Conclusions

Three main conclusions may be drawn from this review of yield assessments made over long periods, and often more than one rotation, and the summary of interventions to sustain yields.

1. Measurements of yield in successive rotations of trees suggest that there is no significant or widespread evidence that plantation forestry is unsustainable in the narrow sense. Where yield decline has been reported, poor silvicultural practices and operations appear to be largely responsible.
2. Evidence in several countries suggests that current rates of tree growth, including in forest plantations, exceed those of 50 or 100 years ago owing to changes in the environment, especially atmospheric composition, and improvements in silviculture.
3. There are several interventions in plantation silviculture which point to increasing productivity in the future, providing management is holistic and good standards are maintained. Genetic improvement in particular offers the prospect of substantial and long-term gains in yield over several rotations.

See also: **Afforestation**: Species Choice; Stand Establishment, Treatment and Promotion - European Experience. **Inventory**: Stand Inventories. **Plantation Silviculture**: Forest Plantations; Rotations; Stand Density and Stocking in Plantations; Tending. **Resource Assessment**: Forest Resources. **Silviculture**: Natural Stand Regeneration. **Sustainable Forest Management**: Certification; Overview. **Tree Breeding, Practices**: Breeding for Disease and Insect Resistance; Genetics and Improvement of Wood Properties. **Tree Breeding, Principles**: Conifer Breeding Principles and Processes.

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Short Rotation Forestry for Biomass Production

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Introduction

Some hardwood species have very rapid juvenile growth and also coppice readily. They are often natural pioneers. High yields can be sustained over many coppice rotations as short as 3–15 years. These properties can be exploited to produce large quantities of woody biomass, which can be used for pulp or to produce energy.

Recent ideas on short-rotation forestry developed during the 1960s with discussions on silage sycamore in the USA. The initial attraction was the prospect of obtaining both high yields and early returns on investment. There was also the added advantage of producing a uniform product by using clones and of rapidly selecting and deploying improved genetic material.

The notion of growing species such as willows, poplars, and eucalypts over short coppice rotations gained momentum as agricultural surpluses in Europe and North America offered the possibility of large areas of fertile land becoming available. At the same time, there was increased interest in biomass as a renewable energy source, while, in the tropics, short rotations enabled exceptionally high yields of wood pulp to be produced, with high financial returns.

This article outlines the extent to which short-rotation forestry is being practiced, the yields being obtained, some aspects of the silviculture, pest and disease problems, the utilization of short-rotation biomass, and environmental impacts.

Short-Rotation Forestry Around the World

Globally, *Eucalyptus* is probably the most widely planted genus. About 10 million ha have been planted worldwide, notably in China, India, Brazil, South Africa, Chile, and Portugal. Much of this area is managed on short rotations, virtually all for pulp. Over recent decades there has been a large increase in international trade in pulp from *Eucalyptus* and other fast-growing plantations.

Aracruz Celulose began growing *Eucalyptus* in Brazil in 1967. It is now one of the world's leading suppliers of bleached eucalypt pulp. Most of the pulp is exported. The plant produces about 1 million tonnes of pulp per year and is supplied by plantations covering about 150 000 ha. Aracruz has not only been commercially successful; it has also pioneered the development of new genetic stock, nursery methods, and clonal propagation.

Elsewhere in the tropics and subtropics, a wide range of species is grown on 10–15-year rotations for pulp and other products, including *Terminalia* spp., *Acacia* spp., *Casuarina* spp., *Virola koschnyi*, *Jacaranda copaia*, and many other species. Mention should also be made of the many woody species used in tropical agroforestry systems, yielding fuelwood, wood products, and green manure. Species such as *Sesbania sesban* have rapid juvenile growth, coppice rapidly, and fix nitrogen.

