Revisión [Review]

ECOSYSTEM SERVICES IN BRAZILIAN'S SOUTHERN AGROFORESTRY SYSTEMS[1]

[SERVICIOS ECOSISTÉMICOS EN SISTEMAS AGROFORESTALES DEL SUR DE BRASIL]

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SUMMARY

Agroforestry systems (AFS) are polycultures with at least one tree species. These systems provide various ecosystem services, income increments and food safety. These ecosystem services include biodiversity conservation, carbon sequestration, reduction of crop diseases, increased biological controls, biological nitrogen fixation and nutrient cycling. A review of potential ecosystem services of AFS on Southern Brazil is presented. In addition, the potential of carbon uptake through conversion to AFS is estimated. The predominant AFS are agroforestry with yerba mate (*Ilex paraguariensis* A. St. Hil.), silvopastures, citrus and banana orchards, and the palm açaí-juçara (*Euterpe edulis* Mart.). Considering the conversion of conventional systems to AFS, the silvopastures present the greatest carbon sequestration potentiality due to the great area used for cattle ranching. The conversion of citrus and banana cropping also present great carbon uptake potential besides reducing fungal and bacterial diseases. Southern Brazil presents more than 15 million hectares which could be converted into silvopasture and other AFS by taking as a model the already well-established experiences. Moreover, AFS has become a strategy for forest restoration. There are no negative trade-offs related to the silvopasture and citrus agroforestry adoption. The reasons for the low adoption of AFS are discussed.
Key words: climate change; sustainability; forest recovery; biological controls; silvopasture.

RESUMEN

Los sistemas agroforestales (SAF) son policultivos que incluyen por lo menos una especie arbórea. Los SAF ofrecen diversos servicios ecosistémicos, aumento de las ganancias y seguridad alimentaria. Los servicios ecosistémicos de los SAF incluyen conservación de la biodiversidad, captura de carbono, reducción de las enfermedades de los cultivos, aumento de los controles biológicos, fijación biológica del nitrógeno y reciclaje de nutrientes. En este artículo se presenta una revisión de los servicios ecosistémicos asociados a los SAF en el sur del Brasil. Además se estima la potencialidad para la captura de carbono de los SAF. Los SAF predominantes son los asociados a la yerba mate (*Ilex paraguariensis* A. St. Hil.), sistemas silvopastoriles, cítricos, plátano y sistemas con la palmera açaí-juçara (*Euterpe edulis* Mart.). Teniendo en cuenta la conversión de sistemas convencionales para SAF, el silvopastoreo presenta la mayor potencialidad de captura de carbono en función de la gran área de creación de ganado. La conversión de los cítricos y banana también presentan gran potencialidad de captura de carbono, además de la reducción de las enfermedades fúngicas y bacterianas. El sur de Brasil presenta más de 15 millones de hectáreas que pueden ser convertidas en SAF teniendo como modelo las experiencias ya bien establecidas. Además, los SAF están siendo adoptados como estrategia de restauración forestal. No se observan relaciones costo-beneficio negativas relacionadas con la adopción de silvopasturas o SAF con cítricos. Las razones para su baja adopción son discutidas.
Palabras clave: cambio climático; sustentabilidad; recuperación de bosques; controles biológicos; silvopastura.

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INTRODUCTION

Agroforestry Systems (AFS) are deliberated consortia of trees with crop plants and/or livestock, in determined space arrangements and sequences along the time, presenting varied interactions among their components (Baumer, 1991; Coelho, 2012). Besides economic and social advantages, the AFS provide ecological benefits such as erosion contention (Franco *et al.*, 2002; Traore *et al.* 2004), increment in the organic carbon in the soil and in the above-ground biomass (Albrech and Kandji, 2003; Mutuo *et al.*, 2005; Verchot *et al.*, 2007; Nair *et al.*. 2009), biodiversity conservation (McNeely and Schroth, 2006; Harvey and Villalobos, 2007; Fajardo *et al.* 2009; Rivera *et al.*, 2013) and the promotion of spontaneous biological control associated with increased yields (Maas *et al.*, 2013). Moreover, agroforestry is agriculture practices which can generate higher ecologic sustainability than the conventional practices, whether organic or not. Agroforestry aggregates ecological functions such as soil erosion control, nitrogen leaching reduction and carbon uptake for which organic agriculture does not reach differentiation in relation to the conventional agriculture (Wilson and Lovell, 2016).

