Eucalypts are a major source of raw material for the pulp and paper industry. Breeding efforts to improve the quality of eucalyptus have been ongoing since the late 1960s [1]. Over the last four decades, advances in genetics, plantation culture, and clonal management techniques have substantially improved the productivity and quality of clonal plantations have attracted private industry investment in eucalypt plantations. Currently, only a handful of species or hybrids are used in plantation efforts. Many more species are being evaluated to either enhance fiber properties or expand the range of eucalypt plantations. Eucalyptus plantations are frequently planted on non-forested land and may be used, in part, as a means of conserving native forests while allowing the production of high quality fiber for economic uses. Finally, eucalypt plantations can provide significant carbon sinks, which may be used to help offset the carbon released from burning fossil fuels. The development and expansion of eucalypt plantations represents a substantial revolution in pulp and paper manufacturing.

Application: By understanding the breeding and clonal developments that have occurred in the past and the results of those developments, the industry may be better equipped to rapidly advance the next stage of eucalypt progress.

Eucalypts can yield commercially desirable interspecies hybrids. Probably the most common one in commercial application today is *E. urograndis* (*urophylla x grandis*). Hybrids are used in most commercial plantations in Brazil, South Africa, and the Congo [1]. Typical breeding programs have selected for high volume yield within the plantation, resistance to major pests and diseases, high pulp yield, and reasonably high bulk density [1]. Recently, breeding programs have also attempted to produce raw materials for pulping that would produce pulps with improved key papermaking properties such as bulk, opacity, formation, softness, porosity, smoothness, absorbency, and dimensional stability [7].

In addition to pulp and paper and energy uses, eucalypts are being used extensively in other forest-based industries. Eucalyptus have been used successfully in Brazil to produce charcoal for smelting iron and steel and to produce wood panels, including low-density and medium-density fiber board, oriented-strand board, and plywood. Value-added wood products such as doors and windows and furniture are also produced from plantation eucalyptus [8].

Significant effort is being expended to extend the range of operational eucalypt plantations. These efforts include selective breeding programs for improved cold tolerance and the introduction of more cold-hardy species such as *E. nitens*, *E. smithii*, *E. maidenii*, *E. camaldulensis*, *E. ampifolia*, *E. dunnii*, and *E. benthamii*, among others [1,9,10]. These programs are focused primarily on South Central China [10], higher elevation areas in Brazil [9], and in the southern United States, from Florida to Texas [11,12].
FIBER SUPPLY

The expansion of eucalyptus plantations into temperate regions and subtropical areas prone to freezing temperatures has not always been easy. As in many tropical regions, there is public concern that monoculture plantations will replace native stands with potentially invasive, non-native species and that the extensive use of hybrid or genetically-modified trees would have significant environmental and ecological impacts in the new areas being opened for eucalyptus plantations [13,14]. Excessive water use is an additional potential concern with eucalyptus plantations [13,14]. Comprehensive research has shown many of the environmental concerns to be relatively minor and identified management practices that will minimize or eliminate the risks for negative impacts. Many environmentalists are now touting the virtues of eucalyptus plantations as a means of protecting native stands, thus maintaining biodiversity, and as a potential carbon sink capable of significant greenhouse gas sequestration [15]. Eucalyptus is also being grown as a source of short rotation, carbon neutral biomass for energy and chemical production [16].

BREEDING AND EXPANSION OF EUCALYPTUS PLANTATIONS

Breeding programs for eucalyptus started in the late 1960s in Brazil, Portugal, and the Congo and spread to Thailand in the 1970s [17]. The first reports of provenance trials of eucalyptus as an exotic species were submitted to the Food and Agriculture Organization (FAO) of the United Nations and covered trials starting in 1966 using seeds collected in Australia during the early 1960s. Extensive progress has been made in breeding eucalyptus for pulp and paper plantations since that time. In addition to traditional selective breeding, eucalyptus lends itself to inter-specific hybridization programs. Eucalypts are quite adaptable to inter-specific hybrid formation. Several of the species are genetically close and frequently produce natural hybrids. Naturally occurring crosses in arboreta and plantations have produced vigorous and well adapted hybrid land races. With improved clonal techniques, large forest product companies in many countries were able to rapidly develop clonal plantations of superior hybrid trees. Continued tree improvements for yield, physical properties, and other desirable characteristics for plantation use are occurring through the current practices of flower induction and controlled crossings.

Developments in plantation methods have also resulted in increases in wood production and reduced rotation times. The use of coppice regeneration was first reported in the Congo in 1973 [18], and Aracruz was widely applying the technique in Brazil in the mid-1970s [19]. From there, improvements in the rooted-cutting system and the development of in vitro culture made cloning a common practice for eucalypts [20]. Further clonal efforts included the development of the mini-cutting system, which integrates in vitro and in vivo multiplication in an intensive manner using auxiliary sprouts collected on vitro-plantlets and cultivated via indoor hydroponic systems [21].

