UNMANNED AERIAL VEHICLE (UAV) REMOTE SENSING FOR SPREADING CONTROL OF WATER CHESTNUT INVASIVE SPECIES IN THE ERIE CANAL SYSTEM, NEW YORK

Tao Tang*, Lily Jiang, Mary Perrelli
Department of Geography and Planning
State University of New York – Buffalo State
1300 Elmwood Ave., Buffalo, NY 14222
*Correspondent author: Phone: 716-878-4138; Email: tangt@buffalostate.edu

ABSTRACT: Drone remote sensing is rapidly becoming a useful tool for collecting data and monitoring changes of geographic features with high spatial and temporal resolutions. The major objectives of this research are 1) to apply unmanned aerial vehicle (UAV) technology to perform rapid detection and coverage estimation of water chestnut (*Trapa natans*) invasive species along the lower reach of the Erie Canal; and 2) to assess the effectiveness of the physical removal by US Fishery and Wildlife Services. Meanwhile, micro-climatic conditions of temperature and relative humidity (RH), and land use and land cover were examined along the section of the canal to assess habitat conditions of water chestnut.

The results indicate that the physical removal of water chestnut by US-FWS has been very effective. Only four plant patches were detected applying UAV sensor in the summer of 2016. The results of temperature and RH survey show that temperature decreases in general as altitude increases. RH values both at the canal surface and at 12 meter above the surface are higher than those at the surrounding land areas along the canal. However, a few exceptions exist at the ground level, which might be influenced by grassland moisture evapotranspiration. In summary, 1) No sufficient evidence was found in this study to illustrate the effects of temperature and RH on water chestnut growth; 2) the highest concentration and re-appearance of water chestnut are either at the areas of public parks with large grassland or at the boat docking sites in the urban areas.

Key words: *unmanned aerial vehicle (UAV) remote sensing, invasive species, water chestnut*, *Erie Canal*

INTRODUCTION

Trapa natans, commonly called water chestnut or water caltrop, is an exotic annual aquatic plant with a floating rosette of leaves which is native to Eurasian and African continents (Countryman, 1978; Naylor, 2003). Water chestnut is one of the most controversial plants (Hummel and Kiviat, 2004). In Asia, especially in China and India, people plant water chestnut as an agricultural species. In Europe and Russia, it is a species with conservation concerns (Hummel and Kiviat, 2004); while, the invasion of water chestnut is a serious environmental problem in North America. This plant grows easily and has already invaded freshwater rivers, ponds, and lakes, including the Hudson River and the Great Lakes watersheds (Kiviat, 1993; Countryman, 1978; Hummel and Kiviat, 2004).

The spread of water chestnut has already caused many ecological and economic impacts. The leaves of water chestnut cover the water surface, block the waterway, and cut off the air that fish and other aquatic life rely on to live (NYIS, 2014; Hummel and Kiviat, 2004; Naylor, 2003). The management of controlling water chestnut has been done during last several years. Various mechanical and chemical methods have been applied to remove extensively spreading water chestnut. However, these methods of removal take a long time to ensure complete eradication and are expensive (NYIS, 2014). For example, from 1982 to 2011, state and federal government agencies spent $9,600,000 on water chestnut control in Lake Champlain (Hunt and Marangelo, 2012). Scientists also attempted to apply some biological controlling methods, for instance, introducing a leaf beetle (*Galerucella birmanica*) from Asia (Ding et al., 2006). However, whether the result of these biological methods is environmentally friendly is still under research and discussion.

T. natans (water chestnut) is a species of the *Lythraceae* family, *Trapoideae* subfamily. The plants die at the end of every growing season and regrow in the spring of next year. *T. natans* has two types of root: the fine root anchoring the plant into the mud, which looks like wires and was born in sediment; while, the other type is photosynthetic root, which is light green or dark brown with pinnate fine crack (Flora of China, 2007). Its stem is 2.5-6 mm in diameter. The petiole of the plant is 5-18 cm long and is swollen distally with pubescence, which is the stalk attaching the leaf blade to the stem (NYIS, 2014). Its leaf blade is glossy and dark green adaxially, greenish purple abaxially, and often with colored spots between veins (Figure 1). The leaf blade is deltoid-rhombic to oblate-rhombic with pubescence in the back. The leaf base is broadly cuneate, and the leaf margin is irregularly dentate distally (Flora of China, 2007). The floating leaves bear in a rosette at the water surface, and each rosette can produce 10 to 15 nuts, and each of which carries 6 grams of wet mass (2.1 dry grams of mass) and 2 to 4 cm wide at maturity (Hummel and Kiviat, 2004). Its petals are white. The fruit is turbinate to shortly rhombic, horned, with a prominent bulge at the crest, and the fruit has tetragonal to rounded or dome-shaped crown and is rarely crownless (Flora of China, 2007).

