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Landscape Development, Forest Fires, and Wilderness Management

Fire may provide the long-term stability needed to preserve certain conifer forest ecosystems.

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The major components of the natural landscape are landforms and vegetation. Their status at any moment is a result of a complex of interacting factors operating over various lengths of time. These dynamic systems attain quasi-equilibria lasting tens or hundreds of years but show sequential developments over longer times. Thus, the form of a hillslope represents a short-term equilibrium among processes of weathering, erosion, and vegetational stabilization under conditions of crustal and climatic stability, but in the long term the hillslope is reduced until the external controlling conditions change. Similarly, vegetation may progress in a short time through successional stages to a climax, but in the long term external factors may control the stability.

Recognition of dynamic landscape development stems from interactions between geology and biology. Lyell's (*1*) synthesis of paleontology and geology in 1830 helped stimulate Darwin (*2*) to develop the theory of organic evolution in 1859. Evolutionary trends were then sought in other sciences. Davis (*3*) introduced the erosion cycle in 1889, in which youth is followed by maturity and finally old age, which persists until the cycle is reinitiated by crustal uplift. In plant ecology, Cowles (*4*) proposed that vegetation stages parallel those of the erosion cycle. Clements (*5*) likened vegetation development to the life cycle of an individual.

These theories of landscape development have been severely criticized. The criticisms are based largely on quantitative analyses of the mechanisms and at least the short-term rates of geomorphic and ecologic processes. However, the schemes of Lyell, Darwin, Davis, Cowles, and Clements involve lengths of time that are difficult to evaluate. For all evolutionary processes, extrapolation from modern rates to past rates must be based on knowledge of past conditions derived from quantitative paleontology, stratigraphy, and geochronology.

The genetic mechanism of evolution is now largely understood. Rates of genetic change and speciation in organisms such as the fruit fly have been determined, but direct application of such rates to other animals is hardly justified. Particle movement on hillsides and in streams has been studied intensively, so that rates of erosion in badlands and of sediment transport in streams are known, but use of such rates to solve problems of long-term landscape development is hazardous. Short-term early plant successions on newly exposed landscapes, along with data on nutrient supply and soil stabilization, are documented, but vegetational development over subsequent decades and centuries is not easy to predict.

Landscape processes can be studied in a wide variety of situations. Even highly disturbed landscapes can provide some insights. Often experimental plots can be designed in which controlling factors can be manipulated. However, studies of long-term landscape development can be carried out only on natural landscapes, where the controlling factors have been operating for hundreds or thousands of years. Large-scale and long-term ecosystem processes can best be studied in large virgin forests.

Preservation of some natural areas may require only that exploitation be curtailed. Elsewhere, certain natural processes that have been eliminated must be restored. Specifically, in certain conifer forest areas, including most of the national parks and wilderness areas of the western and northern United States and Canada, forest fires have been effectively excluded for at least 50 years. Yet recent research shows that the maintenance of natural conditions in these forests depends on frequently occurring fire. Continued fire suppression will upset the ecosystem balance and lead to unpredictable changes.

In this article I evaluate and reconcile certain concepts of landscape development by clarifying the time scales for which the various concepts are applicable. Particular attention is devoted to problems of vegetational succession and climax in the cutover forest of the Appalachian Mountains and the fire-dependent virgin forest of the Boundary Waters Canoe Areas (BWCA) in Minnesota. Inasmuch as many areas of virgin forest, including the BWCA, are part of the national wilderness system, management must understand the effects of disrupting the natural processes that have brought the forest into being. For the BWCA a new management plan has been adopted (*6*) that not only ignores crucial ecological principles but also contravenes the spirit of the Wilderness Act (*7, 8*).

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The Erosion Cycle

In the 1880's Davis (*3*) developed a grand and integrated theory of landform evolution: the sequential erosion of newly exposed land surfaces through stages of youth, maturity, and old age, under conditions of stable crust and stable climate. The end form is a peneplain, which persists until crustal uplift initiates a new cycle (*9*).

Davis's theory of the erosion cycle was conceived for humid temperate regions, for which it received wide acceptance. He later extended the theory to arid regions (*10*), but tropical and polar landscapes were not easily fitted into the model.

Penck (*11*) was the first to offer an integrated theory of landscape development based on premises different from those of Davis. Davis assumes crustal stability during the erosion cycle, but Penck believes that crustal uplift proceeds more or less apace with erosion, and that landforms reflect the relative rates of the two processes.

A cornerstone of Davis's erosion cycle, the concept of the graded stream, was elaborated and effectively defended by Mackin (*12*), but Leopold and Maddock (*13*) showed that streams become graded very early in their development, not just at "maturity." Perhaps the most comprehensive criticism of Davis came from Hack (*14*), who denied the evidence for long intervals of crustal stability and thus for the development of peneplains. From studies in the Appalachian Mountains, Hack concluded that the characteristic "ridge-and-ravine" topography does not result from uplift of an older peneplain or partial peneplain followed by mature dissection, but rather from a dynamic equilibrium, in which the degradation processes of weathering, soil creep, and stream erosion are opposed by rock resistance and crustal uplift. He pointed out that differences in these processes or factors can result in slopes of differing steepness and thus in landscape of differing expression, but he implied that neither the crust nor sea level (which serves as the erosion baselevel for stream systems) is stable long enough to permit the landscape to be lowered to a peneplain.

