An Ecosystem Unraveling?

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Abstract

Continued decline of eastern hemlock forests associated with infestations of hemlock woolly adelgid will bring about major ecological changes. The plant species most likely to expand in declining hemlock stands are mainly hardwoods and invasive alien species that will not provide habitat or ecological functions anything like those of eastern hemlock. Defoliation and mortality of hemlock forests means the loss of distinctive habitat and microclimates, and reduced local and landscape-scale biodiversity. The distribution and abundance of a number of bird species will very probably decline. The temperature and hydrologic regimes of streams with hemlock dominated watersheds or riparian areas will probably become more variable and less stable – in particular, warmer and more likely to dry-up in summer. The distribution and abundance of brook trout will very probably decline, and the diversity of aquatic insects in small streams draining hemlock forests will probably decline. Rates of nitrogen mineralization and nitrification will increase in affected areas. Nitrate and cation (e.g., ammonium, Ca, Mg, Al) leaching in soil water will increase, possibly leading to significant export of these nutrients to streams, and depletion of soil nutrients. Biocontrol agents and pesticides should be used judiciously to suppress HWA populations and maintain hemlock tree health. Active and innovative vegetation management will be necessary to try to mitigate effects of hemlock decline, and restore the ecological conditions as much as possible in affected hemlock stands.

Keywords:

Eastern hemlock, ecology, biodiversity, adelgid, alien.

Introduction: Ecological and Historical Context

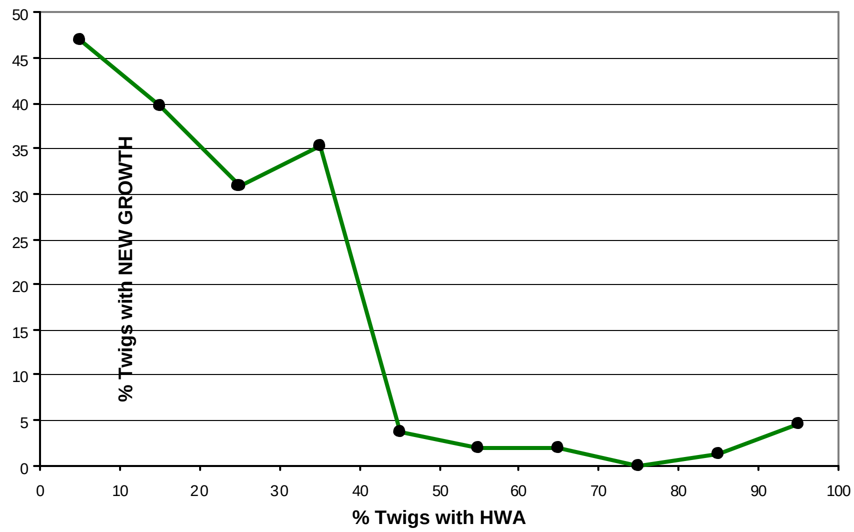
Are eastern hemlock ecosystems unraveling? Yes, at least in many areas that have had prolonged infestations of hemlock woolly adelgid (*Adelges tsugae*). But what does "unraveling" mean? Why does it matter? What can we do about it?

It all starts with the tree. Eastern hemlock (*Tsuga canadensis*) is the state tree of Pennsylvania. I like to refer to eastern hemlock as "the redwood of the east." Eastern hemlock is one of the most shade-tolerant trees in North America. It also is – at least potentially – one of the longest living trees in eastern North America. In the absence of severe stress or disturbance, eastern hemlock trees often live well beyond 400 years, and trees more than 900 years old have been documented. Thus, with appropriate climatic and site conditions, eastern hemlock can dominate a stand for hundreds of years, often accounting for upwards of 75% of stand basal area. Such hemlock dominated stands typically allow only about 5% of incoming sunlight to reach the understory (Battles et al. 2000), and create distinct micro-climates. Soils under hemlock-dominated stands exhibit characteristically low pH, high carbon to nitrogen ratios, and low rates of nitrogen mineralization and nitrification (Mladenoff 1987; Jenkins et al.1999; Yorks 2000). Understory plant species composition, biomass, and productivity are very much constrained by the conditions created by hemlock trees. I suspect that invasive alien plants are much less likely to invade *healthy* hemlock-dominated stands than many other forest types.

