Forest Ecology and Management 497 (2021) 119534

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

AVID: A rapid method for assessing deer browsing of hardwood regeneration

Paul Curtis[a,*], Kristi Sullivan[b], Peter Smallidge[c], Jeremy Hurst[d]

[a] Cornell University, Department of Natural Resources and the Environment, Room 222, Fernow Hall, Ithaca, NY 14853, United States
[b] Cornell University, Department of Natural Resources and the Environment, Room 218, Fernow Hall, Ithaca, NY 14853, United States
[c] Cornell University, Department of Natural Resources and the Environment, Room 219, Fernow Hall, Ithaca, NY 14853, United States
[d] New York State Department of Environmental Conservation, 625 Broadway, Albany, NY 12233, United States

ARTICLE INFO

Keywords:
White-tailed deer
Regeneration
Hardwoods
Seedling growth
Sugar maple
Red oak
White ash
Black cherry
Citizen-science

ABSTRACT

Extensive deer browsing threatens the ability of many forests in the northeastern United States to regenerate and sustain their biodiversity. To reliably assess whether deer are reducing the regeneration of key tree species valued for timber and wildlife, we developed a rapid field protocol for **A**ssessing **V**egetation **I**mpacts from **D**eer (AVID, http://AVIDdeer.com). AVID is a method for foresters, landowners, volunteers, and others to measure the effect of deer browsing on seedling growth. Our objectives were to: 1. Determine if the AVID method could detect differences in growth rates for protected (fenced) and unprotected seedlings, 2. Evaluate AVID's usefulness as a regeneration monitoring tool for citizen-science engagement, and 3. Compare and contrast the relative strengths and weaknesses of common methods for measuring deer impacts to vegetation. We compared fenced and unfenced plots at 10 research sites in New York State to validate the sensitivity of AVID for detecting deer impacts to seedling growth. Tagged seedlings were measured annually for height growth in replicated plots. Deer reduced average seedling height growth of palatable species several fold at these sites often in combination with the effects of site and year. From 2016 through 2020, we conducted 59 AVID training events with 1,399 participants including landowners, students, educators, naturalists, resource management professionals, and land trust staff. Volunteers established plots at 83 sites in 24 New York counties demonstrating that AVID provides a valued citizen-science approach for both teaching people and assessing deer impacts to forest regeneration. Once volunteers consistently monitor a statistically valid number of plots for several years, the New York's Department of Environmental Conservation intends to use AVID data to inform deer management decisions.

1. Introduction

The white-tailed deer *(Odocoileus virginianus)* has significantly influenced regeneration of New York's forests (Blossey et al., 2019; Lesser et al., 2019; Curtis et al., 2020). Deer browsing and interfering vegetation were the greatest problems reported by foresters for establishing regeneration statewide (Connelly et al., 2010). Foresters reported that deer browsing adversely affected 72% of the state's stands that were found to have marginal or failed regeneration, while interfering vegetation affected half the stands (Connelly et al., 2010).

Deer reduce habitat resources both for themselves and for other species, compromising forest ecosystems (Tilghman, 1989; deCalesta and Stout, 1997; Côté et al., 2004). In many areas of the northeastern United States, through selective and intensive browsing (Horsley et al., 2003; Rawinski, 2008), deer affect the kinds and numbers of plants present in an area, impair the growth of new trees, and redirect the structure of the current and future forest. The changes brought about by deer add to other forest stressors resulting in a "regeneration debt" (Miller et al., 2019). This lack of seedlings and saplings affects the quality of the forest and reduces available food and habitat for other wildlife species (Tilghman, 1989). The abundance and number of different types of songbirds, for example, is lower in forests heavily browsed by deer (deCalesta, 1994; Allombert et al., 2005; Baiser et al., 2008). Consequently, deer were considered a "keystone" species in northeastern forests (McShea and Rappole, 1992; Waller and Alverson, 1997).

As selective browsers, deer prefer to eat certain plant species more than other less desirable species (Rossell et al., 2007; Rawinski, 2008).

* Corresponding author.
E-mail addresses: pdc1@cornell.edu (P. Curtis), kls20@cornell.edu (K. Sullivan), pjs23@cornell.edu (P. Smallidge), jeremy.hurst@dec.ny.gov (J. Hurst).

https://doi.org/10.1016/j.foreco.2021.119534
Received 3 June 2021; Received in revised form 9 July 2021; Accepted 11 July 2021
Available online 21 July 2021
0378-1127/

Many of the tree species deer prefer to consume are valued for timber, or as food-producing trees for wildlife including oak (*Quercus spp*.) and maple (*Acer spp*.). Deer also eat many wildflower and understory plants such as trillium (*Trillium spp*., Rooney and Gross, 2003), Canada mayflower (*Maianthemum canadense*), and lady slippers (*Cypripedium spp*.). Deer tend to avoid eating less palatable species such as hay-scented ferns (*Dennstaedtia punctilobula*) and many invasive plant species such as garlic mustard (*Alliaria petiolata*) or barberry (*Berberis spp*.) (Ward et al., 2018). By preferentially eating some species and leaving others behind, deer will reduce biodiversity in a forest (Rooney and Waller, 2003). As the variety of plant species in the forest changes, so can the way that the forest ecosystem functions, including its resilience to natural disturbances and the quality of services provided to society.