Arguments for erosion cycles versus noncyclic dynamic equilibrium revolve around the time factor and the rates of geologic processes. The real ages of landforms are difficult to determine because of lack of radiometrically datable material. For the Appalachian Mountains, the chronology of past events and the rates of geomorphic processes are not well enough established to permit us to evaluate whether the landscape ever did or could reach the peneplain stage. The enigmatic flat crest of parts of the Blue Ridge, strikingly discordant to rock structure—a type of landform not specifically discussed by Hack—suggests the end form of a past erosion cycle, but neither it nor the basement surface beneath the coastal plain sediments is extensive enough or well enough mapped to be identified with certainty as an ancient peneplain. The Appalachian Piedmont is also a dissected plateau with discordant structure. Its identification as a peneplain by Davis was defended by Holmes (*15*).

The debate has reached an impasse. There is as much (or as little) historical evidence of Appalachian crustal stability with occasional uplift as there is of uplift that nearly keeps pace with erosion. Shifts in baselevel resulting from Pleistocene sea level fluctuations did not affect streams far enough inland to control erosional processes in the Appalachian Mountains. The ineffectiveness of Pleistocene baselevel controls indicates that Appalachian peneplain formation was much older than Pleistocene, perhaps as old as Cretaceous, 60 to 100 million years ago. However, the stratigraphic record is inadequate to solve the problem.

Schumm and Lichty (*16*) attempted to evaluate the time factor, and concluded that the controversy results from analyzing geomorphic processes on different time scales. The process geomorphologist may measure the factors in a dynamic equilibrium, but extrapolation of an erosion rate to determine the age of a landform may not be justified because modern rates may be unnatural, owing to human disturbance of the system. The historical geomorphologist may be able to evaluate such extrapolation over a short term if a datable sedimentary record of the erosional process is available. But long-term evaluations are difficult because such geomorphic factors as climate, uplift, and bedrock resistance change independently.

One can conclude with Carson and Kirby (*17*) that evidence for long-term crustal stability in certain regions is sufficiently strong to support the concept of the erosion cycle and the development of peneplains, although mechanisms of slope retreat and development of stream profiles may not be as simple as Davis envisioned. Much care is necessary in historical analysis, not only of the structural and hydrologic controls on the development of terraces and other landforms, but also of the time scale and the rates of geomorphic processes.

Vegetational Development

While Davis and his followers used the erosion cycle to interpret landforms worldwide, Cowles (*4*) and Clements (*5*) developed the theory that all vegetation progresses through successional stages to a stable climax, which persists until some interruption occurs. Cowles (*4, 18*) insisted on a precise resemblance between the climaxes of the erosional and vegetational cycles.

Clements, however, deemphasized the relation to landform evolution, arguing that vegetational succession is limited by climate. He acknowledged that local bare areas produced by vigorous erosion are more common and provide more opportunities for early stages of plant succession in youthful than in mature landscapes. But he noted that successional stages proceed to a climax much more rapidly than Davisian erosion cycles reach old age. Also, a single erosion area might transect various climatic belts with different climax vegetation. Clements used the Darwinian model to postulate that the climax formation actually is an organism, which is generated, grows, matures, reproduces, and dies.

Gleason (*19*) opposed climax theory by introducing the notion that a plant association represents merely an accidental juxtaposition of individuals rather than a naturally interrelated assemblage of species. This controversy continues today. Whittaker (*20*), in reviewing the entire climax concept literature, rejected two points: the concept of a vegetation assemblage as an organism, and the rigid connection between climax and climate. The notion of a polyclimax (*21*) or climax pattern is still supported. Local ecologic conditions such as high soil moisture or disturbance permit the development of a quasi-stable plant association that reproduces itself short of true climax. In Clements' view, the climax represents intermediate edaphic conditions toward which all landforms and soils eventually tend.

Virtually all evaluations of the climax

concept are based on studies of modern vegetation. Despite the use of new techniques of measurement and statistical analysis, results are inconclusive because the historical record has not been considered in the proper time framework, and the vegetational relations may have been significantly affected by timber cutting, agriculture, fire suppression, wildlife extermination, introduction of exotic insects, and other unnatural factors. These elements are taken into consideration in the following examination of the vegetation and history of Appalachian forests and fire-dependent Great Lakes forests. Especially considered are the natural forces in long-term stability, and problems in management of virgin forests.

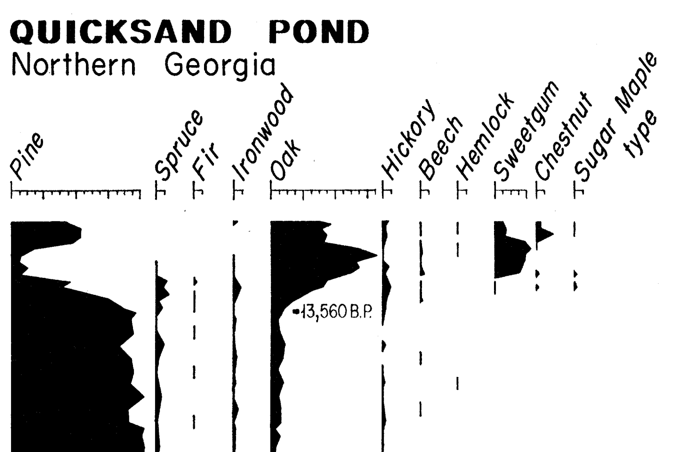
Forests of the Appalachian Mountains

The complexity of Appalachian forest types has long been a challenge as an historical problem. Braun (*22*) found a solution by applying the climax concept to the erosion cycle. The mixed mesophytic forest type (beech, tulip, basswood, sugar maple, sweet buckeye, chestnut, red oak, white oak, and hemlock) thrives on diverse topography, so it is said to have expanded after the uplift and dissection of a mid-Tertiary peneplain, perhaps 30 million years ago. This and other climax associations are thus thought to have persisted for millions of years. Their distribution and extent at various times were controlled by Appalachian erosion cycles. And, in Braun's view, they were essentially unaffected by Pleistocene climatic changes, except for the southward infiltration of northern forest types along coastal plains freshly exposed by sea level depression, or along youthful glacial outwash in river valleys like the Mississippi.