The eastern hemlock forests in existence during the late 20th century, even prior to the arrival of hemlock woolly adelgid, represented only small remnants of a forest type that had been widespread and common throughout much of the eastern United States for several thousand years (Foster 2000). Land clearing and logging (especially for the tanning industry) during the past 400 years has dramatically reduced the abundance of eastern hemlock. Mladenoff (1996) estimated that eastern hemlock now occurs at only 0.5% of its former abundance in the mesic forests of Wisconsin and Michigan. Yet, I suspect that eastern hemlock is well represented in what little remains of relatively undisturbed and “old growth” forests in the eastern United States. For all these reasons, and more to be elaborated below, stands dominated by eastern hemlock are distinctive habitats and ecosystems, and are of substantial conservation value.

The decline and loss of our remaining eastern hemlock stands could be more ecologically significant than the loss of American chestnut (*Castanea dentata*) in the early 1900s due to chestnut blight. Following the demise of American chestnut, an array of native oak and hickory species naturally expanded their populations, and have functioned as “ecological surrogates” for chestnut in providing habitat and mast (nuts) critical to many species of wildlife. In contrast, the species most likely to expand in declining hemlock stands include black birch (*Betula lenta*), red maple (*Acer rubrum*), white pine (*Pinus strobus*), and invasive alien plants like “tree-of-heaven” (*Ailanthus altissima*), Japanese barberry *(Berberis thunbergii*), and Japanese stiltgrass (*Microstegium vimineum*) (Orwig and Foster 1998, Battles 2000). These species will not provide habitat or ecological functions like those of eastern hemlock.

Continued defoliation and loss of hemlock forests will thus bring about major ecological changes. A more homogenous vegetation across the landscape (Foster 2000) means the loss of distinctive habitat and microclimates, and reduced biodiversity. As explained in more detail later, the distribution and abundance of brook trout (*Salvelinus fontinalis*) and a number of bird species will very probably be reduced, and the diversity of aquatic insects in small streams draining hemlock-dominated forests will probably decline. Rates of nitrogen mineralization and nitrification, and nitrate and cation (e.g., ammonium, Ca, Mg, Al) leaching in soil water, will increase in response to hemlock decline (Jenkins et al. 1999; Yorks 2002).



As mentioned earlier, declining hemlock forests are vulnerable to invasion by opportunistic alien plants, especially if roads, ditches, trails, developments, or other disturbed areas are nearby. High densities of white-tailed deer (*Odocoileus virginianus*) in some areas will inhibit or prevent regeneration of many trees, and facilitate the spread of hay-scented fern (*Dennstaedtia punctilobula*) and invasive alien plants. Expanding populations of hay-scented fern can further prevent tree regeneration and exclude other plants. Thus, deeply shaded, late-successional hemlock forests could be replaced by opportunistic alien weeds and open “fern glades.” Active and innovative silvicultural and vegetation management will be necessary to try to mitigate these changes and restore the ecological conditions as much as possible in affected hemlock stands.

Learning from Monitoring and Research at Delaware Water Gap National Recreation Area

Staff at Delaware Water Gap National Recreation Area (“the park”) have been very much concerned about hemlock woolly adelgid (HWA) and hemlock decline ever since HWA was first detected in the park in 1989. Eastern hemlock is a major component of the canopy in 141 forest stands in the park, covering about 3,000 acres (about 1,200 hectares), equal to about 5% of the park (Myers and Irish 1981). Many of our most popular visitor-use areas are within hemlock forests.

Since 1993 we have conducted numerous research and monitoring projects relating to HWA, hemlock tree health, and hemlock ecosystems in the park. Most of this work fits into one of three categories:

1. Permanent plot monitoring: The main purpose of these studies is to document and relate HWA infestation levels with hemlock tree health in the park. With assistance from the USDA Forest Service (Morgantown, WV), we monitor HWA populations and hemlock tree health annually in all, or a large portion of, 81 permanent hemlock plots.

