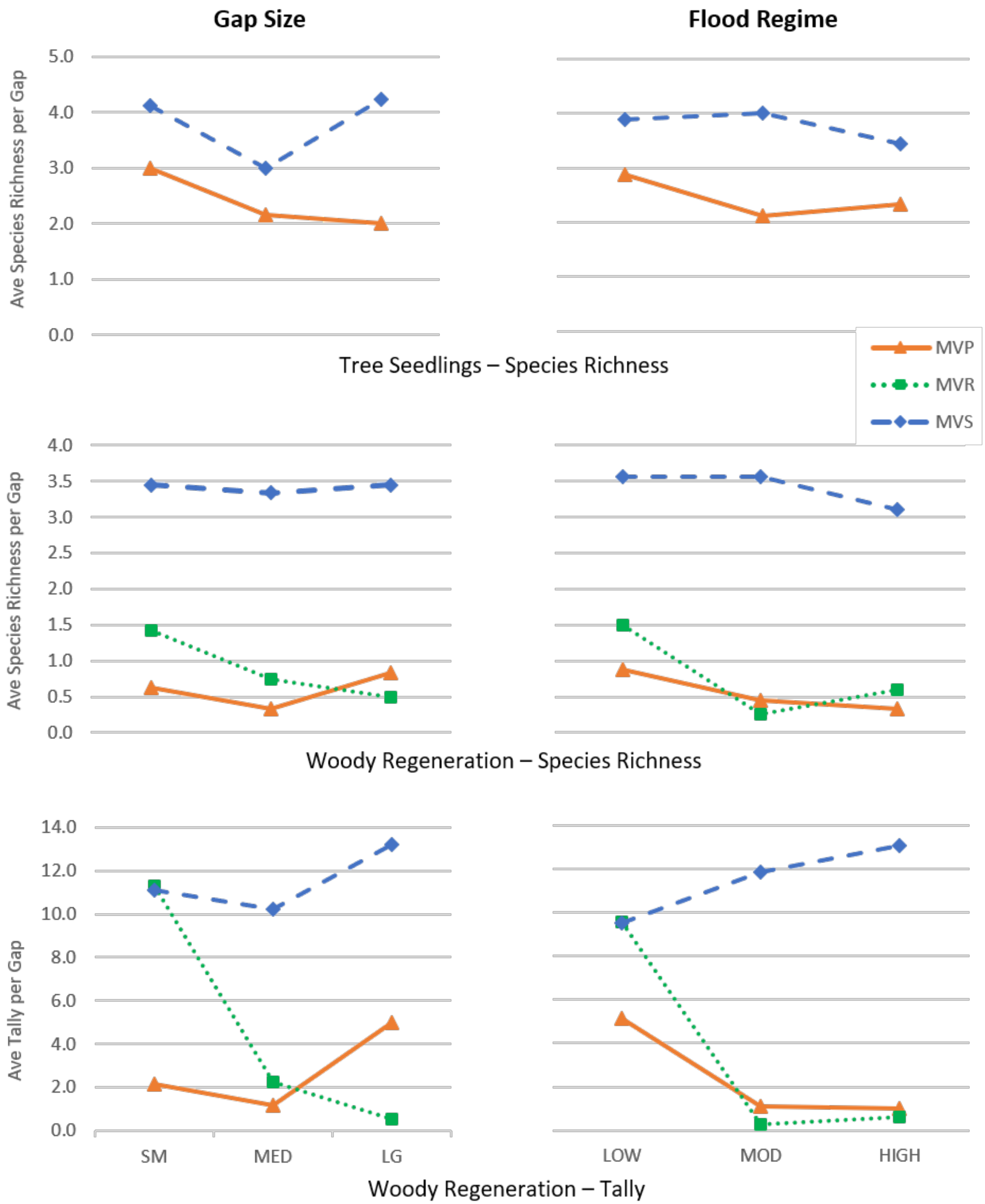


Figure 10. Effects of gap size and flood regime on woody regeneration and seedlings for the field survey gaps.

