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A system lock-in blocks the uptake of mixed sustainable Eucalyptus plantations in Brazil

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A R T I C L E I N F O

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A B S T R A C T

Forest plantation areas across the globe are increasing in size and in 2019 Eucalyptus monocultures in Brazil covered 6.97 million hectares (0.8%). These monocultures hardly provide ecosystem services and do not support wildlife habitats. A transition towards more sustainable Eucalyptus plantations is urgently needed to support the provisioning of ecosystem services and conserve biodiversity. This transition requires the development of sustainable business models. We studied the upscaling of sustainable Eucalyptus plantation alternatives in Brazil, by analysing the potential barriers that need to be overcome using the Technological Innovation Systems perspective and semi-structured interviews of relevant stakeholders across the Eucalyptus value chain. Although the provisioning of ecosystem services is improved by alternative plantation management, we identified four blocking mechanisms that inhibit the functioning of the innovation system and as such hamper upscaling; 1) the productivist approach by incumbent actors on plantation management that is focussing only on short-term profit maximisation and results in a strong resistance to change current practices, 2) the weak societal and governmental vision that does not put sufficient pressure to change practices, 3) additional certification to support alternatives is in its infacy to develop niche markets which also hampers the development of financial support, and 4) failed demonstration projects in the past that have led to a lack of proof of concept for further experimentation and knowledge development. These barriers combined lead to a system lock-in, resistant to change and not capable for a diffusion of sustainable alternatives. We conclude that the directionality of a sustainability transformation should be enhanced by formulating long-term goals and strong commitment of public and private actors. We discuss how a mission oriented approach could foster such directionality for the urgently needed regime transformation in Eucalyptus paper and pulp production.

1. Introduction

Despite the many international pledges to halt deforestation, natural forest areas across the globe are declining (e.g., Garcia et al., 2020), while forest plantation areas continue growing (FAO and UNEP, 2020). The FAO and UNEP (2020, p. 16) define plantations as “intensively managed forests, mainly composed of one or two tree species, native or exotic, of equal age, planted with regular spacing and mainly established for productive purposes”. Globally only a few species are used for plantations and include fast growing Pine, Spruce, Poplar, Eucalyptus or Teak (Brockerhoff et al., 2013). In Brazil, Eucalyptus already comprises 77% of the tree plantation area, covering 6.97 million hectares (0.8% of land cover) in 2019 (IBA Brazilian Tree Industry, 2020). The vast majority (90%) of the plantations belongs to corporations and is primarily located in the Atlantic Forest region, comprising the states of Minas Gerais, São Paulo, and Mato Grosso do Sul (Brancalion et al., 2020; de de de Oliveira Silva et al., 2020; Kröger, 2013). Eucalyptus plantations mostly represent intensively managed monocultures with short rotation cycles of 5–7 years and are therefore preventing the natural regeneration of native plant species (Bremer and Farley, 2010).

Plantations could partly compensate for the loss of wildlife habitats and the ecosystem functions and services natural forests provide (Brockerhoff et al., 2013). However, the general capacity of Eucalyptus monocultures to provide ecosystem goods and services and to conserve biodiversity is minimal (Bauhus et al., 2017; Maron et al., 2012). Short-rotation Eucalyptus monocultures supply wood products and sequester carbon, but have significant negative effects on the environment (The World bank, 2017). The most severe impacts are decreasing

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species diversity and high water consumption (Amazonas et al., 2018b; The World bank, 2017). A shift towards more sustainable forest plantation management approaches is therefore urgently needed for plantations to improve their performance in ecosystem services and to contribute to biodiversity conservation (Bauhus et al., 2010).

Tavares et al. (2019) recommend adapting Eucalyptus plantation management by creating a stand structure similar to naturally grown Atlantic Forest, mixing Eucalyptus with native species, allowing longer rotation periods, reducing the harvesting impact and pest control, and enabling the understory to grow. Bremer and Farley (2010) suggest a similar approach to improve biodiversity conservation in plantations, reaching both environmental and economic targets of forest management. On a landscape level, alternative systems with mixed tree species or higher stand structure heterogeneity can provide more resources and shelter for native fauna, improve abiotic conditions and improve the resilience of the forest plantation itself, but also of its surroundings (Fahrig et al., 2011; Puettmann et al., 2015).

As land-use practices are still mainly driven by short-term financial profitability, a reasonable economic performance of potential alternatives with better ecosystem services provision (hereafter called "alternatives") is key in driving the transition towards more sustainable forest management (Knoke and Huth, 2011). To scale up such a new forest plantation management system, it needs to be translated into an appropriate business model, which in turn needs to be made attractive to plantation owners (Trigkas et al., 2020).

A business model explains how entrepreneurs create, deliver and capture value (Teece, 2010). Changing from monocultures to more environmentally sustainable options requires multiple business model components to adapt, as entrepreneurs offer a different value to their customers and change their key activities. This business model transformation can be framed as the process of sustainable business model innovation (SBMI). While financial profitability is a crucial factor to be taken into account on the firm level (micro) of forest plantation business, the socioeconomic environment enables or hampers alternatives to be scaled up on the macro system level. Important factors influencing the industry include governmental regulations, voluntary market standards and consumer behaviour (Brancalion et al., 2012; Stubbs and Cocklin, 2008). Barriers to SBMI can be of organizational and socioeconomic origin and can be classified as 'soft' and 'hard'. Soft barriers refer to social and institutional factors such as cultural values and regulations, whereas hard barriers reflect financial and technical factors such as lack of training and infrastructure (de Jesus and Mendonça, 2018).

In the current literature, the majority of studies focuses on the ecological impacts of monocultures and investigate governance options to promote the provision of ecosystem services in forestry (Bauhus et al., 2010), or the linkages between policies and certification (Savilaakso et al., 2017). Meijaard et al. (2011), for example, conducted research on opportunities and barriers for ecosystem services certification, but stated their study should not be confused with achieving sustainable management outcomes. Business model innovation in forestry has been addressed by Lee and Chang (2019), whose aim was to understand how small-scale forest firms certified by FSC in Taiwan transform their conventional business models towards a more sustainable approach.

Although there are multiple studies about the transition towards sustainable forest management (Angelstam et al., 2004), there is no scientific research so far that analyses conventional and potential alternative Eucalyptus plantation management from a business model perspective, also studying barriers of the innovation system in the Atlantic Forest in Brazil. As the challenges for sustainable forest management vary widely among countries with different and localized socio-economic circumstances and ecosystems (Angelstam et al., 2004; Savilaakso et al., 2017), studies conducted in other countries with different ecosystems cannot easily be generalized (Brockerhoff et al., 2013).

In a large review, Brockerhoff et al. (2013) indicated that forms of mixed plantations perform better than monoculture stands when considering pest control and water retention, as demonstrated by Amazonas et al. (2018a), while mixed stands may also result in higher individual tree growth (Amazonas et al., 2018b). This raises the question why the use and uptake of mixed forest plantations is not common practice. More specifically, we draw from innovation sciences theory by analysing the current regime of Eucalyptus plantation management and potential disruptive alternatives both on a system level (macro) and firm level (micro) by using the Technical Innovation Systems (TIS) framework (Hekkert et al., 2007; Sixt et al., 2018) to understand upscaling issues. The TIS framework allows drawing a holistic picture of the innovation system and broadens the focus from entirely technological innovations to also recognising business models as subjects of innovation and being part of innovation system dynamics (Laukkanen and Patala, 2014).

Therefore, this research will identify the barriers towards the upscaling of sustainably managed Eucalyptus plantations in the Atlantic Forest region on the organisational and system level. The precondition of the innovative business model was an improved provision of ecosystem services. For this, a business model analysis is carried out for the cases of monoculture Eucalyptus plantations and three alternative management options, while the barrier analysis to SBMI by Laukkanen and Patala (2014) served as a basis for identifying blocking mechanisms through interviews with stakeholders of the Eucalyptus wood production industry. Finally, we connect the identified barriers to TIS to assess the functioning of the innovation system.

2. Theory and methods

2.1. Sustainable business models

Innovative business models have the power to achieve systemic change and therefore to disrupt entire industries, as individual firms influence the wider production and consumption system and drive the introduction of new products and technologies into the market (Boons and Lüdeke-Freund, 2013; Gambardella and McGahan, 2010). A business model describes how to create and deliver value for the customer, capture the value through payments and subsequently turn it into profit (Teece, 2010).

The business model perspective allows identifying which aspects need to be changed at the micro level in order to successfully create sustainability values by integrating social, environmental and economic activities (Schaltegger et al., 2012). Stubbs and Cocklin (2008) propose to take into account stakeholder needs when designing a sustainable business model, thereby also considering nature and biodiversity impacts.

2.2. Transition theory and barriers for sustainable business model innovation

The success of a SBMI is dependent on the regime of the socioeconomic system it operates in. If the system does not support sustainable behaviour, structural and cultural changes are needed on the macro level (Laukkanen and Patala, 2014; Stubbs and Cocklin, 2008). Transition theories can be applied to study sustainable transformation in systems.

