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5: Assessing Potential Sustainable Wood Yield

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5.1 INTRODUCTION

5.1.1 Aims of this chapter

Society is making unprecedented demands on world forests to produce and sustain many values. Chief among them is wood supply, and concerns are rising globally about the ability of forests to meet increasing needs. Assessing this is not easy. It requires a basic understanding of the principles governing forest productivity: how wood yield varies with tree and stand development; the implications of rotation length, utilization standards and silvicultural treatment; and effective techniques for judging site potential and detecting changes in it. This chapter reviews these concepts and suggests workable approaches for assessing a site's ability to sustain wood production.

5.1.2 The sustainability problem

Exploitation has dominated our use of forests for 10 000 years. Of the 6.2 billion ha of forests and woodlands thought to exist at the start of the Holocene, between one-fifth and one-third have been lost to soil erosion, conversion to agriculture, excessive fuelwood gathering and livestock grazing, and desertification from poor land-use practices (Postel & Heise 1988; Waring & Running 1998). Concerns have persisted from the Chou Dynasty in 1127 BC (Hermann 1976) to the present that societal demands on forests are excessive and are compromising the land's capacity for sustaining multiple resources.

5.1.3 Sustainability of what, and for whom?

Society values forests both for the products they produce, such as lumber, fuelwood, lichens, herbs and mushrooms; and for the functions they serve, including watershed protection, runoff moderation, fish and wildlife habitat, recreation and aesthetics (see Volume 1, Chapters 12, 14 and 15; Volume 2, Chapters 2–4 and 10–12). More recently, high value has been placed on the role that forests play in the global carbon cycle (Bouwman & Leemans 1995; Landsberg & Gower 1997). Concerns about sustained production often focus on wood products. But sustainability also applies to other forest properties and functions. Environmentalists, concerned that ecological values have suffered from overemphasis on wood extraction, call for more conservative management practices that reduce wood harvest and preserve or restore other ecological values (Drengson & Taylor 1997).

Such arguments carry strong emotional force and sway public views on how forests should be managed for sustainability. A 'green advocacy' has gained such momentum that it has spawned a cottage industry to certify what is, and is not, 'sustainable forestry' (Anonymous 1995). Many in the private forestry sector are sceptical of third-party 'green certification' where criteria may be based more on speculation than on science (Berg & Olszewski 1995). In general, leading forest scientists agree that timber harvesting, *if carried out carefully enough to preserve potential productivity*, need not compromise other ecosystem values (Attiwill 1994; Kimmins 1996; Nambiar 1996). Yet, ignoring green certification could limit markets for industrial wood.

As currently practised, green certification standards aimed at protecting multiple forest values often are so conservative that wood harvests are less than could be sustained had the sites been severely degraded (Kimmins 1996). Reduced harvests must be accompanied either by reduced demand for wood, or by the substitution of other products. Both are at odds with global realities. Well-intended notions that mineral resources can 'save forests' by substituting for wood when such conversions are powered by fossil fuels make ecological nonsense as long as people are part of the ecosystem (Smith *et al.* 1997). Substitutes manufactured from non-renewable resources demand far more energy than wood products and have a much greater capacity for pollution. Furthermore, reduced wood production by industrialized nations creates a strong incentive for other countries to accelerate forest harvesting beyond sustainable levels to reap the rewards of a global market, irrespective of green certification (Kimmins 1996).

5.1.4 Whose problem is it?

Although forest product consumption is related closely to gross domestic product, high wood use is not restricted to technologically advanced nations. Per capita demands for paper and other wood-based products are mounting in countries where increases in both population and standards of living spell higher demands for wood (Anonymous 1997; Sutton 1999). Recent projections show that the global demand for wood increases by 70–80 million m^3 annually—a volume equivalent to British Columbia's entire allowable harvest in 1993 (Kimmins 1996). Paper consumption is expected to rise in developing countries by 4% to 6% annually, reaching approximately 120 million m^3 by 2010 (Anonymous 1997; Brown *et al.* 1997). Fuelwood deficits will occur in arid and semiarid regions.

Coupled with this is a projected decline in global forest area of over 16 million ha (about 0.4%) annually (Anonymous 1997). While forested area has stabilized in many industrialized nations, it has declined elsewhere (see Volume 1, Chapter 1). As wood becomes scarce, prices rise and consumers in industrialized nations choose alternative products such as brick, concrete, and steel or aluminium (Binkley 1997). But such substitutes carry energy and pollution costs to society that are more than 10 times greater than wood (Sutton 1999). All signs point to crisis, and appeals have been made to international leaders not only to take stock of their existing forest resources, but also to develop effective indices of forest sustainability (Canadian Forest Service 1995). Sustainable yield is everyone's problem. It cannot be ignored.

5.1.5 Searching for solutions

Even where forested area has stabilized, increasing demands from a fixed base lead to shorter rotations and greater utilization. Can yields be sustained? Or will high rates of removal outstrip the site's ability to sustain growth? Questions raised as early as the nineteenth century (Ebermeyer 1876) await convincing answers.

Stocking and competition control

Each forest site has an inherent set of resources as determined by soil, climate and topography. These resources can be partitioned in many ways, but the general focus of forest management for wood yield has been in finding cost-effective ways of directing these resources to achieve the greatest gain in merchantable wood at the least expense to the manager. Obviously, minimal management would produce low-cost yield. However, yields per unit land area also would be low because some units would be understocked, others overstocked. Understocking means that some of the site's potential productivity would be spent on weeds or tree species of marginal value. Overstocking means that intertree competition would keep trees relatively small with a greater proportion of fixed carbohydrate used for maintenance respiration and a lesser proportion used for growth. Trees would be weakened from competition for moisture, light and nutrients. As stresses build, such trees and stands are susceptible to catastrophic losses from insects, diseases, wildfire and the vagaries of climate.

To date, forest management's greatest contributions to improved yield are in the fields of reforestation, weed control and thinning (Smith *et al.*

1997). Reliable regeneration methods, especially planting, have reduced the lag between forest harvest and the establishment of a new stand. Enlightened methods of site preparation and vegetation control have improved survival and allowed young trees to capture fresh sites quickly. Timely applications of thinning have reduced mortality and focused site resources on the most valuable trees with little loss in overall stand productivity. Thinning builds the vigour and mechanical strength of individual trees and their resistance to insects, disease and windthrow. Removing weaker trees in advance of mortality also reduces fuel build-up and the wildfire risk common to unmanaged stands. Because thinning can alter stand composition by removing undesirable trees and by creating canopy gaps, it also creates opportunities for natural regeneration in advance of final harvest. Collectively, stocking and competition control practices have had a monumental impact on the practice of forestry.

But prompt regeneration, vegetation control and thinning cannot improve inherent site quality. Other than manipulating canopy architecture to the degree that site resources are focused more completely on desirable trees so that merchantable sizes are reached faster, the site's productive potential is not improved. While stocking and competition control are absolutely critical to capturing a site's potential for merchantable wood yield, they will not improve that potential.

Genetic salvation?

Genetic improvement has revolutionized agriculture, but parallel gains are not as likely in forestry. Time works against us. Errors in choosing genetic strains of agricultural crops generally can be corrected the following year—an impossible practice with long-lived forest trees. Under warm temperate and subtropical conditions, yield gains of from 14% to 23% per generation—perhaps more—are believed possible (Nambiar 1996). But, in contrast with modern agriculture where drought can be eliminated with irrigation, forests generally are subject to the natural stresses of climate that limit genetic expression. Substantive gains reported under favourable glasshouse conditions are rarely found in the field (Matheson & Cotterill 1990), and large absolute responses to genetic improvement may be restricted to sites with the most favourable growing conditions (Zobel & Talbert 1984).

Genetic progress to date has centred on selecting for better adaptation by weeding out poor performers and by producing hybrids for special-purpose plantings. Selections favouring disease resistance and higher wood quality have been impressive. Yet, little has been done to alter the fundamental mechanisms by which CO_2, nutrients and water are processed to synthesize biomass. Opportunities exist for improving nutrient retranslocation within the tree to make them less dependent on uptake from the soil (Libby 1987). Possibilities for improved drought tolerance and photosynthetic efficiency have been described but have not been achieved (Matheson & Cotterill 1990; Boyle *et al.* 1997).

Current selection strategies simply may mean that stands reach growth ceilings sooner and that a higher proportion of net primary productivity is allocated to merchantable parts of the tree. Reaching merchantable sizes sooner suggests shorter rotation periods and greater rates of nutrient removal from the site. Accelerated harvesting may not be sustained without help from management to maintain potential productivity.

Is soil management a key?