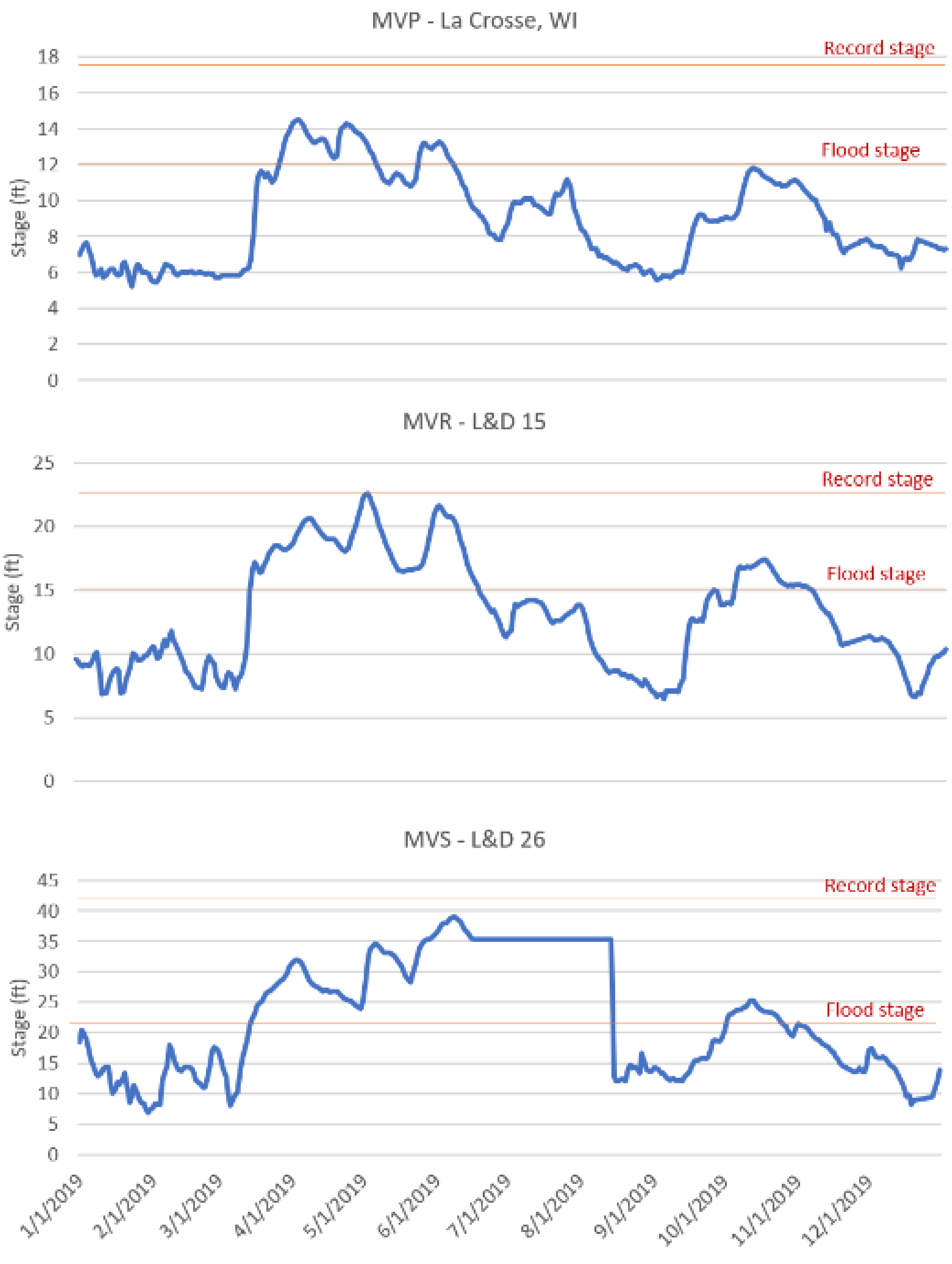


Figure 11. 2019 Mississippi River Flood Stages (source: rivergages.com)

Figure 12. Wild grape thickets in MVS (top), dense patches of silver maple in MVS (middle left) and MVP (bottom left) and eastern cottonwood seedlings in MVS (middle right) and MVP (bottom right). All photos were taken in or near canopy gaps.

Appendix A: Sample Gap Maps and Photos

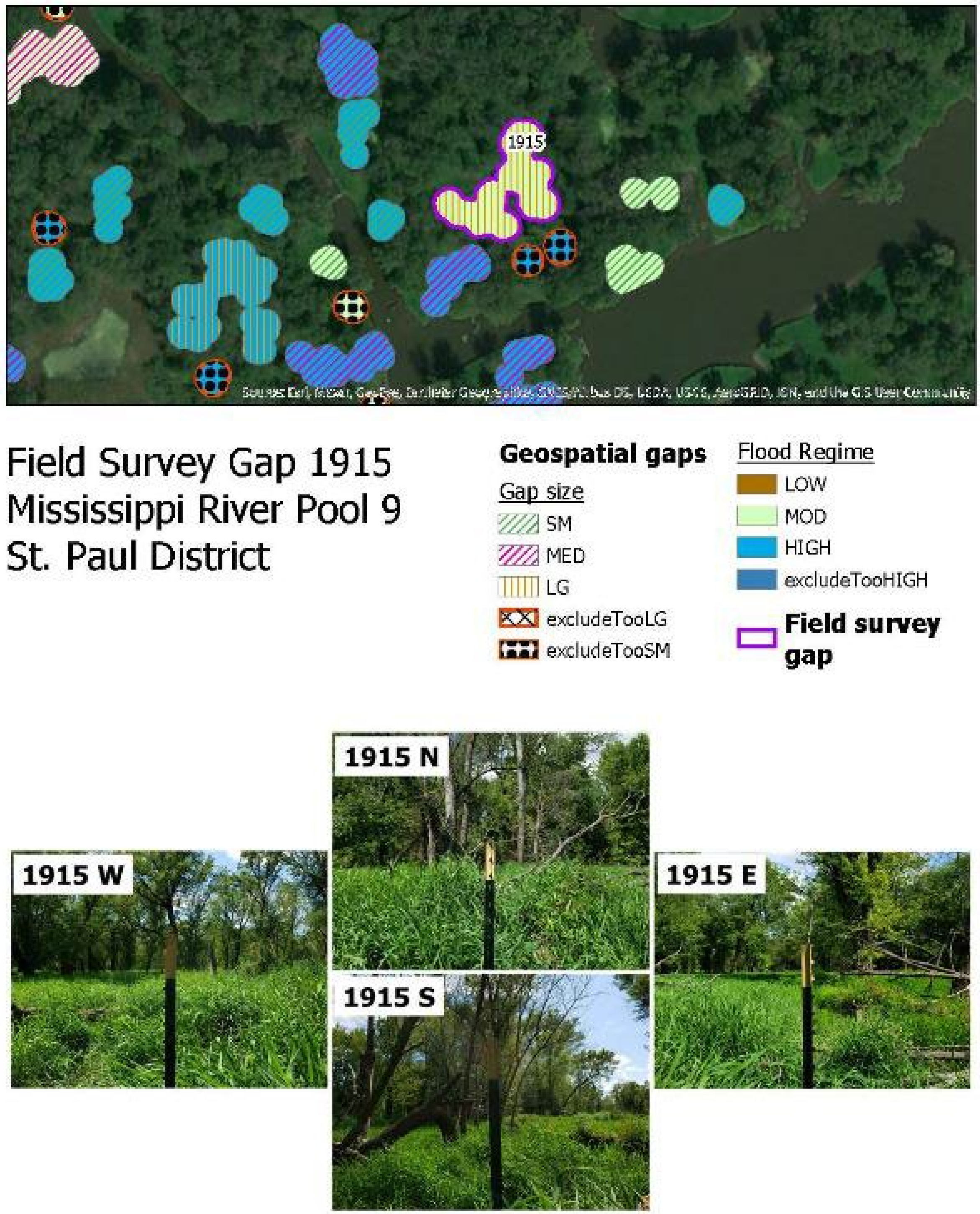


Figure A1. Sample of gap distribution and photos from gap 1915, Pool 9, St. Paul District. The upper image shows all gaps identified in the vicinity via the automated geospatial analysis and characteristics of those gaps, the lower images show photos collected as part of the field survey.

