Part III. Indicators of Progress Towards Forest Recovery

Chapter 9. Indicators of Forest Recovery Useful for Ecosystem Management

Chapter 10. Methods of Estimating Abundance of White-tailed Deer

Chapter 9. Indicators of Forest Recovery Useful for Ecosystem Management

Measurable indicators are the basic tools required for monitoring the success of any program to recover forest structure, diversity, and ecological processes. Their use is a requirement in adaptive resource management to compare model predictions with results in the field. It is impossible to measure directly the changes in every component of the structure and diversity of a forest ecosystem. Indicators are selected that can serve as surrogates for key species and processes that are too costly or difficult to measure. The challenge is to pick those few components whose changes most fully reflect the processes, functions, and diversity trends of the entire ecosystem.[1] The effectiveness of chosen indicators can and should be tested in subsequent research to see if they indeed predict improvement across a broad range of species, structural components, and processes.

One key consideration in designing the monitoring component of an A.R.M. program is cost. In the abstract, according to wildlife ecologist William F. Porter, “many stakeholders are most comfortable with a complete census of indicator species, increasingly uncomfortable with estimates when confidence intervals enter the discussion, and suspicious when presented with indices. However, when they are confronted with the economic realities of getting the data, their comfort begins to change.”[2] For example, accurately estimating deer populations over a relatively modest area in just one year can cost millions of dollars (see Chapter 10). A.R.M. planners should get a feeling early in the planning process for where to strike the balance between monitoring cost and level of monitoring precision by obtaining realistic cost estimates for a range of monitoring strategies.

Indicators are needed to gauge forest recovery, deer browsing pressure, and soil chemistry, including acidity and buffering capacity. Forest ecosystems include many organisms in addition to herbaceous plants, shrubs, understory trees, and canopy trees that are of great interest and have strong relevance to forest recovery. Some have been used as indicators of ecosystem restoration, for example, the diversity and abundance of bird species that use the subcanopy and shrub layers.[3] However, we focus in this report on species that deer affect most directly, namely those that they eat. We assume that birds and other vertebrates, insects and other invertebrates, fungi, and soil microorganisms will also benefit from the recovery of vegetation.[4]

A key quality of indicators is how rapidly they respond to the application of a management practice. The density of the shrub layer, for example, has been shown to be useful for detecting progress in restoring forest structure within 5 years after a significant reduction in deer density, at least where seeds or live root systems are present and shade is not too dense. Results from a study carried out at the U.S. Forest Service’s Northeastern Research Station at Irvine, Pennsylvania,[5] indicate that tree seedlings and certain herbaceous species can serve in documenting change within 10 years after deer density reduction.

At the start of any program to manage deer from an ecosystem perspective, it would be wise to monitor a fairly broad spectrum of indicators and hone it down to a smaller, more cost-effective set in later years as data are analyzed and less-effective measures are identified and dropped. In this way, costs of the overall program can be reduced over time.Indicators of forest structure, such as extent of herbaceous cover and tree regeneration, are essential for measuring progress in ecosystem management, but it is also useful to have some direct measures of deer impact, for example, percentage of browsed twigs of non-preferred species, as consistency checks. Indicators of soil chemistry may be helpful in explaining variation in recovery rates by stand. It is also useful to monitor indicators of deer density to be sure that desired population changes have actually been achieved (see next chapter).

Certain tree species as rapid-response surrogates for all forest plants

Direct sampling of the most vulnerable components — shrubs and understory plants — is problematic in the short term, because recovery in forests that have been severely overbrowsed will likely take many years. Given this problem, Forum members have looked at supplementing direct measures of herbaceous and understory plants that recover rapidly, such as *Rubus* species, with a more rapidly responding surrogate for herbaceous vegetation. The surrogate is a subset of the tree species, namely, those that can regenerate successfully only if browsing pressure is low enough also to permit recovery of shrub and herbaceous plant diversity. The assumption is that seed sources remaining in the canopy are available to initiate recovery of this component of the woody flora quickly, even where the reappearance of most shrubs and herbaceous species will take longer because of the deer-induced decline of local seed sources. Whether deer management policies that enhance the regeneration of the suite of indicator trees will actually enhance the regeneration of understory plants will need to be tested in the years ahead.

In the well-studied northern hardwood forests of northwestern Pennsylvania, many of the trees regenerate at less than 20 deer per square mile; herbaceous vegetation however, needs densities of less than 10 deer per square mile and full recovery of herbaceous and shrub species diversity may require even lower deer densities. As deer density is reduced, seedlings of black cherry (one of the species least preferred by deer) return first, then sweet birch or yellow birch. followed by eastern hemlock, red maple, white ash, and yellow-poplar (species highly preferred by deer). The latter species are useful as indicators of progress toward recovery. Because of regional variation in tree species composition, it will be necessary to tailor the suite of indicator species by region (see Table 4, pages 53-58).

Data collection would focus on the height and density by species of tree seedlings in scattered sample plots within each of a series of study areas across the state. Typically, tree seedlings of species that deer prefer fail to grow over 1 foot tall if subjected to heavy browsing in uncut or partially cut stands.

Not all forest stands are suited for measurements of indicator-tree regeneration. Stands must be selected where light at the forest floor is sufficient to support the relatively rapid growth of seedlings, which generally excludes stands where the most recent cutting was less than 50 years ago unless they are thinned at around the time when management to reduce deer density is begun. Clearcut stands do not qualify because the flush of new growth can temporarily provide enough forage to satiate even a very dense deer population, delaying the detection of differences in tree seedling survival between clearcut sites where the deer population is reduced and comparison clearcuts where deer management is left unchanged. One possibility for measuring rapid vegetation response to deer herd manipulation may be intact stands more than 50 years old with scattered openings in the canopy due to the death of mature trees. The main advantage of such sites is that it is easy to characterize the forest canopy composition in an intact stand, thereby establishing a baseline against which species' rates of seedling survival can be compared. The disadvantage is that indicators will respond slowly and only in patches, due to the localized availability of light. Indicators are likely to respond faster in stands that have had a partial overstory removal in the past 5 years or so, where light is likely to be more uniformly available at ground level. Furthermore, germination from the seed bank is often accelerated by soil disturbance associated with canopy thinning and potential sites should be easy to identify using aerial photographs or records of recent timber sales. However, in recently thinned stands a much more laborious analysis of the cut stumps would be necessary to establish the baseline forest canopy composition for comparison.

Combined sets of indicators for northern hardwood forest regeneration

In recommending indicators of forest recovery, we focus on the northern hardwood forests across Pennsylvania's northern tier because that is the forest region where the most extensive, directly pertinent research has been done, in large part by scientists at the U.S. Forest Service's Northeastern Research Station in Irvine, Pennsylvania. Some, but not all, of these indicators will be useful in other forest types. Developing state-of-the-art sets of indicators for the remainder of the state will require a comprehensive review of past and ongoing research in Pennsylvania and nearby states on oak-mixed hardwood forests and other forest types. Based on a review of data by staff at the Northeastern Research Station in areas treated with different, controlled deer densities, one might expect to detect significant effects on the recommended indicators (see next page) within 3 to 5 years in thinned stands and 5 to 10 years in intact stands more than 50 years old. These estimates are based on the assumptions that (1) deer density is reduced to about 20 per square mile or lower, (2) stands are in a matrix of managed forest, (3) and there is no agricultural land in the surrounding landscape.

Recommended forest recovery indicators for northern hardwood forests in Pennsylvania are:

(1) Number of stems more than 1 foot tall, categorized by size classs, of tree species most preferred by deer (e.g., red maple, white ash, yellow-poplar, cucumbertree, oaks, eastern hemlock; see Table 4, pages 53-58).

(2) Species richness of tree seedlings and saplings between 1 foot tall and browse height (5 feet) per unit of area.

(3) Equitability or evenness among species of tree seedlings and saplings between 1 and 5 feet tall per unit of area (a common measure of this component of diversity is Simpson's index, the probability of any two individuals drawn at random belonging to different species).

The first three recommended indicators are measurements of tree seedling size and diversity. They are a short-term surrogate for total vascular species composition. It is likely that restoration of herbaceous species diversity will take much longer due to lack of propagules in many areas.

(4) Percent ground cover of *Rubus* (increased cover by *Rubus* is an early indicator of low deer impact where shade at the forest floor is not too dense).[6]

(5) Ratio of *Rubus* to hay-scented and New York ferns.

The *Rubus*-to-fern-cover ratio can serve as a short-term surrogate for the development of full-blown shrub and understory layers (partial structural restoration) which will take much longer.

(6) Ratio of cover of seedlings of deer-preferred trees (e.g., oaks, eastern hemlock, red maple, white ash, and yellow-poplar) to cover of seedlings of less-preferred trees (e.g., black cherry, sweet birch, yellow birch)

(7) Trillium height[7]

(8) Percent of Canada mayflower with flowers or seeds[8]

(9) Percent of American beech stems that are browsed, categorized by browsing severity (American beech is very widely distributed in Pennsylvania and resistant to browsing)

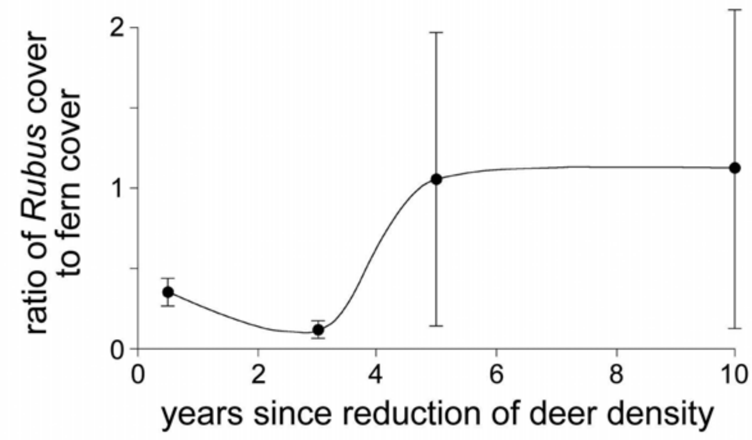
(10) Height of the tallest stem of each preferred species and of the tallest stem of all species combined

Other plants with potential for indicator status that might be considered at some point, either in northern hardwood forests or in other forest types, include wild sarsaparilla[9], sweet-cicely, jack-in-the-pulpit, white baneberry,[10] and Indian cucumber-root.[11] Species considered by various researchers but not recommended for use in Pennsylvania (see endnotes for reasons) include bluebead lily and white wood-lily[12], American yew[13], wood nettle[14], turtlehead, white wood aster, zigzag aster, and jewelweed[15], and eastern hemlock.[16]

For the recommended indicators to be useful in A.R.M., it is necessary to make predictions, based on previously collected data, of their change in response to managed reductions in deer density. For instance, in northern hardwood forests, indicator data (or a composite function of the data) obtained by researchers at the Northeastern Research Station could be graphed as a function of time after deer density reduction, allowing predictions of when the changes would be detectable.

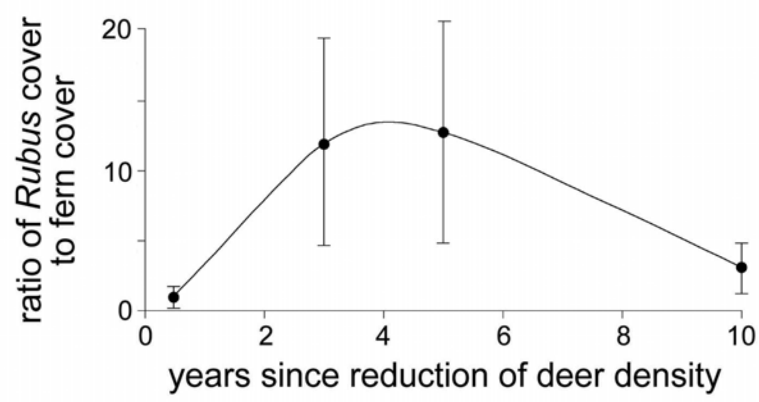
Here we show examples (Figures 5 and 6) based on the ratio of *Rubus* cover to hay-scented and New York fern cover, calculated from data collected in four northern hardwood forest stands in northwestern Pennsylvania.[18] The data were collected after deer density was reduced to approximately 20 deer per square mile from an initial level thought to be about 40 deer per square mile.