Increasingly, soil management is seen as the underpinning of sustainable forest productivity (Powers *et al.* 1990; Dyck *et al.* 1994; Kimmins 1996; Nambiar 1996). Given climatic constraints, forest growth is primarily limited by the soil's ability to supply moisture, air and nutrients in proportion to a tree's potential demand. Yields generally are raised by treatments that enhance soil quality relative to the principal limiting factors (Chapter 6). However soil improvement treatments will not be applied everywhere. High economic returns on such investments are limited to regions of the world with mild climates and favourable moisture regimes. While soil improvement always is an option, our first responsibility is to protect or enhance the land's existing capacity to grow wood. Have we altered this? Can changes be detected? What

levels are sustainable relative to management goals?

5.2 SUSTAINABLE WOOD YIELD

Before we can assess the land's potential for sustainable wood yield we should clarify the terms and principles governing forest growth and measurement. Volume 1 of this handbook covers ecological and physiological principles in detail, but a brief review is useful here.

5.2.1 Definitions

Productivity

The primary measure of forest productivity is the rate at which organic compounds are produced from CO_2 through photosynthesis. Depending on moisture, nutrient and temperature constraints, this *gross primary productivity* (GPP) is a linear function of light interception by the forest canopy (Cannell 1989). It usually is expressed as Mg ha^{-1} $year^{-1}$ (or g m^{-2} $year^{-1}$). GPP is not measured easily and not all of it is converted to growth. As much as two-thirds of GPP is respired back to the atmosphere as the 'cost' of constructing and maintaining living cells. The absolute amount of respired carbon is greater in older stands because the mass of living tissue also is greater. Respiration rates are sensitive to temperature, and essentially double with each 10°C rise (Landsberg & Gower 1997). Thus, respiration rates are higher in summer than in winter and are greatest in warm, humid climates.

The difference between the amount of CO_2 fixed into organic compounds and the amount respired is termed *net primary productivity* (NPP). For forest trees, NPP varies between 0.37 and 0.5 of GPP, but averages a relatively constant 45% (Schulze *et al.* 1977; Ryan *et al.* 1996; Landsberg & Waring 1997). The NPP rate usually is expressed as the annual amount of biomass produced per unit area. NPP is apportioned mainly into the structural materials of roots and mycorrhizae, foliage and reproductive parts, branches and boles, roughly in that order of priority (Waring & Schlesinger 1985; Landsberg & Gower 1997). Difficulty in measuring below-ground conditions limits our understanding of true distributions under field conditions, and most of our knowledge rests on observed changes above ground.

Like respiration, NPP increases with temperature and moisture, but at a faster rate. Therefore, NPP rates generally are highest under moist, tropical conditions where above-ground NPP hovers near 30 Mg ha^{-1} $year^{-1}$ (Leith 1975), and may briefly reach 60 Mg ha^{-1} $year^{-1}$ in fully stocked stands (Binkley *et al.* 1992). Rates generally are half to two-thirds lower at the middle latitudes (Grier *et al.* 1989), and fall to only 5 Mg ha^{-1} $year^{-1}$ where mean annual air temperatures approach freezing (Van Cleve & Powers 1995). As leaf area or mass increases, a greater proportion of NPP is shifted to wood growth, reaching about 50% once crown mass has stabilized (Waring & Schlesinger 1985). In general, maximum wood production occurs at a one-sided leaf area–ground area ratio (LAI) of about 3 (Landsberg & Gower 1997), although the optimal ratio varies with canopy architecture and the photosynthetic efficiency of leaves (Beadle 1997).

Presumably, LAIs greater than 3 impose the risk of periodic water or nutrient stresses on most sites or lower net carbon assimilation from lower- and inner-crown leaves shaded below their photosynthetic compensation point. Thus, very high LAIs may lead not to increased growth, but to increased respiration and mortality (Waring & Schlesinger 1985). Some of the highest leaf areas measured are not in the tropics, but on middle latitude sites of moderate productivity (Beadle 1997). Wood growth rates will increase with leaf area if water, nutrients and temperatures are not limiting, and if sunlight penetrates the canopy sufficiently that all leaves have a positive carbon balance.

Site quality

'Site' defines an area in terms of its environment, and 'quality' is a relative measure of the site's productive capacity to grow forest vegetation. Together, they refer to the potential of a land unit for tree growth when the land is stocked fully. Full stocking occurs when a site is at its 'foliar carrying capacity'. That is, when the forest has attained the amount of leaf biomass that it is

capable of supporting for an extended period. Foliar carrying capacity occurs shortly after crown closure. It is reached early if trees are growing closely together or later if trees are spaced widely. This carrying capacity is a 'potential' determined by climate, soil and topography factors interacting upon a particular forest genotype. It fluctuates about a long-term mean because of annual vagaries in climate and occasional outbreaks of defoliating insects or diseases when trees are under stress.

Unfortunately, foliar biomass is difficult to measure directly and non-destructively, but LAI is a popular and convenient surrogate in many ecological studies, and has correlated linearly with tree growth response to silvicultural treatment (Della-Tea & Jokela 1991). In practice, foliar biomass, LAI and NPP are not the usual measures of site quality. The historical emphasis on wood has made bole wood volume production per annum the conventional standard. Although bole wood ranks relatively low as a sink for photosynthate (Waring & Schlesinger 1985; Landsberg & Gower 1997), bole volume is measured with relative ease. And given that bole wood has a high societal value, its acceptance as a practical measure of site quality is understandable.

Site quality is neither static nor immutable. In the long term, it will aggrade or degrade with changes in climate and stage of soil development (Jenny 1980; Van Cleve & Powers 1995). Changes triggered by the anthropogenic production of air pollutants may affect site quality quickly, particularly in Europe where high atmospheric depositions of SO_x, NO_x and NH_x reportedly have reduced soil pH and base cation status, and raised aluminium solubility (Van Breemen 1990). Site quality also can be altered rapidly for better or worse by management (Powers *et al.* 1990; Nambiar 1996). Examples include fertilization, irrigation, drainage, or tilling to modify limiting site factors; and losses in soil fertility or aeration through careless management.

Yield

Defining 'yield', the amount of wood available from a forest for human use, depends on purpose. In many regions, forests are the principal source of fuel, and branches and twigs are considered a component of yield. Regardless, interest centres mainly on bole wood. Therefore, yield is defined here as the total amount of bole wood available for harvest at a given time (Avery & Burkhart 1983). Yield is usually expressed as volume per unit area ($m^3 ha^{-1}$), but also as biomass ($Mg ha^{-1}$). It is what remains of GPP not lost in respiration, sequestered in foliage, branches or roots, or consumed by animals or disease. Because yield is a cumulative function of stand growth—and because stand growth varies by age, stocking and species—yields will vary over time for a given stand. Also, forest tree species differ genetically in their responses to shade, temperature, moisture, soil physical and chemical properties, and biotic pests. Therefore, adjacent stands of the same age, but stocked with genetically dissimilar trees, will produce different yields. Also because a site's growth potential is conditioned by climatic and edaphic properties, sites differing in climate or soil will differ in potential yields.

Sustained yield

A non-declining, continual supply of wood from a forest over decades or centuries defines a 'sustained yield'. Individual stands within a forest are not appropriate units for assessing sustained yield because such stands would need a perfect balance of multiple age classes occupying equivalent areas and site qualites to ensure regular harvesting of a constant yield without interruption, an ideal not occurring in nature (Smith *et al.* 1997). Sustained yield rests on two requirements. One is the certainty of timely forest regeneration. This simple fact is what separates forest management from forest exploitation. Without a *commitment to successful regeneration*, sustainable yield is impossible. Appropriate regeneration methods ensure rapid, complete reforestation following harvest. Methods vary with tree species, climate and management objectives, but all are an integral part of any sustained yield silvicultural system (Smith *et al.* 1997). The other requirement of sustained yield is that harvesting rates for a forest are balanced by growth.

Sustained yield can be confusing. Yield can be differentiated into total or merchantable wood

production. Historically, some managers have justified high harvesting rates in older stands because low growth rates there were equalled or surpassed by high growth rates in much younger (but submerchantable) stands. In mixed stands, one species may have greater commercial value than others. Selective harvesting of the more favoured species will inevitably alter forest composition so that merchantable yields are not sustained. Sustained yield requires deliberate and persistent management. It is not achieved easily.

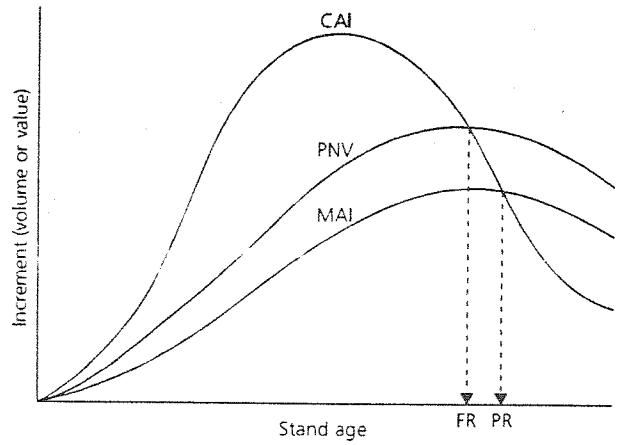

Fig. 5.1 Generalized relationship between current annual volume increment (CAI), mean annual volume increment (MAI) and present net value (PNV) of stands or individual trees. Financial rotations (FR) generally occur sooner than physical rotations (PR). (After Evans 1992.)