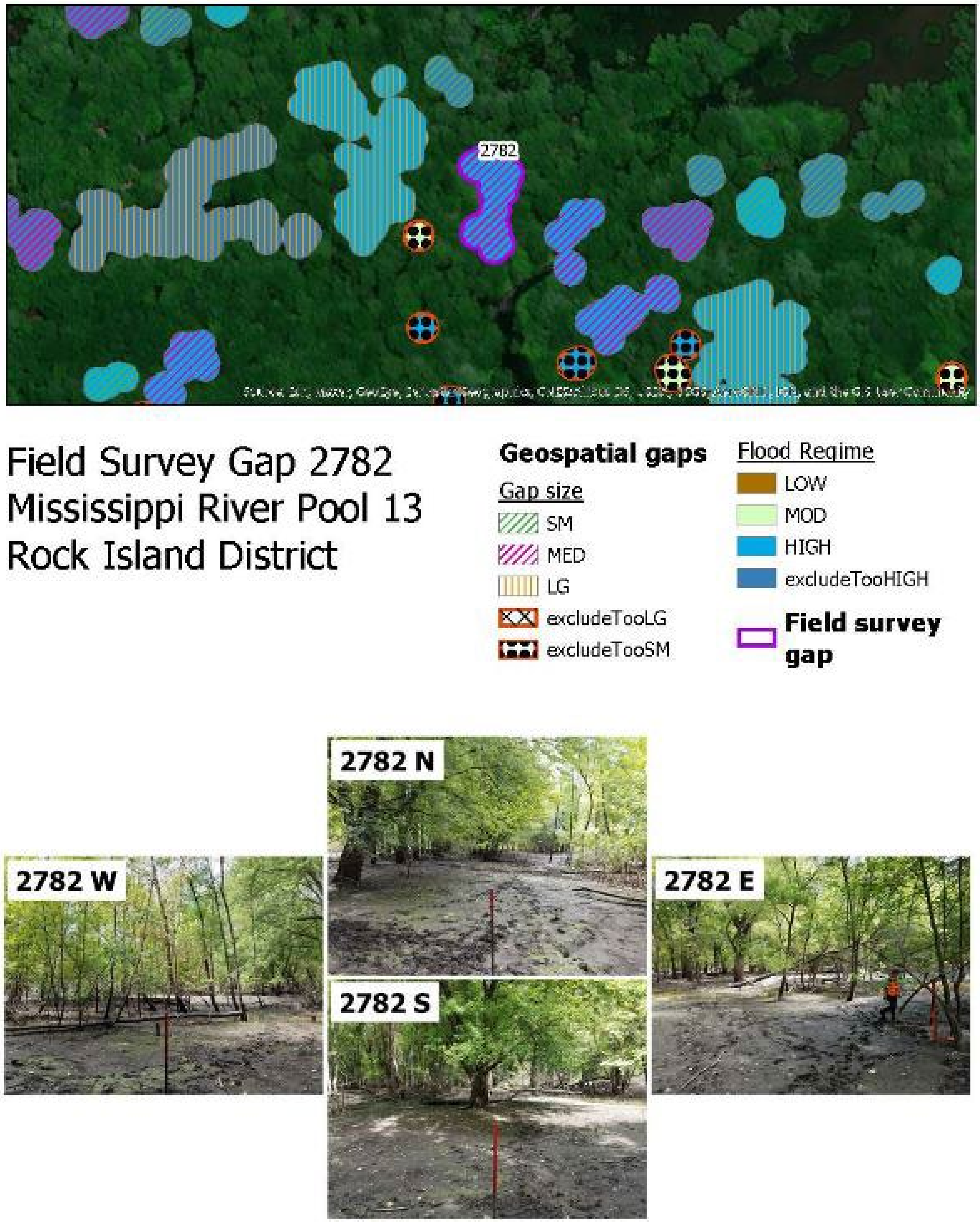


Figure A2. Sample of gap distribution and photos from gap 2782, Pool 13, Rock Island District. The upper image shows all gaps identified in the vicinity via the automated geospatial analysis and characteristics of those gaps, the lower images show photos collected as part of the field survey.

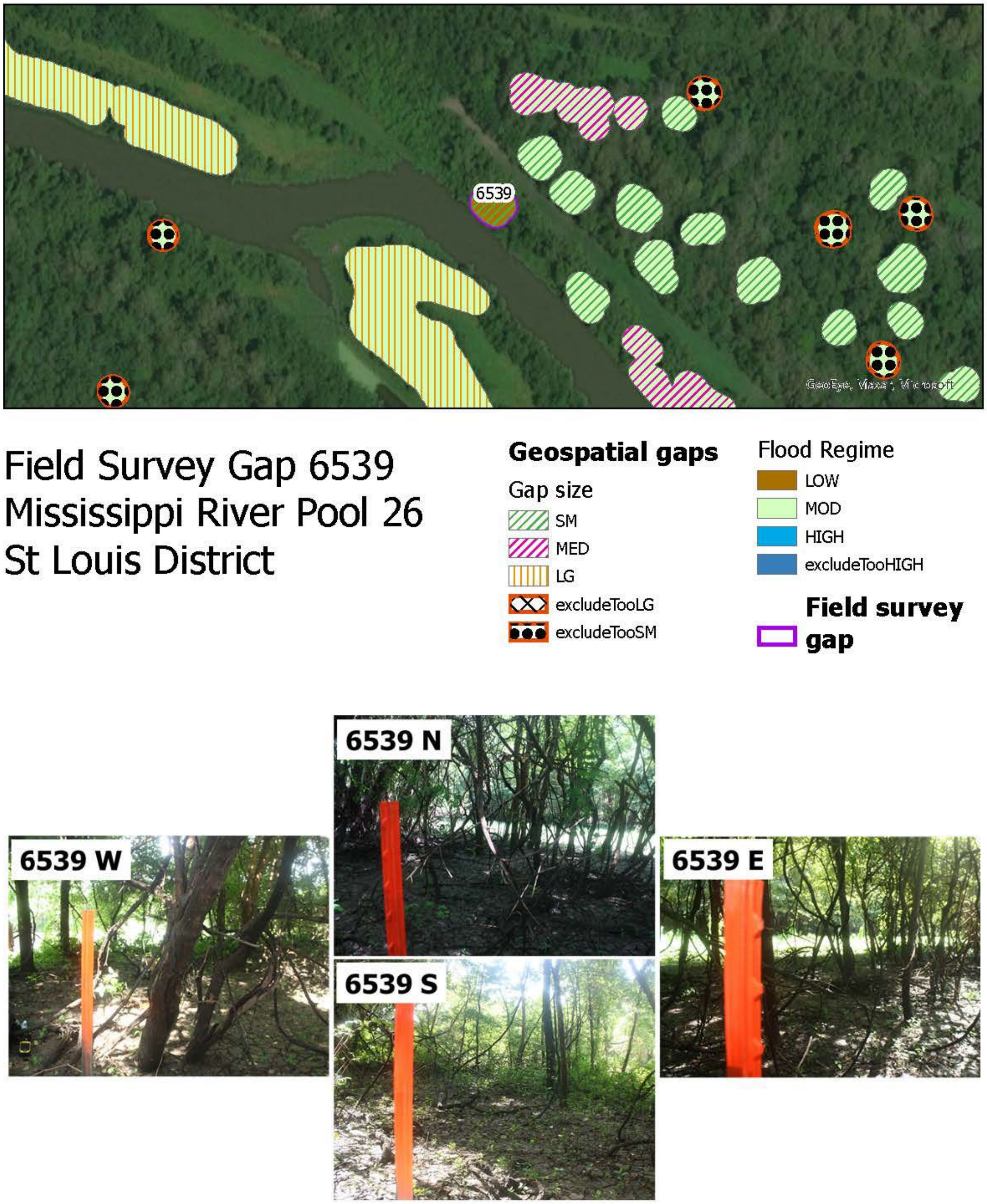


Figure A3. Sample of gap distribution and photos from gap 6539, Pool 26, St Louis District. The upper image shows all gaps identified in the vicinity via the automated geospatial analysis and characteristics of those gaps, the lower images show photos collected as part of the field survey.

