CHAPTER 9

# Land-Use Legacies in Soil Properties and Nutrients

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The preceding chapters have shown that common historical land-use activities in New England such as plowing, pasturing, and logging have persistent impacts on the composition and structure of our forests. A basic question naturally follows from these results: To what extent and for how long does the function of these forest ecosystems depend on past land use? Because the nature and intensity of land management affects vegetation trajectories and the amounts and availability of soil nutrients, historical land use may have persistent effects on such fundamental ecosystem characteristics as the storage of soil carbon and nitrogen, quality of organic matter, activity of microbes, and mineralization of nutrients from organic matter. Here we describe our studies that examine the influence of land-use history on soil processes across the Prospect Hill tract and Montague Plain. Our research has shown that the type and duration of land use, as well as inherent site characteristics, can affect the persistence and nature of these impacts and that nineteenth-century history has an enduring influence on modern ecosystem processes.

## Influence of Nineteenth-Century Agriculture on Soil Processes

While initial clearing of forests by logging and burning can cause important changes in soil organic matter and nutrient availability, long-term cultivation of soils on these cleared sites dramatically alters the carbon content, microbial populations, and nutrient cycling. For example, modern studies have shown that after several decades of plowing, soil carbon on formerly forested sites generally decreases by an average of 30 percent, and nitrogen and phosphorus contents may be reduced by more than 20 percent. Organic matter losses result from numerous processes: accelerated decomposition in plowed soils, removal of plant biomass through harvest or mowing, and erosion of the organic-rich surface horizons. With plowing, relative losses of 50 to 75 percent have been commonly reported for microbial biomass and the light (or easily decomposed) carbon fraction of soils. Such changes in organic matter and microbes are generally also reflected in the nitrogen cycle. Mineralizable nitrogen is often reduced by plowing, but the net production of nitrate is typically high on most tilled sites probably because of increased soil pH from repeated liming, higher ammonium availability from fertilization, and/or limitations on microbial nitrogen immobilization imposed by the relatively low availability of carbon.

While the alteration of soils following the conversion of natural vegetation to various types of agriculture has been documented extensively, soil changes during reforestation of agricultural land have received much less attention. This is surprising given that historical reforestation has been a common process in the temperate and tropical zones and is continuing in many parts of the globe. For example, because of newly enacted European Union policies in response to surplus agricultural production, extensive reforestation of arable land and pastureland will occur in the near future in many regions of Europe. The conservation and forestry opportunities for countries such as Denmark, where forest area is projected to double in the next two decades, are great, as is the need to anticipate how the resulting forest ecosystems will reflect their land-use history. Depletion and recovery of carbon, nitrogen, and phosphorus levels may have long-term implications for the productivity of forests, composition of plant species, sequestration of carbon, and capacity of these ecosystems to retain and respond to atmospheric pollutants. For example, forests on previously plowed soils, perhaps because of reduced amounts of organic matter and lower soil C:N ratios, may have a lower capacity to retain nitrogen than those never tilled. The factors that determine the capacity of forests to retain nitrogen are still incompletely understood, but assessing the role of site history may be an important step toward improving this understanding.

The broadscale changes in the New England landscape over the past 300 years clearly influenced soil properties and microbial processes. Widespread agricultural practices, including deforestation, pasturing, and plowing of hillsides, led to local erosion and declines in soil fertility. Evidence for soil movement across even gently rolling topography is observed throughout central Massachusetts, including the Harvard Forest. This is particularly noticeable where stone walls run across slopes through the forest. Upslope of the stone walls, the upper "A" soil horizons are deep, homogeneous, and stone-free as they are formed from fine material that was washed downslope and accumulated against the wall over the decades when the site was in open agriculture. In contrast, on the downslope side of the stone walls, the soils are rocky and heterogeneous. By the mid-1800s, various soil amendments including potash, manure, and gypsum were widely used to fertilize fields, thereby maintaining productivity. Although soil organic matter may have been depleted through early land clearance and crop removal, manure applications presumably helped to reverse this trend somewhat and to restore soil nitrogen and phosphorus levels, resulting in a relative increase in soil fertility.

