population size. Beetle population size can be assessed by surveying the number of trees recently killed in the area, by assessing the success of broods, and by monitoring baited traps.

A preventive method widely used to control mountain pine beetles (*D. ponderosae*) is stand-thinning. The mechanisms by which this method works are unclear, but may include increased vigor of remaining trees and a less favorable microclimate of thinned stands (warmer and windier). Some studies of thinning, focusing on other bark beetle species, have found no effect or a positive effect of thinning on beetle populations. If thinning is conducted on mature stands, costs of this approach include increased tree damage due to wind sway and wind throw, as well as the requirement to enter the stand multiple times. Thinning is therefore not an approach to be implemented indiscriminately.

See also: **Entomology**: Population Dynamics of Forest Insects. **Health and Protection**: Integrated Pest Management Practices; Integrated Pest Management Principles. **Pathology**: Insect Associated Tree Diseases.

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ENVIRONMENT

Contents

Environmental Impacts

P Maclaren, Rangiora, New Zealand

Introduction and Definitions

There is considerable debate over definitions for the word 'forest' and even for 'tree.' Most vegetation types fall clearly into the categories of forest or nonforest, but there is dispute at the margins. The following are contentious questions:

- Does 'forest' apply to a type of land cover, or to a type of land use? (An apple orchard, for example, may consist of a high density of trees but is not normally considered to be forest, whereas areas of bare land in the phase between clearfelling and replanting are normally included as forest.)
- At what height is a woody species classified as a tree? Does this vary with the age of the plant?
- At what proportion of ground cover do trees collectively form forests? (For example, do widely spaced trees in the African savannah or Australian outback constitute a forest? Do heavily tree-lined cities constitute forests?)

A similar debate rages over the classification of forests into natural and artificial types. On the one hand, we could say that totally natural forests do not exist. There is probably not a single hectare of the earth's surface that has not been modified to some extent by human activity. In some parts of the world, hominids have been a part of the ecosystem for perhaps a million years, often using fire or browsing mammals. Peoples have introduced new species or eliminated species from every land mass, and have even modified the air (which provides a tree with its most important nutrient by weight – carbon). On the other hand, even a 'monocultural' and monoclonal plantation contains a surprising variety of adventitious species and cannot be said to be entirely artificial.

There is widespread public enthusiasm for natural forests, with ever-increasing pressure for their protection and enhancement. The environmental benefits of such forests are well recognized. This contrasts with the opprobrium that is often directed towards commercial plantations. Whereas 'natural' forests tend to be as complex as the climate and soils allow, the profit motive forces managers of plantations into greatly simplified forest systems. In order to minimize costs, and to maximize timber revenues, single commercial timber species are favored. These are best grown in large stands of homogeneous age, and managed in a way that provides a uniform and consistent industrial feedstock. In many nations, it is acceptable to grow horticultural or agricultural crops in large monocultural blocks, but – strangely – public attitudes change where the harvest product is stemwood rather than fruit.

The awe of the natural forest, and the emotional opposition to the artificial version, have spawned a set of beliefs about the negative environmental impacts of the latter, which are often based on prejudice, rather than on demonstrable fact. That said, even groundless fears have a political reality that foresters ignore at their peril.

Effect on Soil

The sustainable productive potential of a soil often cannot be discussed without specifying the intended land use. Thus 'soil quality' is a subjective term. It seems likely that persistent plant species modify the soil to a condition that ensures their long-term survival. Certain species of tree are said to be 'soil improvers' because subsequent agricultural crops grow better, and because the deep topsoil consists of well-mixed organic matter (mull), as in typical agricultural soils. Other tree species are said to be 'soil deteriorators' because they result in – or are found on – soils with a clear separation of surface organic matter from the underlying mineral substrate (mor). The latter appears to be an evolutionary mechanism for the forest to minimize nutrient loss, by controlling (by means of mycorrhizal associations) the decomposition of organic matter.

Given that a mor-type forest contains most of its nutrients in the biomass and relatively undecomposed forest floor, if it is subjected to persistent fire or removal of the forest duff (for fuel, fertilizer, or animal bedding), then it will certainly become less productive over time. It is very often the case that certain forest types gained the reputation for being soil deteriorators because of human extraction of such nutrients.