This paper is aimed at present the traditional and innovative AFS in Southern Brazil, as well as the reported or potential ecosystem services they provide. As the ecosystem services that could be provided by the AFS compound a wide suite of possibilities among cultural, environmental, social and economic perspectives (Fagerholm *et al.*, 2016), only the ecosystem services related to the biophysical aspects were addressed. Such circumscription included climate change and carbon sink, biological controls, reduction of agrochemicals and fertilizers and biological conservation. Economic aspects related to them are also commented. This delimitation is justified also by virtue of the available scientific background based on the region: as far as possible, the review is mainly based on data reports from Southern Brazil in itself and complemented with investigations from other Brazilian regions and even from other parts of the world whenever necessary.

The Southern region of Brazil includes the States of Paraná (PR), Santa Catarina (SC) and Rio Grande do Sul (RS). The humid subtropical climate (Cfa and Cfb in the Köppen-Geiger system) presents an annual average temperature and annual rainfall ranging between 14º to 22 °C and 1,250 to 2,000 mm, respectively (Leite, 1995). The pristine vegetation cover was predominantly forests of the Atlantic Forest Biome and a minor portion of grasslands or savannah-like ecosystems in the southernmost Rio Grande do Sul State, which corresponds to the Pampa Biome (Figure 1).

In the Pampa Biome, the arboreal components are restrained to the gallery forests or as sparse components of woodlands or steppe-savannah complex, particularly at the extreme Southwest. Nevertheless, the highly anthropized grasslands in the Pampa Biome coexist with woody formations in a metaclimax dynamics since the current climate is favorable for both (Pillar and Vélez, 2010). Thus, the integration between livestock and silviculture exhibits high feasibility in this Biome (Saibro *et al.*, 2009).

With its favorable climate for the development of forests, the southern region of Brazil is highly auspicious to the development of agroforestry systems. However, due to historical and cultural factors, these systems remained limited to small areas until now. Meanwhile, in a context of growing environmental and social concerns about modern forms of agricultural managing, AFS have been seen as safer and more sustainable mode of production with diversified environmental benefits or services (Garrity, 2004, Coelho, 2012, Nair and Garrity, 2012).

The predominant agroforestry systems in Southern Brazil are yerba mate (*Ilex paraguariensis* A. St. Hil.), plantations and extractivism, *Citrus* spp. orchards, banana cultivation, açaí-juçara (*Euterpe edulis* Mart.), silvopastures, and in a minor extent coffee systems. Hereafter the key features, the occupied area, the biophysical ecosystem services (reported or potential) and economic aspects are presented and discussed.

Agroforestry systems with yerba mate *(Ilex paraguariensis*)

The yerba mate is a native tree species from Brazil, Argentine and Paraguay, whose cultivation dates back to early European settlement in South America in the seventeenth century, although its extractive use is pre-Columbian (Linhares, 1969, Lagier, 2008). Similar to cocoa and coffee, yerba mate plants are shade-tolerant (Coelho and Mariath, 1996, Coelho *et al.*, 2011) and its evolution occurred amid the forests of the southern portion of the Atlantic Forest Biome. Although yerba mate could be cultivated at full sunlight with high densities as a monocrop, there are systems in which yerba mate is kept partially shaded under remaining native trees, and in which its density can be gradually increased (Figure 2). The shading could change the chemical composition (Coelho *et al.*, 2007a) and taste of yerba mate products (Streit *et al.*, 2007; Pagliosa *et al.*, 2009), and there is a common sense that this change is positive. Thus, the industry tends to pay higher values for raw materials coming from shaded systems. The increased appreciation of shading has promoted the introduction of shading trees in mate plantations, in many cases native species, or the management of spontaneous growth of woody species, for instance *Araucaria angustifolia* (Bert.) O. Kuntze (Figure 2). Among the introduced shading species are the leguminous tree species *Mimosa scabrella* Bentham and *Ateleia glazioveana* Baill.