Substantial evidence supports the assertion that high deer abundance can negatively impact plant communities and biodiversity (Tilghman, 1989; deCalesta, 1994; Waller and Alverson, 1997; deCalesta and Stout, 1997; Horsley et al., 2003; Rooney and Waller, 2003; Côté et al., 2004). The effects of deer browsing may have long-lasting effects on the composition and structure of forests ("legacy effects") that persist for decades even after deer impacts are reduced (Royo et al., 2010; Gorchov et al., 2021). In areas with a history of deer overabundance, regeneration failure – the failure of new, young trees to grow – is having a detrimental effect on forests and the potential to keep areas in forest cover into the future. Obtaining successful forest regeneration requires a comprehensive management strategy and appropriate silvicultural treatments that address both deer and competing vegetation (Marquis et al., 1992; Ward et al., 2018).

Although deer damage to forest vegetation is a pervasive concern, assessing deer damage to plant communities and biodiversity is not a simple process. There are several ways to measure deer impacts to woody vegetation or wildflowers, and no single methods is ideal for all situations and landscape scales. Methods that seem to work well on large landholdings (McRoberts et al., 2005; deCalesta, 2013) may not be suitable for small properties or be too labor intensive. Timing may be critical for documenting wildflower impacts, and the time frame and sampling method may not fit agency staffing or time constraints. Developing a quick and reliable approach for measuring deer-related effects at the plant community level has been challenging. If managers are going to make progress on assessing deer impacts, standardized and relatively simple protocols are needed that can be adapted to a variety of scales (e.g., individual property, community, and landscape).

Given the diversity of habitats and situations where deer conflicts occur, there may not be a single approach that will work in all areas. Researchers and agency staff need to invest more time and effort in developing simple, low-cost methods for evaluating deer impacts at multiple scales. Rawinski (2018) has been using the "Ten-Tallest" seedling approach. Blossey et al. (2019) used transplanted "Oak Sentinel Seedlings" to assess deer browsing, a method that is particularly useful at places where deer impacts are so severe that native wildflowers and tree seedlings are essentially absent from forest understories. Waller et al. (2017) have developed the "Twig-age Method" for assessing deer impacts on species of maple. All these methods are potentially useful, but they have strengths and limitations. For example, all but the oak sentinel seedling approach require sufficient existing vegetation to get reliable sample sizes. These vegetation assessment methods need further refinement and evaluation at multiple spatial and temporal scales.

We developed and implemented the Assessing Vegetation Impacts from Deer (AVID) citizen-science protocol for use in New York State and the Northeast. AVID was designed as a low-cost and simple method to measure recent changes in vegetation growth associated with changes in deer abundance and browsing impacts on tree seedlings. Our objectives were to: 1. Determine if the AVID method could detect differences in growth rates for protected (fenced) and unprotected seedlings, 2. Evaluate AVID's usefulness as a regeneration monitoring tool for citizen-science engagement, and 3. Compare and contrast the relative strengths and weaknesses of common methods for measuring deer impacts to vegetation. To detect differences, we compared seedling growth rates for both fenced, and paired unfenced plots, in New York State woodlands.

2. Study areas

To evaluate the sensitivity of the AVID method, we selected 10 research sites in 8 Upstate New York counties (Broome, Essex, Greene, Lewis, Schuyler, St. Lawrence ($n = 2$), Tompkins ($n = 2$) and Yates; Fig. 1). Stands contained common northern hardwood species (Table 1), and generally had < 50% canopy closure in the overstory. Before choosing locations for plot clusters, we spent 20 to 30 min walking the forested stand, and subjectively located plots to ensure that there were adequate numbers (usually $n = 25$ to 35) of tree seedlings to measure. Plots were selected in areas with adequate light to accelerate seedling growth (Beaudet et al., 2000), which could possibly attract deer with denser seedling numbers. Because our goal was to assess deer foraging impacts on seedling growth, the selection of plots was not random. Rather, plot selection ensured that the growth rate of seedlings reflected site differences associated with varying deer damage levels.

3. Methods

At each of these 10 research sites, 6 AVID plots accessible to deer (unprotected) were paired with 6 plots having fenced deer exclosures (protected). Deer fencing was in place by summer 2015 at the Broome, Essex, Greene (Siuslaw), Lewis, Mt. Pleasant, Schuyler, St. Lawrence-1, St. Lawrence-2, and Yates County sites. Fencing was installed at the Gasline site in Tompkins County in 2018. At the Broome, Greene, Mt. Pleasant, Schuyler, and St. Lawrence-1 sites, deer exclosures were of uniform size and approximately square in shape, with 15.24 m (50 ft) of plastic netting on each side, about 2.13 m (7 ft) high, and secured to trees. At the Essex, Lewis, St. Lawrence-2 and Yates County sites, plastic mesh fences were 1.52 m (5 ft) high, attached to trees, and the fence perimeter lengths varied from 91.44 m to 132.44 m (300–434.5 ft). At the Gasline site, multiple individual fences were installed that were approximately the same area as individual AVID plots with a 1.83 m (6 ft) radius. These fences were approximately square, 3.05 m (10 ft) on a side, consisting of plastic mesh 1.52 m (5 ft) tall, and supported by 4 wooden posts. The mesh fencing was attached to the posts with zip ties.

AVID plots within the larger fences (all sites except the Gasline location) were circular with radius of 1.8 m (6 ft) and were marked with a permanent center stake (Fig. 2). The goal was to measure at least 25 total stems of one tree species contained in a cluster of 6 plots within the same stand and protection classification (fenced or unfenced) at each study site. All plots were located at least 15.24 m (50 ft) from the forest edge, or where the trees met an open field, shrubland, wetland, or other non-forest habitat type, and at least 15.24 m (50 ft) from areas with human disturbance (skid trail, old home site, hiking trail, road, etc.). More detailed information and data sheets are available online at the AVID web site (http://AVIDdeer.com).