Appendix B: Field Sampling Protocol and Field Data Sheets

Title of Project: FOREST CANOPY GAP DYNAMICS: QUANTIFYING FOREST GAPS AND UNDERSTANDING GAP – LEVEL FOREST REGENERATION

Name of Principal Investigator:
Andy Meier, Forester, USACE-St. Paul District, 651.290.5899, Andrew.R.Meier@usace.army.mil

Collaborators (Who else is involved in completing the project):
Dr. Lyle Guyon, Terrestrial Ecologist, National Great Rivers Research and Education Center, One Confluence Way, East Alton, IL 62024, 618.468.2870, lguyon@lc.edu, lead report writing, lead field crews in lower pools, expertise in terrestrial and forest ecology.

Dr. Meredith Thomson, Professor of Biology, University of Wisconsin-La Crosse Biology Department, 1725 State Street, La Crosse, WI 54601, 608.785.8425, mthomsen@uwlax.edu, graduate student oversight, contribution to analysis and report writing, lead field data collection in upper pools, expertise in restoration of invaded habitats and effects on habitat fragmentation on community interactions.

Ben Vandermyde, Lead Forester, USACE-Rock Island District, PO Box 534, Pleasant Valley, IA 52767, 309.794.4522, ben.j.vandermyde@usace.army.mil, lead field crews in middle pools, site selection and project planning

Robert Cosgriff, Lead Forester, USACE-St. Louis District, 301 Riverlands Way, West Alton, MO 63386, 636.899.0074, robert.j.cosgriff@usace.army.mil, site selection and project planning

Equipment: all tools and measurements should be in metric units

- GPS unit with minimum capabilities of navigating to assigned coordinates
- Metal t-post spray-painted blaze orange on top foot.
- Small sledge hammer or t-post pounder
- Camera (can be smartphone camera)
- Sighting compass with azimuth degrees
- 100 meter measuring tape, or other distance measuring tool
- Field data sheets and clipboard (or field computer with appropriate data recording software)
- 1 meter x 1 meter square quadrat, with markings on each edge at 0.5 meters
- Meter stick
- Collapsible height pole
- Small calipers
- Metric diameter tape
- Spherical densitometer
- Soil probe with 2.5 cm diameter and >30 cm core capacity
- Bags for soil samples
- 25 fluorescent pin flags

Step-by-step field procedures

Office (complete by Feb. 28, 2019)

1. GIS coordinate system: UTM NAD83, Zone 15N
2. Gap selection
   a. Stratify all gaps from geospatial dataset by flood regime (low, medium and high) and gap size (small, medium, large)
      i. Classifications should be based on data distributions within final gap dataset
   b. Randomly select a minimum of 3 gaps per combination of flood regime and gap size
      i. From random selection, gaps may be switched out to improve accessibility
   c. For each selected gap, use GIS to calculate a gap centroid

        i. For each centroid, calculate a random azimuth to be used in the field to place the centroid quadrat
   d. For each gap, randomly select three quadrat numbers for soil sampling
   e. Load gap centroid and gap polygons onto a GPS unit and print centroid coordinates and random azimuths
3. Forest inventory data summary
   a. For each selected gap, create a 150 meter buffer around the delineated gap edge and determine whether Corps of Engineers Phase II Forest Inventory plots have been completed within the buffer
        i. If no plots have been completed, a set of pseudo-inventory points will be collected in the field to provide a similar assessment, as outlines in section 3, Forest Matrix Sampling, below

Field (Complete by Oct. 31, 2019)

1. Monumenting the gaps
   a. Navigate to gap centroid. Decide whether that location is a good approximation of the true gap center and, if not, adjust your location to the center. Adjustment to the center should be done visually, but only adjust if you are clearly not at the gap center.
   b. Place a metal t-post to monument the gap center. Avoid logs or particularly wet spots to place the t-post securely as close to the gap center as possible. Place your GPS unit on the t-post oriented towards the southwest and record an averaged waypoint (take this waypoint whether you used the centroid location or not).
   c. Take four photos from the t-post in each cardinal direction (0°, 90°, 180° and 270°)
        i. Photos should be taken in a clockwise direction, starting at 0°
        ii. The photo should be taken from approximately 1 meter behind the t-post, and should include the t-post in each image for reference
        iii. Record a unique photo ID (such as file name) for each azimuth that can be used to document which photo is associated with each azimuth. Download any photos taken with a cell phone at the highest resolution and clearly name each file.
2. Quadrat sampling
   a. Centroid quadrat (Quadrat C)
        i. Move 2 meters from the t-post and at the random azimuth calculated in the office for the gap centroid
        ii. Place a 1 square meter vegetation quadrat to assess woody and herbaceous vegetation and percent forest canopy.
            1. Quadrat should be oriented with corners to the NW (215°), NE (45°), SE (135°), and SW (225°)
            2. The NW corner of the quadrat should be placed at the 2 meter point from the centroid
            3. Quadrat should be recorded with a unique quadrat identifier in the format of pxxgxxquC (e.g., p08g04quN4) for pool 08, gap 04, and the fourth quadrat on the north transect; use C for the center quadrat)
            4. Record the following data:
                a. Herbaceous vegetation (native and non-native) including woody vines and tree seedlings < 0.5 m tall
                    i. Species Group

1. TS: Tree seedlings; G: Graminoid; F: Forb/Herb; R: Reed canarygrass; NW: Wood Nettle; NS: Stinging Nettle; H: Japanese Hops; GRW: Giant Ragweed; GV: wild grapes; BC: Burr cucumber; TC: Trumpet creeper; OV: Other vines. Make note of any other unusual or particularly abundant species.

ii. Cover class (can exceed 100% cover across all herbaceous categories in a quadrat)

1.