Clearly, the range of potential impacts of land-use history on modern forest ecosystems is wide but will depend on many interacting factors. In order to examine these land-use legacies on ecosystem processes, we examined forests on agricultural lands abandoned 50 to 120 years ago in central Massachusetts and focused on several major questions:

- Does land-use history have a long-term effect on the amount of carbon, nitrogen, and phosphorus in the soil?
- How does land-use history influence the cycling and storage of nitrogen after reforestation has proceeded for nearly a century? Is this influence important for our understanding of current forest function and response to disturbance?
- Are there long-term effects of land-use history on the quality of organic matter that are driven by the composition of the plant community or availability of nutrients?
- How long do these effects persist? By what pathway does recovery proceed?

We conducted studies on Montague Plain and Prospect Hill, in conjunction with the vegetation studies described previously. At Montague we examined nitrogen cycling in the sandy outwash soils where the duration of agricultural use was short, only several decades, and the homogeneous soils allowed us to ascribe differences in nutrient cycling to land-use history or vegetation rather than site factors. We also examined carbon, nitrogen, and phosphorus dynamics on Prospect Hill, where agriculture persisted for at least 150 years on relatively hilly, moist, and more variable soils.

## The Contrasting Study Sites

As detailed information on the Montague Plain and Prospect Hill tracts is provided in previous chapters, we concentrate here on characteristics important to soil and ecosystem processes (Table 9.1).

### *Montague Plain*

On the outwash delta of sands and gravel that forms the 2,000-acre Montague Plain, the soil is highly permeable and prone to drought, and the water table is approximately 20 meters below the surface. The soils developed in siliceous sand and gravel; the texture of the upper 15 centimeters of soil is loamy sand to loamy fine sand and is fairly homogeneous.

Logging was the primary land use until the mid-1800s, when large

**Table 9.1.** Descriptions of the Two Study Areas

| | Montague Plain | Prospect Hill |
|---|---|---|
| Topography | Flat, homogeneous sand plain | Rolling, varied upland |
| Soil series | Hinckley, Windsor<br>Typic Udorthents | Canton, Scituate<br>Typic Dystrochrepts |
| Soil drainage | Excessively drained | Well drained |
| Historical land use | 82 percent cultivated; no pasturing; 18 percent primary woodland | 15 percent cultivated; 65 percent pastureland; 20% primary woodland or swamp |
| Woodlot vegetation | Pitch pine, scrub oak | Mixed hardwoods |

sections of the plain were plowed for corn and hay until the early 1900s. There is no evidence of permanent residences and little indication of intense pasturing on the plain itself, presumably because of the dearth of surface water. Consequently, we suspect that most plowed lands were not heavily fertilized with manure or other fertilizers.

The history of use, as either cultivated field or woodlot, strongly controls the structure and composition of the modern vegetation. Forests range up to 120 years old on primarily woodland sites that were last cut or burned in the late nineteenth century and on the oldest secondary forests. More than 97 percent of pitch pine stands occur on formerly plowed sites, and 89 percent of scrub oak stands are located on primary areas that were never cleared. Other vegetation types and associated prior land use include grasses and aspen (*Populus* spp.) on plowed sites that were abandoned as recently as 40 to 55 years ago, pitch pine *(Pinus rigida)* and white pine *(Pinus strobus)*–scarlet oak *(Quercus coccinea)* stands on plowed fields abandoned 55 to more than 100 years ago, and scarlet oak and scrub oak *(Quercus ilicifolia, Quercus prinoides)* stands on sites never plowed. Many aspen stands contain pitch pine, white pine, and oak regeneration and will probably develop into pine-oak communities in the future.

### *Prospect Hill*

The rolling terrain of the Prospect Hill tract supports more loamy and mesic soils and experienced the full range of land-use histories typical for upland areas. We selected twelve plots for study on the Prospect Hill tract from a subset of those used for the vegetation study described in the previous chapter. We examined three major land uses in currently forested areas: woodlot (primary forest), formerly pastured, and formerly plowed. Land-use history was determined using the field and historical evidence described in the vegetation study and by incorporating the extensive historical research of R. Fisher, W. Lyford, H. Raup, S. Spurr, and others. Field indicators of agricultural use other than grazing include the presence of an Ap (plow) horizon, absence of large surface stones, smooth microtopography, absence of ancient mounds and pits, and nearby stone walls composed of small rocks indicative of field improvement. Sites that had been plowed have 16- to 20-centimeter-thick homogeneous surface soil horizons (Ap horizons) with abrupt boundaries to the deeper soil below. We used historical records to differentiate rough pastures from woodlots as there is often little apparent difference in soils.