We tagged and measured approximately 25 to 35 seedlings for each tree species in paired plot clusters with and without fenced deer exclosures (Table 1). Available tree seedlings included white ash (*Fraxinus americana*), black cherry (*Prunus serotina*), red oak (*Quercus sp*.), sugar maple (*Acer saccharum*) and red maple (*Acer rubrum*). Species availability varied, and where feasible, we measured seedling height growth annually for multiple species at a given site. Seedlings were measured for 3 to 5 consecutive years. Relatively few tagged seedlings were actually "lost" during the trial, and it appeared that most "lost" tags were blown or knocked off very small seedlings without a woody branch on the main stem. However, there were several cases where "missing" tagged plants were found one or more years later, and the stem was remeasured. This should not impact the analyses because our statistical response variable was the slope of

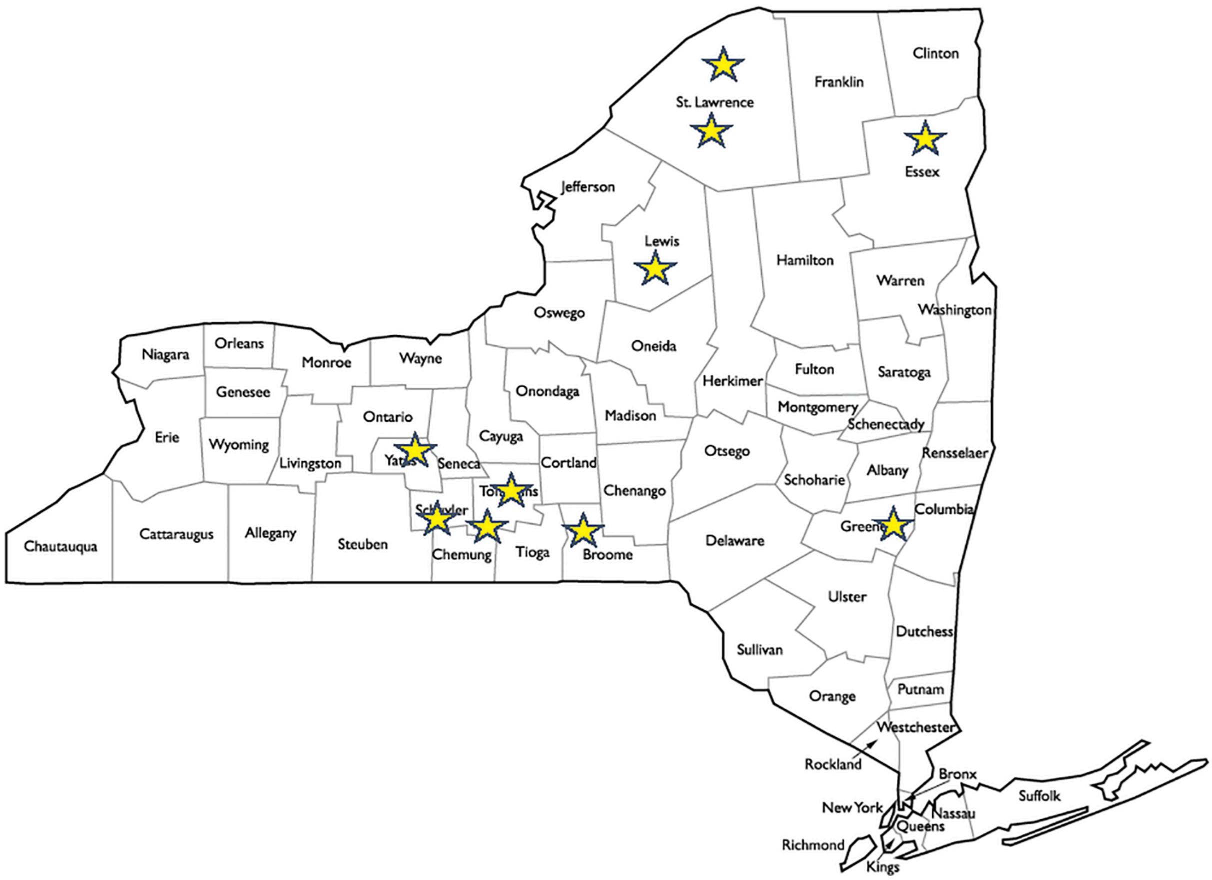

Fig. 1. Location of 10 AVID research sites in 8 Upstate counties of New York State, 2015–2020.

Table 1
Sites, tree species, number of tagged seedlings in fenced and unfenced plots, and number of years sampled for 10 AVID research sites in New York State during 2015 to 2020.

Site	Species	# Years	# Fenced Seedlings	# Unfenced Seedlings
Broome	Black cherry	5	28	34
	Red oak	5	22	36
Essex	Red oak	5	25	26
Gasline	Red oak	3	20	30
	Sugar maple	3	28	30
Lewis	Sugar maple	5	47	63
Mt. Pleasant	Black cherry	5	24	27
	White ash	5	45	31
Schuyler	White ash	5	36	42
Siuslaw	Red maple	5	24	17
	Red oak	5	9	13
St. Lawrence 1	Sugar maple	5	21	26
St. Lawrence 2	Sugar maple	5	31	30
Yates	Red maple	5	15	28
	Sugar maple	5	21	8
TOTAL			396	441

the seedling growth curve over time. Initially tagging a few extra seedlings in each plot allowed for some loss without any concern. If there was a site that had fewer than about 15 seedlings to measure, new replacement seedlings would be tagged and measured annually to maintain an adequate sample size when seedlings were available.