Cover	Classes
1	>0-5%
2	6-25%
3	26-50%
4	51-75%
5	76-95%
6	96-100%

iii. Average height in m to nearest cm if less than 1.5 m; nearest 5 cm if taller. Take a single measurement in center of quadrat of vegetation as it lies, rather than standing things up.

b. Woody vegetation (native and non-native)

i. Tallest woody stem

1. Species
2. Height (meters, to nearest 5 cm)
3. Root collar diameter (centimeters)
4. Diameter at breast height (DBH) of lignified growth, if stem is tall enough (1.4 meters high, centimeters)

ii. All other woody vegetation

1. Count of total stems by species and height class for stems >0.5 meters tall
   a. Height classes:
      1 0.5 m-1.5 m tall
      2 1.5 m-3.0 m tall
      3 > 3.0 m tall

2. Browsing severity index for all woody stems by species. This includes all herbivores, not just deer. (Take notes on what animals – voles, muskrats, beaver, deer, etc.)
   a. Browse severity ratings:

      0 No browsing
      1 At least one bud/leaf bitten/taken from plant, but less than 25% of available forage has been taken. Overall, plant growth unaffected by browsing.

2 25-75% of available forage has been taken. Plant's growth has been affected (e.g. axillary buds have grown new branches).
3 >75% of available forage has been taken; serious defoliation by browsing. Plant growth has been affected. Survival is questionable.

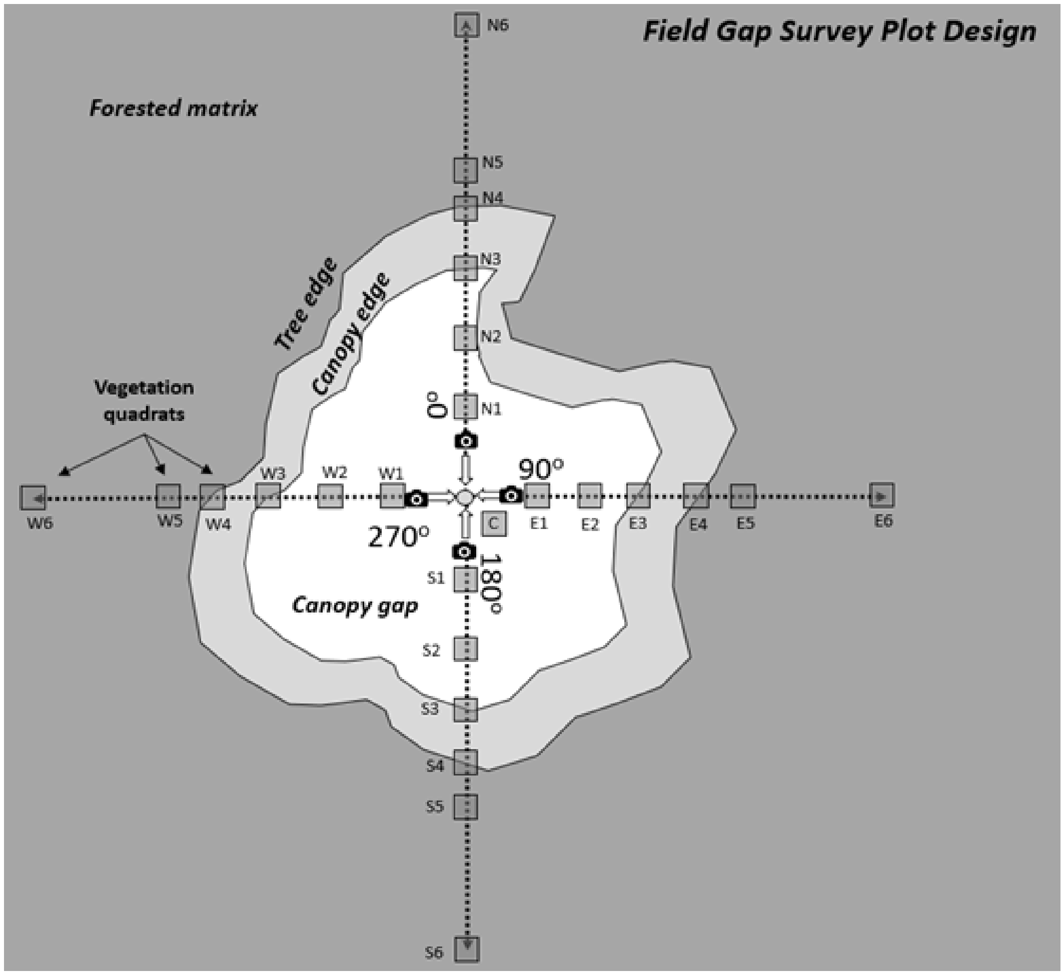
b. Girdling severity ratings:

0 No girdling
1 At least one incidence of girdling on main stem. Overall, plant growth unaffected by browsing.
2 25-75% of main stem circumference has been girdled; locations have been chewed off. Plant's growth has been affected.
3 >75% of circumference has been girdled and severely damaged. Plant growth has been affected. Survival is questionable.

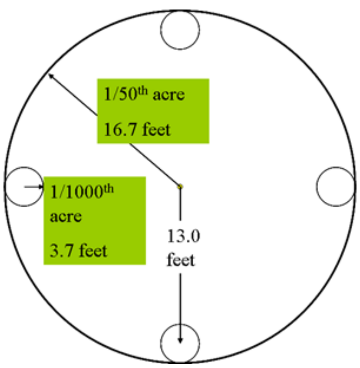
c. Canopy density, recorded using a densiometer held at breast height
   i. Record 4 densiometer readings (raw score = number of dots **not** occupied by canopy) at centroid, quadrats 3 and 6 on each transect quadrat facing each cardinal direction, and record each reading. There is no need to take a densitometer measurement if the canopy is completely open at a given location; simply record that the canopy is fully open.
d. Take a sample of the upper 30 cm of soil at the center of the quadrat and place in a bag labeled with the unique gap number and a gap interior identifier (e.g. p08g04-Gap Interior). Remove any organic layer from the soil surface prior to taking the soil sample.