Deevey (*23*) discussed some untenable aspects of this picture of Appalachian vegetation history. Braun (*24*) countered vigorously, but much of her story collapses in the face of extensive paleobotanical studies of late Pleistocene lake sediments, which indicate that current forest types are only a few thousand years old. During the height of the last glacial period, 22,000 to 13,000 years ago, not only the mountains but also the piedmont and the coastal plain were characterized by a northern conifer forest (*25, 27*). Spruce was a dominant tree as far south as Virginia and North Carolina, and jack pine down to northern Georgia (Fig. 1). Alpine vegetation occurred on some mountain crests (*28*). Components of the mixed mesophytic forest may have been present in small amounts—pollen analysis is not a sufficiently sensitive technique to establish their absence. They probably survived in favorable localities in this area of diversified topography and geology, especially in the more southerly parts. They were apparently not pushed south en masse to Florida, which featured an open vegetation with oak and herbs and xerophytic shrubs at this time (*25*). In any case, northern forest probably predominated in the Appalachians, with enclaves of southern types, rather than the reverse.

For Holocene time, significant vegetational changes are also documented. From Virginia south, oak gave way to pine about 6000 years ago (Fig. 2), when modern mesic forests became established (*29, 30*). Some of these changes may be related to climatic shifts.

In the central and northern Appalachians, the postglacial pollen sequence shows slight changes in the proportions of hemlock, beech, hickory, and chestnut, with oak dominating throughout. This was originally interpreted as representing gradual changes of climax forest types caused by a relatively warm,



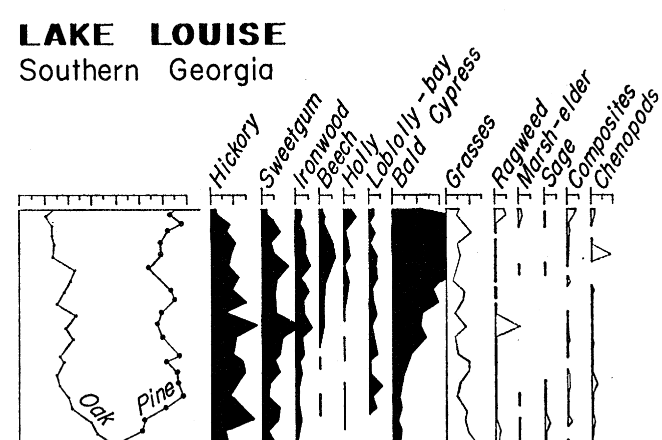


Fig. 1 (left). Selected pollen curves for Quicksand Pond, Bartow County, northern Georgia (*26*). The pine pollen type before 13,000 years before present (B.P.) is determined from pollen size and needle morphology to be jack pine (*Pinus banksiana*), which now does not grow south of New England or the Great Lakes area. Fig. 2 (right). Selected pollen curves for Holocene sediments of Lake Louise, near Valdosta, southern Georgia (*30*). Before about 6000 years ago, dry forests of oak (*Quercus*) and hickory (*Carya*) dominated, with openings marked by prairie plants, including ragweed (*Ambrosia*), sage (*Artemisia*), and other composites and chenopods. The pine after 6000 years ago is probably longleaf pine (*Pinus palustris*). Various mesic deciduous trees, such as sweet gum (*Liquidambar*) and iron wood (*Ostrya* type), expanded about the same time, and swamp trees such as bay (*Gordonia*) and cypress (*Taxodium*) spread over the lake margin soon after. Beech (*Fagus*) apparently did not reach the area in quantity until later.

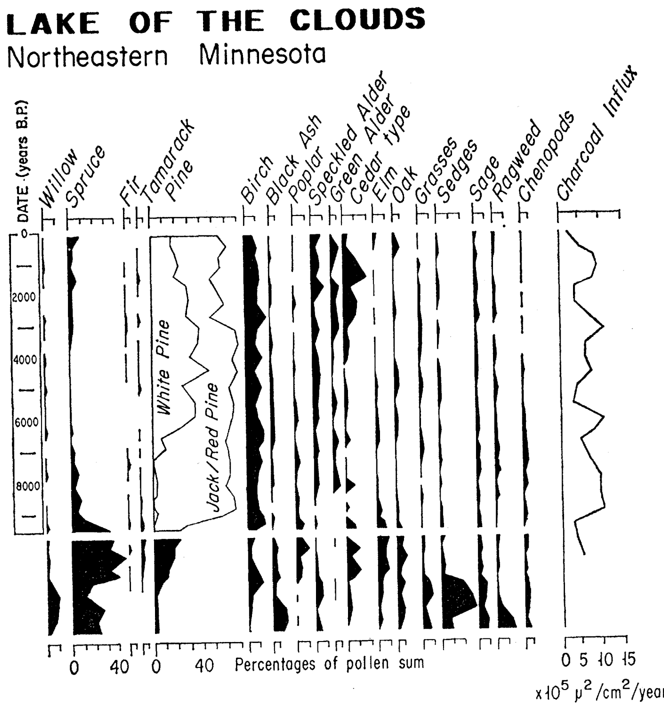


Fig. 3. Pollen (*46*) and charcoal (*43*) diagram for Lake of the Clouds, northeastern Minnesota, showing substantial uniformity of regional pollen rain since development of the pine forest 9000 years ago. The major change was immigration of *Pinus strobus* (white pine) about 6700 years ago. Increase in pollen of *Picea* (spruce) and *Cupressaceae* (probably northern white cedar) and decrease of *Pinus strobus* about 3000 years ago may reflect a trend to cooler climate. The charcoal curve shows that fires have occurred for at least 9000 years. Time scale derived from annual laminations.

dry interval 4500 to 1500 years ago, supposedly indicated by an increase of hickory. However, the climatic requirements of the species are not well enough known to support such conclusions (*31*). The changes might represent delayed migration of particular tree dominants into already established forest, a phenomenon that Braun would not accept. Knowledge of hemlock's response to fire and human disturbances is particularly lacking. Davis (*31*) commented that many maps of present forests show not actual species frequencies but rather theoretical climaxes thought appropriate by some ecologists.