Figure 5. Average ratio of *Rubus* cover to hay-scented and New York fern cover in uncut stands over 50 years old, following abrupt reduction of deer density from 40 to 20 deer per square mile (data are from northwestern Pennsylvania;[17] error bars are ± 1 standard error of the mean).



In uncut stands over 50 years old (Figure 5, above), the ratio increased dramatically by 5 years after deer density reduction. However, the error bars are large in this four-stand average. It would be necessary to take measurements in approximately 64 stands to be confident of finding an effect with reasonable statistical significance.[20]

Figure 6. Average ratio of *Rubus* cover to hay-scented and New York fern cover in recently thinned stands following abrupt reduction of deer density from 40 to 20 deer per square mile (data are from northwestern Pennsylvania;[19] error bars are ± 1 standard error of the mean).



In stands thinned at the same time that the deer population was reduced (Figure 6), the ratio rose dramatically within 3 years. By 10 years, as the stand closed up around the thinned areas, the ratio dropped. Even then, however, the ratio was much higher than it was at the time of deer density reduction. The 10-year ratio in these thinned stands is similar to the ratio at 10 years for the uncut stands (Figure 5). However here again, due the large error bars, to be confident of finding an effect as part of an A.R.M. program, the number of stands would need to be increased to around 64.

Based on the graphical analysis (Figures 5 and 6), it would be reasonable to predict a delay of 3 to 5 years before meaningful feedback could be provided from field measurements following a successful reduction in deer density. In practice, changes in deer densities as part of an A.R.M. process will not be abrupt. An increase in antlerless deer harvest permits will not have its full impact until several years after its introduction. Therefore, an additional delay, say 2 years, would be needed, bringing the total time to 5 to 7 years before the initial weights chosen for A.R.M. could be modified for the first time. Thereafter, corrections could be made as often as monitoring measurements were taken.

The data from the Northeastern Research Station represent a 50% reduction in deer density. Presumably, it would take longer to detect changes in the *Rubus*-to-fern cover ratio following lesser reductions in deer density.

Forum members were not able to obtain data that could be used to test the potential utility of the other indicators listed in the set recommended earlier in this chapter to begin A.R.M. in northern hardwood forests. However, data on some of these indicators are now being collected as part of ongoing work at the Northeastern Research Station and will be available in the future. Using results from this and other ongoing research, analysts and A.R.M. program planners will be able to find combinations of indicators that perform far better than any single indicator, including the *Rubus*-to-fern-cover ratio, in terms of the time necessary to detect a change or in the number of stands that will need to be sampled. Once an adaptive research management program is underway, data collected as part of the A.R.M. protocols will be invaluable in improving the choice of indicators used to provide feedback to managers.

Indicators of soil acidity and other soil chemical properties

Chemical element content of leaf tissue and wood from key indicator species such as shrubs in the genus *Rubus* can be tested to determine nutritional status as affected by interactions among natural soil fertility, atmospheric deposition, and deer management. Foliar tissue collected late in the growing season or recently formed xylem tissue collected in the dormant season from woody species can be used for analysis. Molar ratios of calcium (Ca) or magnesium (Mg) to manganese (Mn) or aluminum (Al) in plant tissue have been found to be useful for monitoring differences in soil fertility among regions and changes in soil fertility over time in a given region.[21] Lower ratios of Ca:Mn, Mg:Mn, Ca:Al, and Mg:Al signify increased stress on plants' growth due to poorer soil fertility relative to areas with higher ratios. Decreases in these ratios over time in a given region suggest changes due to atmospheric deposition, whereas increases in these ratios in a region could indicate positive effects of deer management. Soil fertility should be documented within the various deer management treatments and regions over time. A simple Al stress test is recommended, such as the one performed routinely on soil samples by the Pennsylvania State Analytical Services Laboratory using the strontium chloride extraction method, which approximates mineral nutrient concentrations available to plants. Molar ratios of Ca:Al in soil have been used to indicate stress on plant growth. According to one recent study, "there is a 50:50 risk of adverse impacts on tree growth or nutrition when the soil solution Ca:Al ratio is as low as 1.0, a 75% risk when the soil solution ratio is as low as 0.5 and a nearly 100% risk when the soil solution Ca:Al molar ratio is as low as 0.2."[22]

Tolerances of various plant species such as *Rubus* spp. to soil chemical conditions are major variables to be considered in the design of an A.R.M. program. Plant response to deer management may be rapid in areas with soil chemical conditions favorable to an indicator species' growth but non-existent in areas with unfavorable soil conditions. Little information is available about the responses of many indicator plant species to a range of soil conditions. At a minimum, monitoring of soil fertility indicators is needed to help interpret results.[23] Certain types of results would suggest the need for further experiments to disentangle the effects of soil nutrients from deer impacts.

Findings on indicators

(1) Reasonable indicators of forest recovery for use in ecosystem management and deer A.R.M. include the frequency of occurrence, density, and condition (e.g., height, severity of browsing) of representative plant species, both herbaceous and woody. A candidate set is recommended in this report. Expected response times after substantial reduction of high deer densities range from 3 to 10 years. Indicators of soil quality, such as soil acidity, are included to assist in understanding variations in forest recovery rates. Over time, the most cost-effective set of indicators can be identified as an outcome of the A.R.M. process, discussed in Chapter 12.

(2) Indicators include measurements of tree seedling size, abundance, and species diversity, which are short-term surrogates for recovery of the entire vascular plant species community. It is likely that restoration of herbaceous species diversity (full structural recovery) will take much longer due to lack of propagules in many areas. The *Rubus*-to-fern-cover ratio can

serve as a short-term surrogate for the development of full-blown shrub and understory layers (partial structural recovery) which will take somewhat longer.

(3) Although many of the indicators identified for northern hardwoods will apply to other forest types in Pennsylvania, complete sets of indicators need to be developed for the other forest types. This could be done by an ad hoc scientific advisory committee established by agencies in Pennsylvania responsible for public forestlands.

(4) With input from stakeholders and scientists, agencies should adopt short-term goals and, where a consensus exists, long-term goals on the target values for measurable indicators of forest ecosystem recovery. Where a scientific consensus does not exist on long-term ecosystem recovery goals, a group of scientists should be convened to develop such a consensus.

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[1] Keddy and Drummond 1996; Lindenmayer et al. 2000

[2] Dr. William F. Porter, Professor of Wildlife Ecology, Department of Environmental and Forest Biology, State University of New York, personal communication, 2003

[3] McShea and Rappole 2000; deCalesta 1994

[4] This assumption needs to be tested periodically.

[5] Horsley et al. 2003

[6] In thinned stands, a strong, highly statistically significant relationship has been found in northwestern Pennsylvania between percent ground cover by *Rubus* and deer density (Horsley et al. 2003). The effect was detected in as little as 3 years at one of three study sites (Fools Creek, Warren County). The same phenomenon was seen in uncut stands, but there *Rubus* growth took 10 years for the effect to be large enough to be detected.

[7] The height of large white trillium plants has proved useful as an indicator of browsing intensity in Illinois (Anderson 1994) and Minnesota (Augustine and Frelich 1998). Large white trillium might be a useful indicator in the westernmost quarter of Pennsylvania, the only part of the state in which this species was ever common and abundant (Rhoads and Klein 1993). However, it is possible that only in the extreme southwestern counties does large white trillium remain common enough to be useful. Purple trillium and painted trillium are somewhat more abundant and widespread. Recent research by Susan Stout and colleagues at the Forestry Sciences Laboratory in northwestern Pennsylvania has shown that the height of purple trillium or painted trillium is a useful indicator of deer impact in the northwestern counties (Dr. Susan L. Stout, Silviculturist/Research Project Leader, Forestry Sciences Laboratory, U.S. Forest Service, and Chad D. Kirschbaum, Sand County Foundation, personal communication, 2003). Augustine and deCalesta (2003) suggested that a sensitive indicator of browse intensity can be constructed by observing flowering rate, mean stem height, size class distribution, and browsing rate of *Trillium* plants.

[8] Canada mayflower was suggested as an indicator by Balgooyen and Waller (1995). Research conducted in northwestern Pennsylvania by Rooney (1997) documented larger leaves and greater frequency of flowering shoots in populations growing on large boulders out of the reach of deer compared with those on small boulders that deer could reach. Based on Rooney's work, recently initiated research by the U.S. Forest Service at Irvine,

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Pennsylvania, is using leaf size and flowering frequency of Canada mayflower as an indicator in a quality deer hunting demonstration area study. Canada mayflower is common and abundant in moist forests throughout the state (Rhoads and Klein 1993). It remains visible throughout the growing season. Plants that will flower or have flowered in the current season are readily distinguishable.

[9] Wild sarsaparilla is another species that Balgooyen and Waller (1995) considered to be a potentially useful indicator. It is a plant of widespread occurrence in Pennsylvania, especially in dryish, acidic, upland forests (Rhoads and Klein 1993). Many populations appear to have few if any flowering/fruiting stems, but it is not known if that can reliably be correlated with intensity of deer browsing.

[10] Webster and Parker (2000) evaluated the potential of sweet-cicely, jack-in-the-pulpit and white baneberry to serve as indicators of browsing intensity. They found a correlation between stem height of all three species with herbaceous species cover adjusted to discount the invasive weed garlic mustard and native species observed to increase in heavily browsed areas (wild ginger and mayapple). They concluded that the mean height of mature plants of sweet-cicely, jack-in-the-pulpit, and white baneberry is significantly reduced in deer impacted areas and that flowering is reduced in white baneberry and jack-in-the-pulpit. They suggested that a single indicator is inadequate because of uneven abundance. All three species examined in this study are widespread in Pennsylvania; jack-in-the-pulpit is the most abundant. There is some doubt that mayapple commonly increases in heavily browsed areas; this is certainly not true in the Wissahickon section of Fairmount Park in Philadelphia. In the Wissahickon forest, mayapple stands are almost gone from the most heavily browsed area; all that remains in some sites are a few juvenile shoots that are barely hanging on (A. F. Rhoads, personal observation). The impact of grazing on the leaves of jack-in-the-pulpit was discussed by Ruhren and Handel (2000), who found lower than expected flower and fruit production among affected plants in a study of browsed forests in New Jersey. One reviewer of an earlier draft of this chapter had an alternate view of the usefulness of some of the proposed indicators, stating: “Based on my data, I disagree with, or would suggest amendments or alternatives to, several of the measures proposed as indicators in Chapter 9. Of course, I understand that the report’s list of possible indicators is only a first stab at some likely ones. The A.R.M. team that eventually oversees the application of A.R.M. will obviously have to do their own initial evaluation, and propose assays that seem reasonable within the model’s framework” (Dr. Daniel Townsend, Associate Professor of Ecology, Department of Biology, University of Scranton, personal communication, 2003). We encourage participation by this reviewer and others who have conducted pertinent research in Pennsylvania forests in subsequent evaluations of indicators.

[11] Indian cucumber-root is visible all summer. Blooming plants form a second tier of whorled leaves. Flowering and the formation of the upper whorl appear to be suppressed in heavily browsed areas.

[12] Bluebead lily has been suggested as a browsing-intensity indicator in Wisconsin (Balgooyen and Waller 1995). In Pennsylvania it was historically found in northern counties and at high elevations along the Allegheny Front (Rhoads and Klein 1993). It is much more limited in abundance today, and may have already become too depleted to be a sensitive indicator. It is rarely found blooming. More often just leaves are present and those tend to be at scattered sites. The closely related white wood-lily was once abundant in the western third of Pennsylvania but is now greatly diminished, especially in the northwest.

