RESPONSES OF INVASIVE *PHRAGMITES* PATCHES TO CHANNEL INUNDATION AND HERBICIDE TREATMENTS ALONG THE CENTRAL PLATTE RIVER

Field Methodology and Data Analysis Plan

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I. INTRODUCTION

Non-native *Phragmites* (*Phragmites australis subsp. Australis*; hereafter *Phragmites*) is an invasive weed species associated with wetlands that spreads rapidly and outcompetes many native plants due to its high primary productivity, large above- and below-ground biomass, and clonal propagation (Amsberry et al. 2000). Once established, *Phragmites* alters wetland hydrology, narrows stream channels, and modifies wildlife habitat (Tulbure et al. 2007, Knezevic et al. 2008). In particular, avian species are especially affected by *Phragmites* infestations due to impacts on wetlands and streams that may affect waterfowl and shorebirds, and loss of native, short-grass habitats important to breeding grassland specialist species (Kessler et al. 2011, Robichaud and Rooney 2022, Dinehart et al. 2023).

In the early 2000s, portions of the central Platte River channel in Nebraska narrowed as a result of an intensive *Phragmites* infestation and drought conditions (Galatowitsch et al. 2016). This narrowing of the Platte River channel reduced habitat suitability for waterfowl and migratory waders, most notably the endangered whooping crane (*Grus americana*). Individuals from the migratory Aransas-Wood Buffalo whooping crane population use the Platte River as stopover habitat during their spring and fall migrations to and from their breeding area in Canada. Whooping crane roost sites along the Platte River have been associated with wider unobstructed channel widths (Baasch et al. 2019) because channels that are narrow and have visibility obstructed by tall vegetation reduce the likelihood of detecting predators and increase predation risk. Therefore, management actions to widen channels through reduction of tall vegetation is one key to maintaining highly suitable whooping crane stopover habitat.

The Platte River Recovery Implementation Program (PRRIP or Program) has applied management actions to improve whooping crane stopover habitat since 2007 (Farnsworth et al. 2018, PRRIP 2022). These efforts have included short duration high flow water releases, tree removal, disking, and herbicide treatments to *Phragmites* patches along the banks of the Platte River and its side channels (Knezevic et al. 2013, Farnsworth et al. 2018, PRRIP 2022). Herbicide applications, in particular, have reduced the extent of in-channel *Phragmites* infestations and widened the channel (Johnson 2012, Rapp 2012). However, herbicide treatments alone may not be effective at controlling spread of *Phragmites* and repeated applications in both spring and fall may be necessary (Rapp et al. 2012). One of PRRIP's current science objectives is to contribute to reach-scale *Phragmites* control efforts with a focus on understanding the effectiveness of Program water management actions to control the spread of *Phragmites* to create and maintain suitable whooping crane roosting habitat (PRRIP 2022). In addition to mechanical and chemical control, the Program has an interest in understanding how river flow may be used to slow *Phragmites* rhizome and stolon expansion into the river channel (PRRIP 2022) because periods of low flow associated with drought have been associated with *Phragmites* expansion (Galatowitsch et al. 2016).

The Program's management hypothesis pertaining to flow and *Phragmites* expansion is as follows:

> Releases to achieve a 30-day minimum flow target of 1500 cubic feet per second (cfs) between June 1–July 15 in combination with continued herbicide spraying will slow *Phragmites* rhizome/stolon expansion into the channel and increase the percent of the Associated Habitat Reach channel that remains highly suitable for whooping crane roosting (PRRIP 2022).

This prediction is related to a hypothesized physical process in which *Phragmites* expansion rates into the active river channel are inversely related to the percent of time bare sand substrate is inundated during a 30-day period between June 1–July 15 (PRRIP 2022). To test these hypotheses, we designed a field study to survey *Phragmites* patches along the central Platte River each month of the growing season from May through October to examine: (1) areal growth rates of entire *Phragmites* patches; (2) areal growth rates of stolon reaches and changes in maximum distance of stolon expansion into the river channel; and (3) changes in the lengths of individual stolons. Herein, we describe field methodology used to collect data to address the effectiveness of flow releases to inhibit *Phragmites* patch expansion into the river channel. We also detail our methods for analyses of *Phragmites* patch and stolon reach data collected during 2022 and 2023.

II. METHODS

A. Study Areas

The Program's Associated Habitat Reach (AHR) of the central Platte River extends from Lexington to Chapman, Nebraska (Figure 1). Our study areas consisted of three complexes of PRRIP-owned lands spanning the AHR from west to east along the central Platte River (Figure 1). The Plum Creek study area was comprised of the Cook and Dyer properties south of Overton (Figure 2). The Fort Kearney study area consisted of the Wyoming and Sherrerd properties south of Kearney (Figure 3). The Chapman study area included the Bergen and Robinson properties east of Grand Island (Figure 4).

We established study areas with two adjacent PRRIP-owned or managed lands in an effort to designate one property to have *Phragmites* patches sprayed with herbicide during spring and/or fall and the other property to have no *Phragmites* patches sprayed with herbicide. In the Plum Creek study area, we designated the western Cook property as a no-spray zone and the eastern Dyer property as a spray zone scheduled for herbicide treatments in September. At Fort Kearney, we designated the western Wyoming property as a no-spray zone and the eastern Sherrerd property as a spray zone scheduled for herbicide treatments in June and September. At Chapman, we separated the Robinson property into west and east halves and designated the western half as a spray zone scheduled for herbicide treatments in June and September and the eastern half as a no-spray zone. The Bergren property fell entirely within the spray zone. Both the Robinson and Bergren properties underwent large scale tree removal in the fall of 2021. In addition, in-channel disking took vegetated sandbars back to bare sand in October of 2021. Therefore, in-channel islands and shorelines were in early successional stages at the onset of our study.

B. Sampling Design

a. 2022 Pilot Study Selection of Phragmites Patch Sample

We used a simple random sampling design to select *Phragmites* patches to survey during the 2022 pilot study. We classified patches that were >10 ft from the bankline of a main or secondary river channel as an inland patch. We classified patches that were in or along the bankline of a main or secondary river channel as a bankline patch. We also used a PRRIP water surface elevation (WSE) model to predict the spatial extent of river coverage at a discharge of 1500 cfs in ArcGIS Pro 3.1.1 (ESRI 2022) and classified any patch that intersected the 1500 cfs WSE polygon as a bankline patch. If we observed patches inundated by water during our July 2022 surveys, then we also classified those as bankline patches. In total, the 2022 sample consisted of 68 bankline and 87 inland patches. We provide a description of field methodology and data collected during the 2022 pilot study in the Appendix and a comparison of data collected during 2022 and 2023 in Table A1.

b. 2023 Phragmites Patch Sample Reallocation

Due to the large number of inland patches in our sample during 2022 that were not subject to inundation as a result of our 1500 cfs flow release, we used data collected during the 2022 pilot study and field visits to the study areas in March 2023 to identify additional bankline patches that could be added to the sample to better test the effects of our management action. We also used data from 2022 to identify small inland patches with low *Phragmites* stem density or bankline patches in backwater slough channels or along inland ponds that could be removed from the sample such that field effort could be better allocated to surveying bankline patches along the main river channels. We added 45 new bankline patches to our sample in 2023 and removed 42 inland and backwater patches from the sample that were surveyed during 2022. Therefore, our 2023 sample of bankline patches included 55 patches previously surveyed during 2022 and the 45 new bankline patches that had not been surveyed. Overall, our 2023 sample included 156 patches, of which 100 were classified as bankline patches (Table 1). We retained 56 inland patches that were surveyed in 2022 in our 2023 sample to allow for evaluation of *Phragmites* growth patterns outside the active river channel at 1500 cfs. We surveyed 45 patches in the Chapman study area, 59 in the Fort Kearney study area, and 52 in the Plum Creek study area during 2023 (Table 1; Figures 2, 3, 4).

C. Field Data Collection

a. Phragmites Patch Measurements

We made monthly delineations of all 156 *Phragmites* patches in the sample and recorded patch attributes during May through October 2023. Therefore, for each patch, we had a time series of six consecutive months of patch delineations and attribute data. We separated each month into three 10-day periods and generally surveyed each study area during the same period for each month. In 2023, we generally conducted surveys in the: Plum Creek study area during the first 10 days of the month (i.e., June 1–10); Fort Kearney study area during the second 10 days (i.e., June 11–20); and Chapman study area during the final 10 days (i.e., June 21–30). This ensured consecutive patch measurements were consistently separated by an average of 30 days.

We navigated to *Phragmites* inland and bankline patches included in the sample using the ArcGIS Field Maps (ESRI 2023) application on a mobile phone. We used previously delineated patch boundaries from July 2022 for navigation and patch assessment in May 2023. For surveys conducted after May 2023, we used the patch boundaries delineated during May 2023 surveys. We used a Trimble TSC3 controller and RTK unit (Trimble, Inc., Westminster, Colorado) to delineate *Phragmites* patch boundaries and other patch related attributes, and record elevation. We also recorded data on patch attributes through visual assessments and other measurements.

Although some data collected were the same for inland and bankline patches, we made additional RTK and patch attribute measurements for bankline patches (Tables 2, 3).

i. RTK Job Creation

For each day that we delineated patch boundaries, we created a new job in the Trimble TSC3 coded with the name of the study area and the date. For example, for a survey of the Plum Creek study area on July 3, 2023, we coded the job as "PlumCreek07032023." We specified job properties as follows: "Nebraska 2600 (United States/ Plane 1983)" for the coordinate system; "US survey feet" for units; "Ground" for Cogo settings; and "Previous point" for Media file. We extended the receiver pole to 6.562 ft (2 m). Once the job was created, we selected the "Measure" option to begin taking patch delineation measurements. We selected the "Rapid point" option and entered the height to the base of the antenna mount as 6.562 ft. We began each patch boundary delineation by entering the patch number followed by a ".1" in the point name field and "p" for patch boundary in the measurements code field. For example, for patch no. 184, we began the survey by entering "184.1" in the point name field. This ensured consecutive points delineated with the RTK within patch 184 would be labeled as 184.1, 184.2, 184.3, etc…

ii. Inland Patches

We selected a start point for our patch delineation as one *Phragmites* stem located on the outer boundary of the patch. We placed a surveyor's flag at this point for reference when completing the patch delineation to ensure we fully encircled the patch. We placed the RTK receiver pole at the start point, leveled the pole, and hit "Enter" to record the first point location as "PatchNo.1." We then moved in a counterclockwise direction to the next *Phragmites* stem, or cluster of stems, on the outer boundary of the patch, placed the receiver pole at the point, leveled the pole, and hit "Enter" to record the second point location as "PatchNo.2." We continued this procedure in a counterclockwise direction until we had encircled the patch, fully delineated the outer patch boundary, and returned to the surveyor's flag at the starting point. Maintaining a counterclockwise direction ensured that we kept the *Phragmites* patch on our left-hand side at all times when conducting the delineation. We provide an example of an inland patch boundary that was delineated in 2023 in Figure 5.

If the patch had been sprayed with herbicide during June or September and the effects of the herbicide on the *Phragmites* were visible, then we also used the RTK to delineate a spray zone for the patch. Similar to our patch boundary delineation, we placed a surveyor's flag at the start point of the spray zone. We changed the code in the TSC3 measurements window from "p" to "z" for zone. However, we continued the consecutive point numbering for the patch from the number we left off at the last patch boundary measurement. We delineated the spray zone in a counterclockwise direction and placed the RTK receiver pole at as many points along the outer edge of the spray zone as necessary to map the extent the *Phragmites* patch was sprayed.

After completion of the patch boundary delineation, we recorded additional patch attribute data in pencil on a paper datasheet (Tables 2, 4). We estimated the height of the tallest green, living, and growing *Phragmites* stem to the nearest one-half foot. We used a visual assessment of *Phragmites* stem density and classified it as low (≤33% stem density); medium (33% to 66%); and high

(>66%). Because patches often consisted of uneven spatial distribution of stem density, we recorded the average stem density for the entire patch based on our visual assessment. We recorded the life stage of the *Phragmites* plants as vegetative (V); flowers (F); or seeds (S). We recorded the condition of the *Phragmites* plants as alive/green (A); having partial dieback (P); or brown, dormant, or dead (D). We recorded the percent cover of other non-*Phragmites* vegetation within the *Phragmites* patch boundary as none (N); low (≤33%); medium (33% to 66%); or high (>66%). We recorded whether any stolons were present as a yes/no categorical variable. We also took photograph(s) of the patch to document change over time.

iii. Bankline Patches

As with inland patches, we selected a start point for our patch delineation as one *Phragmites* stem located on the outer boundary of the patch and placed a surveyor's flag at this point. We also identified the upstream and downstream extent of the patch along the channel and placed surveyor's flags at each point. These flags were generally placed on the bankline to provide reference points for the additional stolon boundary, bankline, and edge of water RTK measurements taken for bankline patches (Tables 3, 5). We used the same techniques for mapping the patch boundary of bankline patches as we did for inland patches described in (ii) above. We did not include stolons (horizontal growths into or along channel) or rhizomes protruding from eroded banks in the patch boundary map for bankline patches due to the separate measurements made of a stolon boundary. Therefore, we restricted our patch boundary delineation to the area of *Phragmites* vertical shoot growth for bankline patches.

After completing the patch boundary delineation, we mapped the stolon boundary. Stolons are horizontal *Phragmites* shoots and growths that extend into the channel and/or along the channel (Figure 6). We changed the code in the TSC3 measurements window from "p" to "s" for stolon and continued the consecutive point numbering for the patch from the number we left off at the last patch boundary measurement. We began stolon boundary measurements at the flag placed at the upstream extent of the patch and took RTK measurements at the outermost extent of all *Phragmites* stolons associated with the patch until we ended at the flag placed at the downstream extent of the patch (Figure 6). Therefore, the stolon boundary consisted of a line instead of an enclosed polygon that could be combined with the patch boundary in ArcGIS to calculate the total patch area. If there were no stolons along a portion of the patch, then the outermost extent of the stolon boundary was the same as the patch boundary along the channel.

We then mapped the stream bankline from the upstream to downstream extent of the patch (Figure 7). We defined the bankline for most patches to be the top of the stream bank that designated the channel boundary where the majority of normal discharge occurred. We changed the code in the TSC3 measurements window from "s" to "b" for "bankline" and continued the consecutive point numbering for the patch from the number we left off at the last stolon boundary measurement. We began bankline measurements at the point on the bank closest to the upstream flag. We took RTK measurements along the stream bank until we ended at the point on the bank closest to the downstream flag. Therefore, the bankline measurement consisted of a line that spanned the *Phragmites* patch from upstream to downstream (Figure 7).

Next, we mapped the edge of water and water surface elevation from the upstream to downstream extent of the *Phragmites* patch between the two flags. We changed the code in the TSC3 measurements window from "b" to "eow" for "edge of water" and continued consecutively numbering points for the patch. For each edge of water measurement, we ensured that the bottom of the RTK receiver pole was placed at the surface of the water to record an accurate water surface elevation. We also recorded the time that we began taking edge of water measurements. We encountered five different scenarios when making edge of water measurements.

1. The edge of the water corresponded to the flowing river that intersected the *Phragmites* patch (Figures 8, 9). We made one set of edge of water measurements from the upstream to downstream extent of the patch resulting in a series of dots that could be connected to estimate the proportion of the patch inundated by water.

2. The edge of the water corresponded to the flowing river that did not intersect any of the *Phragmites* patch (Figures 10, 11). We made one set of edge of water measurements from the upstream to downstream extent of the patch resulting in a series of dots that could be connected to estimate the distance from the patch to the nearest water.

3. The entire patch was inundated by the flowing river (Figures 12, 13). We made one water surface elevation measurement to estimate the depth of the patch under water and document the water surface elevation during the patch measurement.