*Caveat*

Reconstructing the detailed history of a 20-by-20-meter plot subject to multiple human and natural disturbances over 200 years is nearly impossible, even through intensive site analysis backed by the excellent historical records in the Harvard Forest Archives. Our land-use categories consequently represent general types and broad differences in intensities of prior use, with an emphasis on the most intensive use of a site over time. We use this simple framework of woodlot, pastured, and cultivated land use to determine whether there are persistent effects from these management practices.

It is important to recognize that inherent soil differences among sites with different histories can confound the interpretation of site factors versus history in controlling modern soil differences. For example, soil properties and prior land use are somewhat related at Prospect Hill, in that farmers tended to avoid the poorly drained areas and converted the level, better drained sites to cultivation. In addition, prior land use can alter vegetation trajectories by affecting dispersal, establishment, and growth rates. We tried to minimize such inherent site differences by keeping slope, soil series, and soil drainage constant across all sites and by stratifying by vegetation type at Prospect Hill. These interactions were much less of a concern for Montague Plain because there is so little variation in soil properties that land-use boundaries appear to be a function of historical ownership rather than of inherent soil properties.

## Soil Legacies on Montague Plain

On Montague Plain, more than 80 percent of the area had been cultivated and subsequently abandoned 40 to more than 100 years ago. Of the plots studied in detail, the two youngest secondary forests were on fields that had been abandoned 40 to 60 years ago. These had the lowest carbon content in the upper mineral soils (0 to 15 centimeters), approximately 30 percent less than the average for the unplowed soils on primary forest sites (Figure 9.1). Soil carbon concentration was also significantly higher in unplowed soils than in all formerly plowed soils.

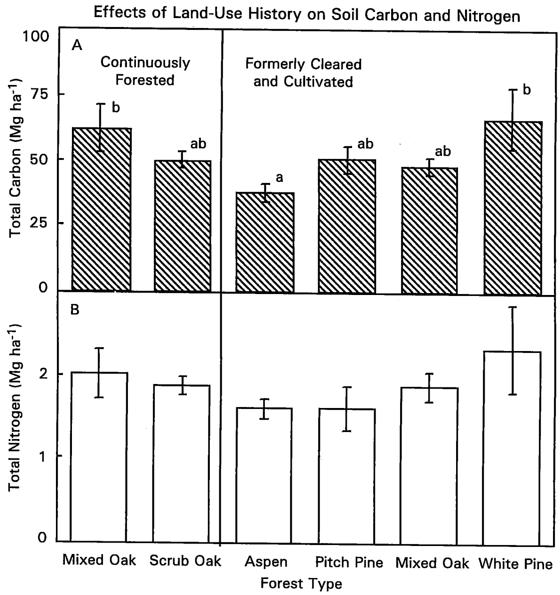


**Figure 9.1.** The influence of land-use history and present vegetation on the carbon (A) and nitrogen (B) contents of forest soils at Montague Plain. All sites currently support forest that is older than seventy-five years; however, some sites were continuously forested and others were previously plowed for agriculture. Within each land-use category, columns that share a letter are not significantly different ($p > .05$) from one another. There are no significant differences in nitrogen across land-use and vegetation types. Bars represent standard errors between plots within each vegetation type ($n = 2$ or 4). Modified from Compton et al. 1998, 539: fig. 1, with permission from Springer-Verlag (copyright 1998).

However, the higher bulk density in formerly plowed soils offset these differences, and there were no significant differences in total carbon content between plowed and unplowed soils. While the actual amount of soil nitrogen was not affected by land-use history or vegetation type, net nitrogen mineralization showed much greater variation. Net nitrogen mineralization measured over the month of August was more strongly related to present vegetation than to land-use history or soil nitrogen content (Figure 9.2) and varied nearly fortyfold among stand types; it was lowest in pitch pine and white pine stands (−0.13 and 0.10 kilograms of nitrogen per hectare, respectively), intermediate in scrub oak stands (0.48), and highest in aspen and mixed oak stands (1.34 to 3.11, respectively).