Rotation

Central to sustained yield is the 'rotation', a concept that applies both to individual trees and to stands. A rotation is the period between tree establishment and the age at which the oldest tree is harvested. Intermediate harvests, or 'thinnings', can occur at any point, but the period of rotation is the age attained by the oldest tree at harvest. As will be seen, rotation length is a management decision that depends on biology, economics and ecological principles.

Rotation lengths traditionally are of two types: 'physical' and 'financial' (Smith *et al.* 1997). Physical rotations are aimed at maximizing yield per unit time, which occurs arithmetically at the culmination of mean annual volume increment of bole wood. This is the point of inflection in the sigmoid growth curve that typifies tree or stand development over time, and is mathematically equivalent to the intersection between current annual volume increment and mean annual volume increment. The age of a physical rotation is indicated by 'PR' in Fig. 5.1. In the tropics this usually occurs at 10–15 years, but in temperate and boreal forests it is much later (40 and 70 years) (Hamilton & Christie 1971; Plonski 1974; Clutter *et al.* 1983; Evans 1992). The range in mean annual increment (MAI) at culmination is remarkably similar on average sites of tropical and temperate latitudes (Table 5.1). Lower MAIs for boreal species reflect low yields of natural, unmanaged stands. With periodic thinnings, MAIs would be greater and culmination age would be extended (Smith *et al.* 1997).

Harvesting at the culmination of MAI assures the maximum yield of wood per unit time. But for slow-growing trees, this rarely is the most profitable rotation strategy. Rather, it is most appropriate for fast-growing, high-value species where costs of production and alternative interest rates of capital are relatively low (Evans 1992). Naturally, biological growth continues much longer, but at a decreasing rate. Financial rotations are determined by the maximum monetary return on a capital investment in silviculture. The higher the compound interest rate on the investment, the shorter the rotation. Generally, financial rotations are less than physical rotations—although they could be longer if there is exceptional value in older trees (such as extremely valuable veneer). They occur at the age of intersection between the stand's present net value and current annual increment ('FR', Fig. 5.1). Should the interest rate for the financial rotation be zero, rotation lengths will be the same.

A third view of rotation length that has gained momentum is that of 'ecological rotation' (Kimmins 1974), in which the harvest interval varies by the time needed for the ecosystem to recover fully from the last harvest. For example, multiple short rotations—or possibly those involving very high rates of organic matter

Table 5.1 Examples of stand conditions at culmination of mean annual volume increment (MAI) for boreal, temperate, and tropical forest tree species on sites of average yield class based mainly on plantation data. (From Hamilton & Christie 1971; Plonski 1974; Evans 1992.)

Species	Age at culmination (yr)	Cumulative volume ($m^3 ha^{-1}$)	Volume MAI ($m^3 ha^{-1} yr^{-1}$)	Top height (m)
Boreal forests				
Betula papyrifera	40	134	3	13
Picea mariana	65	169	2	10
Pinus banksiana	35	156	4	12
Pinus strobus	65	277	4	16
Populus tremuloides	50	342	7	21
Temperate forests				
Abies grandis	55	1100	20	31
Fagus sylvatica	85	680	8	28
Picea abies	75	900	12	25
Picea sitchensis	55	880	16	26
Pinus nigra	60	720	12	22
Pinus sylvestris	75	600	8	22
Populus × euramericana	35	350	10	33
Pseudotsuga menziesii	55	880	16	30
Tropical forests				
Eucalyptus camaldulensis	15	120	8	–
Eucalyptus grandis	9	162	18	–
Gmelina arboria	10	200	20	–
Pinus caribaea	16	320	20	–
Pinus patula	16	288	18	–
Swietenia macrophylla	30	420	14	–

removal or soil disturbance—may remove more nutrients than the site is capable of restoring by the next rotation. Or, more time may be needed for stands to develop ecological conditions of particular social value (structures, flora and fauna characterizing late seral stages of forest development). Ecological rotation strategies recognize that sustained wood yield hinges on more complex factors than suggested by the simple marriage of historical growth trends and recent inventories. Put simply, the ecological rotation is the basis for sustainable yield for wood and myriad other forest products and values. Our understanding of how forest management affects wood production over multiple rotations is strong. Unfortunately, our understating of long-term effects of forest management on other values is weak. Therefore, the discussion that follows will centre on what we know best: wood yield.

5.2.2 Key concepts

Inherent potential productivity

Wood yield depends partly on site quality and partly on management. Many important factors such as genotype, stocking, most biotic pests, and certain soil physical and chemical properties are under silvicultural control. Others, such as climate and topographic features affecting solar radiation and precipitation, are not. These latter factors (climate, soil, and topography) define 'inherent potential productivity' for a site. In short-rotation tropical plantations, the upper limit for inherent, potential productivity varies a few Mg, by about 10 Mg bole wood ha^{-1} $year^{-1}$ in the first decade (Lugo *et al.* 1988). For the rest of the world, it is less. This inherent potential for productivity exists irrespective of tree stocking. It

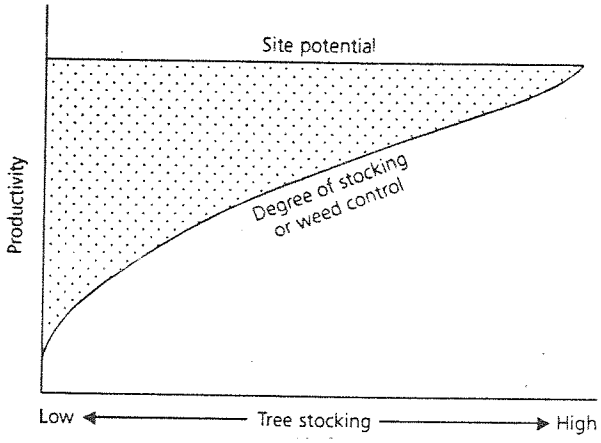

Fig. 5.2 Relationship between degree of stocking (or weed control) and the potential productivity inherent to a site. Improved stocking or weed control captures a greater proportion of the site's inherent potential.

is realized when the unit of land is stocked at its foliar carrying capacity, and is represented by the flat portion of the curve in Fig. 5.2. Whether or not this potential is realized depends on management.

Actual and inherent potential productivity

'Actual productivity' is the current rate of stand growth. Poor stocking, weed competition and damage from pests commonly hold forest production below its inherent site potential. If stands are understocked with trees (the stand is below foliar carrying capacity for that species), only a fraction of the potential productivity is realized. This occurs when stands are very young, trees are spaced widely or thinned too heavily, or much of the site is occupied by weeds. Competition for water and nutrients by adapted weeds can have a substantial impact on early tree growth (Nambiar & Sands 1993), particularly on droughty, infertile sites (Powers & Reynolds 1999b). Even on very productive sites, as much as 50% of stand growth may be lost to weed competition through the first 20 years if trees are widely spaced (Oliver 1990). Long-term projections of early and repeated vegetation control in pine plantations suggest 100% improvements in volume production on the droughtiest sites after 50 years, but only 12% improvements on more fertile and better watered sites (Powers & Reynolds 2000). The nearer that tree stocking approaches full site occupancy (foliar carrying capacity), the greater the proportion of potential productivity that will be captured by the trees (Fig. 5.2).

Assuming that site quality is not altered, greater management investments in stocking, pest control and genetic improvement will increase yield and capture the site's potential earlier. Figure 5.3 illustrates this principle. In Fig. 5.3a, potential productivity is constrained by inherent soil properties. However, actual productivity is less than that because of low stocking. In Fig. 5.3b, stocking is improved either by replanting to a higher density with a better-adapted species, through timely weed control, or because the trees have grown older and larger. With stocking no longer a constraint, the stand has reached the potential productivity permitted by its inherent soil properties. Replanting also is a chance for genetic improvement, meaning that the stand achieves full stocking more rapidly and reaches potential productivity sooner. However, the productive potential remains constrained by soil.

Altering site potential

A site's productive potential is *malleable*—especially when productivity is limited by certain soil properties. Soil management practices that erase physical or chemical limitations will raise potential productivity to a new level (Chapter 6; Nambiar 1996). This is illustrated in Fig. 5.3c by treatments that improve soil quality to a point where productivity is now constrained by climate. Depending on treatment, such gains may be short-lived. Gains in volume growth of 30% are common from a single application of N fertilizer, but the effect usually dissipates by 10 years (Ballard 1984; Allen 1990). Part of this gain is through improved nutrition that increases foliar biomass, but part also is due to improved water-use efficiency (the amount of carbon fixed per unit of water transpired) (Mitchell & Hinckley 1993; Powers & Reynolds 1999). Assuming a deficiency exists, effects of phosphorus fertilization last longer (Ballard 1984).

