Influence of growing *Eucalyptus* trees for biomass on soil quality

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E. Pernilla Brinkman, NIOO-KNAW
Romke Postma, NMI
Wim H. van der Putten, NIOO-KNAW
Aad J. Termorshuizen, SoilCares

E-mail for contact: W.vanderPutten@nioo.knaw.nl

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Recommendations

- *Avoid harvesting at too young stand age: Eucalyptus* plantations in Brazil are intensively managed systems with a high biomass production compared to many other countries. This production level is reached through fertilization and - in some regions - irrigation. There is an ongoing tendency of harvesting the plantations at younger age. That will result in plantations with a short cropping duration, which are more comparable to agricultural systems than to classic forestry, both from the perspective of management intensity and the influence on environmental factors. Such shorter-lived plantations may be more negative to the environment than longer-lived plantations.

- The area in Brazil covered with native forest or savannah is declining and becoming fragmented, resulting in enhanced numbers of endangered species. It has been suggested that *Eucalyptus* plantations may serve as a refuge for native species and connect habitat fragments. However, biodiversity is higher in plantations with long rotation cycles that are extensively managed than in arable crops and poor rangelands. Moreover, as *Eucalyptus* is exotic to South America, fewer organisms are adapted to this tree species. All in all, the biodiversity in *Eucalyptus* plantations is lower than in natural forest, mainly enabling survival of generalist species without specific habitat requirements or species with high dispersal capacity. In any case, longer-term stands will have less negative effects on biodiversity than very short-lived stands. Spatial and temporal stand design might enhance the function of *Eucalyptus* stands as refugia or corridor for species and migrants among original forest and savannah systems. This needs further study.

- The effect of *Eucalyptus* plantations on soil organic matter (SOM) depends on the previous land use: if the plantation is established on natural forest soil, SOM content will first decline and after some decades increase. However, if the plantation is established on poor soils with low SOM content, the SOM will increase. Soil microbial characteristics differ between *Eucalyptus* plantations and native vegetation, but differences become smaller when the age of the plantation increases. Litter accumulation is higher in *Eucalyptus* plantations than in native vegetation, independent of plantation age, probably due to low nutritional quality and low decomposition rate of *Eucalyptus* litter. Therefore, effects of new *Eucalyptus plantations* can only be assessed properly when the local conditions are known.

- The concentration of nutrients in leaves, branches and bark is higher than in the stem wood. However, over time trees allocate relatively more biomass to wood, so that, although the nutrient concentration in the wood is low, the total amount of nutrients in the wood per unit of planted area steadily increases. Large amounts of especially macronutrients N, P and K, but also of micronutrients B, Cu, Fe and Zn are removed with the harvested wood, with a need of fertilization to replace nutrient stocks. Leaving harvest residues in the field limits the removal of especially base cations Ca, Mg and Mn that are present in larger amounts particularly in the bark. From a nutrient removal perspective, it may be wiser to harvest branches than bark for biomass. Removing harvest residues without supplying nutrients via fertilizers will cause a decrease in productivity of successive rotations due to nutrient removal. In addition, leaving harvest residues in the field will increase water availability, prevent soil erosion, protect the soil from compaction by harvesting machines and reduce the germination of weeds. However, there is a lack of information on the amount of residues that needs to be left in the field to sustain biomass production. Therefore, in the planning phase of tree plantations for biofuel and other biomass-related production, site-specific recommendations are required accounting for soil type, land surface steepness, climate, length of the rotation and how these factors influence residue retention and its effect on soil quality and soil functioning.

- Biochar as a rest product from biofuel production may be used to return nutrients to the field and to increase the carbon content of the soil. Addition of biochar also may increase cation exchange capacity (CEC), water holding capacity, drainage capacity, the pH of acid soils and abundance of soil microbes. However, downsides of using biochar is that it may decrease the effectiveness of pesticides and herbicides through adsorption of these chemicals, and the possibility of introducing toxic compounds to the soil. As biochar is very stable, some of these effects may be long-lasting. Wood ash, another rest product of biofuel production, is noted for its acid neutralizing capacity and supply of base cations Ca, Mg and K. Bringing back wood ashes to soil may increase growth conditions for the trees and does not seem to harm soil organisms in the long term, provided that the wood ash is not contaminated with ashes (and toxic compounds) from other sources.

1. Introduction

The HIP project examines the sustainable production of biokerosine for the airports of São Paulo and Rio de Janeiro. The feedstock is produced in the regions Minas Gerais, Campinas and Rio Grande do Sul. The required increase in production of biomass may be attained through higher production efficiency and extension of the area that is used for biomass production. The first requires a change in management practices, the second implies a change in land use. We mainly focus on effects of both these measures on soil quality. The crops that show the most promising potential from a bioengineering and economic perspective are Eucalyptus and pine (both including harvest residues), sugarcane (including bagasse), macauba (*Acrocomia aculeata*; macaw palm, grugru palm) and, of less importance, soybean, oil palm (including residues) and rice straw. We here present results of a desk study with the objective to quantify the effect of intensified land management and changes in land use on soil quality, with *Eucalyptus* as primary example.

Land management

We will describe currently advised agronomical practices for production of *Eucalyptus* and describe effects on soil quality (e.g. nutrient status, soil acidification, organic matter content) in comparison to previous land use. Subsequently we will explore the effects on agronomical practices, soil quality and environment under the scenarios of intensified agriculture and changed land use.

Recent efforts to decrease negative environmental and human health effects of sugarcane harvesting has resulted in a phased banning of the practice of burning the straw before harvesting (Carvalho *et al.* 2017). This practice has resulted in large amounts of straw that have been left in the field, but also are of interest as a feedstock for the production of biofuel. This poses the question how much residue should be left in the field to ensure sustainable production, not only of sugarcane, but also of other biomass crops like *Eucalyptus*. Leaving harvest residues in the fields returns some of the nutrients and organic matter to the soil, which contributes to the maintenance of organic matter and nutrient contents in the soil and nutrient supply to the crop. Soil organic matter is essential for soil structure and water retention, which in turn affects soil microbial activity, suppression of soil-borne pathogens and rootability of the crop. Due to the variation in soil types in the production area, it is important to find specific information or extrapolate from studies in regions with similar climate and soil conditions. One concern about leaving harvest residues in the field is the risk of returning plant parts infested with pathogens or pests as a potential source of infection for the succeeding crop. In this project, we need to define residues of *Eucalyptus* and their potential for soil quality improvement.

The aim of the current report is to analyze biomass production systems and quantification of effects of various scenarios of a more intensive land management on soil quality and crop yield. More specifically, we focus on the quantification of various recycling options to improve soil quality and yield, with the focus on *Eucalyptus*.

Land use change

When the production area for biomass crops is increased, this leads to direct or indirect land use change. In the regions Minas Gerais, Campinas and Rio Grande do Sul, an increase in the area that is used for biomass crops most likely goes at the expense of grassland. This conversion has consequences for the amounts of soil organic matter and nutrients, but also for emission of greenhouse gases and problems with potential pathogens and pests. The production of the remaining grasslands may either be intensified, with increasing fertilizer use and decreasing plant species diversity as a consequence, or the production of grass may be transferred to other regions, often at the expense of forests. This both has ecological implications as well as for soil carbon stocks. These consequences need to be considered in the evaluation of the sustainability of biomass production.

2. *Eucalyptus* plantations: general information

The area planted with trees for industrial purposes in Brazil was 7.8 million ha in 2015 (Ibá 2016), of which *Eucalyptus* plantations covered 5.6 million ha (72%). The main locations of Eucalyptus plantations are in the states Minas Gerais (24% of the total area planted with *Eucalyptus* in Brazil), São Paulo (17%) and Mato Grosso do Sul (15%). The area planted with *Eucalyptus* trees in Mato Grosso do Sul has more than doubled since 2010, while the planted area in the other two states has declined slightly (Ibá 2016). Overall, *Eucalyptus* plantations show over the last five years an annual area increase of 2.8% (Ibá 2016). Wood from *Eucalyptus* trees is mainly used in the pulp, paper, and wood panel industries, as industrial firewood, but also for production of charcoal as fuel for steelworks. The average productivity of *Eucalyptus* plantations in Brazil is 36 m^3 ha^{-1} $year^{-1}$, with a rotation time of about 3-4 years. This productivity is the highest and the rotation time the shortest in the world (Ibá 2016). Recently there has been a development to grow *Eucalyptus* for bioenergy production in short rotation coppice with a rotation time of only two years (Eufrade *et al.* 2016).

Eucalyptus is planted in tropical and subtropical climatic conditions. According to the classification of Köppen, the climate types in the Southeast and South of Brazil where most of the *Eucalyptus* plantations occur are humid tropical with dry winter (Aw), fully humid subtropical with hot summer (Cfa), fully humid subtropical with temperate summer (Cfb), humid subtropical with dry winter and hot summer (Cwa), humid subtropical with dry winter and temperate summer (Cwb). In Aw and Cwa water stress occurs during the dry period in the year, whereas in Cfb and Cwb there is a risk of frost during winter. The original biomes where *Eucalyptus* plantations were established in the Southeast and South are the Atlantic Forest and the Cerrado (Brazilian savanna) (Gonçalves *et al.* 2013).

There is a wide variability in soil types and topography where *Eucalyptus* is planted, but all soils are acidic. Generally, the most weathered soils are found in tropical and subtropical humid conditions that enhance chemical processes and the activity of soil organisms. A relatively flat topography facilitates the development of a soil profile, while with an increase in steepness of slopes, soil profiles become less well developed. Almost half of the area planted with *Eucalyptus* is classified as Oxisol, which is highly weathered (Gonçalves *et al.* 2013). The soils have a loamy to clayey texture, are deep with well-differentiated horizons and a low texture gradient, are well-drained and prone to leaching and generally contain low levels of plant-available nutrients. The physical and chemical conditions of these Oxisols are highly variable and call for specific management strategies. About 25% of the area of *Eucalyptus* plantations are on Ultisols, which are weathered, deep to shallow, vary from well to poorly drained and are low in nutrient content. The soil profile contains a textural gradient, which increases the risk of erosion in areas with steeper slopes. Another 14% of *Eucalyptus* is planted in Inceptisols, which are little developed, mostly shallow and moderately to well drained. The texture ranges from clayey loam to clayey. Physical conditions related to permeability, depth and water retention may limit *Eucalyptus* production on Inceptisols, but the soils are medium to highly fertile (Gonçalves *et al.* 2013). As such, it is not possible to generalize best management practices for the whole Southeast of Brazil.