4. The river channel was mostly dry near the patch, but a remnant pool of water existed in the channel at or near the edge of the patch (Figures 14, 15). We made two or more edge of water measurements. First, we delineated the boundaries of the remnant pool(s). Second, we marked the edge of the flowing river at the edge of water locations closest to the patch and from the upstream to downstream extent of the patch. We coded edge of water measurements for each measurement as "eow1," "eow2," "eow3," etc…

5. The *Phragmites* patch was located on an island, the river channel was dry near one or both sides of the island, and remnant pools of water and the flowing river needed to be mapped (Figures 16, 17, 18, 19). We made three or more edge of water measurements. First, we delineated the boundaries of the remnant pool(s) on both sides of the island if present. Second, we marked the edge of the flowing river at the edge of water locations closest to the patch and from the upstream to downstream extent of the patch on both sides of the island. We coded edge of water measurements for each measurement as "eow1," "eow2," "eow3," etc…

If the patch had been sprayed with herbicide during June or September and the effects of the herbicide on the *Phragmites* were visible, then we also used the RTK to delineate a spray zone for the patch in a similar manner to that described in II.C.a.ii for inland patches.

After completing the patch boundary, stolon boundary, bankline, edge of water, and spray zone (if necessary) delineations, we recorded additional patch attribute data in pencil on a paper datasheet (Tables 3, 5). We recorded the same data as we did for inland patches. We estimated the height of the tallest green, living, and growing *Phragmites* stem to the nearest one-half foot. We used a visual assessment of average *Phragmites* stem density and classified it as low (≤33% stem density); medium (33% to 66%); and high (>66%). We recorded the life stage of the *Phragmites* plants as vegetative (V); flowers (F); or seeds (S). We recorded the condition of the *Phragmites* plants as alive/green (A); having partial dieback (P); or brown, dormant, or dead (D). We recorded the percent cover of other non-*Phragmites* vegetation within the *Phragmites* patch boundary as none (N); low (≤33%); medium (33% to 66%); or high (>66%). We recorded several additional attributes for bankline patches. We recorded whether any stolons were present as a yes/no categorical variable and entered whether or not a stolon boundary was delineated with the RTK. We entered whether or not bankline and edge of water measurements were delineated with the RTK. We recorded the time we began the edge of water measurement. We estimated the percentages of the *Phragmites* patch boundary and stolon boundary inundated by water as a categorical variable as: 0 (0%); 1 (1–25%); 2 (26–50%); 3 (51–75%); 4 (76–99%); and 5 (100%). Finally, we took photograph(s) of the patch to document change over time.

b. Stolon Length Measurements

For bankline patches, we also marked, measured, and recorded the length of randomly selected stolons (Table 6). For each bankline patch, we selected five stolons at random, tied pink flagging to each stolon, measured the stolon length from its base where it emerged from the sand or mud to its tip at the end of the growth, and recorded the length in feet and inches in pencil on a paper datasheet (Table 6, Figure 20). We wrote the stolon number in black permanent marker on each pink flagging corresponding to the number of the stolon being measured on the datasheet. We initially marked up to five stolons (numbered 1, 2, 3, 4, 5), or vertical shoots in the channel that could turn into potential stolons, during May patch visits, searched for the five marked stolons during all subsequent monthly visits, and measured the length of each marked stolon when found. Due to difficulty finding marked stolons during higher water and flow conditions during June, we marked up to five more stolons in each bankline patch and numbered them 6, 7, 8, 9, and 10. Therefore, we had up to 10 stolons to find and measure during patch surveys conducted July through October. We removed stolons from the sample that broke during measurements or had flagging fall off between months.

c. Platte River Elevation and Discharge Measurements

During April and May 2023, we deployed a total of six In-Situ Troll Series data loggers (In-Situ, Inc., Fort Collins, CO) across the three study areas to provide measurements of water surface elevation at 15 min intervals throughout our May through October *Phragmites* surveys (Figure 21). We deployed two data loggers per study area at different locations in the main river channel or side channels. When possible, we placed data loggers close to *Phragmites* patches included in our sample. To minimize the chance the loggers would be damaged during periods of high river flow, we fastened loggers within a PVC tube bolted to a u-post that we secured into the river bottom. We attached the instrument cable leading from the logger to a t-post on the riverbank (Figure 21) and downloaded logger data during subsequent monthly field visits to the study area.

We also downloaded Platte River discharge and stage measurements from U.S. Geological Survey (USGS) stage gages that were located close to our study areas. We used data from the: Overton, NE gage (USGS 2023a) combined with discharge data from the Johnson Hydropower Return for our Plum Creek study area; Kearney, NE gage (USGS 2023b) for our Fort Kearney study area; and Grand Island, NE gage (USGS 2023c) for our Chapman study area. We used the following process to evaluate discharge at the Plum Creek study area. First, we used discharge recorded every 15 min from the USGS Overton gage divided by the average daily discharge from the Overton gage to provide a relative measure of how the 15-min discharge was related to average daily discharge. Second, we multiplied that proportion by the average daily discharge from the Johnson Hydropower Return to estimate a 15-min discharge at the Johnson Hydropower Return.

III. STATISTICAL ANALYSES AND HYPOTHESES

A. Factors Related to Patch Area Changes Over Time in 2023

We examined factors related to the areal changes of the 156 *Phragmites* patches during May through October 2023 at approximately monthly intervals. We defined a patch boundary in GIS by connecting consecutive RTK points coded with a "p" and creating a polygon for each patch for each month of surveys. We then calculated the patch area for each month. For bankline patches that had a stolon boundary measurement, we connected consecutive RTK points coded with a "s" and created a stolon boundary polygon for each bankline patch for each month of surveys. We then calculated the stolon reach area for each month. We calculated the total patch area for each patch for each month by adding the patch area to the stolon reach area.

a. Response Variable

We defined a response variable for each patch, *p*, as the daily areal growth rate ($r_{p,t}$; ft^2/day). We calculated the daily areal growth rate by subtracting the total patch area for month *t* from the total patch area for month *t*+1 and dividing by the number of days between consecutive patch measurements. Therefore, for each patch measured during May through October on a monthly basis, we calculated five areal growth rates.

b. Covariates and Hypotheses

We defined a total of 38 covariates in four suites quantifying *Phragmites* patch attributes, water and flow metrics, herbicide treatments, and statistical variables. We used these covariates in both *a priori* and exploratory analyses to examine their impact on overall *Phragmites* patch growth.

i. <u>*Phragmites* Patch Attributes</u>

We defined seven covariates describing attributes of *Phragmites* patches and other potential explanatory variables. We defined these covariates to assess their role in affecting *Phragmites* growth, which was not necessarily related to our management hypothesis regarding flow and herbicide.

1. *Total patch perimeter*. Total perimeter of the *Phragmites* patch (ft). We hypothesized daily areal growth rates would be positively correlated with total patch perimeter because larger patches would have more established rhizomes that would facilitate patch expansion faster than smaller patches.

2. *Maximum height.* The maximum height of a vertical *Phragmites* stem in the patch (ft). We predicted daily areal growth rates would be positively correlated with maximum height because patches with taller *Phragmites* stems would be indicative of a healthier patch

capable of faster expansion.

3. *Stem density.* A categorical variable denoting the average stem density of *Phragmites* in the patch classified as: low (≤33%); medium (33–66%); and high (>66%). We expected patches with high and low stem density would have the highest and lowest daily areal growth rates, respectively, because patches with higher stem densities would be indicative of a healthier patch with less interspecific competition that was capable of faster expansion.

4. *Life stage*. A categorical variable denoting the life stage of the majority of *Phragmites* stems in the patch classified as: vegetative; flowering; or seeds. We predicted daily areal growth rates would be greatest during the vegetative life stage and lowest during the seed production stage due to how the *Phragmites* stems were allocating resources during the different stages of growth.

5. *Proportion of stolon reach area.* The proportion of the total patch area that was comprised of the stolon reach area. We hypothesized daily areal growth rates would be positively correlated with the proportion of stolon reach area because of the aggressive growth of stolons and rapid expansion of patches that may occur due to stolons.

6. *Distance to river during germination suppression flow release*. The nearest distance from the centroid of the patch to the edge of the river channel as defined by edge of water data from field observations collected during May 30–June 12, 2023, when river discharge was at or near 1500 cfs. We predicted patches closer to the river channel would have higher daily growth rates compared to patches farther from the river due to proximity to surface water.

7. *Aspect*. A categorical variable denoting the predominant aspect of the patch as north, east, south, west, or flat (i.e., no aspect). We expected south-facing patches to have the highest daily growth rates and north-facing patches to have the lowest daily growth rates due to greater exposure to direct sunlight for south-facing patches.

ii. <u>Empirical Water and Flow Metrics</u>

We defined 12 covariates describing weather, water, flow, and patch inundation variables as determined from empirical data collected during field measurements, or from flow gages or weather stations. Covariates that we specifically defined to evaluate our management hypothesis regarding flow at 1500 cfs are denoted with an asterisk (*).

*1. *Proportion of patch inundated by water during June germination suppression flow release.* The proportion of the total patch area that was inundated by water during the target 1500 cfs flow release during the first two weeks of June. We made empirical measurements of the edge of water relative to patch boundaries for all bankline patches during May 30–June 12, 2023, at all three study areas when river discharge was at or near 1500 cfs. We hypothesized daily areal growth rates would be negatively correlated with the proportion of the patch inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water during June.

*2. *Total accumulated time of river discharge ≥1500 cfs*. The total time between consecutive patch area measurements that discharge of the Platte River was ≥1500 cfs based on discharge data at the USGS gage closest to the study area combined with water surface elevation data from our stage gages deployed in each study area. For the Plum Creek study area, we used a combination of flow data from the USGS Overton gage and the Johnson Hydropower Return to quantify discharge. We used data from the USGS Kearney gage for patches in the Fort Kearney study area and data from the Grand Island gage for patches in the Chapman study area. We predicted daily growth rates would be negatively correlated with the total accumulated time ≥1500 cfs due to inhibition of *Phragmites* expansion into the river channel by flowing water at greater discharge. This covariate is also designed to be used as an interaction with covariates 3 and 4 defined below.

3. *Proportion of patch area in river channel.* The proportion of the total patch area that was within the river channel (wet or dry) as defined by the bankline delineation. We hypothesized daily areal growth rates would be positively correlated with the proportion of the total patch area within the river channel due to proximity to water and an increased likelihood that patches with a higher proportion of area in the channel would be in contact with water for longer periods during the growing season. We predicted that daily growth rates would be negatively correlated with a total accumulated time ≥1500 cfs*proportion of patch area in river channel interaction due to inhibition of *Phragmites* expansion into the river channel by flowing water at greater discharge. Daily growth rates of patches with more *Phragmites* in the channel would be affected more by the total time at higher discharge than patches with a low proportion of *Phragmites* in the channel.

4. *Proportion of patch perimeter in contact with river channel along bankline.* The proportion of the total patch perimeter that was within the river channel as defined by the bankline delineation. We predicted daily growth rates would be positively correlated with the proportion of total patch perimeter within the river channel due to similar rationale as for the proportion of patch area in the river channel. Similarly, we expected daily growth rates to be negatively correlated with a total accumulated time ≥1500 cfs*proportion of patch perimeter in river channel interaction.

5. *Average minimum daily river discharge.* The average minimum daily value of Platte River discharge between consecutive patch area measurements based on discharge data at the USGS gage closest to the study area. This covariate is designed to be used in interactions with covariates 3 and 4 to distinguish between effects on bankline and inland patches. We predicted daily growth rates would be negatively correlated with an average minimum daily discharge*proportion of patch area in river channel interaction and an average minimum daily discharge*proportion of patch perimeter in river channel interaction due to inhibition of *Phragmites* expansion into the river channel by flowing water at higher discharge.

6. *Average maximum daily river discharge.* The average maximum daily value of Platte River discharge between consecutive patch area measurements based on discharge data at the USGS gage closest to the study area. This covariate is designed to be used in

interactions with covariates 3 and 4 to distinguish between effects on bankline and inland patches. We predicted daily growth rates would be negatively correlated with an average maximum daily discharge*proportion of patch area in river channel interaction and an average maximum daily discharge*proportion of patch perimeter in river channel interaction due to inhibition of *Phragmites* expansion into the river channel by flowing water at higher discharge.

7. *Total accumulated time >25% of patch was inundated*. The total accumulated time between consecutive patch area measurements that >25% of the *Phragmites* patch was inundated with water. We used our empirical patch boundary, stolon reach boundary, and edge of water delineations made with the RTK to relate the percent of patch inundation with discharge data from the nearest stage gage and USGS gage. We predicted daily growth rates would be negatively related to the total time >25% of the patch was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

8. *Total accumulated time >50% of patch was inundated*. The total accumulated time between consecutive patch area measurements that >50% of the *Phragmites* patch was inundated with water. We used our empirical patch boundary, stolon reach boundary, and edge of water delineations made with the RTK to relate the percent of patch inundation with discharge data from the nearest stage gage and USGS gage. We predicted daily growth rates would be negatively related to the total time >50% of the patch was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

9. *Total accumulated time >75% of patch was inundated*. The total accumulated time between consecutive patch area measurements that >75% of the *Phragmites* patch was inundated with water. We used our empirical patch boundary, stolon reach boundary, and edge of water delineations made with the RTK to relate the percent of patch inundation with discharge data from the nearest stage gage and USGS gage. We predicted daily growth rates would be negatively related to the total time >75% of the patch was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water. We expected the total accumulated time >75% of the patch was inundated to be a better predictor of daily growth rates than the >50% or >25% metrics.

10. *Average proportion of patch inundated by water over previous month*. The average proportion of the entire patch boundary that was inundated by water between consecutive patch area measurements. We predicted daily growth rates would be negatively related to the average proportion of the patch inundated due to inhibition of *Phragmites* expansion into the river channel by flowing water.

*11. *Difference between average patch elevation and water surface elevation at 1500 cfs*. The water surface elevation recorded during flow at or near 1500 cfs subtracted from the average patch elevation based on RTK measurements of the patch and stolon reach boundaries. We made empirical measurements of the edge of water relative to patch boundaries for all bankline patches during May 30–June 12, 2023, at all three study areas when river discharge was at or near 1500 cfs. For bankline patches, we estimated the water surface elevation at the edge of the water corresponding to the intersection between the water surface and patch boundary. For inland patches, we estimated the water surface elevation at the nearest edge of water location to the edge of the inland patch. This covariate is designed to be used with the *distance to river* covariate defined in the previous section to distinguish bankline from inland patches. We predicted daily growth rates to increase as distance to river increased and elevation difference decreased because inland patches with elevations closer to groundwater would grow more rapidly than inland patches with elevations farther above groundwater. Likewise, we predicted daily growth rates to decrease as distance to river decreased and elevation difference decreased because growth of bankline patches inundated by water at 1500 cfs flows would be inhibited into the channel.

12. *Total accumulated monthly precipitation*. The total accumulated precipitation for the month prior to the patch area measurements as recorded at the climate station closest to each of the three study areas (National Weather Service–National Oceanic and Atmospheric Administration 2023). We hypothesized daily areal growth rates would be positively related to the total accumulated precipitation for the month because greater precipitation would promote patch growth and expansion.

iii. Modeled Water and Flow Metrics

We defined 10 covariates describing water, flow, and patch inundation variables as determined from the 2-D hydrodynamic model. Covariates that we specifically defined to evaluate our management hypothesis regarding flow at 1500 cfs are denoted with an asterisk (*).

*1. *Proportion of patch predicted to be inundated by water at 1500 cfs.* The proportion of the total patch area based on June patch delineations predicted to be inundated by water based on a 1500 cfs flow model. We hypothesized daily areal growth rates would be negatively correlated with the proportion of the patch inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water during June.

2. *Total accumulated time >25% of patch was inundated*. The total accumulated time between consecutive patch area measurements that >25% of the *Phragmites* patch was inundated with water based on predicted water surface elevation. We used the 2-D hydrodynamic model to generate predicted water surface elevations corresponding to the range of discharge measurements that occurred during the previous month, which was then used to estimate percent of patch inundation and total time of patch inundation. We predicted daily growth rates would be negatively related to the total time >25% of the patch was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

3. *Total accumulated time >50% of patch was inundated*. The total accumulated time between consecutive patch area measurements that >50% of the *Phragmites* patch was inundated with water based on predicted water surface elevation. We used the 2-D hydrodynamic model to generate predicted water surface elevations corresponding to the range of discharge measurements that occurred during the previous month, which was then used to estimate percent of patch inundation and total time of patch inundation. We

predicted daily growth rates would be negatively related to the total time >50% of the patch was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

4. *Total accumulated time >75% of patch was inundated*. The total accumulated time between consecutive patch area measurements that >75% of the *Phragmites* patch was inundated with water based on predicted water surface elevation. We used the 2-D hydrodynamic model to generate predicted water surface elevations corresponding to the range of discharge measurements that occurred during the previous month, which was then used to estimate percent of patch inundation and total time of patch inundation. We predicted daily growth rates would be negatively related to the total time >75% of the patch was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water. As with the empirical data, we expected the total accumulated time >75% of the patch was inundated to be a better predictor of daily growth rates than the >50% or >25% metrics.