The Technological Innovation System (TIS) by Hekkert et al. (2007) presents a set of key functions (see Table 1) that are essential for well-performing innovation systems. For an innovation diffusion, all seven TIS functions need to perform well. However, throughout the developmental stages of innovation, some functions are more relevant to spur diffusion than others, asking for a determination of the development phase before assessing the TIS functions (Hekkert et al., 2011). The functioning of innovation systems is influenced by elements whose presence and capacities are crucial to the emergence of innovations. These are framed as the four-fold structure of the TIS, consisting of

Table 1
TIS functions adapted to SBMI (Hekkert et al., 2007; Laukkanen and Patala, 2014).

Functions	Original TIS framework (Hekkert et al., 2007)	Adapted and connected to SBMI (Laukkanen and Patala, 2014)
F1 Entrepreneurial Activity	• Creating new business opportunities by making use of new knowledge, networks, and markets • Learning through experimentation under uncertainties and stakeholder feedback	• Collaboration and forming of partnerships with stakeholders around key sustainability issues as a catalyst for new innovations • Risky experimentation and pilot projects supported by encouraging regulations from policy-makers
F2 Knowledge Development	• Patents and R&D investments for tacit (know-how based on personal experience) and explicit (know-what based on codified, objective research) knowledge creation	• Firms need an understanding of the value of sustainability-related to sustained competitive advantage, also negative financial impacts of climate change • Firms need to define new indicators for profitability linked to sustainable development • Universities and research institutes need to create and disseminate knowledge • Policy-makers need to recognize the impact of regulations on businesses
F3 Knowledge Exchange	• Sharing knowledge in networks of business R&D, governments, competitors, and market to create standards and targets based on the latest research • System actors are raising awareness, sharing capacities and resources	• Sharing knowledge in networks between businesses, governments and all relevant stakeholders • Formulating voluntary standards that are more stringent than regulations or supporting them
F4 Guidance of the Search	• Governments, Universities and Businesses are setting the direction of knowledge creation • Defining priorities of R&D investments depending on individual targets • Spreading optimism about innovation to reduce uncertainty and risks	• Prioritise long-term sustainable change with limited R&D resources • Governments steer with regulatory frameworks for emission targets and market shares of sustainable products and technologies • Aligning (inter)national sustainability regulations for a clear future innovation pathway
F5 Market Formation	• Creating a protected space in the form of niche markets for innovative products which are not yet mature • Introducing (temporary or permanent) taxes or regulations favouring the innovation	• Creating niche markets for sustainable products which are not competitive yet • Introducing (temporary or permanent) taxes, sustainability standards and regulations favouring the sustainable innovation • Public procurement preferring sustainable products
F6 Resource Mobilisation	• Financial and human capital to spur innovation especially relevant for function 2 • Resources for development and diffusion of innovation among actors of the targeted system	• Governments provide financial and human capital for R&D programs that target sustainable innovations • Creation of collaborative alliances to increase available resources • Spreading R&D programs among diverse projects to create multiple options for SBMI
F7 Creation of Legitimacy / Counteract Resistance to Change	• Advocacy coalitions can increase legitimacy by promoting new technologies by putting them on the agenda and lobbying for resources and supportive taxes	• Create trust by spreading success stories to increase legitimacy and to encourage SBM innovators • Promotion of sustainable consumption by increasing public awareness of environmental and social issues and showing how SBM can solve those • Forming associations and lobbying for resources and supportive taxes

actors, institutions, interactions and infrastructure (Wieczorek and Hekkert, 2012).

Laukkanen and Patala (2014) show that transition theory can be linked to business model innovation by extending the TIS framework with business model theory. Reike et al. (2017) also suggest applying the TIS model to complement the firm level perspective with its external networks. Hence, TIS is also used in this research to identify potential inertia within the societal and socio-technical system of business innovation.

For the TIS analysis, Laukkanen and Patala (2014) suggest first identifying soft and hard barriers for SBMI. These barriers to the diffusion of sustainable business models can be grouped into three categories: Regulatory barriers; Market and Financial barriers; and Behavioural and Social barriers (see Table 2). Second, they explained those barriers can be overcome through analysing and improving the functions of the innovation systems framework (Hekkert et al., 2007; Laukkanen and Patala, 2014). The functions of the TIS framework are explained in Table 1, also showing how the original TIS framework can be adapted to SBMI.

Table 2
Barriers for SBMI (Laukkanen and Patala, 2014, p. 13).

Barrier groups for SBMI	Barriers
Regulatory barriers	• Lack of long-term legal, regulatory frameworks • Inconsistent and overlapping regulatory mechanisms • Operational environment stability (regulatory risks) • Lack of encouragement to innovativeness • Lack of flexibility and chance of iteration • Lack of normative rules/industrial standards • Lack of involvement of stakeholders in decision making
Market and Financial barriers	• Financial risk • Short-termism • Lack of awareness and understanding among market participants • Lack of marketing know-how
Behavioural and Social barriers	• Lack of consumer/customer acceptance • No stakeholder pressure • Lack of risk-taking • Enterprise culture • Inconsistent leadership • Lack of motivation • Profitability of existing business models/satisfaction

2.3. Data collection and analysis

The research is based on qualitative data obtained from a combination of literature research and interviews. The latter allows capturing the perspectives of relevant actors within the innovation networks of the Eucalyptus industry to gain an understanding of attitudes, experiences and predictions (Rowley, 2012). For the literature analysis, first the currently most applied forms of Eucalyptus plantation management was searched by using Google Scholar with search items (Alternative AND Eucalyptus AND plantation AND management) OR (Sustainable AND Eucalyptus AND plantation AND management) in combination with (Atlantic Forest) OR Brazil) AND (Ecosystem services) OR (Sustainability). Articles providing information about alternative systems were further studied and served as a basis for snowballing. Alternatives chosen for this research are based on the following criteria:

- Alternatives have a positive effect on ecosystem services provision compared to the conventional approach (Puettmann et al., 2015).
- Alternatives include the possibility of Eucalyptus species cultivation to allow a continuous material supply to the pulp and paper industry and/or a smooth transition to new markets.
- Alternatives are providing options for revenue by selling products/services from plantations since financial profitability is considered an essential factor for firms to consider SBMI (Bocken and Geradts, 2020).
- Alternatives ask for different severity of the business model change, from resembling the conventional approach to a different management form to increase possibilities of potential implementation by the industry.
- Trials for the alternatives were done in the Atlantic Forest biome to prove their ecological feasibility.

The conventional business model was analysed through literature research using Google Scholar with the search terms (Eucalyptus AND monoculture AND (management OR (Atlantic AND Forest)), (Ecological impacts) AND (Economic analysis) and gathering grey literature from business reports of the pulp and paper industry. Simultaneously, scientific articles collected from the case study selection were reviewed for the analysis of alternative systems.

The next step of the data collection was validating the desk research through semi-structured interviews guided by the business logic questions of Laasch (2018) and especially paying attention to ecosystem services provision and economic aspects of all four studied management approaches. After asking prior consent, interview partners were questioned about barriers to implement alternative management options, guided by the barriers to SBMI by Laukkanen and Patala (2014) and were further specified to the context of sustainable forest plantation management through literature review.

The functions of the TIS framework by Hekkert et al. (2007) supported the formulation of interview questions by pointing at all relevant aspects influencing the success of SBMI on a system level. The topics conceptualized in Table 2 were discussed with the interview partners to examine their potential impact as barriers for alternative plantation management. Confronting interview partners with a list of potential barriers encouraged participants to overcome their potential tunnel vision of their expert position and consider a holistic sample of barriers to SBMI. Due to a lack of specific knowledge about alternative plantation systems, the interview partners identified barriers representative of the grouped alternative approaches representing SBMI. Furthermore, the interview partners were asked to score the barriers they mentioned from 1 (no or slight barrier) to 4 (very strong barrier), according to how strongly they were perceived.

Interview partners have been selected across stakeholder groups of the Eucalyptus production chain (see Table 3). As a first step, researchers of alternative systems and Eucalyptus plantation owners who provided land for scientific experiments were reached out to and interviewed. These two stakeholder groups made an essential contribution to data collection, as they filled the information gaps of scarce studies about the costs and benefits of alternative approaches with first-hand knowledge, and these interview partners were asked to provide contacts to other plantation owners, governmental institutions, certification organisations, and NGOs. The industry partners of the interviewed researchers were exclusively from the pulp and paper industry, which is why this research focuses on this sector as a potential business model innovator. The snowballing sample method resulted in a total number of 16 semi-structured interviews, all held as video calls and lasting between 35 and 106 min (Table 3). The use of an interview guide increased the reliability of the study by ensuring cross-case comparability (Bryman, 2016). The interview questions for the business model analysis were slightly adapted to the expertise of each stakeholder group, but all interviewees were asked the same questions for the SBMI barrier analysis. The semi-structured interview guide enabled the interviewer to spontaneously respond to unexpected and interesting topics mentioned by the interviewee, which supports the exploratory character of this research (Bryman, 2016). An example of an interview guide is provided in the supplementary material.

Table 3
Interview partners by stakeholder group, date of interview and length of interview (in minutes).