Species of *Eucalyptus* vary with respect to growth rate and rooting, resistance to drought or frost, resistance to diseases and insect pests, wood density and lignin and hemicellulose content (Gonçalves *et al.* 2013). Species choice thus depends on the environmental conditions of the area to be planted. Large-scale *Eucalyptus* plantations were introduced in São Paulo state at the beginning of last century. The main species that were planted are *Eucalyptus grandis*, *Corymbia citriodora* (a closely related species previously named *E. citriodora*), *E. camaldulensis*, *E. saligna* and *E. urophylla*. Seeds were selected from trees from specific origins that thrived in São Paulo conditions. However, from the 1980s the expansion to other regions in Brazil led to problems with drought and frost, but also with diseases and pests. Some pathogens did not occur in the originally planted area, some pathogens were accidently introduced, but also the use of more productive genotypes without prior testing of susceptibility to pathogens caused problems with diseases (Gonçalves *et al.* 2013). Also adoption of new management techniques and especially successive rotations increased problems with diseases (Gonçalves *et al.* 2013). The following diseases, of which many do not naturally occur on *Eucalyptus* in its original range, are important: Eucalyptus cancer (*Chrysoporthe cubensis*) (Wingfield 2003), Eucalyptus rust (*Puccinia psidii*) (Kriticos *et al.* 2013, Silva *et al.* 2013), Ceratocystis wilt (*Ceratocystis fimbriata*) (Zauza *et al.* 2004) and Quambalaria stem girdling and leaf spot (*Quambalaria eucalypti*) (Roux *et al.* 2006). Since the mid-2000s, bacterial diseases like Eucalyptus die-back (*Erwinia psidii*) have increased in importance, but mainly in young plants (Arriel *et al.* 2014). Bacterial wilt (*Ralstonia solanacearum*) and leaf blights and defoliation caused by *Rhizoctonia* spp. and *Xanthomonas axonopodis* are mainly important in clonal production in nurseries and in just planted trees (Dianese *et al.* 1990, da Silveira *et al.* 2000, Neves *et al.* 2014). Leaf blights and defoliation caused by *Cylindrocladium* spp. seem to be of less importance (Sharma and Mohanan 1982). Diseases are mainly managed by choosing resistant plants and, for diseases that mainly are a problem at early plant age, restricting seedling or cutting propagation to a season when environmental conditions are unfavorable for disease development (Gonçalves *et al.* 2013). Leaving harvest residues of sugarcane in the field increases the risk of pest outbreaks (Carvalho *et al.* 2017), but we are not aware of an increased risk of diseases or pests in *Eucalyptus* plantations. Such potential negative effects, if they exist, should however be weighed against a decreased level of soil disease suppressiveness if complete residue removal leads to a decline in organic matter content. This would need further evaluation. *Eucalyptus* species vary in resistance to diseases and pests, so that preliminary assessment of risk of disease and pest outbreak is important. And again, planting those species and varieties that are best adapted to the local edaphic and environmental conditions minimizes the chances for attack by pest and pathogen organisms. Important native pest organisms are leaf-cutting ants, termites, caterpillars and defoliator beetles that are managed by biological or chemical means. During the last decade, pest organisms that have been introduced from Australia are redgum Lerp psyllid (*Glycaspis brimblecombei*), Bronze bug (*Thaumastocoris peregrinus*) and Eucalyptus gall wasp *Leptocybe invasa*). These organisms are managed by integrated pest management with biological and chemical measures (Gonçalves *et al.* 2013).

Interspecific hybrids like *E. urophylla* x *E. grandis* (‘Urograndis’) overcome some of these above-mentioned problems with pathogens and pests, and combine favorable traits from both species. However, genotypes propagated by cloning have a higher risk of incompatibility to a certain environment than seed-propagated trees due to small genetic diversity, so that specific tests are needed to assess suitability for a certain site. In higher altitudes in the Southeast where light frost may occur, the species *E.dunnii* and *E. saligna* are used, whereas *E. bentamii* is planted in areas where frost is more severe and frequent. Other species are adapted to warmer climate with higher water stress, although *Eucalyptus* plantations are not economically viable above 400 mm year^{-1} water deficit (Gonçalves *et al.* 2013).

Young *Eucalyptus* trees are very sensitive to competition with weeds for light, nutrients and water. Competition with weeds can cause a reduction in diameter and height of 60-70% in the first year (Gonçalves *et al.* 2013). Weeds are mainly controlled by a combination of mechanical methods and herbicides. In most plantations, non-selective herbicides like glyphosate are applied to remove present weeds. In addition, pre-emergence herbicides are applied in the crop row to reduce germination of weed seeds. After canopy closure, shading and increased litter fall decrease the growth of weeds (Gonçalves *et al.* 2013).

3. Effects of land-use change

The effects of planting large-scale monocultures of *Eucalyptus* on the environment range from soil characteristics and hydrology to biodiversity. The direction of changes in these characteristics depend on the previous land use and plantation management.

3.1 Soil parameters

Litter accumulation in seven-year-old *Eucalyptus* plantations was higher than in native vegetation, which included both Atlantic Forest and Cerrado (da Gama-Rodrigues *et al.* 2008). Also in extensively managed 60-yr-old plantations, either managed as coppice with a rotation length of 6-10 years or as a high forest, the litter accumulation was higher than in Cerrado (Maquère *et al.* 2008). The accumulation mainly seems to be due to a slower decomposition rate of *Eucalyptus* litter (Pegoraro *et al.* 2012), which may be caused by the lower nutritional quality of the litter, but also by a lower density and diversity of soil organisms involved in decomposition. Bacterial communities in a *Eucalyptus* plantation were found to be variable and dissimilar from those in natural forest, secondary forest and pasture (Ndaw *et al.* 2009). Another study found a lower microbial biomass C and N in a *Eucalyptus* plantation than in secondary forest (Chaer and Tótola 2007). Incorporation of all residues resulted in a smaller difference in microbial characteristics in the subsurface layer between the plantation and secondary forest. The C:N ratio of *Eucalyptus* litter was higher than of the litter in the native vegetation (da Gama-Rodrigues *et al.* 2008, Maquère *et al.* 2008).

In general, microbial biomass and N content was much higher in the litter than in the upper soil layer, suggesting that the litter is an important provider of nutrients for tree growth in these low fertile soils (da Gama-Rodrigues *et al.* 2008). The difference in N content between litter and soil microbial biomass was smaller on clayey soil (da Gama-Rodrigues *et al.* 2008), although this was only based on a small number of observations. Removal of native vegetation to establish *Eucalyptus* plantations temporarily reduced soil enzymatic activities (an indication of microbiological activity), but many of them reached the same values as the native Atlantic Forest after three to five years (Lino *et al.* 2016). Compared with pasture, a 10-year old *Eucalyptus* plantation did not contain lower microbial C-biomass, but microbial activity indicated by soil respiration and C-organic mineralization was lower in the plantation (Sicardi *et al.* 2004). Also activities of enzymes involved in the mineralization of organic matter were lower in the plantation than in the pasture.

In one study, the soil under the *Eucalyptus* stand had a higher pH, higher P, Ca and Mg content and lower SOM (=soil organic matter), S and K content compared to a native early-successional forest (da Silva et al. 2014). Higher nutrient contents is likely caused by fertilization, which is common practice in *Eucalyptus* plantations. In contrast, *Eucalyptus* cultivation decreased soil pH and increased Al^{3+} content compared to pasture (Sicardi *et al.* 2004, Leite *et al.* 2010), but the difference was smaller when compared to native forest soil (Leite *et al.* 2010). Continuous cultivation of *Eucalyptus* for three successive rotations (at least 21 years in total) resulted in increased available P and decreased exchangeable fractions of K, Ca and Mg when compared to native forest or continued unfertilized pasture (Leite *et al.* 2010). Organic P and K were lower in a *Eucalyptus grandis* plantation than in natural vegetation (secondary forest) (Chaer and Tótola 2007).

Many studies, also outside Brazil, that show a general increase in SOM or organic-C content in *Eucalyptus* and other plantations, although effects depend on what the reference situation is: if the reference is natural forest on a soil high in SOM, then organic-C in *Eucalyptus* plantations first decline, and an increase takes place after some decades (Turner and Lambert 2000). The same is true if the reference consists of grassland soils: if these soils are rich in SOM, then an initial decrease is likely to happen, but on poor, low-SOM soils, an increase is generally reported. For example, on low-SOM soils, (Trouve *et al.* 1994) reported a general increase in SOM content in the 0-5 cm soil layer of *Eucalyptus* and *Pinus* plantations in the Congo from 6 to 10-11 mg/g C after 28 yrs when planted on savannah soil. The organic-C originating from the savannah declined in 28 yrs from 6 to 2 mg/g C. Comparable results were obtained by Epron *et al.* (2009).

Mendham *et al.* (2002a) noticed that for Australia, Walkley-Black soil C in the 0-10 cm top soil layer was more influenced by clay content than by land use (which included in this study native vegetation, 20-71 yr-old pasture, 7-10 yr-old *Eucalyptus* plantation on ex-pasture). Overall, land use caused only minor differences in the biological and chemical indicators of organic matter quality across a broad range of sites in SW-Australia. It is indeed well-known that part of the SOM stocks is well-correlated with clay contents (Hassink 1997), so if clay contents are high, effects of land use are likely to become less, and vice versa, on pure sandy soils, they likely become more predominant. The study of Mendham *et al.* (2002a) was a correlation study at different sites and not a chronosequence study.

Maquère *et al.* (2008), for Brazil, discussed effects of short and long rotation Eucalyptus on SOC (=soil organic carbon) stocks. They also discussed methodological effects of including differences in bulk soil density (which was higher on grasslands due to cattle trampling) and on sampling issues when including the litter layer. In general, effects of *Eucalyptus* were positive on SOM stocks when compared to Cerrado.

3.2 Biodiversity

The threat on native vegetation in some areas in Brazil raises the question whether plantations can contribute to the conservation of species (Lapola *et al.* 2010). The growth and increasing productivity of *Eucalyptus* plantations decreases the need of logging trees in native forests. However, the establishment of a plantation implies a change in land use that directly or indirectly may come at the cost of native vegetation. Ecological costs of these monoculture plantations depend on the type of land that was converted. Monoculture plantations contain a much lower diversity of species than do natural primary forests, but the plantations contain more diversity than agricultural land (Gasparatos *et al.* 2017). Plantations with long rotations also contain quite some species if managed in an ecologically friendly way (Fonseca *et al.* 2009). Gradual thinning to a lower tree density in older plantations provides space for a more complex understorey that may be essential for a high diversity of other organisms (Fonseca *et al.* 2009). However, the diversity in plantations with exotic species like *Eucalyptus* is much lower than in plantations of native tree species. Especially taxa with low dispersal ability and specific niche or habitat requirements were missing in the plantations, while species with high dispersal ability and less specific requirements were also found in plantations (Fonseca *et al.* 2009). Mammals belong to the last category and are commonly detected, although abundance and number of species varies with plantation age (Rosalino *et al.* 2014, Timo *et al.* 2015). A common rotation length in plantations for paper and pulp production is 6-7 years. After planting the structure is bush-like, in a few years changing to a forest-like environment with an understorey, while before harvest the understorey is removed resulting in an open environment. Mammals are mostly found in middle-aged plantations where the understorey provides protection (Timo *et al.* 2015). The diversity of organisms associated to leaf litter in *Eucalyptus* plantations was lower than in primary Atlantic Forest (da Rocha *et al.* 2013). Also the diversity of frogs was much lower in plantations than in the forest, with 20 out of 29 species only found in Atlantic Forest (Ferreira *et al.* 2016). This was mainly attributed to the breeding guild, with species that for breeding depend on bromeliads or leaf litter only found in the forest. A broad-scale diversity study in Rio Grande do Sul comparing primary forest and *Eucalyptus* plantations with long rotations (8,14 and 30 years) included small mammals, birds, leaf-litter frogs, butterflies, galling insects, spiders, opiliones, flatworms, woody plants, epiphytic angiosperms, epiphytic ferns, lichens, and fruit-body producing fungi (Fonseca *et al.* 2009). The study showed that species richness, measured in three replicate one-hectare plots, is higher in primary forest

(506 species) than in *Eucalyptus* monoculture (318 species). However, the *Eucalyptus* plantations also harboured species that were not present in the forest, but in nearby natural grasslands.

Monocultures of *Eucalyptus* also affect abundance and diversity of arthropods, which are important for pollination, nutrient cycling, food source for other animals, but also may be pest organisms causing a threat to the plantations (Majer and Recher 1999). Some groups of arthropods were only found in *Eucalyptus* plantations, whereas other groups were restricted to natural forest (Camara *et al.* 2012). However, the arthropod community in the native forest was more complex with an increase in abundance and species richness than in the *Eucalyptus* plantations, although the differences became smaller with an increase in plantation age. In contrast, Pellens and Garay (1999) did not find a lower macroarthropod abundance, but a decrease in evenness in the plantation with certain groups missing, other groups being more abundant and especially a concentration of macroarthropods in the litter layer. In the Atlantic Forest region, the diversity of ants in *Eucalyptus* plantations was lower than in primary and secondary forest, but higher than in pastures (Braga *et al.* 2010). However, ant diversity increased in *Eucalyptus* plantations that had not been managed for decades and were similar to native forest when left unmanaged for a century (Mentone *et al.* 2011). Thus, a decrease in ant diversity may be more attributed to management intensity than to *Eucalyptus* itself. The same pattern was found for an increasing diversity of termites with increasing *Eucalyptus* plantation age, with the highest diversity in forest fragments (Junqueira *et al.* 2009). Termite species richness was also higher in cerrado than in a *Eucalyptus* plantation, while abundance was similar, with a lower proportion of litter feeders in the plantation (Constantino and Pessoa 2010). Termites have an important function in nutrient cycling and soil formation in tropical areas (da Cunha *et al.* 2006). Ants and termites are an important food source for certain animals, but are considered a pest in plantations (Timo *et al.* 2015).