The pollen record thus indicates a major climatically controlled vegetation change throughout the Appalachian Mountains at the end of the Pleistocene, about 11,000 years ago, as well as significant changes in the middle of the Holocene. The present forest types in the Appalachians are closer to 10,000 years old than 10 million, indicating that they depend on the climate, which has changed in major ways during the last 15,000 years, rather than on the erosional cycle, which may not have progressed appreciably in 10 million years.

Similar changes undoubtedly occurred during earlier Pleistocene interglacial episodes. Interglacial records in southern Georgia and central Florida reveal a cyclic development similar to the incomplete Holocene cycle (*25*). Vegetation changes in the Southeast were fully as pronounced as those much closer to the ice front.

Braun's failure to relate vegetation climax to an Appalachian erosion cycle does not vitiate the climax concept for that region, however. Braun simply misconceived the relative time scales of geomorphic and vegetation processes, and she lacked knowledge of the magnitudes of Pleistocene and Holocene climatic and vegetation changes.

To determine the time scale of Appalachian forest development, we must consider succession and reproduction mechanisms that perpetuate climax patterns. Hack and Goodlett (*32*) studied an area near the Shenandoah Valley of Virginia, where the vegetation types in the ridge-and-ravine topography form a distinctive pattern. The pattern is of a definite polyclimax. This interpretation is supported by detailed geomorphic work, which shows the sensitive response of certain tree species to moisture, slope, and soil conditions. Ridge crests and noses are characterized by pitch pine or table-mountain pine, ravines by yellow birch, basswood, and sugar maple, and intermediate slopes by the absence of these species and the presence of certain oaks. Their study shows a dynamic equilibrium between geomorphic processes and vegetation. The crucial question now is: How long after the last major disturbance—11,000 years ago—did it take the present forest to reach climax or equilibrium? Hack (*14*) implied that the ridge-and-ravine topography has persisted virtually since the original Appalachian uplift many million years ago. Rock weathering and erosion proceed at a finite rate, supplying and renewing the soils that help determine forest type. The system is also always losing a finite amount of material by solution transport in streams and groundwater. Even though erosion rates have increased in many areas because man has disturbed the forest and soil cover, measurements of long-term erosion rates indicate that landscape changes controlled by geomorphic processes proceed extremely slowly compared to vegetation changes controlled by climate. In small solution depressions in the Appalachians, for example, very few meters of sediment have been deposited over tens of thousands of years, even though each drainage basin may be several times larger than its catchment area (*26*). These landforms have been essentially stable, therefore, while forest vegetation went through drastic transformations controlled by Quaternary climatic change.

The distribution and extent of polyclimax components are thus controlled by geomorphic processes that provide steady nutrient input, but do not change the topographic and hydrogeologic setting appreciably within the time range of climatic stability. Both the physiography and the vegetation maintain a steady state in dynamic equilibrium. How does the climax forest maintain its overall composition? What factors and mechanism determine what tree will replace one that falls?

In the mixed mesophytic Appalachian forest, windstorms are the major disruptions renewing succession. Old and infirm trees blow over, exposing the entire root mat. The opening is rapidly filled by a microsuccession of plants in which young trees take their place among the old. Goodlett's study (*33*) of the mound microrelief in an Allegheny Plateau forest in Pennsylvania showed that white pine is related to the incidence of windthrow of old hemlock trees. Windthrow opens the canopy, giving light for the germination and early growth of white pine in the seedbed of loose mineral material fallen from the upturned mat of roots. Windthrow is also critical in soil development. Local single-aged stands of white pine are attributed to decimation of large sections of forest by tornadoes or hurricanes that cut across a polyclimax and initiate succession (*33*).

Cloudbursts cause debris avalanches on slopes and washouts in ravines (*32*).

Fire is another natural disturbance that provides opportunity for regeneration in the Appalachians (*34*). The even-aged stands of white pine mentioned above have been attributed alternatively to regrowth after fire. Many pine stands are confined to sandstone ridge crests and plateaus, where dry soils and wind exposure are favorable for fire.

The mixed mesophytic forest of Appalachian hillslopes and hollows, where the forest floor is customarily moist and winds cannot easily penetrate, probably rarely burn. Many of the hardwood species resprout from roots. Here windstorms are the more significant factors in vegetation disruption. For most of the Southeast, however, the historical record of fire is not adequate for quantitative evaluations of its importance.

Although the role of fire and windthrow in Appalachian vegetation development can be generally inferred, studies of modern forests are hampered because of major disturbances by man. The extent to which features and processes are natural or artificial cannot often be determined. Lumbering and agriculture have been extensive in most of the eastern United States, and few large blocks of undisturbed forest remain. Even second-growth forests have been subject to disturbances such as chestnut blight, decimation of browsing wildlife or of predators that control their populations, and sheep and cattle grazing. Although some New England old fields have had 150 years for reforestation under fairly natural conditions (*35*), the effects of past farming on soils and forest succession are difficult to evaluate. Goodlett (*33*) showed that the frequency of windthrow was greatly reduced after clear-cutting, because no high old trees project above the regenerated forest canopy to catch the wind. The modern forest consequently contains no white pine.