[13] American yew has been identified as a species that is preferentially browsed (Allison 1990a, 1990b, 1992) and suggested as an indicator (Balgooyen and Waller 1995). It was widespread in Pennsylvania at one time (Rhoads

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and Klein 1993), but has become so depleted as to be of little use as an indicator today. It persists mainly on steep slopes and cliffs out of reach of deer.

[14] Wood nettle, whose potential value as a browsing-intensity indicator was discussed by Augustine et al. (1998), occurs throughout the state, primarily in low, moist forests and floodplain areas (Rhoads and Klein 1993). It may be too narrowly habitat-restricted to be generally useful as an indicator of browse severity.

[15] Williams et al. (2000) concluded that although turtlehead was frequently browsed, stem height could not reliably be correlated with deer density. Although it occurs throughout the state, turtlehead is limited to riparian and wetland areas (Rhoads and Klein 1993). Williams et al. (2000) suggested that an assemblage of herbaceous species might be more reliable than a single indicator and mention white wood aster, zigzag aster and jewelweed as possibilities. Bluestem goldenrod and silverrod have also been suggested for this purpose (Dr. Daniel Townsend, Associate Professor of Ecology, Department of Biology, University of Scranton, personal communication, 2003). White wood aster, bluestem goldenrod, and silverrod are common and abundant forest plants throughout Pennsylvania, and jewelweed and zigzag aster are common to abundant in wetlands (Rhoads and Klein 1993).

[16] Several researchers have suggested that seedlings of eastern hemlock could serve as an indicator of deer browsing intensity. However, many factors have been shown to affect the establishment and successful growth of hemlock seedlings (Long et al. 1998; Mladendorff and Stearns 1993), making it doubtful that their abundance or condition could reliably be used to infer browsing intensity alone.

[17] S. B. Horsley, unpublished data; see Horsley et al. (2003) for methods.

[18] S. B. Horsley, unpublished data; see Horsley et al. (2003) for methods.

[19] S. B. Horsley, unpublished data; see Horsley et al. (2003) for methods.

[20] Based on $\alpha = 0.1$ and $\beta = 0.2$, i.e., with a 90% chance of correctly accepting the null hypothesis if it is true and an 80% chance of correctly rejecting the null hypothesis if it is false would probably be adequate.

[21] Dr. David R. DeWalle, Professor of Forest Hydrology, School of Forest Resources, Pennsylvania State University, personal communication, 2003

[22] Cronan and Grigal 1995

[23] Dr. David R. DeWalle, Professor of Forest Hydrology, School of Forest Resources, Pennsylvania State University, personal communication, 2003

Chapter 10. Methods of Estimating Abundance of White-tailed Deer

It is difficult to observe deer and estimate abundance using simple counts; nevertheless there have been many methods developed to estimate the abundance of white-tailed deer because they are an economically important species. Methods that provide accurate and precise population estimates usually are expensive. Traditionally, wildlife managers have used estimates or indices of deer abundance to recommend harvest quotas to meet management goals based on deer densities.[1] This approach to deer management does not necessarily explicitly acknowledge the uncertainty (levels of bias and precision) of these population estimates, and public disagreement over deer numbers often leads to confusion for decision makers. Aldo Leopold and colleagues noted, "A common error is to try to appraise [deer numbers] by census, rather than by browse conditions. The public can dispute endlessly about censuses, but it cannot dispute dead browse plants."[2]

In this report we investigate the use of plant indicators for monitoring forest ecosystem conditions and the effect of deer (see Chapters 9 and 11) within an adaptive resource management paradigm. However, to do this one still needs to monitor deer abundance to make certain that management actions intended to reduce (or increase) deer populations actually do so. Because A.R.M. incorporates uncertainty of data inputs into the process, a measure of deer abundance statewide or in large regions within the state could be quite crude and still be useful, for example, an index of deer abundance such as road-kill counts. However, if the importance of deer browsing impacts on forest conditions is to be studied at a more experimental scale (see Chapter 12) then more accurate and precise (and expensive) deer population estimates will be required.

Survey methods can be classified into two general types: indirect methods based on monitoring deer signs (e.g., tracks or harvest numbers) and direct methods that require capturing or observing deer. This chapter describes the various methods that have been developed by wildlife biologists to estimate population abundance or to monitor changes in abundance over time.

Indirect Methods

Most of the indirect methods do not provide estimates of absolute abundance, but are intended to provide an index of relative abundance that can be used to detect relative changes over time. For example, counts of the abundance of deer trails,[3] tracks,[4] deer sightings per kilometer walked on foot,[5] intensity of browsing,[6] abundance of fecal pellet groups,[7] and number of deer killed along roads[8] have all been used as indices of abundance. Hunter harvest data have been used as an index of abundance (e.g., density of buck harvest) as well as to obtain population estimates.[9] All of the index methods assume that potential sources of variability in the index (e.g., deer defecation rates, hunter effort, or movement by deer across the landscape) are constant over time so that even though the method does not provide a measure of absolute abundance, the changes in the index over time reflect changes in population size alone.

In addition to providing an index of abundance, pellet group counts have been used to obtain estimates of absolute (actual) abundance[10] by relying on certain assumptions about deer defecation rates. Although specific field methods used to collect pellet group data vary widely, the following general equation is used to estimate deer density:[11]

$$\textit{deer density} = \frac{G}{R \times Y} \qquad \text{Eq. 5}$$

where G is the density of pellet groups on the study area, R is the defecation rate of an individual deer (pellet groups per deer per day), and Y is the number of days deer have been defecating. A typical method would be to visit a sample of circular plots across the study area and eradicate all existing pellet groups on the plot, then return to those plots Y days later and count the newly deposited pellet groups. By assuming a defecation rate, deer density can be estimated using Equation 5 and abundance can be estimated by multiplying by the size of the study area. The assumptions of this method are that a random sample of plots has been selected, the defecation rate (R) is constant among deer and surveys, and pellet groups are counted accurately on the plots.

There is some value in discussing how the pellet group technique has been used in Pennsylvania, because it has generally been applied somewhat differently from this description.[12] First, the number of days (Y) has been taken to be the number of days since leaf drop. This removes the labor requirement of first eliminating all existing pellet groups on plots, but imposes the assumption that all pellet groups deposited prior to leaf fall have been covered by leaves and that this event occurs on a specific date. Second, pellet groups are typically counted along 6-foot wide transects that are approximately 5,000 feet long; however, current recommendations are to count pellets on 4-foot radius plots located every 100 feet along the transect, and to survey more transects of shorter length.

In applying the pellet group counting method, including modifications of the technique,[13] several factors must be considered to minimize variability and bias in the resulting density estimates: (1) observer skill and fatigue in detecting pellet groups, (2) choice of plot shape, (3) habitat (vegetation) influences on detection of pellet groups, (4) decay rate of pellet groups, and (5) an appropriate sampling design. A study design and data analysis that take into account many of the potential problems with typical pellet group surveys have been described and implemented by a group of researchers in Scotland.[14] They used distance sampling[15] to account for differential detection among habitats, included decay rates of pellet groups, and used a statistically based sampling design. However, even these methods require a number of suspect assumptions, including a constant defecation rate and no variation in decay rates among habitat types. Research on defecation rates indicates that they vary among seasons (presumably because of dietary changes) and age-sex classes[16] and decomposition rates differ according to habitat type.[17]

Indices or estimates of abundance based on hunter harvest data have been commonly used by state agencies because harvest data are readily available. A review of nine general types of methods of estimating abundance using harvest data,[18] including multiple methods within each type, concluded that index-removal, change-in-ratio, and life table analysis methods were least satisfactory because critical assumptions could not be met. Harvest age structure and harvest sex ratio methods were better but did not provide precise population estimates. Population reconstruction methods were sensitive to varying harvest rates but could only provide historical population estimates. Some of the models based on a catch-per-unit-effort (C.P.U.E.) approach were best at closely monitoring trends in abundance. The Lang-Wood and Fraser methods were not as effective as the C.P.U.E. models, but the reviewers suggested they could serve as supplemental methods of analyzing harvest data.[19]

C.P.U.E. techniques can be used if hunter harvest and capture effort are recorded (e.g., hunter-days or trap-nights) and these data are collected over *t* time intervals (usually days or weeks). The simplest form of a C.P.U.E. model assumes the following relationship between harvest (catch), effort, and population size:

$$\frac{harvest}{effort} = kN \qquad \text{Eq. 6}$$

where the t data points are used to estimate N at $t = 0$ (i.e., the population size prior to any removals). The key assumptions of this technique are that the population is closed during the time interval under study (no immigration, emigration, births, or deaths) except for the known removals and that all individuals are equally susceptible to harvest. More complicated models that relax the assumption of closure or equal harvest probability have been developed.[20] One research group who applied the C.P.U.E. technique to deer at Chesapeake Farms, Maryland, found that the population density estimates were, on average, 14% below direct estimates of abundance, but that the method accurately described relative changes in the population.[21]

Direct methods

Methods of monitoring deer populations in which animals are counted in some manner may or may not attempt to adjust for the fact that the probability of detection is less than 100%. If the probability of detection is assumed to be 100%, the counts can be treated as an estimate of absolute abundance; otherwise, the counts are treated as an index of relative abundance. In all the methods discussed hereafter, if the method does not directly incorporate an estimate of detection probability, counts can be adjusted for a probability of detection less than 100% by marking a subset of deer and using them to estimate the probability of detection experimentally.

Drive counts

In fenced areas, researchers have used drives to count deer. Drives involve a line of people traversing the study area and counting all deer observed on the area. Problems found with this technique include (1) double-counting by observers, (2) deer gone undetected in thick vegetation, (3) gaps in the observer drive line where deer escaped undetected, and (4) differences in the behavior of deer among years because of weather conditions and other unknown causes.[22] Even if the protocols used to conduct the count are standardized as much as possible, the estimates are unlikely to have a constant bias, and will simply provide a minimum number of animals on the study area.

Spotlight counts

Spotlight counts have been used to census deer[23] because the species is more active at dusk and can be seen in greater numbers at this time of day. The primary problem is that spotlight counts typically are conducted along roads and do not survey areas inaccessible by vehicles. Spotlight surveys have a probability of detection less than 100% because of the areas not surveyed and because not all animals are visible behind obstructing vegetation.

Aerial surveys

Aerial surveys provide the ability to cover large areas quickly and easily, although the hiring of pilots and rental of aircraft can be expensive. Moreover, to obtain accurate and precise population estimates the probability of detection must be estimated and incorporated into the estimator of abundance. A 1987 review of various estimators applicable to aerial surveys summarized methods of estimating abundance[24] by (1) correcting aerial counts with a subset of areas where both aerial and ground counts are conducted, (2) using observations from independent observers of the same area with Lincoln-Petersen or Zippin estimators, (3) having a marked (e.g., radio-collared) subpopulation of animals to estimate detection probability,[25] (4) multiple counts (e.g., bounded count estimator[26]), (5) distance sampling, and (6) sightability modeling.