The survival and growth of seedlings of tree species native to China was inhibited in a *Eucalyptus* plantation compared to a *Pinus* plantation (Chu *et al.* 2014). The authors attributed the inhibition to allelopathic effects. However, volatiles or decomposing litter did not have a negative effect on all the tree species. This allelopathy may explain the decrease in biodiversity of understorey species that in usually found in *Eucalyptus* plantations. In contrast, the chance of *Eucalyptus* invading native forests seems low. Seeds of *Eucalyptus* germinated when sown at the edge or inside forest fragments, but the seedlings disappeared within less than a year (da Silva *et al.* 2011).

3.3 Greenhouse gas emissions

Eucalyptus emits high amounts of isoprene as compared to grasses, herbs or slower growing natural forest (Rosenkranz *et al.* 2015). In the presence of high concentrations of NO_x, this may lead to the formation of tropospheric ozone, which is a problem for human health and plant productivity (Ashworth *et al.* 2013). High concentrations of NO_x mainly occur in urban areas, so that this is not likely to be a problem in *Eucalyptus* plantations in Southeastern Brazil (Porter *et al.* 2015).

Direct land-use change is likely to have only a small effect on carbon emissions, as most biofuel plantations would replace rangeland areas (Lapola *et al.* 2010). This assumption holds only when land-use change does not involve a decrease in soil carbon stocks (Don *et al.* 2011, Zanchi *et al.* 2012). However, when rangeland areas move to the Amazonian forests causing indirect land-use change, carbon savings may be lost (Lapola *et al.* 2010). This topic goes beyond the focus of this study, but is important to consider.

4. Harvest residues of *Eucalyptus* plantations

Recently, there has been an increased interest in the use of forestry residues (de Oliveira *et al.* 2013) and of short rotation coppice of *Eucalyptus* as a source of renewable energy (Eufrade *et al.* 2016). However, there are also concerns about environmental effects of nutrient removal and a reduction in organic matter that is returned to the soil (Laclau *et al.* 2010). Nutrient budgets, which give an overview of in- and outputs of different elements in a system, may be used to indicate whether depletion of an element may be expected before it is actually possible to be measured in the soil (Ranger and Turpault 1999). The main sources of nutrient inputs in forest ecosystems are from the atmosphere (N) and weathering of soil minerals (P and base cations Ca, Mg and K) (Paré and Thiffault 2016), whereas the main outputs are deep drainage and biomass removal (Fig. 1). As trees often are planted in low fertile soils and weathering is a long-term process, natural inputs are not sufficient to provide trees with sufficient nutrients when they are harvested in short rotations (Ranger and Turpault 1999). In that case, fertilization is needed to compensate for nutrient losses, as is common practice in Brazilian *Eucalyptus* plantations. A complete and accurate nutrient budget is time-consuming and site specific (Ranger and Turpault 1999) and as such not possible to perform for a large heterogeneous area like Southeast Brazil. However, an estimate of nutrient removal with the biomass harvest gives an indication of instant losses to the system. For this purpose, we will quantify biomass production and nutrient content of the different tree components.

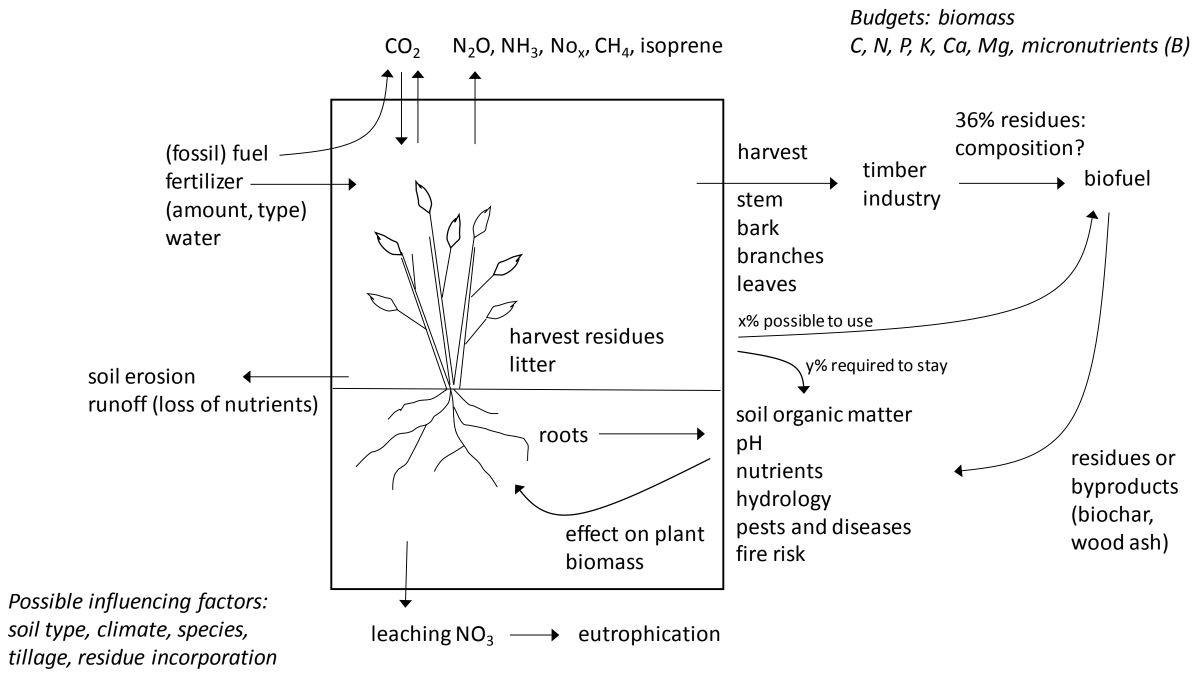

Fig. 1. In- and outputs in a *Eucalyptus* plantation. Percentages of harvest residues that can be used for biofuel production or that need to stay in the field are estimates based on expert judgement and need further investigation (see text). Residues from biofuel production may be biochar or wood ash.

4.1 Biomass production

The dry biomass of the different tree components does not increase equally over time, changing the relative contribution of the different tree components to total biomass production. The variation in composition of the different parts of the trees is considerable, with the wood comprising a large proportion of the total tree biomass (77%), while it contains a much smaller proportion of the nutrients (39%) compared to the harvest residues (Hernández *et al.* 2016). The proportion of wood biomass increases over time: 29% of half-year old trees consists of wood, quickly increasing to 71% in 1-2 year old trees and up to 84% in trees at 6-10 years age (Appendix Table A1). The biomass of wood and bark steadily increases over time, while the biomass of branches levels off and that of leaves even decreases over time (Appendix Table A1). As such, branches and leaves contribute a relatively large proportion to the biomass of young trees compared to older trees. However, biomass production differs significantly among species (Harrison *et al.* 2000, Zaia and Gama-Rodrigues 2004) and selection lines (Rosim *et al.* 2016), both in terms of total biomass production and in investment in the different tree components. Further, spacing of the seedlings influences the investment in the different tree components especially in the first years after planting (Leite *et al.* 2011). Trees that are planted at wider spacing invest relatively more biomass in leaves and bark, but less in wood. However, this difference decreases as time proceeds from 2.5 to almost 7 years after planting (Leite *et al.* 2011). After canopy closure, which is at a later age in wider spaced plantations, the total amount of leaf biomass decreases and the production of wood slows down as a result of an increased allocation of gross primary production to roots and foliar respiration (Ryan *et al.* 1997, Ryan *et al.* 2004). The information on root biomass is too scarce to describe its development over time.

When trees are grown as a coppice stand, total biomass production and allocation to the different tree components varies between the rotation cycles. Due to an increased tree density with several stems growing from each stump, individual tree volume in the second rotation is lower, but total tree volume produced per unit of area is higher than in the first rotation. Trees in a second rotation contain a relatively larger proportion of bark than trees in a first rotation (Miranda and Pereira 2016). As a consequence of differences in biomass allocation, nutrient removal from a site differs between first and second rotations in coppice stands.

4.2 Nutrient content in plant material

Young trees contain a relatively large proportion of biomass and nutrients in the leaves and branches (Leite *et al.* 2011, Witschoreck and Schumacher 2015; Appendix Tables A2 and A3). The concentration of nutrients in leaves, branches and bark is higher than in the stem wood. However, over time trees allocate relatively more biomass to wood (Appendix Table A1), so that, although the nutrient concentration in the wood is low, the total amount of nutrients in the wood per unit of planted area steadily increases (Appendix Tables A2 and A3). As trees grow, the total amount of macronutrients that is retained in the leaves per unit of area decreases. After 4-6 years, the wood contains more N and P than the other tree components, the amount of K, S, B, Cu, Fe and Zn is largest in the wood and the total amount of Ca, Mg and Mn is largest in the bark, especially in trees from 4 years onwards (Appendix Tables A2 and A3). Three and a half years after planting, the roots contained 20-35% of total N and 15-35% of total P in the trees, although detailed measurements are only known from a single study (Harrison *et al.* 2000). It should be noted that the averages are calculated from studies performed with different *Eucalyptus* species or clones, at different planting densities, in different soil types, with different amounts of fertilization added and in different climatic regions, which all may affect total nutrient content of the trees and explains the great variation around the mean (Appendix Tables A2 and A3). Many of these factors are covered by too few studies to generalize the results and part of the studies only report average values without any indication of variation. For example, Zaia and Gama-Rodrigues (2004) report a low biomass production and low nutrient concentration in the trees due to a low level of soil fertility and severe water restrictions. Leite *et al.* (2011) showed that planting densities did not significantly influence the nutrient concentration of the different tree components, whereas there was an optimum planting density for maximum biomass production that decreased over time, leading to different total amounts of nutrient removal from sites that were planted with different tree densities. Some studies explicitly mention the different nutrient concentrations and amounts of biomass produced by different *Eucalyptus* species (Harrison *et al.* 2000, Zaia and Gama-Rodrigues 2004), whereas others even find differences in productivity and nutrient use efficiency of different clones of a hybrid *Eucalyptus* (Rosim *et al.* 2016).

Leaving harvest residues in the field might alleviate the problem of nutrient removal from a site. Different scenarios exist of harvesting only the wood, wood with branches, wood with only bark, wood including bark and branches, or the whole tree including the leaves. We calculated nutrient removal of the different scenarios in two situations: 1) a theoretical situation where the trees would be fully separated into their different components (Appendix Tables A4 and A5), and 2) a more realistic situation where some of the bark remains on the wood and only part of the branches are removed from the field (Achat *et al.* 2015; Appendix Tables A6 and A7). The tables in the Appendix give detailed information about the number of studies and trees considered, as well as minimum and maximum recorded values in the studies. The choice of harvest scenario may depend on the age of the trees at harvest. If trees less than two years old are harvested, both the biomass and the export of most nutrients, except for Mg, of wood and branches is larger than that of wood and bark (Appendix Tables A1, A4 and A5). For trees between 4 and 10 years old, less biomass and N, P, K, S, B, Fe and Zn and far less Ca, Mg and Mn is removed with wood and branches, compared to removal of wood and bark. The amount of Cu that is removed does not differ between the two harvest scenarios for trees between 4 and 6 years old, but for trees between 6 and 10 years old more Cu is removed with wood and branches compared to wood and bark (Appendix Tables A4 and A5). The exact values of removed biomass and nutrients in the different harvest scenarios are closer in the more realistic than in the theoretical situation, but the conclusions remain the same (Appendix Tables A1, A6 and A7).