In general, *T. natans'* flowers bloom from May to October, and it produces fruits from July to November. The fruits grow under water and the individuals go directly beneath their parent plants to prepare for propagating. The parent plant is killed by frost in autumn and decomposes quickly (Hummel and Kiviat, 2004). The seeds can remain dormant in the bottom of sediment for 10-12 years (NYIS, 2014; Muenscher, 1944; Winne, 1950). The seeds can also be spread by shipping, boating, or animal activities, such as ducks and waterfowl. Water chestnut grows best in waterbodies with a pH range of 6.7 to 8.2 (Naylor, 2003). The mature fruits of water chestnut contain various nutrients including protein and starch. Therefore, water chestnut has been regarded as food and medicinal material since ancient times in China, India and countries in southeastern Asia (Zhu, 2016; Hoque et al., 2009).

Figure 1. Water chestnut plant.

Overgrowth of water chestnut has been a regional environmental issue throughout North America (Rector et al., 2015), especially in the northeast region of the United States. Water chestnut was originally introduced as an ornamental in Massachusetts during the mid-1870s and was cultivated in the botanical garden at the Harvard University in late-1870s (Countryman, 1978). Since then, water chestnut started to spread in Massachusetts. In the 1880s, gardeners and horticulturalists brought water chestnut into New York State from Europe (Hummel and Kiviat, 2004). Then, water chestnut spread into several lake and river water bodies. Flooding caused by locks and dams of the New York Erie Canal system allowed water chestnut to escape from the original spreading areas (Winne, 1950). This species grew well and had covered roughly 405~486 hectares of the Mohawk River in 1934 via Collins Creek where water chestnut was originally introduced (Winne, 1950; Countryman, 1978). It also reached the Hudson River from the Mohawk by the late-1930s (Muenscher, 1937; Hummel and Kiviat, 2004). According to literature, the total area of infestation in New York State by 1952 was estimated at 1,416 hectares (Countryman, 1978). In addition to the Hudson River, water chestnut infestations were found in a marshy waterfowl impoundment, numerous artificial and partly natural ponds, and one major tributary within 30 km of the Hudson River, especially in the Dutchess County, New York (Besha and Countryman, 1980; Kiviat, 1993; Tiner, 2000). Water chestnut probably reached Lake Champlain from the Hudson River via the Hudson-Champlain Canal by the seeds clinging to boats, which were first found in the southern end of Lake Champlain in 1940s (Countryman, 1978). The species spread to four other water bodies in Vermont (Bove and Hunt, 1997); it continued to travel north and was observed as far as southern Quebec, Canada in around 1997 (Hummel and Kiviat, 2004). By 1919, water chestnut was discovered in a Potomac Park fishpond in Virginia (Gwathmey, 1945). Prior to 1964, the species was found in four waterways in Maryland, which are all tributaries of Chesapeake Bay (Bickley and Cory, 1955; Countryman, 1978).