Under man's watch, fires in southeastern pine and oak forests have been less frequent than in the natural regime, so even the second-growth forests after cutting are still denied a major ecological influence. Natural ecological relations are thus difficult to work out in any detail.

In a study of Catskill Mountain forests in New York, McIntosh (*36*) noted that sugar maple has gained dominance over beech and hemlock since the area was settled in about 1880, an expansion he attributed to forest disturbance. Another view is that maple is the natural potential climax (*37*). McIntosh (*36*) cautioned, however, "The assessment of potentiality from primeval remnants is now largely precluded over extensive areas of the earth. . . . As the possibility of reconstructing a primeval climax from undisturbed remnants recedes and vanishes we must depend on analyses of current vegetation as it is, not as what it might become."

Forests of presettlement structure may be restored naturally to some degree, but widespread removal of seed sources through clear-cutting precludes this for hundreds of years. In areas cleared for agriculture, even root systems have been removed, so that sprouters, which usually flourish after natural disturbances, are eliminated. In any case, the situation is unsatisfactory for studies of long-term natural succession. Knowledge lost through the destruction of natural forests can never be regained, yet destruction continues. The areas preserved in the East do not include all major forest types and are too small for major studies.

Fire-Dependent Forests and the Vegetation Climax

Clements' climax concept involves successional stages leading to vegetation that reproduces in equilibrium with prevailing climatic conditions. Succession has been documented in numerous studies. Primary succession is relatively easy to describe: observations can be made over a few years, or a complex of fresh land surfaces of different known ages can be studied as a group, as in the case of abandoned river bars, landslide scars, or moraines of retreating valley glaciers. Secondary succession can be studied on old fields.

The dimensions of these situations are usually small, and seed sources for successional plants may be close-by. Starting times and conditions for succession can be determined easily, if not by observation then by techniques like tree-ring analysis. In some cases the time span can be extended by observations in second-generation forest, for example, by counting rings on downed trees on which younger trees have rooted (*38*). However, only evidence for limited spans of time can be examined.

Succession after fires is complicated. In regions where fires commonly occur, certain plants are adapted so that their regrowth is immediate and accelerated, whereas other plants are killed and can be reintroduced only years later at the appropriate successional stage, and then only if seed sources are present nearby. Starting times for trees originating after a fire can be determined by tree-ring analysis, and the dates can be confirmed by identifying fire scars in the ring sequences of trees that survived the fire.

Tree-ring analysis and fire-scar studies were developed principally in Itasca State Park in northwestern Minnesota by Spurr (*39*) and Frissell (*40*). A comprehensive investigation has been made in the virgin forests—more than 500,000 acres (200,000 hectares)—of the Boundary Waters Canoe Area (BWCA) of northeastern Minnesota. Here a systematic survey by Heinselman (*41*) showed the fire dates for the origins of all pine stands. Fires are recorded at intervals of 1 to 8 years somewhere in the BWCA for 71 of the last 377 years. Major fires occurred in 1910, 1894, 1863–1864, 1824, 1801, 1759, 1727, 1692, and 1681. On the average, an area equivalent to the total land area was burned over during each 100-year period. This is the natural fire rotation. Reburn intervals for particular localities ranged from 30 to 300 years.

Because this BWCA study combines ecology and paleoecology and has important implications for concepts of both vegetation history and wilderness management, the ecological situation is described in detail (*41–43*).

The topography of the BWCA is diversified, with rocky hills 20 to 100 m above basins containing bogs or stream-connected lakes. The upland vegetation mosaic, however, is controlled by the incidence of fire rather than by topography (*44*).

An even-aged stand of jack pine dates to a fire that killed the previous stand but provided for regeneration, because jack pine cones persist on trees until they are opened by intense heat. Then seeds fall to the ground, where fire has burned off competitors, opened an area for sunlight, and converted nutrients to easily soluble form in ash. Stands of red and white pine also tend to be even-aged, because periodic fires clear the underbrush for seeds that fall from surviving trees. Even-aged stands of aspen and birch record vigorous sprouting after the canopy is opened by fire. Between fires, pine or hardwood stands tend to be succeeded by fir, spruce, and cedar, which are not fireresistant and would presumably form the climax forest in the absence of fire.

Fire rotation controls the distribution of age classes of stands and the succession within stands. The resulting diversity may represent long-range stability, as implied by the paleoecological record. Suppression of fire may lead to a theoretical climax of spruce and fir, but the succession may be arrested by insect epidemics, resulting in an unpredictable forest composition. The widespread infestation of spruce budworm on balsam fir in the BWCA today may reflect the long interval without fire. The dead trees may fuel a holocaust someday—despite protection. Thus, fire suppression prevents the frequent perturbations under which the forest develops and maintains its diversity. This elimination of the perturbations may be the most profound effect of man on this natural ecosystem (*45*).

The 370 years covered by tree-ring studies in the BWCA represent only a short time in the total life-span of the forest. During those years explorers, fur traders, loggers, fire guards, and tourists may have modified the natural frequency of fire. To determine the natural fire frequency for prehistoric time, our knowledge must be extended backward by paleoecological studies, which depend on finding fossils in a datable stratigraphic sequence. Pollen from lake sediments records the vegetation history, and charcoal concentrations reveal the fire frequency. Radiocarbon dating is possible for the last 40,000 years. Analyses of other microfossils provide independent evidence of environmental conditions.