Ateleia glazioveana is a deciduous species (Figure 2) whose pruning material can be used for mulching, presenting better results than animal manure with the same N contents (Baggio and Soares, 2006). In wild areas, the association between *A. glazioveana e I. paraguariensis* is noteworthy, which could involve some kind of facilitation (Coelho *et al.*, 2011). In addition, *A. glazioveana* could be introduced by direct seeding, with low costs (Escaio *et al.*, 2012).

The biological nitrogen transference from the atmosphere to vegetation is a key process in the secondary succession, being the main limiting nutrient in the early phases (Amazonas *et al.,* 2011). Apart from other benefits such as firewood production and windbreak effect, the use of leguminous trees can reduce the dependence of industrial fertilizers, which constitutes an ecosystem service in itself (Kremen and Miles, 2012). Traditional systems with intercropping and rotation between maize and *M. scabrella* in Paraná State showed 82 kg ha^{-1} of nitrogen surplus after each cycle of six years (Somarriba and Kass, 2001).

Yerba Mate AFS reached a 63 $Mg.ha^{-1}$ of carbon stock on the aboveground biomass (Bastos, 2013), which is equivalent to forest remnants in intermediary successional stages, at the same locations. The plant biodiversity also reached similar values to forest remnants, though the floristic composition differs (Bastos, 2013), possibly caused by a selective management carried out by landowners.

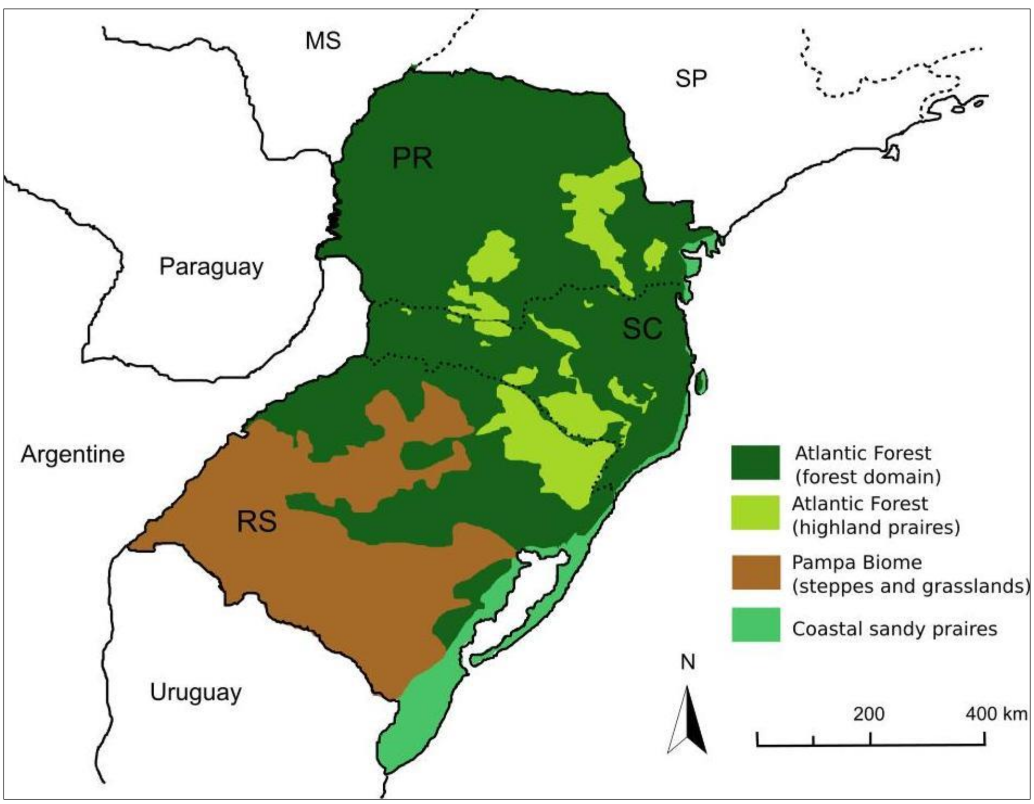

Figure 1. Pristine vegetation cover of Southern Brazil. The Atlantic Forest Biome included the Forest Domain and the Highland Prairies. The Pampa Domain includes the Steppes and Grasslands at the south and southwest, which extends to Uruguay and Argentine.