It is possible (although not satisfactorily proven) that trees can extract nutrients from deep roots and bring these to the surface via litterfall. This could be one reason for the observed boost in agricultural production following a forest cover. Such a boost can even be noted in much-maligned plantations, including those with eucalyptus and conifers. A common criticism of coniferous plantations is that they acidify the soil and create an environment unsuitable for earthworms. Charles Darwin did some excellent work establishing the worth of earthworms in agriculture, but his observations are not necessarily relevant to forestry. Forests develop their own soil fauna that is more appropriate to forest conditions. The slight acidification noted for conifers could be a device to prevent nutrient leaching and ensure controlled nutrient recycling. It is not a permanent effect, as the pH seems to bounce back after removal of the trees. By means of acidification and mycorrhizal action, anions (nitrogen, phosphorus, sulfur) under such trees can be more plant-available than in similar soils that have not experienced a forest cover.

Sustainability of the soil resource is largely determined by the balance of inputs and outputs of key elements. There are losses into the groundwater (i.e., leaching, under the action of rain or irrigation), and losses to the air (i.e., volatilization, often by burning). There are also losses via human removal of agricultural or forestry products. Inputs can come from: biological nitrogen fixation; aerial deposition; and breakdown of the mineral substrate by weathering, possibly stimulated by plant or mycorrhizal exudates. They can also come from deliberate fertilization.

The huge quantities of wood often extracted from a forest may provoke the comment that the land is being 'mined' of significant amounts of essential elements. This ignores the fact that wood differs from many other rural products. Wood consists predominantly of carbohydrates (cellulose, hemicellulose, and lignin), which are predominantly made up of carbon, hydrogen, and oxygen – these elements comprise more than 99.7% of the oven-dry weight of stemwood. They come from rainwater and carbon dioxide, with minimum contribution from the mineral soil. In contrast, products that contain foliage or fruit, or derive from an animal, can be rich in nitrogen, phosphorus, sulfur, potassium, calcium, and magnesium. If such elements are not replaced with fertilizers (organic or mineral), excessive exploitation of the land can easily 'mine' the soil.

To summarize: it is incorrect to state categorically that afforestation – even with monocultural conifer plantations – will cause soil deterioration, without defining what is meant. Soil from such plantations can produce higher yields of subsequent crops than adjacent, unplanted land. Nutrient levels, even in a highly exploited forest, need not decline provided that nutrients are replaced. Furthermore, the debate over soil deterioration can be somewhat academic if the main regional concern is the massive removal of topsoil via soil erosion. If soils are stripped down to the parent rock, this must be ultimate form of soil degradation.

Forests play a vital role in mitigating erosion in most of its dozen forms. Soil erosion is a major global problem, which occurs naturally but has been exacerbated by human actions. It is caused by wind, rain, or mechanical damage (e.g., plowing or livestock pugging (compaction and loss of soil structure in a clay soil)). Trees reduce wind speeds at ground level and thereby reduce wind erosion. They maintain the soil in a drier state, thus minimizing its mobility. Critically, they bind the soil together with their strong, interlocking and relatively deep roots. Erosion rates from mass wasting are typically 10 times lower in forest compared to, for example, pasture.

Effect on Water

There are more misconceptions related to the interaction of trees and water than to any other aspect of forestry. These myths are so widespread that they seem to have formed a self-sustaining body of belief, without recourse to empirical evidence. It is not true, for example, that – in some mysterious way – trees attract or even cause rain, resulting in abundant river flows. Rain is the result of the sun warming the planet and evaporating water, mainly from the oceans. Moisture-laden air masses are driven across the land by winds that would occur even if the earth were devoid of trees. Rain falls when the air cools, for example by rising over a mountain range. Trees affect the albedo (reflectivity) of the earth's surface, but this is not believed to be a major influence in planetary circulation patterns. Having said that, the presence of trees does maintain atmospheric humidity (by means of evapotranspiration). In other words, part of the rain that would have fallen to the ground and entered the groundwater is returned to the atmosphere by trees, and is available to enhance rainfall elsewhere. So, although forests do not greatly influence the total quantity of atmospheric water moved from the ocean to the land, they may well affect the quantity and distribution of rainfall on that land.