Such studies were made of Lake of the Clouds in the heart of the BWCA (Fig. 3). The lake is chemically stratified with organic sediments deposited in annual layers.

Recent fires known from tree-ring counts show stratigraphically as maximums in the charcoal profile in the curve for lamination thickness (possibly representing temporary increases in the inwash of soil from the drainage basin), and in pollen curves for shrubs that sprout after fires (*43*). The record for the last 1000 years shows major fires every 80 years on the average—about the same frequency as during the 18th and 19th centuries. Charcoal analyses of the entire depth of sediment indicate periodic fires in this forest ecosystem for more than 9000 years.

Pollen profiles generally record regional rather than local vegetation. Consequently, even when major fires occurred in the area, the pollen rain into individual lakes was not significantly changed. The pollen diagram for Lake of the Clouds (*46*) shows substantial uniformity since the boreal spruce forest was transformed to pine forest about 9000 years ago (Fig. 3). Slight changes support subdivision of the profiles into pollen zones attributable to climatic change, and independent evidence for this comes from paleolimnologic studies elsewhere in Minnesota. Other long-range changes may result from other external factors, such as progressive soil leaching, or immigration of tree species controlled by such biologic factors as rate of seed dispersal.

The principal result is that the forest has been reasonably stable for 9000 years, despite severe short-term perturbations. A Clementsian climax is never reached, because the evolution of each forest stand is repeatedly interrupted by fire, but in the long range the forest mosaic as a whole maintains an equilibrium.

The long-range equilibrium is also expressed by the aquatic components of the fire-dependent forest ecosystems. Studies of hydrologic and chemical budgets of the Little Sioux fire of 1971 in the BWCA indicate that released nutrients are taken up rapidly by vegetative regrowth and soil storage, so that little reaches the lakes to nourish algal growth (*47*). Chemical and diatom analyses of lake sediments indicate that past fires have had a negligible effect on the quality of the lake water.

The evidence for the dependence of BWCA forests on fire is convincing because it is based on studies of a very large area of virgin forest. Where large areas of virgin forest remain in western North America, all indications point to a similar dependence (*42*). The western forests include most of the designated wilderness areas in North America, for which the stated goal is maintenance of natural conditions. Knowledge of successional relations in such virgin forests is essential for intelligent management. Yet where such knowledge exists, as for the BWCA, it is difficult to modify traditional fire-protection policies of management.

Management of Wilderness Areas

Most potential wilderness areas in the eastern United States are forests that were cut more than 100 years ago and reforested with new composition. We do not know how much they differ from the primeval forests they replaced because the remaining virgin areas are too small for comparison, and the role of large-scale factors like fire cannot be evaluated. Although many second-growth forests serve some of the recreational functions of designated wilderness areas, they are man-made and cannot take the place of primeval wilderness. The wilderness experience diminishes when one encounters a cut stump or a fence in what superficially resembles a virgin forest. Further, scientific investigations of natural regimes cannot be conclusive when data have been affected by significant human disturbance.

Considering the scarcity of true wilderness, designated wilderness areas should be managed to reestablish natural regimes, so that visitors can see primeval wilderness, scientific research can progress, and complete primeval ecosystems can persist, whether for the benefit of man or not.

The 1964 Wilderness Act (*7*) states that wilderness areas must be managed to maintain their primitive character. Heretofore, management has suppressed fire, under the assumption that fire destroys forests. However, the ecological studies recounted above indicate that fire is a major factor in maintaining the dynamic equilibrium of many natural ecosystems. Fire-suppression policies should therefore be changed. The situation is critical for the BWCA, where evidence for fire adaptation is overwhelming, and where a new management plan (*6*) has been adopted. The new plan ignores ecological principles and wilderness preservation, for it authorizes timber cutting in more than a quarter of the remaining virgin forest, rejects fire as a forest-maintenance tool, and introduces instead the concept of "administrative cutting" in virgin forest to reduce fuel buildup.

Timber cutting (*8*) in the largest area of virgin forest east of the Rocky Mountains will reduce an area whose large size is one of its major scientific values. Large size is vital for large-scale ecological studies such as determining the distribution and extent of past fires and studying the movements and territories of mammals like moose, bear, and wolf, and for preserving the genetic variation in natural populations. Cutting also removes attractive virgin forest from the most heavily visited area of the Federal Wilderness System, at a time when use is increasing at about 10 percent per year.

Although the virgin stands of jack pine and black spruce constitute the last major source of long-fibered pulpwood in the Great Lakes region, their long-term value for wilderness recreation and scientific study far exceeds the short-term return from timber sales, especially when the cost of preparation for sale, administration, and replanting is counted. Modern logging practices of clear-cutting, rock-raking, and road-building destroy the natural landscape. Recovery takes hundreds or even thousands of years. Nutrients are removed through increased runoff and soil erosion (*48*), breakdown of the nitrogen cycle in the soil (*49*), and removal of biomass that ordinarily decomposes and releases its nutrients for vegetative regrowth (*50*). Streams are affected by inflow of excess nutrients (*49*). The stratigraphic records for lakes affected even by nonmechanized logging indicate that abrupt changes in water quality follow cutting (*51*).

The decision not to use fire to restore the virgin forest is based largely on fear that visitors will be endangered and that fire might spread to Canada or on to private property. It is based on the traditional view that virgin forest is destroyed by fire, and on a fear of adverse public reaction after so many years of Smokey Bear warnings. However, lakes and streams in the BWCA provide excellent firebreaks for limiting prescribed fires, and experience with free-running lightning fires at Sequoia–Kings Canyon National Park indicates that the public will accept a change in management based on sound scientific principles (*52*).