2. Intensive ecological studies: The main purpose of these studies is to document in detail the variety of species and environmental conditions that occur within individual hemlock stands, and thus provide a detailed baseline to assess future changes. Through contracts and collaborations, we have completed "intensive" studies in two hemlock stands of the following: vegetation -- including bryophytes (Battles et al. 2000), small mammals and amphibians (Sciascia et al. 1995), ground arthropods (Shrot 1998), and breeding birds (unpublished; staff and volunteers).
3. Extensive ecological studies: The main purpose of these studies is to be able to make statistically valid inferences about the influence of hemlock stands on park biodiversity and environmental conditions. The Leetown Science Center of the USGS Biological Resources Division (BRD) designed an "extensive" landscape scale study that pairs each of 14 hemlock stands and streams with a hardwood stand and stream (28 stands total) based on terrain similarity (Young et al. 2002). To date, the BRD has completed studies of breeding birds (Ross this volume), stream insects, fish, and temperatures (Snyder et al. 2002) at these 14 pairs of hemlock and hardwood sites in the park. In addition, Penn State completed a study of the tree species composition at these 28 sites (Sullivan et al. 1998), and the Wildlife Conservation Society completed a survey of stream and riparian salamanders at these sites (Brotherton et al. 2001). We have collaborated with the State University of New York, College of Environmental Sciences and Forestry since 1999 to collect and analyze monthly stream water samples at these 28 sites for major cations, anions, and other parameters.

Here I will highlight only some of the results from studies in groups 1 and 3.

One of the ways we relate HWA populations to hemlock tree health is to count the number of twigs on selected branches, and determine the proportion of those twigs that are infested with HWA, as well as the proportion of those twigs that produce new growth (Evans 1996). Figure 1 shows that as the proportion of HWA infested twigs increase, the proportion of twigs that produce new growth decreases sharply. When more than 45% of the twigs on a branch were infested, virtually no new growth occurred. Figure 2 shows that at the forest stand scale, virtually no new growth occurred when HWA infested more than 30% of the twigs in a stand. I suspect that the proportion of twigs infested in a stand is correlated with the length of time the stand has been infested with HWA, and hence reflects the "cumulative dose" of HWA the stand has experienced. The longer HWA has infested a stand, the higher the proportion of twigs infested with HWA, and the lower the proportion of new growth on branches.

What might be the consequences of hemlock decline on birds in the park? To address this question, Ross (2002) recently completed a survey of breeding birds in the 14 pairs of hemlock and hardwood stands in the park (Young et al. 2002). While he found that bird species richness is typically lower in hemlock forests than hardwood forests, he also found that several species common in hemlock forests are rare in hardwood forests. Thus, hemlock forests increase bird diversity at a landscape scale. Birds common in, and apparently dependent on, hemlock forests for breeding habitat include the blackburnian warbler (*Dendroica fusca*), black-throated green warbler (*Dendroica virens*), and blue-headed vireo (*Vireo solitaris*). Populations of these species will very likely decline in the park as hemlock forests decline (Ross 2002). These conclusions are consistent with those drawn from studies in the western Great Lakes region (Howe and Mossman 1995) and New Jersey (Benzinger 1994a and 1994b).

Figure 1. Relationship between the HWA infestation level and new twig growth on hemlock branches during summer 2000. Branches with 45% or more twigs infested with HWA produced almost no new growth. A total of 318 branches, and 16,154 twigs, were evaluated. To generate this figure, "raw" data were first condensed into categories of HWA infestation level (% of twigs with HWA); 0-10%, 11-20%, 21-30%, etc. The 80th percentile of new growth was then determined and plotted for each category of HWA infestation level.