The effect of trees in a particular catchment is to reduce the yield of water, not to enhance it! Two effects cause this: interception and transpiration. Interception is where the rain wets the canopy and does not reach the ground. Readers will remember when they have stood under trees in a light shower and remained dry. Short vegetation (e.g., grass) also intercepts rainfall, but there is a critical difference: tree canopies readily evaporate the water, even during rain. Grass stays wet. This means that the trees are constantly intercepting and reexporting rain, whereas the first shower wets the grass and the second can penetrate to the ground. The reason why grass evaporates less water than trees is because it is shorter, and there is less wind at ground level. It is not a coincidence that people hang out their washing to dry on lines high above the ground!

Transpiration is the second way that trees reduce the water in a catchment. Plants have holes (stomata) beneath their leaves that allow the absorption of carbon dioxide from the air. These also permit the escape of moisture, which has been conducted upwards from the roots. When conditions are dry, plants close their stomata and moisture loss is minimized. This applies to both trees and to short vegetation, but the difference is that trees usually have deeper roots. Long after grass has closed its stomata and stopped transpiring, trees will continue to pump water from deep soil horizons. A light rain will recharge the water in the grass-covered soil, but it will require heavy or persistent rain to do the same for the forested soil.

The myth goes that 'forests act like a sponge, soaking up water during wet periods and releasing it slowly during dry periods.' A home experiment can soon confirm that even sponges do not work in this way: large pores release their water within minutes, under the influence of gravity. In smaller pores, capillary action is stronger than gravity and the water is not released. In soil, water in such micropores can be removed only by movement towards, and evaporation from, the surface or by active uptake by roots. Very small pores contain water that is inaccessible even to roots. Decreased water flow as a result of afforestation can be expected at all times of the year. So can forests act as a buffer, smoothing out flood peaks? That depends.

It is easy to observe that a bucket of water poured on to the forest floor usually penetrates quickly. Holes left by dead roots and gaps around living roots may provide the mechanism for rapid and deep infiltration. In contrast, water poured on to a bare or grass-covered soil may run along the surface for a considerable distance. Often, the soil may have been baked hard by the sun or compacted by grazing animals. Therefore we would expect that it would take longer for rain to reach the river in a forest, where it has to filter through the soil, than it would in a pasture, where much of the water flows overland. This has often been observed experimentally, but it is not always the case. In a heavy and prolonged downpour, the interception capacity of a tree canopy is quickly overwhelmed. The soil becomes saturated and instant penetration of water under the forest merely results in instant discharge along the riverbank – if a hosepipe is full, turning on the tap results in immediate release of water from the nozzle.

Another complication is that, while improved infiltration rates under trees may smooth flood peaks in small storms and small catchments, this does not usually occur in large river systems where the worst flooding damage takes place. As a storm passes over a large catchment, the rainfall peaks at different times in each tributary. Moreover, it can take many hours or days for the flood peaks from the mountainous headwaters to pass down the river and coalesce in the main channel. By this time, the smoothing effects attributable to the forest have all but disappeared. In short, the direct benefits of forestry for flood control have been grossly exaggerated. It is important to remember, however, that a major cause of flooding is the restriction in the cross-sectional area of river channels caused by upstream soil erosion. Forestry is highly important in this regard.

The lowering of water tables following from afforestation has at least one desirable side-effect: it can prevent and even (in nonchronic cases) reverse salinization. Salt is common in deeper horizons of soils that have not evolved under conditions of high rainfall. Irrigation has enabled crops to be grown in many drier parts of the world, but poor irrigation practices can allow this salt to migrate to the surface, by means of persistent soaking which dissolves the salt and distributes it throughout the soil profile. When the water evaporates from the surface the salt crystallizes out of solution, eventually creating conditions unsuitable for cropping and – in extreme situations – salt pans. Even in the absence of irrigation, salinization is a common result of deforestation and establishment of pasture. It may take many years of flushing by rainfall to lower the topsoil salt levels to a stage where trees can successfully be reestablished and the water table can be lowered by such means.