Appreciable net nitrification was observed only in the most recently abandoned aspen plot (0.82 kilograms of nitrogen per hectare), which was the youngest stand and the only area where we believe that agricultural lime added to the soils by farmers in the twentieth century in order to enhance productivity may continue to influence nutrient dynamics. The C:N ratios increased and pH declined with stand age or time since abandonment. Higher bulk density and C:N ratios and slightly lower carbon concentrations in the surface mineral soils persist today as long-term legacies of historical agriculture on Montague Plain. However, the relatively brief duration of agriculture and the low initial carbon and nitrogen concentrations in these nutrient-poor, sandy soils appear to have limited the long-term effects of agriculture on soil carbon and nitrogen content and nitrogen cycling.

Although long-term effects of land-use history on vegetation patterns at Montague Plain were striking (see the previous chapter), agricultural effects persisted in only a subset of the soil properties examined. The increase in soil bulk density associated with plowing is certainly a dramatic long-term change in these soils that could influence soil water availability, root distribution, and biological activity well into the future. The unplowed soils had higher C:N ratios and slightly more total soil carbon per gram of soil. Only the most recently abandoned sites, which had received modern liming and fertilizing treatment, show residual impacts of cultivation on soil carbon content and nitrification. After reforestation proceeds for more than fifty years, carbon and nitrogen levels are quite similar to those of unplowed areas, and net nitrogen mineralization is controlled largely by tree species composition, presumably through differences in litter quality, instead of direct land-use effects. Although plowing undoubtedly had important short-term ef-

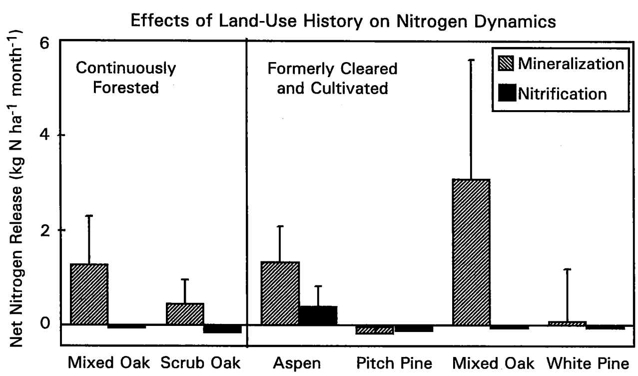


**Figure 9.2.** The effects of forest type and land-use history on nitrogen cycling (net nitrogen mineralization and nitrification) on Montague Plain. All sites currently support mature forest or scrub oak vegetation. Bars are standard errors between plots within each vegetation type ($n$ = 2 or 4). Modified from Compton et al. 1998, 540: fig. 3b, with permission from Springer-Verlag (copyright 1998).

fects on soil carbon storage, long-term effects were not observed, indicating that the marginal agriculture at Montague Plain did not dramatically influence soil properties other than bulk density. The impact of soil disturbance on the vegetation, notably the establishment of white pine and pitch pine stands in old fields, indirectly resulted in important long-term differences in net nitrogen mineralization.

## Soil Legacies on Prospect Hill

Even 70 to 140 years after agricultural abandonment, the impacts of different land-use histories on the forests on Prospect Hill are apparent in soil carbon, nitrogen, and phosphorus contents. In forests on old plowed fields, the amount of soil carbon was approximately 15 percent lower than in permanent woodlots, while nitrogen and phosphorus contents were slightly higher (Figure 9.3), especially in hardwood forests. The C:N ratios were lower on the plowed soils, as was the amount of what we call light fraction or easily decomposed organic matter. These results confirm that the levels and quality of organic matter are altered for a very long time after cultivation and reforestation on these loamy soils.