It should be realized that considerable amounts of nutrients are also exported with the wood. These nutrients need to be replaced in some way to maintain a sustainable production. Depending on the nutrient levels that are found in the soil, the use of mineral fertilizers is generally recommended in *Eucalyptus* plantations, as well as the use of organic amendments to improve the organic matter content of the soil (Santarosa et al. 2014). Normal applications in average rotations of 7 years are up to 2 Mg ha^{-1} of lime, 60–80 kg ha^{-1} of N, 60–80 kg ha^{-1} of P_2O_5, 140–160 kg ha^{-1} of K_2O, 1–5 kg ha^{-1} of B depending on local water deficit, and 1 kg ha^{-1} of Cu and Zn (Gonçalves *et al.* 2013). These fertilizers are not added in a single application, but are split and timed for optimal uptake by the trees. Increasing levels of fertilization beyond current operational rates does not further increase biomass production, whereas irrigation does (Stape *et al.* 2010).

4.3 Decomposition of plant material

Litterfall consists of leaves and branches that are left on the ground to decompose. Deposition of litterfall in a *Eucalyptus* plantation was twice as high as in a native forest, while also the proportion remaining after six months of incubation *in situ* was highest in *Eucalyptus* plantations (Pinto *et al.* 2016). During decomposition of litterfall material, about 30 % of the contained K will be released in one year due to mineralization (Leite *et al.* 2011). The concentration of the other macronutrients N, P, Ca and Mg in the litterfall did not change significantly within one year (Leite *et al.* 2011). However, this study did not mention if the biomass and thus the total amount of nutrients in the litter bags changed. In another study, leaf litter biomass decreased with about 40% of the initial biomass remaining after two years of decomposition (Bachega *et al.* 2016). The concentration of N and P in the litter increased over time.

Eucalyptus may be mixed with leguminous trees as provider of biologically fixed nitrogen. Tree species that are used for this purpose are for example *Acacia*, an exotic tree, and Guachapele (*Pseudosamanea guachapele*), which is native to Central America and Mexico. The initial decomposition of litter originating from *Eucalyptus* was faster than that from *Acacia*, although initial concentrations of N and P were higher in the *Acacia* leaves (Bachega *et al.* 2016). Decomposition was related to litter quality (e.g. easily degradable compounds *vs*. lignin) and to P availability, with a higher N:P ratio for the *Acacia* than for the *Eucalyptus* leaves. It is likely that adding *Acacia* leaves will change the rate of decomposition of *Eucalyptus* leaves. The release of N, K and Mg was faster from Guachapele leaves and a mixture of Guachapele and *Eucalyptus* leaves than from *Eucalyptus* leaves alone (Balieiro *et al.* 2008). The guachapele trees could contribute between 59 to 108 kg N ha^{-1} y^{-1} from biological nitrogen fixation (Balieiro *et al.* 2008). In addition to contributing to N fertilization, Guachapele leaves could accelerate the decomposition of *Eucalyptus* leaves and thus the possible availability of nutrients for the trees. However, nutrients that are released from decomposing plant litter do not necessarily become all available for plant growth, as they may, at least initially, be incorporated in the decomposer microorganisms (Swift *et al.* 1979) or be lost by leaching (Paré and Thiffault 2016).

Harvest residues may consist of leaves, branches and bark that are left on the ground, or be incorporated into the soil. Piling of harvest residues has a different effect than spreading the residues evenly over the soil: piled residues are more prone to leaching of nutrients to the groundwater (Lattimore *et al.* 2009). As with the litter, nutrients that are retained in harvest residues do not all become available for plant growth (Paré and Thiffault 2016). In general, recovery rates of Ca and Mg are rather high, whereas that of K is much lower as it easily leaches out of the soil profile. Further, the nutrients may not all be released at the time that the demand of the tree is highest (Paré and Thiffault 2016). Maintaining bark with the harvest residues in a *Eucalyptus* plantation reduced nutrient removal of the plantation and increased the decomposition rate of the residues, which decreased the half-life time from 1.44 to 1.13 years (de Souza *et al.* 2016). When harvest residues were incorporated into the soil, the half-life time decreased to about the same extent (de Souza *et al.* 2016). However, these effects did not occur in all the soils that were studied. Both environmental and soil conditions are important for the decomposition of harvest residues (de Souza *et al.* 2016). Factors leading to higher decomposition rates (MAP (Mean annual precipitation), T_{max}, MAT (Mean annual temperature), sand content, and soil pH), were negatively correlated to SOC content, both for the POM (Particulate organic matter; fraction >53 µm) and MAC (Mineral associated carbon; fraction < 53 µm) fractions. Otherwise, those variables leading to slower decomposition rates (clay content and exchangeable Al) were positively correlated to the C content within the POM and MAC fractions. MAP and pH together explained 74% of the variation of half-life time.

5. Effects of residue management on biomass production and soil parameters

Harvest residues consist of treetops, thick branches, twigs, leaves, bark, but also stems that are accidently left behind in the field. Depending on the requirements by the company and the harvesting method, the quantity and composition of the residues that are left in the field may vary (Foelkel 2007, Achat *et al.* 2015). Machine harvesting may remove about 80% of the bark, whereas this is not possible when harvesting by chainsaw; in that case about 20% of the bark is removed (Achat *et al.* 2015). Requirements of industrial companies about minimum and maximum stem diameter cause that some trees or parts of trees are left in the field. Further, sectioning the stems in shorter logs, removing thick branches and cutting the stem unnecessarily high above the ground may lead to wood losses of 2-8% (Foelkel 2007). The thin wood that may not be of interest to the pulp industry may be collected by smaller companies to be used as firewood (Foelkel 2007), but maybe also for biofuel production. In short rotation coppice, the tree is harvested including branches and leaves, because *Eucalyptus* does not shed leaves in the dry season and removing leaves of the young trees is costly (Eufrade *et al.* 2016). However, removing the stems from the field with a delay may allow the foliage to dry and fall off the branches (Achat *et al.* 2015), although this requires another round of entering the field, which is expensive and may further damage soil structure. The focus on increasing sustainability of the production in short rotation coppice generally is on selecting trees with smaller crowns, which reduces the amount of litter that is exported from a site when the whole tree is harvested, and on fertilization management (Eufrade *et al.* 2016).

5.1 Biomass production

Retention of harvest residues may have different effects depending on site properties and management, and depending on plantation age (Mendham *et al.* 2014). In the short term, removal of harvest residues may not affect biomass production at a productive site, but after several rotations biomass production declined (Mendham *et al.* 2014). However, a decrease in production may appear at an earlier stage in Brazilian soils, which are generally less productive as they often are low in nutrient content. The type of residue management in a replanted *Eucalyptus* plantation had effects on productivity of the trees. Eight years after planting, the biomass production of the trees was 88% when harvest residues were removed compared to when harvest residues were retained (Rocha *et al.* 2016) and even decreased to 63% when also the litter was removed (Gonçalves *et al.* 2007, Rocha *et al.* 2016). After harvesting the trees and remaining harvest residues in all treatments, the differences were smaller but still visible in the replanted trees (Rocha *et al.* 2016). The response to forest residue management in wood productivity was higher than in similar studies of *Eucalyptus* forests in other regions. Probably in tropical wet conditions and low fertility soils, the maintenance of forest residues has a greater influence on site productivity than in temperate conditions (Rocha *et al.* 2016). This difference mainly seems due to a deficiency in P and Ca, where N probably becomes limiting only after a few rotations. This may be typical for a site with low original soil fertility and seasonal water deficit (Gonçalves *et al.* 2007). Other studies showed an even stronger effect of harvest residue removal (73% of the biomass when residues are retained), while also the removal of thick branches (> 3 cm diameter) and bark caused a decrease to 84% (Paes *et al.* 2013). They mainly attributed the decrease to nutrient removal. In addition, they pointed out that residues that remain on the ground increase the water availability in the upper soil layer at least in the first years after planting (Dedecek *et al.* 2007) and protect the soil from compaction by harvesting machines, which improves growth conditions for the roots. Further, harvest residues that remain on the ground prevent soil erosion and water run-off, especially in the first years after planting when litter fall from the trees and ground cover by understory plants is limited (Cândido *et al.* 2014). Harvest residues that remain on the ground also reduce the germination of weeds and therewith increase the availability of light and water for the planted trees (Paré and Thiffault 2016). Competition with weeds is mainly important in early stages of tree growth before the canopy is closed (Gonçalves *et al.* 2013).

The studies that describe effects of harvest residues all use an approach comparing removal of all harvest residues with either leaving different compartments of the trees, or adding an additional amount of residues. However, we are not aware of studies that modify the fraction of harvest residues that is left behind. This knowledge gap has also been noticed in other production systems like sugarcane, advising to give site specific recommendations of the amount of residues that need to be left behind (Carvalho *et al.* 2017). Recommendations on the fraction of harvest residues that should be left in temperate and boreal forests with long rotation cycles range from 20 to 50% and are merely based on expert judgement (Titus *et al.* 2009, Lamers *et al.* 2013, de Jong *et al.* 2017). The advice distinguishes between the amounts of aboveground tree parts and stumps. Aboveground tree parts contain the larger amount of especially base cations, but stump removal has a large impact disrupting soil structure and mixing layers. Factors that are taken into account are acidification, eutrophication, toxicity to the environment and biodiversity. The authors stress that recommendations need to be site specific, so extrapolating these figures to tropical conditions on low fertile soils only may be used as a starting point for further investigation.

5.2 Soil organic matter

In a worldwide survey on effects of whole-tree harvesting, Wall (2012) arrived at the conclusion that mitigation was needed to avoid decline of organic matter and a too high removal of nutrients. Mitigation activities concentrate on leaving behind the leaves as residues. Effects on SOM of whole-tree harvesting however strongly depend on residue production during tree growth and thus on the tree species involved and the duration of a cropping cycle, as older trees generally produce more litter than young trees.

For Brazil, (Fialho and Zinn 2014) arrived in an extensive literature review at the conclusion that for 0-20 and 20-40 soil depth, SOM did not change significantly for 1st and 2nd Eucalyptus rotation crops. Similarly, a study of over 300 sites in Brazil showed that overall soil carbon stocks slightly decreased during 3 *Eucalyptus* rotations over a period of about 20 years of *Eucalyptus* cultivation, while for the region of São Paulo soil carbon stocks did not significantly change over time (Cook *et al.* 2016).

Mendham *et al.* (2002b) considered the effects of *Eucalyptus* residues at 2 soil types in Australia. Residues consisted of 9 Mg/ha leaves + branches + 8 Mg/ha bark for the grey sand site and for the red earth site 12 + 13 Mg/ha resp. Treatments were (1) burn all residues (B; not allowed in Brazil), (2) remove all residues (0R), spread residues evenly (1R), and idem but double the amount of residues (2R). Effects on SOM or soil total N were absent after 1 and 5 years after treatments at soil depths 0-5, 5-10 and 10-20 cm and the effect on permanganate oxidizable C (which is a measure for SOM) was quite limited (only an increase at the red earth site at soil layer 0-5 cm for the 2R treatment). Microbial biomass generally increased with higher residues amounts, especially 1 year after application and in more so in the top soil layers. Where there were effects on microbial biomass, they were in the order of magnitude of an increase of maximum a doubling (when 0R was compared with 2R). The higher microbial biomass likely lead to higher SOM turnover and thus may explain the limited effect on SOM content. It is also possible that the duration of the experiment (5 years) was too limited to find any differences.

Laclau *et al.* (2010) looked in the Congo at *Eucalyptus* performance as function of organic residue maintenance (ranging from 0-46.5 Mg/ha). There was a strong, positive correlation between organic matter amount and yield which was ascribed to nutrient maintenance in the residues. This could not be confirmed by nutrient analysis of the top 0-5 cm soil layer. The stands did receive artificial fertilizer also, so the residues may have acted as slow-release fertilizers.

On top of the above-mentioned positive effects of *Eucalyptus* plantations on SOM, mixing *Eucalyptus* with N-fixing tree species (*Albizia*, *Acacia*), increases SOM relative to *Eucalyptus* monocultures (e.g. Kaye *et al.* 2000, Resh *et al.* 2002, O'Brien *et al.* 2003, Macedo *et al.* 2008, Forrester *et al.* 2013). This effect may become apparent only after some time, probably because in an early phase litter production by *Eucalyptus* is higher than that of *Acacia*. This may explain that, contrary to the before-mentioned studies, Voigtlaender *et al.* (2012) reported a Brazilian experiment where after 6 years, SOM stocks were 66% less in *Eucalyptus*/*Acacia* mixtures relative to the pure *Eucalyptus* stands.