With the rapid pace of superior tree development and improvements in plantation and seedling development, there is an ongoing debate about the optimal use of established clones and coppicing systems in eucalypt plantations. Continued usage of the same clone via the coppicing process might delay the introduction of superior species into the plantation process [22]. The use of newer hybrids instead of established clones might be more desirable as a means to make rapid gains or maintain or increase genetic diversity in the clonal program.

Reports from Morocco suggest production of between 100 and 200,000 crosses of E. grandis and E. camaldulensis per year [23]. Chile is satisfying about 40% of its seed requirements with controlled pollination of E. globulus and E. nitens [24]. The results of these large-scale crosses are plantations with improved production and the development of “superior trees” for next generation clonal production. Crossing on a large scale is now the common practice, facilitated by flower induction techniques and controlled pollination [25,26].

According to a 2005 FAO survey, eucalyptus is the most valuable and widely planted hardwood in the world, with more than 18 million hectares (ha) in cultivation in 90 countries [27]. In 2009, eucalypt plantings filled more than 20 million ha [28]. Eucalypts are grown extensively as exotic plantation species in tropical and subtropical regions throughout Africa, South America, and Asia, and in more temperate regions of Europe, South America, and North America. They are grown as naturally occurring forests and as managed plantations in tropical, subtropical, and temperate regions of Australia. India had 8.0 million ha of mostly low productivity plantations. Brazil had 3.0 million ha of mostly intensively cultivated plantations in 2000. The Brazilian plantations achieved average productivities of 45-60 m³/ha/year, with some areas in Brazil averaging 100 m³/ha/year [29].

Of the 12.75 million hectares of eucalypt plantations reported to FAO in 2005, about 12 million hectares were classified as productive forest [30]. Since that time, productive plantation land has expanded in Brazil and China [31]. Productive plantations were reported to exist in only 12 countries. Eucalypt planting has intensified in recent years and continues to do so, especially in tropical countries. In these regions, rotations as short as 5 years, with yields as high as 70 m³/ha/year, have been reported. Commercially planted eucalypts are also reported in the Congo, Indonesia, Malaysia, Thailand, France, Portugal, New Zealand, and the United States. China is currently committed to expanding commercial eucalypt plantations at a rate of 3,500-43,000 ha/year. Plantation area in southern China has more than tripled, from 325,000 to 1.1 million ha in 20 years. Extensive effort is being conducted in China to develop cold tolerant eucalypt species for use in higher elevation plantation areas [10].

RISKS ASSOCIATED WITH EUCALYPT PLANTATIONS

One potential risk associated with intensive plantation development is a reduction in soil fertility. However, eucalyptus plantations are frequently established on lower quality land that has been degraded by poor harvesting practices, farming,
and ranching [10,13]. Phosphorous and nitrogen deficiencies may be overcome by fertilization techniques typically used in agriculture during the rotation and at the time of replanting.

Erosion and soil degradation or sterilization are two more concerns that have been raised against the formation of exotic eucalyptus plantations. Several species of eucalyptus have a high content of oils in their leaves and bark, which slows the decomposition of tree litter. It is true that eucalyptus litter does degrade somewhat slower than does litter from some other trees, but it does decay in a reasonable timeframe and contributes toward long-term organic matter enrichment [33]. Additionally, eucalypt oils have not been found to inhibit other forms of herbaceous growth. In fact, one potential problem with eucalypt plantations is that intensive weeding and weed control is required during the first 1-2 years of the plantation life to prevent weeds from invading and dominating the plantation at the expense of the eucalypt seedlings [32].

Eucalypt plantations are often grown on land that has been degraded by other sources [33]. Limited fertilizer application tends to work well with many eucalypt species resulting in vigorous plantations on land that has been devoid of other uses. Eucalyptus are often planted on lands that have already experienced significant erosion and are often used to revitalize areas of limited productivity. As with all types of plantations or agricultural applications, some amount of thought and planning must be used to ensure that erosion does not become significant; however, this is not an aspect specific to eucalyptus but rather of the use of accepted agricultural and silviculture practice.

Water use is another potential issue associated with intensive eucalyptus plantation development. In some areas, eucalypt plantings have been used to mitigate marshy ground. Most fast growing species consume more water than slower growing species, but eucalyptus is also highly adaptable to drought. Eucalyptus can reduce its water uptake as the soil dries out, controlling its water loss by regulating the opening of stomata, the microscopic pores on the underside of their leaves. In general, eucalypts use less water per kilogram of biomass production than other agricultural applications. For instance, eucalypts use about 785 kg of water per kilogram of biomass, whereas potatoes require about 1000 kg of water per kg of biomass [10]. Relative to most forest tree species, eucalypt species typically exhibit high water use efficiency.