On this rolling upland site both vegetation composition and land-use history influence the amount and ratios of important soil elements. The C:N ratios in mineral soils were lower in formerly cultivated and hardwood soils than in permanent woodland or conifer forests (Figure 9.4). Such long-term alteration of soil nutrient ratios can have profound consequences on a range of forest ecosystem processes. In particular, they could increase the rate of nitrogen cycling through plants and microbes and increase decomposition rates. Such changes would tend to maintain lower C:N ratios and thus could be self-perpetuating.

The cycling of nitrogen is also influenced by both land-use history and present vegetation (Table 9.2). Net nitrogen mineralization is primarily controlled by present vegetation and was higher in hardwood sites. This result agrees well with the observation of the lower C:N ratios of hardwood soils. In contrast, nitrification was more strongly influenced by land-use history and was greater in cultivated sites. Nitrification potential and the biomass of nitrifying microbes were higher in both pastured and cultivated soils, yet only cultivated soils had higher net nitrification, suggesting that higher immobilization in pastured soils may reduce net nitrification.

Higher soil nitrogen and phosphorus and higher nitrification rates in the plowed areas 70 to 140 years after abandonment suggest that the addition of manure to these crop fields in the 1800s had a remarkably persistent influence on these sites. At least 65 percent of the land area across Prospect Hill and most of the Massachusetts uplands were used for pasture in the eighteenth and nineteenth centuries, leading to a con-

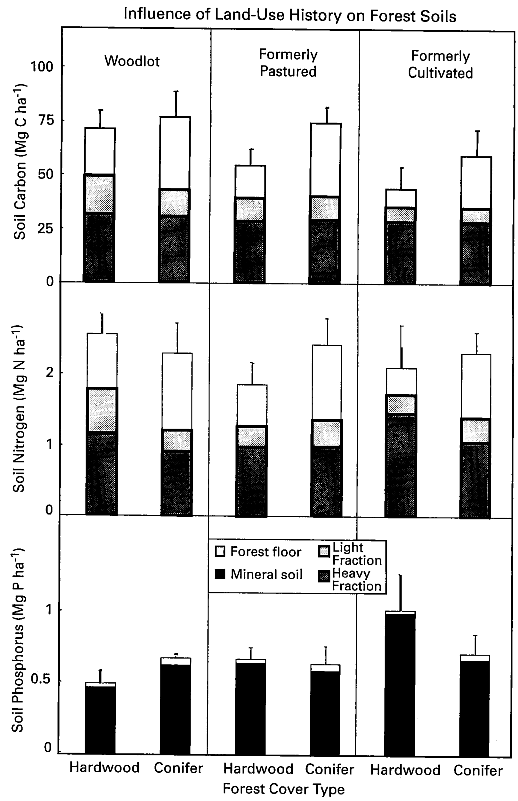


**Figure 9.3.** Total carbon, nitrogen, and phosphorus in the forest floor and top 15 centimeters of mineral soil by prior land use and modern vegetation on the Prospect Hill tract. The light fraction is organic matter that is relatively recent in origin; the heavy or mineral-associated fraction is more recalcitrant and older. Standard error bars ($n = 2$) are shown for the forest floor plus mineral soil. Based on Compton and Boone 2000.

tinual removal of nutrients and carbon from these areas. Farmers then transferred small portions of these nutrients to the plowed cropland through the process of manure applications. In order for a given plot of land to maintain productivity over the more than 100-year period during which it was typically farmed in New England, organic matter amendments were often applied. This movement of nutrients may have produced a wider range of variation in soil nutrients across the landscape than might be expected in native forests.

Soil-vegetation feedbacks on litter quality have occurred since the reestablishment of the forest, as indicated by our results that forest floor C:N, carbon-to-phosphorus, and nitrogen-to-phosphorus ratios are still low in former agricultural sites. Interactions between land-use history and vegetation were important in determining soil carbon, nitrogen, and