In North America, there are not many examples of short-rotation forestry being practiced commercially, but there are vigorous research and development programs. In Canada, attention has focused on poplars in Ontario province, grown on rotations of about 10 years, harvested with feller/bunchers. In the USA, the Short Rotation Woody Crops Program and the Biofuels Feedstock Development Program have examined the potential of growing fast-growing hardwoods on suitable agricultural land. Extensive trials involving about 150 species have been conducted since 1978. Databases exist on species yields in different regions, effects of varying spacings, fertilizer responses, pesticide prescriptions, and harvesting methods. The most productive species, besides *Eucalyptus* in Florida and Hawaii, have been *Populus* clones, *Liquidambar styraciflua*, *Acer saccarum*, *Platanus occidentalis*, and *Robinia pseudoacacia*.

In Europe, extensive short-rotation *Eucalyptus* plantations are grown for pulp along the Atlantic seaboard in Portugal and Spain. Elsewhere, Sweden pioneered the growth of willow and poplar as biofuels in the Swedish Energy Forestry Project, launched in 1976. Currently, 15% of Sweden's energy is supplied from biomass. Commonly, willow is grown over 6-year rotations on abandoned farmland, yielding biomass for small combined heat and power plants. New clones have been selected, cultural prescriptions defined, and harvesting machinery developed. Elsewhere in Europe, short-rotation forestry is practiced in most countries, but on a relatively small scale. However, the ambition of the European Commission to meet 12% of the European Union's primary energy demand from renewable sources by 2010 might require up to 10 million ha of energy crops, much of which would be short-rotation coppice.

Considerable research on short-rotation biomass plantations has been coordinated by the International Energy Agency (Bioenergy) since 1974, particularly within the task group Short Rotation Crops for Bioenergy Systems. The country partners are Sweden, Norway, Netherlands, Denmark, UK, Croatia, USA, Canada, Australia, and New Zealand.

Biomass Yields

Yields of *Eucalyptus* at Aracruz reach 40–50 $m^3\,ha^{-1}\,year^{-1}$, in excess of 30 $t\,ha^{-1}\,year^{-1}$ dry matter, over 7-year rotations. Similar extraordinarily high yields can be achieved over 4–8-year rotations by *Eucalyptus* in New Zealand and *Leucaena leucocephala* in Florida and other subtropical regions. Record yields approach 100 $m^3\,ha^{-1}\,year^{-1}$.

During the 1970s, some exaggerated claims were made for the potential yields of poplar and willow in temperate regions. Claims were based on yields in small plots, with large edge effects, which can give yields four to seven times greater than those in extensive commercial plantations. Also, breeding is unlikely to increase biomass yields as much as has occurred in agricultural crops, where yield has been increased largely by increasing the fraction harvested (the harvest ratio) rather than total biomass.

In Sweden, dry biomass yields of coppice willow from well-designed trials average about 8–9 t ha^{-1} $year^{-1}$ in the north-east, 9–10 t ha^{-1} $year^{-1}$ in the east, 11–12 t ha^{-1} $year^{-1}$ in the far south, and peak at 16–17 t ha^{-1} $year^{-1}$ along the west coast. In England, dense plantings of the erect willow clone 'Jorunn' have produced 11–12 t ha^{-1} $year^{-1}$ on 3-year rotations, while hybrid poplar clones have produced 12–14 t ha^{-1} $year^{-1}$ on 4-year rotations on wet sites. Overall, biomass yields of well-tended short-rotation poplar and willow growing on fertile sites in central and northern Europe are likely to be 8–12 t ha^{-1} $year^{-1}$. However, when in extensive cultivation on less-than-ideal sites, yields are lower, often in the range 4–8 t ha^{-1} $year^{-1}$.

Clones of willow, poplar, and other species differ severalfold in yield. Analyses suggest that these yield differences are mainly due to differences in the amount of light intercepted during the growing season, because clones differ in times of leaf emergence, leaf-fall and canopy structure. Early spring foliation is particularly important. Clones differ less in the amount of biomass produced per unit of light intercepted, commonly around 0.8–1.5 g MJ^{-1}, similar to agricultural crops with the same photosynthetic mechanism.

Profitability

Short-rotation pulp production using *Eucalyptus* in tropical and subtropical regions is clearly highly profitable in some locations and has attracted substantial venture capital. The same is true for the short-rotation pulp plantations in countries like Chile, China, India, and Portugal.