There is no doubt that freshwater is a scarce and underrated resource in many parts of the world, and that individual catchments will generate more usable water if they do not have a forest cover. But water quality is also important. Water that is polluted by salt, sediment, pathogens, or nutrient run-off is not as useful as clean water. Planning authorities, in a difficult balancing act, must ensure that river flow is maximized but water pollution is minimized. One way to do this is to afforest only the riparian areas. Water reduction from a forest cover depends on the proportion of the catchment that is forested, whereas water pollution is caused mainly by humans and animals having direct contact with the waterway.

The reason why human pathogens (viruses, bacteria, plasmodia, etc.) are more likely to be found in agricultural – as opposed to forestry – catchments is that many domestic mammals share the same intestinal diseases. The reason why polluted water normally has low transparency is that it is either filled with sediment from erosion, or with microorganisms fertilized by nutrient runoff. Enhancement of aquatic growth at first glance may be seen as beneficial to the environment, but there are usually negative impacts. Algae commonly excrete toxins, and when they decay they extract oxygen from the water (eutrophication), making it unsuitable for fish. The major plant nutrients are nitrogen and phosphorus, and while it is sometimes possible to keep the less-soluble phosphorus away from waterways, nitrogen is a more intractable problem. Nitrate salts are highly soluble and once they find their way into groundwater they can quickly bypass or overwhelm any barrier, such as riparian strips. To counteract the nitrogen via natural means usually requires filtration through a high-carbon medium, such as peat swamp. Nitrates and nitrites are often considered a health hazard in drinking water, although the evidence for this is not convincing.

Arguably, pollution of rivers is not as serious as pollution of lakes and aquifers. Whereas, if the source of pollution is removed, rivers can flush themselves clean within weeks, pollutants can persist in lakes for decades. Aquifers may contain water that fell as rainfall thousands of years ago, and it is most important to ensure that activity at ground level (including livestock farming) does not contaminate this valuable heirloom.

A major source of river pollution is siltation, often caused by deforestation in steep headwaters. As well as blocking the river channels and causing flooding, the sediment can cause major problems when it enters hydroelectric dams or the ocean. Siltation limits the useful life of many dams to a few decades, and silt particles rapidly erode the turbines. Deforestation can be the direct cause of siltation of harbors and decline in certain fisheries.

Effect on Air

It is now common knowledge that there is a connection between forestry and the enhanced greenhouse effect, but there is still considerable public confusion on the details. The concentration of atmospheric carbon dioxide (CO_2) has been rising for the last century, leading to the concern that it will cause global warming. The evidence is overwhelming that the increase in CO_2 is human-induced: the cause is both combustion of fossil fuels and deforestation (historically, one-third, but becoming less important). It is easy to imagine how burning coal – or burning a forest – could increase the atmospheric levels of the main combustion product, carbon dioxide. Why then is it so difficult to comprehend that establishing a forest is merely the reverse of this process? Deforestation puts carbon into the air, afforestation removes it from the air, but the mere maintenance of an existing forest usually has no net effect.

The process of photosynthesis has been understood for a long time. Plants use the energy of sunlight to combine water and carbon dioxide (obtained only from the air, via the stomata) into sugars. Oxygen is released as a byproduct. Half the dry weight of wood or other biomass is carbon, and therefore a forest represents a considerable amount of carbon that is not available to cause global warming. Whereas all green plants photosynthesize, only forests and swamps accumulate carbon to any great extent. It is conceptually simple to examine an ecosystem such as pasture or forest, and to observe the quantity of carbon it contains. Above knee-height, anyway, it is undeniable that a forest contains more carbon than a pasture, and that conversion of the pasture to the forest will result in extraction of atmospheric carbon. Because CO_2 is present in such small concentrations (0.036% of the atmosphere), the removal of approximately 100 tonnes of carbon per hectare by means of forest establishment has a major influence. Such afforestation could strip the air of all its carbon in an area six times the size. In contrast, the effect on oxygen is insignificant. It is often said that 'forests are the lungs of the planet' and provide us with our oxygen, but this is a gross exaggeration. If all the atmospheric carbon were removed by trees (an impossibility), this would increase the concentration of oxygen by only 0.036% from its existing 21%.