In conclusion, SOM effects depend on land use history, but if plantations are established on poor soils, the effects are likely to be positive. It is recommendable that at harvest leaves are left behind and also mixing *Eucalyptus* with N-binding trees is recommendable.

6. Addition of industrial rest products to soil

6.1 Biochar

Biochar is one of the rest products from the production of biofuel. It is a carbon rich product that is formed during the pyrolysis of biomass. The application of biochar to soil is advocated for several reasons, including carbon sequestration and enhancement of soil fertility (Jeffery *et al.* 2015). However, there may also be downsides and trade-offs in the production and use of biochar. Jeffery *et al.* (2015) discussed the possibilities to maximize all mentioned benefits simultaneously, and conclude that this is not realistic. A relevant trade-off in the pyrolysis process is that between energy or biofuel production and biochar production: adjusting the pyrolysis process in such a way that biochar production is maximized, will lead to a decrease in energy production. With regard to the pyrolysis conditions, fast and slow pyrolysis can be distinguished. Fast pyrolysis is intended to maximize the biofuel production and reduces the amount of biochar produced with respect to slow pyrolysis. IEA (2006) indicated that the proportion of biochar produced from the initial feedstock is about 12% with fast pyrolysis and 35% with slow pyrolysis. However, if the stability of the biochar from fast pyrolysis is higher than that of slow pyrolysis, it could lead to the same C abatement value (Crombie *et al.* 2013).

The stability of the biochar depends on several factors, among which are pyrolysis conditions, local climatic conditions, soil type and soil biota (Jeffery *et al.* 2015). The effect of the properties of the feedstock on the chemical and physical composition of the biochar is stronger at lower pyrolysis temperatures, whereas differences become smaller at higher pyrolysis temperatures (McBeath *et al.* 2014). Biochars that are made of wood usually contain a high percentage of aromatic compounds, which means that they are relatively stable, and are estimated to have a mean residence time of at least several centuries in the soil (McBeath *et al.* 2014). Lopez-Capel *et al.* (2016) indicated that there is a trade-off between biochar stability and reactivity: with increasing aromaticity the stability increases and the reactivity decreases. In general, the hydrogen and oxygen contents of biomass are decreasing with increasing pyrolysis temperature, while the carbon content and stability are increasing.

With an increasing pyrolysis temperature, the concentration of nutrients in biochar from wood increased (Enders *et al.* 2012). This can be explained by the relatively high loss of hydrogen and oxygen contents at high temperature. Lopez-Capel et al. (2016) indicated that about 50% of N that is originally present in the feedstock is getting lost during the pyrolysis process, but that almost all P, K, Ca, Mg and trace elements in the feedstock will end up in the biochar. This means that most nutrients in the feedstock may be recycled to the soil as biochar, provided that it is clean and safe and has no adverse effects on soil quality. However, the increase in soil fertility when biochar is applied is highly variable (Jeffery *et al.* 2015). Biochars made from wood generally contain low amounts of nutrients compared to biochars made from other feedstocks, supporting smaller increases in plant productivity (Jeffery *et al.* 2015). Average values of N, P and K contents in biochar made from wood vary between 1 and 10 g per kg biochar (Lopez-Capel *et al.* 2016), but in addition to the total nutrient content, the availability of the nutrients to plant growth is also of importance (Angst and Sohi 2013).

In addition to the positive contribution of biochar to nutrient availability, biochar application may affect other chemical, physical and biological soil properties (Cross *et al.* 2016). Effects mentioned in various studies are an increased cation exchange capacity (CEC), water holding capacity, drainage capacity, liming effect (pH increase of acid soils) and an increased abundance of soil microbes (e.g. Biederman and Harpole 2013, Jeffery *et al.* 2015, Cross *et al.* 2016). Several research experiments show that biochar can reduce nutrient leaching mainly by increasing water holding capacity and cation exchange capacity (CEC) of soils (Atkinson *et al.* 2010, Biederman and Harpole 2013). Regarding nitrogen leaching in particular, Zheng *et al.* (2013) and Clough and Condron (2010) also reported decreased leaching due to enhanced N immobilization and ammonia adsorption.

The above mentioned effects of biochar on soil fertility aspects can be explained with the properties of the biochar itself. Kuppusamy *et al.* (2016) summarizes the nature of biochar with the terms “aromatic structure”, “surface functionality” and “sorptive characteristics” describing well the stable structure with large sorption surface leading to a limitation of losses to the environment of carbon and minerals. The high stability and sorption capacity of biochar does not only bring advantages from an agronomic perspective: nitrogen immobilization can lead to limitations in crop N uptake and thus crop yields (Gonzaga *et al.* 2017), pesticides such as herbicides could be reduced in their effectiveness (see further) and toxins and heavy metals could be applied together with the biochar (see further; Kuppusamy *et al.* 2016).

Effects of biochar addition may be plant species dependent, increasing the growth of some plant species while suppressing the growth of others (Lehmann *et al.* 2011, van de Voorde *et al.* 2014). It is therefore important to determine the effect on the intended plant species. More in general, Biederman and Harpole (2013) showed in a meta-analysis that biochar application to soil resulted in an increased plant productivity and reduced nutrient leaching.

Biochar addition has variable effects on soil organisms. In many cases, addition of biochar increased mycorrhizal infection of roots and total microbial biomass. However, negative effects on soil microbes have been reported as well and effects may vary among different groups of organisms (Lehmann *et al.* 2011). Effects on soil fauna have been less well studied: earthworms mostly showed a positive response to biochar addition, while in other cases the effect was negative. The few studies on nematodes showed an increase in abundance in response to biochar addition (Lehmann *et al.* 2011, McCormack *et al.* 2013). Some plant diseases are suppressed when biochar is added to the soil, whilst others are enhanced. Further, pesticides and herbicides may be less effective when adsorbed to biochar, whereas environmental benefits may be a decreased uptake of these chemicals by the crop and decreased leaching (Lehmann *et al.* 2011).

Biochars contain a higher salinity and concentration of heavy metals, which may be toxic, than the original feedstocks from which they are produced (Domene *et al.* 2015) and could release organic contaminants like phenol, polycyclic aromatic hydrocarbons and dioxin (Qadeer *et al.* 2017). Biochar from clean wood generally contains low amounts of toxic compounds, whereas biochar made from waste products like urban waste contains much higher levels of toxic compounds (Domene *et al.* 2015). On the other hand, biochar may be used to bind persistent organic pollutants and pesticides in contaminated soils (Jeffery *et al.* 2015). Biochar from wood was not toxic to collembola (a proxy for soil organisms) when applied in commonly used dosages of < 20 Mg $\cdot$ ha^{-1}, but toxicity increased when higher dosages were applied (Domene *et al.* 2015). The authors propose that bioassays should be performed to assess toxicity, as chemical analysis only can cover a limited amount of targeted compounds. It should be kept in mind that toxic compounds may accumulate when biochar is repeatedly added to the soil.

6.2 Wood ash

Ash is another by-product of biofuel production. Biomass ashes composition includes mostly (a) inorganic matter, composed of non-crystalline (amorphous) and crystalline to semi-crystalline (mineral) constituents, (b) an amount of subordinately organic matter, consisting of char and organic minerals; and (c) some fluid matter (Vassilev *et al.* 2013). The composition and properties of wood ash are dependent on the feedstock and combustion process. Hardwood tree ashes, like ash from *Eucalyptus* trees, generally contain more K and P than softwood tree ashes but less Ca (Pitman 2006). Ashes from combustion of bark or foliage contain up to ten times more nutrients than ashes from stemwood (Pitman 2006). The temperature of combustion and the type of boiler will also influence the amount of ash produced from the feedstock and the concentrations of elements. Volatilization of K and S occurs above 800-900°C and 1000-1200°C respectively, resulting in strong reduction in K and S concentrations (Pitman 2006). Fly ashes contain higher nutrient contents but also higher concentrations of heavy metals compared to the coarser bottom ashes (Pitman 2006). Wood ashes also contain heavy metals, especially cadmium, copper, chromium, lead and arsenic and the organic contaminants PAH, PCB and dioxins. Heavy metals can be phytotoxic, however, no significant effect of ash additions on soil solution concentrations in forest soils is detected for most heavy metals (Pitman 2006, Augusto *et al.* 2008). Heavy metals are bound to the soil organic matter and the rise in pH due to ash additions decreases the solubility of the metals. No negative effects were observed on soil biota or fauna or vegetation, except for a very short time period after application, most notably in soil fungi (Augusto *et al.* 2008). Concentrations of organic microcontaminants are considered too low to affect ecosystem functioning (Pitman 2006).

Bringing back ashes to soil may increase growth conditions for the trees (de Jong *et al.* 2017). Wood ash is noted for its acid neutralizing capacity and supply of base cations Ca, Mg and K (Saarsalmi *et al.* 2001). Common median values for nutrients in wood ashes are 250 mg g C, 200 mg g^{-1} Ca, 30 mg g^{-1} K, 15 mg g^{-1} Mg, 3 mg g^{-1} P and less than 1 mg g^{-1} N, however these values show wide range of variation (Augusto *et al.* 2008). Ca is mainly present mainly as $CaCO_3$, which is formed during the combustion process. The neutralizing value of the wood ashes is 50% compared to limestone (Pitman 2006).

Effect of ash application on the soil pH are long lasting, with increases in pH of up to 2.5 units after 6-16 years (Saarsalmi *et al.* 2001, Pitman 2006, Augusto *et al.* 2008). The increase in pH stimulates the activity of the soil microflora (Bang-Andreasen *et al.* 2017), with concomitant increase in soil organic matter mineralization. Soil fauna is not adversely affected by the ash application (Pitman 2006, Augusto *et al.* 2008, Qin *et al.* 2017), however shifts in faunal composition – enchytraeids to earthworms- due to increases in pH have been observed (McCormack *et al.* 2013) Ash addition results in significant higher concentrations of cations in the soil solution. These higher concentrations do not increase growth by increased uptake or nutritional status of the roots or aerial parts of forest trees on mineral soils, where growth is generally N-limited (Pitman 2006, Augusto *et al.* 2008). On organic soils, tree growth is enhanced by improved uptake of N, K, Ca, P and B, and this effect is long-lasting. The higher bioavailability of the base cations is primed by the rise in soil pH and consequent organic matter decomposition. The growth promotion is thus primarily a liming effect rather than a fertilization effect (Augusto *et al.* 2008).

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Appendix.

Table A1. Weighed average biomass removal (tonnes · ha^{-1}; based on number of sampled trees) with different harvest intensities of *Eucalyptus* trees of different age classes, minimum and maximum reported average value, number of sampled trees (X) and number of publications from which data were extracted (Y). Two scenarios are presented: potential biomass when the different tree parts are fully separated, and a more realistic scenario where some of the bark and branches are left in the plantation. In the realistic scenario it is assumed that with the wood-only harvest, still 20% of the bark is removed from a site; with wood+bark harvest, 80% of the bark is removed; with wood+bark+branches harvest, 80% of the bark and 60% of the branches is removed; with whole tree harvest, 80% of the bark, 60% of the branches and all the leaves are removed (see Achat et al. 2015). In cases where minimum and maximum values do not differ from the mean, only one average value was given in a publication.