Fertilizing repeatedly with multiple nutrients

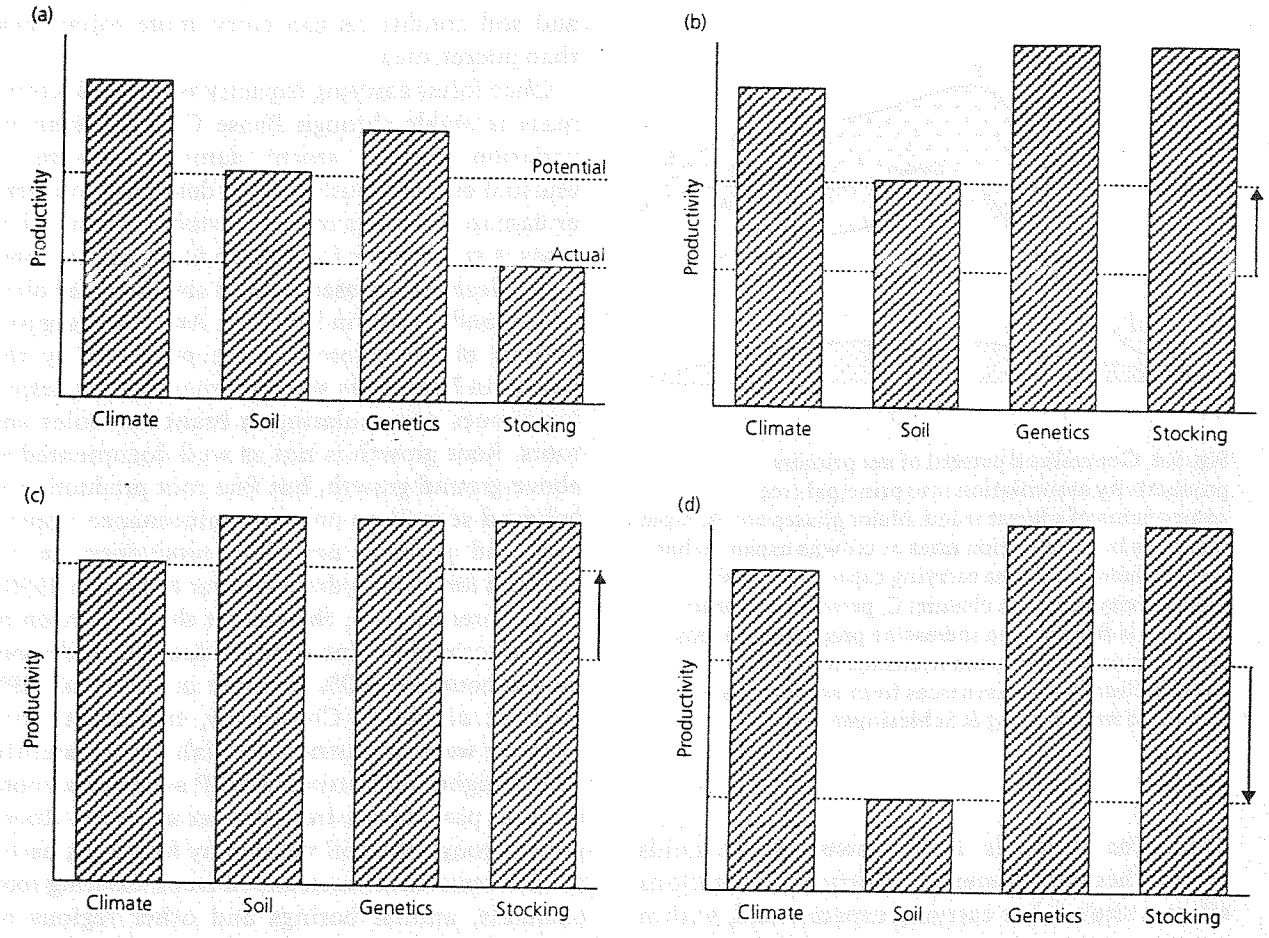

Fig. 5.3 Relationship of climate, soil, tree genetics and tree stocking to potential and actual site productivity. (a) Poor stocking holds actual productivity below the potential as limited by soil factors. (b) Potential productivity (as limited by soil) is achieved through improved stocking. (c) Soil improvements raise potential productivity to the limit set by climate. (d) Soil degradation leads to a loss in potential productivity. (From Powers *et al.* 1996.)

at rates proportional to stand demand may alter site quality fundamentally, conceivably doubling volume growth through the first 50 years if soil moisture is not severely limiting (Powers & Reynolds 2000). Alternatively, poor management practices leading to soil degradation from erosion, compaction or nutrient drain can reduce potential productivity from its inherent level (Powers *et al.* 1990) (Fig. 5.3d). Overcoming site, stocking or genetic constraints requires capital and intervention. Consequently, many managers operate at lower, less costly levels of intensity. Regardless, an important element of sustained productivity lies in protecting or enhancing the soil resource.

Growth and the partitioning of biomass

Yield assessment is helped by a working knowledge of how forests and individual trees develop and how dry matter is partitioned above and below ground. Given freedom from disturbance, biomass production of stands (or individual trees) follows a general pattern of increase from establishment, to maximal rates near crown closure (or attainment of a dominant canopy position) (Fig. 5.4). Essentially, this is a function of leaf area per unit ground area (or per tree) because primary productivity is related linearly to canopy light interception (Cannell 1989). This linear trend seems unaffected by water or nutrient stress

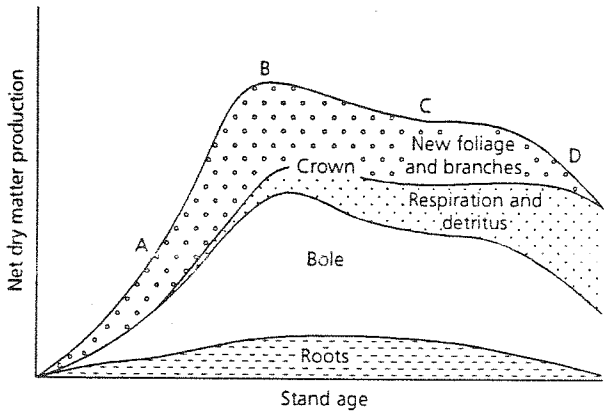

Fig. 5.4 Generalized pattern of net primary productivity assimilation into principal tree components of a forest stand. Major phases are: A, rapid increases in assimilation rates as crowns expand when stand is below leaf area carrying capacity; B, peak productivity at crown closure; C, period of maturity—leaf area is fixed and an increasing proportion of gross assimilation is used as maintenance respiration; D, rapid decline as stand senesces from natural causes. (Modified from Waring & Schlesinger 1985.)

(Della-Tea & Jokela 1991; Powers & Reynolds 1999b) because water or nutrient limitations affect a site's foliar carrying capacity and, within temperature constraints, its rate of photosynthesis. The first priority for photosynthate is cell respiration. Rates increase with gains in living tissues, essentially doubling with each 10°C rise in temperature, and can account easily for half or more of gross primary productivity (Waring & Schlesinger 1985). Carbohydrate remaining beyond respiratory needs is partitioned into biomass (NPP).

Production rates (and yields) are low per unit ground area when forest stands are very young and foliage mass has yet to reach site carrying capacity (Fig. 5.4). Much of the carbon assimilated in this phase is directed to foliage and branch production. Total production rates rise exponentially as crown mass expands during Phase A, and then become sigmoid as the stand reaches foliar carrying capacity in Phase B (Switzer & Nelson 1972; Waring & Schlesinger 1985). During Phase B, nutrient uptake peaks and leaf area and mass stabilize. Sites characterized by favourable climate and soil conditions can carry more foliar mass than poorer sites.

Once foliar carrying capacity is reached, crown mass is stable through Phase C, other than for variation due to storm damage, seasons of unusual climate, outbreaks of defoliating insects, or damage to stems or root systems. Because leaf mass is stable, new foliage produced in the upper crown leads to senescence and abscission of older foliage and a surge in litterfall. An increasing proportion of the photosynthate produced by the foliage in Phase C is spent on maintaining respiring tissues accumulating in branches, boles and roots. Root growth is not as well documented as above-ground growth, but fine root production is believed secondary only to maintenance respiration and perhaps new leaf production in its demand for carbohydrate (Oliver & Larson 1990). The poorer the site, the greater the proportion of NPP allocated to fine root production, and roots may account for 40% or more of the total NPP (Vogt *et al.* 1997). Conversely, treatments that improve water or nutrient availability apparently shift a higher proportion of NPP away from roots to other parts of the tree (Vogt *et al.* 1997). Roots grow through the soil volume by following paths of least resistance, such as ped faces, existing root channels, animal borings and other regions of moist but aerated, low-strength soil. Eventually, roots will exploit the full volume of available soil. Shallow soils will be occupied sooner, deeper soils later. To a large extent, root growth probably parallels the pattern of foliage production.

