Estimating the effects of heterogeneous competition in an agent-based ecological model using GIS raster color

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Presented at the 45th International Winter Simulation Conference (WSC '13)

Abstract

It is hypothesized that inter-species competition is one of the main factors that determine the range and distribution of Sensitive joint-vetch (SJV), a rare, tidal wetlands annual. The precise effects of this competition, however, are poorly understood by ecologists and difficult to quantify. We have constructed a detailed, agent-based simulation of SJV in its Holts Creek, Virginia, habitat. In order to elucidate these landscape-scale effects, we propose a new method of distinguishing poor from high quality plots that uses GIS to correlate the pixel color of an individual m2 plot to its propensity for sustaining joint-vetch. This propensity is then used to determine the vital rates of a given plot and is applied to all plants within it. Results indicate that inter-species competition plays a limiting, though by no means exclusively important, role in the spatial arrangement and rarity of joint-vetch.

Fig. 1: *Aeschynomene virginica*, or sensitive joint-vetch. *art.state.gov.* **Fig. 2**: Holts Creek, Virginia. *Panoramio user: KDfromRichmond.*

Introduction

Sensitive joint-vetch is a rare, tidal wetlands annual that is extinct in most of its historical range. As a rare plant, it is in conservationists' interests to determine and implement the most promising methods for preserving the plant, while taking into account limited resources. This decision area is ripe territory for ecological modelling, as it can better inform decision makers and allow them to see underlying patterns and emergent properties in empirical data that would not otherwise be visible.

We hypothesis that there are several factors in decline of the plant. SJV is a poor competitor and thus it must rely on less populated patches for survival. Because of this limitation, it is keenly vulnerable to habitat loss. If this is the case, some possible conservation strategies may include:

1. creating new, non-competitive plots by cutting existing flora
2. adding seeds to existing plots
3. increasing average plant fecundity by cutting vegetation in existing plots

We seek to help decide which approach is the most likely to succeed and how best to implement it. To this end, we have constructed an agent-based simulation of Sensitive joint-vetch in its Holts Creek, Virginia, habitat that is designed to test several hypotheses about the plant. The following protocol was used to test the first, that inter-species, heterogeneous competition is the primary factor in its decline.

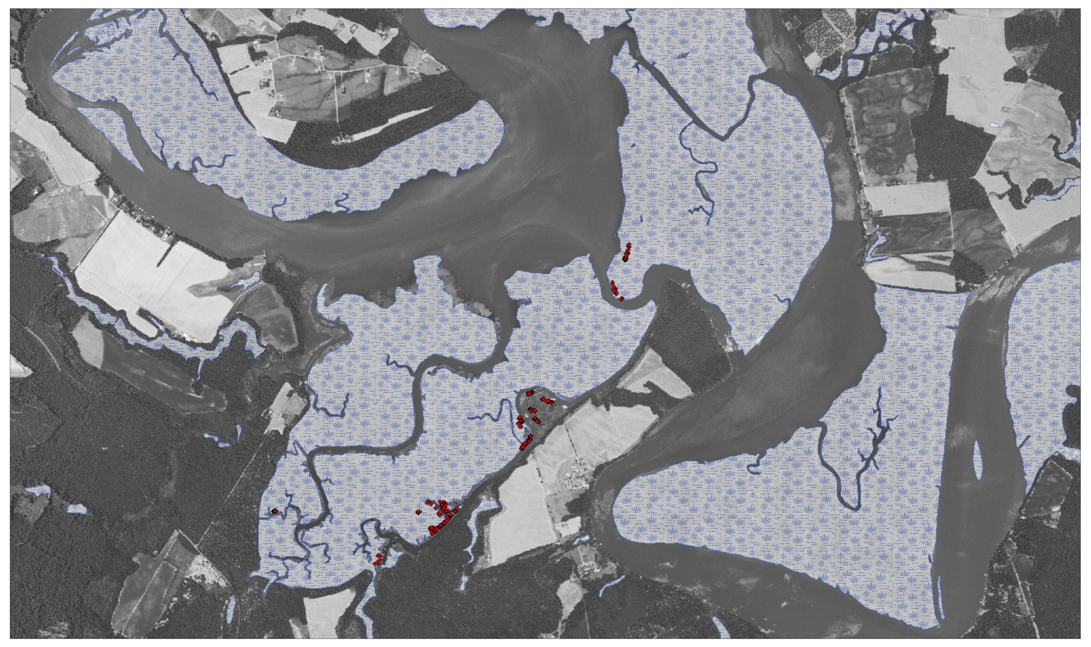


Fig. 3: Holts Creek, VA with known Sensitive joint-vetch populations in red and the "waterbody" in light blue. *Data courtesy of: The Nature Conservancy (joint-vetch population), USGS (Hydrography dataset waterbody), USDA (aerial photography)*

