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Article

Scientific Basis for Sustainable Management of *Eucalyptus* and *Populus* as Short-Rotation Woody Crops in the U.S.

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Abstract: Short rotation woody crops (SRWC), fast growing tree species that are harvested on short, repeated intervals, can augment traditional fiber sources. These crops have economic and environmental benefits stemming from their capability of supplying fiber on a reduced land base in close proximity to users and when sensitive sites cannot be accessed. *Eucalyptus* and *Populus* appear to be genera with the greatest potential to provide supplemental fiber in the U.S. Optimal productivity can be achieved through practices that overcome site limitations and by choosing the most appropriate sites, species, and clones. Some *Eucalyptus* species are potentially invasive, yet field studies across multiple continents suggest they are slower to disperse than predicted by risk assessments. Some studies have found lower plant and animal diversity in SRWC systems compared to mature, native forests, but greater than some alterative land uses and strongly influenced by stand management, land use history, and landscape context. *Eucalyptus* established in place of grasslands, arable lands, and, in some cases, native forests can reduce streamflow and lower water tables due to higher interception and transpiration rates but results vary widely, are scale dependent, and are most evident in drier regions.

Keywords: biomass; eucalypts; poplar; certification; bioenergy; invasiveness; exotic; biodiversity; water; plantations

1. Background

Short-rotation woody crops (SRWCs) can be highly productive sources of fiber and energy feedstocks suitable for a variety of uses. SRWCs can be genetically diverse and can occupy a wide variety of sites not suitable for other crops [1]. It has been estimated that SRWCs could be planted on 24 million ha of marginal cropland in the U.S., with *Eucalyptus* and *Populus* (largely hybrid poplar) the two most widely planted genera with the greatest potential to contribute feedstocks for bioenergy and bioproducts [2,3].

Eucalyptus has been widely planted in Australia, Asia, South America, and Africa, with plantations established in the U.S. beginning in the mid-1800s [4]. Field trials in the 1970s in the South identified at least 8 *Eucalyptus* species potentially adaptable to local climate: *E. camaldulensis*, *E. benthamii*, *E. viminalis*, *E. macarthurii*, *E. grandis*, *E. robusta*, *E. saligna*, and the hybrid *E. urograndis* [5]. Additionally, *E. amplifolia* has been planted in Florida [6]. Many *Eucalyptus* species are highly productive with wood properties desirable for multiple uses, and the development of cold-hardy varieties may allow plantings across an expanded geographic range in the southeastern U.S. Hybrid poplar is also planted across a wide geographic area and is commercially deployed on over 10,000 ha in the North Central U.S., over 17,000 ha in the Pacific Northwest, and over 11,000 ha in the Mississippi River Valley [1]. This paper synthesizes relevant literature on sustainable management of SRWCs and the implications of their establishment in the U.S. for invasiveness, biological diversity, and water use.

2. Sustainable Management and Site Productivity

Short-rotation woody crops generally have lower resource requirements and more favorable environmental implications than intensive agricultural systems [7]. For example, converting annual agricultural crops to perennial herbaceous or woody crops has been found in a number of studies to enhance soil quality and C storage, and reduce erosion and nutrient losses via runoff and leaching [8–13].

Eucalyptus is adaptable to a wide range of soil conditions but, as with managed forests in general, limitations related to nutrition, water, and drainage must be overcome for it to achieve optimal growth [1,14]. Improved genetics and management have led to increases in productivity of up to three-fold for *Eucalyptus* in Brazil [15]. Site selection, spacing, site preparation that includes competition control, bedding and/or subsoiling on poorly drained sites, and alleviation of N, P, and micronutrient deficiencies with fertilizer are common practices used to sustain productivity [1]. Soil texture is a particularly important site factor influencing productivity due to its effect in regulating soil moisture [16]. Effects of genetic, site, and management factors on productivity of *Eucalyptus* tend to be additive, meaning that there is little interaction among them [17,18]. One study across five sites in South Africa found that practices such as stocking, fertilization, and weed control were more important for productivity than improved genotypes and matching of species and site [17]. However, the fact that

Eucalyptus species vary considerably in their suitability for planting in particular climates, regions, and sites and only a small number of species and their hybrids dominate commercial plantations suggests that correct selection of genotypes is also important [1,19].