Stakeholder group	Interview partner (in-text reference)	Date (2021)	Length (min.)
Scientists as experts for alternative plantation management options	Interviewee 1	25.05	69
	Interviewee 2	17.05	106
	Interviewee 3	27.05	63
Eucalyptus plantation owners, represented by pulp and paper industry	Interviewee 4	09.06	62
	Interviewee 5	09.06	76
	Interviewee 6	21.06	81
	Interviewee 7	10.06	71
	Interviewee 8	05.07	76
	Interviewee 9	18.06	52
Consultant for small-scale Eucalyptus farmers*	Interviewee 10	21.07	58
Governmental body Brazil	Interviewee 11	18.06	60
International pulp market expert	Interviewee 12	03.06	72
NGOs and Private Standard initiatives	Interviewee 13	01.07	76
	Interviewee 14	06.07	87
	Interviewee 15	02.06	36
European Pulp Customer	Interviewee 16	05.07	35

* Note: In this study farmers with up to 50 ha are categorized as small-scale farmers, farmers with 50 up to 200 ha as medium-scale farmers

Interviews with representatives of the following five pulp and paper companies operating in Brazil were held: Suzano S.A., Klabin S.A., International Paper do Brasil, CENIBRA, and Veracel. These companies all manage their Eucalyptus plantations as short-rotation monocultures embedded in a so-called mosaic structure together with native forests. Their aim is profit maximization by selling pulp and paper from plantation wood to national and international markets. Hence, a similar business model approach applied by the addressed companies can be assumed. Furthermore, Suzano S.A., International Paper do Brasil, and CENIBRA participated in field research for at least one of the proposed alternatives to explore future business model opportunities, being able to provide first-hand data based on their own experiences. The supplementary material provides a short overview of these companies.

After transcription of the interviews, the answers were coded in Nvivo through categorizing the content into overarching topics, such as ‘Business model’, ‘Ecological impact’, ‘Economic aspects’, ‘Barriers’, and ‘Drivers’. The open coding approach and thematic analysis is characterised by a data-driven and iterative process resulting in different levels of detail. Sub-levels were continuously grouped in more generalized codes through axial coding (Gibbs, 2007). As the codes can be exposed to subjective perception (Campbell et al., 2013), validity was enhanced by sending the coded barriers per interview to the individual interview partners to confirm the author's interpretation. Out of 16 interview partners, 11 took part in this second round. The interview partners were given the possibility of validating the results by decoding wrongly interpreted barriers, changing their initial barrier scores and weighing barriers they did not score during the interview. After the interviewee iteration round, only 5 out of 152 barriers had to be decoded, which confirmed the reliability of the coding process. As a next step, the barriers were assigned to the TIS functions based on the topic categorisation explained in Table 1.

2.3.1. Barrier and function scoring

To represent the importance of barriers, first the total number of interviewees mentioning the individual barriers were taken into account across stakeholder groups. Second, the average score given by the interview partners to the specific barriers was calculated to present how strongly these are perceived by multiplying the number of interviewees (mentioning the individual score) with the score (given by them), summarizing the different products per score and dividing them by the total number of interviewees mentioning scores for this barrier.

The barrier scores can be used to determine which TIS functions face the largest blocking mechanisms that prevent upscaling of alternative Eucalyptus plantation management. Functions with the strongest barriers are assumed to be the least fulfilled (Hekkert et al., 2011). To estimate the performance of the TIS functions, a weighted average barrier score per function was calculated to reflect both the number of interview partners who scored the barriers as well as the scores themselves. For this the individual average barrier scores per function were multiplied with the individual number of interviewees giving a score to them, summarizing those per function and then dividing this value by the summarized number of interviewees giving a score to barriers per function. Additionally, the average number of interviewees addressing barriers per function was calculated to represent which challenging function created the most awareness across interviewees.

3. Eucalyptus plantation models

Brazil started Eucalyptus breeding programs in 1941 to improve the phenotypic qualities, and mainly *Eucalyptus grandis, Eucalyptus urophylla* and hybrids were used for improved pulp production (Castro et al., 2016; Paula et al., 2020). Conventional Eucalyptus plantation management includes intensively managed monocultures primarily representing genetically identical trees. This silvicultural approach represents the majority of Eucalyptus plantations in the Atlantic Forest. The forestry model is used to achieve high wood yields and shows a high demand for resources such as water and nutrients (Amazonas et al., 2018a; Bremer and Farley, 2010). The intensively managed short-rotation monoculture represents the status quo of the commercial business model in Brazil.

In general, conventional monoculture plantation management leads to a very limited capacity of ecosystem services provisioning (Calviño-Cancela et al., 2012; Zhou et al., 2018). Native flora diversity is replaced and mature Eucalyptus monocultures show only a minimal capacity to provide habitats for native forest fauna (da Rocha et al., 2013). Other negative impacts are loss of soil fertility and productivity (Paula et al., 2020), decreasing biodiversity through extensive use of insecticides, fertilisers and weed control and higher vulnerability for pest diseases, storms and fires. Monocultures also have a limited ability to trap nutrients in the soil and consume higher levels of water than natural forests due to their fast and high tree growth (Liu et al., 2018). The severity of the impact of water use by Eucalyptus on surrounding ecosystems depends on local climate and soil conditions (Lima et al., 2012). However, effects on ecosystem services vary with previous land use, climatic conditions and management practices (Brockerhoff et al., 2013). Examples are allelopathic effects of Eucalyptus (Becerra et al., 2018) and reduction in soil moisture (Robinson et al., 2006), which were mainly observed in drier climates but are less problematic in tropical regions with wetter climates (Brancalion et al., 2020).

Alternative Eucalyptus plantation management options that could lead to business model innovations were explored through literature research and three management options could be identified: 1) Duo-aged and two-layered monoculture with coppice for short-rotation pulpwood and standard trees for high-quality roundwood, 2) Plantation with two species: Eucalyptus and nitrogen-fixing *Acacia mangium*, and 3) A mix of Eucalyptus with 23–30 native tree species. Table 4 provides an overview of the plantation management, economic aspects and the impacts on ecosystem services of the three alternative Eucalyptus plantation types.

3.1. Coppice-with-standards management (duo-aged and two-layered monoculture)

This alternative consists of two layers, a low density of standard trees forming the overstory and providing seeds to the understory treated as coppice (Ferraz Filho et al., 2014). Due to their excellent sprouting capacity and possibility for large dimensions, Eucalyptus species such as *E. grandis* are well suited for this approach (Higa and Sturion, 1991; Sims et al., 1999). In addition, the product diversification potential makes this system especially interesting for small- and medium-scale landowners to spread the risk of financial loss among multiple income sources (Reynders, 1984; Soares et al., 2003).

Research on economic aspects is very limited, only one study on *E. grandis* could be found where duo aged stands was more profitable than simple coppice, if standard trees were sold for a 1.4 times higher price than of regular coppice (25 standard trees/ha) (Inoue and Stohr, 1991). In general, duo-aged plantations show a higher diversity in wildlife compared to coppice without standard trees, as these form an additional layer and therefore provide a more complex structure serving as habitat for insects and bird species (Fuller and Warren, 1993; Lassauce et al., 2012; Lindenmayer and Hobbs, 2004). The standard trees also serve as dead wood sources, supporting saproxylic insect diversity (Lassauce et al., 2012). Flora diversity may also be enhanced due to understory plant regeneration (Ferraz Filho et al., 2014).

3.2. Plantation with Eucalyptus and nitrogen-fixing Acacia mangium

Acacia mangium is a tropical tree native to South-East Asia and Australia, where it is frequently used in plantations. Like Eucalyptus, it is highly productive and adapted to very poor soils. Its wood qualities (hard white wood and high calorific value) allow usage for a variety of purposes such as furniture, charcoal and pulp (Hegde et al., 2013). As *A. mangium* is a nitrogen fixing species, it can support Eucalyptus productivity through enhancing nitrogen availability in the soil in mixed plantations (Brandani et al., 2020; Forrester et al., 2006). The similarities and facilitating attributes make *A. mangium* an interesting option to be applied in mixed plantations (Bouillet et al., 2013). Studies show different productivity outcomes of Acacia and Eucalyptus mixed plantations compared to Eucalyptus monocultures, so an increased economic benefit from stemwood revenue cannot be generalized for such mixed species plantations (Bouillet et al., 2013; Santos et al., 2016). However, a clear advantage of mixed species is a decreased need for N fertiliser (Bouillet et al., 2013; Laclau et al., 2008).

Behling et al. (2011) reported a reduction in weeding costs by the faster canopy closure through Acacia in mixed plantations. The enrichment of the soil with organic matter and nutrients without losing wood productivity is an essential aspect of mixed Eucalyptus and Acacia plantations in Brazil, where most forest plantations are located on poor, sandy soils. Higher litter fall of Eucalyptus mixed with Acacia show potential for increased soil carbon sequestration compared to monocultures (Bouillet et al., 2013). Santos et al. (2016) pointed out that the canopy is more stratified, as Eucalyptus outcompetes Acacia in height growth. A more complex structure could serve as better habitat for

Table 4
Characteristics of the three alternative sustainable Eucalyptus business models.