The uptake of short-rotation forestry in North America and most of Europe has been more constrained. In England, the only significant power plant to be fueled by willow coppice (ARBRE in Yorkshire) has ceased operation. The obstacles to short-rotation forestry are primarily: (1) the relatively low cost of electricity generated from fossil fuels; (2) the high cost of agricultural land, often inflated by agricultural subsidies; and (3) the lack of an industry infrastructure for handing biomass. The technologies for cultivation, harvesting, and conversion do not seem to be the main constraints, although advances can be made.

Research in many countries has quantified the costs of cultivation, storage, transport, and conversion to electrical energy. Profitability is normally very sensitive to energy prices and coppice yields, provided transport distances do not exceed about 100 km. However, there appears to be a 'catch-22' of investors reluctant to finance tree planting without guaranteed markets or conversion plants without guaranteed feedstock supplies. Some market intervention is required to develop both a level playing field with other land uses and energy sources and to establish industries with a critical mass.

Silviculture

Species and Breeding

As indicated above, a variety of species are used for short-rotation biomass production, the only condition being that they have rapid juvenile growth and coppice readily. The same selection strategies are used as in conventional tree-breeding programs, except the vegetative propagation is normally much easier, so that clones and multiclone mixtures can be selected. Most countries have lists of approved and recommended clones, based on screening for yield and pest and disease resistance.

In Europe and many other regions, *Eucalyptus globulus* is the preferred eucalypt species for short-rotation pulp production.

Poplars are the most universally grown species in temperate regions, being hugely diverse and tolerant of a wide range of conditions. Poplars of the *Aigeiros* and *Tacamahaca* sections respond to nutrient-rich, well-watered conditions and are easily propagated by cuttings, whereas species of aspen belonging to the *Leuce* section root less easily but are tolerant of a wide range of site conditions.

The *Salix* genus is hugely variable and is characterized, like poplar, by hybridization and the selection of clones, several hundred of which have been screened for their potential to produce biomass.

Site Conditions

The idea of short-rotation forestry is to obtain high yields over short periods of time, capitalizing on rapid juvenile growth. That rapid growth will only occur on fertile soils, rich in nutrients and with adequate water. A ready supply of both nutrients and water is required for rapid canopy development and photosynthesis. Former agricultural land, able to sustain arable crops, is ideal, but less fertile grassland can be used with fertilization. The rootable depth should be at least 1 m and, to allow mechanization, there should not be more than 6% side-slope and 10% in-row slope.

Forests, including coppices, use more water than short vegetation because they intercept 10–30% of rainfall, which evaporates from leaf surfaces without reaching the ground. Thus, short-rotation forests have similar effects on local hydrology to high forests, potentially decreasing groundwater and river flows. In Sweden, it has been estimated that the evaporation of intercepted rain accounts for 11% of total annual evaporation. Also, rapid photosynthesis by fast-growing species is always accompanied by high transpiration of water. Poplar and willow coppice transpire about 1 kg water for every 3.5 g of stem-wood produced, so $10\,\mathrm{t\,ha^{-1}\,year^{-1}}$ is equivalent to 286 mm rainfall — allowing for no groundwater recharge. Thus, an adequate water supply is crucial, and areas with summer droughts, or where groundwater supplies need to be sustained, may not be suitable.

Cultivation

The International Energy Agency (Bioenergy) has produced a Production Systems Handbook for Seven European countries and the USA. It provides a decision support system on species, spacing, cultivation, harvesting, and production costs.

It is normally assumed that sites need to be deep-ploughed. As mentioned, the sites need to be fertile enough to support fast-growing broad-leaved species. Willow and poplar grow best on mildly acidic soils with pH 6.0–7.0. Fertilizers are generally required to make good the nutrient losses from harvesting. High nutrition speeds canopy development, maintains a high leaf area index, a low root-to-shoot ratio and high light conversion efficiency. Herbicides are normally needed to suppress ground vegetation and temporary fencing may be needed to protect trees from browsing.