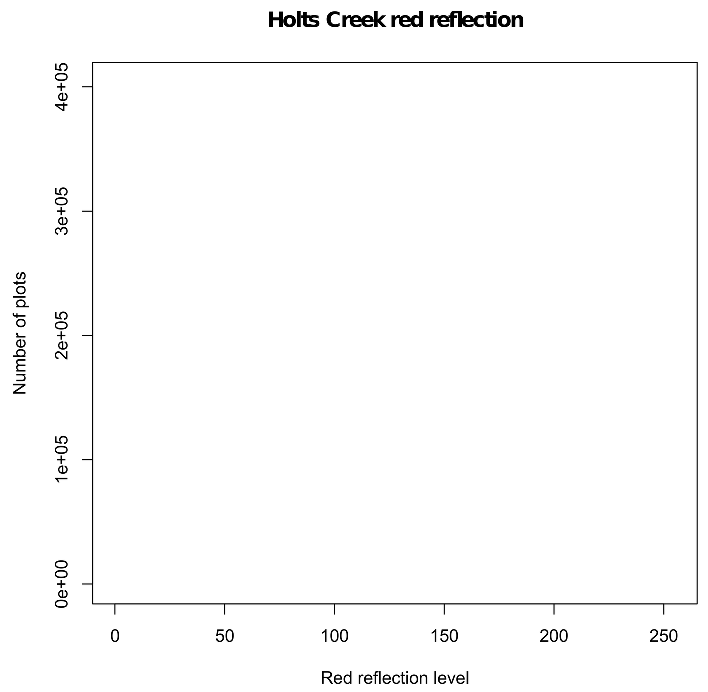


Fig. 4: The distribution of the intensity of red that the plots in Holts Creek as a whole reflect. In spatial analysis, the red raster band is often used to measure how much photosynthesizing biomass is in an area. There are a total of 13,591,050 m2 plots in Holts Creek.

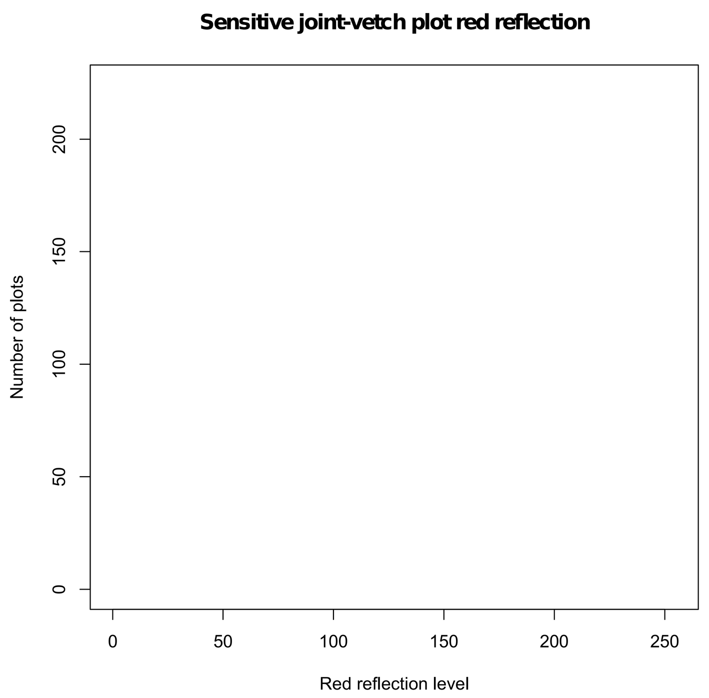


Fig. 5: The distribution of the intensity that squares within 3m of a population of SJV reflect. There are 6065 m2 plots in total. The mean is statistically significant in its difference from Holts Creek as a whole.

The non-parametric Mann-Whitney test was used to calculate statistical difference. U=56057, and p<2.2e-16.