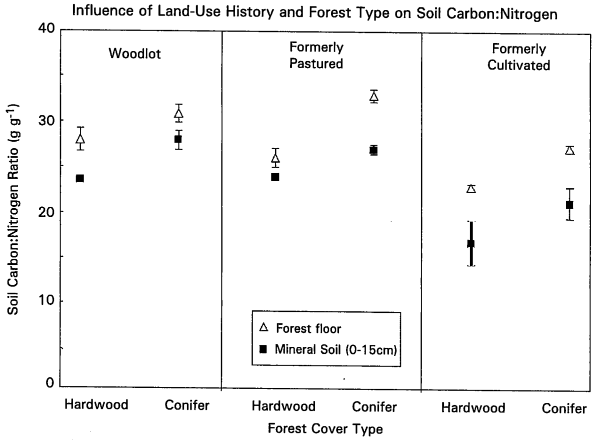


**Figure 9.4.** The ratios of total carbon to nitrogen in the forest floor and top 15 centimeters of mineral soil on Prospect Hill by prior land use and present vegetation. Standard error bars are shown ($n = 2$). Based on Compton and Boone 2000.

phosphorus contents as well as nitrification, and the hardwood sites generally exhibited greater residual impacts of prior land use. Our findings lead to the conclusion that the effects of agriculture on soil carbon, nitrogen, and phosphorus contents; microbial populations; and nitrogen cycling can persist for more than a century after abandonment. These effects may result from residual impacts of agricultural practices such as manuring or from the influence of land use on the pattern of vegetation recovery during reforestation.

**Table 9.2.** Effects of Land-Use History on Nitrogen Cycling on the Prospect Hill Tract

| | Nitrogen Mineralization (kg $ha^{-1}$ $yr^{-1}$) | Nitrification (kg $ha^{-1}$ $yr^{-1}$) | Nitrification (% of N mineralization) |
|---|---|---|---|
| **Conifer** | | | |
| Cultivated | 7.9 (3.5) | 0.8 (0.5) | 9.3 (2.4) |
| Pastured | 8.2 (0.6) | 0.5 (0.2) | 6.0 (2.1) |
| Woodlot | 7.7 (0.1) | 0.1 (0.0) | 1.6 (0.1) |
| **Hardwood** | | | |
| Cultivated | 18.1 (0.7) | 4.3 (0.3) | 23.7 (2.5) |
| Pastured | 11.8 (1.6) | 0.6 (0.2) | 4.6 (1.3) |
| Woodlot | 14.7 (0.0) | 0.6 (0.1) | 4.1 (0.5) |

*Source:* Reprinted from Compton and Boone 2000, with permission from the Ecological Society of America.
*Note:* Growing season net nitrogen mineralization (net ammonium plus nitrate accumulation in buried bags), nitrification, and nitrification as a percentage of nitrogen mineralization are shown. The time period is May 11 through October 31, 1995. Standard error of the mean of two plots is shown in parentheses.

## Consistent Patterns and Differences between Sites

Collectively, these results indicate that three important factors play major, though variable, roles in controlling modern soil characteristics and important aspects of forest biogeochemistry: inherent soil properties, historical land-use practices, and vegetation composition. These factors interact through time to regulate the long-term recovery of soil characteristics and processes after agricultural abandonment, logging, or other activity. As noted by New England settlers and scientists alike, trees and then forests quickly reclaim pastures, hay fields, or croplands once the grazing, mowing, or plowing ceases. However, the recovery of critical soil characteristics such as soil organic matter and microbial populations may lag decades behind the development of the new forests. Thus, the appearance of forests can be deceptive and may hide major differences in ecosystem function resulting from historically distant activities. From our comparison of contrasting sites, we can conclude that the recovery of soil carbon lost due to deforestation and cultivation requires at least 70 years of reforestation and that the rate of carbon sequestration may be slowed by other consequences of agriculture, including a self-perpetuating increase in the quality and decomposition of soil organic matter on some sites. Forests on former agricultural sites have persistently lower soil C:N ratios. These results fit a general pattern that is emerging from our work as well as the few studies available from other ecosystems. For instance, recovery of soil carbon appears to require at least 50 years after abandonment of grasslands in Colorado and forests of the southern Appalachians, while more than 200 years may be necessary to regain soil carbon lost in the more slowly growing forests of New Hampshire.

Our work also illustrates that the type and intensity of land use are quite important in influencing the subsequent recovery pattern. On the poor-fertility soils of Montague Plain, agricultural use was short in duration and probably did not include intensive amendment of cultivated areas with animal manures or other fertilizers. After more than fifty years of reforestation, soil carbon levels are approaching 90 percent of levels observed in soils that were never plowed, and nitrogen cycling is very similar between stands with different land-use histories. However, the legacy of prior land use on the forest vegetation is more pronounced than that on soil nitrogen cycling at Montague Plain, and in turn, present vegetation appears to have a much stronger effect on soil properties and processes.