5. *Average proportion of patch inundated by water over previous month*. The average proportion of the entire patch boundary that was inundated by water between consecutive patch area measurements as predicted by the 2-D model. We predicted daily growth rates would be negatively related to the average proportion of the patch inundated due to inhibition of *Phragmites* expansion into the river channel by flowing water.

*6. *Difference between average patch elevation and predicted water surface elevation at 1500 cfs.* The predicted water surface elevation at 1500 cfs subtracted from the average patch elevation based on RTK measurements of the patch and stolon reach boundaries. For bankline patches, we estimated the water surface elevation at the edge of the water corresponding to the intersection between the water surface and patch boundary. For inland patches, we estimated the water surface elevation at the nearest edge of water location to the edge of the inland patch. This covariate is designed to be used with the *distance to river* covariate defined in the previous section to distinguish bankline from inland patches. We predicted daily growth rates to increase as distance to river increased and elevation difference decreased because inland patches with elevations closer to groundwater would grow more rapidly than inland patches with elevations farther above groundwater. Likewise, we predicted daily growth rates to decrease as distance to river decreased and elevation difference decreased because growth of bankline patches inundated by water at 1500 cfs flows would be inhibited into the channel.

7. *Average daily water surface elevation*. The mean daily water surface elevation between consecutive patch area measurements as predicted by the 2-D model. For bankline patches that were at least partially inundated, we estimated the water surface elevation at the edge of the water corresponding to the intersection between the water surface and patch boundary. For bankline patches that were not inundated, we estimated the water surface elevation at the edge of the water located nearest to the patch edge. For inland patches, we estimated the water surface elevation at the nearest edge of water location to the edge of the inland patch. We expected daily growth rates of bankline patches to be negatively

related to the average daily water surface elevation because higher water surface elevations would be indicative of greater river discharge, which would inhibit patch expansion into the channel. However, for inland patches we expected daily growth rates to be positively related to average daily water surface elevation because of the potential decrease in distance between inland patches and ground water.

8. *Monthly minimum water surface elevation*. The minimum water surface elevation between consecutive patch area measurements as predicted by the 2-D model. We estimated water surface elevations for bankline and inland patches as described in (7) and made similar predictions for bankline and inland patches.

9. *Monthly maximum water surface elevation*. The maximum water surface elevation between consecutive patch area measurements as predicted by the 2-D model. We estimated water surface elevations for bankline and inland patches as described in (7) and made similar predictions for bankline and inland patches.

10. *Average maximum daily shear stress at patch edge.* The maximum daily shear stress due to flow along the patch edge averaged over the period between consecutive patch measurements. We used the 2-D hydrodynamic model to generate predicted shear stress values where the patch edge intersects the edge of water at various flow conditions experienced during the month and estimate the maximum value of shear stress for each day. We averaged the maximum value of shear stress for each day over the period between consecutive patch measurements to derive an average shear stress value for each patch for each month. We predicted daily growth rates would be negatively correlated with average maximum daily shear stress for bankline patches because more shear stress at the patch edge would inhibit stolon expansion into the channel and restrict patch growth to along the bankline.

iv. <u>Herbicide Treatments</u>

We defined six covariates describing herbicide treatments on *Phragmites* patches. Covariates that we specifically defined to evaluate our management hypothesis regarding herbicide are denoted with an asterisk (*).

*1. *Proportion of patch sprayed with herbicide in June 2023.* The proportion of the *Phragmites* patch that was sprayed with herbicide during the June 2023 treatment as determined from the overlap between our patch boundary map and the July and/or August spray zone maps. We hypothesized daily growth rates during July, August, and September would be negatively related to the proportion of the patch sprayed in June.

*2. *Proportion of patch sprayed with herbicide in September 2023.* The proportion of the *Phragmites* patch that was sprayed with herbicide during the September 2023 treatment as determined from the overlap between our patch boundary map and the October spray zone map. We hypothesized daily growth rates between September and October would be negatively related to the proportion of the patch sprayed in September.

*3. *June 2023 spray.* An indicator variable denoting the patch was sprayed with herbicide during the June 2023 treatment. We expected daily growth rates during July, August, and September would be lower in patches sprayed during the June treatment.

*4. *September 2023 spray.* An indicator variable denoting the patch was sprayed with herbicide during the September 2023 treatment. We expected daily growth rates between September and October would be lower in patches sprayed during the September treatment.

*5. *June 2022 spray*. An indicator variable denoting the patch was sprayed with herbicide during June 2022 based on visual inspection of the patch during 2023 and spray zone polygons from June 2022. We predicted daily growth rates in 2023 would be lower in patches sprayed during 2022.

*6. *September 2022 spray*. An indicator variable denoting the patch was sprayed with herbicide during September 2022 based on visual inspection of the patch during 2023 and spray zone polygons from September 2022. We predicted daily growth rates in 2023 would be lower in patches sprayed during 2022.

v. Statistical Variables

We defined three covariates as variables to account for the statistical design of our study. These variables were included in our models to account for repeated measurements over time or unexplained variability in our data.

1. *Patch Number.* A unique identifying number for each patch to be included in mixed-effects models as a random effect.

2. *Month.* A continuous variable denoting the month of data collection to be used in mixed-effects models as a random effect to account for temporal correlation between consecutive patch area measurements. We assigned the number 1, 2, 3, 4, 5, and 6 for the months of May, June, July, August, September, and October, respectively.

3. *Study area.* A categorical variable denoting the study area in which the patch was located (Chapman; Fort Kearney; Plum Creek) to be used as a fixed effect blocking factor. Use of study area as a blocking factor may help reduce unexplained variability and better assess the influence of other covariates. We expected patches in the Chapman study area to have the highest rates of growth because of the braided nature of the Platte River through this study area makes for less incised banks, a broader flood plain, and closer proximity of vegetation to ground water. In contrast, we predicted patches in the Plum Creek study area would have the lowest rates of growth because the river bankline is generally steep, incised, and *Phragmites* patches at top of banks and inland are farther from ground water.

c. Modeling Approach

We used a stepwise approach to examine covariates for inclusion in our final analysis. First, we developed univariate models and models consisting of two covariates and an interaction when use of an interaction was appropriate using covariates from suites (i) *Phragmites* patch attributes, (ii) empirical water and flow metrics, and (iv) herbicide treatments. We used mixed-effects regression techniques (Pinheiro and Bates 2000, Zuur et al. 2009) in R (R Core Team 2022, Pinheiro et al.

2023) to fit models with *Patch Number* as a random effect to account for repeated area measurements in the same patch over time. We also included *Month* nested within *Patch Number* to account for temporal correlation in area measurements between and across months. We determined the strength of relationships by assessing whether 95% confidence intervals (CIs) of coefficient estimates include 0 and whether they are centered on 0 (sensu Arnold 2010). We included covariates with 95% CIs that did not include 0 or had a small extent of overlap with 0 in the next step of our analyses.

Second, we developed multiple competing hypotheses expressed as mixed-effects regression models consisting of additive combinations of main effects and interactions of covariates carried forward from our step one analyses. We assessed multicollinearity among covariates included in each candidate model by calculating variance inflation factors (VIFs; Neter et al 1996) and excluding models containing covariate combinations with VIFs > 5. We calculated an AICc value and Akaike model weight (w) for each model, and ranked and selected the best-approximating models based on models with ΔAICc < 2 (Burnham and Anderson 2002).

Third, we systematically added and substituted covariates from suite (iii) (modeled water and flow metrics) for those from suite (ii) for all models in our candidate model list developed in step two to determine whether modeled covariates provide a better fit to the data than empirically derived covariates. We calculated an AICc value and Akaike model weight (w) for each model, and ranked and selected the best-approximating models based on models with ΔAICc < 2 (Burnham and Anderson 2002). We compared AIC values for models from step two to those from step three and selected the models with the lowest AIC values for further interpretation.

Finally, in exploratory work, we examined the data to determine if nonlinear relationships were present between the response variable and continuous covariates. We conducted exploratory analyses using non-linear mixed models or generalized additive mixed models (GAMM; Zuur et al. 2009) to assess whether inclusion of nonlinear covariate terms improved model fit.

B. Factors Related to Stolon Reach Areal Growth Rates and Patch and Stolon Expansion into the Channel Over Time

We examined factors related to the areal changes and expansion of stolon reaches into the river channel of 100 bankline *Phragmites* patches during May through October 2023 at approximately monthly intervals. To accomplish this, we used stolon reach boundaries defined for our analyses in III.A to calculate the stolon reach area and maximum stolon reach distance into the channel for each month of patch measurements. We also examined factors related to the areal changes of the entire patch into the river channel of the 100 bankline patches during May through October 2023 at approximately monthly intervals. For this effort, we determined the portion of the total patch boundary that was contained within the channel for each month of measurements.

a. Response Variables

We defined one response variable for each stolon reach from each bankline patch, p, as the daily stolon areal growth rate ($s_{p,t}$; ft^2/day). We calculated the daily areal growth rate by subtracting the stolon reach area for month t from the stolon reach area for month t+1 and dividing by the number of days between consecutive patch measurements. Therefore, for each bankline patch measured during May through October on a monthly basis, we calculated five stolon areal growth rates.

We defined a second response variable for each stolon reach from each bankline patch as the maximum distance of stolon expansion into the river channel (ft). We used a combination of the bankline and stolon reach boundaries for each bankline patch to determine the maximum distance from the bankline to the outer edge of the stolon reach boundary for each patch for each month.

We defined a third response variable for each bankline patch as the daily areal growth rate within the active channel ($c_{p,t}$; ft^2/day). We calculated the daily areal growth rate by subtracting the portion of the total patch area within the active channel for month *t* from the portion of the total patch area within the active channel for month *t*+1 and dividing by the number of days between consecutive patch measurements.

b. Covariates and Hypotheses

We used many of the same covariates that we defined to examine total patch area growth rates for our daily stolon areal growth rate, stolon expansion, and daily areal growth rate within the active channel analyses. However, because our stolon growth rate and expansion analyses did not use data from inland patches, we restricted our covariates only to those applicable to bankline patches. In addition to those previously defined, we defined new covariates specific to the stolon reach and active channel that are listed below. Covariates unique to these analyses are denoted with an †. Covariates that we specifically defined to evaluate our management hypothesis regarding flow at 1500 cfs are denoted with an asterisk (*).

i. *Phragmites* Patch Attributes

We defined four covariates describing attributes of *Phragmites* patches.

1. *Total patch perimeter*. Defined above. We hypothesized daily areal stolon reach growth rates and daily areal total patch growth rates in the active channel would be positively correlated with total patch perimeter because larger patches would have more established rhizomes that would facilitate patch and stolon reach expansion faster than smaller patches. We also expected the maximum distance of stolon expansion into the river channel would be positively correlated with total patch perimeter.

2. *Stem density.* Defined above. We expected patches with high stem density would have the highest daily areal stolon reach growth rates and daily areal total patch growth rates in the active channel, and greatest maximum distance of stolon expansion because patches with higher stem density would be indicative of a healthier patch capable of faster expansion through rhizomes and above ground stolons.

3. *Aspect*. Defined above. We expected south-facing patches to have the highest daily areal stolon reach growth rates and daily areal total patch growth rates in the active channel, and maximum distance of stolon expansion due to greater exposure to direct sunlight for south-facing patches, which would promote patch and stolon growth.

4. †*Maximum angle of bankline curvature.* The maximum angle of the bankline extending through the patch relative to the primary direction of flow. We defined the angle of patches

on the inside of river channel bends to be negative and the angle of patches on the outside of river bends to be positive for a comparison of the effects of flow on patches located inside and outside of bends in the channel. We predicted daily areal stolon reach growth rates, daily areal total patch growth rates in the active channel, and maximum distance of stolon expansion would be negatively related to maximum angles of curvature due to increased velocity and shear stress that *Phragmites* stolons and vertical shoots would experience during the germination suppression flow release and at discharge >1500 cfs.

ii. Empirical Water and Flow Metrics

We defined 11 covariates describing empirically derived water, flow, and stolon reach inundation variables.

1. **Total accumulated time of river discharge ≥1500 cfs*. Defined above. We predicted daily areal stolon growth rates, daily areal total patch growth rates in the active channel, and maximum distance of stolon expansion would be negatively correlated with the total accumulated time ≥1500 cfs due to inhibition of *Phragmites* expansion into the river channel by flowing water at greater discharge.

2. *Average minimum daily river discharge.* Defined above. We predicted daily areal stolon growth rates, daily areal total patch growth rates in the active channel, and maximum distance of stolon expansion would be negatively correlated with average minimum daily discharge due to inhibition of *Phragmites* expansion into the river channel by flowing water at higher discharge.

3. *Average maximum daily river discharge.* Defined above. We predicted daily areal stolon growth rates, daily areal total patch growth rates in the active channel, and maximum distance of stolon expansion would be negatively correlated with average maximum daily discharge due to inhibition of *Phragmites* expansion into the river channel by flowing water at higher discharge.

4. *†Total accumulated time >25% of stolon reach was inundated*. The total accumulated time between consecutive patch area measurements that >25% of the stolon reach area was inundated with water. We used our empirical stolon reach boundaries and edge of water delineations made with the RTK to relate the percent of stolon reach area inundation with discharge data from the nearest USGS gage and water surface elevation data from the nearest stage gage. We predicted daily stolon reach area growth rates, daily areal total patch growth rates in the active channel, and the maximum distance of stolon expansion would be negatively related to the total time >25% of the stolon reach was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

5. *†Total accumulated time >50% of stolon reach was inundated*. The total accumulated time between consecutive patch area measurements that >50% of the stolon reach area was inundated with water. We used our empirical stolon reach boundaries and edge of water delineations made with the RTK to relate the percent of stolon reach area inundation with discharge data from the nearest USGS gage and water surface elevation data from the nearest stage gage. We predicted daily stolon reach area growth rates, daily areal total

patch growth rates in the active channel, and the maximum distance of stolon expansion would be negatively related to the total time >50% of the stolon reach was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

6. †*Total accumulated time >75% of stolon reach was inundated*. The total accumulated time between consecutive patch area measurements that >75% of the stolon reach area was inundated with water. We used our empirical stolon reach boundaries and edge of water delineations made with the RTK to relate the percent of stolon reach area inundation with discharge data from the nearest USGS gage and water surface elevation data from the nearest stage gage. We predicted daily stolon reach area growth rates, daily areal total patch growth rates in the active channel, and the maximum distance of stolon expansion would be negatively related to the total time >75% of the stolon reach was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

7. *†*Proportion of patch within active channel inundated by water during June germination suppression flow release.* The proportion of the entire patch within the active channel that was inundated by water during the target 1500 cfs flow release during the first two weeks of June. We made empirical measurements of the edge of water relative to patch boundaries for all bankline patches during May 30–June 12, 2023, at all three study areas when river discharge was at or near 1500 cfs. We hypothesized daily areal total patch growth rates in the active channel would be negatively correlated with the proportion of the patch within the active channel inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water during June.

8. †*Average proportion of patch within active channel inundated by water over previous month*. The average proportion of the entire patch boundary contained within the active channel that was inundated by water between consecutive patch area measurements. We predicted daily areal total patch growth rates in the active channel would be negatively related to the average proportion of the patch inundated due to inhibition of *Phragmites* expansion into the river channel by flowing water.

9. *†*Proportion of stolon reach area inundated by water during June germination suppression flow release.* The proportion of the stolon reach area that was inundated by water during the target 1500 cfs flow release during the first two weeks of June. We hypothesized daily stolon reach area growth rates and maximum distance of stolon expansion would be negatively correlated with the proportion of the stolon reach area inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water during June.