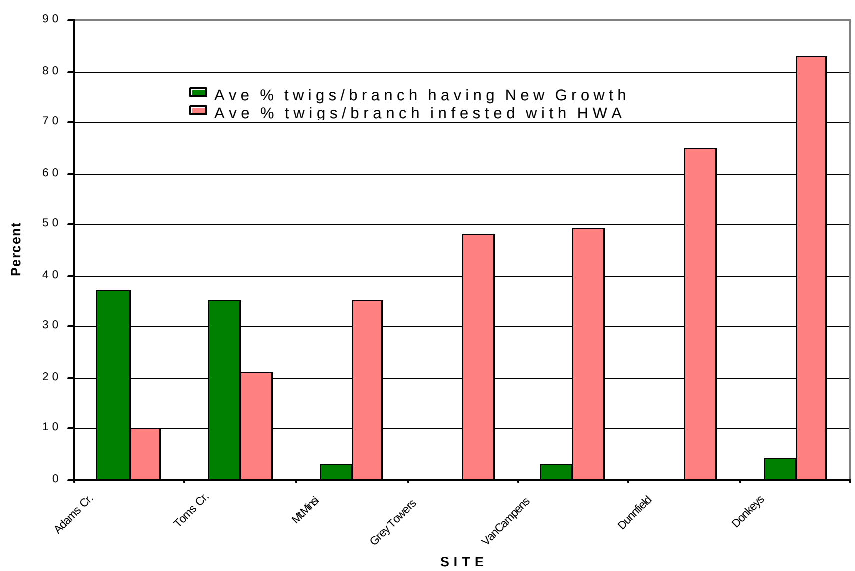


Figure 2. Different HWA infestation levels and amount of new twig growth observed at different sites during summer, 2000. HWA infestation level was measured as the average percent of twigs per branch having HWA; the amount of new twig growth was measured as the average percent of twigs per branch producing new growth.

What might be the consequences of hemlock decline on stream ecosystems and biodiversity in the park? To address this question, Snyder et al. (2002) sampled fish and macroinvertebrates in small headwater (first and second order) streams draining the 14 pairs of hemlock and hardwood stands in the park. In addition, electronic temperature data loggers were installed in 10 pairs of hemlock and hardwood streams, and recorded stream temperatures every hour for one year. A previous study (Evans et al. 1996) had shown that summer temperatures in a stream gradually declined 3 to 4°C as the stream passed through a hemlock ravine, and that the cooling effect of the ravine was essential for maintaining temperatures tolerable to native brook trout (Figure 3). However, this single site study could not address the extent to which this stream cooling might occur throughout the park or larger regions.

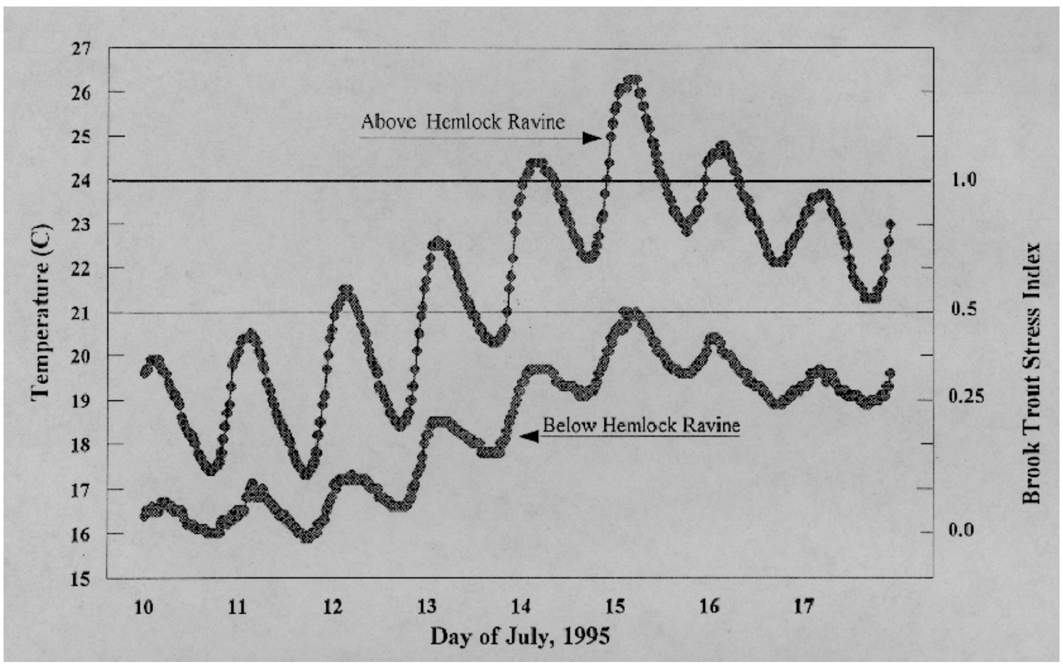


Figure 3. Stream temperatures at the upper and lower ends of Adams Creek hemlock ravine ("above" and "below"), in relation to a temperature stress index for brook trout (Raleigh 1982). Temperatures decreased gradually as the stream passed through the hemlock ravine. The cooling effect of the ravine is essential for maintaining stream temperatures tolerable to brook trout.