The Prospect Hill farms have been abandoned for a longer time than the Montague farms, yet because of the more intensive and more prolonged agricultural use at Prospect Hill, the long-term effect of past agriculture on soil C:N ratios and nitrate production is enhanced (Figure 9.5). In fact, our results suggest that intensive agriculture actually in-

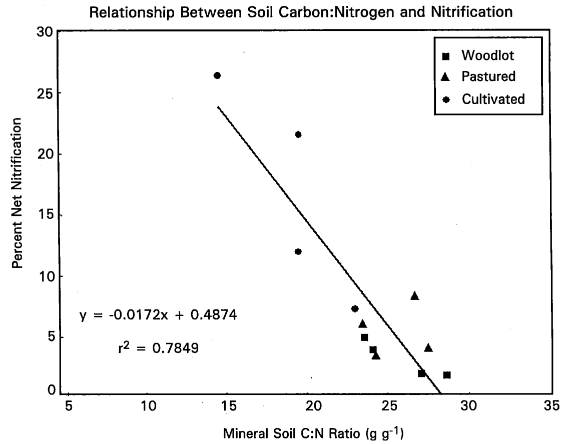


**Figure 9.5.** Relationship between nitrification and C:N ratios for forest soils with different land-use histories on the Prospect Hill tract. Based on Compton and Boone 2000.

creased nitrogen cycling rates, probably as a result of incorporation of animal manures into the soil in pastured and cultivated sites. These additions are still evident as slightly higher soil nitrogen and phosphorus contents, lower C:N and carbon-to-phosphorus ratios, and higher nitrification rates in cultivated soils. Our results clearly do not support the commonly held notion that early New England farming depleted soil fertility; rather, because nineteenth-century farming practices moved organic materials from one area to another within the farm, some areas may have been enriched in carbon, nitrogen, and phosphorus, while others were depleted.

These findings indicate that prior land use has persistent, important effects on the dynamics of soil organic matter and on nutrient storage and availability. Cultivation and manure amendments appear to have long-lasting effects on soil properties and microbial nutrient processing, resulting in a pattern of recovery that is decidedly different from that observed for other disturbances such as logging, fire, and windthrow. Given the possibility, however, that not all cultivated lands were treated with the same type and amounts of organic amendments, the simple land-use categories described here may not completely reflect the complex history of a given plot of land. In addition, the patterns of nitrogen availability following reforestation are not just the direct effects of land use but are also driven by the resulting indirect changes in vegetation and feedbacks to forest floor decomposition.

## How Will Land-Use History Influence the Forest's Response to Future Changes?

In order to understand important ecosystem processes such as forest growth and carbon storage or the ability of forests to retain added nitrogen, future researchers should carefully examine land-use history. In our comparisons of forests with different land-use histories at Prospect Hill, intensive cultivation increased soil nitrate production by decreasing the C:N ratio (and perhaps through increases in nitrogen through manure additions). This effect was maintained for a very long time. Because of this long-term legacy of cultivation and organic matter amendments, it is possible that forests regrowing on cultivated sites could be more susceptible to the effects of nitrogen saturation than pastured or logged sites. Recognizing the differences in land-use history of the chronic nitrogen experimental plots (see Chapter 12) has proved to be important in understanding the responses to nitrogen additions. The formerly cultivated sites could have an accelerated response to nitrogen deposition, even overcoming the presumed roles of species differences (pine versus hardwood) in controlling soil and ecosystem processes.

Forest regrowth on former agricultural lands is a major sink for atmospheric $CO_2$ in the eastern United States. High nitrogen availability on former farms may allow rapid regrowth of forests, allowing these ecosystems to serve as a major carbon sink for decades after agricultural abandonment. The long-term influence of specific land-use practices on forest regrowth (cultivation versus pasture versus logging) is not yet clear, but the legacies could also drive the variations in this important mechanism of carbon storage across the landscape and region.