Age		Potential			Realistic		
(years)	Harvest intensity	mean	min; max	X; Y	mean	min; max	X; Y
<1	wood	0.7	0.6; 0.8	6; 1	0.7	0.6; 0.8	6; 1
	wood+bark	0.9	0.8; 1.0	6; 1	0.9	0.7; 1.0	6; 1
	wood+branches	1.3	1.1; 1.6	6; 1	1.1	1.0; 1.3	6; 1
	wood+bark+branches	1.5	1.3; 1.8	6; 1	1.2	1.1; 1.4	6; 1
	whole tree	2.4	2.1; 2.8	6; 1	2.1	1.9; 2.4	6; 1
1-<2	wood	30	7; 59	60; 2	31	7; 60	60; 2
	wood+bark	34	8; 63	60; 2	33	8; 62	60; 2
	wood+branches	36	13; 64	60; 2	34	11; 63	60; 2
	wood+bark+branches	40	15; 69	60; 2	37	12; 65	60; 2
	whole tree	43	19; 72	60; 2	40	16; 69	60; 2
2-<4	wood	37	13; 59	41; 2	38	14; 61	41; 2
	wood+bark	36	17; 67	61; 3	41	16; 66	41; 2
	wood+branches	43	15; 68	61; 3	42	15; 66	41; 2
	wood+bark+branches	42	19; 76	61; 3	45	18; 71	41; 2
	whole tree	47	22; 85	61; 3	51	20; 80	41; 2
4-<6	wood	67	51; 83	33; 3	69	52; 85	33; 3
	wood+bark	76	59; 94	33; 3	75	57; 92	33; 3
	wood+branches	74	55; 90	33; 3	73	55; 87	33; 3
	wood+bark+branches	83	62; 99	33; 3	79	59; 94	33; 3
	whole tree	87	65; 105	33; 3	82	62; 97	33; 3
6-10	wood	150	73; 167	81; 2	154	76; 171	81; 2
	wood+bark	167	84; 186	81; 2	164	82; 182	81; 2
	wood+branches	158	78; 176	81; 2	158	78; 176	81; 2
	wood+bark+branches	175	89; 195	81; 2	168	85; 188	81; 2
	whole tree	178	91; 198	81; 2	172	87; 191	81; 2

Data source: Zaia and Gama-Rodrigues (2004), Leite *et al.* (2011), Viera *et al.* (2012), Viera *et al.* (2013), Gatto *et al.* (2014), Guimaraes *et al.* (2015), Viera *et al.* (2015), Eufrade *et al.* (2016), Rosim *et al.* (2016).

Table A2. Weighed average content of N, P, K, Ca, Mg and S ($kg \cdot ha^{-1}$) in different parts of *Eucalyptus* in trees of different age classes, minimum and maximum reported average value, number of sampled trees (X) and number of publications from which data were extracted (Y). In cases where minimum and maximum values do not differ from the mean, only one average value was given in a publication.

Age		N			P			K			Ca			Mg			S		
(years)	Tree part	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y
<1	leaves	32	30; 35	6; 1	1.8	1.4; 2.2	6; 1	7	6; 9	6; 1	7	6; 7	6; 1	1.7	1.6; 1.7	6; 1	1.8	1.7; 1.8	6; 1
	branches	4	4; 5	6; 1	0.5	0.4; 0.5	6; 1	5	4; 6	6; 1	4	3; 4	6; 1	0.7	0.7; 0.7	6; 1	0.3	0.2; 0.3	6; 1
	bark	1	1; 1	6; 1	0.1	0.1; 0.1	6; 1	1	1; 1	6; 1	2	2; 2	6; 1	0.4	0.3; 0.4	6; 1	0.1	0.1; 0.1	6; 1
	wood	4	4; 4	6; 1	0.4	0.4; 0.4	6; 1	4	4; 5	6; 1	1	1; 1	6; 1	0.4	0.4; 0.4	6; 1	0.2	0.2 0.2	6; 1
1-<2	leaves	63	26; 107	60; 2	3.7	1.3; 6.8	60; 2	27	14; 43	60; 2	25	7; 42	60; 2	7.4	3.4; 10.5	60; 2	4.9	4.9; 4.9	24; 1
	branches	18	10; 23	60; 2	2.1	1.0; 3.0	60; 2	24	12; 36	60; 2	52	13; 90	60; 2	8.1	3.8; 10.4	60; 2	1.6	1.6; 1.6	24; 1
	bark	13	6; 21	60; 2	1.2	0.8; 2.1	60; 2	17	10; 28	60; 2	42	17; 71	60; 2	9.5	3.9; 20.2	60; 2	0.4	0.4; 0.4	24; 1
	wood	38	15; 59	60; 2	3.6	2.1; 5.9	60; 2	36	25; 49	60; 2	30	14; 53	60; 2	6.8	3.3; 11.8	60; 2	1.5	1.5; 1.5	24; 1
2-<4	leaves	113	49; 224	142; 5	7.7	2.8; 14.7	142; 5	37	21; 74	115; 4	42	15; 73	115; 4	13.5	4.9; 34.5	115; 4	5.2	5.2; 5.2	20; 1
	branches	21	6; 40	142; 5	3.5	0.8; 6.3	142; 5	25	6; 33	115; 4	62	7; 107	115; 4	9.7	1.1; 17.7	115; 4	4.3	4.3; 4.3	20; 1
	bark	18	8; 28	122; 4	2.8	0.6; 5.9	122; 4	27	14; 55	95; 3	97	39; 151	95; 3	16.7	6.5; 29.0	95; 3			
	wood	51	8; 97	122; 4	9.1	1.3; 24.3	122; 4	58	17; 121	95; 3	31	13; 64	95; 3	9.3	2.2; 24.3	95; 3			
	roots	82	38; 71	32; 2	3.7	2.6; 5.2	32; 2	56	38; 68	5; 1	141	86; 178	5; 1	21.2	14.4; 25.7	5; 1			
	litter	88	88; 88	54; 1	5.0	4.9; 5.1	54; 1	20	17; 22	54; 1	150	108; 178	54; 1	19.9	15.2; 23.0	54; 1			
	forest floor	48	30; 65	21; 1	2.1	1.3; 2.8	21; 1	12	7; 16	21; 1	80	49; 107	21; 1	12.7	7.8; 17.0	21; 1			
4-<6	leaves	103	40; 131	75; 4	7.9	2.1; 11.6	75; 4	42	26; 50	75; 4	41	10; 59	75; 4	14.4	3.4; 21.6	75; 4	6.3	6.0; 7.1	12; 2
	branches	32	15; 39	75; 4	4.1	1.6; 6.2	75; 4	37	28; 56	75; 4	70	12; 106	75; 4	15.2	2.9; 22.8	75; 4	3.4	3.4; 6.3	12; 2
	bark	32	17; 42	75; 4	4.9	1.7; 6.7	75; 4	56	35; 144	75; 4	159	50; 195	75; 4	28.3	6.6; 43.8	75; 4	3.9	1.6; 4.7	12; 2
	wood	113	51; 171	75; 4	13.6	2.5; 23.1	75; 4	114	19; 144	75; 4	61	12; 88	75; 4	27.4	1.9; 49.6	75; 4	26	24.8; 26.4	12; 2
	roots	89	50; 127	9; 2	7.4	5.7; 10.1	9; 2	61	30; 81	9; 2	166	113; 202	9; 2	27	19.7; 34.3	9; 2	9.5	9.5; 9.5	3; 1
	litter	93	52; 121	45; 2	6.1	3.6; 7.4	45; 2	20	3; 24	45; 2	197	72; 238	45; 2	28.1	15.1; 33.4	45; 2	7.9	7.9; 7.9	3; 1
	forest floor	116	84; 134	21; 1	4.4	3.2; 5.0	21; 1	33	24; 39	21; 1	112	81; 129	21; 1	18.9	13.7; 21.8	21; 1			
6-10	leaves	70	42; 101	114; 3	4.3	2.1; 6.8	114; 3	30	22; 41	114; 3	23	9; 31	114; 3	8.9	4.0; 13.5	114; 3	4.0	4.0; 4.0	60; 1
	branches	34	17; 39	114; 3	3.5	1.5; 4.1	114; 3	34	19; 38	114; 3	61	12; 74	114; 3	16.3	2.6; 21.0	114; 3	3.0	3.0; 3.0	60; 1
	bark	62	28; 75	114; 3	10.8	3.3; 15.0	114; 3	102	50; 131	114; 3	301	46; 429	114; 3	66.6	12.5; 92.0	114; 3	11.0	11.0; 11.0	60; 1
	wood	182	73; 266	114; 3	16.5	3.7; 32.2	114; 3	138	51; 210	114; 3	95	22; 170	114; 3	27.4	4.4; 57.7	114; 3	13.0	13.0; 13.0	60; 1
	roots	120	110; 131	6; 1	9.7	9.0; 10.5	6; 1	71	60; 81	6; 1	196	171; 221	6; 1	36.4	27.2; 45.6	6; 1			
	litter	134	114; 139	96; 2	6.1	5.5; 7.1	96; 2	17	15; 23	96; 2	166	143; 243	96; 2	35.4	23.6; 39.0	96; 2	8.0	8.0; 8.0	60; 1
	forest floor	147	108; 171	21; 1	5.0	3.6; 5.8	21; 1	18	14; 21	21; 1	84	62; 98	21; 1	16.5	12.2; 19.3	21; 1			

Data source: Harrison *et al.* (2000), Zaia and Gama-Rodrigues (2004), Leite *et al.* (2011), Viera *et al.* (2012), Viera *et al.* (2013), Gatto *et al.* (2014), Guimaraes *et al.* (2015), Witschoreck and Schumacher (2015), Eufrade *et al.* (2016), Rosim *et al.* (2016).

Table A3. Weighed average content of B, Cu, Fe, Mn and Zn (g · ha^{-1}) in different parts of *Eucalyptus* in trees of different age classes, minimum and maximum reported average value, number of sampled trees (X) and number of publications from which data were extracted (Y). In cases where minimum and maximum values do not differ from the mean, only one average value was given in a publication.

Age (years)	Tree part	B			Cu			Fe			Mn			Zn		
		mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y
<1	leaves	36	29; 44	6; 1	11	10; 13	6; 1	96	84; 108	6; 1	2071	2030; 2133	6; 1	19	17; 21	6; 1
	branches	10	9; 11	6; 1	5	4; 5	6; 1	11	10; 13	6; 1	682	682; 683	6; 1	8	7; 9	6; 1
	bark	6	5; 8	6; 1	1	1; 1	6; 1	5	5; 5	6; 1	314	293; 335	6; 1	1	1; 2	6; 1
	wood	5	4; 5	6; 1	4	3; 4	6; 1	6	6; 6	6; 1	191	186; 196	6; 1	8	6; 9	6; 1
1-<2	leaves	110	110; 110	24; 1	40	40; 40	24; 1	200	200; 200	24; 1	9986	9986; 9986	24; 1	70	70; 70	24; 1
	branches	74	74; 74	24; 1	41	41; 41	24; 1	110	110; 110	24; 1	6494	6494; 6494	24; 1	68	68; 68	24; 1
	bark	34	34; 34	24; 1	5	5; 5	24; 1	41	41; 41	24; 1	2265	2265; 2265	24; 1	13	13; 13	24; 1
	wood	35	35; 35	24; 1	26	26; 26	24; 1	110	110; 110	24; 1	969	969; 969	24; 1	62	62; 62	24; 1
2-<4	leaves	160	160; 160	20; 1	20	20; 20	20; 1	830	830; 830	20; 1	600	600; 600	20; 1	40	40; 40	20; 1
	branches	50	50; 50	20; 1	20	20; 20	20; 1	410	410; 410	20; 1	550	550; 550	20; 1	40	40; 40	20; 1
4-<6	leaves	78	18; 194	30; 2	25	12; 43	30; 2	1350	464; 2078	30; 2	2197	797; 4468	30; 2	54	17; 118	30; 2
	branches	69	42; 108	30; 2	37	14; 81	30; 2	372	269; 578	30; 2	2884	936; 6911	30; 2	51	18; 117	30; 2
	bark	207	134; 319	30; 2	36	26; 46	30; 2	759	190; 1343	30; 2	7117	3253; 13623	30; 2	60	37; 84	30; 2
	wood	423	326; 531	30; 2	139	112; 183	30; 2	1801	1234; 2623	30; 2	1492	499; 3495	30; 2	296	244; 398	30; 2
	roots	221	221; 221	3; 1	97	97; 97	3; 1	25783	25783; 25783	3; 1	2091	2091; 2091	3; 1	335	335; 335	3; 1
	forest floor	549	396; 633	21; 1	23	17; 27	21; 1	25388	18312; 29299	21; 1	7337	5292; 8467	21; 1	549	396; 633	21; 1
6-10	leaves	64	49; 90	21; 1	25	21; 39	81; 2	298	158; 982	81; 2	1406	907; 1684	81; 2	25	20; 38	81; 2
	branches	89	71; 120	21; 1	59	52; 108	81; 2	206	155; 476	81; 2	2376	997; 2768	81; 2	74	21; 91	81; 2
	bark	188	147; 221	21; 1	55	32; 60	81; 2	542	446; 671	81; 2	6981	2930; 8111	81; 2	80	26; 97	81; 2
	wood	266	191; 327	21; 1	262	73; 318	81; 2	4040	3120; 8190	81; 2	2715	1725; 2956	81; 2	924	810; 1535	81; 2
	litter				151	151; 151	60; 1	14857	14857; 14857	60; 1	8471	8471; 8471	60; 1	278	278; 278	60; 1
	forest floor	437	321; 509	21; 1	187	138; 218	21; 1	45397	33386; 52922	21; 1	7881	5796; 9187	21; 1	437	321; 509	21; 1

Data source: Leite *et al.* (2011), Viera *et al.* (2012), Viera *et al.* (2013), Guimaraes *et al.* (2015), Viera *et al.* (2015), Eufrade *et al.* (2016).