Because different seedling species were not well distributed across sites, and some sites had multiple tree species, we lacked a full factorial design and thus could only make comparisons among certain species. Based on field observations, we determined that deer breached the exclosure at the Essex site and browsed the red oak seedlings. There was no evidence of deer damage inside the other deer exclosures.

Seedling height growth measurements were not normally distributed, so we log-transformed the data prior to analyses. We then used a linear mixed-effects model (JMP Pro Version 14, SAS Institute, Cary, NC, USA) with the log of seedling height as the dependent variable. We included year, whether the seedling was protected from deer or not, site-species combinations, and all interactions as fixed effects. We also included tag number (which represented the individual seedlings), and plot number as random variables. For the interaction of species and site, we compared the slope of log seedling height inside and outside of the deer exclosures for each tree species at each site. We modeled the log height by the categorical variables of enclosed, year, and site-species. The coefficients for year (slopes) that we calculated for each site-species (inside or outside the fenced exclosure) can be back-transformed and represented the percent change in height associated with a one-unit increase in year. The initial height was incorporated into the log-linear model as a data point for the earliest year. This technique was useful because seedlings were measured over differing ranges of years.

To reduce the likelihood of a false positive given that we had 15 site-species combinations, we then applied Holm's *p*-value correction (Holm, 1979). The *emtrends* function of the *emmeans* R-package (R Core Team, 2018) was used to compare the slope of trend lines for seedling heights inside versus outside of deer exclosures for each site-species combination. In addition, slopes from the linear model were re-expressed as percent change in growth for each tree seedling species and site. We used percent growth because seedlings started at different heights and grew for a different number of years depending on the site selected.

Fig. 2. Layout of AVID plots in forested stands at 10 sites in New York State, 2015–2020.

4. Results

Deer reduced seedling height growth for all 5 tree species at 12 of 15 species-site combinations evaluated between 2015 and 2020 (Fig. 3). Year, seedling protection status (unfenced vs. fenced), and site were most significant, along with their interactions (Table 2). Generally, seedlings protected from deer achieved significantly greater height ($F = 37.87$, $p < 0.0001$) than unprotected seedlings at the same site (Table 2). The average slope of growth was significantly steeper for seedlings within the deer exclosures for all but black cherry at the Broome site, red oak at the Essex site, and white ash at Mt. Pleasant (Fig. 3). Deer breached the exclosure and browsed oak seedlings at the Essex site reducing their height growth. Also, slow growth rates of white ash at Mt. Pleasant, and black cherry at the Broome site, limited our power for detecting deer effects.

Site-species effects significantly influenced seedling growth rates (Table 2, $F = 16.89$, $p < 0.0001$). Tree species such as red oak, red maple, and white ash generally tended to grow at faster rates and achieve greater heights than sugar maple or black cherry (slope of the lines, Fig. 3). However, growth rates for tree seedlings outside of deer exclosures was nearly flat, and some were even slightly negative (e.g., black cherry at Mt. Pleasant, and red oak at Siuslaw; Table 3),