Foundations for SBMI	Coppice-with-standards management in Eucalyptus grandis plantation	Mixed plantation with N2-fixing species Acacia mangium	Mixed plantation with highly diverse native tree species
Plantation management	• Duo-age monoculture with standard trees and understory coppice. • Short rotation periods for coppice, longer rotation periods for standard trees. • Pruning of standard trees for high-quality timber.	• Eucalyptus intercropped with Acacia trees. • Pruning of Acacia trees.	• Eucalyptus intercropped with ∼ 30 native tree species. • Model designed for restoration purposes but also feasible for permanent commercial wood production. • Thinning of poorly formed native trees.
Economic aspects	• Short-term revenue from Eucalyptus pulpwood. • Long-term revenue from high-quality Eucalyptus roundwood of higher diameters. • Costs similar to conventional approach, extra costs for pruning.	• Short-term revenue from Eucalyptus and Acacia pulpwood. • Potential for long-term roundwood production with Acacia. • Decreased expenses for fertiliser. • Reduction of weeding costs due to sooner canopy closure. • Potential for increased wood growth productivity due to nitrogen-fixing of Acacia trees. • Higher harvesting costs.	• Short-term revenue from Eucalyptus pulpwood. • Long-term revenue from high-quality native species timber. • Higher productivity of individual Eucalyptus trees compared to monoculture. • Higher harvesting costs.
Impact on Ecosystem services	• Higher wildlife biodiversity through more stratified canopy. • Higher flora diversity due to understory plant regeneration. • Still considerable negative impact on ecosystem services due to monoculture and intensive plantation management.	• Improved soil nutrients cycle. • Higher fungus and bacteria diversity in soil. • Improved habitat for native fauna due to stratified canopy. • Invasive character of Acacia.	• Increased biodiversity of native fauna and flora. • Improved habitat for fauna due to more complex stand structure. • Improved nutrient cycle in the soil. • Lower water consumption. • Decreased wood production.

native fauna. Soil acidification could cause problems as nitrogen-fixing species produce Ammonium, while non-native Acacia is also an invasive species in Brazil.

3.3. Mixed plantation of Eucalyptus with diverse native tree species

Mixed species forestry provides an option to combine internationally demanded forest restoration in the tropics of Brazil with the delivery of multiple-purpose wood products (Chazdon et al., 2017; FAO, 2015). Such a system can be attractive for the pulp industry and local farmers by planting fast-growing Eucalyptus for short-term income together with a variety of native species that provide a conservation value as well as long-term income through high-value timber (Brancalion et al., 2012).

For a mixed species plantation of Eucalyptus and native trees, the silvicultural management approach by Amazonas et al. (2018b) found that a mixed forest plantation model could be used for permanent production systems. Other researchers suggest thinning of poorly formed or suppressed trees in tropical mixed species plantations. It would generate income and support the regeneration of native species that suffered from competition (Erskine et al., 2005; Nguyen et al., 2014). In the experiments of Amazonas et al. (2018b), the clonal Eucalyptus grew faster than native trees, leading to a slower diameter growth of native species compared to pure native stands. Although native species experienced intense competition for light, they showed no mortality.

In mixed plantations with native tree species, 50% of Eucalyptus plants produced 75% of the wood harvested in monocultures, achieved by larger diameters of Eucalyptus individuals compared to those in monoculture plantations. Moreover, the nitrogen-fixing native trees supported Eucalyptus growth (Amazonas et al., 2018b). The high productivity and fast growth of Eucalyptus in this system allow rapid economic return within a relatively short rotation time of 4–5 years. Nguyen et al. (2014) stressed that silvicultural design needs to be adaptive to the market for the promotion and economic success of mixed species plantations. Due to similar silvicultural operation measures applied compared to Eucalyptus monocultures, costs are also not expected to deviate significantly. Weed control costs could be expected to be lower due to quicker canopy closure in mixed plantations (Brancalion et al., 2020), but harvesting costs are expected to be greater due to the complexity of the stand structure in mixed species plantations (interviewee 3).

The increased biodiversity of flora compared to monocultures is very clear in the mixed plantations of Eucalyptus and native wood species. Tree diversity leads to a heterogeneous canopy as an attractive habitat for many bat and bird species. The richness of regenerating native tree species may not be negatively impacted by Eucalyptus competition or harvesting (Brancalion et al., 2020). Pereira et al. (2019) addressed the increase of nitrogen and carbon in the soil of mixed plantations with Eucalyptus and nitrogen-fixing native tree species. The mixed species plantations by Amazonas et al. (2018b) show no allelopathic effects and soil moisture reduction, as previously reported about Eucalyptus plantations (Becerra et al., 2018; Robinson et al., 2006). A lower timber production in these systems results from lower planting density of Eucalyptus compared to monocultures, but in trials no productivity decrease of Eucalyptus was found.

4. Results

Many industry interviewees have participated in field research in collaboration with universities or even attempted to carry out larger projects. The trials have all been completed, and none of the alternatives (Section 3) is currently being implemented on a larger scale by the companies. Interviewee 7 gave an example: "*20 years ago, Fibria was trying to do that* [mixed species plantation] *in South of Bahia. They were trying to build a very big sawmill and then it didn't work out because they had a problem with logistics. They have problems selling the product and the company focus wasn't wood, it was pulp and paper. So yeah, in a big crash in 2009 and 2010, they decided, no, let's stop doing that because this is not our core business, our core business is pulp and paper and then they gave up*". Hence, there is no working prototype and in the TIS analysis the three studied alternatives are grouped together to represent potential SBMI.

4.1. Functional analysis

The average weighted barrier scores are represented per function in Fig. 1A. All functions show average scores above 2, indicating that overall barriers are considered at least medium strong. Function 2 'Knowledge Development' shows the lowest average barrier score, indicating this function is the best fulfilled. Function 1 'Entrepreneurial Activity', function 5 'Market Formation', and function 7 'Counteract

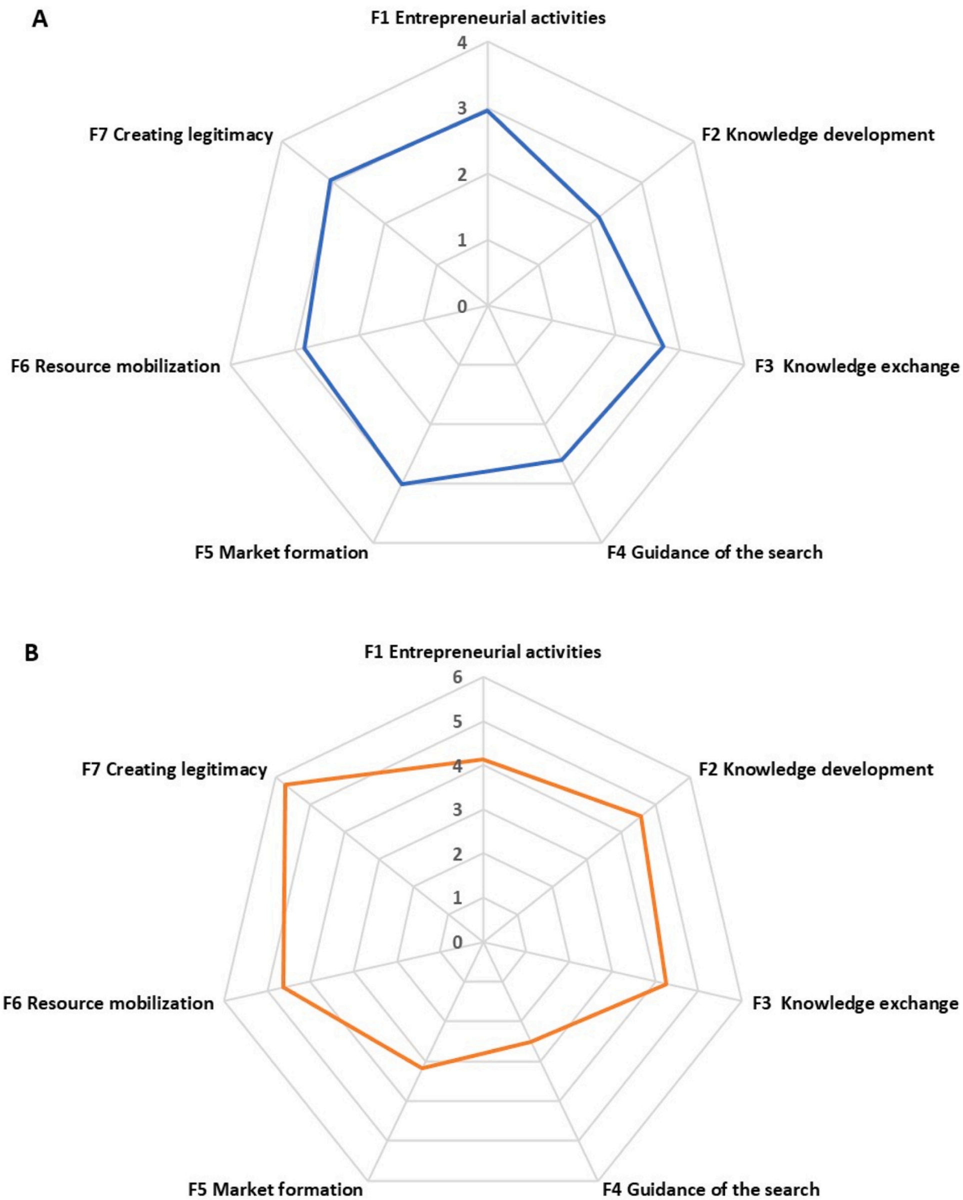

Fig. 1. Spider diagram of the average weighted barrier score per function (**A**), based on a Likert scale of 1 = no/slight barrier, 4 = very strong barrier, and (**B**) average number of interviewees (N) addressing barriers per function.