Researchers have identified three types of control methods for water chestnut (Hummel and Kiviat, 2004) via chemical, physical, and biological methods. An herbicide, 2,4-dicholorophenoxy acetic acid (2,4-D), was applied to the Mohawk River, the Hudson River, and the Lake Champlain. This action reduced water chestnut population successfully (Greeley, 1960; Countryman, 1978; Rector, et al., 2015). However, the high concentration of 2,4-D also impacted many native wetland plant, fish, and aquatic invertebrate species (Cronk and Fennessy, 2001; Countryman, 1978; Kiviat, 1993). Physical removal is the most common method used to control water chestnut spreading. Water chestnut, as an annual plant, is best removed before its fruits mature and seeds fall to the bed of the waterways (Hummel and Kiviat, 2004), which is exactly what US-FWS has been doing in the Erie Canal and Tonawanda Creek waterways. Normally, physical removal can be accomplished with machines, such as underwater cutters and harvesters, or by hand pulling (Countryman, 1978; NYIS, 2014). During a mechanical removal process, workers should be careful not to let any mature fruits to fall into bed sediments; the process ensures that no potentially activated seeds are hiding in sediments, which could be dormant for 10-12 years (Elser, 1964). Therefore, the annual water chestnut removal activities should be done no later than July before mature fruits may start to drop (Countryman, 1978). Physical control methods have been proven effective in many cases, such as the management plans in the Lake Champlain, the Hudson River, the Chesapeake Bay region, the Potomac River, as well as other water bodies (Bickley and Cory, 1955; Elser, 1964; Hunt and Marangelo, 2012; Bove and Hunt, 1997; Madsen, 1993). However, physical control methods always consume a long period of time, a lot of money, and large quantity of human resources. For instance, it was estimated physical removal of water chestnut cost roughly $9,000 and took more than 20 years at the Potomac River to achieve a success result (Madsen, 1993).

The basic idea of biological control of invasive species is to employ the natural enemies of the species. In order to control water chestnut, several different species were introduced to establish competition. According to the literature, grass carp (*Ctenopharyngodon idella*) were introduced from Europe and have controlled water chestnut in some regions (Krupauer, 1971). A pathogenic fungus, *Sclerotium hydrophilum Sacc*, which was cultured from a diseased plant, is found can be used to kill young rosettes of water chestnut (Hall, 1982). An herbivorous insect species, *Galerucella birmanica Jacoby* (*Coleoptera: Chrysomelidae*), regarded as the most promising species, was introduced from China (Ding et al., 2005). However, introduction of these species may cause some other problems as well. The grass carp should be monitored because this kind of fish may also destroy other native species and may escape from where it is expecting to stay. The fungus should be artificially cultured every spring, and the leaf beetle can only damage part of the leaf tissue rather than the entire plant. Therefore, biological methods cannot be guaranteed to stop the regrowth of water chestnut (Krupauer, 1971; Hall, 1982; Ding et al., 2005). Recent research (Sosa, et al., 2017) of alien plants invasion in Argentina indicated that habitat conditions of local temperature and relative humidity (RH) might contribute a significant role on successful spreading of the invasive species. Another research (Estrada-Pena, 2019) for insect transferred Lyme disease on tree species in US also indicated warming local temperature has an important impact on the tick invasions. Therefore, it is very important to study the habitat conditions of local temperature and RH of invasive species.

Drone or UAV remote sensing is rapidly becoming a useful tool for collecting data and monitoring changes of geographic features with high spatial and temporal resolutions. Zhang and Tang (2014) utilized UAV remote sensing to study rapid parking lot occupations during a school day at one urban university campus. The results demonstrated that short time period changes of geographic features can be effectively detected using drone remote sensing. Pádua, et al. (2017) analyzed the significant potentials for utilizing drone platform to aid the agricultural productions. Based on field researches on vineyard and local farms, Bagheri (2017) and Hunt and Daughtry (2018) concluded that UAV is one important component of precision farming. Tang and Zhang (2018) indicated UAV or drone remote sensing not only largely improved understandings of geographic events of very high spatial resolution, but also revolutionized the detection ability on temporal scales. Woellner and Wagner (2019) conducted detailed river channel and vegetation cover analysis for a small watershed in Germany using drone remote sensing method. The research concluded that UAV remote sensing technology is the most effective way of monitoring the vegetation species for biological conservations. It saves both money and time for the researchers and practitioners.

The objective of this research was to detect and assess the extent of water chestnut (*Trapa natans*) invasive species along the lower reach of the Erie Canal system using a low-cost UAV. The US Fishery and Wildlife Services (US-FWS) has been conducting the physical removal of water chestnut in the study area every summer since 2010. Therefore, the second objective of this research was to assess the effectiveness of the physical removal. Both land use and land cover types and micro-climatic conditions of temperature and relative humidity (RH) were analyzed along the research section of the canal in order to assess the habitat conditions of water chestnut growing.