Figure 2. Agroforestry systems with yerba mate (*I. paraguariensis*). A. forest converted to high density yerba mate (in the foreground and amid the higher trees) cultivation with remaining wild trees in Machadinho, RS, 2007; B. agroforestry with yerba mate and *A. glazioveana* (timbó) in the superior strata in Chapecó, SC, 2013; C. agroforestry with yerba mate and *A. angustifolia* associated with pasture in Chapecó, SC, 2010; D. consortia with yerba mate, *M. scabrella* (bracatinga) and dairy cattle in Augusto Pestana, RS, 2009.

In Brazil, mate cultivation is virtually exclusive to the Southern States occupying 77,340 hectares (Table 1; IBGE, 2009, 2016). The total annual production of raw material is around 660 Gg and 1/3 is provided from agroforestry (Signor, 2013). Nevertheless, the total area maintained in agroforestry systems (managed forests + converted yerba mate plantations) is unknown. Assuming that 2/3 of the mate cultivation can be converted into agroforestry, and according to available reports (Bastos, 2013), near 1.0 Tg C could be incorporated in the aboveground biomass. The data regarding the potential for incorporating carbon in belowground biomass are not available (this point will be discussed forward).

On the other hand, the expansion of yerba mate cultivation through conversion of undisturbed forests or those at an advanced successional stage can represent a liquid transference of carbon to the atmosphere. Mature undisturbed forests in Southern Brazil can contain more than 150 Mg ha^{-1} C on the aboveground biomass (Mognon *et al.*, 2013). Thus, a simplification of the ecosystem to levels that allow a satisfactory productivity of yerba mate could represent losses of approximately 80-100 Mg C ha^{-1}.

Despite the evidence that AFS generally reduce pest incidence and pesticide needs (Steffan-Dewenter *et al.*, 2007; Maas *et al.*, 2013), the few available data from yerba mate systems indicate a similar level of herbivory in both monocropping and agroforestry systems (Avila *et al.*, 2016). Further analyses are needed to validate these findings.

Table 1. Area of the three Brazilian Southern States and the total area occupied by the agricultural activities which present the more expressive agroforestry or silvopasture experiences, and also with higher potential of conversion to agroforestry. RS = Rio Grande do Sul State, SC = Santa Catarina State, PR = Paraná State, BR(%) = percent of the area in relation to the total area of the country. According to IBGE (2009, 2016).

	RS	SC	PR	Southern region (total)	BR(%)	Brazil
Area (km^2)	281,748	95,346	199,315	576,409	6.77	8,515,767
Pastures	9,206,664	1,701,519	4,702,546	15,610,729	9.75	160,042,064
Citrus	39,798	28,107	37,459	105,364	12.34	854,010
Banana	12,226	29,534	11,000	52,760	10.10	522,300
Açaí/Palm heart	6	3,301	1,108	4,415	8.97	49,242
Yerba Mate	35,240	13,467	28,629	77,336	99.62	77,630
Coffee	--	--	38,333	38,333	0.19	2,002,151
Total	9,293,934	1,775,928	4,780,742	15,850,604	9.81	162,093,457

Table 2. Major ecosystem services contributions from the agricultural activities which present the more expressive agroforestry or silvopasture experiences and higher potential of conversion to agroforestry in Southern Brazil.

	Carbon uptake and stocking	Pesticide reduction	Biodiversity conservation	Decrease of industrial fertilizers dependence and biological fixation of N	Erosion control and watershed protection
Pastures	High	?	Low to High [2]	Mid to High [2]	High
Citrus	High	High	High	High	High
Banana	High	High	High	High	High
Açaí/Palm heart	Managing dependent [1]	?	High [4]	?	Managing dependent [1]
Mate	Managing dependent [1]	Low?[3]	High	High	Managing dependent [1]
Coffee	Mid to High	Mid to High	High	High	?

[1] The conversion of monocropping into agroforestry systems can increase the ecosystem services**,** while the conversion of forests to agroforestry with yerba mate or açaí may produce the opposite effect.

[2] Dependent of the species used; for example, there are frequent silviculture of *Eucalyptus* (and other exotic species) with pastures that do not present high native diversity or leguminous trees with biological fixation of nitrogen.

[3] Based in the only reference available (Avila *et al.*, 2016).

[4] Considering a good conservation of canopy diversity.