10. †*Average proportion of stolon reach area inundated by water over previous month*. The average proportion of the stolon reach boundary that was inundated by water between consecutive patch area measurements. We predicted daily stolon reach area growth rates and maximum distance of stolon expansion would be negatively related to the average proportion of the patch inundated due to inhibition of *Phragmites* expansion into the river channel by flowing water.

11. *Total accumulated monthly precipitation*. Defined above. We hypothesized daily areal stolon growth rates, daily areal total patch growth rates in the active channel, and maximum distance of expansion would be positively related to the total accumulated precipitation for the month because greater precipitation would promote patch growth and expansion through both rhizomes and above ground stolons.

iii. <u>Modeled Water and Flow Metrics</u>

We defined nine covariates describing modeled water, flow, and stolon reach inundation variables.

1. **†Proportion of stolon reach predicted to be inundated by water at 1500 cfs.* The proportion of the stolon reach boundary area based on June patch delineations predicted to be inundated by water based on a 1500 cfs flow model. We predicted daily stolon reach area growth rates, daily areal total patch growth rates in the active channel, and the maximum distance of stolon expansion would be negatively correlated with the proportion of the stolon reach inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water during June.

2. †*Total accumulated time >25% of stolon reach was inundated*. The total accumulated time between consecutive patch area measurements that >25% of the stolon reach area was inundated with water based on predicted water surface elevation. We used the 2-D hydrodynamic model to generate predicted water surface elevations corresponding to the range of discharge measurements that occurred during the previous month, which we then used to estimate percent of stolon reach inundation and total time of stolon reach inundation. We predicted daily stolon reach area growth rates, daily areal total patch growth rates in the active channel, and the maximum distance of stolon expansion would be negatively related to the total time >25% of the stolon reach was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

3. †*Total accumulated time >50% of stolon reach was inundated*. The total accumulated time between consecutive patch area measurements that >50% of the stolon reach area was inundated with water based on predicted water surface elevation. We used the 2-D hydrodynamic model to generate predicted water surface elevations corresponding to the range of discharge measurements that occurred during the previous month, which we then used to estimate percent of stolon reach inundation and total time of stolon reach inundation. We predicted daily stolon reach area growth rates, daily areal total patch growth rates in the active channel, and the maximum distance of stolon expansion would be negatively related to the total time >50% of the stolon reach was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

4. †*Total accumulated time >75% of stolon reach was inundated*. The total accumulated time between consecutive patch area measurements that >75% of the stolon reach area was inundated with water based on predicted water surface elevation. We used the 2-D hydrodynamic model to generate predicted water surface elevations corresponding to the range of discharge measurements that occurred during the previous month, which we then used to estimate percent of stolon reach inundation and total time of stolon reach

inundation. We predicted daily stolon reach area growth rates, daily areal total patch growth rates in the active channel, and the maximum distance of stolon expansion would be negatively related to the total time >75% of the stolon reach was inundated by water due to inhibition of *Phragmites* expansion into the river channel by flowing water.

5. †*Average proportion of stolon reach inundated by water over previous month*. The average proportion of the stolon reach boundary that was inundated by water between consecutive patch area measurements as predicted by the 2-D model. We predicted daily stolon reach growth rates and maximum distance of stolon expansion would be negatively related to the average proportion of the stolon reach inundated due to inhibition of *Phragmites* stolon expansion into the river channel by flowing water.

6. †*Average maximum daily shear stress at stolon edge.* The maximum daily shear stress due to flow along the edge of the stolon boundary averaged over the period between consecutive patch measurements. We used the 2-D hydrodynamic model to generate predicted shear stress values where the stolon boundary edge intersects the edge of water at various flow conditions experienced during the month and estimate the maximum value of shear stress for each day. We averaged the maximum value of shear stress for each day over the period between consecutive patch measurements to derive an average shear stress value for each patch for each month. We predicted daily stolon reach area growth rates, daily areal total patch growth rates in the active channel, and the maximum distance of stolon expansion would be negatively correlated with average maximum daily shear stress because more shear stress on stolons would inhibit stolon expansion into the channel and restrict their growth to along the bankline.

7. *Average daily water surface elevation*. Defined above. We predicted daily stolon reach area growth rates, daily areal total patch growth rates in the active channel, and the maximum distance of stolon expansion would be negatively related to the average daily water surface elevation because higher water surface elevations would be indicative of greater river discharge, which would inhibit patch expansion into the channel.

8. *Monthly minimum water surface elevation*. Defined above. We made similar hypotheses about our response variables and monthly minimum water surface elevation as in (7).

9. *Monthly maximum water surface elevation*. Defined above. We made similar hypotheses about our response variables and monthly maximum water surface elevation as in (7).

iv. <u>Herbicide Treatments</u>

We defined six covariates describing herbicide treatments on *Phragmites* patches. Covariates that we specifically defined to evaluate our management hypothesis regarding herbicide are denoted with an asterisk (*).

*1. *Proportion of patch sprayed with herbicide in June 2023.* Defined above. We hypothesized daily areal stolon growth rates and daily areal total patch growth rates in the active channel during July, August, and September would be negatively related to the proportion of the patch sprayed in June. Likewise, we predicted maximum distance of stolon expansion would be negatively related to the proportion of patch sprayed.

*2. *Proportion of patch sprayed with herbicide in September 2023.* Defined above. We hypothesized daily areal stolon growth rates, daily areal total patch growth rates in the active channel, and maximum distance of stolon expansion between September and October would be negatively related to the proportion of the patch sprayed in September.

*3. *June 2023 spray.* Defined above. We expected daily areal stolon growth rates and daily areal total patch growth rates in the active channel during July, August, and September 2023 would be lower in patches sprayed during the June treatment.

*4. *September 2023 spray.* Defined above. We expected daily areal stolon growth rates and daily areal total patch growth rates in the active channel between September and October would be lower in patches sprayed during the September 2023 treatment.

*5. *June 2022 spray*. Defined above. We predicted daily areal stolon growth rates, daily areal total patch growth rates in the active channel, and maximum distance of stolon expansion in 2023 would be lower in patches sprayed during June 2022.

*6. *September 2022 spray*. Defined above. We predicted daily areal stolon growth rates, daily areal total patch growth rates in the active channel, and maximum distance of stolon expansion in 2023 would be lower in patches sprayed during September 2022.

v. <u>Statistical Variables</u>

We defined three covariates as variables to account for the statistical design of our study.

1. *Patch Number.* Defined above.
2. *Month.* Defined above.
3. *Study area.* Defined above.

c. Modeling Approach

We used the same stepwise approach and model selection techniques described in III.A.c for our analyses of stolon reach area growth rates and maximum distance of stolon expansion into the river channel. For each response variable, we used mixed-effects regression techniques (Pinheiro and Bates 2000, Zuur et al. 2009) in R (R Core Team 2022, Pinheiro et al. 2023) to fit models with *Patch Number* as a random effect to account for repeated measurements in the same patch over time. We also included *Month* nested within *Patch Number* to account for temporal correlation in measurements between and across months. For each analysis, we separately ranked and selected the best-approximating models based on models with ΔAICc < 2 (Burnham and Anderson 2002).

We conducted exploratory analyses determine if nonlinear relationships were present between the response variable and continuous covariates using non-linear mixed models or GAMM (Zuur et al. 2009) to assess whether inclusion of nonlinear covariate terms improved model fit.

C. Factors Related to Changes in Length of Individual Stolons

We used data from length measurements of individually marked stolons to examine changes in stolon lengths over time. We used measurements from stolons marked in May, June, and/or July, and found and measured in at least one subsequent month of surveys during June through October. We also used data from stolon length measurements for which the stolon was initially marked and measured, but never relocated for subsequent measurements such that we had one length measurement of the stolon for the entire growing season.

a. Response Variable

We defined a response variable as the individual stolon length, $length_{p,i,t}$, in ft, where *p* denoted the *Phragmites* patch identifying number; *i* denoted the number of the stolon marked in the patch (i.e., 1, 2, 3, …8, 9, 10); and *t* denoted the month of the measurement (i.e., 1 (May), 2 (June), …, 5 (September), 6 (October)).

b. Covariates and Hypotheses

We used many of the same covariates for our individual stolon length analysis as we did for our daily stolon areal growth rate analysis as defined in section III.B.b (Table 7). We did not use several covariates from III.B.b because we were interested in factors related to individual stolon lengths and growth, and not expansion into the river channel. Some of our hypotheses regarding covariate relationships with individual stolon lengths were also different than our predictions for daily stolon areal growth rates and maximum distance of expansion into the channel (Table 7). In particular, we expected increased duration and extent of stolon inundation with water would promote individual stolon growth because of the presence of water. Our field observations noted that stolons continued growing rapidly when inundated in flows with higher discharges. However, instead of growing and expanding into the river channel, the stolons grew along and parallel to the bankline. We also defined two new temporal covariates to be used in the analysis that are listed below.

1. *Day*. Day of the survey season with May 1 equal to *day* = 1 and October 31 equal to *day* = 184. We expected individual stolon lengths to be positively related to *day* with lengths increasing the fastest during the first 90 days of the survey season when *Phragmites* resources were devoted to horizontal and vertical growth and expansion. We expected individual stolon lengths to continue increasing during the final 90 days of the survey season, but at a lesser rate than during the first 90 days because *Phragmites* resources switch to flowering and seed production, and vertical growth begins from rooted stolons.

2. *Week*. Week of the survey season with May 1–7 equal to *week* = 1 and October 23–29 equal to *week* = 26. We expected individual stolon lengths to be positively related to *week* with lengths increasing the fastest during the first 13 weeks of the survey season due to the same rationale as described above for the *day* covariate.

c. Modeling Approach

We used the same stepwise approach and model selection techniques described in III.A.c for our individual stolon length analysis. We used mixed-effects regression techniques (Pinheiro and Bates 2000, Zuur et al. 2009) in R (R Core Team 2022, Pinheiro et al. 2023) to fit models with *p,i* as a random effect to account for repeated measurements of the same stolon in the same patch over time. We also included *t* nested within *p,i* to account for temporal correlation in measurements between and across months. We ranked and selected the best-approximating models based on models with ΔAICc < 2 (Burnham and Anderson 2002).

We conducted exploratory analyses determine if nonlinear relationships were present between the response variable and continuous covariates using non-linear mixed models or GAMM (Zuur et al. 2009) to assess whether inclusion of nonlinear covariate terms improved model fit.

D. Comparisons Between Empirical and Modeled Estimates of *Phragmites* Inundation

We examined the relationship between empirically collected measurements of *Phragmites* patch inundation using data from 2023 to those predicted from the 2-D hydrodynamic flow model. Although empirical data may provide more accurate estimates of inundation at the time and day of the measurement, the data are time consuming to collect across 100 bankline patches and may only be obtained once or twice a month. In contrast, model-derived estimates can give daily estimates of water surface elevations, velocity, and shear stress, and may potentially have more utility in understanding water-*Phragmites* patch relationships in a multiple regression modeling framework. Therefore, understanding the utility and limitations of empirical data relative to model-based predictors was of paramount importance before continuing extensive empirical data collection in the field.

We used ArcGIS to calculate the proportion of each *Phragmites* patch that was inundated with water on the day and at the time of sampling using our monthly empirical RTK measurements of total patch boundary (i.e., stolon reach and *Phragmites* vertical growth) and edge of water. Overall, we had six empirical estimates of the proportion of patch inundation for each patch on the day and at the time of sampling from May through October 2023. We used the date and time of the patch's edge of water measurements to determine Platte River discharge (cfs) to the nearest 15 min at the U.S. Geological Survey stage gage closest to the study area. We used data from the: Overton, NE gage (USGS 2023a) combined with discharge data from the Johnson Hydropower Return for our Plum Creek study area; Kearney, NE gage (USGS 2023b) for our Fort Kearney study area; and Grand Island, NE gage (USGS 2023c) for our Chapman study area.

We used this Platte River discharge measurement for the date and time of patch sampling to parameterize our 2-D hydrodynamic flow model to estimate the WSE at each sampled patch at the corresponding discharge to the nearest 500 cfs. We used ArcGIS to calculate the proportion of each *Phragmites* patch that was inundated with water using the intersection between our monthly empirical RTK measurements of total patch boundary and the WSE polygon at the corresponding discharge. Overall, we had six modeled estimates of the proportion of patch inundation for each patch on the day and at the time of sampling from May through October 2023.

We compared empirical and modeled estimates of the proportion of the *Phragmites* patch inundated with water for each patch from May through October 2023. We used generalized linear mixed-effects models (Zuur et al. 2009) with a binomial distribution with the empirical estimate of the proportion of patch inundation as the response variable and the modeled estimate of the proportion of patch inundation as the independent variable. We included *Patch Number* as a random effect to account for repeated measurements in the same patch over time, and *Month* nested within *Patch Number* to account for temporal correlation in measurements between and across months. We estimated the regression coefficient and its standard error to determine the relationship between modeled and empirical proportion of inundation estimates. We also calculated pseudo-R^2 values for the mixed effects model, which is represented by the conditional and marginal coefficients of determination (Zuur et al. 2009) using package *MuMIn* in R (R Core Team 2022, Bartoń 2023). The marginal coefficient of determination represents the variance explained by fixed effects in the model, whereas the conditional coefficient of determination provides a measure of the variance explained by the entire model consisting of both fixed and random effects.

E. Factors Related to Total Patch Area Changes During 2022 and 2023

Data collected during 2022 using the Trimble TSC3 controller and RTK included the boundary of the entire *Phragmites* patch with no separate delineations for the stolon reach boundary and *Phragmites* patch boundary consisting of vertical growth. Additionally, no bankline or edge of water measurements were taken with the RTK, and no lengths of individual stolons were measured during 2022. Therefore, we could not conduct the analyses described in III.A, III.B, and III.C using data from 2022 and 2023 combined. We used a modified version of the analyses described in III.A to examine factors related to growth rates of total *Phragmites* patch areas during 2022 and 2023, which are described below.

a. Response Variables

For 2023 data, we used our estimates of total patch area that were calculated as described in III.A. For 2022, we used the entire delineated patch boundary to calculate the total patch area in ArcGIS for each patch for each month. We defined a response variable for each patch, *p*, as the daily areal growth rate ($r_{p,t,y}$; ft^2/day) for year *y* (2022; 2023). We calculated the daily areal growth rate by subtracting the total patch area for month *t* from the total patch area for month *t*+1 and dividing by the number of days between consecutive patch measurements. Therefore, for each patch measured during May through October on a monthly basis, we calculated five areal growth rates. Patches surveyed in both 2022 and 2023 had at most a total of 10 areal growth rates whereas patches surveyed in only 2022 or only 2023 had at most five growth rates.

We defined a second response variable as the growing season areal patch growth rate ($g_{p,y}$; ft^2/day) for each patch for each year. We calculated $g_{p,y}$ for each year by subtracting the total patch area delineated during May surveys from the total patch area determined during October surveys and dividing by the number of days between May and October patch measurements. Patches surveyed in both 2022 and 2023 had two growing season areal growth rates whereas patches surveyed in only 2022 or 2023 had one growth rate.

b. Covariates and Hypotheses

We used many of the same covariates for our analyses of combined 2022 and 2023 *Phragmites* daily areal growth rates as we used for our analyses using only 2023 data (see section III.A.b; Table 8). Because we did not collect empirical edge of water measurements at patches or deploy stage gages during 2022, we used the nearest USGS gage to provide an index of duration of flow

≥1500 cfs and average minimum and maximum daily river discharge when combining data from both 2022 and 2023 (Table 8). In addition, we defined *year* as a categorical variable denoting the year the patch measurements were taken (2022; 2023). We expected areal growth rates to be higher in 2023 compared to 2022 due to above average precipitation during summer 2023 and drought conditions during 2022.

We defined suites of new covariates for our analyses of growing season areal patch growth rates to account for patch attribute, water, and flow conditions across the entire May through October growing season. Hypotheses for the comparable monthly versions of previously defined covariates are provided in section III.A.b.

i. *Phragmites* Patch Attributes

1. *Maximum growing season height.* The maximum height of a vertical *Phragmites* stem in the patch (ft) across the entire growing season.

2. *Maximum growing season stem density.* Categorical variable (low; medium; high) denoting the maximum recorded stem density in the patch during the entire growing season.