As trees grow larger, more photosynthate is required to maintain living tissues. This leads ultimately to Phase D, marked by a gradual decline in net wood growth. Eventually, respiration/production imbalances, nutrient stress, increased hydraulic resistance in tall trees, and crown loss from wind abrasion lead to sharp declines in vigour and growth (Waring & Schlesinger 1985; Ryan *et al.* 1997). Phase D marks a period of senescence that ends in mortality. For further discussion, see Volume 1, Chapters 8 and 9.

Biomass and nutrient accumulation

Because foliar biomass is fixed once the stand

reaches foliar carrying capacity, wood increments depicted in Fig. 5.4 accumulate on the bole so that total bole biomass surpasses the biomass in foliage and limbs. Beyond crown closure, tree boles will accumulate as much as 10 times more biomass than in the crown (Kimmins *et al.* 1985). This dry matter difference belies the fact that nutrient concentrations are disproportionately higher in foliage than in wood, meaning that the nutrient *content* of crowns and boles can be similar. Figure 5.5 shows a typical trend for the distribution of N in the standing biomass of a developing forest.

Potential sustainable yield

To date, no international consensus exists on the definition of forest sustainability (Sullivan 1994; Jaggi & Saandberg 1997; Nambiar & Brown 1997). Largely, this is due to conflicts between ecocentric and anthropocentric views and the forces at play in wood-based economies. The concept that wood harvests should centre only on trees facing imminent mortality (Camp 1997) is naïve, given economic and political realities and the paucity of evidence that more aggressive wood harvests cannot be sustained. Binkley (1997) has shown that global forest area would have to be increased by 1.1 billion ha (one-third) to meet current wood demand if all forests were managed under current concepts of green certification (MAI = 0.7 $m^3 ha^{-1}$ $year^{-1}$). Switzerland's policy of allowing more silvicultural flexibility (Jaggi & Sandberg 1997) seems more practical. The Swiss model strives to find a balance between ecology, economy and culture. It aims at ensuring a steady flow of diversified forest products and a more stable local forest economy, but it clearly is labour intensive. Furthermore, the Swiss approach cannot meet the internationally rising need for raw wood.

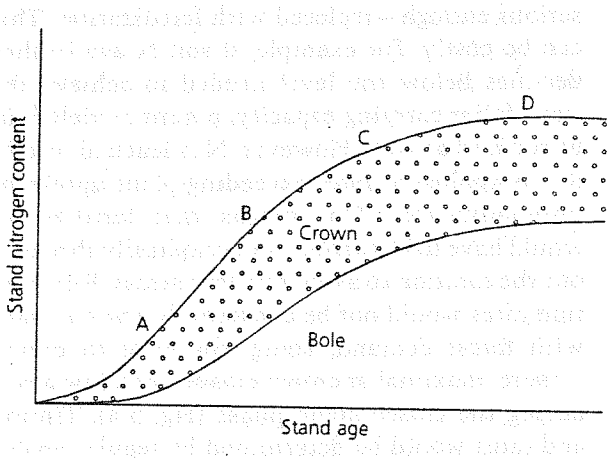

Fig. 5.5 Generalized pattern of nitrogen accumulation in above-ground biomass of a developing stand—derived from Fig. 5.4.

Assuming an average MAI of 10 $m^3 ha^{-1}$—increments quite common to temperate and tropical forests (Table 5.1)—today's global demand for wood could be met simply by increasing the area of planted forests from its current 3% of the world's forest area to 5% (Binkley 1997). But demand continues to rise. By mid-century, global wood production may need to rise by at least 2 billion m^3 (Sutton 1999). At an MAI of 10 m^3 ha^{-1}, this projects to a new managed forest area twice the size of Nigeria or British Columbia. Given international pressures to de-emphasize timber harvests in native forests, new highly productive plantations are the only hope for meeting this shortfall (Nambiar 1999). Most likely, new plantations will be extended into grassland, shrubland and agricultural regions of marginal value. We must recognize that sustained, high wood production has a legitimate place on the forest management continuum between farm forestry and wilderness management (Nambiar 1996).

Texts exist on procedures for determining maximum sustainable yield (Assmann 1970; Clutter *et al.* 1983), but conventional approaches rest on the assumption that site potential is static. Once a site's inherent potential productivity is recognized, some or all of it may be captured in a rotation. However, if harvesting affects the site to the degree that soil properties are degraded (Fig. 5.3d), that potential will not be realized in subsequent rotations unless the soil has been restored to its original condition. The quantity of wood that can be removed per unit time without lowering the site's inherent potential productivity is defined as 'potential sustainable yield', and the time needed to do so is the ecological rotation. But for a variety of reasons (lack of historical

records, changes in rotation length, genotype and silvicultural practices) we must recognize that there is no immutable reference point for assaying potential sustainable yield (Nambiar 1999). The challenge is to develop analytical methods for guiding appropriate management.

5.3 PROTECTING THE RESOURCE

5.3.1 A nutritional balancing act

The question of nutrient drain

Rotation length and intensity of utilization determine the amount of biomass and nutrients removed from a site over time. How this relates to the concept of ecological rotation can be demonstrated from Fig. 5.5. Two consecutive harvests made at stage B of stand development would remove considerably more biomass than a single harvest at stage D during the same time-span. Assuming that soil compaction or erosion does not occur with more frequent entry, and that soil organic matter is not depleted severely by more frequent site preparation and warmer soil temperatures, the mere act of removing more wood per unit time should not affect the site's productive potential.

Nutrient removal is another matter, particularly if utilization standards are high. Nutrients, especially N, are removed at very high rates when crowns are harvested along with boles (Fig. 5.5). Switzer and Nelson (1972) estimated that three 20-year rotations of whole-tree harvests in southern pine plantations would remove three-quarters more biomass, more than double the N, but roughly the same amount of calcium as one 60-year rotation. Whether or not this degrades potential sustainable yield depends on quantity of nutrient removal, the existing fertility of the soil and the rate of nutrient replenishment (Chatper 7). To sustain the site's inherent potential productivity, rotation length would be determined by the time it takes for the site to re-establish its inherent productivity.

Productive sites generally have fertile soils. Frequent nutrient removals on such sites should have no effect on potential productivity as long as nutrient supply meets forest demand. Natural rates of nutrient input through precipitation, biological N fixation and mineral weathering presumably are higher on productive sites with favourable climate than on poorer sites where rooting volume, soil moisture or temperature are limiting. Therefore, short rotations and high utilization standards will surely degrade the potential productivity of poorer sites.

There is no sound evidence that moderate rotations coupled with low-intensity site preparation practices have a detrimental effect on soil fertility and sustainable yield on most sites. Declines that have occurred are associated with coarse-textured soils ranking low in organic matter and nutrient retention properties (Powers *et al.* 1990; Morris & Miller 1994; Nambiar 1996). Even there, growth declines are not associated with harvest removals *per se*, but with extreme site preparation practices (intense slash burning, heavy equipment, topsoil removal) that reduce soil rooting volume and deplete soil organic matter and nutrients. Alternatives to these practices are well known and practicable (Chapters 6 and 7).

Avoiding nutritional problems

A key to maintaining soil fertility in sustained yield planning is to balance nutrient losses with nutrient replacement (Kimmins 1974; Van Miegroet *et al.* 1994). Two pathways are recognized. In the more intensive approach, nutrient losses associated with harvest and site preparation are minimized where possible, and—where serious enough—replaced with fertilization. This can be costly. For example, if soil N availability declines below the level needed to achieve the site's foliar carrying capacity, potential yield will be reduced as well. However, N is leached readily if it is applied at rates exceeding plant uptake or immobilization. This means that fertilization would have to be carried out periodically throughout the rotation to avoid nutrient stress. Fertilization rates would not be constant, but would vary with forest demand, being low prior to crown closure, maximal at crown closure, and low again during the closed stand phase (Fig. 5.4). Timing and rates would be determined by regular analyses of foliar nutrient status. The second pathway is to set harvest schedules by the time needed for the ecosystem to restore itself nutritionally (Kimmins 1974). This approach (to be discussed

later) involves process simulation using computer models of varying complexity (Proe *et al.* 1994).

5.3.2 Soil physical changes

While much attention has been paid to nutritional aspects of management practices on sustainable yield, soil physical aspects are equally important. Mass wasting and surface erosion obviously have catastrophic consequences because natural restoration takes centuries or millennia. But beyond this, the most serious problem is compaction. Compaction degrades potential site productivity by the loss of soil macroporosity. Substantive loss in macroporosity reduces soil aeration, water infiltration and available water-holding capacity, and increases physical resistance to root penetration (Sands *et al.* 1979; Powers *et al.* 1990, 1998). Loss of aeration also shifts soil microbial activity to bacterially dominated processes that slow organic matter decomposition and nutrient mobilization. Reductions in such obligate aerobes as fungi reduce mycorrhizal symbiosis and can lead to phosphorus deficiency.