Results from the fish and macroinvertebrate surveys in first and second order streams draining paired hemlock and hardwood forests indicated the following: Brook trout were three times more likely to occur in hemlock streams than in hardwood streams. The average number of aquatic macroinvertebrate taxa found in hemlock streams was 37% greater than that found in hardwood streams (55 versus. 40 taxa). Fifteen macroinvertebrate taxa were strongly associated with hemlock streams, and three taxa (two trichopterans (caddisflies) *Hydropsyche ventura* and *Polycentropus* sp., and a chironomid (midge) *Natarsia* sp.) were found only in hemlock streams. No macroinvertebrate taxa were strongly associated with hardwood streams.

Stream temperature data showed that hemlock streams were consistently cooler in summer (May through September), and also warmer in winter (December through February), than their paired hardwood streams (Figure 4). During June, July, and August, median daily temperatures in hemlock streams were typically 1°C to 2°C cooler than their hardwood stream counterparts. These stream temperature differences are potentially important to brook trout condition and survival. Temperatures above 20°C are increasingly stressful for brook trout. Figure 5 shows that the maximum daily temperature in hemlock streams exceeded 20°C only 3% of the time, whereas the maximum daily temperature in hardwood streams exceeded 20°C 18% of the time.

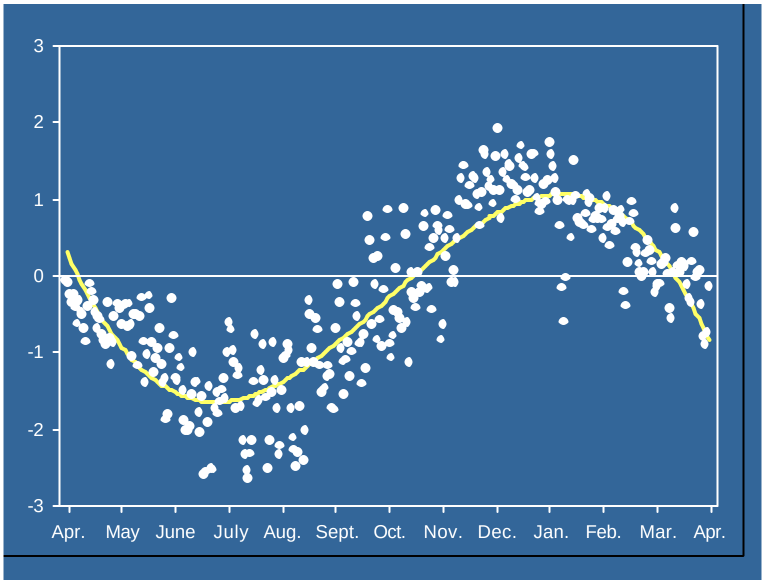


Figure 4. Mean difference in median daily stream temperatures of hemlock and hardwood site pairs from April 1997 to April 1998. Hemlock streams were substantially cooler than hardwood streams from May through September, and warmer from December through February.

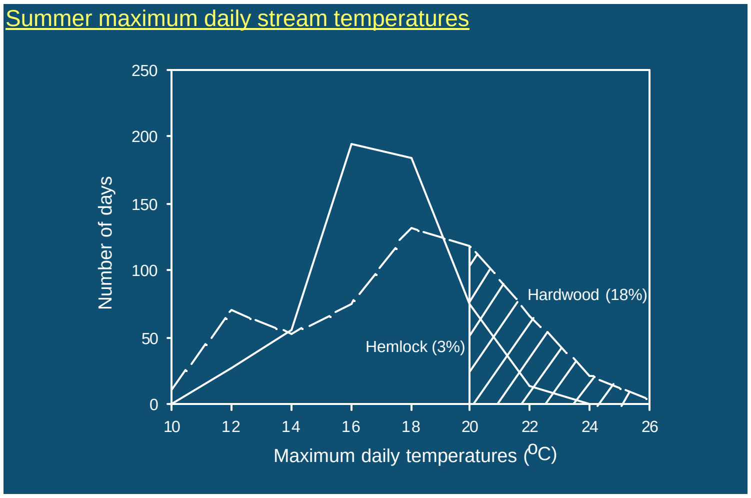


Figure 5. Distribution of maximum daily temperature values for streams draining hemlock (solid line) and streams draining hardwood (dashed line) forests. Figure showcases the number of days that exceed 20 C (threshold for brook trout survival) for comparison.