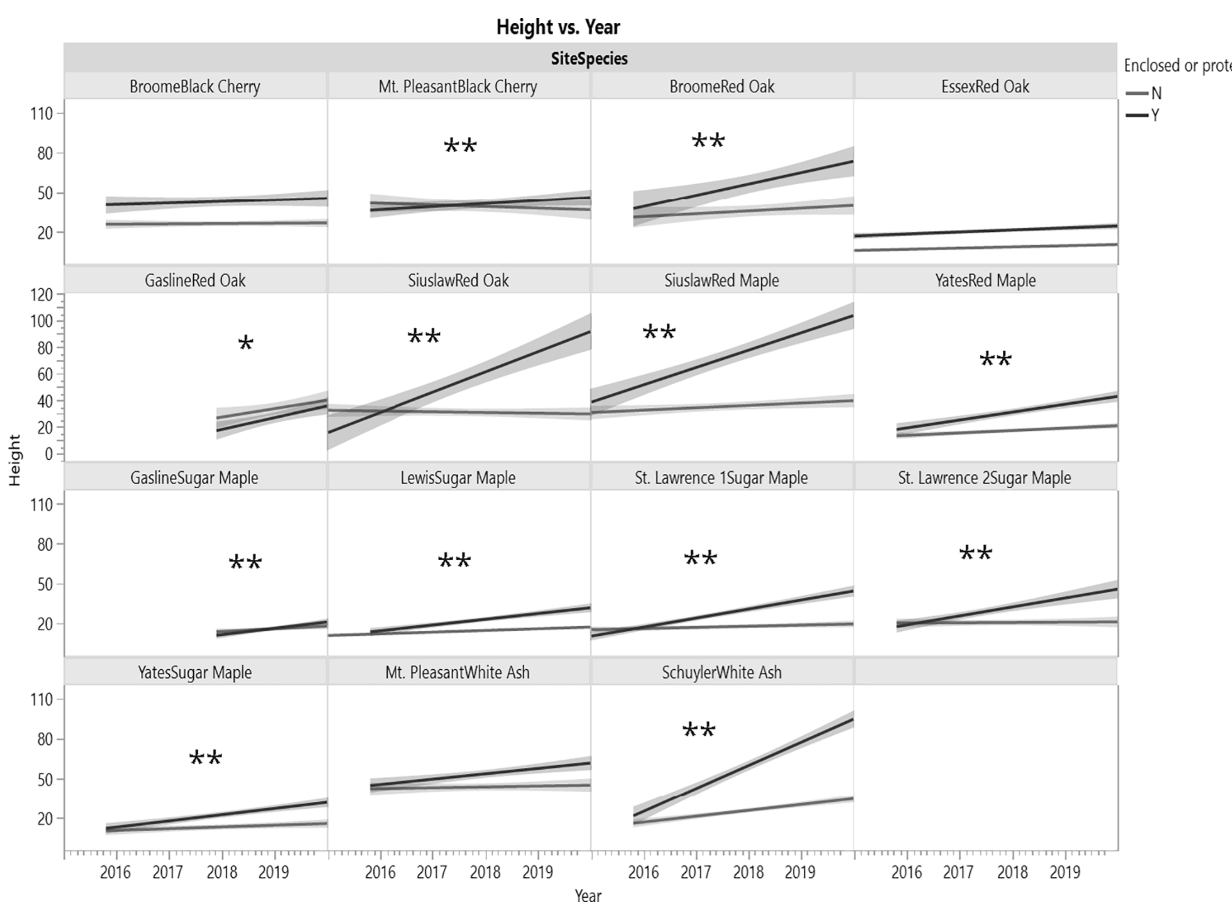

Fig. 3. The mean slope of seedling height growth (cm) for each tree species enclosed or protected by fences (dark line), and unprotected by fences (light line), for 15 species-site combinations in New York State during 2015–2020. The 95% CI is shaded and bounds the slope line. Significant slope differences are indicated as: $^*P < 0.05$; $^{**}P < 0.01$.

Table 2
Significant differences in tree seedling height at AVID plots associated with protection status, site, and year in Upstate New York during 2015 to 2020.

Source	DF	DFDen[1]	F-Ratio	Prob > F
Protected	1	79.67	37.87	<0.0001*
Year	1	2533.00	1313.24	<0.0001*
Protected*Year	1	2533.00	347.94	<0.0001*
Site-Species	14	83.93	16.89	<0.0001*
Protected*Site-Species	14	83.93	2.59	0.0038*
Year*Site-Species	14	2533.00	39.71	<0.0001*
Protected*Year*Site-Species	14	2533.00	12.06	<0.0001*

[1] DFden stands for denominator degrees of freedom, and we present the Type III Sum of Squares. The numerator degrees of freedom are shown here as DF. These two numbers allow translation of the F-Ratio into a P-value (Prob > F).

Table 3
Percent change in tree seedling height growth at AVID plots associated with protection status (fenced or open) by species and site in Upstate New York during 2015 to 2020. Significant slope differences between inside and outside fences were calculated using the Holm (1979) approach and are indicated as: *P < 0.05; **P < 0.01.

Species	Site	Inside Fence	Outside Fence	Difference
Sugar maple	Gasline**	29.6%	11.3%	+18.3%
	Lewis**	19.8%	11.1%	+8.7%
	St. Lawrence 1**	33.7%	7.0%	+26.7%
	St. Lawrence 2**	26.1%	1.7%	+24.4%
	Yates**	24.9%	9.1%	+15.8%
Red oak	Broome**	24.8%	6.0%	+18.8%
	Essex	11.6%	6.4%	+5.1%
	Gasline*	35.3%	19.1%	+16.2%
	Siuslaw**	35.9%	−0.4%	+36.3%
Red maple	Siuslaw**	19.5%	5.7%	+13.8%
	Yates**	21.5%	9.5%	+12.0%
White ash	Mt. Pleasant	4.5%	0.3%	+4.2%
	Schuyler**	35.8%	16.3%	+19.5%
Black cherry	Broome	3.3%	0.4%	+2.9%
	Mt. Pleasant**	4.9%	−4.1%	+9.0%

indicating deer impacts to seedling growth and regeneration were widespread across New York.

5. Discussion

If data associated with field conditions are to guide forest and wildlife management, we need reliable methods to efficiently assess how deer are affecting patterns of forest regeneration across whole landscapes. AVID appeared capable of detecting and quantifying deer impacts on tree seedling growth based on our paired comparisons inside and outside of fenced plots at 10 sites in New York State woodlands. These data showed 20–35% increases in average height growth for protected seedlings (Table 3), a rate that could be decisive for the survival of many seedlings and seedling populations.

However, at most AVID sites across the state, volunteers lack fenced plots for comparison. Annual changes in seedling height growth could still provide useful measures of deer impacts by allowing managers to compare changes in seedling growth rates over time and space. For sugar maple ($n = 5$ sites) and red oak ($n = 4$ sites), seedlings averaged 27% height growth when protected from deer, and only 8% height growth in areas accessible to deer browsing, a 3.4 times faster growth rate in fenced plots. For red maple and white ash, each at 2 different sites, seedlings in fenced plots averaged 20% height growth vs. 8% height growth in unfenced plots.

Having a reliable threshold indicator to identify when deer browsing seriously impedes the growth of key tree seedlings would be useful. We propose such a threshold: when average seedling height growth declines to <10%, deer impacts may be substantially reducing seedling growth. Although the 10% threshold we observed was an interesting pattern across multiple sites, that threshold was not calibrated to known deer densities, browsing impacts, or other site-specific factors. Further field evaluation and analyses are warranted.