Table A4. Weighed average potential (theoretical) amount of N, P, K, Ca, Mg and S (kg · ha^{-1}) that is removed with different harvest intensities of *Eucalyptus* trees of different age classes, minimum and maximum reported average value, number of sampled trees (X) and number of publications from which data were extracted (Y). In cases where minimum and maximum values do not differ from the mean, only one average value was given in a publication.

Age		N			P			K			Ca			Mg			S		
(years)	Harvest intensity	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y
<1	wood	4	4; 4	6; 1	0.4	0.4; 0.4	6; 1	4	4; 5	6; 1	0.8	0.8; 0.8	6; 1	0.4	0.4; 0.4	6; 1	0.2	0.2; 0.2	6; 1
	wood+bark	5	5; 6	6; 1	0.5	0.5; 0.5	6; 1	5	5; 6	6; 1	3	3; 3	6; 1	0.8	0.7; 0.8	6; 1	0.3	0.3; 0.3	6; 1
	wood+branches	8	7; 9	6; 1	0.9	0.8; 0.9	6; 1	9	8; 11	6; 1	5	4; 5	6; 1	1.1	1.1; 1.1	6; 1	0.5	0.4; 0.5	6; 1
	wood+bark+branches	9	8; 10	6; 1	1.0	0.9; 1.0	6; 1	11	9; 12	6; 1	7	6; 7	6; 1	1.5	1.4; 1.5	6; 1	0.6	0.5; 0.6	6; 1
	whole tree	42	38; 45	6; 1	2.8	2.3; 3.2	6; 1	18	15; 21	6; 1	13	12; 14	6; 1	3	3; 3	6; 1	2.3	2.2; 2.4	6; 1
1-<2	wood	38	15; 59	60; 2	3.6	2.1; 5.9	60; 2	36	25; 49	60; 2	30	14; 53	60; 2	7	3; 12	60; 2	1.5	1.5; 1.5	24; 1
	wood+bark	51	22; 77	60; 2	4.8	2.9; 6.7	60; 2	53	35; 77	60; 2	73	42; 106	60; 2	16	7; 28	60; 2	2.0	2.0; 2.0	24; 1
	wood+branches	57	38; 75	60; 2	5.7	4.8; 7.0	60; 2	60	56; 61	60; 2	82	47; 104	60; 2	15	11; 21	60; 2	3.2	3.2; 3.2	24; 1
	wood+bark+branches	70	44; 87	60; 2	7.0	5.9; 8.7	60; 2	77	69; 89	60; 2	125	110; 132	60; 2	24	18; 31	60; 2	3.6	3.6; 3.6	24; 1
	whole tree	132	113; 151	60; 2	10.7	8.1; 12.7	60; 2	103	87; 114	60; 2	149	131; 173	60; 2	32	28; 36	60; 2	8.5	8.5; 8.5	24; 1
2-<4	wood	51	8; 97	122; 4	9.1	1.3; 24.3	122; 4	78	17; 121	95; 3	42	13; 64	95; 3	14	2; 24	95; 3			0
	wood+bark	64	20; 125	142; 5	10.7	2.2; 29.3	142; 5	100	38; 167	115; 4	136	57; 214	115; 4	28	9; 50	115; 4	22.5	22.5; 22.5	20; 1
	wood+branches	74	14; 128	142; 5	13.0	2.1; 30.6	142; 5	104	23; 150	115; 4	111	20; 170	115; 4	25	3; 42	115; 4			0
	wood+bark+branches	86	26; 156	142; 5	14.2	3.2; 35.6	142; 5	125	44; 196	115; 4	198	64; 321	115; 4	38	11; 64	115; 4	26.8	26.8; 26.8	20; 1
	whole tree	198	75; 371	142; 5	21.9	6.5; 50.2	142; 5	170	65; 268	115; 4	250	78; 394	115; 4	54	16; 87	115; 4	32.0	32.0; 32.0	20; 1
4-<6	wood	113	51; 171	75; 4	13.6	2.5; 23.1	75; 4	114	19; 144	75; 4	61	12; 88	75; 4	27	2; 50	75; 4	26.0	24.8; 26.4	12; 2
	wood+bark	145	75; 209	75; 4	18.5	6.2; 29.9	75; 4	170	55; 236	75; 4	220	61; 281	75; 4	56	9; 93	75; 4	29.9	26.5; 31.1	12; 2
	wood+branches	144	68; 204	75; 4	17.7	4.4; 29.3	75; 4	152	64; 180	75; 4	131	40; 195	75; 4	43	7; 70	75; 4	31.5	28.2; 32.6	12; 2
	wood+bark+branches	176	92; 243	75; 4	22.6	8.1; 36.0	75; 4	207	100; 264	75; 4	290	102; 388	75; 4	71	15; 114	75; 4	35.4	29.8; 37.3	12; 2
	whole tree	279	152; 367	75; 4	30.5	11.4; 47.6	75; 4	249	134; 297	75; 4	331	129; 447	75; 4	85	25; 127	75; 4	41.7	36.9; 43.4	12; 2
6-10	wood	182	73; 266	114; 3	16.5	3.7; 32.2	114; 3	138	51; 210	114; 3	95	22; 170	114; 3	27	4; 58	114; 3	13.0	13.0; 13.0	60; 1
	wood+bark	244	110; 319	114; 3	27.2	7.8; 39.6	114; 3	240	137; 265	114; 3	396	73; 508	114; 3	94	18; 113	114; 3	24.0	24.0; 24.0	60; 1
	wood+branches	216	95; 297	114; 3	20.0	5.6; 35.6	114; 3	172	76; 248	114; 3	156	37; 233	114; 3	44	8; 75	114; 3	16.0	16.0; 16.0	60; 1
	wood+bark+branches	278	132; 350	114; 3	30.8	9.2; 43.0	114; 3	274	156; 303	114; 3	456	85; 582	114; 3	110	20; 134	114; 3	27.0	27.0; 27.0	60; 1
	whole tree	348	174; 451	114; 3	35.1	11.4; 48.1	114; 3	304	179; 334	114; 3	479	94; 605	114; 3	119	25; 142	114; 3	31.0	31.0; 31.0	60; 1

Data source: Harrison *et al.* (2000), Zaia and Gama-Rodrigues (2004), Leite *et al.* (2011), Viera *et al.* (2012), Viera *et al.* (2013), Gatto *et al.* (2014), Guimaraes *et al.* (2015), Viera *et al.* (2015), Witschoreck and Schumacher (2015), Eufrade *et al.* (2016), Rosim *et al.* (2016).

Table A5. Weighed average potential (theoretical) amount of B, Cu, Fe, Mn and Zn (g · ha^{-1}) that is removed with different harvest intensities of *Eucalyptus* trees of different age classes, minimum and maximum reported average value, number of sampled trees (X) and number of publications from which data were extracted (Y). In cases where minimum and maximum values do not differ from the mean, only one average value was given in a publication.

Age		B			Cu			Fe			Mn			Zn		
(years)	Harvest intensity	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y
<1	wood	5	4; 5	6; 1	4	3; 4	6; 1	6	6; 6	6; 1	191	186; 196	6; 1	8	6; 9	6; 1
	wood+bark	11	9; 13	6; 1	4	4; 5	6; 1	11	10; 11	6; 1	505	489; 521	6; 1	9	8; 10	6; 1
	wood+branches	14	13; 16	6; 1	8	7; 10	6; 1	17	16; 19	6; 1	873	868; 879	6; 1	15	13; 18	6; 1
	wood+bark+branches	21	18; 24	6; 1	9	8; 10	6; 1	22	21; 23	6; 1	1187	1172; 1203	6; 1	17	14; 20	6; 1
	whole tree	57	47; 67	6; 1	20	17; 23	6; 1	118	105; 131	6; 1	3259	3201; 3316	6; 1	36	31; 41	6; 1
1-<2	wood	35	35; 35	24; 1	26	26; 26	24; 1	110	110; 110	24; 1	969	969; 969	24; 1	62	62; 62	24; 1
	wood+bark	68	68; 68	24; 1	32	32; 32	24; 1	151	151; 151	24; 1	3234	3234; 3234	24; 1	75	75; 75	24; 1
	wood+branches	108	108; 108	24; 1	67	67; 67	24; 1	220	220; 220	24; 1	7463	7463; 7463	24; 1	130	130; 130	24; 1
	wood+bark+branches	142	142; 142	24; 1	72	72; 72	24; 1	261	261; 261	24; 1	9729	9729; 9729	24; 1	143	143; 143	24; 1
	whole tree	251	251; 251	24; 1	113	113; 113	24; 1	461	461; 461	24; 1	19715	19715; 19715	24; 1	213	213; 213	24; 1
2-<4	wood			0			0			0			0			0
	wood+bark	180	180; 180	20; 1	120	120; 120	20; 1	1560	1560; 1560	20; 1	1770	1770; 1770	20; 1	180	180; 180	20; 1
	wood+branches			0			0			0			0			0
	wood+bark+branches	230	230; 230	20; 1	140	140; 140	20; 1	1970	1970; 1970	20; 1	2320	2320; 2320	20; 1	220	220; 220	20; 1
	whole tree	390	390; 390	20; 1	160	160; 160	20; 1	2800	2800; 2800	20; 1	2380	2380; 2380	20; 1	260	260; 260	20; 1
4-<6	wood	423	326; 531	30; 2	139	112; 183	30; 2	1801	1234; 2623	30; 2	1492	499; 3495	30; 2	296	244; 398	30; 2
	wood+bark	629	510; 809	30; 2	176	139; 222	30; 2	2560	1424; 3780	30; 2	8609	3760; 17118	30; 2	356	283; 455	30; 2
	wood+branches	491	376; 580	30; 2	176	129; 214	30; 2	2173	1504; 3011	30; 2	4376	1589; 10406	30; 2	347	266; 419	30; 2
	wood+bark+branches	698	558; 854	30; 2	212	156; 256	30; 2	2932	1693; 4168	30; 2	11493	4842; 24029	30; 2	406	304; 476	30; 2
	whole tree	776	590; 883	30; 2	238	173; 299	30; 2	4282	2157; 5949	30; 2	13689	6217; 28497	30; 2	461	330; 582	30; 2
6-10	wood	266	191; 327	21; 1	262	73; 318	81; 2	4040	3120; 8190	81; 2	2715	1725; 2956	81; 2	924	810; 1535	81; 2
	wood+bark	455	378; 548	21; 1	317	115; 378	81; 2	4582	3652; 8861	81; 2	9696	5014; 10934	81; 2	1005	907; 1574	81; 2
	wood+branches	355	281; 447	21; 1	321	152; 370	81; 2	4246	3275; 8666	81; 2	5091	2991; 5591	81; 2	998	901; 1571	81; 2
	wood+bark+branches	543	448; 669	21; 1	377	185; 430	81; 2	4789	3807; 9337	81; 2	12072	6011; 13702	81; 2	1079	956; 1610	81; 2
	whole tree	608	499; 759	21; 1	401	206; 454	81; 2	5086	3965; 10319	81; 2	13478	6961; 15182	81; 2	1104	976; 1648	81; 2

Data source: Leite *et al.* (2011), Viera *et al.* (2012), Viera *et al.* (2013), Gatto *et al.* (2014), Guimaraes *et al.* (2015), Viera *et al.* (2015), Eufrade *et al.* (2016).