Resistance to Change/Legitimacy' face the largest blocking mechanisms to system innovation. With regard to the average number of interviewees that addressed barriers related to the individual TIS functions, Fig. 1B shows a clear consistency of importance of function 7, representing the highest values in both analyses, whereas the highly scored barriers of functions 1 and 5 were mentioned by less interview partners than challenges for other functions.

4.1.1. Function F1: entrepreneurial activities

The reasons for failed projects in the past and non-continuation are diverse, but all point at the lack of financial profitability, representing the most frequently mentioned barrier of F1. If the new business model is not as profitable as the current one, entrepreneurs lose motivation to innovate by trying alternative Eucalyptus management concepts. Interviewee 4 framed it as follows: "*I think the key point is the economic issue. The other points are also important, but first of all, we have to show and prove that this other way to plant a forest can be competitive with Eucalyptus plantations*". Then companies would continue to invest in exploring alternatives on a larger scale.

The lack of profitability can be explained by the lower productivity of alternative systems compared to Eucalyptus monocultures. A reason given for that is lower growth rates of Acacia in the optimal zones for Eucalyptus, such as expressed by interviewee 4: "*We have two different kinds of climates. In one region, it's more hot and the other more cold. In the cold areas the growth of Acacia is not satisfactory. In hot areas they grow well, but in the cold area it is a little bit more complicated for us*". He also pointed out that the pulp yield of Acacia wood is lower, as Eucalyptus has a 10–20% higher wood density. For the management or a mix with native tree species, longer payback periods lead to financial loss in the short-term. This challenge is especially relevant for small-scale farmers, as "*it would occupy a part of their lands that they can't set aside for the time the native trees need*" (interviewee 10). As interviewee 3 indicates, also for the big players of the pulp and paper industry maximizing short-term profits is very important. This mindset also puts great pressure on managers to achieve high yields, so they do not take the risk of experimenting with new approaches. This barrier was given the highest average score in the first TIS function and can be underlined by the following quote: "*They can fire you within one day if you don't reach the* *goals. It is not a good situation to take risks*" (interviewee 2).

Although the industry shows reluctance to implement the alternatives, it considers them a suitable option for smallholder farmers, such as emphasized by interviewee 6: "*Suzano is interested in this management, but not for their own areas*". Especially in southern Brazil, where the availability of new plantation land is limited, the industry relies on sourcing from smallholders, who do not always want to plant only Eucalyptus in their area. Instead of currently planted crops, they could implement mixed Eucalyptus plantations to have a diversified income (interviewee 6). Contrary to this statement, and despite being mentioned only once and ranked as the lowest barrier, small-scale farmers value Eucalyptus monocultures as risk-free income and medium-scale farmers (~200 ha) prefer monocultures that require low effort, as they consider their plantations as savings and pursue other jobs in their daily lives (interviewees 12 & 10).

4.1.2. Function F2: knowledge development

The barriers show a lack of motivation to change the business-as-usual due to missing research about potential alternatives, their biodiversity impacts and how to monitor these. The barrier mentioned by most interview partners was missing research about alternative Eucalyptus plantation management options (Table 5). The average score of 3 out of 4 also shows that the lack of information on ecological impact, financial viability and operational management of the alternatives was perceived as a strong barrier. Interviewee 13 addressed the intensive research focus on the improvement of Eucalyptus monocultures in Brazil, whereas other species were neglected: "*It's been 70, 80 years of research of all the best universities in Brazil to focus on Eucalyptus. We don't have enough research on native options […] and that is why we are only looking for projects with Eucalyptus and not for other projects*". Interviewee 15 added to that, explaining that especially technical and forestry management information is still very scarce for options that integrate native species in Eucalyptus plantations. Concerning the coppice with standards approach, interviewee 1 explained: "*it is not at all largely applied in Brazil because if you try to find it, you'll see there is very, very little information on Brazilian trials*". Interviewee 3 criticised one-sided research demonstrated by the example of Acacia and a lack of attention to the invasiveness of the species: "*This is an example on the ecological side how focussing on one problem, like adding nitrogen to the system, may create a much higher environmental problem if you don't have a broader vision on the surrounding and evaluate how the species will behave on that ecosystem in particular*". The risk of Acacia spreading in legal reserves should be highlighted, as the Forest Code would require landowners to remove the species from those reserves (interviewee 10). Due to climatic conditions, Acacia disseminates fast in the north of Brazil, while it is not much of a problem in the southern part of the Atlantic Forest (interviewee 6). Other risks associated with planting Acacia are soil acidification or root-rot disease, but these aspects were only mentioned by one interview partner and given low relevance as it can be compensated for by appropriate forest management (interviewee 2). Interviewee 3 concluded as follows: "*So I think that we have some individualised research on mixed plantations, but it's not yet framed to present a full new package to the forestry sector*".

For firms to implement the alternative approaches, they need to understand their value for sustained competitive advantage. Seven interview partners addressed missing information about the benefit of increased biodiversity for the pulp and paper industry as a medium to strong barrier. For example, interviewee 7 stated: "*we know that the native forest provides us with ecosystem services. But today we cannot measure that. […]. So I don't understand the impact of ecosystem services in my business*". This statement also introduces the barrier of how to monitor and hence prove additionality of ecosystem services when implementing alternative management approaches instead of Eucalyptus monocultures. This information would be particularly important if missing revenues from alternative systems need to be compensated by payment for ecosystem services schemes (interviewee 3). In addition,

Table 5
Frequently mentioned barriers by function, indicated by the number and share of interviewees who mention the barrier and the average scoring of the barrier on a 1–4 Likert scale (1 = no/slight barrier, 4 = very strong barrier).

Function	Barrier	Nr and % of interviewees	Average score (1–4)
F1: Entrepreneurial activities	Lacking productivity and profitability of alternative systems	10 (63%)	3.11
	Focus on short-term profitability with monocultures	5 (31%)	3,20
	Focus of pulp industry on small-scale farmers to implement alternatives	5 (31%)	3
	Failed projects in the past	5 (31%)	2.25
	Risk aversion of managers in pulp industry due to high pressure	2 (13%)	4
	Eucalyptus monocultures are risk-free income for small farmers	1 (6%)	1
	Medium-scale farmers (200 ha) want simple management	1 (6%)	-
F2: Knowledge development	Missing research about alternative models, focus exclusively on Eucalyptus species	9 (56%)	3
	Missing information about biodiversity benefits in pulp and paper industry	7 (44%)	2.57
	Acacia is invasive in parts of Brazil	6 (38%)	3
	Pulp and paper industry sees no need to change	4 (25%)	2.66
	Ecosystem services are hard to monitor	4 (25%)	1.5
	Impact and vulnerability of monocultures need to be evaluated	1 (6%)	4
	Other negative ecological impacts Acacia (besides invasiveness)	1 (6%)	1
F3: Knowledge exchange	Missing trust in alternatives and role models for smallholders	11 (69%)	2.54
	Partnerships and dialogue across whole supply chain needed	4 (25%)	3
	FSC ES certification hard to use for other areas than reserves	1 (6%)	4
	Lacking stakeholder involvement for FSC regulations	1 (6%)	3
F4: Guidance of the search	Brazilian governance is split up in 26 largely autonomous states	4 (25%)	2.5
	Lacking implementation of Forest Code	3 (19%)	2.5
	Insecurity about Forest Code enforcement	3 (19%)	2.5
	Government approving monocultures	2 (13%)	2.5
	Missing public policy interventions for long-term success of alternatives	2 (13%)	3
	Fear of harvesting ban if plantations are too diverse	1 (6%)	-
F5: Market formation	Missing market structure for alternative wood products	6 (38%)	3

(*continued on next page*)

Table 5 (*continued*)

Function	Barrier	Nr and % of interviewees	Average score (1–4)
	FSC certification does not differentiate between management approaches	5 (31%)	2.75
	High international competition to produce cheap pulp	4 (25%)	3.25
	Missing market structure for ecosystem services	2 (13%)	3.5
	Illegal harvesting increases market competition	1 (6%)	3
	Lacking EU regulations for sustainability of imports	1 (6%)	2
F6: Resource mobilisation	Harvesting and transport complexity of alternatives	7 (44%)	3.57
	Needed general change of operations & management for alternatives	7 (44%)	2.83
	Needed training, technical assistance, seedlings, extra workforce for small-scale farmers	7 (44%)	2.33
	Land sparing instead of land sharing approach by industry	5 (31%)	2.4
	Missing subsidies for pulp and paper industry	5 (31%)	2
	No material uniformity for pulp mills with different species	4 (25%)	3.5
	Missing subsidies for small-scale farmers	4 (25%)	3
F7: Creating legitimacy / Counteract resistance to change	Missing pressure from pulp and paper customers to change	12 (75%)	2.8
	Missing awareness & pressure from society to change	7 (44%)	3.11
	Corporate paradigm, force of habit with Eucalyptus monocultures	7 (44%)	3.5
	Focus on technologies of industry plants and Eucalyptus genotypes but not on changing plantation management	5 (31%)	3
	Missing awareness of biodiversity benefit for society	4 (25%)	1.66
	Lacking FSC stringency and power	3 (19%)	4

interviewee 3 indicates that "*you have to demonstrate the additionality of the mixed plantation's for one specific ecosystem service in order to pay for them*".