Effects of compaction on forest growth are not always obvious. For example, trees established on compacted landings and skid trails often grow at lower stocking and have less competition from weed species. Consequently, early growth can be equivalent to that of trees on less-compacted areas which generally grow at greater stocking densities and with higher levels of weed competition (Powers 1999). In time, differences between tree growth on compacted and less-compacted areas become even less apparent because of the localized nature of compacted units and the large edge effect.

Many forest managers assume that soil compaction is a surface effect that dissipates with time through such natural processes as frost heaving. However, frost heaving is not an important process at the lower latitudes, and compaction may be irreversible without human intervention. Even where frost heaving does occur, compaction may persist for a quarter century (Froehlich *et al.* 1985).

In a unique experiment, Tiarks and Haywood (1996) compared first and second rotation responses of *Pinus elliotii* to three site preparation treatments on a silt loam soil in Louisiana. Treatments were established in 1960 following the harvesting of a natural stand of pines. Logging slash was burned, and sites received either no further treatment ('Check'), disking, or disking plus bedding. Trees were planted and measured regularly, and the plantations were harvested in 1983. Growth analysis showed that trees were substantially taller in the disking plus bedding treatment. Slash was burned again on all plots, but mechanical site preparation was not repeated. The same plots were replanted and trees were measured regularly through year 10.

Comparing 10-year growth for first and second rotation stands showed that trees in the Check treatment grew consistently faster in the second rotation than either of the mechanically site-prepared treatments. Measurements of soil strength at 10 years in the second rotation revealed that a compaction pan existed beneath the two mechanically site prepared treatments and had persisted for 33 years (Fig. 5.6). The pan was continuous below 20 cm in disked plots, and was similar but discontinuous where soil had been shaped by plough into furrows and mounds ('bedding'). Soil strengths below 20 cm often were at or above 2 MPa, meaning that root growth was likely reduced (Sands *et al.* 1979). The net effect was that roots in the second rotation were confined to a shallow, impoverished soil zone which largely was depleted of available phosphorus in the first rotation, causing incipient deficiency in the second. Similar effects of mechanical treatment were shown for first and second rotation plantations on sandy soils in Australia where logs had been skidded by tractor (Sands *et al.* 1979). The cumulative effect of mechanical traffic can seriously alter soil physical properties at depths not normally probed by a spade, and effects will persist without management intervention.

5.4 DETERMINING SUSTAINABLE YIELD

5.4.1 Assessing site potential

Inherent productivity

A key to developing a sustainable yield strategy is to know the inherent productivity of the forest

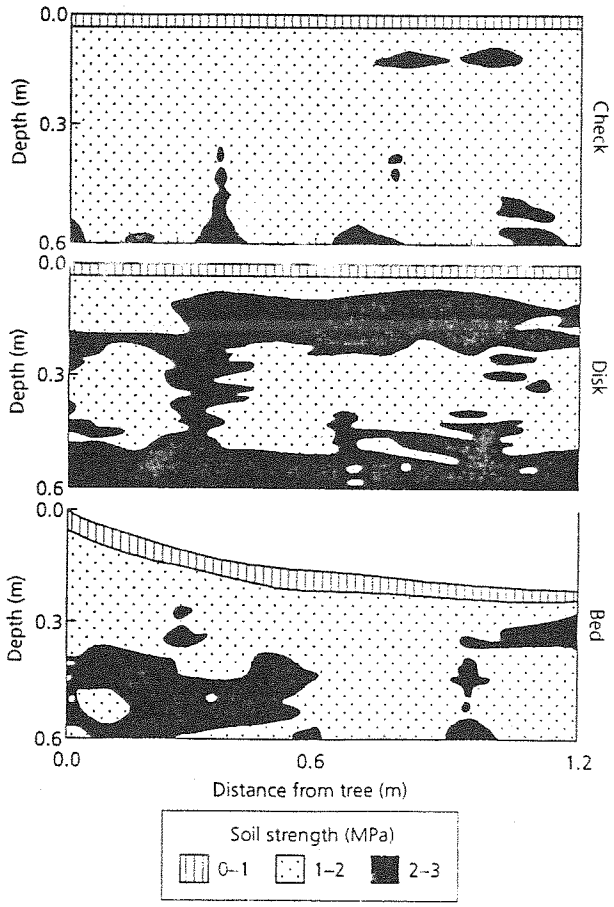

Fig. 5.6 Penetrometer measurements of soil strength on burned only (Check), burned and disked (Disk) and burned, disked and bedded (Bed) treatments 13 years after site preparation in the second rotation. Measurements taken at 10-cm intervals from planted trees. (From Tiarks & Haywood 1996.)

and how it is affected by various management options (Fig. 5.3). Both tree and stand volumes can be estimated non-destructively using established mensurational methods (Avery & Burkhart 1983), and data may exist from previous rotations for tracking stand development to final harvest. Provided that management continues in a similar way from one rotation to the next, that yield trends show no decline, and that site quality is not altered by factors beyond management control, historical records offer a reasonable basis for planning sustainable yield. Lacking historical records, stand inventories must be made, records kept of growth and yield, and trials established that encompass appropriate silvicultural options (Beets *et al.* 1994). Results would provide a basis for evaluating effects of management on productivity at an operational scale. Powers *et al.* (1994) suggest methods for establishing such trials with statistical reliability.

Direct measures

Site index, the height that the largest trees in a stand attain at some specific age, is the traditional estimator of site quality and potential productivity (Smith *et al.* 1997). But as Avery and Burkhart (1983) have noted, site index has many problems:

1 Stand age often is difficult to determine, and small errors can compound to larger errors in the site index estimate.
2 The concept is suited mainly for even-aged, pure stands.
3 Stand density measures are not considered.
4 Site index is assumed to be constant, yet height growth can change dramatically with climatic cycles.
5 Rarely can the site index of one species be translated into the site index of another.

Site index alone is too imprecise a measure of productivity potential or productivity change. In summary, site index simply amalgamates all the historical events that have shaped the height growth pattern for a particular stand. It is not reliable for projecting the effect of new site or stand conditions (Waring & Running 1998). Nor is it practicable for sites lacking older trees with no history of suppression.

Obviously, the best measure of sustained wood yield is yield itself—bole wood production at harvest. Differences in bole wood yields in successive rotations of the same age indicate changes in potential sustainable yield. Results would be precise and seemingly convincing, but there are problems. Converting unmanaged, natural stands to plantations almost always leads to yield improvement simply because stocking is controlled throughout the life of the stand. Even in consecutive rotations of plantations, similar yields could result from improved competition control or genetic composition in the current rotation that masks a true decline in site quality

(Powers *et al.* 1990; Burger 1996). Such confounding is especially likely in short rotation strategies because factors that temporarily override soil impacts are most effective when stands are young. Climatic differences between consecutive rotations also will affect yield outcomes. In general, yield records from consecutive rotations are not safe indicators of sustainable yield unless yields clearly are declining. Evans & Masson (2000) (this volume, Chapter 18) report a careful study over three rotations of pine and found no significant decline in yield despite no fertilizer application and more adverse climatic conditions.

Squire *et al.* (1985) largely overcame this problem by collecting seeds from one rotation to produce tree seedlings for the next (thereby keeping genotype constant), then treating the second-generation stand similarly to the first both on the same and on matched sites (keeping silvicultural treatments constant and short-term climate similar). Careful comparisons of stand development in consecutive or concurrent rotations indicated that site productivity was sustained if logging slash was retained. Nambiar (1996) concluded that the effect was due mainly to nutrient availability and that productivity could be sustained from one rotation to the next by combining weed control with fertilization. Such trials, of course, are expensive in capital and time.

Another problem is that precise measures of stand productivity are not obtained easily. Bole wood volume for a stand is determined from site-specific equations that estimate volume from an easily measured variable such as bole diameter, doing this for all trees in a stand inventory, and summing the bole volumes for the whole stand. Developing such equations requires either felling trees so that measurements may be taken on the ground, or by measuring upper bole diameters and heights so that volume can be estimated non-destructively. Several procedures have been developed to accomplish this (Avery & Burkhart 1983). But because bole form can change with different degrees of competition and different positions of the live crown, mathematical equations must be robust enough to account for form changes that normally occur throughout the life of a stand. Done diligently, periodic volume estimation is an excellent way to track the expression of productivity in a stand. Individual tree and stand-growth simulators have been developed for more general use, and can be parameterized for specific site and tree conditions (Landsberg & Gower 1997), and offer sizeable advantages over former ways of estimating growth and yield. The problem is, if changes have or are occurring, empirical methods such as direct measurement and growth simulation offer no insight as to the causes.

