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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

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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.

Some relatively expensive nonplant fibers derived from mineral resources are also used in papermaking (e.g., synthetic plastic fibers) but very small quantities and only in some specialized paper or paperboard products.

Resources derive value from their utility in producing goods or services, but utility varies among different fiber resources and utility varies as technology and product demands shift over time. Different plant fibers have different physical properties that influence their utility in pulping and papermaking. Utility of industrial resources also depends on profitability, or availability of resources at competitive market prices. Market demands for fiber products and supplies of fiber resources vary over time, and thus the market value and utility of fiber resources are variable over time. Some resources have competing multiple uses and alternative values in society. Forest resources have value in producing a range of different wood products, not just pulp and paper products. Forest resources also have alternative values in society because they produce other important services such as recreational, spiritual, environmental, or aesthetic services.

For example, selected species of trees grown in monoculture (single-species) plantations may have high intrinsic value in pulping or papermaking because of uniformity in fiber quality or desirable fiber characteristics, but cultivating trees in plantations can be more expensive than relying on natural regeneration of trees in a forest. The typically more heterogeneous mixture of tree species found in a naturally regenerated forest may have less intrinsic value in pulping or papermaking because of less uniformity or less desirable fiber characteristics, but may have utility in any case because of lower cost. However, a natural forest will likely have high value to society in terms of ecological or aesthetic amenities. Also, advances in plantation systems or biotechnology can yield faster-growing trees or more desirable trees for pulping, which can affect the market value of fiber resources. The actual market values of wood and fiber resources are determined by shifting patterns of resource abundance and overall demand. This article describes various categories of fiber resources used for pulp and paper products, factors influencing their utility and relative market values, and trends in fiber resource supply and demand.

Pulping Processes

Understanding the utility and value of pulp and paper fiber resources begins with an understanding of how fiber resources are converted into products of value to society through modern pulping and papermaking processes. Pulping generally refers to various industrial processes used to convert raw plant materials or recycled paper into a fibrous raw material known as pulp, which is used primarily to make paper or paperboard products (and, to a smaller extent, other products derived from cellulose such as synthetic rayon). Plant materials such as wood, straw, or bamboo generally contain cellulose fibers together with lignin, a natural binding material that holds together cellulose fibers in wood or in the stalks of plants.

Although pulping and papermaking are ancient technologies, commercial pulping and papermaking processes have advanced significantly since the eighteenth century, toward more capital-intensive and increasingly large-scale automated production processes, with continued emphasis on improvement in product uniformity and quality as well as production efficiency. Modern society places considerable value on uniformity of quality and efficiency in production of pulp, paper, and paperboard products. At the present time, most pulp produced worldwide is wood pulp (pulp made from wood that is either harvested from trees or obtained as wood residues or byproducts from other wood-manufacturing processes).

Wood pulps are categorized by pulping process, with two major categories known as chemical and mechanical. Actually both types of processes typically use a combination of chemical and mechanical means to reduce wood into pulp. Chemical pulping relies mainly on chemical reactants and heat energy to soften and dissolve lignin in wood chips, followed by mechanical refining to separate the fibers. Mechanical pulping often involves some pretreatment of wood with steam heat and/or weak chemical solution, but relies primarily on mechanical equipment to reduce wood into fibrous material by abrasive refining or grinding.

The chemical pulping processes involve reaction or 'cooking' of wood chips with a solution of chemicals in a heated digester vessel for an extended period (up to several hours or more) followed by mechanical refining. Principal chemical pulping processes include the alkaline sulfate (or kraft) pulping process, acid sulfite, and semichemical pulping. Mechanical pulping processes include thermomechanical pulping (TMP), chemimechanical (CMP), chemithermomechancial pulping (CTMP), and groundwood pulping. The TMP, CMP, and CTMP processes involve reduction of wood chips into pulp in mechanical disk refiners, usually after pretreatment of chips with steam and/or weak chemical solutions. The older groundwood process involves grinding of wood bolts (small logs) into pulp against a grindstone.

Mechanical and semichemical pulps typically have much higher yield than kraft or sulfite pulps, as measured by weight of pulp produced per weight of wood input (over 90% yield for mechanical pulps and over 80% for semichemical pulp, versus 50% or less for kraft or sulfite pulps). However, kraft and sulfite pulps usually have higher market value because they have higher costs of production and because their fiber quality is usually better and more uniform, with generally less lignin or other wood constituents and proportionately more cellulose fiber and more intact fibers. Kraft and sulfite pulps can be more readily bleached to yield high brightness or whiteness that is desirable in many paper products, and kraft pulp typically produces a stronger sheet of paper or paperboard.