METHODS AND APPROACHES

The study area is along the lower reach of the Erie Canal in Western New York State, where the canal joins lower Tonawanda Creek and drains in the Niagara River (Figure 2). DJI Phantom 3 and DJI Inspire Pro 1 UAVs with integrated RGB digital cameras were applied as the remote sensing platforms. The aerial survey of water chestnut was conducted in the summer of 2016, and the UAV was launched from a research boat traversing the entire water surface in the study area of the canal (Figure 3). In specific, each of the surveying run covered a 50-meter section of the canal. The UAV was flown along one shoreline searching for water chestnut, crossed the creek/canal and flown a return path along the opposite shoreline then to the boat that was parked in the middle of the section. The UAVs equipped with GPS and 14-megapixel sensor that can yield one-inch ground resolution images with GPS coordinate stamp on each of the images. Concurrent video images were inspected by two researchers onboard of the boat in the field, and single aerial image frame was taken when one of the field researchers identified the leaves of the plant on the water surface. ERDAS Imagine remote sensing software platform was used to extract the patches of invasive species. Micro-climatic or habitat conditions of temperature and relative humidity (RH) were surveyed separately during the same summer. A HOBO Temperature and Relative Humidity (RH) Data Logger was attached to the drone to collect data in the selected vertical profiles along the seven sampling transects across the canal (Figure 2). Each of the vertical profiles were surveyed from surface to 12 meter above the ground with one-meter survey intervals. Along each of the seven surveying transects, two to three land based vertical profiles were measured on each side of the canal, and one vertical profile was measured from the middle surface of the canal. A total of 37 vertical profiles were surveyed.

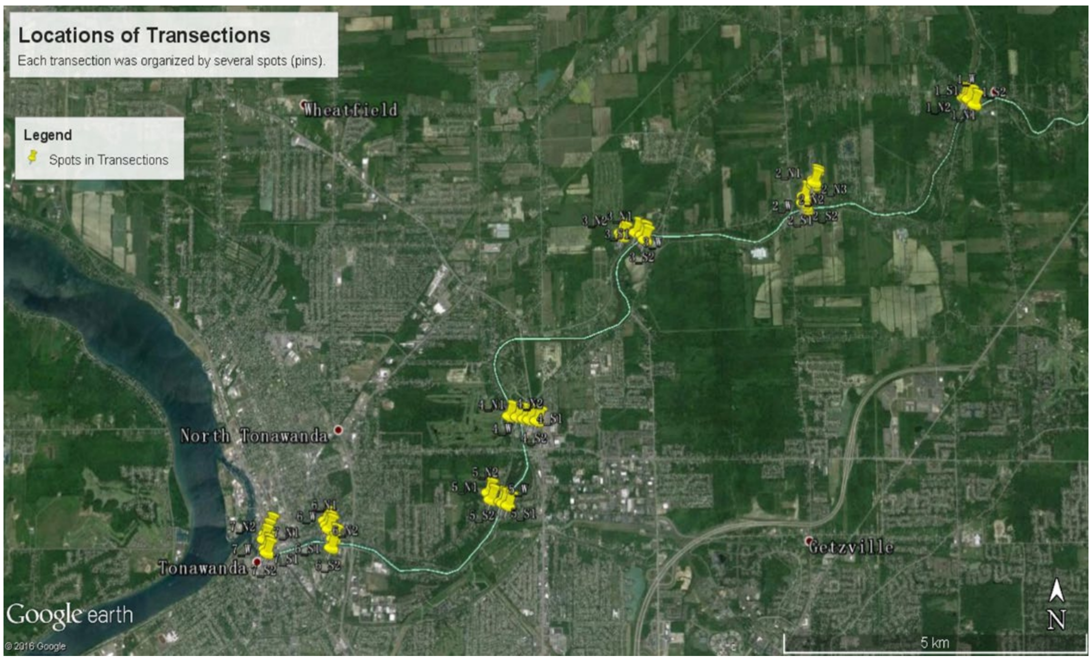


Figure 2. The locations of field transect

Spatial deterministic interpolation method of spline in GIS was used to interpret the three-dimensional (3D) distributions of temperature and RH along the seven surveying transects. Spline interpolation method uses a mathematical function that minimizes overall surface curvature to estimate values (Childs, 2004). When using this method, the smooth surface formed by the interpolation results passes exactly through those input points (Goovaerts, 2000; Childs, 2004). This method is commonly used to predict ridges and valleys and is the best approach to representing the smoothly varying surface of phenomena such as climatological variables (Childs, 2004; Hutchinson, 1995; Ninyerola et al., 2000; Fotheringham et al., 2002). The spline model uses the following algorithm to do the surface interpolation:

$$S(x, y) = T(x, y) + \sum_{j=1}^{N} \lambda_j R(r_j)$$

Where: j=1, 2, …, N; N is the number of points; λ_j are coefficients found by the solution of a system of linear equations; r_j is the distance from the point (x, y) to the j^{th} point; $T(x, y)$ and $R(r)$ are defined differently, depending on the selected option (Jeffrey et al., 2001).

Figure 3. Method of drone aerial survey of water chestnut invasive species on the Erie Canal waterway.

The 2014 high spatial resolution (0.5 feet) orthophotos were downloaded from New York State GIS Clearinghouse web site (http://gis.ny.gov/gateway/mg/index.html) for land use and land cover analysis. Remote sensing software, ERDAS Imagine (Hexagon Geospatial, Inc., Norcross, Georgia, US) was applied to process the data. Five categories of land use and land cover were identified in referencing the US Geological Survey land use and land cover classification scheme in this study (Jansen and Di Gregorio, 2002; Veldkamp and Verburg, 2004; Saadat et al., 2011). These categories include waterbody, urban land, grass land, bare soil, and forest. The maximum likelihood method of image classification was used to classify the land use and land cover in the study area (Rundquist, 2010).

RESULTS AND DISCUSSION

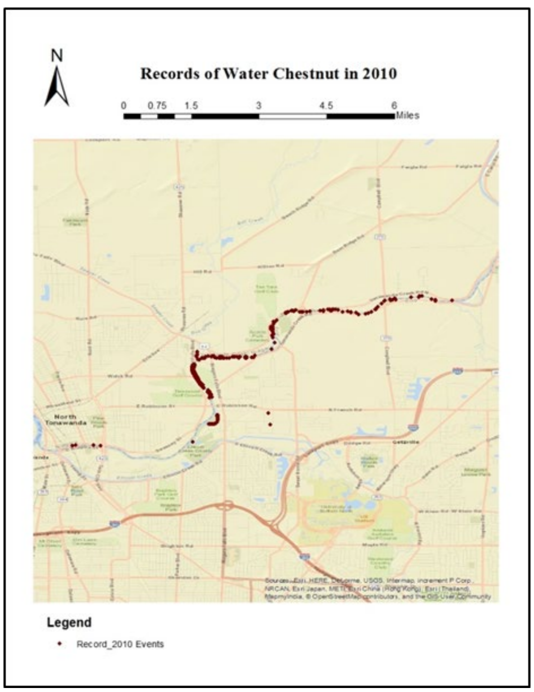
Only four water chestnut patches were detected using UAV sensor survey in the summer of 2016 (Figure 4b). Since 2010, the researchers and biologists at the Lower Great Lakes Fish and Wildlife Conservation Office of US-FWS have physically removed water chestnut every summer. In order to understand the annual variation intuitively, the numbers of discovered plants and pulled plants are shown in Table 1. The results indicate that physical pulling is an effective method of removing water chestnut over the years (Figure 4).

The results of the UAV based temperature survey show that the temperature decreases in general as the altitude increases (Figure 5). However, different sites have different intensities of temperature decrease. Vertical temperature differences in transects 6 and 7, which are located in the urban areas, are smaller than those of other five transects. Relative humidity (RH) surveys indicate that RHs both at the canal water surface and at 13 meter above the water surface are generally higher than those at the surrounding land areas along the transects (Figure 6). However, a few exceptions exist at the ground surface level, which might be influenced by grassland moisture evapotranspiration. In summary, the results of this study cannot supply sufficient evidence to illustrate the effect of habitat conditions of temperature and relative humidity (RH) on the growth of water chestnut. In order to draw clear relationships, long time and recursive monitoring and surveys are needed.