Theoretical development and application of distance sampling in aerial surveys has been greatly expanded since the 1987 review; the methods were reviewed in detail in 2001 by another research group.[27] Line transect distance sampling assumes that all objects on the transect line are detected, but in reality detection probability may decline away from the transect line. By modeling this decline as a mathematical function, a detection probability can be estimated for any distance an object is located from the transect line. The difficulty with applying distance sampling for deer via aerial surveys is that the assumption that all objects on the transect line are detected is likely to be violated.[28]

Sightability estimators model the probability of detection as a function of animal and background environmental characteristics (e.g., group size, vegetation cover, behavior of the animal).[29] This model is developed from data collected by marking animals, conducting aerial surveys, and then recording the characteristics of each animal and whether it was observed or not. The method is appealing because once a sightability model is developed, additional animals do not have to be marked, which greatly reduces the cost of the technique. However, in a study of elk in Pennsylvania the population estimates were found to be too variable for use as a management tool.[30]

Thermal imagery

The primary problem with using aerial surveys for white-tailed deer in Pennsylvania is the visual obstruction by vegetation. Wildlife agencies in the western United States rely primarily on aerial surveys to estimate abundance of big game species,[31] but visual obstruction in sagebrush and other open habitats is a far less significant problem than in the forested habitats of Pennsylvania. Moreover, snow cover is not consistent in Pennsylvania, and snow enhances visibility of animals for aerial surveys.[32] One technological solution to the visibility problems associated with aerial surveys of deer is the use of thermal imagery. Researchers in Florida reported that standard aerial survey methods counted only 58% of the number of deer counted using thermal imagery;[33] however, whether the thermal imagery detected all deer is unknown. Detection probabilities of 72 to 87% were reported using a helicopter to survey white-tailed deer in forested habitat in Missouri with snow cover,[34] which suggests that thermal imagery may have greater detection rates than other aerial survey methods.

Mark-recapture

Mark-recapture methods involve individually marking deer and comparing the proportion of marked deer recovered in the harvest with the total harvest. The estimator is the same as that used in aerial surveys described above.[35] This method is expensive because a large number of deer need to be marked — at least 45% of the deer if the population is small (less than 200 animals). In addition, the method is based on the assumption that marks are never lost and that deer do not emigrate from the study area. The mark-recapture method has been shown to overestimate deer population size because of unknown mortality of marked deer and emigration from study areas.[36] Accurate monitoring of mortality and emigration requires the use of radio-collars in place of marks. Another problem with this method is that every deer is assumed to have the same probability of being harvested, which is unlikely to be true. Harvest rates are likely to differ between sexes because of harvest regulations (limited antlerless permits) and hunter preferences, and among deer of different ages (e.g., lower harvest rates of older age-classes).

Camera surveys

Infrared emission-triggered cameras have been used to collect sighting-resighting data to estimate the population size of white-tailed deer,[37] in some cases using the Lincoln-Petersen estimator with photographic "recaptures" of previously radio-collared deer.[38] Camera surveys have also been used to derive minimum deer population estimates using the ratio of spike-to-branch-antlered bucks, the fawn-to-doe ratio, and the number of unique branch-antlered bucks photographed.[39] However, unless the study area is saturated with cameras, the capture probabilities among deer will be heterogeneous and population estimates will be biased low. A 1997 estimate of the cost of a 140-day survey, at one camera per 160 acres, was 52 cents per acre per year with the cost of equipment amortized over 5 years.[40]

Change-in-ratio

The change-in-ratio technique, when used for deer, requires surveys of the ratio of antlered to antlerless deer prior to and following a hunting season, as well as the number of deer harvested.[41] Although the data are relatively simple to collect, the assumption that antlered and antlerless deer are seen with the same probability is likely to be violated;[42] however, if only one type of animal (e.g., only antlered deer) is removed during the hunt, the population estimate for that type is unbiased.[43] An evaluation of the method at Chesapeake Farms, Maryland, in relatively open habitat showed that sample sizes to obtain adequate precision of population estimates could be achieved.[44] The observation rate there was 196 deer per 100 miles of survey route. A drawback is that if a deer population is managed near a 1:1 antlered-to-antlerless ratio then the change-in-ratio estimator will not work because the change in ratio will be near zero.

Findings on methods of estimating abundance of white-tailed deer

(1) Within A.R.M., confirmation of changes in deer abundance following management actions will be necessary to ascertain that management actions intended to decrease (or increase) deer populations actually do so.

(2) Precise and accurate estimates of deer abundance are expensive. For large areas (e.g., the Pennsylvania Game Commission's 21 wildlife management units covering all of

Pennsylvania; see Figure 4A), relatively crude but easy-to-measure indices of abundance may have to be used.

(3) If deer populations are manipulated on a small area (e.g., several square miles) to learn more about the effect of deer browsing on forest conditions in an experimental context, more accurate and precise population estimates will be required.

Recommendations on methods of estimating abundance of white-tailed deer

(1) The Pennsylvania Game Commission currently obtains accurate estimates of deer harvest, by wildlife management unit, to estimate the deer population prior to the hunting season; this method of population estimation would likely be sufficient for A.R.M. applied on a statewide basis.

(2) Experimental areas where deer populations are intentionally manipulated to provide a more direct test of competing models under A.R.M. will require more expensive methods of population estimation. Because the best method depends upon the characteristics of the study area, specific recommendations are not possible within the scope of this report.

Endnotes

[1] E.g., Kubisiak et al. 2001
[2] Leopold et al. 1947: p. 175
[3] McCaffery 1976
[4] Yanosky and Mercolli 1994
[5] Vincent et al. 1991
[6] Morellet et al. 2001
[7] Neff 1968
[8] McCaffery 1973
[9] Roseberry and Woolf 1991
[10] Neff 1968
[11] Neff 1968
[12] deCalesta 1991
[13] deCalesta 1991
[14] Marques et al. 2001
[15] Buckland et al. 2001
[16] Rogers 1987
[17] Dr. Duane R. Diefenbach, Assistant Unit Leader, Pennsylvania Cooperative Fish and Wildlife Research Unit, Pennsylvania State University, unpublished data
[18] Roseberry and Woolf 1991
[19] Roseberry and Woolf 1991
[20] DuPont 1983; Laake 1992
[21] Lancia et al. 1996

Endnotes

[22] McCullough 2001

[23] Rakestraw et al. 1998

[24] Pollock and Kendall 1987

[25] Bartmann et al. 1987

[26] Robson and Whitlock 1964

[27] Buckland et al. 2001

[28] Quang and Lanctot 1991

[29] Samuel and Garton 1994

[30] Cogan and Diefenbach 1998

[31] Rabe et al. 2002

[32] Samuel et al. 1987; Beringer et al. 1998

[33] Havens and Sharp 1998

[34] Beringer et al. 1998

[35] Pollock and Kendall 1987

[36] Kubisiak et al. 2001

[37] Garner et al. 1995

[38] Jacobson et al. 1997

[39] Jacobson et al. 1997

[40] Jacobson et al. 1997

[41] Conner et al. 1986

[42] McCullough 2001

[43] Seber 1982: p. 359

[44] Conner et al. 1986

Part IV. Details of How Deer Might be Managed in Pennsylvania from an Ecosystem Perspective

Chapter 11. Management of White-tailed Deer Populations

Chapter 12. How Deer Might be Managed in Pennsylvania from an Ecosystem Perspective Using Adaptive Resource Management

Chapter 11. Management of White-tailed Deer Populations

Regulating deer densities in forested regions is a crucial tool for managing deer from an ecosystem perspective. However, it is only feasible for managers to affect deer populations directly in large forest tracts by changing just one of the four components of the classical population equation:[1]

$$N_{t+1} = N_t + \mathit{births} - \mathit{deaths} + \mathit{immigrants} - \mathit{emigrants} \qquad \text{Eq. 7}$$

namely deaths, by regulating hunting rates. Nonetheless, the ways that management actions can affect deer densities are complex. Hunting rates can be regulated separately for bucks and does and for different age classes and manipulating habitat and predators can affect deer populations indirectly. In an ecosystem-based model of the effect of various white-tailed deer management schemes developed for the Huntingdon Forest in New York's Adirondack Mountains,[2] the included variables were winter severity, population density, fawn survival, predation, illegal hunting, area inhabited, habitat quality, deer reproduction, deer recruitment, hunting, and roadkill. Preliminary model predictions indicate that reaching and maintaining population levels of 10 to 20 deer per square mile at that site will require simultaneous manipulation of five control parameters: the harvest rates of adult males, yearling males, and females, manipulation of habitat quality, and predation.

Ecology of deer and their role in ecosystems

White-tailed deer are herbivores that primarily feed on woody browse during the winter, leafy browse and herbaceous plants during spring and summer, and mast (primarily acorns) and agricultural crops when available. Deer are selective, preferring some plant species over others, but they are considered to be dietary generalists because they consume a wide range of plant species as availability changes among seasons, years, and habitats.

Deer are highly adaptive and thrive in urban, agricultural, and forested ecosystems throughout the country.[3] Climate, habitat type, and quality and quantity of habitat determine the ecological carrying capacity, or number of deer a particular area can support without substantially altering the vegetation[4] (see box on page 16). The size of a deer population in relation to a habitat's carrying capacity has a strong influence on the impacts deer have on the ecosystem. As deer numbers approach or exceed the carrying capacity, preferred foods become less abundant per capita and deer begin to eat less-preferred plants. Plant diversity decreases as preferred plants become less abundant. Consequently, the impacts deer have on ecosystems are dramatically increased when deer numbers approach or exceed the carrying capacity.

Carrying capacities vary across space and time because food and cover resources are more abundant in some areas than in others and in some years and seasons. Thus, a population of 40 deer per square mile in a heavily forested region where there is a low carrying capacity for deer will have greater impacts on the ecosystem than the same deer density in a woodlot surrounded by agricultural fields where the carrying capacity for deer is higher. The extent to which agricultural crops buffer the impacts deer have on the ecosystem has not been studied extensively;[5] however, it is reasonable to assume that the presence of cropland buffers deer impacts on nearby forests, because crops are preferred foods and comprise much of the diet of deer when available.[6]

Furthermore, deer populations and carrying capacities vary according to the scale of observation. Work conducted from 1958 to 2003 on the Huntington Forest in the New York's Adirondack Mountains showed a spatially variable response of tree regeneration to reductions in deer population density.[7] Telemetry studies involving more than 600 radio-tagged deer have shown that deer are patchy in distribution, with some areas of around 500 acres experiencing about 40 deer per square mile even though the estimated overall density in the region is less than 10 deer per square mile.[8] Conventional wisdom has held that, when deer density is reduced locally, deer fill in quickly, equalizing the density across the broader area. Recent evidence refutes this assumption. At Huntington Forest, removal of a matrilineal group resulted in a significantly lower deer density than that of surrounding areas for 5 years.[9] (In practice, seasonal fidelity of deer to home ranges renders knowledge of familial relationships unnecessary.) Recent studies have shown this phenomenon in a range of environments from wildlands to suburbs.[10] Importantly, such studies show that it is possible to manage deer populations at scales of 1,000 to 10,000 acres, and perhaps at the stand level (10 to 100 acres), by focusing removal on smaller groups of deer. Thus, it is reasonable to suppose that our proposed reductions of deer densities in 10-square-mile (6,400-acre) treatment areas as part of A.R.M. (see Chapter 12) will not be undermined by rapid immigration.

Historical assumptions about deer population dynamics at landscape and regional scales have come under review in recent years.[11] For example, New York's Adirondack region has been generally treated by wildlife managers as a single entity but the deer population appears actually to be about five subpopulations, each responding differently to management and natural environmental pressures.[12] Until shown otherwise, it should be assumed that the same is likely to be true across Pennsylvania, probably to an even greater degree because of the state's much larger size, regional variation in environmental factors, and uneven distributions of agricultural, urban, and suburban land uses. Moreover, hunting effort is not spread uniformly across the forest landscape, among forested areas within counties, or among regions within the state. For example, hunters tend to cluster near roads and on public lands. It is crucial that future research and A.R.M. programs, including the theories on which they are based, should be designed and formulated with explicit attention to differing expectations at different spatial and time scales.