Of course, brook trout cannot live in areas that do not have water. In the course of our stream sampling, we discovered that small streams draining hardwood forests are much more likely to dry up during summer droughts than similar small streams draining hemlock forests (Table 1). The extent and frequency of stream channel drying is very likely a major factor controlling the aquatic macroinvertebrate assemblages, as well as the occurrence of brook trout, in these small streams. The higher species richness in small hemlock streams compared to small hardwood streams may well be related to the frequency or likelihood of these streams drying up.

Table 1. Comparison of the Percent (and Number) of Hemlock and Hardwood Streams That Dried up in the Summer of 1997 and 1999, and Probability Values of Chi-Square Tests.

Forest Type	1997	1999
Hemlock	0% (0)	7% (1)
Hardwood	29% (4)	43% (6)
Chi^2 p-value	0.013	0.023

The fact that small hemlock streams have more stable temperature and hydrologic regimes than small hardwood streams in our area could be due to differences in groundwater inputs to the streams, as well as differences in forest type. It may well be that there is more groundwater input to streams draining hemlock stands than to streams draining hardwood stands. This might lead some to think that the observed differences are due entirely to groundwater inputs, independent of forest type. However, forest type very likely exerts some control over groundwater inputs to streams. Because hemlock trees have extremely shallow root systems, they must get their water from upper soil layers, and they can not withdraw water from deeper soil layers or groundwater. Most hardwood trees, in contrast, have deeper root systems, and thus can withdraw water from deeper soil layers and/or groundwater – preventing the water from seeping into stream channels. The fact that several of the hardwood study sites once supported hemlocks, as evidenced by old stumps, suggests that "inherent" site soil moisture and groundwater conditions by themselves do not account for the differences in existing forest type, or stream temperature and hydrologic regimes. It is not just foliage and crown structure of hemlocks that influence stream conditions, but the whole tree, including the roots.

Management of Hemlock Forests: Maintain, Mitigate, and Restore

We are just beginning to develop a hemlock management plan for the park. I expect this plan to follow a strategy of prioritizing sites for the following management efforts: trying to maintain healthy hemlock trees; mitigating effects of hemlock defoliation and mortality; and restoring native vegetation and conditions of impacted sites, to the extent feasible. Until very recently, we have focused on trying to maintain healthy hemlock trees through (very limited) application of horticultural oil, and release of *Pseudoscymnus tsugae* beetles. With the assistance of the USDA Forest Service (Morgantown, WV) and the New Jersey Beneficial Insect Laboratory, we have released a total of 25,000 *P. tsugae* beetles in two hemlock stands (12,500 in each stand) during the past two years (Evans 2000, 2001). In the near future we expect to treat trees in priority visitor-use areas with Merit or a similar systemic pesticide. We are also trying to maintain good soil conditions for hemlock trees by trying to discourage and control visitor traffic in vulnerable areas.

Ecological studies such as those discussed above provide us with some knowledge of the “natural condition targets” for mitigation and restoration. We have learned that we should be thinking about ways to retain not only evergreen canopy cover, but also stable stream flows, relatively low nitrification rates, and high carbon-to-nitrogen ratios in the soil. We should be taking steps to minimize invasion by alien plant species. One possible method to address these “desired conditions” is to apply woodchip mulch from dead hemlock trees on soils of impacted sites. The relative success or failure of our management efforts should be judged in large part by, for example, the extent to which brook trout and affected bird species are retained, and the extent to which alien plants are excluded from affected sites.

Other actions and ideas to mitigate effects of hemlock decline and to restore impacted sites include the following: Removing hazard trees (we have begun removing hazardous dead and dying hemlock trees in visitor-use areas this year); reducing dead wood fuel loads where necessary; removing bark from hemlock trees infested with hemlock borer beetles (*Melanophila fulvoguttata*); maintaining other canopy trees, especially white pine, and encouraging regeneration of hemlocks, white pine, and other native species; reducing or excluding browsing by white-tailed deer (may require fencing).

Conclusion

I conclude with a paraphrase of a statement Aldo Leopold made more than 50 years ago in one of his *Essays on Conservation from the Round River* (“Oregon and Utah: Cheat Takes Over”):

> “Is there, as yet, no sense of pride in the husbandry of wild plants and animals, no sense of shame in the proprietorship of a sick landscape?”

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