The missing proof of benefits from alternatives leads the pulp and paper industry to see no need of changing their business model. According to them, the mosaic structure of their plantations and native forests sufficiently fulfils ecosystem services. Interviewee 12 criticised that "*they might as well in their speeches say the amount of forest they are preserving […] but in one area you have kind of a dead space because you just have one culture and it's distant from the ones with more diversity*." Another interviewee from the industry pointed out: "*everybody, our company, like our CEO, they think Eucalyptus plantation is the best thing in the world. You are positive, climate positive because you plant trees, tree is life*" (interviewee 7). This quote confirms the importance of raising awareness about the impact of Eucalyptus monocultures. Only mentioned once but given the highest score in this function is the need for a vulnerability evaluation of the current plantation system. Interviewee 4 stated their priority is to deal with the impacts of increased soil densities through heavy machines and water stress due to climate change before they can address aspects of diversity in their plantations.

4.1.3. Function F3: knowledge exchange

The overarching barrier is a need for dialogue and awareness creation about ecological impacts and the general potential of alternative plantation management approaches, including all stakeholders that are affected throughout the cellulose production chain. By far the most addressed barrier is the missing trust in alternative systems by smallholders, as mentioned by 11 interviewees (Table 5). The origin of doubt frequently is lacking education or a limited information flow, as interviewee 12 pointed out: "*Quite many of them don't have the same level of education, and the corresponding environmental awareness and also the benefits of preserving*". Interviewee 11 addressed that research about alternative systems is often reporting general sustainability advantages for the environment and society, but does not address the direct profit for the plantation owners, who might think: "*you are coming from the city to tell me that it will be good for you, but what about myself*". Therefore, missing role models that reassure smallholders are needed, as the following quote underlines: "*You have to try to find the leaders and the ones that will be able to show the idea if it works*" (interviewee 11). Interviewee 13 also highlights the importance of rural farmer associations in the transition process as follows: "*If we don't include the stakeholders, the part of the supply chain that will implement* [rural farmers]*, we are failing*".

Connecting stakeholders across the whole cellulose production process to assist each other with know-how or sharing responsibilities would require partnerships. Interviewee 7 even stated that: "*The only way I see Suzano working with alternative eucalypt plantation management systems is doing partnerships*", and provided an example: "*A sawmill partner is going to use our land to do this kind of alternative Eucalyptus plantation in our legal reserve, for example. […] And then if things start to get better you're going to our plantation*".

Two barriers that are connected to knowledge exchange and participation around the FSC certification were only mentioned once but scored as a very strong barrier (applying FSC ES certification) or as a strong barrier (stakeholder involvement). The FSC ES certification (FSC, 2021) was developed by the Forest Certification for Ecosystem Services (ForCES) project (Ningsih et al., 2020), to measure and communicate the provision of ecosystem services in FSC certified forests (FSC, 2017; Savilaakso and Guariguata, 2017), but appears to be difficult to apply due to context specific conditions. Industry interviewee 9 said they were using FSC ES in a natural reserve to certify biodiversity conservation as an ecosystem service. However, the application of the tool is very complex and needs time to be integrated, as "*even the people that do the certification, they were not really familiar with that*". Furthermore, stakeholder involvement in the creation and discussion of FSC regulations is lagging, as few invited groups have shown interest in participating (interviewee 15).

4.1.4. Function F4: guidance of the search

Barriers identified are mainly uncoordinated and lacking sustainability regulations and governmental support that lead to uncertainties about new approaches (Table 5). Concerning regulatory frameworks, the Brazilian Forest Code lacks in implementation. Interviewee 11 stated: "*I think we have a very good law in Brazil. We have this law for 10 years but we are still struggling to implement it*". Stricter enforcement could spur innovation of alternative approaches, such as mixed plantations with native species, that can be tested in Legal Reserves before being applied in plantation areas (interviewee 3). Closely connected to that is the barrier of separated regulations among the federal states of Brazil, which each need to set up their own indicators to track the Forest Code implementation, as expressed by the following quote: "*Now we have about 10 states, so almost half of the states already have indicators for monitoring the process. But we still have more than 10 states that still need to develop and launch indicators for monitoring this process. So still, we have a* *long way to walk*" (interviewee 11). The lack of implementation can also be explained by the doubt of landowners as to whether the Forest Code will really be enforced, as "*people wait some time to see if it will not change. So we need to be confident that this will really be enforced*" (interviewee 11). Another barrier connected to legislation is lacking guidance of the search by the Brazilian government, as they are approving monocultures instead of pushing the industry to change their approach. Interviewee 1 stressed that: "*I think for the large-scale companies […], it has to be mandatory or they're not going to do it*". Interviewee 11 mentioned that landowners are afraid of not being allowed to harvest their plantations anymore if they would allow their understory to grow. Such insecurities need to be ruled out by clear regulations that support the applicability of mixed species plantations. Policy interventions to ensure long-term success of alternative plantation management are missing in general, as framed by the following quote: "*We have farmers that are models, we have pilot implementations everywhere, but they're not organised. So we need public policy that connects that. And I think that's something that the state can do*" (interviewee 13).

4.1.5. Function F5: market formation

Identified barriers of market formation are in general perceived to be relatively strong, also representing very high average scores. The challenges address an unequal playing field for alternative products and range from the lack of market structure and strong competition to the lack of support for market development through standards or regulations. When addressing the missing market structure for alternative products, interview partners mentioned it would be hard to find an offtaker for other wood than Eucalyptus. There is a lot of insecurity around alternative species and regularity of their demand, as underlined by interviewee 13: "*We need the offtaker. We need the one that is going to sign a contract and says, look, I'm going to buy your production, whatever it takes*" and interviewee 15: "*If Eucalyptus, which already has a consolidated market in Brazil, already brings this "price" problem, imagine planting a species that doesn't even have a market*". Two interview partners also addressed the missing market structure for ecosystem services, which represents the strongest barrier within this function. The main points of critique are that ecosystem services other than carbon are neglected and that the source of carbon sequestration itself is not seen critically enough, as explained by interviewee 7: "*We need to think about carbon not as just carbon. We need to think about green carbon that comes from a land that also gives us water, good water, biodiversity and stuff like that.*"

Intense competition in the production of cheap pulp due to pressure from international markets (China, Indonesia, Africa) or illegal logging in Brazil also promotes the persistence of highly productive Eucalyptus monocultures. The following quotes represent these strong barriers of competition: "*The forest sector is competing in the world against people that are producing pulp with native species, are producing pulp by devastating areas, so most of the time their costs are lower than here in Brazil*'' (interviewee 6). Interviewee 1 stated, that: "*It's not that you can really compete with this illegal forestry. There's no way you're going to get that price, you're not going to be able to fight this*".

Lacking support from certification schemes in creating a market for products from alternative plantation management was scored as a medium to strong barrier. Interviewee 1 made the following suggestion: "*FSC or any other kind of certification scheme could put a premium on these different types of management to show that you have a different kind of forest and it's not just monoculture but there is other services, and I don't think I've seen a certification that has this kind of grade*". One interview partner also identified missing EU regulations or goals that target ecosystem services provisioning when sourcing pulp and paper products from international markets like Brazil (interviewee 12).

4.1.6. Function F6: resource mobilisation

Considering resource mobilisation, most addressed and highest ranked are the difficult harvesting conditions in mixed or uneven-aged plantations and the transport complexity due to the organisation of different offtakers for multiple wood products. Harvesting needs to be done more carefully, so native trees in mixed plantations are not damaged, as these should be sold at premium prices. Interviewee 1 also gives an example where harvesting complexity terminated a coppice with standards project: "*A high leading forest guy in one of these large companies was telling me the difficulty with this kind of system [CWS] is when you take the standards out, you have a lot of damage to the coppice, so they said that this was complicated, so they stopped doing it*". Inflexibility and efficiency of Eucalyptus monoculture harvesting by big companies was explained by interviewee 3: "*Harvesting today is kind of like, it's a kind of factory, it's an in-line production. […] So it's all mechanised, all homogenised, all standardised*".

However, small-scale farmers also face operational obstacles that hamper the implementation of alternative approaches. They would need technical assistance and training, the provision of seedlings and extra workforce to learn about and apply new silvicultural systems. "*Forest management in this way takes time, takes management, it takes planning, it takes a lot of elements to build that. And I don't think that's a reality for most of the small and medium farms*", as expressed by interviewee 13. The needed planning addressed in the previous quote reflects the barrier of required time management skills to successfully implement mixed species or uneven-aged plantations. Different species are planted for multi-purposes and show varying growth rates. It requires excellent knowledge and experience to develop a feeling for the right planting and harvesting times as well as the right moment for the application of fertilisers (interviewees 3 & 8). The pulp mills also have difficulties adapting to mixed tree plantations, as they need homogeneous wood to ensure a certain wood quality. The mills are precisely adjusted to one Eucalyptus genotype and are therefore not flexible enough to process acacia wood, which would also be suitable for pulp production.

Another scarce resource is available land to establish new plantation areas. Therefore, the pulp industry follows the approach of land sparing instead of land sharing. This means it focuses on highly efficient production at its plantation sites and, at the same time, sets aside purely natural forest areas with native species to compensate for its intensive land management. The industry argues that it would need to expand its plantation frontiers if it were to establish mixed species plantations in order to achieve the same production capacity as with monocultures. Interviewee 14 explained it as follows: "*The idea is that if we can produce much more wood in the same area, we are not going to use land that is going to be for, I don't know, conservation*".