Productivity of *Populus* varies widely across different climates and soil types [20]. As with *Eucalyptus*, soil texture has been identified as a key factor affecting productivity [21,22]. Control of competing vegetation, due to its influence on soil water and nutrients, and fertilization are particularly important management practices for sustaining productivity [21,23]. By contrast to some studies of *Eucalyptus*, highly significant site x clone interactions have been shown for hybrid poplar clones [24,25]. One study in the upper Midwest found both generalist genotypes with high productivity across the region and specialist genotypes with high productivity on specific sites [24].

3. Invasiveness

Invasiveness is a concern for introduced commercial species. Once introduced species spread beyond planting sites, control can be both expensive and ineffective [26]. Thus, assessment of invasiveness is critical. One of the best indicators of invasive potential is evidence that a species is invasive elsewhere. We review such evidence as it exists in this section for genera currently showing the greatest potential for commercial scale plantings in the U.S.

Although there is significant variation among species, the biological characteristics of *Eucalyptus* coupled with its high productivity under intensive management have raised questions about its potential invasiveness. *Eucalyptus* characteristics that may increase its potential invasiveness include rapid growth and maturation, adaptation to poor soil and variable conditions, evergreen character with no dormant period, high seed production, and dispersal of seeds via water [27–29]. However, field evidence suggests *Eucalyptus* species in general have been much slower to invade than would be predicted by their rapid growth and climate tolerance. This evidence includes a general lack of success as invaders in most circumstances, very slow rates of spread in its native range, and frequent observations of high mortality following seeding and planting [27,30–32]. Characteristics of *Eucalyptus* seeds, including the lack of dispersion through wind or animal vectors and protective capsules that reduce seed release in the absence of fire, likely reduce the risk of significant invasion [27,28]. Studies in Australia and South Africa have also shown that most seeds fall in close proximity to parent trees, limiting its potential spread [27,29,33].

In South Africa, many planted *Eucalyptus* species have been slow to invade [33–35] and have failed after planting [36]. *Eucalyptus* might be expected to spread easily in Australia, but this does not seem to be the case. Meers *et al.* [37] report that *Eucalyptus* seedlings were absent from 35-year-old *Pinus radiata* plantations adjacent to native *Eucalyptus* forest and that *Eucalyptus* seeds that could germinate were virtually absent from soil seed banks (see also [38,39]). Meers *et al.* [37] also report that over a 45 year span, abandoned farmland in Western Australia has been poorly colonized by Eucalypts. This inability to colonize even in Australia could be due to lack of mycorrhizal symbionts on abandoned farmland and in pine plantations, combined with poor seed dispersal [30,36,37,40].

Data on invasiveness of individual *Eucalyptus* species are limited and sometimes contradictory. *E. camaldulensis* is a widespread river course invader in South Africa, where it was planted along rivers and spread by water [41–43] and is almost universally naturalized (*i.e.*, having reproduction

sufficient to maintain its population) where it has been planted [43], including Florida [6]. *E. amplifolia* is not widely covered by surveys. Rockwood *et al.* [44] state that it is non-invasive in Florida, and Gordon *et al.* [6] describe it as naturalized there. No information could be located on *E. benthamii* or *E. urograndis* except for a study showing seeding failure of *E. urograndis* in Brazil [31].

E. grandis introduction to New Zealand failed [45], although Richardson and Rejmánek [46] list it as invasive in Asia, South Africa, and South America. Rejmánek and Richardson [43] classify it as naturalized in California, Florida, New Zealand, South Africa, and possibly Argentina and Nigeria, and Rockwood *et al.* [44] describe it as non-invasive in Florida. In a seeding study in Brazil, all *E. grandis* seeds that initially germinated in the field were gone by day 270 [31]. Gordon *et al.* [6] list it as naturalized in Florida. The inconsistencies described above no doubt result from the lack of clear criteria and absence of quantitative surveys until 2011.

E. macarthurii, *E. robusta*, *E. saligna*, and *E. viminalis* are generally considered non-invasive. *E. macarthurii* is not listed as invasive by Richardson and Rejmánek [46] but is naturalized in California, New Zealand, and possibly South Africa. *E. robusta* is listed as almost universally naturalized by Rejmánek and Richardson [43] but only invasive in Africa (not South Africa). *E. saligna* is one of the top three eucalypts planted in New Zealand [45] and is naturalized there, in Western Australia, Florida, and Hawaii as well as possibly in South Africa, Sri Lanka and Uganda [43] but is not listed as invasive by any of those sources. *E. viminalis* is listed as naturalized only in California, Hawaii, New Zealand and possibly South Africa [43].