Despite the potential high water consumption, eucalyptus is considered to be a fire hazard. Eucalyptus contain a high amount of oils and extractives, which are highly flammable [34]. Oils vaporized from some plantations have been known to create a blue haze in the air above the forests, leading to the name of blue gum trees for some species of eucalyptus. There are recorded instances of wildfires where trees have exploded. The oil content also slows the decomposition process of tree litter, further increasing the potential for fire. In intensively managed plantations, this is not a particular problem because the trees are harvested within 5-7 years and the litter is plowed back into the soil. This litter is typically composed of bark, leaves, branches, and seedpods [10]. Eucalyptus forests in California have been cited as contributory factors in the frequent wildfires in the state, but no extensive documentation is available to prove this hypothesis [35]. Recent modeling studies suggest that eucalyptus plantations with limited undergrowth present no more of a fire danger than do southern pine plantations [36].

**INSECT AND FUNGAL SUSCEPTIBILITY**

Even though eucalyptus are exotic species, monoculture plantations could be subject to local or introduced pests and diseases. Insect and fungal contamination can significantly reduce wood production in infected plantations. Insect infestation has been documented all over the world. For example, *Helopeltis sboutrdeni* (mosquito bugs) has been shown to cause severe damage to young plantations in the Congo [37]. *Phoracanta semipunctata* (eucalyptus long-horned borer) attacks drought-stressed trees in *E. globulus* plantations in the Mediterranean area and has been reported to have spread into California [38]. *Goniiperus scutellatus* (eucalyptus snout beetle) has been shown to defoliate commercial species in Australia, South Africa, and Spain [39].

Fungal attack has also been documented. *Cryptobacter cubensis* has been shown to cause cankers on tree trunks [40]. *Puccinia psidii*, *Cylindrocladium spp.*, and *Coniothirriun spp.* have been shown to cause rust in nurseries [41]. *Myosphaerella juvens* causes significant damage, including defoliation to juvenile species [42].

In spite of the myriad of insect and fungal pests that are able to attack exotic eucalypt plantations, typical control strategies such as chemicals application, hybridization, and selective breeding programs have been able to produce robust plantations, which have allowed eucalyptus fiber to dominate the market for short fiber pulp. The use of pest and disease resistance clones has been a powerful tool in controlling many of these potential pests, even though the genetic base is reduced through clonal application [43]. Brazil and other regions have been extremely successful in the use of natural biological controls to reduce the impact of disease and insect attack on eucalyptus plantations [44-46]. The creation of transgenic, genetically modified organism (GMO) eucalyptus has also been demonstrated, in limited and contained studies, as another potential method of controlling against susceptibility toward parasite attack [47,48]. However, legislation and public opinion [49,50] would need to be ensured if the GMO approach was adopted on a commercial scale.

**BIODIVERSITY**

The objective of eucalyptus plantations is to supply a maximum volume of wood per hectare, not to increase the biodiversity of a specific location. Ironically, the use of intensively grown eucalypt plantations has been found to improve the biodiversity of the surrounding areas. Specifically, eucalypt plantations are frequently planted on savannahs or on abandoned pasture and agricultural land, which reduces...
the pressures on natural forests. Sustainably managed plantations provide a high-quality wood resource with minimal environmental footprint, while protecting biodiversity by providing an alternative source of wood supply to the harvesting of native forest [51]. Intensively grown eucalypt plantations reduce the area of forest required to service active industrial needs such as fuel production and pulpwood for paper mills. Thus, pressure is reduced on natural stands, allowing for industrial and human use of the forest and continued biodiversity.

Eucalyptus is well known as an effective reforestation tree species because of its fast growth and high adaptability to various environments. In the specific area of the eucalypt plantation, the indigenous plant species are reduced after about 2-3 years of intensive plantation growth, when crown closure is achieved. The indigenous plant species in most of the eucalypt plantations studied had greater plant diversity than those of other exotic species plantations, mainly because of the unique eco-physiological characteristics of eucalyptus and the plantation design and harvesting techniques, among which human factors played leading roles [52].

**CARBON SINKS**

Eucalyptus plantations have been cited as potential sites of carbon storage [53-55]. Sequestration of carbon in forests and wood products helps to offset emissions of carbon dioxide to the atmosphere that can result from deforestation, forest fires, and fossil fuel emissions. With the development of carbon markets within the United States, trees are being used as a method of carbon sequestration and in developing markets as carbon sinks [56]. In addition to the above ground woody biomass of trees, root biomass is also a contributor in carbon sequestration. The use of eucalypt plantations as sites for carbon sequestration has been modeled and verified [57]. Studies have been performed that determine the optimal rotation time for coppiced and non-coppiced plantations, taking carbon sequestration into account [58].