Once the forest has been established, it is not obvious whether this ecosystem is a sink (has more inputs than outputs), a source (the opposite) or merely a carbon reservoir (contains carbon but is not necessarily a sink or source). Forests consist of trees of all ages and sizes, and while all growing trees are individually sinks, the whole forest may not be a sink. Carbon is lost by the decomposition of biomass or by extraction of woody material. Over the long term, we can say that forests are not carbon sinks, because if they were to gain (say) only 1 t per hectare per year of carbon, then after 1000 years there would be an extra 1000 t. This would be clearly visible to the naked eye, and would not need sophisticated measurement.

The role of wood products in the global carbon cycle is also a cause for confusion. Wood products are carbon sinks only if the stock of such carbon is increasing every year. This may be the case, but it would be a trivial quantity. More important is the role of wood as a substitute for materials, such as steel, aluminum, concrete, and plastics that require large quantities of fossil fuels to manufacture. CO_2 emitted from burning wood is considered 'carbon-neutral' because it is merely recycled atmospheric carbon rather than additional carbon from beneath the earth's surface.

Effect on Wildlife and People

The main difference between forests and other terrestrial ecosystems is that trees have a more pronounced vertical component. In terms of the volume of space bounded by the ground and the top of the canopy, forests contain considerably more volume than all other terrestrial ecosystems combined. Within this space, there are many biological niches and an abundance of plant and animal wildlife can develop. These species are interesting because they add variety to the world, and because some of them can be useful to humans.

Just as in that other three-dimensional biospace – the oceans – the base of the biological pyramid is photosynthetic plant life. The primary productivity of the forest understory or the deeper ocean is often constrained by the sunlight that can penetrate – which is one reason why greater biodiversity is found in tropical forests. The high productivity of a natural forest (where little sunlight is wasted) can often support more human inhabitants than the degraded landscape that so often replaces it. Tropical forces often contain most of their nutrients in the trees and associated litter, and their removal (by repeated burning and browsing) can cause a long-term impoverishment of the soil and the people who live on it. Forests are often cleared to make way for food crops, but it is worth remembering that, while food is vital, so are shelter and fuel provided by wood. People can starve because they have not grown sufficient food, but they can also starve because there is no means to store that food or to cook it. Many staple foods (corn, cassava, potatoes, wheat, rice) must be cooked to be digestible.

There is often outrage when a timber plantation replaces a natural forest. Undoubtedly, such conversion reduces biodiversity – unlike the situation where plantations displace agriculture. But the high productivity of useful timber from plantations can take the pressure off overexploitation of natural forests. Most commonly, the opposition to plantation forestry is not because of the change in vegetation so much as the change in land ownership and control. Large plantations are associated with large companies, often transnational, whose prime interest is said to be profit rather than the well-being of local inhabitants. Locals who have traditional foraging rights in the forest may find themselves excluded by the plantation owners, and the wide range of useful products from a natural forests is reduced to a narrow range. Instead of the multipurpose role of natural forests (medicines, honey, game, fruits, rattans, slow-burning charcoal), locals must participate in the money economy to satisfy their various needs.

The comparison between natural forests and plantation forests is unfortunate, as the world needs more forests of any sort. Conversion of natural forest to plantations can be prohibited by legislation, as in most countries there is adequate degraded agricultural land than could be used for the latter purpose.

Summary

For environmental reasons, the world needs more forests and it needs more wood. Forests of all kinds protect the soil, water, and air – which are the basic life-sustaining resources of the planet. Wood is a benign product because it is biodegradable, and because it has been created by the combination of water and a greenhouse gas under the action of sunlight. Trees are a natural biological solar panel.

Plantation forests should not be seen as an alternative to natural forests. They are additional to natural forests, and there is sufficient degraded agricultural land to enable the area of plantations to increase without threatening natural forests.

See also: **Environment**: Carbon Cycle; Impacts of Elevated CO_2 and Climate Change. **Genetics and Genetic Resources**: Genetic Aspects of Air Pollution and Climate Change. **Hydrology**: Hydrological Cycle; Impacts of Forest Management on Streamflow; Impacts of Forest Plantations on Streamflow; Soil Erosion Control. **Soil Biology and Tree Growth**: Soil and its Relationship to Forest Productivity and Health. **Soil Development and Properties**: Water Storage and Movement. **Tree Physiology**: Forests, Tree Physiology and Climate.

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