We caution that other site-specific factors may constrain seedling growth (e.g., light conditions, soils, disturbance history, etc.). The utility and precision of AVID data may be enhanced by additional analyses to statistically control for some of the site differences affecting growth rates. Additional applications of AVID by users across a broader geographic area and having greater landscape diversity that incorporates other factors could provide further support for the pattern we observed.

Most agencies and organizations do not have time or resources to annually sample forest plots and measure seedling growth. Citizen-science volunteers who are interested in forest management on both private and state lands can sample AVID plots annually to determine seedling growth rates and evaluate deer impacts. If average seedling growth rates are <10%, then excessive deer browsing pressure may be occurring.

Although AVID plots were easy to install and evaluate, better data are needed for comparing the relative quality and cost-efficiency of obtaining deer impact information for the various available assessment methods. Ongoing research will address some of these concerns. The utility of any program to monitor deer impacts will improve as data are obtained from more sites and across additional years. If hundreds of sites can be established on a regional basis, then annual changes in deer browsing intensity may be used to adjust deer harvest quotas and potentially reduce deer impacts to tree regeneration. However, the same method to assess deer impacts must be consistently used across all sites. To date, only 5.9% of people (83 of 1,399) who were made aware of the AVID method have installed field plots and submitted data online. Additional incentives may be needed to enhance volunteer participation.

Techniques for evaluating deer impacts to vegetation require different levels of materials and skills. Rawinski's (2018) Ten-Tallest approach requires basic tree seedling identification and the ability to measure and count plants. Although this method was simple and straight-forward, it tracked the growth of plant populations and not individual seedlings. There was no way to evaluate seedling survival as the plants measured in a plot may change between years. Also, monitoring only the tallest stems biases the growth rates. A recent study found that this method was not able to detect significant differences in seedling growth inside and outside of deer exclosures after the fences were in place for > 7 years.

Waller et al.'s (2017) Twig-Age approach was able to document changes in deer browsing impacts between fenced and unfenced plots. This method required identifying both tree seedling species, bud scars, and new growth on twig tips. It can be readily accomplished with some training and experience. It would be a suitable method for documenting deer impacts if sufficient woody seedlings were available at a site.

The Oak Sentinel Seedling method (Blossey et al., 2019) provided a reliable measure of deer impacts to woody seedlings. It was the only suitable method in heavily over-browsed stands where there were few or no existing seedlings to measure. The primary drawback was that red oak seedlings must be raised in a greenhouse to plant out in the woods during spring, requiring an investment in materials, labor, and time to plant oaks, then evaluate tagged seedlings later in the growing season. Oaks are intermediate in browsing pressure by deer, and sensitive wildflowers such as trilliums may still be heavily damaged by deer even when oak seedlings survive.

The AVID approach required having existing seedlings to measure (similar to the Ten-Tallest or Twig-Age methods), so it cannot be used in severely deer-impacted sites. Plots were relatively easy to establish, requiring just a few hours per stand during the first year. Materials costs were minimal including stakes to mark plot centers, plastic plant tags, and a measuring tape. It was relatively easy to train volunteers in the field, and all necessary information to use this method (user's guide, data sheets, computer data entry) were available online (https://aviddeer.com/). Online data entry allows for graphical representation by property, county, deer management unit, or state. We plan to have a mobile app for in-field data entry available during fall 2021. Following the fate of tagged seedlings allowed AVID users to document significant differences in seedling growth rates and associated deer impacts.

Having fenced (protected) seedlings near AVID plots was useful for documenting potential seedling growth rates in the absence of deer. However, it does take time and effort to appropriately maintain fencing so that it functions properly. The deer exclosure at the Essex site was not easily accessible and thus infrequently maintained, and these fenced seedlings had regular exposure to deer browsing damage. Consequently, there were no significant differences in growth rates of red oak seedlings inside and outside of the fenced plot in Essex County.

Many landowners are interested in regenerating their forests. During 2016 through 2020, we conducted 59 Cooperative Extension events where the AVID method for sampling forest regeneration was discussed or presented (Table 4). These extension events included workshops, conference presentations, training events, and field days. Primary audiences included forest landowners, extension educators, resource management professionals, land trust personnel, agency foresters and biologists, Master Forest Owner and Master Naturalist volunteers, park staff, and college students. To date, volunteers have submitted seedling growth data from 83 sites in 24 counties across New York State.

Our long-term goal is to develop a network of volunteers providing annual data concerning deer impacts to forest regeneration that can be used by the New York State Department of Environmental Conservation (DEC) to determine deer harvest quotas on a regional basis. DEC has invested in using AVID to provide a measure of deer impacts in aggregated Wildlife Management Units across New York State. As outlined in the new statewide Deer Management Plant for 2021–2030 (NYSDEC, 2021), DEC staff intend to use indices of regeneration debt to identify regions of the state having unacceptable or vulnerable regeneration. In their decision matrix to integrate deer impacts and public preferences for deer population changes, DEC will prioritize AVID impact data in areas they classify as vulnerable or unacceptable, based on the regeneration debt indices, which included most of the southern two-thirds of New York State.

6. Conclusions

In this study, we evaluated the sensitivity of the AVID approach for detecting deer impacts, and we observed significant differences in tree seedling growth inside versus outside of paired deer exclosures for 12 of 15 site-species combinations (Fig. 3). Deer impacts to forest regeneration were widespread in stands across New York State, and AVID plots should continue to be monitored annually. For sugar maple and red oak, seedlings averaged 3.4 times faster growth rate in fenced vs. unfenced plots (27% vs. 8%; Table 3). It appeared that if average seedling height growth averaged < 10% for red and sugar maple, red oak, or white ash, this was a proposed threshold indicator of deer impacts, and deer browsing pressure impeded plant growth. We will continue recruiting volunteers to establish and monitor new AVID sites throughout the New York State.