Interview partners mentioned that missing financial funds and subsidies would be needed to allow risk-free exploration of alternative management systems. Especially small-scale farmers need economic support, as "*they normally lack the money for really basic things. So to develop a new forest project, you need some capital to start that and the return will be in the long term*" (interviewee 11). Farmers also do not have access to knowledge about how to unlock existing funds (interviewee 13). Also, bigger landowners would need economic incentives to consider alternatives, as interviewee 11 addressed: "*We normally target smaller landholders, because they need more incentives, but I think it's also important to give subsidies to projects, big projects also with Eucalyptus that embrace biodiversity*". Lastly, governmental funds mainly focus on the agricultural sector, which enjoys a powerful position in Brazil. Therefore, there is a need for better cooperation between the forest and agricultural sector to make funds available for a broader range of industry players, including forest plantation owners (interviewee 13).

Certification hurdles for small-scale farmers are perceived to be quite strong. About ten years ago, the pulp and paper industry followed the market demand for certified wood and supported farmers financially and technically to become FSC certified. However, a few years ago, the market started to accept non-certified wood, so the companies stopped their support. As a result, more than 500 farms lost their sustainable forest management certifications, which were supposed to be a driver for new standards and thus innovative silvicultural approaches that support ecosystem services (interviewee 10).

4.1.7. Function F7: creating legitimacy /counteract resistance to change

The lack of legitimacy for innovative plantation management concepts is reflected in the lack of awareness of the negative environmental impacts of monocultures and the missing pressure on the pulp and paper industry to change. Absence of pressure is most frequently addressing customers, but the role of society as a whole is also highlighted and scored as a strong barrier to change. Resistance to change can be represented by a very strong corporate paradigm of the pulp and paper industry holding on to monocultures.

Brazilian customers prioritise cheap products, China (a highly important export country) also does not care about sustainability impacts (interviewees 15 & 4). Only European and American clients slowly start questioning sustainability more (interviewee 4), although "*they only look if it is certified, then it's good*" (interviewee 2). Interviewee 7 stressed the importance of missing pressure from pulp and paper customers as follows: "*If the big guys don't ask us to change, we are not going to change, as you said FSC is OK with that, the government is OK with that, our customers so far are fine with that. So we need this kind of pressure. Big companies, our bigger partners, like consumers, as I said, like Unilever, Nestlé . They need to ask us to change it and then we are going to change.*"

Missing pressure from the society in Brazil is very present for interviewee 7, he stated: "*Brazil so far as a society is OK with monoculture. The only guys who are concerned about Eucalyptus monoculture, people like environmentalists, and our neighbourhood, people that are suffering the impact every day, like water, for example. But I mean, it's like 10% of our neighbourhood, less than that.*" This lack of interest or awareness could be justified by the population having to deal with more pressing problems: "*I believe that they don't understand very well the depth of the trouble. Because here in Brazil, we have other problems to deal with. Unfortunately, few people understand the importance of this kind of problem in Brazil*" (interviewee 4). Four interviewees addressed the missing awareness of society about the benefits of biodiversity as a reason for lacking societal demand for more diverse plantations. For the innovative business model to spread and persist, it needs awareness and acceptance of the society, as explained by interviewee 13 "*The challenge in the long term is how to guarantee the long persistence of this forest. With the society recognising the value, and that can be by products. Because otherwise we're going to have a huge challenge in the future. I don't want to have forest regeneration and society is left behind and doesn't have a value for them. Otherwise they're going to cut, because society is not going to get a connection with that. So this has to be one part of the solution.*" In addition, and refering to the development and implementation of Payments for Ecosystem Services (PES) in the state of São Paulo, interviewee 13 mentions "*I think payments for environmental services need to include all the cycles and look for opportunities for the rural farmers, […] to guarantee the long term conservatation*".

Another very strong barrier contributing to lacking legitimacy for alternatives is the decreasing power of FSC. The organisation is certifying Eucalyptus monocultures and not differentiating between different management models. Interviewee 13 explained the loss of power as follows: "*FSC was created for tropical forest and didn't deliver any impact on that*". He further stated: "*They [pulp and paper companies] said they are getting the same impacts with their work without FSC*", giving the certification less relevance for the development of sustainable forest management.

A very strong barrier to change is the corporate force of habit. The pulp and paper industry has an intensive focus on their profit-driven business way of managing Eucalyptus plantations. Therefore, forest management needs to be the simplest way possible (interviewee 1). Interviewee 12 framed the resistance to change as a conscious decision, addressing knowledge availability and power relations "*Access to knowledge is no barrier, but utilising the knowledge, then, is a different thing. […] It's like being big, dominant, and especially like in some regions, knowledgeable about alternatives, and so if they wanted, they could mobilise to change. […] They don't want to diversify, even if that would bring more wealth. And wealth in many senses, like maybe financially but also environmentally, and that would benefit others. It's also that view, like profit for me alone*".

A barrier related to the corporate mindset is the continuous focus on Eucalyptus genotype development and technological improvement of monoculture management. Interviewee 2 described a meeting with industry representatives, where he suggested mixed plantations in the North of Brazil to adapt to climate change. His colleague answered: "*Oh no! We will find clones adapted*". Hence, experience with alternative species and management approaches is very limited (interviewee 4).

4.2. Blocking mechanisms

In the previous section, the barriers mentioned for each TIS function were provided separately. In this section we will explore further why the innovation system of mixed Eucalyptus plantations is not functioning. Drawing on Wieczorek and Hekkert (2012) Hekkert et al. (2007) and Vermunt et al. (2022) we can identify four mechanisms inhibiting the upscaling of mixed plantations (Fig. 2).

The first blocking mechanism is rooted in the production-oriented focus on plantation management, which is referred to as a '*productivist' approach by regime actors* (e.g., Duru et al., 2015). This productivist approach can be characterized by the strong focus on the use of technologies (i.e., breeding genetic material, intensification and land sparing) to solve (environmental) problems and on short-term profit maximisation, leading to a strong resistence to change current practices. The second blocking mechanism is a *lack of vision* on the future of sustainable Eucalyptus plantations *by government, businesses and society*, which leads to a lack of pressure to change the current status quo of incumbent practices. A lack of awareness to produce and consume sustainably, and the focus on Forest Code implementation are one of the main elements. This blocking mechanism, that lacks pressure to change practices is therefore also reinforcing the firt identified blocking mechanism.

The lack of information on ecological impacts of alternative plantations and the immaturity of adapting forest management to the FSC ES certification leads to the third blocking mechanism of a *lack of experience with additional certification*. This blocking mechanism leads to a lack of (protected) niche market development and as such hampers uptake of financial incentives, such as subsidies or price premiums to entrepreneurs, to develop alternative practices further.

The failed projects in the past, the missing trust across the various actors involved, which also hampers further collaboration, and missing knowledge on the application of FSC ES certification lead to the fourth blocking mechanism of a *lack of proof of concept*. As such it also limits resource allocation to training and education and leads to a lack of motivation to change current certification.

5. Discussion

We studied the innovation system of mixed Eucalyptus plantations in Brazil by analysing the sustainable business models and applying the Technical Innovation System (TIS) framework to understand the fulfillment of the underlying system functions. Here we will first discuss the upscaling failure of the mixed plantation business models by also drawing on recent findings on transition issues in agroecological systems. Next, we will discuss potential pathways for interventions to overcome the current system lock-in.

5.1. Upscaling failure of mixed Eucalyptus plantation models

The TIS analysis on alternative Eucalyptus business models showed a poor fulfillment of all seven functions, indicated by the numerous barriers found for each system function. The barriers combined lead to four blocking mechanisms, which in turn leads to a system lock-in. As such a stalemate is created in the development of alternative business models. The identified blocking mechanisms are 1) *a productivist approach* by

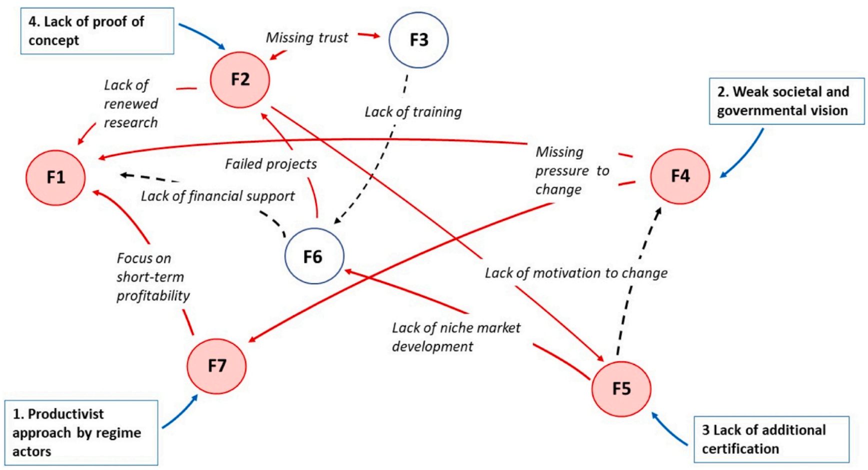

Fig. 2. Blocking mechanisms on system functioning of alternative mixed Eucalyptus plantations, indicated by the rectangular boxes 1–4. TIS functions are depicted as circles (F1 = Entrepeneurial activity, F2 = Knowledge development, F3 = Knowledge exchange, F4 = Guidance of the search, F5 = Market formation, F6 = Resource mobilisation, F7 = Creating legitimacy). Coloured circles indicate the TIS functions mostly affected by blocking mechanisms. Red arrows indicate main effects of the blocking mechanisms, dashed arrows indicate the remaining effects.

regime actors on Eucalyptus plantations focussing on short-term profitability, 2) *a lack of a shared vision* on sustainability issues of land production systems, such as forestry, by government, businesses and society, leading to a lack of pressure put on the forestry system to change, 3) *a lack of (additional) certification* to protect niche markets of alternative Eucalyptus plantations which hampers the development of financial support such as price premiums, and 4) failed projects in the past leading to *a lack of proof of concept* to change incumbent practices leading to a lack of new research on sustainability issues, training and education.