Ecologists sometimes refer to deer as a "*K*-selected" species, which means they are large, mature slowly, have low reproductive rates, and are long-lived relative to most other animal species.[13] Such species tend to have density-dependent mechanisms that stabilize their population numbers near carrying capacity. Preferred foods become less available for each deer as deer numbers approach carrying capacity, which adversely affects their physical condition. Reduced physical condition results in lower body weights, reproductive rates, and fawn survival, which in turn result in reduced population growth rates.[14]

Population ecology of white-tailed deer

Managing white-tailed deer herds and understanding the population ecology of deer — how deer herds respond to environmental conditions — is more complex than many people believe. It often is believed that more deer can be harvested if there are more deer in the population. In fact, the management of game animals for a long time was based on this concept, known as the "annual surplus" theory.[15] However, research over the past several decades has improved our understanding of how population ecology relates to deer harvest management. Scientific studies examining productivity and mortality rates in deer populations have determined that maximum numerical harvests occur when deer populations are intermediate in size; the number of deer available to harvest begins to decline as habitat conditions deteriorate due to too many deer eating a diminishing amount of food.[16] Therefore, the annual surplus theory is correctly applied only when deer densities are very low and all deer in the population are in good health. In order to explain why this is so, it is necessary to set the stage with some additional background on population ecology.

Population growth rates

Deer population growth rates can increase exponentially under optimum conditions, where there is no shortage of food, cover, or space and diseases or predators are not affecting the population. In this situation, the birth rate is maximized and the death rate is at a minimum, which allows the population to grow at the fastest rate possible. The general model explaining this relationship, called the exponential model, is:

$$\textit{annual change in number of deer} = r \times N \qquad \text{Eq. 8}$$

where r is the maximum annual reproductive rate and N is the number of deer in the population. This model suggests that 10 female deer with a typical maximum birth rate of 1.9 fawns[17] and a 50:50 sex ratio at birth can grow to 4,076 deer in 10 years (Figure 7, on next page).

Although deer herds can grow very rapidly,[18] it is obvious that the assumptions of the exponential model cannot be met in the real world because food, cover, and space are finite. The population will not grow exponentially if: (1) the amount of food resources does not meet the demand by the deer population, (2) there is not adequate cover for all of the deer, (3) predators increase in number as a response to a larger deer herd, or (4) disease increases mortality rates as a result of high deer densities. Previous studies have shown limited nutritional availability,[19] inadequate habitat,[20] predators,[21] and disease[22] reducing deer populations. These factors may affect a population by decreasing the reproductive rate or increasing the mortality rate so that the population does not grow indefinitely. The general model explaining this relationship is referred to as the logistic model and is described by:

$$\text{annual change in number of deer} = \frac{dN}{dt} = r \times N \times \frac{K - N}{N} \qquad \text{Eq. 9}$$

where r is the maximum annual reproductive rate, N is the current number of deer, and K is the maximum number of deer the area can support (i.e., carrying capacity). This more realistic model suggests that the deer population will grow exponentially as long as the number of deer is below 50% of carrying capacity. This point often is referred to as the inflection point; it is where the annual population growth rate (the slope of the curve) reaches a maximum (Figure 8).

Using the logistic model with the same reproductive rates used in the exponential model, but assuming a particular area has a carrying capacity of 4,076 deer, it takes a deer herd 15 years to reach the same number of deer modeled by the exponential equation in 10 years. This is due to the relationship between high deer numbers and the number of deer the environment can support

Figure 7. Deer population sizes derived from the exponential growth model

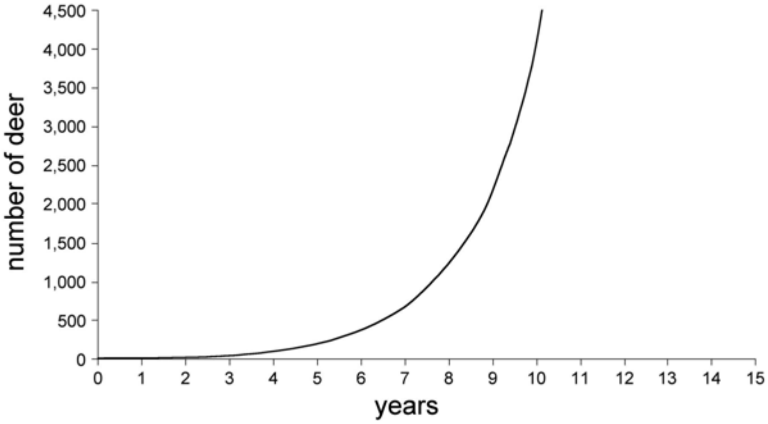
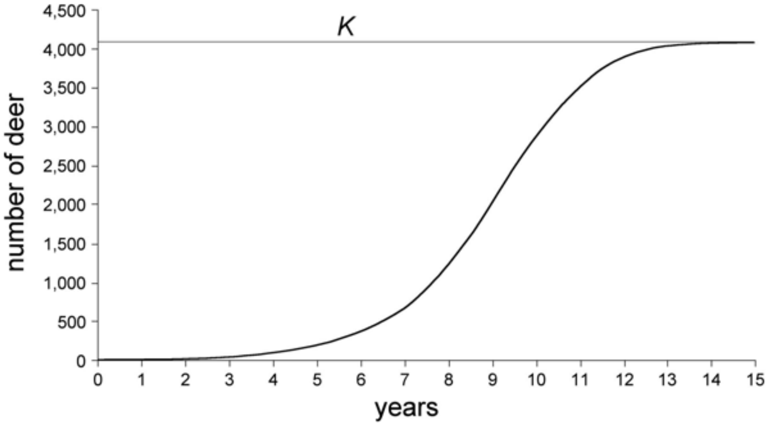


Figure 8. Deer herd sizes modeled by the logistic model. *K* (carrying capacity) was assumed to be 4,076 for comparison to the exponential model in Figure 7.



(Figure 8).[23] Because the population growth rate depends on the density of the deer population itself, the pattern of population change described by the logistic model is said to be a *density-dependent* process.

Sustained harvest yield theory

The logistic model is part of the foundation of deer harvest management. A deer population will grow to K (carrying capacity) if it is not hunted and density-*independent* sources of high mortality (e.g., severe winter weather) are not continuously affecting the population. Along the periphery of a species' range, density-independent factors may control population numbers rather than density-dependent factors.[24] However, the white-tailed deer's range extends well to the north of Pennsylvania suggesting that (1) density-dependent factors should control deer numbers most of the time (infrequent exceptions may occur during unusually severe winters, but even then only in a fraction of the state's area) and (2) the logistic model is useful for describing population growth rates as well as population responses to various harvest management options.

The number of deer born each year that survive to the following year (recruitment) in relation to the number of adults that survive determines whether the population increases or decreases. The deer population will increase if the number of fawns recruited into the population exceeds the number of adults that die. Conversely, the population will decrease if the number of adults that die exceeds the number of fawns recruited in a given year. The population will be stable if recruitment and mortality are identical. Consequently, the effect of the number of deer harvested on the total population depends exclusively on the number of deer recruited each year. If more deer are harvested than recruited, the population will decline and if more deer are recruited than harvested, the population will grow. Again assuming a population with the same birth and death rates as described above in the logistic model example, a sustained harvest rate of 400 deer per year can be taken when there are either about 500 or about 3,400 deer (Figure 9, on next page). This occurs because the low-density deer population has a high recruitment rate but the high-density deer population has a low recruitment rate. Thus, the total number (but not the rate per adult female) of fawns recruited is similar in both scenarios as are the numerical harvests.

Management tools can be applied to increase future annual harvests, but they differ between the two scenarios. For the smaller herd, future annual harvests can be increased by under-harvesting the herd for 1 year or more, allowing more does (N) to survive and produce fawns at the maximum reproductive rate. For the larger herd, annual harvests can be increased by decreasing the population, making more resources available for each doe and thereby increasing the per capita recruitment rate. The maximum sustained yield (M.S.Y.) occurs experimentally at about 56% of K, which is essentially the same as the inflection point on the population growth curve produced by the logistic equation.[25]

The general principles of sustained harvest yield theory are: (1) hunted populations cannot be maintained at *K* (carrying capacity); (2) sustained yield (S.Y.) is achieved when numerical harvests are equal to the number of animals recruited into the population; (3) the same S.Y. occurs at two population densities — a low population density with high recruitment and harvest rates and a high population density with low recruitment and harvest rates; (4) the deer population will be driven to extinction if the population is on the left arm of the curve (Figure 9) and harvest continually exceeds recruitment; (5) if the population is on the right arm of the curve and harvest exceeds recruitment (but is less than M.S.Y.), the deer population will decline to the balance point (where harvest = recruitment) on the right arm of the curve, whereas if the harvest is less than recruitment, the population will increase to the balance point on the right arm of the curve.[26]

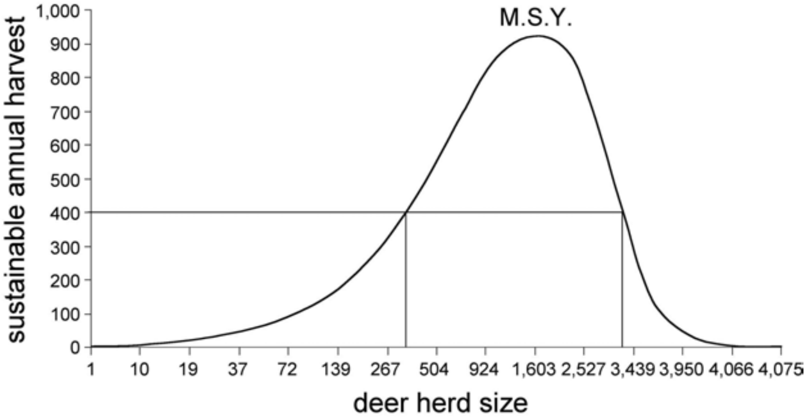


Figure 9. Number of deer available to harvest (sustained yield), based on the number of deer recruited at each population size calculated in Figure 8. In this example, approximately 400 deer can be sustainably harvested when there are either 500 or 3,400 deer, and maximum sustained yield (M.S.Y.) occurs at about 2,000 deer.

Thus, even though deer densities will decrease in Pennsylvania as a result of managing deer from an ecosystem perspective, numerical harvests should be expected to increase for many areas in Pennsylvania that have deer numbers presently exceeding the level that would produce M.S.Y. because recruitment rates will be stimulated as the habitat recovers. There may be fewer deer seen by hunters, but sustainable harvest rates will be increased wherever recruitment rates increase. Assuming that there are sufficient numbers of hunters or levels of effort per hunter, this translates into higher numerical harvests for both antlerless deer and adult bucks in those areas.[27]

Immunocontraception as an alternative to hunting

Perhaps the most often cited possible alternative to hunting for reducing deer populations is lowering the birth rate using contraception. Although the technology for inducing contraception in wild large-mammal populations is advancing, no technique has been developed that is effective in any but small, isolated populations and all methods developed to date are extremely expensive.

Immunocontraception using porcine zona pellucida protein (PZP) has been successfully used to control ungulate populations in zoos and other captive herds. However, to be most effective, repeated injections of each treated animal have been necessary.[28] The difficulty of successfully administering the vaccine to free-ranging animals has been barrier to the wider use of this technique.

Several recent research papers address efforts to utilize PZP to control free-ranging deer in suburban settings. One study in Connecticut indicated that treatment of about 70% of a free-ranging suburban white-tailed deer population is possible.[29] However, the cost to treat 30 deer for 2 years was estimated at $33,833 ($1,128 per deer). Another study of the potential for controlling free-ranging deer with PZP was conducted in a 17-square-mile suburban community in New York State with about 400 deer.[30] The authors concluded that immunocontraception has the potential for holding suburban deer populations at 30 to 70% of ecological carrying capacity, but is likely to be effective only in localized populations where the number of females to be treated is less than 200.

We were unable to locate any published research that addressed the potential for using PZP to control deer in large forested tracts. However, the Humane Society of the United States reports that a one-shot form of PZP known as SpayVac™ produced by ImmunoVaccine Technologies, Halifax, Nova Scotia, has demonstrated long-term effectiveness.[31] It is not clear to what extent this new product will overcome the obstacles and costs cited above. It would be difficult and is likely to be prohibitively expensive to administer even a single shot to enough female deer to effectively limit reproduction over large areas.