Spacing has little effect on biomass yield, provided a full canopy cover is established rapidly, but it obviously has a large effect on average stem size. A rule-of-thumb is that the optimum spacing is that required to reach the point of self-thinning by the end of the rotation. However, the market determines the type of biomass required and hence the spacing and harvest machinery. For poplar and willow grown for bioenergy in Europe, planting 5000–10 000 cuttings per hectare is recommended, with a rotation of 4–6 years. Rotations of 6–10 years are favored in parts of the USA, with 1000–2500 cuttings per hectare. Very short rotations of 1–3 years are rarely economic because of high establishment costs, weakened stools, and difficulty in handling small stems.

Harvesting

Mechanization is essential and is part of the attraction of short-rotation forestry. Commercial short-rotation forestry harvesting machines are available using single pass cut and chip and whole stem systems. The latter are used to harvest larger stems produced over longer rotations. Harvesting accounts for over half the costs of production, so considerable research has been done to produce dedicated machines. Clearly, harvesters can compact the soil when wet and harvesting is best done in winter when the ground is frozen.

Pests and Diseases

Warnings that clonal plantations of fast-growing species would be vulnerable to outbreaks of pests and diseases have proved to be justified. Pests and diseases have become serious issues in most places where large areas of poplars and willows have been grown in trial plantations. There are around 130 known pest species on poplar and willow and many fungal pathogens. It is uneconomic to apply pesticides or fungicides. However, there are resistant types. For instance, poplar susceptibility to defoliation is roughly in the order *Populus nigra* < *P. trichocarpa* < *P. deltoides* × *nigra* < *P. trichocarpa* × *deltoides* and resistant clones can be found.

In Sweden, gall midge (*Rhabdophaga terminalis*) became a serious pest on *Salix alba*, with the result that this species was rejected from the bioenergy program.

In the UK, willow beetle (*Phratora vulgatissima*) affected over half of the willow bioenergy trials, with very heavy infestations on young trees. Research has identified volatile organic production by the leaves as being related to beetle resistance and semiresistant clones have been selected. Also, it has been shown that mixtures of five or more clones, including resistant clones, slow the build-up of beetle populations.

Fungal pathogens are also a serious problem. Rust (*Melampsora epitea*) is probably the most important factor limiting willow yields in the UK. It is also a serious pathogen on poplar. The fungus expresses great variation in virulence types and specificity to clones, and alternates (spends half its life cycle) on *Larix* (also *Ribes*, *Allium*, and *Saxifraga*). It is therefore wise to locate willow or poplar plantations distant from these alternate hosts. Again, mixed clonal stands delay the onset and progress of the disease and can provide an effective means of control.

Coppicing exposes the stools to infection and particular care has to be taken to treat stumps to inhibit rot fungi.

Utilization

At present, short-rotation forestry can compete, in some instances, with traditional forestry in the production of pulp, especially in the tropics and warm temperate countries. There are also limited markets for poles and stakes, and in the future there may be demand for biomass as a chemical feedstock.

As mentioned, the economics of growing biomass for energy (other than traditional fuelwood in the tropics) is currently uncertain. In most regions, biomass energy is competitive at current fuel prices only if: (1) yields are high; (2) plantations are close to conversion plants; (3) residues and waste materials are used as well as newly grown biomass; and (4) there are, preferably, saleable products from the biomass plantations in addition to bioenergy. It is, of course, possible to establish short-rotation forestry enterprises that produce pulp in the first instance and then make the transition to supply energy at a later date.

Nevertheless, concerns about carbon emissions and future energy security have stimulated considerable research on the potential to produce renewable energy from biomass. The energy content of dry woody biomass is about 18.5 $MJ\,kg^{-1}$, regardless of species. Clearly, energy is used to cultivate, harvest, dry, and transport biomass to electricity-generating plants, but this is commonly only about one-twentieth of the energy contained in the biomass delivered to the plant. One tonne of dry biomass contains about 0.5 t of carbon and has about the same amount of chemical energy as 0.5 t of coal (which is carbonized biomass) or 0.44 t of oil or 0.28 t of methane gas. Globally, if 200–400 million hectares of high-quality land were used to grow biomass (14–28% of the current cropland area), with an average yield of 10 $t\,ha^{-1}\,year^{-1}$, it could, theoretically, generate 37–74 $EJ\,year^{-1}$ (9–18% of current global energy production from fossil fuels), offsetting 15–30% of global carbon emissions. A more conservative estimate of the likely contribution of biomass to global energy supplies by 2050–2100 is 9–37 $EJ\,year^{-1}$, requiring 50–200 million hectares. As mentioned, European renewable energy ambitions might require 10 million ha of biomass energy crops by 2010, and there is the potential to increase this 10-fold during this century.