Estimating competition

To understand how the landscape scale effects of competition influence Sensitive joint-vetch in Holts Creek, it is necessary to approximate these processes in silico. Unfortunately, there is no foundation of data to build from and simulate interspecies competition. However, we do have thorough, empirically derived distributions for SJV's vital rates in a "typical competition" setting [1]. We also have contemporary rasterized aerial photography of the marsh, as well as population coordinates (Fig. 1). Because the red color band is often used to visualize how much photosynthesizing biomass is present in an area [4], we attempt to correlate the frequency of SJV occurrence on different levels of "red" reflection to vital rates from different ranges of the distributions.

To derive an approximation of landscape scale competition inside Holts Creek, we used the following process:

1. Isolate Holts Creek in raster form using the USGS Hydrography dataset waterbody.
2. Isolate all squares within 3m of SJV populations.
3. For each redness level, divide the SJV frequency by the Holts Creek frequency and normalize the result, creating a "propensity" for each level of red reflection to have joint-vetch be found near it. For example, the SJV frequency at red value 135 is 38 and the Holts Creek frequency is 7045. On other other hand, the SJV frequency at red value 100 is 89 and the Holts Creek frequency is 178,460. After dividing to get the propensity, we discover that red value 135 is 11 times more likely to contain SJV than red value 100 is (propensity[135] = 0.041, propensity[100] = 0.0038.)

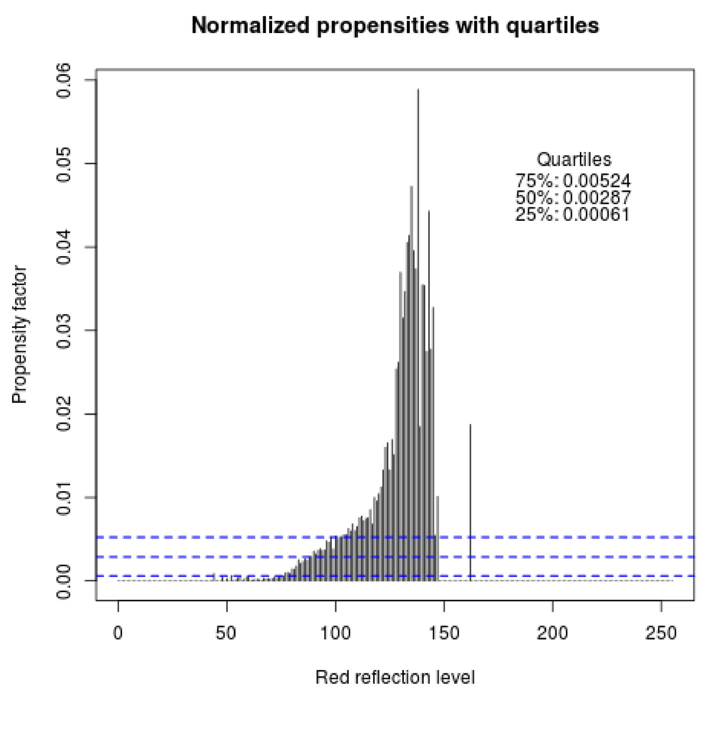


Fig. 6: The propensity of any given redness-reflection rate to have SJV near it. This shows that, in general, SJV grows near areas where there is more red reflected. In other words, there are fewer plants to absorb red light.

Quartiles shown are for the entire Holts Creek habitat, not simply for this range of colors: i.e., one quarter of all plots in Holts Creek are of a color that corresponds to a propensity less than or equal to the 25% quartile number.