With rejection of fire as a management tool in fire-dependent virgin forest, the manager must either continue fire suppression, with the resulting fuel buildup and insect infestation until an uncontrollable fire inevitably occurs, or initiate "administrative cutting," which presumably means the felling of dead and diseased trees, removal of underbrush, and perhaps prescribed burning. Although administrative cutting is preferable to fire suppression, it is not a way to preserve the virgin character of the wilderness. The time has come for serious experimentation with natural and prescribed fires under controlled conditions, so that virgin forest can be renewed rather than destroyed, and so that true wilderness areas will be available for future generations of visitors.

Conclusions

Both the landforms and the vegetation of the earth develop to states that are maintained in dynamic equilibrium. Short-term equilibrium of a hillslope or river valley results from intersection between erosional and depositional tendencies, controlled by gravitational force and the efficiency of the transporting medium. Long-term equilibrium of major landforms depends on crustal uplift and the resistance of the rock to weathering. In most parts of the world landscape evolves toward a peneplain, but the reduction rate approaches zero as the cycle progresses, and the counteracting force of crustal uplift intercedes before the end form is reached.

Davis described this theoretical model in elegant terms. Leopold and Hack have provided a new and quantitative understanding of short-range geomorphic interactions that tend to discredit the Davisian model in the eyes of many. However, the substitute models of quasi-equilibrium or dynamic equilibrium merely describe short-range situations in which this or that Davisian stage is maintained despite uplift or downwasting. Given crustal stability and an unchanging climate, landforms would presumably still evolve through Davisian stages. However, the Davis model cannot be tested, for despite tremendous inventions in geochronology and impressive advances in stratigraphic knowledge, we cannot yet establish the rates or even the fact of crustal uplift in most areas. We are left with an unresolvable problem, for the sedimentary records of erosional history are largely inaccessible, undatable, and indecipherable, at least in the detail necessary to describe long-term evolution of the landscape.

We know more about the evolution and maintenance of vegetation assemblages than about landform evolution, for even long-term vegetation sequences are within the scope of radiocarbon dating, and the biostratigraphic record is detailed. Even here, however, distinctions between short-term and long-term situations must be made, so that Clements' grand scheme of vegetational climax—created soon after Davis's model of landform development—can be evaluated in terms of modern knowledge. Disillusion with the climax model paralleled disillusion with Davis's model in the 1950's, but the climax model can be tested, because the record of vegetational history is accessible, datable, and decipherable.

In the short term of a few decades, successional vegetation stages occur in a variety of situations, as confirmed by observation or by techniques such as tree-ring analysis. The successional vegetation stages are reactions to nutrients, weather, competition, and consumption. Such succession implies long-term disequilibrium, or at least unidirectional development.

The long-term controlling factor in Clements' model of vegetation development is climate. With climatic stability the succession will proceed to a climax. In the Appalachian Mountains, geomorphic, microclimatic, and edaphic conditions limit climax development, producing a polyclimax, which is generally sustained by the dominance of these factors. Death and regeneration of single forest trees is controlled mostly by windstorms. The distributional pattern may be locally transected by lightning fires, major windstorms, or washouts. However, the long-term stability of Appalachian forests is demonstrated by pollen stratigraphy.

Although we can infer the long-term stability of Appalachian forests, the trends and mechanics of short-term vegetational succession are not fully understood, because lack of sizable areas of virgin forest limits investigations of natural conditions. In this respect, the eastern United States is already much like western Europe, where climatic and disturbance factors in vegetational history cannot be disentangled.

In the Great Lakes region, a large area of virgin forest exists in the BWCA of northeastern Minnesota. Here short- and long-term studies show that for at least 9000 years the principal stabilizing factor has been the frequent occurrence of fire. Major fires occur so often that the vegetation pattern is a record of fire history. All elements in the forest mosaic are in various stages of postfire succession, with only a few approaching climax. Fire interrupts the successful sequence toward climax. Geomorphic and edaphic factors in vegetational distribution are largely submerged by the fire regime, except for bog and other lowland vegetation. Fire recycles nutrients and renews succession. Nevertheless, despite the fire regime, the resulting long-term equilibrium of the forest mosaic, characterized by severe and irregular fluctuations of individual elements, reflects regional climate.

In the BWCA and the western mountains, large virgin forests can be preserved for study and wilderness recreation. These wilderness areas must be managed to return them to the natural equilibrium which has been disturbed by 50 to 70 years of fire suppression. The goal should be to maintain virgin forests as primeval wilderness. This can be done by management that permits fire and other natural processes to determine the forest mosaic. Mechanized tree-felling and other human disturbances should be kept to an absolute minimum.

Natural landforms also should be preserved for study and for certain nondestructive recreational activities. It is somewhat late for the Colorado River and other rivers of the West, because natural balances are upset by drainage-basin disturbances. Modification of plant cover on hillslopes changes infiltration and erosion rates and thus the stream discharge and sediment load, so the stream balance is altered from primeval conditions. Scenic Rivers legislation should thus be used to restore certain river systems and their drainage basins.

Mountain meadows, badlands, desert plains, and patterned permafrost terrain are extremely fragile and sensitive. Intricate stream and weathering processes leave patterns easily obliterated by mechanized vehicles. Tire tracks can last for decades or centuries. The mineral patina or lichen cover on desert or alpine rocks are records of long stability, and slight differences in their development record the relative ages of landforms, to the year in the case of lichens. Delicate color differences in a talus slope or desert fan show long-term effects just as does the arboreal vegetation mosaic in another climatic setting.