Findings on deer population management

(1) It often is believed that more deer can be harvested if there are more deer in the population. However, scientific studies examining productivity and mortality rates in deer populations have determined that maximum numerical harvests occur when deer populations are intermediate in size. The number of deer available to harvest begins to decline as habitat conditions deteriorate due to too many deer eating a diminishing amount of food.

(2) Even though deer densities will decrease statewide as a result of managing deer from an ecosystem perspective, numerical harvests should increase in many areas where deer

numbers presently exceed levels that would produce the maximum sustained yield, because recruitment rates will be stimulated as the habitat recovers. Hunters may see fewer deer but sustainable harvest rates will increase wherever recruitment rates increase. Assuming sufficient hunter numbers and levels of effort per hunter, this translates into higher numerical harvests for both antlerless deer and adult bucks in those areas.

(3) Contraception is often mentioned as a possible alternative to hunting for reducing deer populations. Although the technology for inducing contraception in wild large-mammal populations is advancing, no technique has been developed to date that is effective except in small populations isolated in suburban forest fragments, and all methods so far are extremely expensive.

Endnotes

[1] Where *t* is a point in time and the numbers of births, deaths, immigrants, and emigrants are those that occur during the interval from *t* to *t* + 1.

[2] Sage et al. 2003a

[3] Nixon et al. 1991; Van Deelan et al. 1997; Grund et al. 2002

[4] McCullough 1979

[5] But see Taylor 1984; Underwood and Porter 1997; Augustine and Jordan 1998.

[6] Nixon et al. 1970

[7] Dr. William F. Porter, Professor of Wildlife Ecology, Department of Environmental and Forest Biology, State University of New York, personal communication, 2003; see also Didier and Porter 2003.

[8] Dr. William F. Porter, Professor of Wildlife Ecology, Department of Environmental and Forest Biology, State University of New York, personal communication, 2003

[9] Dr. William F. Porter, Professor of Wildlife Ecology, Department of Environmental and Forest Biology, State University of New York, personal communication, 2003; see also McNulty et al. 1997.

[10] Porter et al. 2004

[11] Porter et al. 1991; Mathews and Porter 1993

[12] Dr. William F. Porter, Professor of Wildlife Ecology, Department of Environmental and Forest Biology, State University of New York, personal communication, 2003

[13] Fowler 1981

[14] Woolf and Harder 1979; Severinghaus and Moen 1983; Nielsen et al. 1997

[15] Caughley 1976

[16] McCullough 1979; White and Bartmann 1997

[17] Downing and Guynn 1985

[18] E.g., McCullough 1979

[19] McCullough 1979

Endnotes

[20] DePerno et al. 2000

[21] Mech and Nelson 2000

[22] Gross and Miller 2001

[23] Previous studies have demonstrated that *K*-selected species do not exactly conform to the logistic model (Fowler 1981), but the deviation is insignificant for our purposes. The inflection point for deer is reached at 56% of carrying capacity (McCullough 1987), which is quite close to the 50% predicted by the logistic model.

[24] Krebs 1978

[25] McCullough 1987

[26] McCullough 1984

[27] McCullough et al. 1990; McCullough 2001

[28] Turner et al. 1996

[29] Walter et al. 2002

[30] Rudolph et al. 2000

[31] Humane Society of the United States 2003

Chapter 12. How Deer Might be Managed in Pennsylvania from an Ecosystem Perspective Using Adaptive Resource Management

There is sufficient evidence to justify significant reductions in deer densities in large areas of forestland in Pennsylvania. The Pennsylvania Game Commission has issued increased numbers of antlerless deer harvest permits in the last few years, which should lead to some reductions. Powerful advantages would accrue if the issuance of permits were tied to an adaptive resource management protocol, with field monitoring providing feedback in the decision loop. In the case of managing deer to promote forest recovery, however, the self-correction feature of A.R.M. will not begin immediately. Because of lags in achieving deer density reductions and in detecting forest improvement, there will be a delay of 5 or more years before meaningful feedback can be applied to improve management decisions. Forum members believe that current knowledge of deer impacts is sufficient to commit to an initial set of weights for use in an A.R.M. program. The self-correction process, one of the greatest strengths of the A.R.M. approach, would not begin until measurable changes in indicators are achieved, expected in 5 or perhaps as many as 10 years after the start of the program.

The simplest statewide A.R.M. protocol would combine forest-structure monitoring with the issuance of permits. Possibly, the U.S. Forest Service's Forest Inventory Analysis (F.I.A.) could be adapted to provide the necessary data. A formula would then be devised for adjusting antlerless deer harvest permits based on the success of different models in predicting the impacts of deer density reduction, as discussed in Chapter 9. Because there is a nearly universal scientific consensus that high deer densities are causing the damage to forest structure, agencies should give this view a very high weight in initial decisions on deer harvest permits, other deer control actions, and other ecosystem management policies. An appropriate initial weighting would be 90% assigned to the consensus view that white-tailed deer are harming forest structure and a 10% weight assigned to theories that white-tailed deer are relatively unimportant.

A more scientifically sophisticated approach than applying a single set of management actions statewide would be to divide the forest areas known to be damaged into two sets of large "treatment" and "comparison" areas, one set where measures would be taken to reduce deer densities dramatically and the other, where hunters would operate as usual. The two sets of areas would serve as replicated treatment and control plots, enabling sound, scientifically valid conclusions about the effectiveness of management actions in promoting forest recovery.

However, Forum members realize that reducing deer densities across the state dramatically rather than incrementally, no matter how well justified, might be very difficult in the short term because of limitations in the number of additional permits that the state's hunters could absorb. And even if hunter numbers were not a limitation, it might be difficult to reach a political consensus on dramatic reductions in light of high-profile theories that challenge the importance of deer in the decline of forest structure and diversity in the first place. Therefore, the Deer Management Forum proposes a two-tiered A.R.M. program. The first tier, already described in general terms (Chapter 2), would apply to the state as a whole. The second tier would apply A.R.M. at a smaller scale, to multiple, 10-square-mile forest treatment areas and comparison areas (untreated experimental “controls”) in all of the major forest regions of the state, but with a wider range of management treatments (reductions in deer densities), as well as a wider range of tests of alternative theories. Lessons would be learned faster with such smaller-scale manipulations.

For instance, if the consensus view should somehow turn out to be incorrect, it will become obvious as data are collected while monitoring these 10-square-mile areas. Theories about the effects of soil acidity, how to speed up recovery, and optimal deer densities could be tested in this manner as well. We recommend this two-tiered approach to the application of A.R.M. so that changes in management can be implemented immediately at the state level based on the best current knowledge, while uncertainty is reduced as the models are subjected to rigorous tests in a spatially replicated, scientifically valid fashion. The results of the model predictions on the 10-square-mile areas would be used, along with the results of the statewide monitoring program, to weight management decisions applied to the entire state each year.

There exist a number of research protocols that could be chosen for both A.R.M. tiers. In this chapter, we present an illustrative example, with the second tier restricted to state lands. We do not propose to include federal lands in the example because of the complex procedures necessary to gain approval for treatments on federal lands.

Steps that would be needed to develop an A.R.M. program both statewide and in the smaller test areas are listed in Table 6. We envision any actual research protocol to be chosen by Pennsylvania Department of Conservation and Natural Resources (D.C.N.R.) and Pennsylvania Game Commission (P.G.C.) staff with the advice of a broad-based, ad hoc research advisory committee. In addition we suggest that a public advisory committee, also ad hoc, should be formed to represent public constituencies. The public advisory committee would be kept informed of ongoing scientific progress and provide feedback to the agencies and research advisory committee to help ensure that choices are made that will be supported by stakeholders and the general public. From this point on, we refer to the designated D.C.N.R. and P.G.C. staff together with the ad hoc advisory committees as the “A.R.M. team,” recognizing that final decision authority always rests with the agencies.

The A.R.M. team would request researchers to propose theories relating deer densities and other factors to regeneration of woody and herbaceous vegetation. Estimates would also be needed of changes required in deer harvest permit allocations to reach a detectable level of

Table 6. Steps that might be taken to develop a protocol for managing deer using adaptive resource management in multiple, 10-square-mile forest treatment and comparison areas

step	comment
Formation of an ad hoc research advisory committee	To be chosen by D.C.N.R. and P.G.C.
Formation of an ad hoc public advisory committee	To be kept informed of scientific progress and provide feedback to D.C.N.R., P.G.C., and the research advisory committee.
First cut at research protocol	The A.R.M. team would choose (1) the number, size, and location of forest areas to be treated, (2) the range of target deer densities, the control techniques to be tested, and the deer monitoring methods (3) the alternative treatments to be included, such as seeding, liming, or fencing, (4) the sets of plant indicators and the frequency of measurements.
Baseline (pre-treatment) measurement of indicators in A.R.M. areas (year 0)	Permission to monitor plots in the treated areas would need to be obtained. If drought, late spring freeze, or other unusual weather were to give anomalous measurements in year 0, a second baseline data set would be collected in the following year.
Providing guidance to theorists; attempting to reach consensus on data to be collected	Workshops would be held to explain the A.R.M. process to persons who might propose theories to test, including the necessity to accompany any theory with an estimate of the expected rate of error. Workshops would also be held to provide guidance to agency staff on what data should be collected as part of the A.R.M. process.
Garnering public views on initial weights to be assigned to theories	A meeting would be held to provide guidance to agency staff on the initial weights to be assigned to proposed theories.
Initial weighting of theories	Agency staff, advised by the scientific advisory committee and public input, would assign percentage weights to the various theories.

(Table continued on next page.)

step	comment
Deciding on and applying a range of deer control methods to test in 10-square-mile areas or regions including them (first tier)	In the early years of the program, a range of innovative control options would be tried, such as varying permit allocations, permit price, and the number and duration of hunting seasons.
Monitoring the success of deer control methods in changing the number of deer taken per year in the control regions (years 2 and 3) and, if necessary, adjusting the methods used	Monitoring would compare the number of tags paid for or granted to hunters and the number of deer taken per tag.
Monitoring the success of deer removals in changing deer density and, if resulting declines are inconsistent with the desired target range, adjusting control strategies accordingly (years 2 and 3)	Methods of estimating deer abundance would be applied to see whether target ranges for deer density have been reached
Ongoing measurement of indicators and evaluation of success of theories (years 5, 8, 11, and thereafter)	The criteria for success in improving forest structure are statistically significant improvements in indicators of forest structure.
Conducting research to develop a combination of indicators that responds faster than the ratio of *Rubus* to hay-scented and New York fern cover	Forum members believe that a suite of indicators and indicator ratios can be determined that will respond quickly to changes in deer density, thereby decreasing the lag time before feedback can be applied to annual management decisions.
Reweighting and allowing for theory modification (year 5 and each year afterward)	Relative model weights would be adjusted and model proponents would adjust their models, if the data indicate that they need improvement.
Benefiting from lessons learned	Management actions, such as permit issuance rates, would be adjusted to favor the best-performing models.
Evaluation of A.R.M. program	Participating agencies would schedule program performance evaluation at regular intervals.

improvement. P.G.C. biologists would provide assistance in this regard. Workshops would be held to explain the A.R.M. process. Only theories that are quantitative, or theories that the A.R.M. team can make quantitative predictions from, could be considered. To qualify for consideration a theory also would have to include an estimated rate of uncertainty.[1]

After submission of the models for consideration, the agency staff portion of the A.R.M. team would use its best judgment, informed by advice of the scientific advisory committee, to assign initial percentage weights to the various theories. These weights would be used, along with considerations of public safety, to pick the initial range of treatments to be applied to the A.R.M. areas. In subsequent years, as data come in from measuring indicators, standard A.R.M. procedure would be used to update the original weights based on the success of each theory and to update treatment ranges and indicator choices. Over the years, these updated weights could be used by agencies to adjust their management practices on lands outside the A.R.M. areas. Private landowners could also benefit if they chose to adopt the updated management practices for their region of the state.