After wood pulp, the second largest and growing share of pulp produced worldwide is pulp made from recycled paper or paperboard. In the recycling process, recycled paper or paperboard is rewetted and reduced to pulp principally by mechanical means, followed by separation and removal of inks, adhesives, and other contaminants, through chemical deinking and mechanical means. Because the fibers in recycled paper and paperboard have been fully dried and then rewetted, they generally have different physical properties than virgin wood pulp fibers (for example, microfibrils on the surface of recycled fibers tend to be collapsed), and a portion of the fibers tends to be broken or damaged because of recycling. Without further processing, these differences in fiber properties would contribute to lower product quality (e.g., weaker interfiber bonding and hence lower strength in recycled paper or paperboard products), while contaminants contribute to lower and less uniform product quality (lower brightness, sheet defects, etc.).

To a large extent modern processing technology can compensate for inherent disadvantages of recycled fiber, but additional processing results in additional costs. Modern mechanical refining is used, for example, to resurrect surface fibrils, and modern papermaking machines and coatings can enhance sheet strength and surface properties, while the efficiency of contaminant removal has been improved by modern deinking systems. The market value of recycled fiber is influenced by intrinsic challenges associated with producing uniform product quality (contaminant removal and differences in fiber surface properties), challenges that can be overcome, but at a cost.

A smaller but still substantial volume of pulp is made from non-wood plant fibers, including agricultural fibers such as straw and other plant fibers such as bamboo, bagasse (residual of sugarcane refining), and annual fiber crops such as kenaf. In general, non-wood plant fibers are more costly to collect and process than wood fiber in regions of the world where wood supplies are adequate, and thus pulp is produced almost exclusively from wood fiber in most regions of the world. However, substantial quantities of non-wood pulp are produced in regions of Asia and Africa where wood fiber is relatively less abundant and non-wood fibers are available. **Table 1** summarizes estimated global pulp production in the year 1999 by principal category, and by major region.

The estimated 1999 worldwide total pulp production was 304 million metric tons (including pulp from recycled fiber). This compares to worldwide paper and paperboard output of 315 million metric tons in 1999. There is a difference between the output tonnages because many paper products contain the added weight of coatings, additives, or fillers, such as clay coatings on coated printing papers. In addition, there are some minor losses of pulp in conversion into paper or paperboard, and also a small fraction of pulp production (around 1%) goes to products other than paper or paperboard

Table 1 Global pulp production by category and region, 1999, in million metric tonnes

Region	*Chemical wood pulp*[a]	*Mechanical wood pulp*[b]	*Recycled pulp*[c]	*Nonwood pulp*[d]	*Totals*
Europe[e]	28.3	14.6	36.3	0.5	79.7
North America	66.1	16.3	35.7	0.2	118.3
Asia[e]	17.8	2.3	44.9	15.2	80.2
Australia and New Zealand	1.0	1.2	1.7	0.0	3.9
Latin America	9.9	0.4	6.9	1.1	18.3
Africa	1.7	0.3	1.3	0.7	4.0
World totals	124.8	35.1	126.9	17.7	304.4

[a] Chemical pulp includes sulfate (kraft), sulfite, and semichemical pulp.
[b] Mechanical includes thermomechanical, chemithermomechanical, and groundwood pulp.
[c] Recycled inferred from paper consumed for recycling, adjusted for yield estimate ($\sim$88%).
[d] Nonwood includes pulp from straw, bamboo, and various agricultural plant fibers.
[e] Data for Europe include all of Russia; data for Asia include all of Turkey.
Source: International Fact & Price Book (2001) Brussels, Belgium: Pulp & Paper International (PPI)/Paperloop.

(such as dissolving pulp used to produce rayon or other cellulose synthetics).

Papermaking

The utility and value to society of paper or paperboard products depend on their physical properties, such as the strength of paperboard used in corrugated containers, the softness and absorbency of tissue paper, or the smoothness and printability of paper used for printing or writing. Papermaking, the process of making paper or paperboard products from pulp, has been described classically as a felting process, in which a mat of randomly distributed pulp fibers is formed and then pressed into a sheet and dried. Variation in modern methods of sheet forming, intensity of pressure and energy applied in sheet pressing, and other process variables strongly influence physical properties of the finished sheet, which can range from the soft and absorbent properties of modern facial tissue to the rigid strength properties of modern containerboard.