Weed risk assessment tools have been used to develop qualitative invasiveness potential scores for individual species based on their biological properties. High scores from such tools indicate potential for invasiveness and a need for further study in context of an overall assessment of a species' potential benefits and risks as a SRWC. One of the most widely tested tools is the Australian Weed Risk Assessment (AWRA) system [47]. Other tools or processes also exist [48], but they are all similar and the AWRA tool will be the focus of this discussion.

The AWRA tool consists of a questionnaire covering topics such as climate suitability, response of the species to disturbance and fire, and whether the species is a pest elsewhere. Questions tend to focus on agricultural weeds, so some questions (e.g., response to plowing, short generation time) are not relevant to trees. Other questions relate to characteristics thought to enhance potential spread such as wind dispersal of seeds. Multiple tests of the AWRA tool [48–51] show that it generally has a high accuracy (>90%) in properly classifying current weeds or invasives. The tool poses a risk of circular reasoning, however, as existing botanical information sources for the questionnaire often describe species as weeds, pests, or invasives and, coupled with the knowledge of qualified botanists, invasion risks are likely to be characterized with good accuracy without the tool [51]. For non-invaders, which include species that are naturalized in a country but are not pests, typical AWRA classification accuracy is about 85% [48]. Thus, some species are falsely identified as invasive and excluded from introduction even when they may not cause economic or ecological damage. Smith *et al.* [49] conclude that a species should only be excluded if its potential control or damage costs exceed eight times the benefit of introducing it.

Based on application of the AWRA to *Eucalyptus* in Florida, Gordon *et al.* [6] predicted that *E. camaldulensis* and *E. grandis* have a high probability of being invasive in that state. However, in a field survey of existing *Eucalyptus* plantations of up to almost 40 years in age that included these two

species, seedlings were found at only 4 of the 16 sites surveyed in Florida with only two seedlings detected at distances >45 m from plantation boundaries [52]. In the same survey, no seedlings were present at 3 plantation sites in South Carolina. Callaham *et al.* [52] concluded that results of their survey indicate that "under current conditions, the spread of *Eucalyptus* spp. from plantations should be possible to manage with appropriate monitoring, but this should be evaluated further before *Eucalyptus* spp. are adopted for widespread planting."

Unlike *Eucalyptus*, invasiveness of *Populus* has not been widely discussed and most attention has been focused on indirect implications of potential hybridization between exotic and native *Populus* species [53–58]. The dilution or alteration of native populations, potential pest and pathogen outbreaks, and impacts on sensitive ecosystems have been cited as potential risks. Movement via wind and water can facilitate long-distance *Populus* pollen transport, although its spread and biological consequences are constrained by the overwhelming dilution by genes from wild and non-transgenic trees, by their requirements for moist, disturbed sites, and by typically short rotation ages relative to the onset of flowering [59,60]. *Populus* is also capable of vegetative propagation, but this likely facilitates only local spread [60].

4. Biological Diversity

Short-rotation woody cropping systems have the potential to influence biological diversity. Riffell *et al.* [61] recently reviewed literature related to biodiversity and SRWCs in the U.S. and conducted a meta-analysis of bird and small mammal responses where sufficient data permitted. They characterized their findings as "tentative" due to the small number of studies; seven studies had data sufficient to allow meta-analysis of bird responses and only two studies provided enough information to allow meta-analysis of small mammal responses. Riffell *et al.* [61] addressed *Populus* plantations because information about biodiversity response to other SRWC species in the U.S. was lacking.

Riffell *et al.* [61] found that, at the stand level, diversity and abundance of bird species tended to be lower in SRWCs than reference forests while individual bird species responses were highly variable. Species commonly associated with dense, shrubby habitat structure (e.g., yellow-breasted chat (*Icteria virens*), eastern towhee (*Pipilo erythrophthalmus*)) often reached higher densities in SRWCs than did mature forest associates and/or cavity nesters (e.g., redbellied woodpecker (*Melanerpes carolinus*), brown thrasher (*Toxostoma rufum*)), likely due to the limited availability of large stems in SRWC stands that provide cavities for cavity-nesting birds. Riffell *et al.* [61] concluded that bird communities in SRWC plantations may be less diverse than in bottomland hardwoods yet more diverse than in upland hardwoods or in agricultural land uses (e.g., row crops, pasture). They hypothesized that differences in bird diversity between SRWCs and reference forests would decline as SRWCs age and grow taller, become more structurally heterogeneous, and as the number of different nesting and foraging substrates increases.