Less direct measures

A fundamental measure of yield potential is a site's carrying capacity for foliar biomass, and anything altering this alters sustainable yield. Therefore, periodic measures of foliar mass in the stable period following canopy closure (Fig. 5.4, phase C) should provide powerful, physiologically based indices of productive potential. Because foliar mass is linked directly with NPP, foliar-based productivity inferences require no knowledge of average tree size, age or stocking (Waring & Running 1998). Unfortunately, foliar mass is difficult to measure directly and non-destructively, but LAI is a popular and convenient surrogate. Instruments for measuring light transmitted through the canopy are the most common way of estimating LAI, although leaf area–sapwood area allometric relationships also are used (Beadle 1997; Landsberg & Gower 1997; Waring & Running 1998).

While leaf area meters are versatile, they underestimate mass if foliage is clumped. Cherry *et al.* (1998) have shown that very accurate measures of true LAI can be made if meters are calibrated for specific stands. Foliage mass also changes over a season and, to be useful, sampling should be standardized seasonally along permanent transects. If allowances are made for changes due to thinning, long-term trends in LAI should provide an effective index of stand productivity. Sapwood area measurements also offer a physiological basis for estimating foliar mass, but destructive sampling such as increment coring is needed to estimate sapwood area if the leaf area–sapwood area ratio is known. Otherwise, the relationship must be established by intensive and destructive sampling of whole trees. Leaf area–sapwood area

Table 5.2 Typical soil quality threshold standards used by the USDA Forest Service to indicate detrimental changes in soil productivity. In general, at least 85% of the activity area must be within threshold standards. (Modified from Powers *et al.* 1998.)

Nature of disturbance	Threshold value for detrimental disturbance in surface horizons
Area affected	Total area of detrimental disturbance should not exceed 15% of the activity area, exclusive of roads and landings
Altered wetness	Area becomes perennially flooded or drained, and the natural function and value of the land is lost
Erosion	Sheet or rill erosion exceeds estimated natural rates of soil formation over a rotation
Soil cover	Effective cover on less than 50% of the area, or as modified by slope
Organic matter	Forest floor missing from 50% or more of the area
Infiltration	Reduced by 50% or more
Compaction	Bulk density increase of 15% or more, or reduction of 10% or more of total porosity
Rutting and puddling	Ruts to at least 15 cm deep for more than 3 m
Detrimental burning	Forest floor consumed, mineral soil reddened
Displacement	Removal of half or more of the A horizon over an area at least 6 m^2 and 1 m wide

relationships vary with species, bole position, stand age, stocking density and possibly site quality. Therefore, ratios established elsewhere may not be appropriate for the stand of interest. Regardless, both LAI and leaf area–sapwood area methods should be seen as indices which are probably two or more levels removed from direct estimates of productive potential, such as bole wood production. Calibrated properly, they should provide good assessments of the trend in stand productivity. But as with direct tree measures, causal factors are not explicit.

Indirect measures

Burger (1996) called for an unbiased measure of soil quality and potential site productivity that is independent of stocking and genetic influences on current growth. Because soil is a major factor determining potential productivity, and because it is readily affected by management and largely independent of current stand conditions, soil-based variables have been recommended as alternative indices of sustainable productivity (Canadian Forest Service 1995; Burger 1996; Powers *et al.* 1998). Accordingly, the United States Forest Service has adopted a programme for monitoring soil condition as a surrogate for site quality. Each of the geographical regions of the USA is developing operationally practicable sampling criteria for detecting soil changes that would lower site quality and potential sustainable yield over a rotation (Powers *et al.* 1998).

Soil quality is assumed to reflect inherent potential productivity, but standards are not meant to be precise estimators. Rather, they are used as 'early warning signals' that something may be impairing potential sustainable yield. Standards vary from region to region, but the general concept for 10 threshold soil conditions used by the United States Forest Service is described in Table 5.2. Shortcomings of such standards are that subsoil conditions are not addressed, correlations have not been made with site potential, and important processes are not well integrated.

Are more precise indices feasible? Van Miegroet *et al.* (1994) presented a more detailed list of fundamental, soil-based variables that could be measured to develop precise indices of soil quality status. Repeated sampling on given sites would offer valid measures of soil quality change, and might suggest possible causes. For example, substantially increased cation leaching and exchangeable acidity, and decreased pH would suggest acidification from atmospheric deposition. Increases in soil nitrate would suggest that the cause was N deposition as noted near European feedlots (Van Breemen 1990). Along with static measures (soil chemistry, moisture-holding capacity, biotic diversity) are process-based measures (decomposition, mineralization, immobi-

Table 5.3 Partial list of soil properties, processes, and methods of assessment that relate to site quality and potential sustainable yield. (Modified from van Miegroet *et al.* 1994.)

Soil property	Key processes	Assessment
Soil fauna	Detrital fragmentation/mixing Soil aeration	Pitfall traps and counting Heat extractions and counting
Soil microbiota	Decomposition Nutrient transformation Soil aggregation	Dilution plate Incubation/fumigation Respiration
Forest floor	Energy substrate Decomposition Nutrient cycling	Gravimetric/chemical analysis Decomposition in litterbags Isotopic techniques
Mineralization potential	Nutrient release Nutrient transformations	Incubations/exchange resins Solution lysimetry
Reaction	Proton exchange (H and Al) Nutrient availability	pH Exchangable acidity
Organic matter	Energy substrate Nutrient supply/retention Water retention	Combustion Fractionation Spectroscopy/^{13}C NMR
Fertility	Nutrient availability	Kjeldahl analysis Chemical extractions
Oxygen content	Soil biotic activity Redox reactions	Soil gas analysis Redox potential measures
Water input	Recharge Availability to roots	Infiltrometry Hydraulic conductivity
Water content	Uptake by plants/soil biota Nutrient availability	Gravimetric analysis Neutron scattering Resistance blocks/TDR
Porosity/strength	Gas diffusion Water availability Root impedence	Bulk density Pore size analysis Mechanical resistance

lization, leaching). Typical measures are indicated in Table 5.3. If tailored to a particular climatic regime and soil type, periodic readings would provide a reliable index of site quality trends and inference into possible causes. However, sampling complexities and the cost of detailed analyses relegate such detailed soil-based indices to only a few intensively studied research sites. Findings must be interpreted carefully. For example, soil organic N, carbon and microbial biomass were appreciably lower following 30 years of continuous weed control in a pine forest than in adjacent, control plot soils (Busse *et al.* 1996). Rather than indicating a decline in soil fertility from weeding, this simply suggests that long-term weeding slows the rate at which soil fertility aggrades.

Recognizing this, Powers *et al.* (1998) called for a simple set of integrative measures for extensive soil quality monitoring in forests of the US. To be effective, such measures must: (i) reflect physical, chemical, and biological soil processes important to sustained productivity; (ii) integrate multiple properties and processes; (iii) be operationally practicable on a variety of sites; and (iv) be sensitive to the overriding conditions of climate. They proposed that penetrometer measurements of soil strength, anaerobic incubations of soil N

availability and (indirectly) microbial biomass, and physical signs of soil invertebrate activity (biopores, faecal aggregates) serve as first-approximation surrogates for more detailed (and costly) measures of soil physical, chemical and biological properties.

These biologically relevant, integrative measures are particularly useful for operational monitoring. Soil strengths above 2 MPa indicate increasing stress to root growth (Taylor *et al.* 1966), and root growth essentially ceases beyond 3 MPa (Sands *et al.* 1979). Figure 5.6 (p. 118) indicates how soil strength can detect degraded soil quality and forest productivity over two rotations on a pine site in Louisiana (Tiarks & Haywood 1996). Nitrogen mineralized anaerobically correlates well with site quality in such diverse regions as Australia, California and Maine (Powers *et al.* 1998), and with field rates of N mineralization (Adams & Attiwill 1986).

Although direct correlations between soil invertebrates and forest productivity have yet to be established, their significance in ecosystem processes is unquestioned (Van Cleve & Powers 1995) and is recognized particularly well in Europe (Shaw *et al.* 1991). Soil invertebrates are difficult to measure directly, but the functional products of their activity—biopores, faecal aggregates, and stable soil aggregates—are not (Powers *et al.* 1998). Findings from such soil sampling would not be interpreted in an absolute sense. Rather, they would serve as baselines for measuring soil quality trends at each particular site. As the concept of soil quality evolves, so do standards for effective monitoring.