An illustrative example of A.R.M. was given in Chapter 2, showing the use of probability theory to update the model weights. In that case, only two models were considered. However, many more could be included. In fact, given the uncertainties in predicting forest recovery rates, it would be wise to consider a series of submodels for each basic model. Each submodel would use a different value of an uncertain parameter. For example, consider a model developed to predict the relationship between permit allocations and a detectable increase in a fast-response, composite indicator of forest recovery.[2] Submodels might be chosen with two values for permit allocations below and two above the basic model. Including the basic model, there would be a total of five submodels. The initial weight assigned to the basic model would be divided among the five submodels and updated based on future monitoring data. As a result, not only would monitoring data be used to choose between different theoretical models of forest dynamics, but the data would also be used to pick out the best deer harvest permit allocation to use in conjunction with the model. Data from the more experimental, second-tier A.R.M. areas would have the greatest power to pick out the best submodels, because a wide range of deer densities could be achieved.

As an illustration, we have estimated the percentage increase in permit allocations and number of hunting days that might be required for the forest-recovery indicator example given in Chapter 9, the ratio of *Rubus* cover to hay-scented and New York fern cover (Table 7). These estimates are illustrative only and would need to be refined by the A.R.M. team.

The A.R.M. team would determine the nature of the treatment and comparison areas, choosing (1) the number, size, and location of forest areas across the state under agency management to be treated, (2) the range of target deer densities and harvest permit allocations,

(3) the range of deer control techniques to be tested, (4) the target range for any alternate treatments chosen, such as seeding, liming, or fencing, (5) the indicator sets to be used, and (6) the frequency and timing of indicator measurements.

An example of a second-tier A.R.M. protocol

The A.R.M. team chooses 20 forest treatment and comparison areas, each 10 square miles in size (the size of squares with 3.16-mile sides or 3.57-mile diameter circles), spread across the state to be treated to reduce deer density. Five are comparison areas with no change in hunting rules or deer management methods, five treatment areas are reduced to 20 deer per square mile, five to 13 deer per square mile, and five to 7 deer per square mile. The A.R.M. team identifies a suite of control methods designed to reach these targets. Nearest neighbor blocks receive different treatments so that as much as possible models may be tested for a range of deer densities within each forest type.[3] Modelers participating in the A.R.M. exercise take into account likely variations due to the passage of time and differences among locations.

Table 7. Examples of quantitative goals for adaptive management to improve forest conditions, as measured by the ratio of *Rubus* cover to hay-scented and New York fern cover in sites with moderate light levels at the forest floor

item	quantity
Deer density reduction target needed to detect change in 3 years after target is reached	From 35 to 20 deer per square mile[a]
Deer management actions that might be sufficient to achieve the 20 deer per square mile over a 3-year period in a 10-square-mile forest tract	75% increase in antlerless permits and a 33% increase in the number of hunting days[b]
Other values that might be tested in A.R.M. as submodels	5, 10, 15 deer per square mile

[a] Based on a fit to data in Chapter 9 with an 80% chance of seeing an effect at the 95% confidence level.

[b] Assuming these actions will produce a harvest of 100 deer out of a population of 400 located within a 10-square-mile forest tract.

The 10-square-mile size of each treatment and comparison area is a compromise, small enough to make reducing deer density practical in a relatively short time and large enough that immigration would not quickly fill the void.[4] Treatment/comparison areas are embedded in larger contiguous forest areas to avoid edge effects and influences of adjoining land usesThe perimeter of each treatment and comparison area is at least 1 mile from the edge of any nonforested area of significant size, including clearcuts less than 5 years old of 25 acres or larger and cultivated areas of 10 acres or larger, and deer harvest treatments are applied to a 1-mile-wide buffer zone surrounding each treatment area as well as to the treatment area itself.

Wherever possible, treatment and comparison areas are situated where monitoring deer populations is relatively easy and the human population is receptive to the changes in deer density needed for the 10-square-mile treatment areas. Ideally, treatment and comparison areas are distributed evenly between the two major forest regions in the state: northern hardwoods in much of the northern one-third of the state, extending southward at high elevations, and oak-mixed hardwood forests in much of the southern two-thirds.

In each treatment and comparison area, four randomly located forest stands are sampled in an effort to average out the spatial variability across the 10-square-mile area in a host of factors, including deer density, that may affect indicator responses.[5] First, a sequence of random locations is assigned within each treatment or control area; the first four that prove to meet a set of previously developed criteria when examined on the ground are chosen as the forest stands where forest recovery indicator data are collected. To be included in the sampling array, a forest monitoring stand must possess characteristics for which at least one competing model predicts a change detectable in 3 to 5 years of treatment.[6] Data are collected only where (1) adequate sunlight is available at the forest floor to support substantial new growth (shelterwood cuts, thinnings, or areas where natural disturbance has thinned the canopy) and (2) a strong "legacy effect" of long-term deer overbrowsing is absent (i.e., areas without an interfering cover of unpalatable or browsing-resistant species, mainly striped maple, American beech, hay-scented fern, or New York fern). The selection criteria will assure that changes in indicators, if they occur, may be detected within a reasonably short period of years.[7] Within each forest stand, 18 subplots are randomly located for sampling.

In the example, the data consist of measurements of *Rubus* cover and hay-scented and New York fern cover, for computation of the *Rubus*:fern cover ratio, and a set of additional indicators chosen from the list provided in Chapter 9 or otherwise selected by the A.R.M. team. The indicators chosen are those expected to respond rapidly, even within 1 year, to the complete exclosure of deer, but whose response rate is not known when deer densities are reduced to levels above zero. Average costs of vegetation monitoring alone over 5 years are estimated to be $42,000 per year (Table 8). Also included in the program is a measurement of soil acidity in the first year, which is used to test predictions about the effects of soil acidity on response rates. The estimated cost averaged over 5 years, including the acid rain component but with deer monitoring costs excluded, is $50,500 per year. Agency commitment to the forest monitoring part of the A.R.M. program is estimated to be 2 person-months per year in each of the two agencies, P.G.C. and D.C.N.R.

The cost of the statewide first-tier A.R.M. program, which would include stands beyond the 80 targeted for monitoring in the second-tier program, is estimated to be considerably less, because measurements would be taken half as frequently. The statewide program, averaged over the first 5 years, would add only an estimated $12,000 to the total cost per year. Thus, the grand total for forest monitoring over the first 5 years in both tiers of the proposed A.R.M. program is an estimated $62,500 per year (Table 8).

Table 8. Forest monitoring cost estimates for the second tier (experimental component) of the adaptive research management protocol

item	quantity
Number of treatment and comparison areas and forest stands in which monitoring would be conducted each year	20 treatment/comparison areas 80 forest stands (4 per area) 1,440 subplots (18 per stand)
Cost to locate and classify treatment and comparison areas and, within them, forest monitoring stands (a first-year cost)	$36,000[a]
Cost to measure indicators for a single year in one forest monitoring stand	$500[b]
Cost to monitor all 80 forest monitoring stands (needed every third year; more often if unusual weather results in anomalous measurements in one or more years[c])	$40,000
Supervisory costs and data-analysis costs in year data are collected	$6,000
Total cost of vegetation monitoring alone averaged over first 5 years	$42,000 per year
Agency staff commitment per year	2 person-months in P.G.C. 2 person-months in D.C.N.R.
Cost in first year to measure soil acidity in 80 forest monitoring stands	$43,000[d]
Total cost of monitoring program, including acid rain component, averaged over first 5 years	$50,500 per year

[a] Assumes supervisor can identify and classify two acceptable forest monitoring stands per day, hourly rate of $50 per hour, overhead rate as 100% of wages, extra travel expenses of $100 per day. Marking the 18 subplots within a forest monitoring stand is assumed to require two technicians for two hours per stand.

[b] Assumes two field workers paid $20 per hour who together can cover three forest monitoring stands per day, overhead rate as 100% of wages, extra travel expenses of $100 per day.

[c] Drought, late spring freeze, or other unusual weather in the first year is assumed to give anomalous measurements requiring remeasurement in the following year 33% of the time.[d] Assumes sample collection will add no more than 45 minutes per forest monitoring stand, equipment costs are $5,000, laboratory analysis costs are $25 per sample. If acidity monitoring equipment must be left and picked up later, two visits are required. The cost of a second visit, which we assume is necessary, increases the total cost from $27,000 to $43,000.

To keep costs to a minimum, the monitoring program is designed to discriminate between models only at the scale of the entire state, not at the scale of regions within the state. However, every effort should be made to distribute treatment areas among regions to maximize the likelihood of extracting information that will be statistically valid at the regional level. With only a few of the 10-square-mile areas in each specific combination of forest type, local climate, terrain, deer population history, and other factors that vary among regions, analysts will not always be able to say with confidence that a particular model is best in an individual region, nor will it always be possible to assign model weights that vary with region. Still, previous studies of the effects on vegetation of manipulating deer numbers give good reason to be confident that, with careful placement of treatment areas, useful information pertaining to particular regions should be obtainable, especially where recovery is found to be relatively rapid. Deer density has been found to be such a strong factor that its effects have shown clearly (and statistically significantly) through the “noise” of variation in many other site and environmental factors.[8]

It would be considerably more expensive to design the monitoring program specifically to account for regional variations. However, agencies or institutions responsible for forest research may well become interested in building on the A.R.M. program and may support their own research within the monitoring blocks, gathering data from additional stands that could benefit the A.R.M. program. Such synergism would be encouraged if the research opportunities available as add-ons to the A.R.M. program were publicized among the research community.

Additional monitoring stands beyond the 80 funded under the A.R.M. program could be used to test models of forest dynamics that would be useful in deer management, even though their main function might be to advance pure research or address non-deer management problems. With the addition of extra treatment and comparison areas beyond the 20 in the A.R.M. proposal, model performance might be testable in regions within the state, which would be of great interest to regional stakeholders.

The illustrative program presented here assumes that one model will work for all regions in the state that contain treatment and comparison areas. If, on the other hand, different models had to be used for, say, northern hardwood forests and oak-mixed hardwood forests, then there would probably not be sufficient monitoring stands in our example to test separate models for each of the two forest types. If it is determined to be a priority to focus initially on one forest type, the A.R.M. program might begin by putting all 20 treatment and comparison areas in that forest type to keep the total cost down while the program is proving its usefulness.

The cost of deer monitoring, which is necessary to determine if deer numbers have indeed been reduced to target levels, is not low. Even kept to a minimum level, our rough estimates of deer monitoring costs turn out to be comparable to the costs of monitoring vegetation response to deer reductions. For purposes of cost estimation, we assume that both hunter surveys and deer pellet counts are used to assess success at reaching the target deer densities set in the A.R.M. program. Hunters with licenses to hunt in a 10-square-mile A.R.M. tract are surveyed by telephone after the deer season. Data from this survey indicate hunter effort. In addition, the number of deer taken per hunter day is a relative measure, albeit indirect, of deer populations, because success per hunter day should decline as deer populations decline. To assess the reliability of information gained from hunter surveys, results from 5 of the 20 ten-square-mile tracts are compared with deer pellet counts. The approximate cost of the proposed deer monitoring would be $43,000 per year, averaged over the first 5 years (Table 9). Estimating the costs of monitoring deer populations is difficult and our rough estimates would need to be refined as part of A.R.M. implementation.

Combining the $43,000 per year estimated for deer monitoring with the $62,500 per year estimated for vegetation response monitoring gives a total of approximately $105,500 per year. Thus, we expect the cost of the A.R.M. program to be about $100,000 per year in outside expeditures, with a total agency staff commitment of 7 person-months per year. Although not insignificant, such a cost is small compared to P.G.C.'s total budget, which is in excess of $60 million per year.