Riffell *et al.* [61] found that studies of small mammals in SRWCs in the U.S. have yielded mixed results. Small mammal species diversity was higher in cottonwood plantations compared with bottomland hardwoods in Mississippi [62], but lower in cottonwood plantations relative to surrounding wooded habitat in the upper Midwest [63]. Total abundance of small mammals and species' abundances were consistently lower in SWRC than in reference forests.

The extent to which these findings apply to *Eucalyptus* plantations in the southeastern United States is uncertain. Studies in countries where planted *Eucalyptus* is not native have also yielded mixed results. Some studies have reported lower plant and animal diversity in *Eucalyptus* plantations relative to mature, native forests and some other forest types or seral stages [64–69]. In Brazil, for example, da Rocha *et al.* [70] found fewer species of lizards, anurans, and selected invertebrate taxa in *Eucalyptus* plantations than in large remnants of primary Atlantic Forest. They concluded that *Eucalyptus* plantations have a "moderate capacity" to harbor species of the fauna associated with primary Atlantic forest and noted the potential value of plantations for increasing connectivity among patches of primary forest. In Tasmania, Bonham *et al.* [71] found that native land snails and millipedes were less diverse in *Eucalyptus* plantations than in native forests, and introduced land snails were several times more abundant in plantations. Many taxa, however, including a velvet worm previously considered to be threatened by plantation development, and including almost half the taxa represented by 10 or more specimens, were found at least as commonly in plantations as in native forests [71].

Other studies, including studies from Australia, have again provided contrasting results. Chey *et al.* [72] found that moth diversity in *Eucalyptus* plantations in Malaysia was as high as that in natural secondary forest, a finding attributed to the fact that *Eucalyptus* plantations had a very diverse understory both in terms of structure and plant species composition. Yirdaw and Luukkanen [73] reported high species richness of understory wood plants in *Eucalyptus* plantations in the Ethiopian highlands. In Australia, Loyn *et al.* [74] found that mean abundance of forest and woodland birds was higher in *Eucalyptus* plantations than in cleared farmland and only marginally lower than in native forest. In Australia, Hobbs *et al.* [75] reported that amphibian, reptile, bird, and mammal use of *Eucalyptus* plantations was lower than in adjacent remnant vegetation but greater than in open pasture. They concluded that *Eucalyptus* plantations provide habitat for some species, including some of conservation concern, and suggested managing for greater structural complexity would enhance habitat quality for some species. Hsu *et al.* [76] compared avifauna richness, abundance and composition in five broad habitat types in Australia—dryland native hardwood forests, riparian native hardwood forests, dryland *Eucalyptus* plantations, riparian *Eucalyptus* plantations, and riparian pastures (strips of riparian vegetation surrounded by pastures). *Eucalyptus* was a dominant species in both native forest types. Species richness and abundance were comparable among all habitat types except dryland *Eucalyptus* plantations, which supported fewer species and in lower numbers.

The studies described above indicate that plant and animal communities in *Eucalyptus* plantations are strongly influenced by stand management, land use history, landscape context, and other factors. Lindenmayer and Hobbs [77] reported that almost all research undertaken in Australian plantations, both in conifers and eucalypts, highlighted the importance of landscape heterogeneity and stand structural complexity for fauna conservation. They acknowledged, however, that management of even-aged plantations to promote landscape heterogeneity and stand structural complexity will, in many cases, involve trade-offs in wood production that may not be economically feasible. Research is needed to determine plant and animal response to *Eucalyptus* plantations in the U.S. relative to other forest types of comparable age or structure and to alternative land uses.

5. Water Use

Forest plantations and SRWCs established on grasslands, arable lands, and native forests can reduce streamflow and lower the water table in some situations due to a combination of higher transpiration rates and, compared to grassland and cropland, higher interception and evaporation of precipitation [78–82]. Some studies in South America and South Africa have shown higher water use by *Eucalyptus* than by the native grasslands and in some cases the agricultural croplands they replace [41,83–85]. High transpiration rates associated with the rapid growth of *Eucalyptus* is a primary factor affecting water use [78,80,86]. Effects on streamflow are most apparent in dry regions and years [80] and on sites with coarse-textured soils [81,83].