Preservation of virgin wilderness for study is viewed by some as a selfish goal of scientists, to be achieved at the expense of commercial and recreational development. However, scientific study and nonmechanized recreational uses are compatible in wilderness areas. Furthermore, the public does appreciate intellectual stimulation from natural history, as witnessed by massive support for conservation, the Wilderness Act, and a dozen magazines like *National Geographic*. Finally, no knowledgeable American today is unaware that ecological insights are necessary to preserve the national heritage. Western dust bowls, deforested slopes, gullied fields, silted rivers, strip mine wastelands, and the like might have been avoided had long-term problems been balanced against short-term profits. Many economic questions cannot be answered intelligently without detailed knowledge of extensive virgin ecosystems. Long-term values are enhanced by those uses of natural resources that are compatible with the preservation of natural ecosystems.

Esthetically, virgin wilderness produced by nature is comparable to an original work of art produced by man. One deserves preservation as much as the other, and a copy of nature has as little value to the scientist or discerning layman as a reproduction of a painting has to an art scholar or an art collector. Nature deserves its own display, not just in tiny refuges but in major landscapes. Man is only one of literally countless species on the earth. Man developed for a million years in a world ecosystem that he is now in danger of destroying for short-term benefits. For his long-term survival and as an expression of his rationality and morality, he should nurture natural ecosystems. Some people believe that human love of nature is self-protective. For many it is the basis of natural religion.

The opposition of many Americans to the Alaska pipeline is a manifestation of almost religious feeling; most never expect to see the Alaskan wilderness, but they are heartened to realize that it exists and is protected. The same can be said of those who contribute to save the redwoods in California. Here cost analysis fails to account for the enormous value people place on nature and on the idea of nature as contrasted to the private gain of a few developers. Americans admire European preservation of works of art. Europeans admire American foresight in setting aside national parks. However, the distribution of protected natural areas in America is uneven and inadequate, and vast areas continue to be developed or badly managed despite widespread new knowledge about long-term human interest in wilderness preservation.

Darwin turned nature study into the study of natural history. He could observe natural features in vast undisturbed areas with no thought that human interference had been a factor in their development. Today such natural landscapes have practically vanished. Those that remain should be preserved as extensively as possible, and managed with scientific knowledge of the natural processes that brought them to being. At the present accelerating rate of exploitation, massive disturbance, and unscientific management, soon no natural areas will be left for research or wilderness recreation. Some say that scientific curiosity and the ability for recreation define man. This is reason enough for wilderness preservation. However, a more ominous conclusion is that the survival of man may depend on what can be learned from the study of extensive natural ecosystems.

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53. Discussions leading to this article started with M. L. Heinselman and E. J. Cushing around a winter campfire in the BWCA, and I thank them and numerous students for continued incentive to evaluate the time factor in landscape evolution and to demonstrate a scientific rationale for wilderness preservation. I also appreciate the editorial and the substantive critique of R. A. Watson.

From Mars with Love

Missions to return a Mars surface sample are feasible, but pose potential back-contamination problems.

Richard S. Young and Donald L. DeVincenzi

Soil samples can now be returned to the earth from another planet by using unmanned spacecraft. One possible consequence of this ability is the potential for returning a viable extraterrestrial organism that may interact with terrestrial life forms.

The bioscience community is polarized on the issue of back-contamination of the earth; some believe the risk is virtually nonexistent while others believe it is high. There is no question that scientific interest in exploring the surface material of another planet is great. The problem arises in determining the method of study that is the most productive and cost-effective, that is, in situ on the planetary surface with automated landers or by direct study of returned samples in terrestrial laboratories.

The purposes of this article are to outline the mission possibilities for returning surface samples from Mars, to review experience gained from returned lunar samples, and to discuss the scientific value of sterilized samples compared to unsterilized samples. This is not a statement of NASA policy, and there is no intention to take sides on the issue of back-contamination. Our aim is to describe the mission options and the potential back-contamination problems they pose and thus to stimulate thought that we hope will generate solutions.

Historical Considerations

In July 1964, a conference on the potential hazards of back-contamination of the earth by returned extraterrestrial samples was held under the auspices of the Space Science Board of the National Academy of Sciences (*1*). The participants included representatives of the Space Science Board's Life Science Committee, the Department of Agriculture, the National Institutes of Health and Public Health Service, and NASA, as well as selected scientists with backgrounds in public health and pathology from various universities. The committee considered the question of returning samples from the moon and the ,planets, the potential hazards to terrestrial life, and the need for action to assure the safety of life on the earth.

The committee stated its belief that the existence of life on the moon or on the planets could not be precluded, and that the likelihood of life on the moon was much less than on Mars. It reviewed the history of the harmful spread of biological agents on the earth (for example, tuberculosis, smallpox, and measles), where disease agents were inadvertently introduced into human populations that had not previously been exposed to the disease and therefore had not evolved protective mechanisms. The committee also reviewed the history of nonhuman epidemics (such as the Irish potato famine, in which a fungus infection literally destroyed the potato crop on which Ireland depended). The group pointed out that organisms harmless to man but pathogenic to plants or animals might be as deleterious to man as those which affect him directly. It was felt that the introduction of a completely new (extraterrestrial) organism must be considered a potential catastrophe since terrestrial forms of life would have had no previous history of exposure and therefore no opportunity to have developed natural immunities or artificial vaccines. The committee concluded that extraterrestrial life, and the concomitant possibility of back-contamination, must be presumed to exist, and that any "policies of defense against back-contamination must be based on the proposition that if infection of the earth by extraterrestrial organisms is possible, it will occur."

The committee therefore strongly

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