Author Contributions

PC was involved with data collection and management, statistical analyses, funding acquisition, field methods, project administration, supervision of field technicians, drafting the original manuscript plus reviews and editing. KS was involved with conceptualization, field methods, data collection and management, statistical analyses, and review and editing of manuscript. PS was involved with conceptualization, data collection, concept review, funding acquisition, field methods, and review and editing of manuscript. JH was involved with conceptualization, funding acquisition, and review and editing of manuscript.

Table 4
Extension workshops, conference presentations, training events, and field days other events conducted annually during 2016 to 2020 where the AVID method for sampling forest regeneration was discussed or presented.

Year	No. of Events	No. of Participants
2016	6	253
2017	13	262
2018	11	154
2019	8	163
2020[1]	21	567
Total	59	1,399

[1] Six of the events in 2020 were required to be online because of Covid-19 restrictions limiting in-person meetings and conferences. About 5.9% of people (83 of 1,399) who were made aware of the AVID method have installed field plots and submitted data online.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Many professional colleagues have contributed to the development of the AVID approach for sampling forest regeneration and helped deliver extension events. We would like to thank J. Frair, M. Doviack, from SUNY-College of Environmental Science and Forestry, M. Lesser from SUNY Plattsburgh, and staff with the New York State Department of Environmental Conservation (DEC), who participated in early discussions concerning development of the AVID protocol. DEC staff provided financial support for extension workshops and development of online AVID resources. M. Ashdown established numerous plot arrays and fenced exclosures and measured seedlings. T. Testo helped with extension program delivery and data collection in eastern New York. E. Mudrak assisted with statistical analyses. We appreciate the private woodland owners who allowed access including: D. Allen, H. Bullock, B. Chedzoy, Highlands Forest Owners (E. Hall), S. Kutney, and H. Yancey. Federal formula funds from the National Institute for Food & Agriculture (NIFA)/USDA McIntire Stennis Project 2014-15-132, and financial support from DEC, allowed development of the AVID protocol, online resources, and extension program delivery.

References

Allombert, S., Gaston, A.J., Martin, J.-L., 2005. A natural experiment on the impact of overabundant deer on songbird populations. Biol. Conserv. 126, 1–13. https://doi.org/10.1016/j.biocon.2005.04.001.

Baiser, B., Lockwood, J.L., La Puma, D., Aronson, M.F.J., 2008. A perfect storm: two ecosystem engineers interact to degrade deciduous forests of New Jersey. Biol. Invasions 10, 785–795. https://doi.org/10.1007/s10530-008-9247-9.

Beaudet, M., Messier, C., Hilbert, D.W., Lo, E., Wang, Z.M., Lechowicz, M.J., 2000. Leaf- and plant-level carbon gain in yellow birch, sugar maple, and beech seedlings from contrasting forest light environments. Can. J. For. Res. 30 (3), 390–404. https://doi.org/10.1139/x99-220.

Blossey, B., Curtis, P.D., Boulanger, J.R., Dávalos, A., 2019. Red oak seedlings as bioindicators to assess browsing pressure and efficacy of white-tailed deer management. Ecol. and Evol. 9, 13085–13103. https://doi.org/10.1002/ece3.5729.

Connelly, N.A., Smallidge, P.J. Goff, G.R., Curtis, P.D., 2010. Foresters' perceptions of forest regeneration and possible barriers to regeneration in New York State. https://ecommons.cornell.edu/bitstream/handle/1813/40444/HDRUReport10-2.pdf?sequence=1&isAllowed=y (Accessed 9 July 2021).

Côté, S.D., Rooney, T.P., Tremblay, J.-P., Dussault, C., Waller, D.M., 2004. Ecological impacts of deer overabundance. Ann. Rev. Ecol., Evol., and Systematics 35, 113–147. https://doi.org/10.1146/annurev.ecolsys.35.021103.105725.

Curtis, P.D., Smallidge, P.J., Blossey, B., and Sullivan, K., 2020. Protecting the future health of forests in New York State. https://www.scientia.global/dr-paul-curtis-dr-peter-smallidge-dr-bernd-blossey-protecting-the-future-health-of-forests-in-new-york-state/ (Accessed 9 July 2021).

deCalesta, D.S., 1994. Effects of white-tailed deer on songbirds within managed forests in Pennsylvania. J. Wildl. Manage. 58, 711–718. https://doi.org/10.2307/3809685.

deCalesta, D.S., 2013. Reliability and precision of pellet-group counts for estimating landscape-level deer density. Human-Wildl. Interact. 7 (1), 60–68 (Accessed 9 July 2021). https://www.jstor.org/stable/24874117.

deCalesta, D.S., Stout, S.L., 1997. Relative deer density and sustainability: a conceptual framework for integrating deer management with ecosystem management. Wildl. Soc. Bull. 25 (2), 252–258 (Accessed 9 July 2021). https://www.jstor.org/stable/i292242.

Gorchov, D.L., Blossey, B., Averill, K.M., Davalos, A., Heberling, J.M., Jenkins, M.A., Kalisz, S.J., McShea, W., Morrison, J.A., Nuzzo, V., Webster, C.R., Waller, D.M., 2021. Differential and interacting impacts of invasive plants and white-tailed deer in eastern U.S. forests. Biol. Invasions (2021) https://doi.org/10.1007/s10530-021-02551-2 (Accessed 30 June 2021).