Environmental Impacts

When compared with natural forests, short-rotation biomass plantations are at odds with the paradigm of an environmentally desirable land use. They are even-aged, regularly clear-felled, have no large dead trees and woody debris, and have little recreational value and a limited range of habitats for wildlife.

However, when compared with agricultural land, short-rotation forests offer some benefits and few disadvantages. Increased litter fall can improve soil conditions after some years. Land in the USA, which lost 18 $t\,ha^{-1}\,year^{-1}$ of soil by erosion under arable cropping, lost only 2 $t\,ha^{-1}\,year^{-1}$ when converted to short-rotation forestry. Compared with arable agriculture, nitrogen leaching to groundwater may be decreased, with less nitrous oxide emission. Short-rotation forests can, in fact, be used for sewage sludge disposal, and as wastewater filters to purify municipal wastewater, landfill leachate, and sewage. In Sweden, wastewater with 160–190 $kg\,N\,ha^{-1}\,year^{-1}$ has been applied to fast-growing willow coppice without substantial nitrate leaching and, in some instances, the trees have taken up heavy metals, reducing levels in soils.

Short-rotation forests can sustain levels of biodiversity that are equal to, although different from, those on farmland. Arthropods are abundant on willows and poplars (sometimes as pests), which support a high bird population. The bird populations in hybrid poplar plantations in the USA are higher than those in crop fields. Short-rotation forests can also be used as cover for game.

See also: **Environment**: Carbon Cycle. **Hydrology**: Impacts of Forest Plantations on Streamflow. **Non-wood Products**: Energy from Wood. **Pathology**: Diseases affecting Exotic Plantation Species; Rust Diseases. **Plantation Silviculture**: Forest Plantations. **Silviculture**: Coppice Silviculture Practiced in Temperate Regions. **Temperate Ecosystems**: Poplars. **Tree Breeding, Practices**: Genetic Improvement of Eucalypts. **Tropical Ecosystems**: Eucalypts.

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Propagation *see* **Genetics and Genetic Resources**: Propagation Technology for Forest Trees. **Tree Breeding, Principles**: A Historical Overview of Forest Tree Improvement; Current and Future Signposts; Forest Genetics and Tree Breeding. **Tree Physiology**: Physiology of Vegetative Reproduction; Tropical Tree Seed Physiology.

Protection *see* **Health and Protection**: Biochemical and Physiological Aspects; Diagnosis, Monitoring and Evaluation; Forest Fires (Prediction, Prevention, Preparedness and Suppression); Integrated Pest Management Practices; Integrated Pest Management Principles. **Soil Biology and Tree Growth**: Soil and its Relationship to Forest Productivity and Health. **Tree Breeding, Practices**: Breeding for Disease and Insect Resistance.

PULPING

Contents
Fiber Resources
Chip Preparation
Mechanical Pulping
Chemical Pulping
Bleaching of Pulp
New Technology in Pulping and Bleaching
Physical Properties
Chemical Additives
Environmental Control

Fiber Resources

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Introduction

In economics, primary inputs or factors of production define the term 'resources.' Resources include land resources (plants, animals, and minerals), labor, capital, and entrepreneurship. Almost all pulp and paper fiber resources are plant materials obtained from trees or agricultural crops. These resources encompass plant materials harvested directly from the land (wood, straw, bamboo, etc.), plant material byproducts or residuals from other manufacturing processes (wood chips from sawmills, bagasse fiber from sugarcane processing, cotton linter, etc.), and fibers recovered from recycled paper or paperboard.