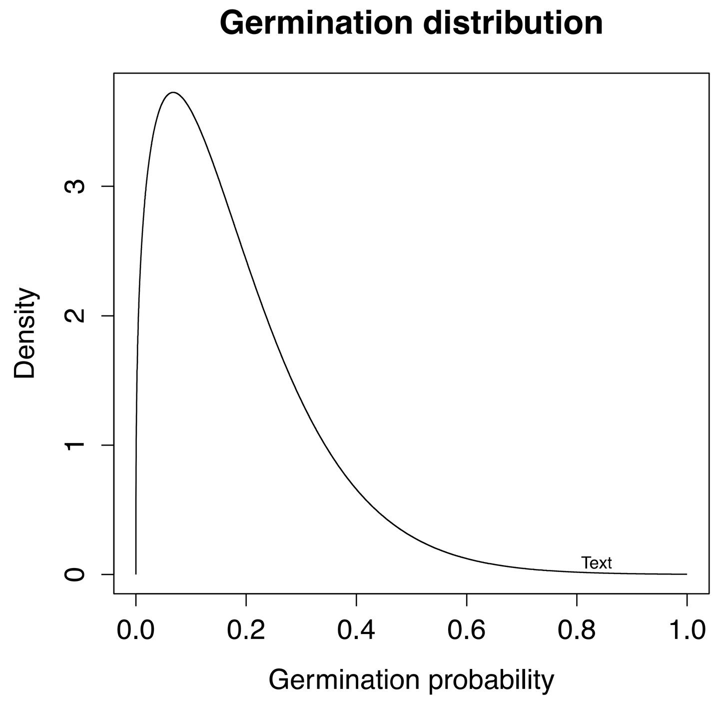


Fig. 7: The empirically derived distribution of germination probabilities. The 50th percentile has a germination probability of 15%. The 90th is 37%.

Transforming propensity to vital rates

A vital rate is a measure of how many individuals of a species generally progress from one life stage to the next. There is some variation in the actual value of a vital rate due to the particular environmental conditions present in a given plot. Thus, the actual vital rate that a group of collocated organisms will experience can be modeled as a probability distribution. For example, for the transition from non-germinated seeds to established seedlings (empirical data for which is found in [2]), we fit a Weibull distribution with a shape=1.32 and scale=0.197134. This means that 50% of seeds have less than a .15 probability of surviving to germinate. Joint-vetch has three vital-rates: germination, seedling survival to adulthood, and fecundity.

To transform our new data on relative competition into specific vital-rate transitions, we compose a cumulative distribution function by extrapolating the propensity distribution to all the plots in Holts Creek. In other words, we transform the data so we can query it to answer questions such as, "what percentile of Holts Creek has a propensity less than .02." Answer: 94%. By querying the vital rate distributions at each color's percentile of propensity, we can derive a new distribution for each of the three vital rates that shows each color's value.

To integrate this new competition into the model, a plant will use its plot's vital rate transitions. The vital rates are static throughout the simulation, so plots that have joint-vetch on them with a positive rate of growth will continue to grow.

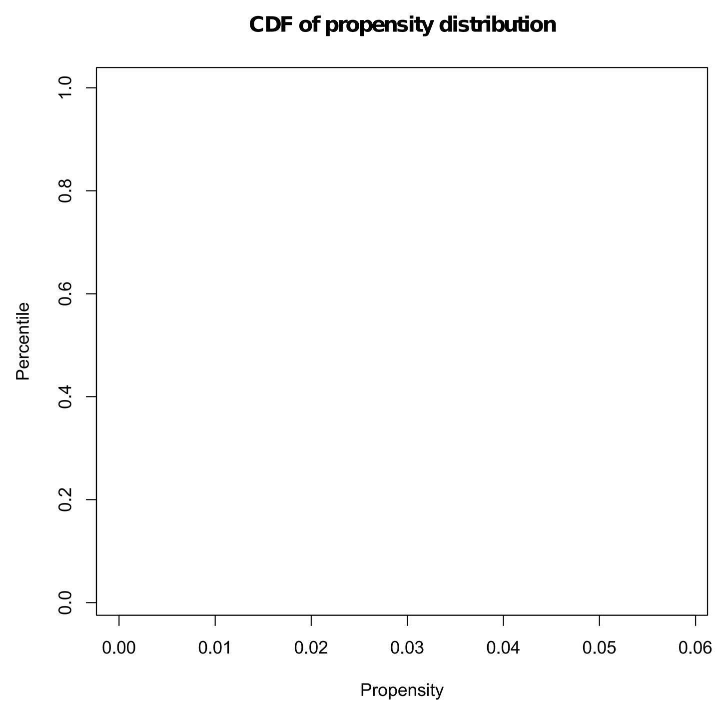


Fig. 8: The CDF of propensities in Holts Creek. Notice that the range of the x-axis is identical to the minima and maxima values of the normalized propensities. Using this CDF, we can conclude that that almost all of the squares in Holts Creek have a propensity less than 0.01.