Effects of SRWCs and forest plantations on streamflow and water tables vary widely and depend on a host of factors, however. Some studies found that water use in *Eucalyptus* is similar to that in native forest, due in part to lower interception of precipitation in *Eucalyptus* canopies offsetting their higher transpiration rates [84,87]. One assessment concluded that total water loss from *Eucalyptus* stands in the tropics is often no greater than from native hardwoods but is greater than from (non-irrigated) agricultural crops [78]. Another study in southeastern China showed that *Eucalyptus* plantations had no significant influence on water supply [88]. Across a *Eucalyptus* productivity gradient in Brazil, Stape *et al.* [15] found that although more productive stands used more water at the stand level than less productive stands, they also had higher water and nutrient use efficiencies and could produce the same quantity of wood with about half the land area and water than required for less productive stands.

Model simulations of forests in Minnesota led investigators to conclude that SRWCs, including hybrid poplar, could either reduce or have no effect on streamflow [79,89]. Investigators in Germany concluded that establishing *Populus* plantations on a large scale would reduce groundwater recharge [11]. Water use, water use efficiency, and drought resistance vary substantially among hybrid poplar clones [90–92], making clone selection an important strategy for minimizing impacts in areas where water is limiting.

Although water use and water use efficiency vary substantially among *Eucalyptus* and *Populus* species and clones, the scale of SRWC plantation establishment is probably the most important factor influencing water use and water budgets across a catchment or landscape. For example, investigators concluded from hydrological assessments that changes in vegetation, including *Eucalyptus* plantations, that comprised less than 20% of catchment areas would not have a detectable effect on streamflow [93] and that landscape mosaics that include native forest would be effective in regulating total water use [94]. Fallow periods between rotations can also reduce water use, and thinning and fertilization can reduce water stress in some environments [95,96]. Potential impacts may also be less on sites and landscapes of finer textured soils compared to those with coarse textured soils [81]. Busch [81] found that short rotation *Salix*/*Populus* coppice systems in Germany used more water when managed on longer rotations and suggested that rotations be kept at 2–4 years where water deficits occur. Monitoring key physiological and hydrological indicators during and following plantation establishment could help refine projections of water use by SRWCs.

6. Environmental Standards and Criteria

Most environmental standards and criteria for managed forests focus on traditional plantations rather than SRWCs. The Sustainable Forestry Initiative (SFI) and American Tree Farm System (ATFS) are two Programmes for the Endorsement of Forest Certification (PEFC)-recognized sustainable forestry certification standards that are widely applied in the U.S. South. The 2010–2014 SFI Standard [97] applies to both natural and plantation forests, but states that "Short rotation woody crop operations and other high-intensity forestry operations, while they may serve a role in the production of bioenergy feedstocks, are beyond the scope" of that standard.

By contrast, the Forest Stewardship Council (FSC) addresses planted trees in two categories; conventional plantations and "Principle 10 plantations" [98]. Principle 10 Plantations, which include exotic trees such as *Eucalyptus*, block plantings of cloned trees, and planted forests established on native non-forest ecosystems such as native prairies or that do not exhibit traits of natural forests, require special provisions of the landowner. Principle 10 Plantations also include species not native to the area, short harvest cycles or "ongoing, systematic application of chemical pesticides or mechanical treatments (like tiling) that would prevent the establishment of a natural understory," and the use of management practices that promote single species on sites normally occupied by multiple-species forests. Principle 10 Plantations are not eligible for FSC certification if they were established on lands with natural or semi-natural stands more recently than November 1994. Owners of forest lands containing Principle 10 Plantations are required to retain or restore a percentage (typically 10% to 20% for family forests) of their forest land in/to natural forest. There are additional requirements as well that include tree retention during harvests and opening size limits.

Other criteria and standards relevant to SRWCs focus specifically on exotic species. Described below are some of these as they relate to invasiveness, biodiversity, and water use.