Table 1. Numbers of Water Chestnut During 2010 to 2016

Year	Number of		
	Sites	Observed Plants	Pulled Plants
2010	288	1058	NA
2011	198	2052	1947
2012	88	555	509
2013	68	341	341
2014	6	214	214
2015	35	266	264
2016	4	4	4

(2010-2015 data were calculated according to the shapefile database provided by the Lower Great Lakes Fish and Wildlife Conservation Office, 2016 data were based on the field survey).



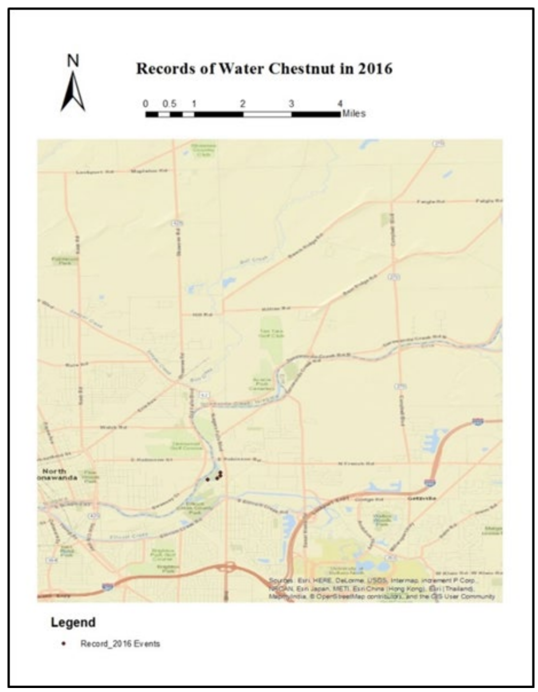


Figure 4. Comparison of detected patches of water chestnut invasive species of 2010 (left), and 2016 (right).

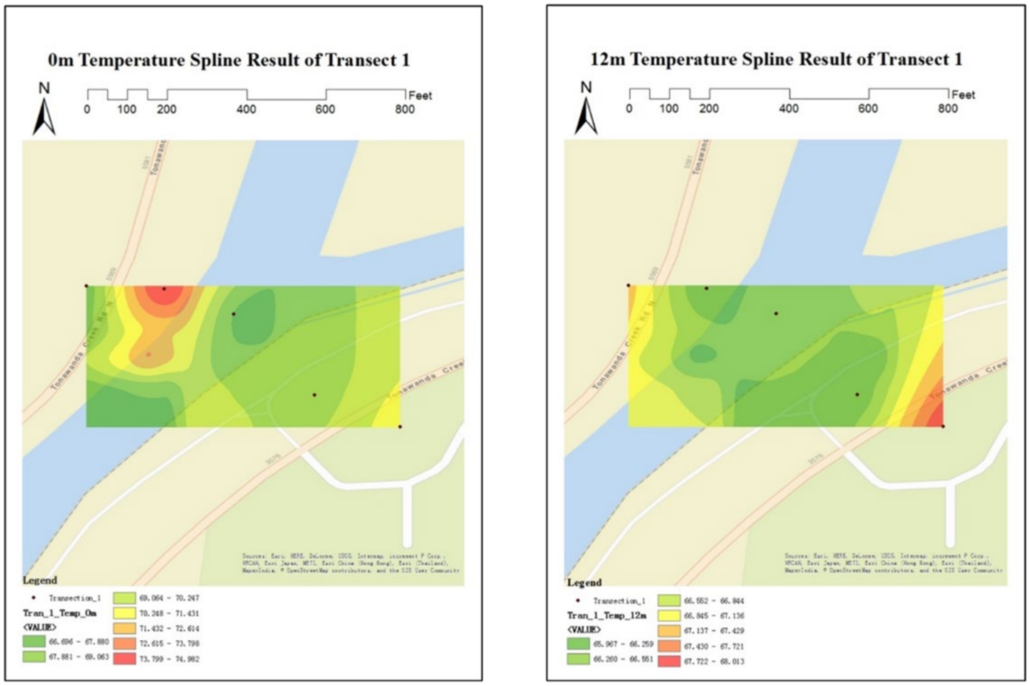


Figure 5. Temperature interpolation of transect 1 at (left) surface (1 meter); (right) 13 meters.