In the case of Eucalyptus production in Brazil, previous experiments with different business approaches have increased doubts about their prospects due to the strong focus on short-term financial profitability by the incumbent regime actors, and inhibited by a fierce competition on the national and international paper and pulp markets. The studied alternative business models are mostly presenting an improved provision of ecosystem services such as biodiversity of fauna and flora, however none of those models could compete with the short-term financial profitability implied by the current regime and as such were not implemented by businesses after experimentation.Thus the alternatives face strong difficulties as they compete with monoculture plantations on the same market. This is also supported by findings of Forrester and Bauhus (2016) who indicated yields of monoculture Eucalyptus stands in the Atlantic Forest region are found near the physiological optimum. This finding contradicts earlier global patterns found of increased wood biomass in mixed plantings or uneven-aged Eucalyptus stands (Brockerhoff et al., 2013).

In agriculture, a productivist approach on food production is defined as agricultural systems that rely on technological advancement to reduce (input) costs by applying synthetic inputs, strong mechanisation, standardization, scale enlargements and selective breeding to increase yields (e.g., Duru et al., 2015). As such the approach challenges sustainability issues, multi-functionality and biodiversity conservation (Duru et al., 2015). Lamine et al. (2012) indicated that historical path dependencies result in a particular innovation trajectory that becomes dominant due to feedbacks and convergence of knowledge and resources of both the providers of innovation (knowledge brokers, suppliers, value chain actors, public institutions, industry) and consumers (farmers, foresters), leading to a reinforcement of a rigorous productivist regime resistant to change (e.g., Weber and Rohracher, 2012). Transition lock-ins caused by such socio-technical regimes can often be framed as 'chicken-and-egg' problems (Lachman, 2013). To explain in the context of sustainable Eucalyptus plantations, producers who want to sell their more expensive products from mixed plantations need consumers to buy, but since there is hardly any supply, products remain costly due to a lack of economies of scale which in turn leads to less demand and therefore weak interest of producers to invest. This lock-in is reinforced by a lack of shared vision exemplified by low public awareness and as such a lack of societal pressure on solving sustainability problems. With a lack of pressure, public policies that hinder the uptake of more extensive plantation systems are very diffult to curb. In turn, it also negatively affects further knowledge development as research budgets may decrease.

Recent studies on agroecological transitions indicate a slow diffusion of sustainable practices is also due to a lack of financial incentives (e.g., Gaitán-Cremaschi et al., 2019; Vermunt et al., 2022). While agroecological practices provide important ecosystem services, limit the use of chemical inputs and conserve biodiversity, the financial profits for producers are lower due to lower yields. Thus, higher production costs should be compensated for by adding a price premium for complying to sustainability standards (Yokessa and Marette, 2019). Although the FSC label for responsible forest management still certifies intensively managed monocultures and does not differentiate between conventional and alternative management options, the FSC certification for ecosystem services has been developed to measure, verify, and communicate the provision of ecosystem services in FSC certified forests (Ningsih et al., 2020; Savilaakso and Guariguata, 2017), and may allow FSC certification holders to demonstrate the impact of their forest management (Ningsih et al., 2020). Stakeholder participation in creating the FSC regulations is lagging, since a large part of the international market accepts non-certified wood, which is decreasing the legitimacy of the standard. Yokessa and Marette (2019) suggest to complement eco-labels with governmental regulations and subsidies supporting potential alternatives. However, interviewees reported lacking enforcement of the Forest Code in Brazil, missing governmental subsidies and lacking technical assistance to support more sustainable Eucalyptus management. In comparison, Payment schemes for Ecosystem Services (PES) in Brazil have been developed and forests gains have been reported, while also decreasing Eucalyptus plantation cover, but the positive impacts of these PES may be very vulnerable to a lack of legal additionallity, while the relative short-term contracts may not lead to long-term positive impacts (Ruggiero et al., 2019). Moreover, there is a lack of market infrastructure for wood products from Acacia and native species, while there is also a non-existent market for ecosystem services provided by alternative forest plantations.

Finally, in well studied transitions in the energy or transport sector (e.g. Markard et al., 2012), very often innovations that challenge the incumbent socio-technical regime to change are introduced by new entrants who will eventually determine a new socio-technical regime. In land-based production systems, such as agriculture and forestry, land is the most important production factor and very often in the hands of regime actors. Therefore, any change to the socio-technical regime should come from regime actors rather than from new entrants (Verburg et al., 2022; Vermunt et al., 2022), which is coined in the transition literature as a regime transformation (e.g., Markard et al., 2012; Vermunt et al., 2022). Such regime transformations are very difficult to make, since regime actors are stuck in their productivist thinking. Moreover, Ningsih et al. (2020) also showed that state regulations can be antagonistic towards the uptake of ES certification, indicating regime transformations should come from regime actors, leading to lock-in. Although the Brazilian Legal framework prohibits the planting of solely exotic trees in so-called Legal Rerserves or Areas of Permanent Protection, the planting of mixed forest stands still needs better governmental regulation (de Moraes et al., 2020). As de Moraes et al. (2020) pointed out, recent govermental decisions, however, do not deliver more sustainable solutions.

5.2. Lock-in interventions by mission-oriented innovation policy

While the TIS analysis provided a clear overview of the current barriers related to the seven innovation system functions, the framework has limitations towards a better understanding of the larger transformational needs for upscaling (El Bilali, 2019; Lachman, 2013). Recent advancements in innovation sciences indicate mission-oriented innovation policies can address 'grand challenges' such as environmental-friendly production systems (e.g., Hekkert et al., 2020; Mazzucato, 2018; Wittmann et al., 2021). Although mission-oriented innovations are not new and have been applied to classical 'man on the moon' problems (Mazzucato, 2018), recently the larger societal challenges that involve wicked sustainability problems have gained traction in mission-oriented innovation theory, as it requires long-term commitment from public and private actors (Janssen et al., 2021; Mazzucato, 2018).

The current lock-in observed for sustainable Eucalyptus plantations in Brazil is foremost caused by a lack of directionality, emphasised by a lack of shared vision and the strong resistance from incumbents to change. As such, there is no 'dot on the horizon' as to what alternatives should look like and how they could eventually be practised, due to the dominant 'short-termism' of profitability focussing on monocultures only. Although the alternative models explicitly address sustainability issues, these are not clearly included in societal values, policy and actions, such as business investments and public and private policy making. Mazzucato (2018) identified four points relevant to mission-oriented innovations and can be translated for the sustainable Eucalyptus innovation system; 1) missions should be well defined in terms of (long-term) sustainability goals, 2) it should not comprise a single innovation project but a suite of different solutions, 3) the missions should include different actors across the value chain as well as other public and private partners to put further societal pressure, and 4) missions depend largely on joined policy making where sustainability goals are transferred into tangible actions and decisions.

A mission-oriented approach can therefore create the currently lacking directionality. As such, missions will tilt, rather than levelling the playing field where the role of the public sector is to facilitate the 'de-risking' of the private sector by providing rewards and enabling policy change for business transformation (Borrás and Edler, 2020; Mazzucato, 2016). To develop niches, some form of protection is needed and recent experiences with for example different 'sustainability tiers' in certification have shown it can accelerate consumer uptake (Verburg et al., 2022). Finally, mission-oriented approaches can transcend national boundaries (Klerkx and Begemann, 2020) as many value chain actors are involved in the paper and pulp industry. As such, mission-oriented approaches for sustainable plantations can take the form of a global innovation system where national and international contexts are connected (Klerkx and Begemann, 2020). It therefore calls for an integrated approach in which the diverse international timber and plantation initiatives join, to provide directionality, guidance, policy and niche protection.

To conclude, further niche development including a price premium for applying the FSC Ecosystem Services Procedure certification could aid a diffusion of alternative Eucalyptus plantations. However, the lack of societal pressure and the productivist approach by incumbents are deeply rooted in the current system lock-in and need to be solved as well. The lessons learned from agroecological transformations indeed show that various transformation problems can only be addressed in conjunction with each other (Vermunt et al., 2022).

CRediT authorship contribution statement

Verburg René: Project administration, Resources, Supervision, Writing – review & editing, Funding acquisition, Methodology. **Bellink Miriam:** Formal analysis, Writing – original draft, Investigation, Methodology.

Declaration of Competing Interest

The authors state that this manuscript has not been not published elsewhere and is not under review with another scientific journal.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2023.106882.

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