b. Return to the gap centroid and lay out the north (0°) transect
   i. Use a measuring tape or other measuring device to measure the distance to the canopy edge from the gap centroid along the 0° azimuth.
   ii. Divide the distance by 3 to determine locations for the 0° gap quadrats (e.g. a 60 meter gap would have quadrats placed at 20 meters and 40 meters from gap centroid); record distances to each quadrat on the data sheet
   iii. Temporarily mark the location of the gap quadrats with flagging tape or other highly visible material

iv. Walk to the gap edge and sight back to the gap center with a compass; temporarily mark the location of the gap edge quadrat when aligned with the 0° azimuth
v. Repeat step iv for the tree edge quadrat
vi. From the tree edge, measure 25 meters along the 0° azimuth; temporarily mark the two forested matrix quadrat locations at 5 meters and 25 meters into the forested matrix
vii. Starting with the final forested matrix quadrat (N6), sample the quadrats back to the gap center following the process described for the centroid quadrat
    1. Quadrats should be recorded with a unique quadrat identifier in the format of pxxgxxquXx, where "p" is the pool number, "g" is the gap number and "qu" is the unique quadrat number (e.g. p08g04quN6)
    2. The quadrat should be placed so that the 0.5 meter mark on the north and south edges are placed on the transect line, with the mark on the north edge placed directly on the temporary quadrat marker.
    3. Soil samples will be collected only at the previously randomly selected quadrat locations
        a. For soil samples in gap quadrats, aggregate with the initial centroid quadrat soil sample bag
        b. For soil samples in the forested matrix, created a new soil bag with a unique gap number and forest matrix identified (e.g. Pool 8, Gap 4, Forest); all forested soil samples will be aggregated in one bag.
    4. Remove the temporary marking once each quadrat is sampled
viii. Repeat the process for the north transect for the remaining three transects (90°, 180° and 270°)
    1. The quadrat edge that is placed at the temporary quadrat marker should be the edge associated with the azimuth (e.g. the 90° quadrats should have the 0.5 meter mark on the east edge placed at the quadrat marker, 180° should have the south edge, and 270° should have the west edge)


Field Gap Survey Plot Design
Forested matrix
Tree edge
Canopy edge
Vegetation quadrats
Canopy gap
N6
N5
N4
N3
N2
N1
0°
90°
270°
180°
C
W6
W5
W4
W3
W2
W1
E1
E2
E3
E4
E5
E6
S1
S2
S3
S4
S5
S6

3. Forest matrix sampling (“pseudo inventory points”)
    a. Assess forest matrix at quadrat 6 along each transect. If any quadrat falls within water or marsh, randomly select additional sample points at the same distance from the gap center along a randomly-selected azimuth.
    b. At each pseudo inventory point:
        i. Place a temporary plot center marking
        ii. At each plot record the following
            1. Tree basal area, quantified using a 10 square feet basal area factor tool, taken from the plot center
            2. Regeneration rating



1/50th ac plot	1/1000th ac plots	Regen rating
0	0	0
1	0	1
1	1	2
1	2	3
1	3	4
1	4	5

                a. A score of 0-5 for each plot
                    i. Note presence/absence of <u>trees</u> greater than or equal to 0.5 meters tall and less than or equal to 10 cm DBH in 1/50 acre plot (16.7 radial feet, 5.09 radial meters) from plot center. Possible values are 0 (trees absent in 1/50th ac plot) or 1 (1 or more trees present in 1/50th ac plot).
                    ii. Note presence/absence of <u>trees</u> greater than or equal to 0.5 meters tall and less than or equal to 10 cm DBH in four 1/1000th acre plots (3.7 radial feet, 1.12 meters) in cardinal directions at 13 feet (3.96 meters) from plot center (see diagram). Possible scores consist of 0 (no trees in 1/1000th acre plot) to 4 (trees in each of the 1/1000th acre plot), with one point for each 1/1000th ac. plot containing 1 or more tree seedlings or saplings.
                    iii. Sum the score from the 1/50th acre and 1/1000th acre plots for the final regeneration rating
                b. Regeneration species
                    i. Record the three most dominant species of tree regeneration within the regeneration rating area and meeting the size criteria for the regeneration rating, using USDA species codes; if less than three species are present, record only those species; the first species recorded should be the most dominant
            3. Invasive species
                a. Record, using the same procedure as for regeneration species,
                    i. The three most dominant woody invasive species
                    ii. The three most dominant herbaceous (including grasses) invasive species

DATA COLLECTION CHECKLIST/PROTOCOL NOTES

Data Collector(s): ___________________________ Date: ___________________ Pool: _____ Gap: _____

Centroid coordinates: _______________________________ **Notes:** ________________________________
**Avoid logs/particularly wet spots when placing T-post. Orient GPS to SW when getting avg waypoint.*

Photos*: ☐ **0°** (#________) ☐ **90°** (#________) ☐ **180°** (#________) ☐ **270°** (#________)

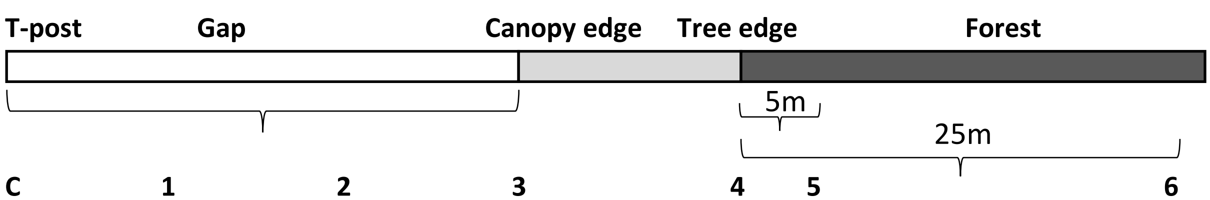
**All photos taken ~1m behind centroid t-post, with t-post included; go clockwise from 0°.*

Random **azimuth** for center quadrat: _____ - *place NW corner of quadrat at 2 m distance from t-post*

Center Data collection: ☐ Herbaceous ☐ Woody ☐ Densiometer readings

Soil collected/labeled: ☐ p__ g__-GapInterior *(upper 30 cm of soil @ center of quadrat)*

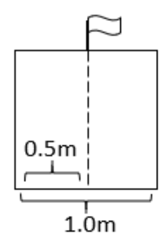
Placing temporary markers for quadrat locations along cardinal transects:



(C-3 ÷ 3 for distances C-1, 1-2, and

Quadrat distances from centroid *(to the nearest 0.25 meter)*:

N3		**E3**		**S3**		**W3**	
N1		**E1**		**S1**		**W1**	
N2		**E2**		**S2**		**W2**	



*Associate marker with correct

TRANSECT DATA COLLECTION PROGRESS *(H = herbaceous, W = woody, D = densiometer readings)*

NORTH	*H*	*W*	*D*
N6			
N5			
N4			
N3			
N2			
N1			

EAST	*H*	*W*	*D*
E6			
E5			
E4			
E3			
E2			
E1			

SOUTH	*H*	*W*	*D*
S6			
S5			
S4			
S3			
S2			
S1			

WEST	*H*	*W*	*D*
W6			
W5			
W4			
W3			
W2			
W1			

SOIL SAMPLE COLLECTION *(centroid + 4 int, 4 forest)*

GAP (int)	
QUADRAT	*taken*
C	
N	
E	
S	
W	

FOREST (p__g__Forest)	
QUADRAT	*taken*
N	
E	
S	
W	

PSUEDO-INVENTORY *(4 azimuths)*

LOCATION	*taken*
N6	
E6	
S6	
W6	

WOODY HEIGHT CLASSES

1	0.5m-1.5m tall
2	1.5m-3.0m tall
3	>3.0m tall

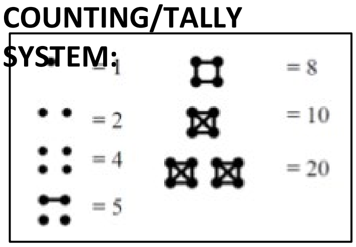
COVER CLASSES

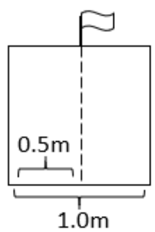
1	>0-5%
2	6-25%
3	26-50%
4	51-75%
5	76-95%
6	96-100%