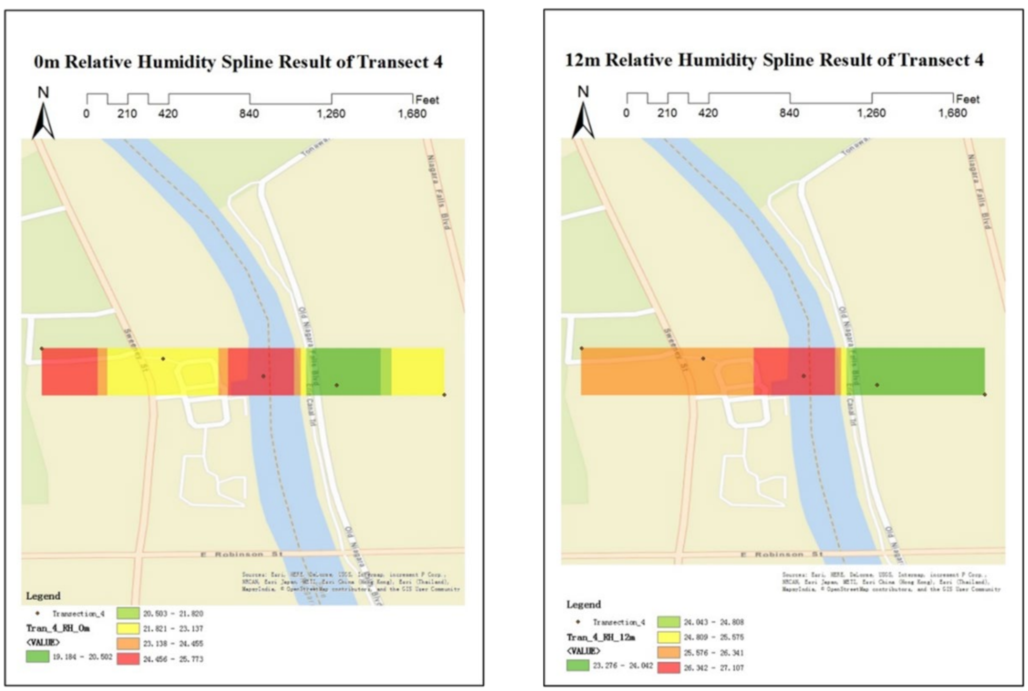


Figure 6. Relative humidity interpolation of transect 4 at (left) surface (1 meter); (right) 13 meters.

The results indicate that land use and land cover types along shoreline of the canal have some strong impacts on the growth of water chestnut along the creek. Water chestnut prefers a habitat with intensive human activities. The highest concentration and re-appearance of water chestnut invasive species are either at the areas of public parks with large grass land cover or at the boat docking sites in the urban areas. The impacts of micro-climate conditions of temperature and relative humidity (RH) on the growth of water chestnut invasive species were not clearly detected in this research simply because the single field survey or even low frequency field surveys in a single year were not long enough for data collections. Long term and recursive field data collections of temperatures and RHs are needed in order to address the issue of habitat conditions of invasion.

CONCLUSIONS

This research demonstrates that UAV or drone based close-range remote sensing is an effective means to detect and assess the patches and distributions of water chestnut invasive species on the water surface, such as rivers and lakes. The UAV method can not only help researchers to discover relatively tiny leaves of the invasive species in a large area along rivers, but also to detect temporal changes of distributions of invasive species with very high resolution. The results of this research verified and approved the effectiveness of physical removal method that was practiced during the six-year period by US-FWS. However, the impacts of temperature and relative humidity (RH) on water chestnut invasive species were not detected in this research simply because the single field survey conducted did not yield sufficient data. Long term monitoring and frequent surveys on the daily base during at least one-year period are needed in order to draw some conclusions.

Woellner and Wagner (2019) indicated in order to support decision making and monitoring of implemented measures for conservation and restoration of our natural resources and ecosystems, in particular to investigate habitat environment and abiotic conditions of plant species, UAVs or drones are significant for researchers to collect data. The results of this research approve this conclusion. Meanwhile, more integrations of artificial intelligence (AI) into the UAV data collections in reducing human labor and increase recursive measuring in short time period with long time range will increase the accuracy of data analysis and decision making. In summary, UAV remote sensing data collection and analysis revolutionized the temporal scale and temporal resolution in geographic studies (Tang and Zhang, 2018).

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