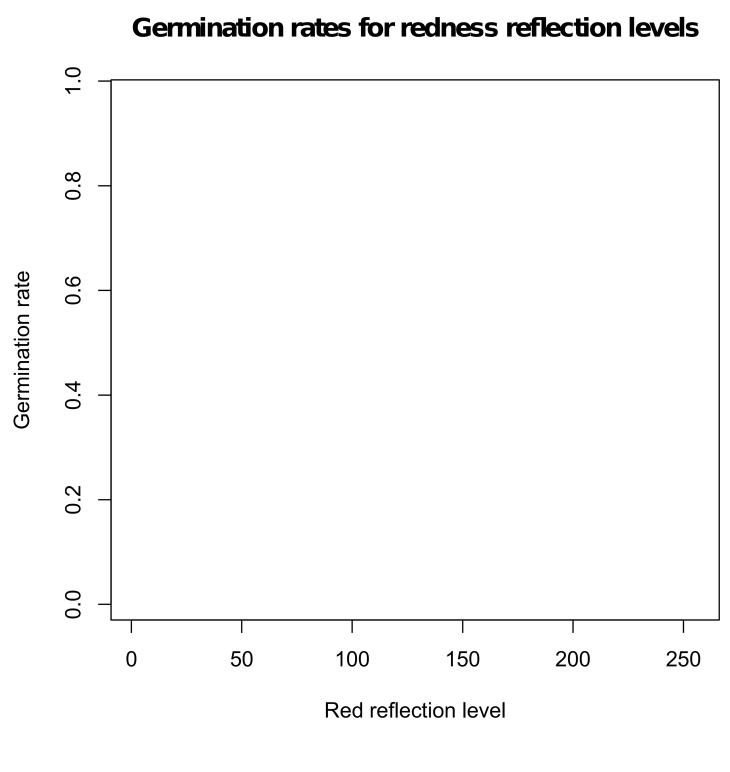


Fig. 9: Germination rates for each red reflection level. For very good absorption levels, the germination rate is quite high. For more common reflection rate (average competition in Holts Creek), the germination rate is almost prohibitively low.