3. *Distance to river during germination suppression flow release*. Defined in section III.A.b.i.

4. *Aspect*. Defined in section III.A.b.i.

ii. Empirical Water and Flow Metrics

1. *Total accumulated time of river discharge ≥1500 cfs across the entire growing season*. The total time between May 1–October 31 that river discharge at the USGS gage closest to the *Phragmites* patch was ≥1500 cfs.

2. *Maximum proportion of patch area in river channel*. The maximum proportion of the total patch area that was contained in the active river channel based on the monthly patch delineations from 2022 and 2023, and bankline measurements from 2023.

3. *Maximum proportion of patch perimeter in contact with river channel along bankline*. The maximum proportion of the total patch perimeter that was contained in the active river channel based on the monthly patch delineations from 2022 and 2023, and bankline measurements from 2023.

4. *Average minimum daily river discharge across entire growing season*. The average of daily minimum river discharge measurements May 1–October 31 at the USGS gage closest to the *Phragmites* patch.

5. *Average maximum daily river discharge across entire growing season*. The average of daily maximum river discharge measurements May 1–October 31 at the USGS gage closest to the *Phragmites* patch.

6. *Total accumulated precipitation during growing season*. The sum of monthly precipitation measurements between May 1–October 31 as recorded at the climate station

closest to each of the three study areas (National Weather Service–National Oceanic and Atmospheric Administration 2023).

iii. Modeled Water and Flow Metrics

1. *Proportion of June patch boundary predicted to be inundated by water at 1500 cfs*. Defined in section III.A.b.iii.

2. *Average proportion of patch inundated by water over growing season.* The average proportion of the entire patch boundary that was inundated by water based on daily predictions from the 2-D hydrodynamic model and monthly patch boundaries.

3. *Total accumulated time >25% of patch was inundated across growing season*. The total time between May 1–October 31 that >25% of the patch was predicted to be inundated by water based on daily predictions from the 2-D hydrodynamic model and monthly patch boundaries.

4. *Total accumulated time >25% of patch was inundated across growing season*. The total time between May 1–October 31 that >50% of the patch was predicted to be inundated by water based on daily predictions from the 2-D flow model and monthly patch boundaries.

5. *Total accumulated time >25% of patch was inundated across growing season*. The total time between May 1–October 31 that >75% of the patch was predicted to be inundated by water based on daily predictions from the 2-D hydrodynamic model and monthly patch boundaries.

6. *Difference between average patch elevation during June and predicted water surface elevation at 1500 cfs*. Defined in section III.A.b.iii.

7. *Average maximum daily shear stress at patch edge during growing season*. The average of the maximum daily shear stress at the patch edge across the May 1–October 31 growing season as predicted by the 2-D flow model.

8. *Mean daily average water surface elevation during growing season*. The mean daily average water surface elevation during May 1–October 31 as predicted by the 2-D flow model at the patch edge. To be used as an interaction term with the *maximum proportion of patch area in river channel* or *maximum proportion of patch perimeter in contact with river channel along bankline* covariates to distinguish inland from bankline patches.

9. *Mean daily minimum water surface elevation during growing season*. The mean daily minimum water surface elevation during May 1–October 31 as predicted by the 2-D flow model at the patch edge. To be used as an interaction term with the *maximum proportion of patch area in river channel* or *maximum proportion of patch perimeter in contact with river channel along bankline* covariates to distinguish inland from bankline patches.

10. *Mean daily maximum water surface elevation during growing season*. The mean daily maximum water surface elevation during May 1–October 31 as predicted by the 2-D flow model at the patch edge. To be used as an interaction term with the *maximum proportion*

of patch area in river channel or *maximum proportion of patch perimeter in contact with river channel along bankline* covariates to distinguish inland from bankline patches.

11. *Standard deviation of water surface elevation during growing season*. The standard deviation of daily water surface elevation during May 1–October 31 as predicted by the 2-D flow model at the patch edge. To be used as an interaction term with the *maximum proportion of patch area in river channel* or *maximum proportion of patch perimeter in contact with river channel along bankline* covariates to distinguish inland from bankline patches.

12. *Coefficient of variation of water surface elevation during growing season*. The coefficient of variation of daily water surface elevation during May 1–October 31 as predicted by the 2-D flow model at the patch edge. To be used as an interaction term with the *maximum proportion of patch area in river channel* or *maximum proportion of patch perimeter in contact with river channel along bankline* covariates to distinguish inland from bankline patches.

iv. Herbicide Treatments

1. *June 2023 spray.* Defined in section III.A.b.iv.
2. *September 2023 spray.* Defined in section III.A.b.iv.
3. *June 2022 spray*. Defined in section III.A.b.iv.
4. *September 2022 spray*. Defined in section III.A.b.iv.

v. Temporal Variables

1. *Year.* Defined above.

vi. Statistical Variables

1. *Patch number.* Defined in section III.A.b.v.
2. *Study area.* Defined in section III.A.b.v.

c. Modeling Approach

For our analyses of daily areal total patch growth rates, we used a similar stepwise approach and model selection technique as described in section III.A.c. However, because we did not have empirical data on edge of water and patch inundation from 2022, we were not able to include covariates that used these data in our model step. Likewise, we were not able to directly substitute modeled water and flow covariates for their empirically derived counterparts. We used mixed-effects regression techniques (Pinheiro and Bates 2000, Zuur et al. 2009) in R (R Core Team 2022, Pinheiro et al. 2023) to fit models with *Patch Number* as a random effect to account for repeated measurements in the same patch over time. We also included *Month* nested within *Patch Number* to account for temporal correlation in measurements between and across months. We ranked and selected the best-approximating models based on models with ΔAICc < 2 (Burnham and Anderson 2002) for the final steps of the analyses.

We also used a stepwise approach and model selection technique similar to that described above and in section III.A.c for our analyses of growing season areal patch growth rates. Because we did not have repeated measurements of the same patch across months, we used mixed-effects regression techniques (Pinheiro and Bates 2000, Zuur et al. 2009) in R (R Core Team 2022, Pinheiro et al. 2023) to fit models with only *Patch Number* as a random effect to account for repeated measurements in the same patch over the two years. We ranked and selected the best-approximating models based on models with ΔAICc < 2 (Burnham and Anderson 2002) for the final steps of the analyses.

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V. TABLES

Table 1. Summary of the sample of bankline and inland *Phragmites* patches surveyed by study area during May through October 2023 along the central Platte River, Nebraska.

Study area	No. of bankline	No. of inland	Total no. patches
Chapman	30	15	45
Fort Kearney	39	20	59
Plum Creek	31	21	52
Total	100	56	156

Table 2. Sample of a data sheet used for data collection on inland *Phragmites* patches during May through October 2023 along the central Platte River, Nebraska.

INLAND PATCHES **SITE:** ____________ **OBSERVER(S):** ____________ **DATE:** ____________

Patch ID	Patch bndry map? (p)	Max phrag height (ft, in)	Phrag stem density	Phrag life stage	Phrag condition	Stolon/ rhizome present?	Other plant cover	Spray zone map? (z)	Photo times/IDs	Notes / additional photos

Phrag stem density: L (≤33%); M (33-66%); H (>66%)
Phrag life stage: V (vegetative); F (flowers); S (seeds)
Phrag condition: A (alive/green); P (partial dieback); D (brown/dormant/dead)
Other plant cover: N (none); L (≤33%); M (33-66%); H (>66%)

Table 3. Sample of a data sheet used for data collection on bankline *Phragmites* patches during May through October 2023 along the central Platte River, Nebraska.

BANKLINE PATCHES

SITE: ______________ **OBSERVER(S):** ______________ **DATE:** ________

Patch ID	Patch bndry map? (p)	Max phrag height (ft, in)	Phrag stem density	Phrag life stage	Phrag condition	Stolon / rhizome present?	Stolon reach map? (s)	Other plant cover	Bank line map? (b)	Edge of water map? (eow)	Time of EOW msmt	% veg in water	% stolon in water	Spray zone map? (z)	Photo times or IDs	Notes / additional photos

Phrag stem density: L (≤33%); M (33-66%); H (>66%)

Phrag condition: A (alive/green); P (partial dieback); D (brown/dormant/dead)

% veg in water: 0 (0%); 1 (1-25%); 2 (26-50%); 3 (51-75%); 4 (76-99%); 5 (100%)

Phrag life stage: V (vegetative); F (flowers); S (seeds)

Other plant cover: N (none); L (≤33%); M (33-66%); H (>66%)

% stolon in water: 0 (0%); 1 (1-25%); 2 (26-50%); 3 (51-75%); 4 (76-99%); 5 (100%)

Table 4. Definitions of data entry fields for data collection on inland *Phragmites* patches during May through October 2023 along the central Platte River, Nebraska. Data entry fields correspond to the sample datasheet provided in Table 2.

Datasheet entry field	Description
Patch ID	Patch identification number corresponding to the patch number in ArcGIS field maps and hard copy maps
Patch bndry map? (p)	**Y/N:** was the patch boundary mapped? Code patch boundary in RTK as "p"
Max phrag height (ft)	Measurement of the tallest *Phragmites* stem in the patch to the nearest one-half foot (in feet, inches)
Phrag stem density	Stem density of *Phragmites* in the patch categorized as: **L (≤33%); M (33-66%); H (>66%)**
Phrag life stage	Life stage of *Phragmites* categorized as: **V (vegetative); F (flowers); S (seeds)**
Phrag condition	Above ground *Phragmites* condition categorized as: **A (alive/green); P (partial dieback); D (brown/dormant/dead)**
Stolon / rhizome present?	**Y/N:** are stolons or visible rhizomes present?
Other plant cover	Average cover of non-*Phragmites* plant species in patch categorized as: **N (none); L (≤33%); M (33-66%); H (>66%)**
Spray zone map? (z)	**Y/N:** was the spray boundary mapped if the patch was previously sprayed in spring or fall? Code spray zone in RTK as "z"
Photo times or ID	Record the time or camera IDs for any photos of the patch that are taken
Notes / additional photos	Description and IDs/times of additional photos; make notes on back of sheet if more space needed

Table 5. Definitions of data entry fields for data collection on bankline *Phragmites* patches during May through October 2023 along the central Platte River, Nebraska. Data entry fields correspond to the sample datasheet provided in Table 3.

Datasheet entry field	Description
Patch ID	Patch identification number corresponding to the patch number in ArcGIS field maps and hard copy maps
Patch bndry map? (p)	**Y/N:** was the patch boundary mapped? Code patch boundary in RTK as "p"
Max phrag height (ft)	Measurement of the tallest *Phragmites* stem in the patch to the nearest one-half foot (in feet, inches)
Phrag stem density	Stem density of *Phragmites* in the patch categorized as: **L (≤33%); M (33-66%); H (>66%)**
Phrag life stage	Life stage of *Phragmites* categorized as: **V (vegetative); F (flowers); S (seeds)**
Phrag condition	Above ground *Phragmites* condition categorized as: **A (alive/green); P (partial dieback); D (brown/dormant/dead)**
Stolon / rhizome present?	**Y/N:** are stolons or visible rhizomes present?
Stolon reach map? (s)	**Y/N:** was the stolon reach boundary mapped? Code stolon boundary in RTK as "s"
Other plant cover	Average cover of non-*Phragmites* plant species in patch categorized as: **N (none); L (≤33%); M (33-66%); H (>66%)**
Bank line map? (b)	**Y/N:** if present, was the bank line boundary mapped? Code bankline in RTK as "b"
Edge of water map? (eow)	**Y/N:** was edge of the nearest water surface in the channel mapped? Code edge of water in RTK as "eow"
Time of EOW msmt	The time the edge of water mapping began
% veg in water	Estimated % of patch (vertical vegetative growth) covered by water: **0 (0%); 1 (1-25%); 2 (26-50%); 3 (51-75%); 4 (76-99%); 5 (100%)**
% stolon in water	Estimated % of stolons / emergent rhizomes covered by water: **0 (0%); 1 (1-25%); 2 (26-50%); 3 (51-75%); 4 (76-99%); 5 (100%)**
Spray zone map? (z)	**Y/N:** was the spray boundary mapped if that patch was previously sprayed? Code spray zone in RTK as "z"
Photo times or ID	Record the time(s) or camera IDs for any photos of the patch that are taken
Notes / additional photos	Description and IDs/times of additional photos; make notes on back of sheet if more space needed

Table 6. Sample of a data sheet used for data collection on stolon lengths during May through October 2023 along the central Platte River, Nebraska.

BANKLINE - STOLON LENGTH

SITE: ________________________ **OBSERVER(S):** ________________ **DATE:** _______

Patch ID	Stolon length 1 (ft, in)	Stolon length 2 (ft, in)	Stolon length 3 (ft, in)	Stolon length 4 (ft, in)	Stolon length 5 (ft, in)	Notes

Table 7. Covariates used in the analysis examining factors related to changes in the lengths of individual stolons from *Phragmites* patches surveyed during May through October 2023 along the central Platte River, Nebraska. For each covariate, the definition and hypothesized direction of correlation with the response variable are provided. If applicable, the section in which covariates were previously defined in the main text is provided.

Covariate	Definition	Hypothesis
	Phragmites Patch Attributes	
Total patch perimeter	Section III.B.b.i	$\beta > 0$
Stem density	Section III.B.b.i	$\beta > 0$
Aspect	Section III.B.b.i	$\beta > 0$ for *Aspect* = south; $\beta < 0$ for *Aspect* = north
	Empirical Water and Flow Metrics	
Average minimum daily river discharge	Section III.B.b.ii	$\beta > 0$
Average maximum daily river discharge	Section III.B.b.ii	$\beta > 0$
Total accumulated time >25% of stolon reach was inundated	Section III.B.b.ii	$\beta > 0$
Total accumulated time >50% of stolon reach was inundated	Section III.B.b.ii	$\beta > 0$
Total accumulated time >75% of stolon reach was inundated	Section III.B.b.ii	$\beta > 0$
Total accumulated monthly precipitation	Section III.B.b.ii	$\beta > 0$
Average proportion of stolon reach area inundated by water over previous month	Section III.B.b.ii	$\beta > 0$
	Modeled Water and Flow Metrics	
Total accumulated time >25% of stolon reach was inundated	Section III.B.b.iii	$\beta > 0$
Total accumulated time >50% of stolon reach was inundated	Section III.B.b.iii	$\beta > 0$
Total accumulated time >75% of stolon reach was inundated	Section III.B.b.iii	$\beta > 0$
Average proportion of stolon reach area inundated by water over previous month	Section III.B.b.iii	$\beta > 0$
Average daily water surface elevation	Section III.B.b.iii	$\beta > 0$
Monthly minimum water surface elevation	Section III.B.b.iii	$\beta > 0$
Monthly maximum water surface elevation	Section III.B.b.iii	$\beta > 0$
	Herbicide Treatments	
June spray	Section III.A.b.iv	$\beta < 0$
September spray	Section III.A.b.iv	$\beta < 0$
Sprayed in June 2022	Section III.A.b.iv	$\beta < 0$
Sprayed in September 2022	Section III.A.b.iv	$\beta < 0$

	Temporal Variables	
Day	Section III.C.b	$\beta > 0$
Week	Section III.C.b	$\beta > 0$
	Statistical Variables	
Patch number (p)	Section III.A.b.v	Random effect
Stolon number (i)	Unique identifying number for each stolon marked in the patch	Random effect
Month (t)	Section III.A.b.v	Random effect
Study area	Section III.A.b.v	Random effect

Table 8. Covariates used in the analysis examining factors related to daily areal growth rates of *Phragmites* patches during 2022 and 2023 along the central Platte River, Nebraska. For each covariate, the definition and hypothesized direction of correlation with the response variable are provided. If applicable, the section in which covariates were previously defined in the main text is provided.