Process simulators

Mathematical models based on physiological processes and the site factors that affect them offer a promising means for estimating how forests grow under differing management regimes. For a general discussion see Volume 1, Chapters 8–10. Early process-based simulation models were based on the simple premise that a single factor (a nutrient, light or soil moisture) was the principal determinant of tree or stand behaviour. Thus, they were inherently unrealistic. More sophisticated models involving foliar mass as a determinant of growth have emerged in the last two decades (Landsberg & Waring 1997). Growth projections may follow assumptions on how photosynthate is partitioned into biomass components according to light interception and canopy temperatures. Nutritional or water factors are handled through less dynamic submodels. For example, BIOMASS (McMurtrie *et al.* 1992) is a stand-level simulator that models photosynthetic and respiratory processes as a function of air temperature. Soil properties interact through the assumption that assimilation is a linear function of foliar N concentration and that water deficits control stomatal behaviour (Landsberg & Gower 1997).

Other 'biogeochemical' simulators are driven by soil nutrient or water availability submodels that affect foliar production and assumed partitioning of carbon, and are a large step forward in modelling the concept of an ecological rotation. Century—originally a grassland model modified recently for forests (Metherell *et al.* 1993)—is a soil-based model of organic matter decomposition that is tied loosely with NPP (Landsberg & Gower 1997). Recognizing the need to couple below- and above-ground processes and conditions, researchers have combined model components to try and simulate a more realistic picture of ecosystem processes. For example, G'DAY (McMurtrie *et al.* 1992) combines elements of Century with BIOMASS, a physiological model of forest vegetation, to account for short-term changes due to rises in atmospheric CO_2. In turn, such combined models have been further modified to simulate longer-term processes (Murty *et al.* 1996). The most advanced models marry both elements. For example, Forest BGC (Running & Coughlan 1988) is a landscape-scale ecosystem model based on leaf area as influenced by climate, leaf water status and soil N availability. It simulates the carbon cycle by modelling photosynthesis, respiration and the partitioning of NPP into above- and below-ground components. Characteristics of these and other simulation models are outlined in Table 5.4 and are discussed in more detail elsewhere (Proe *et al.* 1994; Landsberg & Gower 1997; Homann *et al.*, 2000).

One should recognize that all models are abstractions of reality because our understanding of most site processes is imperfect. Therefore,

Table 5.4 Examples of mathematical process models that simulate forest growth and their attributes. From Homann *et al.* (in press), Landsberg and Gower (1997), Landsberg and Waring (1997) and Proe *et al.* (1994).

Model	Calibrating variables	Timestep	Reference
BIOMASS	Climatic	Monthly	McMurtrie *et al.* 1992
Century–Forest	Climatic, Soil	Monthly	Metherell *et al.* 1993
FOREST-BGC	Climatic	Yearly	Running & Coughlan 1988
G'DAY	Climatic, Soil	Monthly	Comins & McMurtrie 1993
LINKAGES	Climatic	Yearly	Post & Pastor 1996
NuCM	Climatic, Soil	Daily–monthly	Liu *et al.* 1991
PnET	Climatic	Monthly	Aber & Federer 1992
3-PG	Climatic, Soil	Monthly	Landsberg & Waring 1997

many critical processes affecting water and nutrient availability are modelled implicitly using assumed relationships with standard growth functions. Biogeochemical models attempt a more realistic approach, but their outputs still rest on many assumptions and uncertainties awaiting further research. Recently, Homann *et al.* (2000) compared soil chemistry predictions from several calibrated biogeochemical models with independent data not used in the calibration. Errors between observed and predicted values averaged between 24% and 56%, with individual discrepancies as great as 1000%.

Practical problems with the more advanced simulators are that many of the calibration parameters must be estimated because they are not directly measurable, and that calibration may be operationally impracticable. In their validation efforts with FOREST-BGC, Milner *et al.* (1996) voiced the need for better soil data and the need for other modifiers of stockability for marginal sites and ecotones. They also expressed frustration at configuring even-age stand simulators to make reasonable projections for multiaged stands. Uncertainties surrounding nutrient dynamics and the overriding significance of climate led Landsberg and Waring (1997) to consider only climatic variables, soil water-holding capacity and stand leaf area in their physiological model of forest productivity, 3-PG. Recent tests of 3-PG predictions against 30-year growth data from Australian and New Zealand plantations showed excellent correlations (Landsberg & Waring 1997).

The history of simulation models mirrors the evolution in our understanding of how ecosystems function. They serve an extremely useful scientific purpose for integrating knowledge and testing hypotheses, but to date they cannot be extrapolated with confidence to specific sites or new situations. However, models can be used as a 'gaming' tool to develop first approximations of sustainable yield strategies if reasonable calibration data are available. In the absence of site-specific data, tabulations such as those by Kimmins *et al.* (1985) may provide first approximations. Also the availability of climatic and leaf area data from remote sensing furthers the ease of parameterization. The key for the general acceptance of simulation models, though, is that they be logical, easily calibrated, validated, and upgraded as needed. Easily parameterized, physiologically based growth models such as 3-PG seem exceptionally promising. Coordinated programmes like the North American LTSP study (Powers *et al.* 1990) will help to validate them.

5.4.2 Scheduling the harvest

Area regulation

Assuming management strategies that protect site quality, one classical way of managing for sustained yield is through the *area method of regulation* (Smith *et al.* 1997). It occurs when a forest contains multiple even-aged stands that collectively comprise all age classes in a rotation. Individual stands may be of varying extent—the only criterion being that each age class occupies equivalent ground area. *If* site quality is similar for all stands; *if* they are tended as needed to

assure adequate stocking and vigour; *if* harvesting from a particular age class is balanced by ingrowth from the next youngest age class; *if* site quality and gene pools have not been degraded; and *if* no catastrophic events occur from fire, flood, wind or pestilence—then sustained yield has been achieved. Despite all the conditional 'ifs', area regulation is a popular means for achieving sustained yield in even-aged management systems. It is particularly useful if the area in sub-merchantable age classes is recognized for other values, such as wildlife habitat or fuelwood production. But it seems unlikely that all the 'if' conditions can be met.

Volume regulation

Another management strategy for sustained yield is the *volume method of regulation* (Smith *et al.* 1997). Unlike area regulation, it does not require a balance of age classes occupying equal ground areas. Its main characteristic is that the forest contains an appropriate distribution of size classes that describe an 'inverse J-shaped' (negative exponential) curve. In such a regulated forest, harvesting would occur in all age classes in order to maintain stocking that ensures healthy, orderly and predictable growth. Also ideally, there would be a ready market for all sizes of harvested materials. Rarely does this occur. Markets for small, young trees often are marginal or non-existent, and only the largest and oldest trees have high value. Although it is difficult under these conditions, sustained yield may still be achieved, provided that the volume removed in larger trees is met by accelerated growth in smaller size classes through various silvicultural treatments such as weeding, thinning and fertilization. Volume regulation demands more knowledge of stand conditions and more silvicultural input than area regulation. Therefore, it is the more technically demanding of the two. However, it is a more flexible system because it frees the forester from rigid adherence to area regulation, and is equally appropriate in even- or uneven-aged management strategies.

A special case often applies to plantations where the objective is to maximize wood yield over time. In Britain, this requires thinning at an intensity of 70% of the maximum mean annual volume increment for that yield class and, of course, to fell the crop at the age of maximum mean annual increment (Fig. 5.1). If the productivity of the successor plantation is expected to be greater than the current, maximum mean annual increment will occur earlier in the successor rotation (e.g. FR in Fig. 5.1) and a shorter rotation may be justified for the current plantation (Evans 1992).

Infrequent stand entries, low levels of extraction, and just enough ground disturbance to secure regeneration as proposed for 'ecological forestry' (Drengson & Taylor 1997) equate to yields that presumably can be sustained indefinitely, although they may be less than the site's yield potential. Conditions suitable for the biotic diversity characterizing late seral forests would be maintained, and a continuous forest cover would enhance many watershed values.

5.5 SYNTHESIS AND SUMMARY

Society places high value in wood. Therefore, sustaining or enhancing wood yields from one rotation to the next should be both an ethical and economic goal of forest managers. Achieving this depends on management practices that sustain or enhance the site's foliar carrying capacity for the forest species of interest. This capacity, varying by genotype, is set by climate, topography and soil. Of these, only soil is amenable to management. Therefore, sustained productivity and yield hinge on good soil management.

Recent innovations in harvesting technology, the conversion of natural stands to plantations, rises in air pollution, and the spectre of global climate change compound the difficulty in assessing potential sustainable yield. Practicable methods are needed for monitoring trends in site potential. Direct observations of growth and yield give true measures of stand performance, but are labour intensive. Such measures are conditioned by stand history and, if changes occur, offer little information on possible causes. Trends in foliar mass or area can be monitored non-destructively by periodic surveys of LAI once canopies have closed. If changes are noted, causes may be inferred from changes in soil properties and

processes revealed through soil quality monitoring. Long-term field studies of multiple treatments representing forest management strategies are needed both to determine the true impact of management on potential sustainable yields, and to calibrate or validate mathematical models meant to simulate fundamental site processes affecting yield. Despite their recognized imperfections, computer simulators may be our best means for projecting the sustainability of any forest management system and come closest to the concept of *ecological rotation*.

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