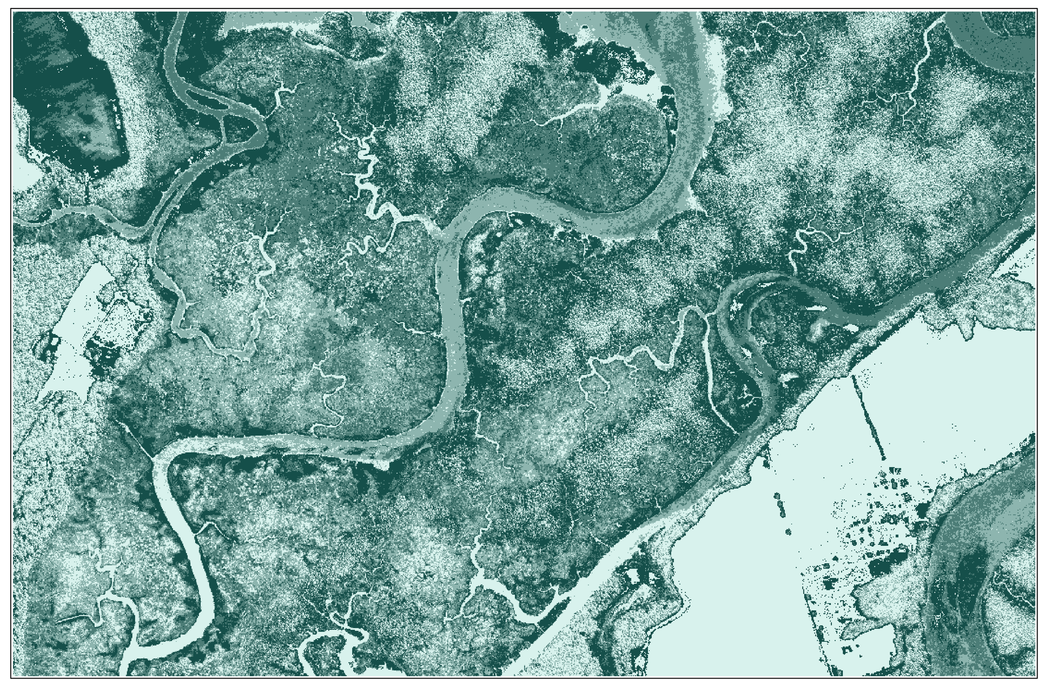


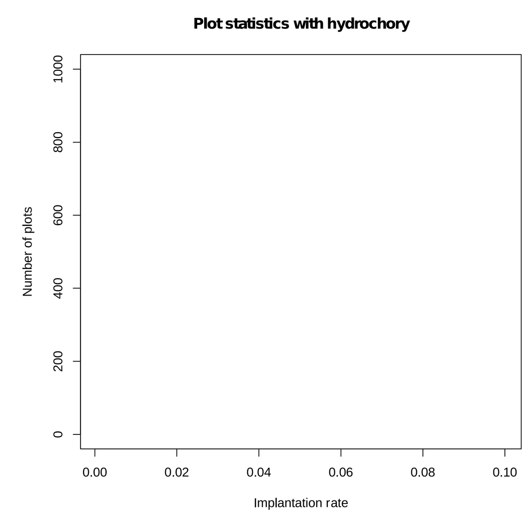
Fig. 10: A reclassification of every square inside Holts Creek, based on its propensity for SJV. Darker squares draw better vital rates than lighter.

Results

In pattern-oriented modeling [3], the investigator seeks to reproduce patterns that are seen in the system they are modeling. We compared our simulation results to two known patterns that joint-vetch exhibits:

1. The division of populations into two general categories: high performing populations that have reached carrying capacity and mediocre populations that do not reach carrying capacity, which is 50 plants/m2.
2. Constrained growth. For the Holts Creek habitat, realistic population counts range from the high hundreds to mid-thousands [4].

Parameterizing the simulation, we find that pattern #1 is upheld, while constrained growth (pattern #2) varies largely with the success rate of water-based seed dispersal, an unknown variable.



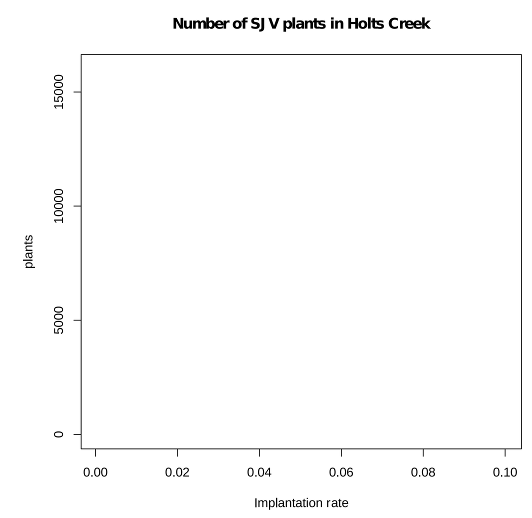


Fig. 11, left: The distribution of plots reached based on the level of successful hydrochory. Implantation rate is the rate at which seeds successfully implant in the stream bank per hour in our model. Note that for all levels pattern 1 is maintained. **Fig. 12, right:** The number of plants in Holts Creek versus implantation rate, with hydrochory on and off. More hydrochory means more plots reached and more SJV.

References

[1] Griffith, Alan B., and Irwin N. Forseth. 2003. "Establishment and Reproduction of Aeschynomene Virginica (L.) (Fabaceae) a Rare, Annual, Wetland Species in Relation to Vegetation Removal and Water Level." *Plant Ecology* 167 (1) (July): 117–125.

[2] ———. 2005. "Population Matrix Models of Aeschynomene Virginica, a Rare Annual Plant: Implications for Conservation." *Ecological Applications* 15 (1): 222–233. doi:10.1890/02-5219.

[3] Grimm, et al. 2005. "Pattern-Oriented Modeling of Agent-Based Complex Systems: Lessons from Ecology." *Science* 310 (5750) (November 11): 987–991.

[4] Tucker, Compton J. 1979. "Red and Photographic Infrared Linear Combinations for Monitoring Vegetation." *Remote Sensing of Environment* 8 (2) (May): 127–150. doi:10.1016/0034-4257(79)90013-0.

[5] Tyndall, R. Wayne. 2011. "Long-term Monitoring of Two Subpopulations of the Federally Threatened Aeschynomene Virginica (Sensitive Joint-vetch) in Maryland." *Castanea* 76 (1) (March): 20–27.

[6] "Sensitive Joint-Vetch (Aeschynomene Virginica) Recovery Plan." 1995. Hadley, Massachusetts: U.S. Fish and Wildlife Service.

Geospatial Data Sources

New Kent County, VA, 2012 National Ag. Imagery Program Mosaic, United States Department of Agriculture. 2012.

New Kent County, VA, 2012 National Hydrography Dataset, The National Map, United States Geological Survey. 2012.

Sensitive joint-vetch population data provided by The Nature Conservancy.