6.1. Invasiveness

Some forest management standards and certification systems contain general guidance related to non-native species. The FSC-US Forest Management Standard [98] states that the use of non-native species should be "carefully controlled and actively monitored to avoid adverse environmental impacts" and "is contingent on the availability of credible scientific data indicating that any such species is non-invasive and its application does not pose a risk to native biodiversity." This standard also states that non-natives should be used only when their provenance, location, and ecological effects, including unusual mortality, disease, and insect outbreaks, are monitored and when their performance is greater than that for native species. More specifically, this standard restricts the planting of non-native species in the Mississippi Alluvial Valley and the Appalachian and Southeast regions unless they are used for "site remediation." The Standard does not identify the technical basis for this restriction but notes that state lists of invasive/non-native species, state plant councils, and other state experts should be consulted to determine if a species is considered invasive.

The FSC also has standards specific to many other countries that contain indicators related to the use of exotic species [99]. There is considerable variability across these country-specific standards but indicators commonly require exotic species, when they are allowed, to be justified by greater

performance than native species and carefully controlled and actively monitored. Some FSC standards also require managers to provide evidence of no invasiveness risk, introduction of pests or diseases, or other adverse ecological impacts associated with the introduction of exotics.

The PEFC International Standard [100] states, "Only those introduced species, provenances or varieties shall be used whose impacts on the ecosystem and on the genetic integrity of native species and local provenances have been evaluated, and if negative impacts can be avoided or minimized." This Standard also states that the impact of introduced species, provenances, and varieties need to be evaluated during the planning and management stages of the production cycle.

The 2010–2014 SFI Standard states that managers using non-native species outside the context of SRWCs are asked to minimize plantings and provide research-based documentation that exotic tree species, planted operationally, pose environmental minimal risk. Program participants are encouraged to limit the introduction, impact and spread of invasive exotic plants and animals that directly threaten or are likely to threaten native plant and animal communities. The ATFS 2011–2015 Standards of Sustainability [101] requires managers to monitor for changes (e.g., due to presence of invasive species) that could interfere with objectives in the management plan and to take reasonable actions when problems are found.

The Roundtable on Sustainable Biomaterials (RSB) [102] states, "If the species is recorded as highly invasive under similar conditions (similar climate, similar local ecosystems, and similar soil types), this species shall not be used." It also states that operators shall conduct a weed risk assessment during feedstock selection and development to identify the risk of invasion and that species deemed to be highly invasive not be used. It recommends that invasion be minimized, escape be monitored and immediately mitigated, and the potential presence of pests and pathogens be addressed in management plans.

The North Carolina Department of Agriculture and Consumer Services, North Carolina Cooperative Extension, and the Biofuels Center of North Carolina recently developed gbest management practices to help bioenergy feedstock growers and processors reduce the risk of unintentional escape and spread of potentially invasive species [103]. Although the guidance appears designed for horticultural production of bioenergy crops, portions of it may be relevant to SRWCs. Examples include: (1) avoid locating production fields directly adjacent to major dispersal corridors such as streams or irrigation canals; (2) if viable seeds are produced, choose late-flowering cultivars or harvest prior to seed maturation to minimize risk of dispersal; (3) establish a buffer area around plantings that is maintained with perennial cover; (4) inspect field boundaries, buffer areas, and adjacent areas regularly for propagules/seedlings; and (5) prepare an eradication plan for potential use should escapes be documented.

6.2. Biodiversity

Sustainability standards developed by the Council on Sustainable Biomass Production [104], the FSC [98], the PEFC [100], the RSB [102], and the Sustainable Biodiesel Alliance [105] include criteria and indicators related to biological diversity. Some criteria and indicators apply at the stand scale while others apply to the management unit. Examples include the following:

- Identify, protect, and/or conserve ecologically important forest areas and old growth forest;

- Assess and protect rare species and communities and species legally designated as threatened or endangered;
- Establish or protect corridors to minimize impacts of habitat fragmentation;
- Do not allow newly established plantations to replace existing natural ecosystems or diminish their ecological integrity;
- Retain some habitat components and associated stand structures (e.g., dominant green trees, snags, down woody debris) in harvested stands, particularly in larger stands (e.g., >32 ha);
- Allow adjacent stands to reach a minimum age (e.g., 5 years), height (e.g., 10 feet), or degree of canopy closure before a plantation is harvested;
- Conserve plant and animal habitats in riparian management zones and representative samples of existing ecosystems within managed landscapes;
- Where natural ecosystems were previously converted to plantations, maintain and/or restore a percentage of the total management area to natural or semi-natural cover.