Holm, S., 1979. A simple sequentially rejective multiple test procedure. Scand. J. Statistics 6 (2), 65–70 (Accessed 9 July 2021). https://www.jstor.org/stable/4615733.

Horsley, S.B., Stout, S.L., deCalesta, D.S., 2003. White-tailed deer impact on the vegetation dynamics of a northern hardwood forest. Ecol. Applications 13(1), 98–118. https://doi.org/10.1890/1051-0761(2003)013[0098:WTDIOT]2.0.CO;2 (Accessed 9 July 2021).

Lesser, M.R., Dovciak, M., Wheat, R., Curtis, P., Smallidge, P., Hurst, J., Kramer, D., Roberts, M., Frair, J., 2019. Modelling white-tailed deer impacts on forest regeneration to inform deer management options at landscape scales. For. Ecol. Manage. 448 (395–408), 2021. https://doi.org/10.1016/j.foreco.2019.06.013 (Accessed 9 July).

Marquis, D.E., Ernst, R.L., Stout, S.L., 1992. Prescribing silvicultural treatments in hardwood stands of the Alleghenies (revised). Gen. Tech. Rept. NE-96, USDA, For. Serv., Northeastern For. Expt. Sta., Radnor, Pennsylvania, USA. 102pp.

McRoberts, R.E., Bechtold, W.A., Patterson, P.L., Scott, C.T., Reams, G.A., 2005. The Enhanced Forest Inventory and Analysis Program of the USDA Forest Service: historical perspective and announcement of statistical documentation. J. Forestry 103 (6), 305–308. https://doi.org/10.1093/jof/103.6.304.

McShea, W.J., Rappole, J.H., 1992. White-tailed deer as keystone species within forested habitats of Virginia. Virginia J. Sci. 43, 177–186 (Accessed 9 July 2021). http://www.vacadsci.org/vjsArchives/V43/43-1B/43-177.pdf.

Miller, K.M., McGill, B.J., Frair, J., 2019. Compounding human stressors cause major regeneration debt in over half of eastern US forests. J. Appl. Ecol. 56, 1355–1366. https://doi.org/10.1111/jpe.2019.56.issue-610.1111/1365-2664.13375.

New York State Department of Environmental Conservation, 2021. Management Plan for White-Tailed Deer in New York State, 2021-2030. NYSDEC Bureau of Wildlife, Albany, NY, 84pp. (June 2021) https://www.dec.ny.gov/docs/wildlife_pdf/deerplan21.pdf (Accessed 1 July 2021).

Rawinski, T.J., 2008. Impacts of white-tailed deer overabundance in forest ecosystems: an overview. Northeastern Area State and Private Forestry, USDA-For. Serv., Newtown Square, PA, 8pp. https://buffalo.extension.wisc.edu/files/2011/01/Impacts-of-White-Tailed-Deer-Overabundance-in-Forest-Ecosyst.pdf (Accessed 1 July 2021).

Rawinski, T.J., 2018. Monitoring white-tailed deer impacts: the ten-tallest method. USDA For. Serv., Northeastern Area State and Private Forestry, Durham, NH. 13pp. https://flnps.org/sites/default/files/newsletters/Ten-tallest%20Method%20Instructions%202018.pdf (Accessed 1 July 2021).

R Core Team, 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Rooney, T.P., Gross, K., 2003. A demographic study of deer browsing impacts on *Trillium grandiflorum*. Plant Ecol. 168, 267–277. https://doi.org/10.1023/A:1024486606698.

Rooney, T.P., Waller, D.M., 2003. Direct and indirect effects of white-tailed deer in forest ecosystems. For. Ecol. Manage. 181, 165–176. https://doi.org/10.1016/S0378-1127(03)00130-0.

Rossell Jr., C.R., Patch, S., Salmons, S., 2007. Effects of deer browsing on native and non-native vegetation in a mixed oak-beech forest on the Atlantic coastal plain. Northeastern Naturalist 14 (1), 61–72. https://doi.org/10.1656/1092-6194(2007)14[61:EODBON]2.0.CO;2.

Royo, A.A., Stout, S.L., deCalesta, D.S., Pierson, T.G., 2010. Restoring forest herb communities through landscape-level deer herd reductions: Is recovery limited by legacy effects? Biol. Conserv. 143, 2425–2434. https://doi.org/10.1016/j.biocon.2010.05.020.

Tilghman, N.G., 1989. Impacts of white-tailed deer on forest regeneration in northwestern Pennsylvania. J. Wildl. Manage. 53 (3), 524–532. https://doi.org/10.2307/3809172.

Waller, D.M., Alverson, W.S., 1997. The white-tailed deer: a keystone herbivore. Wildl. Soc. Bull. 25, 217–226 (Accessed 9 July 2021). https://www.jstor.org/stable/3783435.

Waller, D.M., Johnson, S.C., Witt, J.C., 2017. A new rapid and efficient method to estimate browse impacts from twig age. For. Ecol. Manage. 404 (361–369), 2021. https://doi.org/10.1016/j.foreco.2017.09.001 (Accessed 9 July).

Ward, J.S., Williams, S.C., Linske, M.A., 2018. Influence of invasive shrubs and deer browsing on regeneration in temperate deciduous forests. Can. J. For. Res. 48, 58–67. https://doi.org/10.1139/cjfr-2017-0208.