Covariate	Definition	Hypothesis
	Phragmites Patch Attributes	
Total patch perimeter	Section III.A.b.i	$\beta > 0$
Maximum height	Section III.A.b.i	$\beta > 0$
Stem density	Section III.A.b.i	Patches with high and low stem density would have the highest and lowest growth rates, respectively
Life stage	Section III.A.b.i	Growth rates would be greatest during the vegetative life stage and lowest during the seed production stage
Proportion of stolon reach area	Section III.A.b.i	$\beta > 0$
Distance to river	Section III.A.b.i	$\beta < 0$
Aspect	Section III.A.b.i	$\beta > 0$ for *Aspect* = south; $\beta < 0$ for *Aspect* = north
	Empirical Water and Flow Metrics	
Total accumulated time of river discharge ≥1500 cfs	Section III.A.b.ii. We will not have empirical edge of water data from our patches for 2022 and will have to use data from the nearest gage as an index	$\beta < 0$
Proportion of patch area in river channel	Section III.A.b.ii	$\beta > 0$. Growth rates would be negatively correlated with a total accumulated time ≥1500 cfs*proportion of patch area in river channel interaction
Proportion of patch perimeter in contact with river channel along bankline	Section III.A.b.ii	$\beta > 0$. Growth rates would be negatively correlated with a total accumulated time ≥1500 cfs*proportion of patch perimeter in river channel interaction
Average minimum daily river discharge	Section III.A.b.ii	Growth rates would be negatively correlated with an average minimum daily discharge*proportion of patch area in river channel interaction

Average maximum daily river discharge	Section III.A.b.ii	Growth rates would be negatively correlated with an average maximum daily discharge*proportion of patch area in river channel interaction
Total accumulated monthly precipitation	Section III.A.b.ii	$\beta > 0$
	Modeled Water and Flow Metrics	
Proportion of patch predicted to be inundated by water at 1500 cfs.	Section III.A.b.iii	$\beta < 0$
Total accumulated time >25% of patch was inundated	Section III.A.b.iii	$\beta < 0$
Total accumulated time >50% of patch was inundated	Section III.A.b.iii	$\beta < 0$
Total accumulated time >75% of patch was inundated	Section III.A.b.iii	$\beta < 0$
Average proportion of patch inundated by water over previous month	Section III.A.b.iii	$\beta < 0$
Difference between average patch elevation and predicted water surface elevation at 1500 cfs	Section III.A.b.iii	To be used in interaction with *distance to river* covariate. We predicted daily growth rates would increase as distance to river increased and elevation difference decreased. We predicted daily growth rates would decrease as distance to river decreased and elevation difference decreased.
Average daily water surface elevation	Section III.A.b.iii	$\beta < 0$ for bankline patches $\beta > 0$ for inland patches
Monthly minimum water surface elevation	Section III.A.b.iii	$\beta < 0$ for bankline patches $\beta > 0$ for inland patches
Monthly maximum water surface elevation	Section III.A.b.iii	$\beta < 0$ for bankline patches $\beta > 0$ for inland patches
Average maximum daily shear stress at patch edge	Section III.A.b.iii	$\beta < 0$
	Herbicide Treatments	
June 2022 spray	Section III.A.b.iv	$\beta < 0$
September 2022 spray	Section III.A.b.iv	$\beta < 0$
June 2023 spray	Section III.A.b.iv	$\beta < 0$
September 2023 spray	Section III.A.b.iv	$\beta < 0$
	Temporal Variables	
Year	Categorical variable denoting the year	$\beta > 0$ for *year* = 2023

	(2022; 2023)	
	Statistical Variables	
Patch number (p)	Section III.A.b.v	Random effect
Year (y)	Categorical variable denoting the year (2022; 2023)	Random effect
Month (t)	Section III.A.b.v	Random effect
Study area	Section III.A.b.v	Random effect

VI. FIGURES

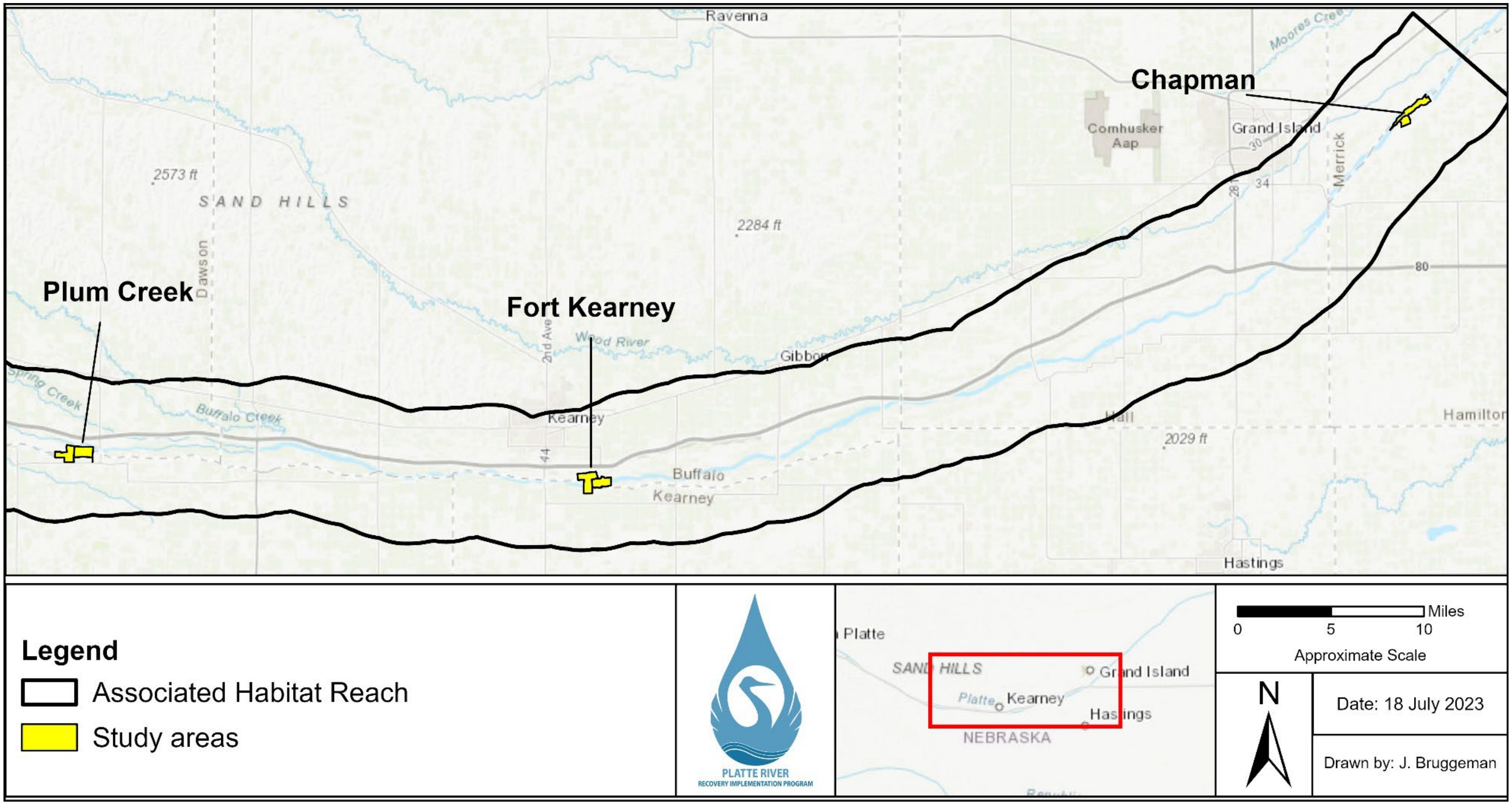

Figure 1. Locations of three study areas in the Associated Habitat Reach along the central Platte River, Nebraska in which *Phragmites* patches were surveyed during 2022 and 2023.

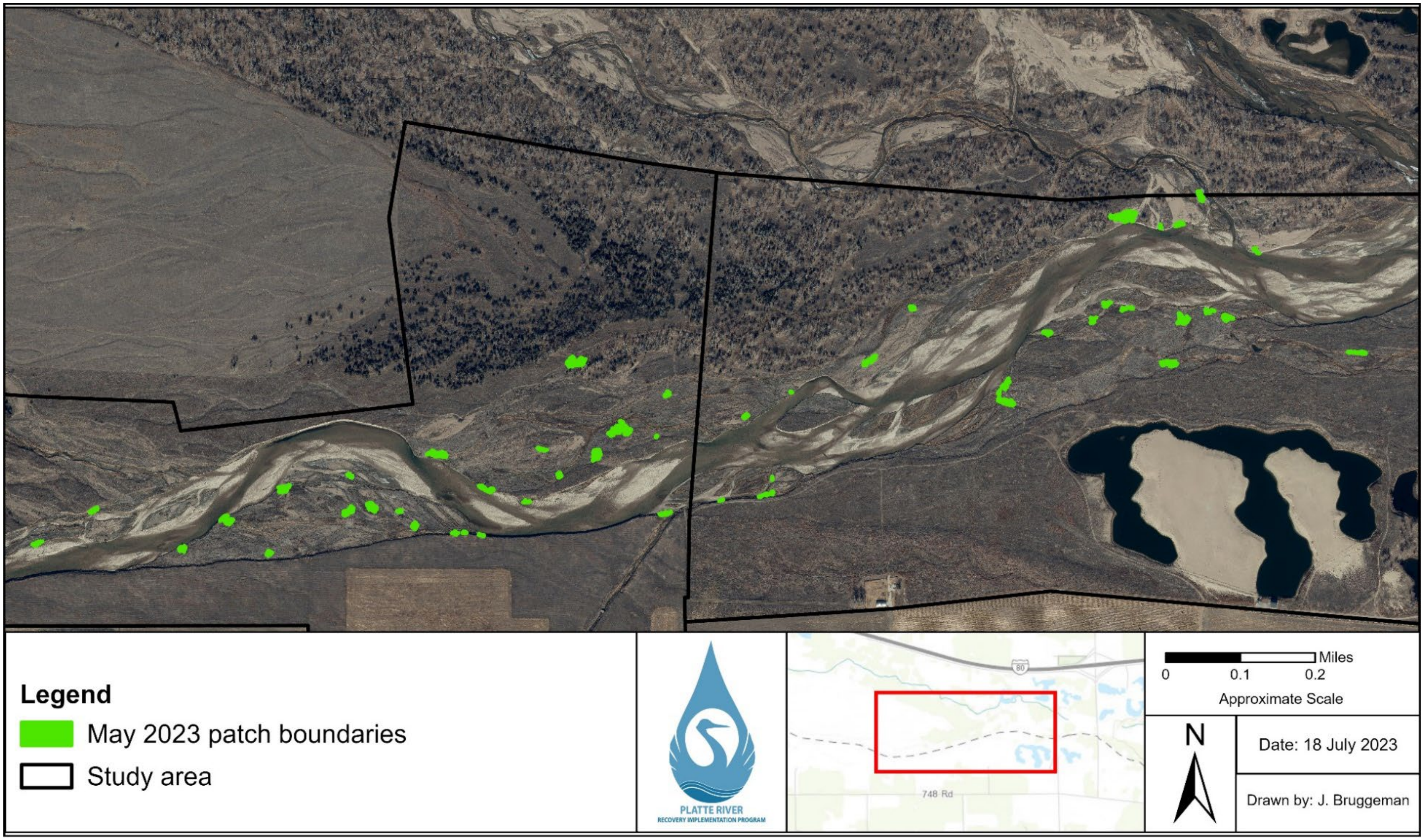

Figure 2. Distribution of *Phragmites* patches in the Plum Creek, Nebraska study area that were surveyed during May through October 2023. *Phragmites* patch boundaries delineated during May 2023 surveys are depicted. The Plum Creek study area consists of the Cook tract (located in the west polygon; non-herbicide zone) and Dyer tract (east polygon; herbicide spray zone).

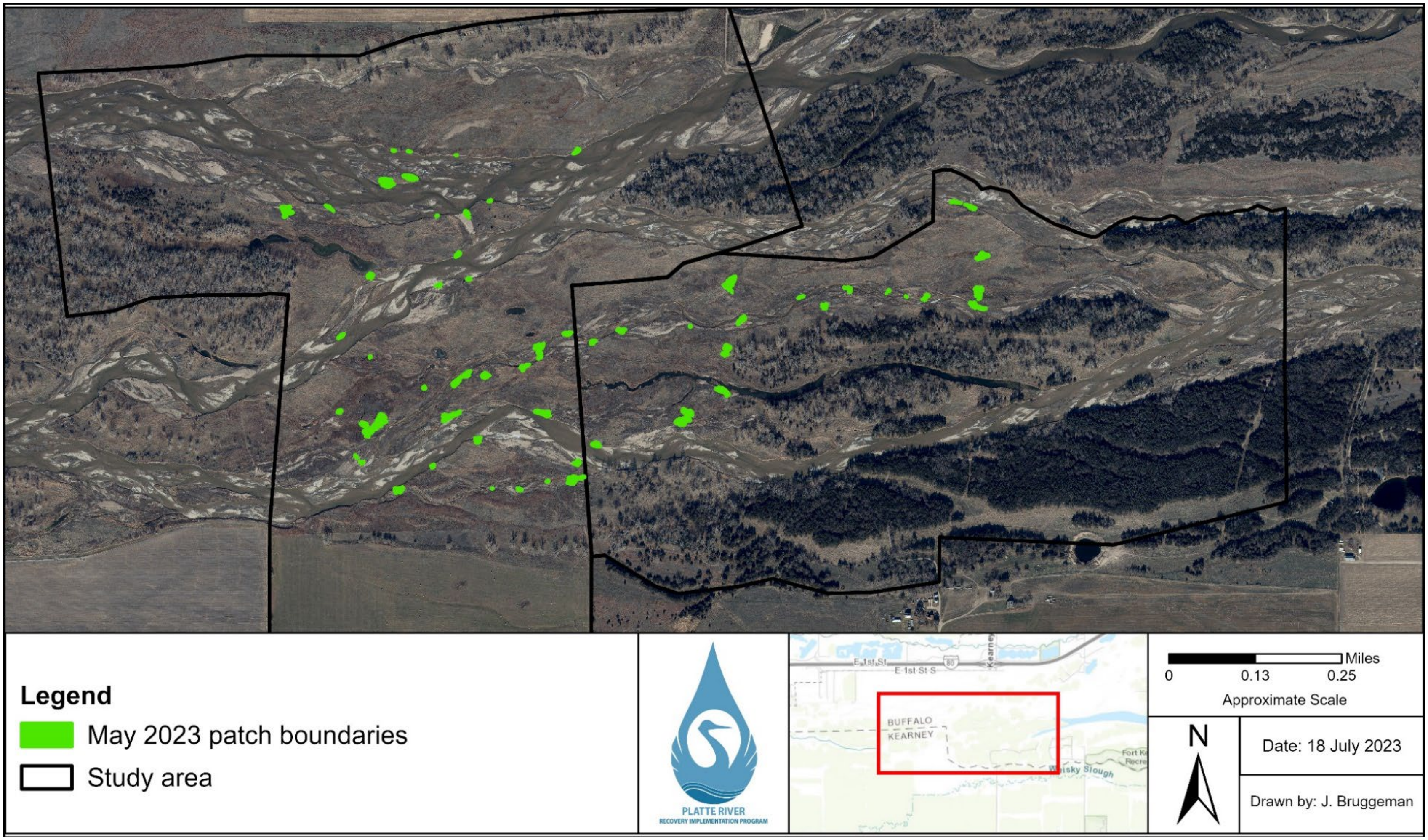

Figure 3. Distribution of *Phragmites* patches in the Fort Kearney, Nebraska study area that were surveyed during May through October 2023. *Phragmites* patch boundaries delineated during May 2023 surveys are depicted. The Fort Kearney study area consists of the Wyoming tract (west polygon; non-herbicide zone) and Sherrerd tract (east polygon; herbicide spray zone).