6.3. Water Use

Organizations that include the FSC [98], the PEFC [100], the RSB [102], the Council on Sustainable Biomass Production [104], and the Sustainable Biodiesel Alliance [105] have developed standards and criteria related to water resources. Common objectives, elements, and provisions for water use standards and criteria include the following:

- Recognize the importance, value, and vulnerability of water supply and quality;
- Biomass production should not contribute to depletion of ground or surface water supplies;
- Biomass and bioenergy production maintains or improves water resources;
- Identify and define measures to maintain or enhance water resources (and other forest services);
- Use results of credible scientific analysis, best available information, and local knowledge and experience to assess short- and long-term impacts on water resources and associated riparian habitats and hydrologic functions;
- Include a water management plan which aims to use water efficiently and to maintain or enhance the quality of the water resources that are used for biofuel operations;
- Demonstrate commitment to the improvement of water efficiency over time through the implementation of water-saving practices;
- Establish buffer zones between the operation site and surface or ground water resources.

7. Conclusions

Eucalyptus, *Populus*, and other SRWCs are highly productive woody crops that can help meet demands for fiber and energy feedstocks on a smaller land base and in closer proximity to processing facilities than many forest or agricultural alternatives. Forest products companies and agencies are committed to sustainable forestry practices associated with both traditional fiber sources and non-traditional sources such as SRWCs. Although characteristics of some *Eucalyptus* species may increase their invasiveness risk, strong and consistent field evidence for significant invasiveness is lacking. Scientists recommend monitoring regeneration and spread to minimize risks, particularly as

the scale of plantation establishment increases in a landscape or regional context [27,29,106]. Current standards and guidelines emphasize that selection of species and practices be based on best scientific evidence to minimize invasiveness and that escape and the presence of pests and pathogens be monitored and mitigated.

Studies in the U.S. suggest that the relationship between SRWCs and biodiversity likely depend upon what type of ecosystem occupied the site prior to plantation establishment, how the SRWC plantation is managed, landscape context, and scale of analysis [107]. *Populus* and other SRWCs that replace cropland are likely to increase bird diversity at the stand scale while SRWCs that replace mature native forests or other high-diversity plant communities may decrease local diversity [61]. SRWC plantations, regardless of the dominant tree species, likely will not provide stand-level habitat for the full complement of species found in mature, native forests because of their simpler structural characteristics. However, SRWC plantations typically represent only one component of a landscape and diversity response is best understood when multiple spatial and temporal scales are considered.

Implications of *Eucalyptus* plantations for biological diversity have not been investigated in the United States. Research from elsewhere suggests that *Eucalyptus* plantations may have lower stand-level diversity than in native forests, particularly relative to mature seral stages, but greater diversity when compared to some alternative land uses. Based on a review of the literature, Brockerhoff *et al.* [108] concluded that *Eucalyptus* plantations provide important habitat resources for wildlife species, including many birds and mammals. In forested landscapes, SRWCs have the potential to provide habitat conditions that complement those found in native forest retained as buffers along streams, in inoperable areas, and in other locations or on other ownerships. More broadly, some investigators have suggested that planted forests contribute to the conservation of natural forests by way of their relatively greater productivity (*i.e.*, planted forests serve as an alternative source of wood) [109–111].

Eucalyptus water use can be higher than non-irrigated agricultural crops, pasture, and, in some cases, native forests due to its rapid growth and high evapotranspiration rates. Significant impacts on water are most apparent in dry environments and when plantations comprise a large proportion of the landscape. Effects of *Eucalyptus* establishment on water resources is sometimes offset by its high water use efficiency and smaller land base required to produce an equivalent amount of wood. Hybrid poplar water use and effects of its establishment on water resources varies substantially among clones and site environmental conditions. Potential effects of SRWCs on water use, streamflow, and groundwater recharge in vulnerable environments can be reduced by limiting the proportion of the landscapes or watersheds on which they are established and by selecting species and clones with lower transpiration rates. Standards and guidelines state that SRWCs should not deplete ground or surface water supplies, that buffers be placed between operations and water sources, and that management plans and practices be based on best available scientific information.

Author Contributions

All co-authors contributed to the research and writing for this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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