Citrus and other fruit cultivation

Different *Citrus* species can be cultivated under the canopy of shading trees (Figure 3). The tree species of the upper stratum can provide benefits for the cultivation in several ways: biological fixation of nitrogen, nutrients cycling, protection against weather stresses. At shaded citrus orchards, the incidence and severity of typical diseases such as the bacteria *Xanthomonas axonopodis* (citrus canker) and the fungi *Guignardia citricarpa* (citrus black spot) have been significantly decreased (Gonzatto, 2009; Gonzatto *et al.*, 2010). On the other hand, the yields are not affected by moderate shading (Syvertsen *et al.*, 2003; Cohen *et al*., 2005) or even increase (Gonzatto, 2009). Species like *Citrus sinensis* Osbeck and *C. limon* (L.) Osbeck show photosynthetic saturation at 30-40 % of the full sunlight, and temperatures over 20-30 °C (depending on humidity) can inhibit the photosynthesis (Kriedemann, 1968; Wheaton *et al.*, 1978; Jifon and Syvertsen, 2003). The inhibition of the citrus canker could be related to the windbreak effect of the associated trees (Tamang *et al.*, 2010), which reduces the damage of leaves.

However, agroforestry can promote higher infestation of citrus blackfly *Aleurocanthus woglumi* Ashby, 1915 (Sternorrhyncha: Aleyrodidae) compared with conventional cultivation (Silva *et al.* 2011a), although the difference on damages was not evaluated. The citrus blackfly was more commonly associated with the warmer regions of Brazil and the first observation was in Pará State, Amazonas region; the occurrence in Southern region is rare until this moment (Molina *et al.*, 2014).

Shading increases the longevity of the *Citrus*, which maintains high productivity for a longer time span. According to landowner's information, citrus plants in shaded orchards from the Rio Grande do Sul State provide high yields even after 25 years.

Despite the strong evidence of economic and ecological benefits of agroforestry over conventional orchards, this form of cultivation is still an exception. Brazil has more than 850.000 ha of citrus plantations (Table 1). In the absence of reliable inventories, one could estimate that *Citrus* agroforestry performs less than 2-3 % of the total area. The inexistence of tradition, cultural resistance and lack of knowledge among the rural extension agents are explanatory factors for this situation.

Conversion of *Citrus* orchards to agroforestry can incorporate carbon in expressive amounts. Available estimation in the region indicates values around 25 Mg C ha^{-1} in the aboveground biomass (20 % is from *Citrus* plants), which corresponding to 50 % of the aboveground biomass at forest remnants in pairwise comparisons in the same region (Bastos, 2013). The government census (IBGE, 2009, 2016) estimates 105,000 ha of citrus cultivation area at the Southern region, thus the potential to incorporate C on the aboveground biomass is around 2.1 Tg, e.g. an addition of 20 Mg C ha^{-1}. On the other hand, the data regarding the potential for incorporating carbon in belowground biomass are not available.

Figure 3. Agroforestry systems with fruit cultivation. A. agroforestry with Citrus with a row of shading native trees arranged by the cutting management in Aratiba, RS, 2015; B. agroforestry with açaí-juçara (*Euterpe edulis* Mart.) in the understory and an individual of *Plinia peruviana* (Poir.) Govaert in the foreground on the left in Barra do Turvo, São Paulo State, 2009; C. agroforestry with Citrus with *Parapiptadenia rigida* (Benth.) Brenan in the canopy (a leguminous tree with biological fixation of nitrogen) in Tupandi, RS, 2009; D. banana agroforestry with *Machaerium stipitatum* Vogel (another leguminous tree with BFN) in Dom Pedro de Alcântara, RS, 2009.

The banana cultivation also presents benefits when moderately shaded, eventually showing higher productivity with mild shading. The beneficial effect of shading increases inversely with the latitude (Norgrove, 1998). The yellow Sigatoka (*Mycosphaerella musicola*), one of the main diseases that affect this crop, is reduced significantly with the presence of the shading trees in agroforestry (Norgrove and Hauser, 2013), a fact also observed in Southern Brazil, according to reports from producers. The reduction of the yellow Sigatoka and also of the black Sigatoka (*Mycosphaerella fijiensis*) observed in Brazil can occur due to different factors, such as windbreak effect and the consequent reduction of foliar damage, better nutrient cycling, and the reduction of leaf surface temperature, which impair the fungus development; however, excessive shading can increase Sigatoka incidence, possibly by increased humidity (Favreto *et al.*, 2007).