Coppiced plantations are formed when stumps from harvested trees are allowed to selectively sprout and grow [59,60]. The best sprout is selected and all other sprouts are cut off from the stump. This single sprout will then rapidly develop into a new tree, with the advantage of having an already developed root system. Coppice-managed plantations may undergo two to as many as five growth and harvest cycles prior to the land being replanted with new seedlings or clones. After a few growth and harvest cycles, the growth process slows down. At that point, it is no longer economical to continue growing trees on a coppiced plantation and the land is replanted with improved seedlings or clones. Non-coppiced plantations are replanted after one growth and harvest cycle.

Studies have been conducted that show eucalypts are not as good at storing carbon as are nitrogen-fixing trees [61]. Studies of carbon storage were conducted in 17-year-old multispecies plantations (Albizia and Eucalyptus) planted on old sugarcane fields. These inter-planted stands were compared with stands of the two pure species. Above ground tree carbon accumulation showed a synergistic response to increasing a percentage of Albizia, with the mixed stands having more tree carbon than pure stands of Eucalyptus or Albizia. In addition, areas of pure albizia sequestered about 20% more carbon in the soil than did the pure eucalyptus stands [62]. One theory is that nitrogen added to the soil by the albizias might inhibit the decomposition of old, sugarcane-derived soil carbon relative to eucalyptus. Nitrogen additions also might decrease carbon turnover in the field [62].

**RECENT DEVELOPMENTS**

Recently, a portion of the genetic development work has shifted from increased production per hectare toward improved end use properties [63-69] and cold and frost tolerant species [3,9-11]. A significant amount of work has focused on density improvements and the relationship between wood density, pulp yield, and pulp quality [65,66,68]. Ongoing scientific and technical advances with eucalyptus fibers are being directed at modifying fiber properties for specific paper properties [70].

Two distinctly different approaches have been used to extend eucalypts into frost prone areas. One is the selection of naturally frost tolerant species [3,9]. The other is the use of genetic manipulation using traditional intra-specific and inter-specific breeding and hybridization to improve frost tolerance [71-73]. Both methods are currently being used in the southeastern United States.

**CONCLUSIONS**

The use of eucalyptus plantations to supply short fiber demand has grown substantially since the initial exotic plantation trials in the late 1960s. It has been projected that eucalypts will supply more than half of the short fiber market pulp demand in 2015. Eucalyptus has been shown to be a favorable species with respect to reforestation of depleted land. Eucalyptus plantations have relatively low fertilizer requirements and high productivity rates. These plantations provide a good method of carbon sequestration and contribute to the conservation of natural forests by limiting the land area required to support commercial development, thus actually contributing to biodiversity at the landscape scale. Eucalyptus plantations have been identified as potential sources of fuels production (both as firewood and as charcoal for iron production), value-added solid timber applications, hardboard and structural lumber production, and for pulp and paper applications. Eucalyptus has an extremely varied genus, which lends itself to genetic improvement and to intensified farming techniques. Recent efforts to expand eucalypts into colder regions have met with some success and show continued promise. From the humble beginnings in the early 1960s, eucalypt plantation development continues to attract multinational corporate interest and capital. Recent efforts to improve the volume of wood per hectare and improve the end product properties through genetic and
hybridization improvements are only enhancing the value of eucalyptus plantations. The development and exploitation of eucalypt plantations for economic and ecological gains has represented a true revolution to the short fiber supply for the pulp and paper industry. **TJ**

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*ABOUT THE AUTHORS*

The current work was conducted as part of a raw materials review prepared for the TAPPI 100th anniversary celebration at PaperCon 2015. Because eucalyptus fiber has rapidly become the predominant short fiber in the world, it was decided that a review of its past and development into the predominant short fiber was warranted. The current paper is simply a review so readers can better understand the history and development of the eucalyptus revolution. The paper sets the stage for the next steps in eucalyptus development.

Currently, a considerable amount of research and breeding effort is being expended to extend the range of viable eucalyptus plantations into frost-prone areas. Additionally, eucalyptus breeding efforts are focused on enhancing the papermaking properties associated with eucalyptus fiber. The current paper reviews the accomplishments to date that have helped make eucalyptus a predominant fiber source for papermaking.

So much material has been published about eucalyptus over the last 40 years that is was difficult to limit the review paper to a reasonable size. As such, significant limitations had to be adhered to during the writing. For example, nothing about hexi-uronic acid or bleaching eucalyptus was reviewed. With the multitude of eucalyptus species available, only nine are currently being exploited for extensive commercial application. The next steps are to continue working with the breeding programs to enhance the desirable papermaking and frost tolerant properties of some of the eucalypt species.

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