In our example, four theories are proposed for testing:

No-impact theory — Prediction: There will be no change in indicators from year to year from current trends, regardless of treatment. Estimated rate of error is the average year-to-year fluctuation around the current trend.

Deer-dominance theory — Predictions: (1) Indicators will improve in areas where deer populations are reduced. (2) Response times for recovery of forest structure will be faster in areas of the state where deer densities have historically been in excess of 20 per square mile for less than 10 years, based on the likelihood that forest-floor plant propagules still exist in those areas. (3) Response times will be faster in areas where light reaches the forest floor, e.g., in recently cut forest stands or in stands over 50 years old in which self-thinning has taken place. Furthermore, change is expected to be slow where dense understories of hay-scented fern, New York fern, American beech, or striped maple already are well established (legacy effect). Estimated rates of error for these predictions are provided by advocates of the deer-dominance theory. In areas where deer have been densely populated for more than a decade, seeds of indicator species are applied in randomly selected areas within each treatment and comparison

Table 9. Deer monitoring cost estimates for second tier (experimental component) of the adaptive research management protocol

item	quantity
Number of forest stands in which deer monitoring would be conducted	80 forest stands
Number of stands per 10-square-mile tract	4[a]
Cost of post-season phone surveys for hunters with special-area licenses (to obtain hunter effort and success per hunter day)	$32,500 per year [b]
Cost of pellet counts in five of the 10-square-mile treatment and comparison areasas a check on inferences from phone survey (includes 15 of 80 stands)	$53,000 per year [c]
Total cost of program averaged over first 5 years	$43,000 per year [d]
Agency staff commitment per year	3 person-months in P.G.C.

[a] Stands are assumed to be less than 200 acres in size. It is also assumed that all four stands for a forest district can be located in the same 10-square-mile (6,400-acre) treatment/comparison area.

[b] Assumes $3.50 per survey, 300 hunters per 10-square-mile treatment/comparison area, and 20 treatment/comparison areas. Survey development and data analysis are assumed to require 200 hours at an hourly rate of $50, which includes a 100% overhead charge.

[c] Assumes pellets can be counted at the rate of 0.5 to 1.5 square miles per person per day, an hourly cost plus overhead of $25 per hour, 100 hours of supervisory time per tract at a cost plus overhead rate of $50 per hour, and travel and equipment costs of $3,100 per treatment/comparison area.

[d] Assumes measurements are made every year for the first 3 years and every 2 years thereafter.

area to test the hypothesis that loss of propagules slows recovery of forest structure. In areas where little light is reaching the forest floor, the tree canopy is thinned in randomly selected areas within each treatment area to test quantitative predictions of the degree to which recovery of forest structure will be speeded up by allowing light to reach the forest floor.

Acid rain-dominance theory — Predictions: (1) Indicators will not differ between areas with different deer density reduction treatments. (2) Plant indicators will improve where some optimal amount of lime is applied. (3) Regeneration will be better in valleys underlain by limestone than ridges of sandstone or other non-calcareous rock, because soils weathered from calcareous rock have greater buffering capacity (valleys also generally have more mesic soil moisture regimes and ridges are more xeric — a potentially confounding factor). Proponents of the theory provide estimated error rates. In the 10-square-mile areas with high initial deer populations, lime treatments are applied in randomly selected portions of each treatment and comparison area to test quantitative predictions of the acid rain-dominance theory. Values for the amount of lime to be used in treatments are chosen by the proponents of the theory.

Deer and soil acidity interaction theory — Prediction: Recovery response times of forest structure following deer reductions will be faster in areas with non-acidic soils. Estimated rates of error are determined by agreement between proponents of the two parent theories.

The quantitative predictions of each theory are modified by consideration of regional factors such as historic duration of deer overbrowsing and soil characteristics.

The A.R.M. team decides on the methods of deer control to be used and tested. Based on analysis of controlled studies of vegetation response due to changes in deer densities, Forum members have estimated that a 50% reduction in deer density would be needed to make detection of a vegetation response possible in 3 to 5 years. Achieving such large reductions (e.g., from 40 to 20 deer per square mile) will take time, further delaying the acquisition of useful feedback after the program's start. It is also not clear that there will be sufficient hunters in the 10-square-mile A.R.M. areas to make use of the required two- to three-fold increase in harvest permit allocations.

A major task of the team is to devise control measures to achieve the desired target levels while maximizing hunter satisfaction to the greatest possible extent. A number of innovative methods should be explored, including the use of baiting and spotlighting. Also, hunters could be offered a free permit to take an antlerless deer, with the permit replaced at no cost every time a hunter turns in a used tag. The effectiveness of such methods in stimulating hunters to take and use additional permits could be tested in an A.R.M. weighting process. Feedback in this part of the A.R.M. program would be rapid.

As the next step in the A.R.M. process, baseline monitoring of forest recovery indicators in all treatment and comparison areas is completed. Next, the chosen deer density reduction treatments are applied and their effectiveness checked, using methods of population estimation. Once deer control methods achieve the desired target densities, monitoring of forest recovery indicators resume. Deer control treatments continue, with adjustments as needed based on continued population monitoring to maintain the target densities. Success in improving forest structure, as opposed to success in testing theories, is obtained when statistically significant improvements in indicators of forest structure are found.

As field data are analyzed, the relative weights assigned to each theory are reweighted by agency staff using probability theory.[9] Field data may spur some proponents to modify their theories. In such cases, to be fair no modified theory could be reweighted until a subsequent year's data had been collected. As the various weights of the tested theories go up or down over the years, land managers across the state interested in ecosystem management could adjust their practices accordingly. At regular intervals, the A.R.M. program would be evaluated by the participating agencies.

We recognize that, in focusing on the programmatic details of an A.R.M. proposal, we have glossed over the vital social science aspects. Specialized expertise will need to be tapped to develop effective ways of getting the cooperation of stakeholders, local communities, and local governments in supporting the establishment of the second-tier A.R.M. treatment and comparison areas and the special hunting efforts that will be required in them.[10] In this regard, the advice of the proposed ad hoc A.R.M. public advisory committee will be extremely important. Consultation with experts in the human dimensions of wildlife management may also be required.

Findings on how A.R.M. might work in Pennsylvania

(1) There is already sufficient evidence to justify significant reductions in deer densities in large areas of forestland in Pennsylvania, and applying A.R.M. to the state as a whole.

(2) Reducing deer densities across the state dramatically rather than incrementally, no matter how well justified, might be very difficult, particularly in light of theories that challenge the importance of deer in the decline of forest structure and diversity in the first place.

(3) Practical applications of A.R.M. to deer require agency staff commitments for multiple years. Financial support is also necessary, but the advantages of a science-based methodology that is designed to deal with uncertainty and controversy would be a compensation.

(4) The initial commitments involved in preparing A.R.M. alternatives could be made within existing budget authorizations, provided agencies are willing to assign staff to the process. However, because of the great damage that has already been done to the structure of forests and because of the depletion of the seed supply in many parts of the state, a long-term commitment to the A.R.M. process is needed.

(5) The sooner effective treatments are implemented, the sooner further deterioration will be prevented, saving larger areas of forested land in Pennsylvania from slipping below the threshold for fast recovery.

Recommendations on how A.R.M. might work in Pennsylvania

(1) Forum members propose a two-tiered A.R.M. program. The first tier would apply to the state as a whole. Its initial treatments would take into account factors that go beyond ecosystem management, for example, budgetary constraints and local traditions. The second tier would apply A.R.M. at a smaller scale, to multiple 10-square-mile forest treatment and comparison areas in all of the major forest regions of the state. In contrast to the first tier, treatments on these forest recovery-monitoring tracts would include a range of deer densities, as well as tests of alternative theories on causes of forest degradation and recovery. The focus would be exclusively on ecosystem management. Lessons learned from these smaller-scale manipulations could be applied to forested areas across the state as a whole in subsequent years.

(2) State land-managing agencies should begin the process of developing a set of alternative A.R.M. proposals. Once agency staff has developed a suitable set of options, they should seek authorization approval.

(3) As a fast-track planning tool, D.C.N.R. and P.G.C. should manage significant portions of lands under their jurisdiction using a formal adaptive resource management paradigm. At the start, these could be the multiple 10-square-mile areas around the state recommended in the proposed A.R.M. program’s second tier to be subjected to varying levels of deer population control.

(4) An ad hoc, external scientific advisory committee should be established to assist the agencies in the choice of test areas, the size of buffer areas that might be needed, and indicator measurement protocols. An ad hoc citizens advisory committee also should be formed to help in developing consensus on the A.R.M. process.

Endnotes

[1] The greater the rate of error proposed by a theory’s proponent, the less likely the theory is to be conclusively refuted, but at the same time it will be less likely to prove influential in future management decisions.

[2] Such predictions could be extracted from the consensus theory of forest damage as follows. Consider one fast-response indicator, the ratio of *Rubus* to hay-scented and New York fern cover. Graphs of the change of this ratio over time have been calculated from field data already collected in northern hardwood stands across a broad range of deer densities by U.S. Forest Service researchers at the Northeastern Research Station, Irvine, Pennsylvania, following reductions in deer density. They would allow an estimate to be made of the time it takes to achieve a

Endnotes

statistically significant increase in the indicator ratio in northern hardwoods, assuming various sample sizes, for reductions from 40 or more deer per square mile to a series of lower target densities. Next, it would be necessary for experts on deer population biology to estimate the changes in deer harvest permit allocations needed to bring deer density down to those target densities

[3] I.e., fulfilling the “interspersion of treatments” rule for most effectively achieving true experimental replication (Hurlbert 1984)

[4] Aycrigg and Porter 1997

[5] $N = 5$ experimental replicates in our design. The four forest monitoring stands within each of the 20 A.R.M. forest monitoring areas are subsamples intended to account for spatial variability, and can in no sense be considered as replicates. Prior to statistical analysis, data are averaged across the four stands to yield a single value for each measured indicator in each forest monitoring area. The predictions by modelers for each indicator would also be averaged across the four stands before they are statistically compared with the measured averages.

[6] Prior to stand identification, modelers provide a list of generic stand characteristics that will allow the identifying team to (roughly) rank a stand’s suitability for inclusion in the monitoring program. Modelers set threshold criteria for determining when, according to their model, a stand should show a detectable change in 3 to 5 years. If no stand qualifies after examinaton of several stands, the field team relaxes the threshold criteria for each model. In Pennsylvania, there are only two models in contention, the deer-damage model and the acid-rain model. If the number of models exceeds two, then the site-selection criteria for each would need to be made stricter (at least two models must predict a detectable change in indicators before a stand is accepted).

[7] The A.R.M. approach generally assumes that at least one model is a reasonable predictor of the system dynamics (Johnson et al. 2002).

[8] E.g., Horsley et al. 2003

[9] It should be noted that the weightings would represent a true probability-based assignment only if the standard deviations assigned by the modelers represent true standard deviations, but in practice this may well not be the case. Thus it is more correct to say that agency staff will be using a “scoring function” to assign weights, one that is based on a probabilitistic framework with uncertain parameters. If no model should perform reasonably well with the values assigned for standard deviations, then the A.R.M. team would have to make adjustments to avoid computing meaningless model weights. For instance, as an alternative, the A.R.M. team could increase all of the models’ assigned standard deviations to be equal to the average differences between the predictions and the measured quantities. In effect, this would force a model’s weight for an individual indicator to vary inversely with the average deviation of its predictions from the measurements. For simplicity, the agency staff might pick this scoring approach from the start. It would obviate the need for modelers to assign a standard deviation to their predictions. However, we do not necessarily recommend such a step, because the discipline of having to assign a model error can be sobering for a modeler and lead to more careful model development.

[10] Schaeffer 2001