QUANTIFYING BROWSE / GIRDLING SEVERITY
**If B and G levels differ, use most severe*

0	No browsing	No girdling
1	At least one bud/leaf bitten/taken, but <25% of available forage	At least one instance of girdling, but <25% of circumference
	Plant growth unaffected	
2	25-75% of available forage has been taken	25-75% of stem circumference has been girdled; locations chewed off
	Plant's growth **is** affected	
3	>75% of available forage has been taken; serious defoliation	>75% of circumference has been girdled; severely damaged
	Growth affected; survival questionable	

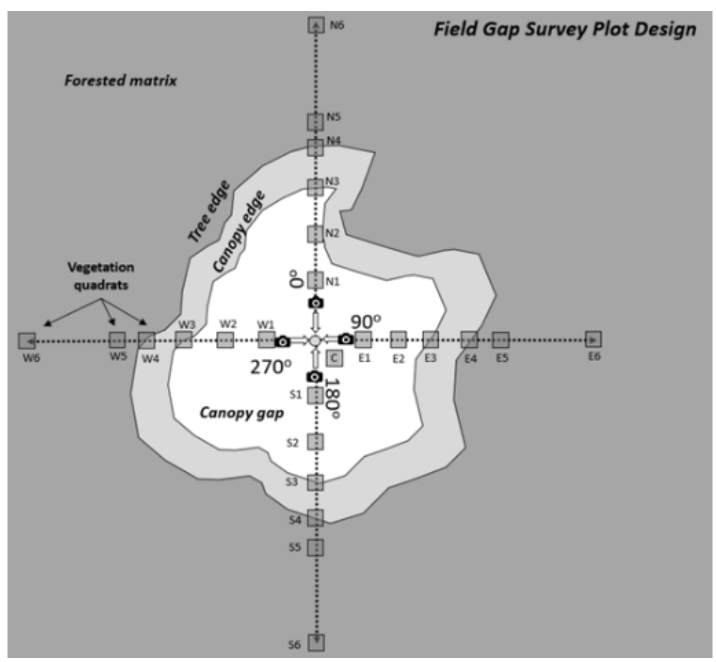
COUNTING/TALLY SYSTEM:





SPC/GRP CODES (herbs, vines, tree seedlings)	
G	Graminoid
F	Forb/Herb
R	Reed Canarygrass
NW	Wood Nettle
NS	Stinging Nettle
H	Japanese Hops
GRW	Giant Ragweed
GV	Wild Grape
BC	Burr Cucumber
TC	Trumpet Creeper
OV	Other vines
TS	Tree Seedlings >0.5m

RANDOM AZIMUTHS				
247	258	65	290	351
310	244	255	266	356
54	319	192	180	97
7	76	8	126	8



HERBS, VINES, SEEDLINGS DATA COLLECTION

Data Collector(s): ________________________ Date: ________________ Pool: _____ Gap: _____

QUAD	SP/GRP	COVER CLASS	AVG. HEIGHT

QUAD	SP/GRP	COVER CLASS	AVG. HEIGHT

SP/GRP CODES (herbs, vines, tree seedlings)			
G	Graminoid	**GRW**	Giant Ragweed
F	Forb/Herb	**GV**	Wild Grape
R	Reed Canarygrass	**BC**	Burr Cucumber
NW	Wood Nettle	**TC**	Trumpet Creeper
NS	Stinging Nettle	**OV**	Other vines
H	Japanese Hops	**TS**	Tree Seedlings <0.5m

COVER CLASSES	
1	>0-5%
2	5-25%
3	26-50%
4	51-75%
5	76-95%
6	96-100%

QUAD	SP/GRP	COVER CLASS	AVG. HEIGHT

QUAD	SP/GRP	COVER CLASS	AVG. HEIGHT

SP/GRP CODES (herbs, vines, tree seedlings)			
G	Graminoid	**GRW**	Giant Ragweed
F	Forb/Herb	**GV**	Wild Grape
R	Reed Canarygrass	**BC**	Burr Cucumber
NW	Wood Nettle	**TC**	Trumpet Creeper
NS	Stinging Nettle	**OV**	Other vines
H	Japanese Hops	**TS**	Tree Seedlings >0.5m

COVER CLASSES	
1	>0-5%
2	5-25%
3	26-50%
4	51-75%
5	76-95%
6	96-100%

NOTES:

WOODY DATA COLLECTION

Data Collector(s): ________________________ Date: _________________ Pool: _____ Gap: _____

TALLEST WOODY STEM *(height to nearest 5 cm, diameters in cm, DBH must be lignified growth)*

QUAD	SPECIES	HEIGHT	RCD	DBH
C				
N6				
N5				
N4				
N3				
N2				
N1				
E6				
E5				
E4				
E3				
E2				
E1				

QUAD	SPECIES	HEIGHT	RCD	DBH
S6				
S5				
S4				
S3				
S2				
S1				
W6				
W5				
W4				
W3				
W2				
W1				

OTHER WOODY VEGETATION (>0.5 m tall)

QUAD	SPECIES	STEM COUNT			BROWSE (0-3)	GIRDLING (0-3)
		0.5 – 1.5 m	1.5 – 3.0 m	>3.0 m		

QUAD	SPECIES	STEM COUNT			BROWSE (0-3)	GIRDLING (0-3)
		0.5 – 1.5 m	1.5 – 3.0 m	>3.0 m		

NOTES:

DENSIOMETER DATA COLLECTION

Data Collector(s): ___________________________ Date: ___________________ Pool: _____ Gap: _____

DENSIOMETER READINGS *(total of 4 readings per quadrat, facing each cardinal direction, hold @ BH)*
**no need to take reading if canopy is completely open at given location*
***Method:** record the number of dots NOT occupied by canopy to determine raw score*

QUADRAT	0°	90°	180°	270°
Center				
N6				
N3				
E6				
E3				
S6				
S3				
W6				
W3				

NOTES:

PSEUDO-INVENTORY DATA COLLECTION

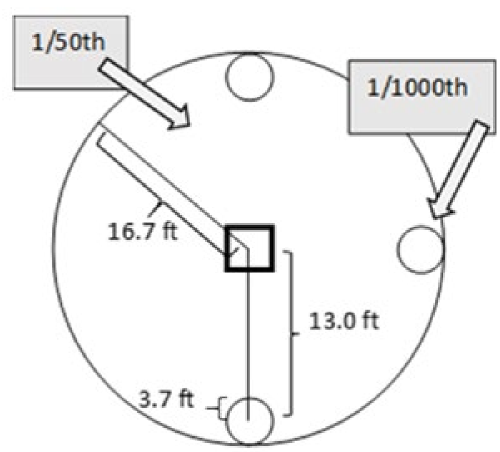
Data Collector(s): ___________________________ Date: ___________________ Pool: _____ Gap: _____

LOCATION	TREE BASAL AREA	1/50th AC PLOT	1/1000th AC PLOT	REGEN RATING
N6				
E6				
S6				
W6				

LOCATION	REGENERATION SPECIES	WOODY INVASIVE SPECIES	HERB. INVASIVE SPECIES
N6	1. 2. 3.	1. 2. 3.	1. 2. 3.
E6	1. 2. 3.	1. 2. 3.	1. 2. 3.
S6	1. 2. 3.	1. 2. 3.	1. 2. 3.
W6	1. 2. 3.	1. 2. 3.	1. 2. 3.

TREE SPECIES CODES	

INVENTORY INSTRUCTIONS	
1/50th	Note absence (0) or presence (1) of trees >0.5 m tall and <10 cm DBH in 1/50th acre plot (within 16.7 radial feet from quadrat)
1/1000th	Note absence (0) or presence (1 to 4) of trees >0.5 m tall and <10 cm DBH in lateral cardinal location points (3.7 radial feet in size) 13 feet from quadrat location
Regen Rating	Sum scores from 1/50th and 1/1000th acre plots for final regeneration rating (score can range from 0 to 5)
RS/HS/IS	Rank 3 most dominant per category



Appendix C: Comprehensive List of Plant Species

Table C1. Comprehensive list of plant species referenced in this report.

USDA Code	Scientific Name	Common Name
ACNE2	*Acer negundo*	boxelder
ACSA2	*Acer saccharinum*	silver maple
ALPE4	*Alliaria petiolata*	garlic mustard
AMTR	*Ambrosia trifida*	great ragweed
BENI	*Betula nigra*	river birch
BERBE	*Berberis spp.*	barberry
CACO15	*Carya cordiformis*	bitternut hickory
CAIL2	*Carya illinionensis*	pecan
CALA21	*Carya laciniosa*	shellbark hickory
CARA2	*Campsis radicans*	trumpet creeper
CARYA	*Carya spp.*	hickory
CEOC	*Celtis occidentalis*	common hackberry
CEOC2	*Cephalanthus occidentalis*	buttonbush
CORA6	*Cornus racemosa*	gray dogwood
CORNU	*Cornus spp.*	dogwood
DIVI5	*Diospyros virginiana*	common persimmon
EUFO5	*Euonymus fortunei*	winter creeper
FOAC	*Forestiera acuminata*	eastern swampprivet
FRANG	*Frangula spp.*	buckthorn
FRPE	*Fraxinus pennsylvanica*	green ash
GLTR	*Gleditsia triacanthos*	honeylocust
GYDI	*Gymnocladus dioicus*	Kentucky coffeetree
HUJA	*Humulus japonicus*	Japanese hops
ILDE	*Ilex decidua*	deciduous holly
ILVE	*Ilex verticillata*	common winterberry
JUNI	*Juglans nigra*	black walnut
LACA3	*Laportea canadensis*	Canadian woodnettle
LEOR	*Leersia oryzoides*	rice cutgrass
LINDE2	*Lindera benzoin*	spicebush
LOMA6	*Lonicera maackii*	Amur honeysuckle
MAPO	*Maclura pomifera*	osage orange
MOAL	*Morus alba*	white mulberry
MORU2	*Morus rubra*	red mulberry
MORUS	*Morus spp.*	mulberry
PHAR3	*Phalaris arundinacea*	reed canarygrass

USDA Code	Scientific Name	Common Name
PLOC	*Platanus occidentalis*	American sycamore
PODE3	*Populus deltoides*	eastern cottonwood
QUBI	*Quercus bicolor*	swamp white oak
QUEL	*Quercus ellipsoidalis*	northern pin oak
QUMA2	*Quercus macrocarpa*	bur oak
QUPA2	*Quercus palustris*	pin oak
QURU	*Quercus rubra*	northern red oak
RHCA3	*Rhamnus cathartica*	common buckthorn
SAIN3	*Salix interior*	sandbar willow
SALIX	*Salix spp.*	willow
SANI	*Salix nigra*	black willow
SIAN	*Sicyos angulatus*	oneseed bur cucumber
SNAG	*snag*	snag
ULAM	*Ulmus americana*	American elm
URDI	*Urtica dioica*	stinging nettle
VITIS	*Vitis spp.*	grape
ZAAM	*Zanthoxylum americanum*	common pricklyash

Appendix D: Final Datasets

Component	Dataset	Description	Data Location
Geospatial	Digital surface models	Used to create the canopy height model used to identify areas of little to no forest canopy	https://www.sciencebase.gov/catalog/item/5f3543ce82cee144fb352943
Geospatial	Broken forest Esri shapefiles	Areas within analysis polygons that had a forest canopy height of 0-10 meters and could potentially be identified as a forest canopy gap	https://www.sciencebase.gov/catalog/item/5f32a98382cee144fb31382d
Geospatial	Forest canopy gaps Esri shapefiles	Areas identified in the broken forest layer that were larger enough (greater than 0.026 ha) and wide enough (18.288 m diameter) to be considered a forest canopy	https://www.sciencebase.gov/catalog/item/5f3299c082cee144fb30dd06
Geospatial	R Script: Identify forest canopy gaps using Lidar	This script uses Lidar digital elevation data to locate forest canopy gaps and produces a canopy height model, a broken forest shapefile, an analysis polygons shapefile, and a forest canopy gaps shapefile.	https://www.sciencebase.gov/catalog/item/5f0c7cba82ce21d4c402ee81
Field	Field survey canopy gaps Esri geodatabase	Two data layers; the first representing the final field survey gaps selected from the complete forest canopy gaps dataset as polygons and the second representing the field-collected gap centers as a point file	Submitted with completion report
Field	Field gap data	Excel spreadsheet with raw field collected data and some preliminary data summaries	Submitted with completion report