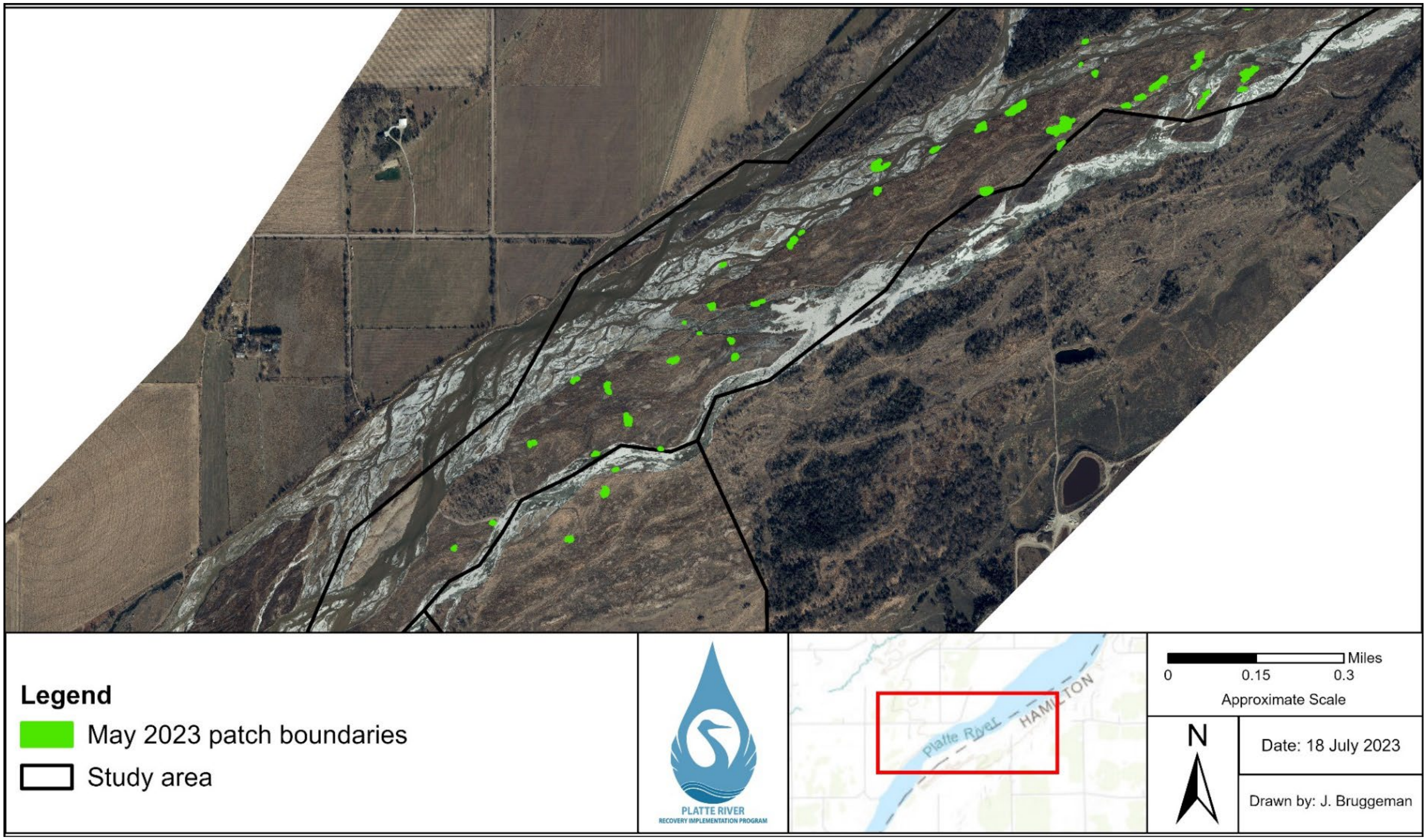

Figure 4. Distribution of *Phragmites* patches in the Chapman, Nebraska study area that were surveyed during May through October 2023. *Phragmites* patch boundaries delineated during May 2023 surveys are depicted. The Chapman study area consists of the Bergen tract (southwest polygon) and Robinson tract (north large polygon). The herbicide spray zone consisted of the western half of the entire study area and the non-herbicide zone consisted of the eastern half of the Robinson tract.

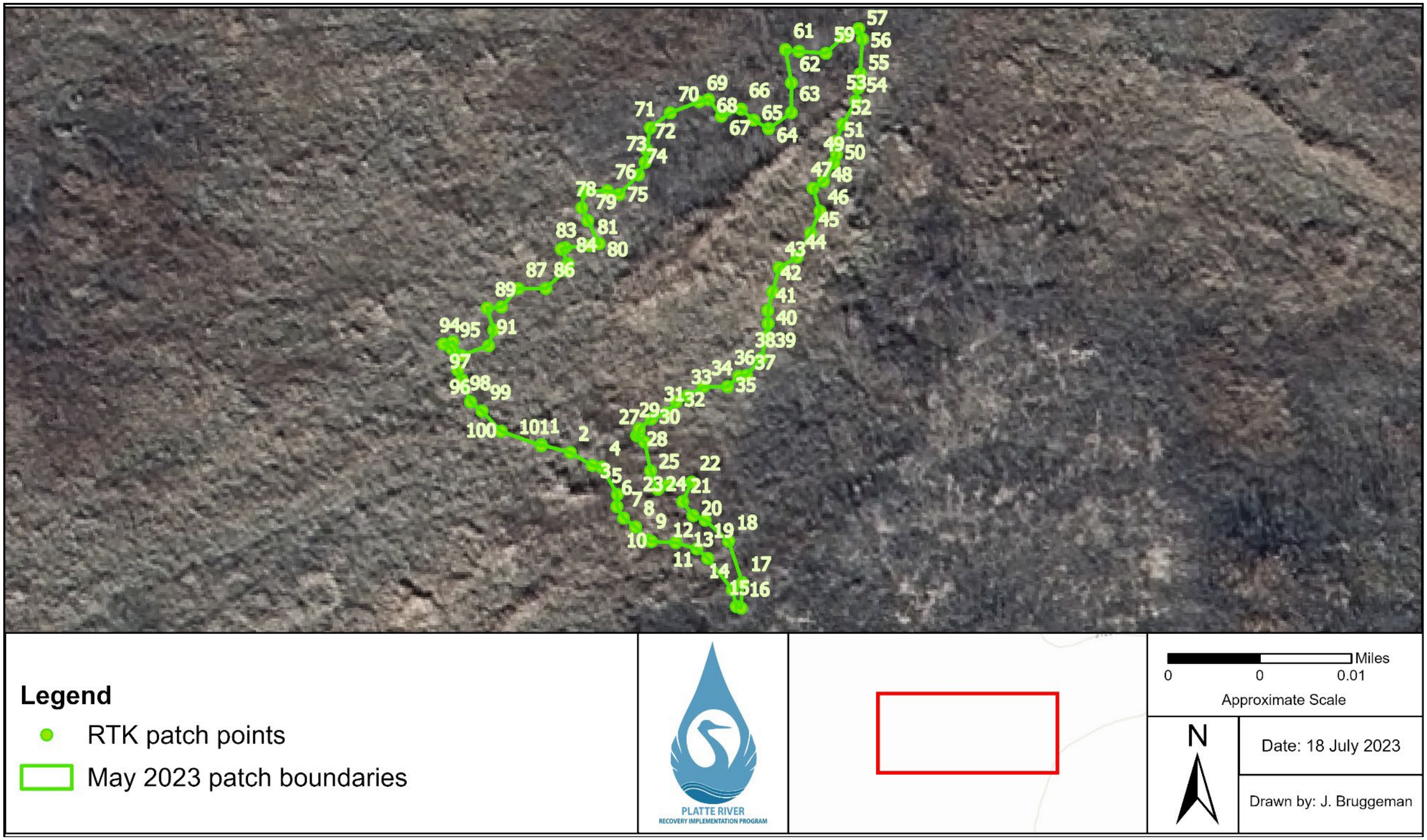

Figure 5. Example of a delineated boundary of an inland *Phragmites* patch that was surveyed during May 2023. The RTK points used to define the patch boundary are depicted along with the point number that ranged from 1 to 101.

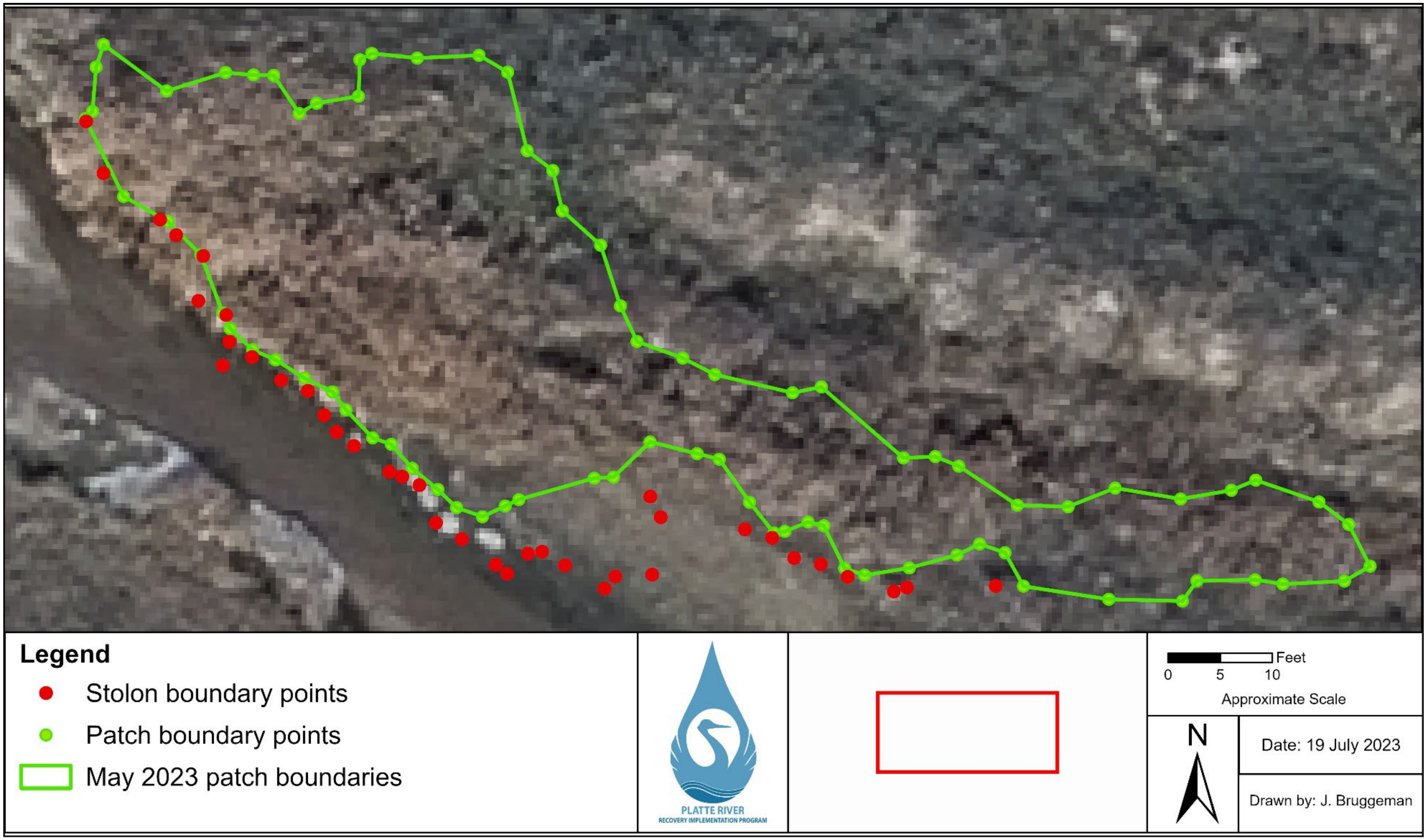

Figure 6. Example of delineated boundaries of a bankline *Phragmites* patch (green circles and line) and corresponding stolon reach (red circles) surveyed during May 2023. Circles depict individual RTK points taken to define the boundaries.

Figure 7. Example of delineated boundaries of a bankline *Phragmites* patch (green circles and line), stolon reach (red circles), and river channel bankline (light green circles) surveyed during May 2023. Circles depict RTK points taken to define the boundaries. Satellite imagery shown is from fall 2022 and does not depict water conditions during the time of the May survey.

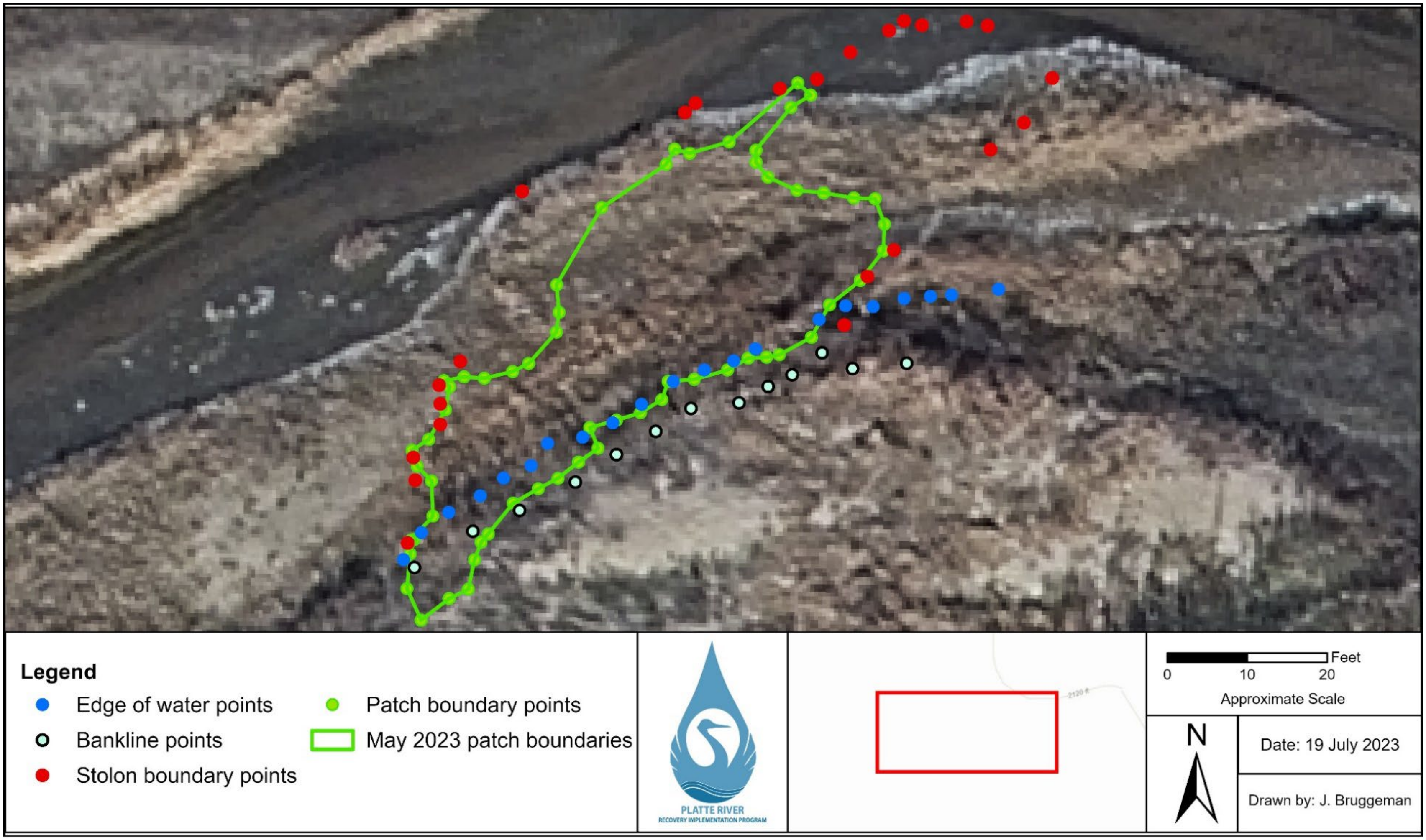

Figure 8. Example of delineated boundaries of a bankline *Phragmites* patch (green circles and line), stolon reach (red circles), river channel bankline (light green circles), and edge of water (blue circles) surveyed during May 2023. Circles depict RTK points. Satellite imagery shown is from fall 2022 and does not depict water conditions during the time of the May 2023 survey.

Figure 9. Photo of the bankline patch (in foreground) corresponding to the patch depicted in Figure 8. This photo was taken on the southeast corner of the patch and facing to the northwest.