Products of a felting process derive strength, integrity, and other physical properties differently than other common fiber-based products, such as woven products (e.g., textiles) where intertwining of fibers into threads and weaving of threads into fabric provide strength and integrity, or composite fiber products (e.g., fiberglass) where an adhesive or bonding agent combines with fibers to provide strength and integrity. The strength and integrity of finished paper or paperboard products depend on random interlacing and weak (nonchemical) bonding among fibers, and this is influenced by the papermaking process and by the inherent properties of individual pulp fibers, such as fiber length, flexibility, and fiber surface properties. Other paper properties such as sheet smoothness and printability are also influenced by fiber properties, such as the length and stiffness of individual fibers.

There is substantial variation in fiber properties among different plant species, and different types of pulp fibers have distinctly different physical characteristics, which influence the quality and utility of fiber resources in papermaking. For example, wood fibers from softwood (coniferous) trees are generally longer and more flexible while wood fibers from hardwood (deciduous) trees are generally shorter and more rigid, properties that tend to give quality advantages of sheet tensile strength to softwood fibers but sheet smoothness and printability to hardwood fibers. Chemical pulps generally afford stronger and more uniform sheet properties than mechanical pulps, and chemical pulps are more easily bleached to a high degree of whiteness or brightness, but chemical pulps generally have lower yield and are more costly to produce. Pulps made from recycled paper are generally associated with some degradation of fiber properties or more fiber breakage relative to virgin fibers, and use of recycled materials also introduces contaminants (inks, adhesives, etc.). Variations in quality and characteristics of fiber resources can thus substantially influence the market value of various fiber resources.

Paper and paperboard products serve several primary categories of end uses, each of which subtends a fairly unique range of functions and product requirements. Primary end uses for paper and paperboard include: (1) printing and communication, with requirements for sheet smoothness, brightness, and printability; (2) packaging and wrapping, with requirements for strength and protection at the most affordable cost; and (3) sanitary products with requirements for absorbency, bulk, and softness. Although these product characteristics depend directly on properties of individual fibers and the source of fiber raw material, they also depend on characteristics of the papermaking process.

The physical properties and hence the utility and value of paper or paperboard products can be greatly enhanced or influenced by the papermaking process, or by subsequent processes of sheet coating or finishing. In some cases this can partially or wholly overcome inherent limitations of certain fiber resources or pulp categories. The techniques used in sheet forming, pressing, and drying can influence properties such as sheet strength and smoothness. For example, softwood fiber was historically preferred in products where sheet strength was highly valued, such as in linerboard (paperboard used in corrugated boxes) because the longer and more flexible softwood fibers inherently provided more interfiber bonding and sheet strength. However, advances in sheet pressing and drying technology (higher-intensity pressing, extended presses, and multilayer forming) have significantly improved interfiber bonding and thus advanced the strength properties of linerboard made from recycled fiber and even hardwood fiber.

Other advances in sheet forming, pressing, and drying have enhanced physical properties such as softness and absorbency in tissue paper products, while the smoothness of printing paper has been improved by additional press finishing or supercalendering. Likewise, applications of coatings, pigments, and fillers have enhanced the quality and economy of printing, publishing, and packaging paper products. With advances in papermaking technology, improvements in product quality and uniformity have been achieved while expanding the use of lower-valued fiber resources.

Fiber Markets

Demands for pulp and paper fiber resources are derived from society's dependence on paper, paperboard, and related products for human welfare and prosperity. Society has come to depend on paper and paperboard products for many purposes integral to human welfare and prosperity, including education, information storage, and product advertising (in pages of books, magazines, catalogs, newspapers, and countless other forms of printed media or written communication), protection, transportation and security of goods in transit and in storage (in corrugated boxes and shipping containers, food packaging, and an enormous variety of other packaging and industrial applications), and protection of human health and sanitation (via tissue and sanitary paper products).

Although there is a direct correspondence between demands for pulp and paper fiber resources and the demands for paper and paperboard, there is not such a direct correspondence between trends in value or prices of fiber resources and trends in paper or paperboard commodity prices. **Figure 1** illustrates, for example, historical trends in the US average real price indexes for pulpwood, recovered paper (wastepaper recovered for recycling), and paper and paperboard commodities.