Table A6. Weighed average amount of N, P, K, Ca, Mg and S (kg · ha^{-1}) that is removed with different harvest intensities of *Eucalyptus* trees of different age classes, minimum and maximum reported average value, number of sampled trees (X) and number of publications from which data were extracted (Y). It is assumed with the wood-only harvest, still 20% of the bark is removed from a site; with wood+bark harvest, 80% of the bark is removed; with wood+bark+branches harvest, 80% of the bark and 60% of the branches is removed; with whole tree harvest, 80% of the bark, 60% of the branches and all the leaves are removed (see Achat et al. 2015). In cases where minimum and maximum values do not differ from the mean, only one average value was given in a publication.

Age		N			P			K			Ca			Mg			S		
(years)	Harvest intensity	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y
<1	wood	4	4; 4	6; 1	0.4	0.4; 0.4	6; 1	5	4; 5	6; 1	1.2	1.2; 1.2	6; 1	0.5	0.5; 0.5	6; 1	0.2	0.2; 0.2	6; 1
	wood+bark	5	4; 5	6; 1	0.5	0.5; 0.5	6; 1	5	4; 6	6; 1	2.4	2.3; 2.6	6; 1	0.7	0.6; 0.7	6; 1	0.3	0.3; 0.3	6; 1
	wood+branches	7	6; 7	6; 1	0.7	0.7; 0.7	6; 1	8	6; 9	6; 1	3.5	3.2; 3.8	6; 1	0.9	0.9; 0.9	6; 1	0.4	0.3; 0.4	6; 1
	wood+bark+branches	7	7; 8	6; 1	0.8	0.7; 0.8	6; 1	8	7; 10	6; 1	4.7	4.4; 5.1	6; 1	1.1	1.1; 1.1	6; 1	0.4	0.4; 0.5	6; 1
	whole tree	40	36; 43	6; 1	2.6	2.1; 3.0	6; 1	16	13; 18	6; 1	11	11; 12	6; 1	2.8	2.7; 2.8	6; 1	2.2	2.1; 2.3	6; 1
1-<2	wood	41	16; 61	60; 2	3.8	2.2; 6.0	60; 2	39	27; 54	60; 2	39	20; 56	60; 2	9	4; 13	60; 2	1.6	1.6; 1.6	24; 1
	wood+bark	49	20; 73	60; 2	4.6	2.7; 6.5	60; 2	49	33; 71	60; 2	64	36; 92	60; 2	14	6; 24	60; 2	1.9	1.9; 1.9	24; 1
	wood+branches	52	30; 70	60; 2	5.1	4.0; 6.7	60; 2	53	49; 62	60; 2	70	56; 80	60; 2	14	10; 18	60; 2	2.6	2.6; 2.6	24; 1
	wood+bark+branches	60	34; 79	60; 2	5.9	4.5; 7.3	60; 2	64	55; 78	60; 2	95	90; 108	60; 2	19	13; 26	60; 2	2.9	2.9; 2.9	24; 1
	whole tree	122	101; 141	60; 2	9.6	7.4; 11.3	60; 2	90	78; 98	60; 2	120	111; 132	60; 2	27	23; 30	60; 2	7.7	7.7; 7.7	24; 1
2-<4	wood	55	10; 103	122; 4	9.7	1.5; 25.3	122; 4	84	21; 130	95; 3	59	22; 85	95; 3	18	4; 28	95; 3			0
	wood+bark	67	18; 122	122; 4	11.7	2.0; 28.3	122; 4	101	34; 158	95; 3	108	48; 149	95; 3	27	8; 44	95; 3			0
	wood+branches	69	14; 121	122; 4	12.0	2.0; 29.1	122; 4	99	25; 148	95; 3	103	26; 157	95; 3	24	4; 39	95; 3			0
	wood+bark+branches	80	21; 139	122; 4	13.7	2.6; 32.1	122; 4	116	37; 175	95; 3	158	52; 239	95; 3	34	9; 51	95; 3			0
	whole tree	199	71; 352	122; 4	22.1	5.9; 46.7	122; 4	165	58; 248	95; 3	215	67; 312	95; 3	52	14; 78	95; 3			0
4-<6	wood	119	56; 178	75; 4	14.6	3.3; 24.5	75; 4	126	26; 151	75; 4	93	22; 127	75; 4	33	3; 58	75; 4	26.8	25.1; 27.3	12; 2
	wood+bark	138	70; 202	75; 4	17.5	5.5; 28.5	75; 4	159	48; 207	75; 4	188	51; 243	75; 4	50	7; 85	75; 4	29.1	26.1; 30.1	12; 2
	wood+branches	138	66; 198	75; 4	17.1	4.4; 28.2	75; 4	148	54; 173	75; 4	135	46; 191	75; 4	42	7; 71	75; 4	30.1	27.2; 31.1	12; 2
	wood+bark+branches	157	81; 222	75; 4	20.0	6.6; 32.2	75; 4	181	75; 224	75; 4	230	76; 306	75; 4	59	11; 97	75; 4	32.4	28.1; 33.9	12; 2
	whole tree	260	140; 346	75; 4	27.9	9.8; 43.8	75; 4	223	109; 259	75; 4	271	104; 366	75; 4	74	21; 110	75; 4	38.7	35.2; 39.9	12; 2
6-10	wood	194	81; 276	114; 3	18.6	4.5; 33.6	114; 3	159	71; 221	114; 3	155	34; 211	114; 3	41	8; 68	114; 3	15.2	15.2; 15.2	60; 1
	wood+bark	232	103; 308	114; 3	25.1	7.1; 38.1	114; 3	220	122; 254	114; 3	336	64; 422	114; 3	81	15; 101	114; 3	21.8	21.8; 21.8	60; 1
	wood+branches	215	94; 295	114; 3	20.7	5.7; 35.7	114; 3	179	85; 244	114; 3	192	43; 251	114; 3	50	9; 79	114; 3	17.0	17.0; 17.0	60; 1
	wood+bark+branches	252	116; 327	114; 3	27.2	8.0; 40.2	114; 3	240	133; 277	114; 3	372	71; 467	114; 3	90	17; 111	114; 3	23.6	23.6; 23.6	60; 1
	whole tree	322	158; 428	114; 3	31.5	10.2; 45.2	114; 3	270	157; 308	114; 3	395	80; 490	114; 3	99	21; 123	114; 3	27.6	27.6; 27.6	60; 1

Data source: Harrison *et al.* (2000), Zaia and Gama-Rodrigues (2004), Leite *et al.* (2011), Viera *et al.* (2012), Viera *et al.* (2013), Gatto *et al.* (2014), Guimaraes *et al.* (2015), Viera *et al.* (2015), Witschoreck and Schumacher (2015), Eufrade *et al.* (2016), Rosim *et al.* (2016).

Table A7. Weighed average amount of B, Cu, Fe, Mn and Zn (g · ha^{-1}) that is removed with different harvest intensities of *Eucalyptus* trees of different age classes, minimum and maximum reported average value, number of sampled trees (X) and number of publications from which data were extracted (Y). It is assumed with the wood-only harvest, still 20% of the bark is removed from a site; with wood+bark harvest, 80% of the bark is removed; with wood+bark+branches harvest, 80% of the bark and 60% of the branches is removed; with whole tree harvest, 80% of the bark, 60% of the branches and all the leaves are removed (see Achat et al. 2015). In cases where minimum and maximum values do not differ from the mean, only one average value was given in a publication.

Age		B			Cu			Fe			Mn			Zn		
(years)	Harvest intensity	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y	mean	min; max	X; Y
<1	wood	6	5; 7	6; 1	4	3; 4	6; 1	7	7; 7	6; 1	254	253; 255	6; 1	8	6; 9	6; 1
	wood+bark	10	8; 12	6; 1	4	4; 5	6; 1	10	9; 10	6; 1	442	430; 454	6; 1	9	7; 10	6; 1
	wood+branches	12	10; 13	6; 1	7	6; 7	6; 1	14	13; 14	6; 1	663	662; 664	6; 1	13	11; 15	6; 1
	wood+bark+branches	16	13; 18	6; 1	7	6; 8	6; 1	17	16; 17	6; 1	852	840; 863	6; 1	13	11; 16	6; 1
	whole tree	52	42; 61	6; 1	18	16; 17	6; 1	112	100; 125	6; 1	2923	2870; 2976	6; 1	32	28; 37	6; 1
1-<2	wood	41	41; 41	24; 1	27	27; 27	24; 1	118	118; 118	24; 1	1422	1422; 1422	24; 1	64	64; 64	24; 1
	wood+bark	62	62; 62	24; 1	31	31; 31	24; 1	142	142; 142	24; 1	2781	2781; 2781	24; 1	72	72; 72	24; 1
	wood+branches	86	86; 86	24; 1	52	52; 52	24; 1	184	184; 184	24; 1	5319	5319; 5319	24; 1	105	105; 105	24; 1
	wood+bark+branches	106	106; 106	24; 1	55	55; 55	24; 1	209	209; 209	24; 1	6678	6678; 6678	24; 1	113	113; 113	24; 1
	whole tree	215	215; 215	24; 1	96	96; 96	24; 1	409	409; 409	24; 1	16664	16664; 16664	24; 1	183	183; 183	24; 1
2-<4	wood			0			0			0			0			0
	wood+bark			0			0			0			0			0
	wood+branches			0			0			0			0			0
	wood+bark+branches			0			0			0			0			0
	whole tree			0			0			0			0			0
4-<6	wood	464	363; 586	30; 2	147	117; 190	30; 2	1953	1272; 2854	30; 2	2916	1157; 6219	30; 2	308	252; 410	30; 2
	wood+bark	588	474; 751	30; 2	169	134; 214	30; 2	2409	1386; 3548	30; 2	7186	3109; 14393	30; 2	344	275; 444	30; 2
	wood+branches	505	393; 615	30; 2	169	127; 200	30; 2	2176	1434; 3087	30; 2	4646	1807; 10366	30; 2	338	265; 422	30; 2
	wood+bark+branches	629	503; 780	30; 2	190	144; 224	30; 2	2632	1548; 3781	30; 2	8916	3758; 18540	30; 2	374	288; 456	30; 2
	whole tree	707	533; 809	30; 2	216	161; 258	30; 2	3982	2012; 5562	30; 2	11113	5086; 23008	30; 2	428	314; 519	30; 2
6-10	wood	304	229; 371	21; 1	273	82; 330	81; 2	4149	3226; 8324	81; 2	4112	2480; 4445	81; 2	940	829; 1543	81; 2
	wood+bark	417	342; 504	21; 1	306	107; 366	81; 2	4474	3546; 8727	81; 2	8300	4428; 9312	81; 2	988	888; 1566	81; 2
	wood+branches	357	283; 444	21; 1	309	130; 361	81; 2	4272	3319; 8610	81; 2	5537	3240; 6106	81; 2	985	884; 1564	81; 2
	wood+bark+branches	470	391; 576	21; 1	342	153; 397	81; 2	4598	3639; 9012	81; 2	9725	5026; 10973	81; 2	1033	938; 1588	81; 2
	whole tree	535	442; 667	21; 1	367	175; 421	81; 2	4896	3797; 9994	81; 2	11132	5976; 12453	81; 2	1059	959; 1625	81; 2

Data source: Leite *et al.* (2011), Viera *et al.* (2012), Viera *et al.* (2013), Gatto *et al.* (2014), Guimaraes *et al.* (2015), Viera *et al.* (2015), Eufrade *et al.* (2016).