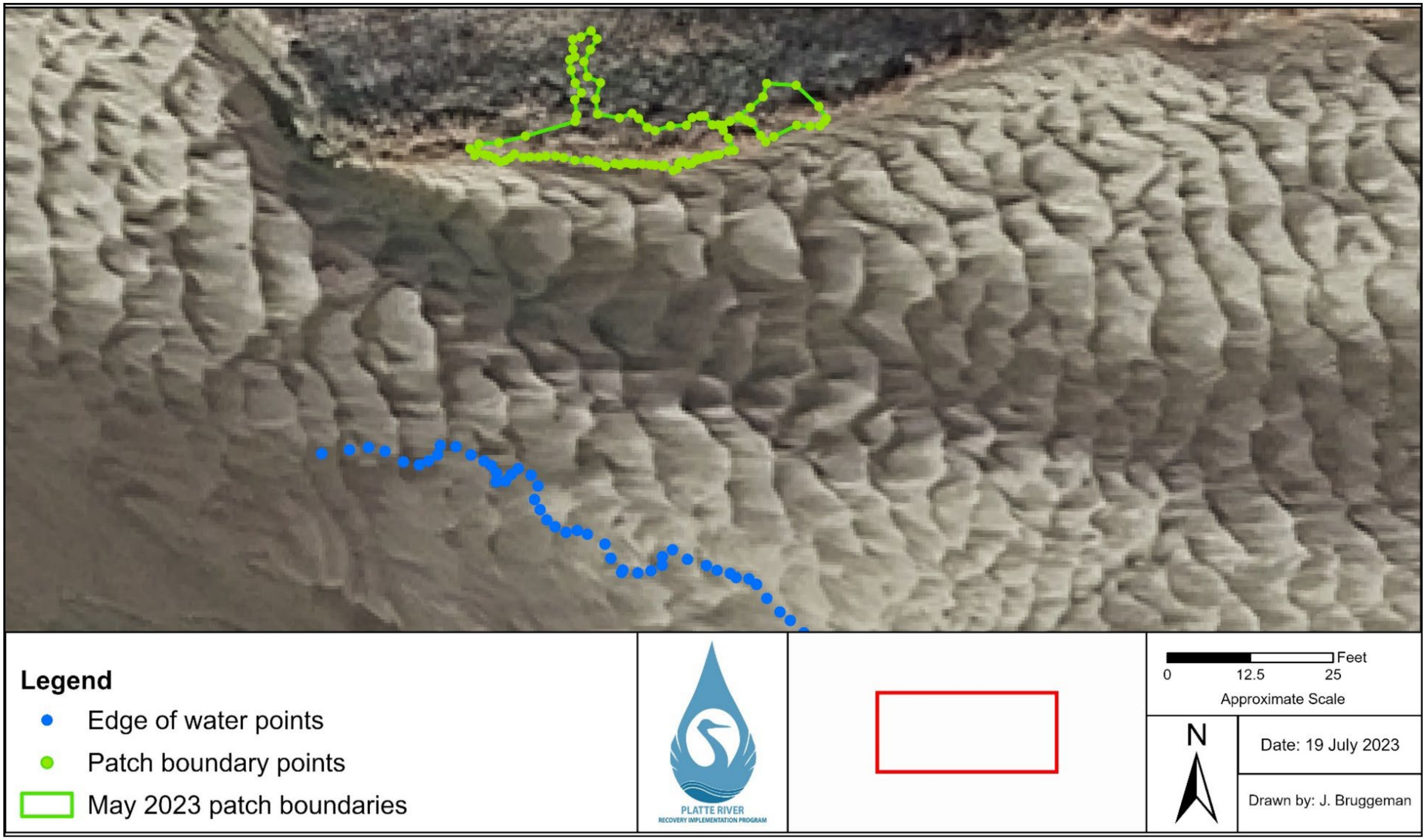

Figure 10. Example of delineated boundaries of a bankline *Phragmites* patch (green circles and line) and edge of water (blue circles) surveyed during May 2023. Circles depict RTK points. Satellite imagery shown is from fall 2022 and does not depict water conditions during the time of the May 2023 survey.

Figure 11. Photo of the bankline patch corresponding to the patch depicted in Figure 10.

Figure 12. Example of delineated boundaries of a bankline *Phragmites* patch (green circles and line) surveyed during June 2023 and corresponding water surface elevation measurement (blue circle). Circles depict RTK points. Satellite imagery shown is from fall 2022 and does not depict water conditions during the time of the May 2023 survey.

Figure 13. Photo of the bankline patch corresponding to the patch depicted in Figure 12 that was completely inundated by flowing water in the river channel.

Figure 14. Example of delineated boundaries of a bankline *Phragmites* patch (green circles and line), stolon reach (red circles), and two edges of water (blue circles) surveyed during May 2023. Circles depict RTK points. Satellite imagery shown is from fall 2022 and does not depict water conditions during the time of the May 2023 survey.

Figure 15. Photo of the bankline patch corresponding to the patch depicted in Figure 14.

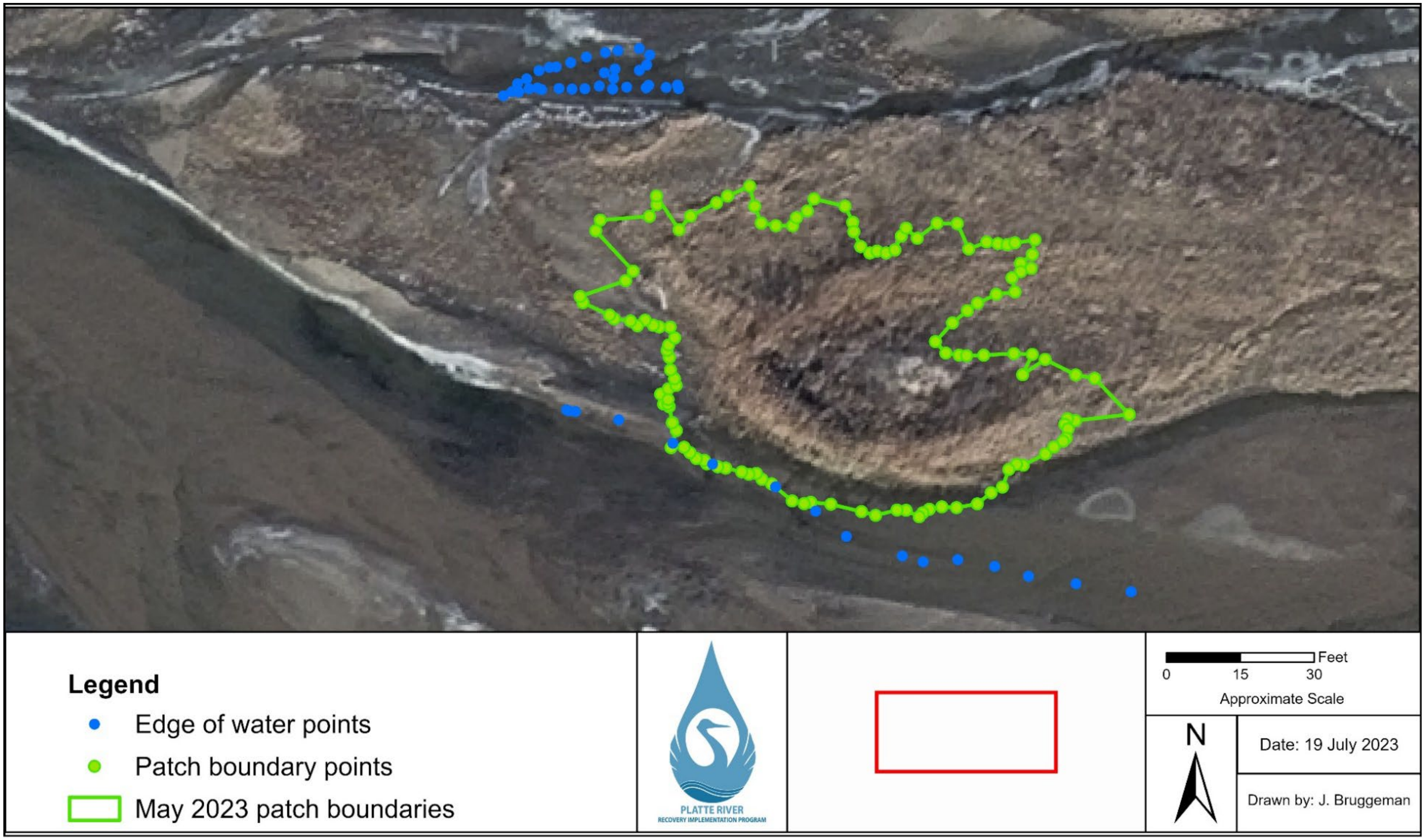

Figure 16. Example of delineated boundaries of an island bankline *Phragmites* patch (green circles and line) and two edges of water (blue circles) surveyed during May 2023. Circles depict RTK points. Satellite imagery shown is from fall 2022 and does not depict water conditions during the time of the May 2023 survey.

Figure 17. Photo of the island bankline patch corresponding to the patch depicted in Figure 16.

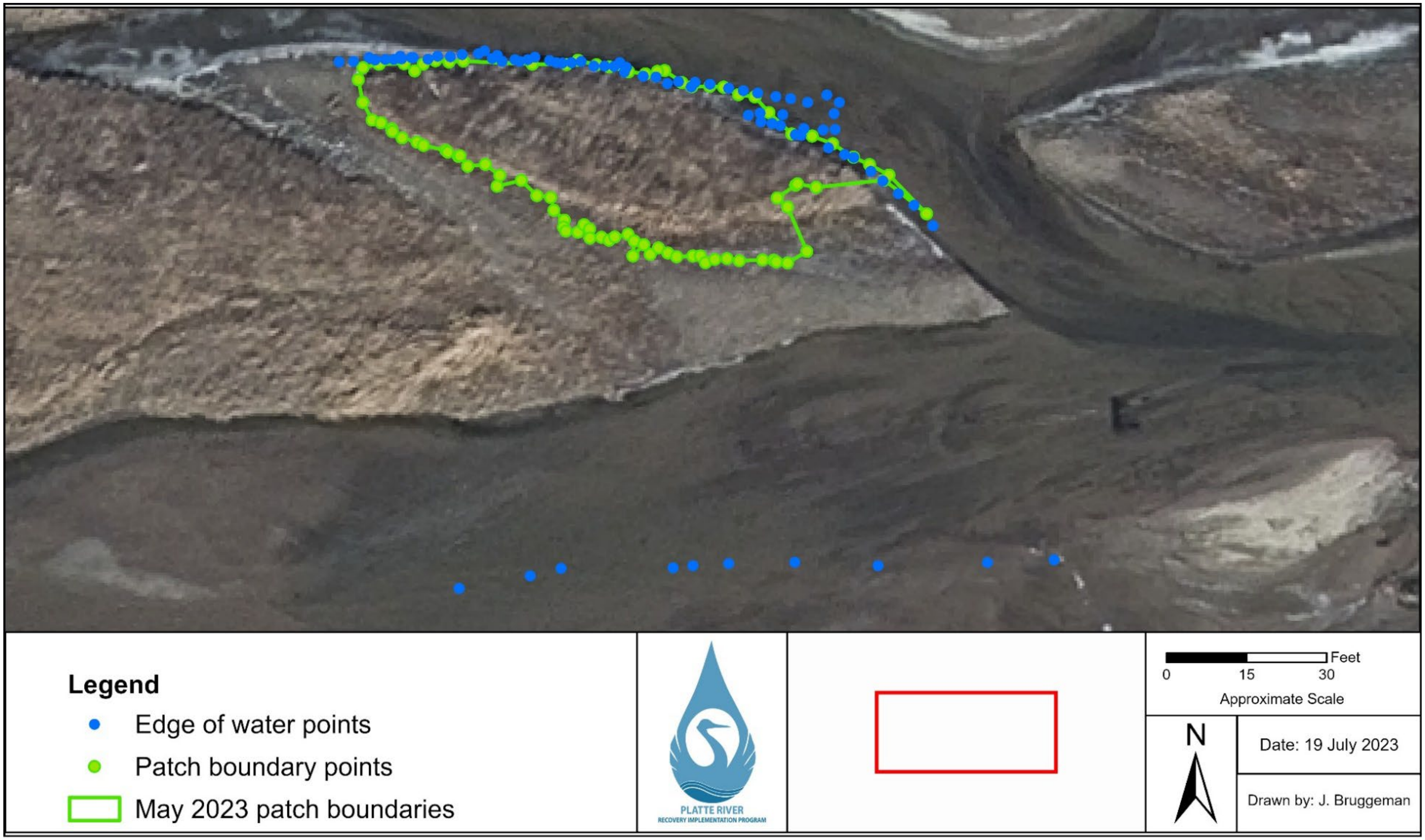

Figure 18. Example of delineated boundaries of an island bankline *Phragmites* patch (green circles and line) and two edges of water (blue circles) surveyed during May 2023. Circles depict RTK points. Satellite imagery shown is from fall 2022 and does not depict water conditions during the time of the May 2023 survey.

Figure 19. Photo of the island bankline patch corresponding to the patch depicted in Figure 18.

Figure 20. Example of a stolon that was flagged and measured as part of the study on changes in individual stolon length over time.

Figure 21. A stage gage assembly that was deployed in the Platte River at the Fort Kearney study area during May 2023.

VII. APPENDIX.

A. Description of Field Methodology Used During the 2022 Pilot Study

During the 2022 pilot study, we made RTK measurements to delineate the entire *Phragmites* patch boundary consisting of both the area of vertical shoot growth and the horizontal stolon reach. We did not conduct separate delineations to distinguish area of vertical shoot growth from horizontal stolon reach, and we did not define the edge of water relative to the patch or the bankline. Similar to 2023, we selected a start point for our patch delineation as one *Phragmites* stem located on the outer boundary of the patch. We placed the RTK receiver pole at the start point, leveled the pole, and hit "Enter" to record the first point location as "Patch.1." We then moved in a counterclockwise direction to the next *Phragmites* stem, or cluster of stems, on the outer boundary of the patch, placed the receiver pole at the point, leveled the pole, and hit "Enter" to record the second point location as "Patch.2." We continued this procedure in a counterclockwise direction until we had encircled the patch, fully delineated the outer patch boundary including the stolon reach (if present), and returned to the starting point. Maintaining a counterclockwise direction ensured that we kept the *Phragmites* patch on our left-hand side at all times when conducting the delineation.

During 2022 we recorded additional patch attribute data on a paper datasheet similar to what we recorded in 2023; however, we did not record the percent of patch and stolon reach inundation for bankline patches as we did in 2023 (Table A1). We estimated the height of the tallest green, living, and growing *Phragmites* stem to the nearest one-half foot. We used a visual assessment of *Phragmites* stem density and classified it as low (≤33% stem density); medium (33% to 66%); and high (>66%). We recorded the life stage of the *Phragmites* plants as vegetative (V); flowers (F); or seeds (S). We recorded the condition of the *Phragmites* plants as alive/green (A); having partial dieback (P); or brown, dormant, or dead (D). We recorded the percent cover of other non-*Phragmites* vegetation within the *Phragmites* patch boundary as none (N); low (≤33%); medium (33% to 66%); or high (>66%). We identified and listed the other species contained within the patch for heterogenous patches.

Table A1. Comparisons of *Phragmites* patch attribute, boundary, and RTK measurement data collected during 2022 to that from 2023 for inland and bankline patches along the Central Platte River, Nebraska.

Measurement	Collected in 2022	Collected in 2023
Inland and Bankline Patch Attributes		
Maximum stem height	Yes	Yes
Stem density	Yes	Yes
Life stage	Yes	Yes
Condition	Yes	Yes
Percent cover of other (non-*Phragmites*) vegetation	Yes	Yes
Stolons present? (yes/no)	Yes	Yes
Identification of other plant species in patch	Yes	No
Bankline Patch Attributes		
Percent of patch inundated by water	No	Yes
Percent of stolon reach inundated by water	No	Yes
Time of edge of water measurements and percent inundation assessment	No	Yes
RTK Measurements of Inland Patches		
Vertical growth boundary	Yes	Yes
Herbicide spray zone	No	Yes
RTK Measurements of Bankline Patches		
Combined vertical growth and stolon reach boundary	Yes	Yes
Vertical growth boundary	No	Yes
Stolon reach boundary	No	Yes
Bankline	No	Yes
Edge of water / water surface elevation	No	Yes
Herbicide spray zone	No	Yes