As shown in **Figure 1**, the real price index for paperboard commodities increased in the 20-year period from 1982 to 2002, ending the period up by about 25%. Likewise, the real price index for paper

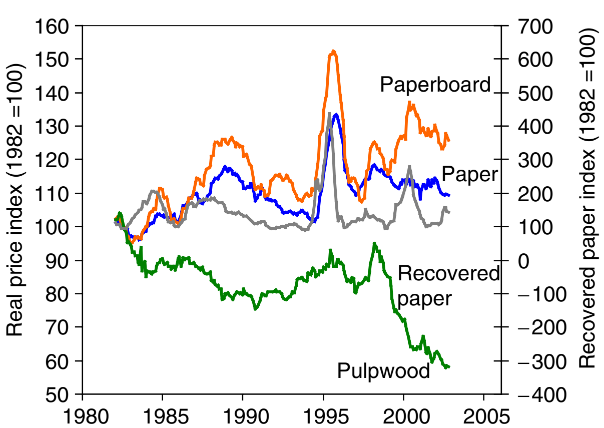

Figure 1 US real price indexes for pulpwood, paper, and paperboard, 1982–2002. Paper, paperboard, and pulpwood indexes plotted on left axis, recovered paper index plotted on right axis.

commodities increased over the same period, ending the period up by about 10%. The real price index for recovered paper (wastepaper recovered for recycling) was much more volatile (plotted against the right axis in **Figure 1**), although trends in the price index for recovered paper generally followed the trends for paper and paperboard over the same period, and also ended the period up by more than 40%. The real price index for pulpwood exhibited considerably different behavior over the same period, and by the end of the period had declined by more than 40%. The variation in price behavior among these different indexes reflects the role of different market forces influencing market prices.

The variable price history of paper and paperboard commodities is primarily a function of variation in product demands in relation to available production capacity (the output capacity of paper and paperboard mills). To some extent there is a reflection of trends in fiber resource prices in the trends of paper and paperboard prices (**Figure 1**), but the variation in paper and paperboard prices is more strongly influenced by variation in demands for paper and paperboard commodities and by capacity utilization. Paper and paperboard commodities are used widely throughout society in virtually all sectors of the economy – domestic, institutional, commercial and industrial. Thus the trend in overall demand for paper and paperboard tends to be correlated with cyclical trends in broad indicators of economic activity, such as overall industrial production and per capita gross domestic product (GDP). The production capacity of mills that produce pulp, paper, and paperboard commodities establishes the short-run supply potential, with actual production varying in response to market demand. The ratio of actual production to available capacity (capacity utilization ratio) is a key determinant of product prices, with prices tending to be high when capacity utilization is high and low when capacity utilization is low.

The market value or price of fiber resources also tends to be influenced by the demand and price situation for paper and paperboard, and this has been particularly true for recovered paper prices (**Figure 1**). However, there are other important market forces that influence the supply of fiber resources, and thus the trends in market value for fiber resource do not precisely follow the trends in paper and paperboard prices. Indeed, for pulpwood in the USA (and in some other regions) the price trend has been opposite to the trend for paper and paperboard prices (i.e., downward as opposed to upward, as shown in **Figure 1**). Fiber resource supply tends to influence the market value of fiber resources as much as fiber resource demand, and fiber resource supply varies over time depending on such factors as the periodic volume of timber growth and availability for harvest, the area of forests or plantations managed for pulpwood production, and trends in recovery of wastepaper for recycling.

In the USA, for example, in the period between 1982 and 2002 there was a significant increase in the recovery of wastepaper for recycling, particularly during the period from the late 1980s to the early 1990s, reflected in a period of relatively depressed real prices for recovered paper (**Figure 1**). By the mid-1990s, however, the utilization of recovered paper had increased substantially, both in domestic paper and paperboard mills and in foreign mills that were increasingly importing recovered paper from the USA. Thus, in the mid-1990s the increased demands for recovered paper (domestic and export) helped to stimulate a significant spike in recovered paper prices. However, with the rapid escalation in US recovered paper prices, export demands subsided and prices rapidly declined. The mid-1990s' price spike in recovered paper markets also coincided with a price spike for paper and paperboard commodities, induced in part by speculative purchasing of market pulp and by relatively strong demands for paper and paperboard during the mid-1990s. Pulpwood prices also showed some firmness in the early to mid-1990s, but pulpwood prices in the USA were eventually dominated by expanding supplies of timber with expansion and maturation of pulpwood plantations, particularly pine plantations in the South USA, where millions of additional hectares of pine plantations were established in the 1980s and 1990s. In addition, the increased use of recycled fiber (which more than doubled in the USA during that period) also tended to offset growth in pulpwood demand and dampened the trend in real pulpwood prices.

Trends in Fiber Resource Supply and Sustainability

Although global demands for pulp and paper fiber resources have been increasing and are expected to continue increasing in the future, the available supply of fiber resources has likewise been increasing, and both supply and demand appear increasingly sustainable into the foreseeable future. In part this is because consumption of paper and paperboard products is not rising exponentially in developed countries such as the USA, but rather consumption is decelerating (continuing to grow but at a slower pace over time) with declining consumption per unit of GDP. Also, there remains vast potential to increase output from fiber plantations worldwide, and there is potential to increase paper and paperboard recovery for recycling. Indeed, in recent years (since the mid-1990s) pulpwood and recovered paper prices have been subsiding globally.

In the USA, which produces and consumes more pulpwood by far than any other country, wood pulp production declined by 12% while consumption of pulpwood at wood pulp mills declined by approximately 15% from the mid-1990s to 2001. Real prices of softwood pulpwood in the USA also declined in recent years, with prices in the South USA (the principal production region) declining to the lowest recorded levels in modern history (several decades over which pulpwood prices have been surveyed and reported). Pine plantations in the South have the potential to supply significantly greater volumes of fiber in the future, although expansion of supply may be inhibited by low prices and limited growth in demand.

Although paper and paperboard production and demands for fiber resources are going up in other developing regions of the world, such as in Asia and Latin America, global development of fiber resources is keeping pace with capacity expansion. China, for example, is experiencing fairly rapid economic growth, with expanding production capacity in modern papermaking facilities, but mills in China are able to rely in the near term on expanded wood pulp production in East Asia (in countries such as Indonesia) as well as global supplies of market pulp and recovered paper. For the future China can also rely on indigenous sources of fiber supply, having established a larger area of tree plantations than any other country.

Globally, wood fiber supply has expanded with the expansion of fast-growing plantations of species such as pines, eucalyptus, and acacia. Although plantations have in some areas displaced native forests, managed plantations account for only a small fraction of forested land area (e.g., only 6% in the USA, for example). Plantations generally have a potential to supply a much greater volume of wood fiber per unit of land area than unmanaged or native forests, and thus the use of a small fraction of land area for plantations can offset the harvest of pulpwood on large areas of forest. Environmental certification of forests and forest plantations has expanded globally over the past decade and is now common in many areas of the world, with increased emphasis on preventing illegal logging and encouraging sustainable forestry practices. Managed plantations are an integral part of ensuring the sustainability of forest resources in the future. Globally, plantations are expected to increase their share of total wood production from around 20% to upwards of 50% by 2050.

The recovery and use of paper for recycling have been on the increase, as the proportion of fiber obtained by recycling has been increasing. Globally, recycled fiber accounts for well over 40% of pulp fiber (**Table 1**), and some countries have achieved much higher rates (over 50% in Japan and around 60% in Germany). Although product needs and capacity growth may constrain the use of recycled fiber in some cases, there is still the potential to expand its recovery and use in the future.

See also: **Papermaking**: Overview; The History of Paper and Papermaking; World Paper Industry Overview. **Pulping**: Environmental Control.

Chip Preparation

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Introduction

Wood chips used in pulp mills are small, engineered pieces of wood cut from logs and wood pieces left over from the manufacture of solidwood products such as lumber and plywood. The target dimensions of a chip are usually 4–6 mm thick, 15–20 mm in length and width (**Figure 1**). This is the size range that will allow most batch and continuous chemical and mechanical pulping systems to reduce the wood uniformly to individual fibers and fiber bundles. There is no ‘perfect chip’ since wood variability does not allow consistently making the same chip over and over. There is an ideal chip size distribution that matches the needs of the mill’s digester(s). This article will describe the process of making chips that meets the specifications of pulp mills. The basic chip production processes are:

Figure 1 Typical pulp chips sampled after going through the chip screen system.

- debarking of logs increases pulp yield and cleanliness
- chipping of logs and wood products residuals makes small particles (called chips) in as uniform size distribution as possible
- chip screening removes fines and oversize chips to improve pulping uniformity
- prevention of contamination of chip flows with metal, rocks and especially, plastic
- chip transportation and storage systems receive, store, convey, and meter chips without damaging them
- quality control programs monitor chip production and deliveries.

Mill Layout

The area in the mill that logs and chips are received, stored and processed is called the woodyard. The building or structure that contains debarking, chipping, and screening equipment is the woodroom. In cold climates, almost all the functions are contained in heated buildings to prevent freezing of equipment and people. In more temperate zones, only a sheltering roof is used to protect the chipper and screen from rain.

The goals of the woodyard and woodroom organizations are to:

- produce chips that are not only the right size for the mill’s digesters, but also have very low short-term variability (i.e., hourly and daily)
- deliver chips to the pulp mill that have little or no contamination and a bark content that is below the mill’s tolerance level
- manage the inventory of logs and chips at target levels that do not create a loss in chip value from deterioration in storage
- monitor the quality of chips received at the mill, made in the wood room and delivered to the digester with sampling and testing frequency consistent with the use of the data for decision-making.

Debarking

Bark is essential for a tree’s growth and health. It is a protective layer around the wood that resists drying, attack by molds, wood staining and rotting fungi,