The açaí-juçara (*Euterpe edulis* Mart.) is a crop with growing value in Southern Brazil, with annual expansion rates of over 7 % (IBGE, 2009). It is native of the Atlantic Forest Biome and presents a high shade tolerance, growing spontaneously in the dense forests along the coast and in the middle Paraná River basin, among Brazil, Paraguay and Argentine border. Traditionally, extrativism has focused on the meristematic apex, the 'heart of palm' or 'palmito'. However, extraction of the stem apex implicates the loss of the plant, which has conducted the species to the edge of extinction. Nowadays, their fruits reach higher commercial value, preserving the stem and the plant. As a shade-tolerant species, *E. edulis* is very well adapted to the agroforestry regime (Figure 3). On the other hand, as an endangered species, a great challenge to producers is to comply with the restrictions in the Brazilian environmental laws for its cultivation and commerce (Chaimsohn and Chiquetto, 2013).

Supposedly, agroforestry with *E. edulis* can contribute to the biological conservation, if high canopy diversity is maintained. However, the dynamics of biodiversity associated with açaí-juçara and consequently the very contribution to ecosystems services from this crop is poorly investigated.

Silvopastures

The integration between trees and pastures or simply silvopastures (Figures 2, 4) is possibly the agroforestry practice most prevalent in Brazil. Beef or dairy cattle achieve higher animal comfort and productivity (Yamamoto *et al.*, 2007; Paciullo *et al.*, 2011), which is also valid for the sheep (Magalhães *et al.*, 2001). Regarding the ecosystem services, silvopastures can contribute to carbon uptake, nutrient cycling, erosion control, biodiversity conservation and reduce the dependence of external inputs (Murgueitio *et al.*, 2011). In addition, many tree species are good quality foragers with high levels of protein and minerals (Mpairwe *et al.*, 1998; Datt *et al.*, 2008; Santos *et al.*, 2010; Perez *et al.*, 2013).

Brazil has 160 million hectares of pastures (IBGE, 2009). By assuming a potential of 4.6 Mg ha^{-1} y^{-1} of carbon uptake in aboveground biomass (Kim *et al.*, 2016), it means a total potential uptake or 0.74 Pg C $year^{-1}$, which corresponds to 61.7 % of Brazilian annual carbon emissions. The southern region of Brazil takes 9.8 % of the total Brazilian pastures (Table 1). The rate of carbon uptake in new silvopastures and other agroforestry systems can remains at this level for at least 25 years (Kim *et al.*, 2016), which can constitute a propitious contribution while a transition in energy matrix sources takes place in order to reduce carbon emission.

Carbon uptake can be more than doubled by taking into account the belowground carbon. Agroforestry systems can accumulate 24 Mg C ha^{-1} in the soil over the conventional croplands considering a 0.4 m depth (Maia *et al.*, 2007). However, the soil carbon contents in silvopastures could be even higher below 0.75 m (Haile *et al.*, 2008), and the carbon uptake from conversion to agroforestry systems can surpass 100 Mg C ha^{-1} including levels below 1.0 m (Makumba *et al.*, 2007). The deeper development of the tree roots in relation to annual herbaceous crops can explain this increment (Lorenz and Lal, 2014), the tree roots connecting atmosphere to subsoil as a carbon transfer path. Moreover, root-derived carbon is retained in soils much more efficiently than are above-ground inputs of leaves and needles (Schmidt *et al*. 2011). In such wise, summing the carbon uptake rates of above and below ground biomass and of soil, a value of 14.0 ± 4.1 Mg ha^{-1} y^{-1} can be registered for silvopastures (Kim *et al.* 2016). Notwithstanding, Udawatta and Jose (2012) estimated an uptake of 6.1 Mg ha^{-1} y^{-1} for silvopastures in North America. Biomass stocks and increment is highly variable, which points out the importance of regional inventories and reliable methodologies (Agevi *et al*., 2017).

Other agroforestry experiences

The aforementioned cases are the more expressive in terms of area and economic influence. However, it is important to address other agroforestry cases at Southern Brazil, such as agroforestry with coffee plantations. Despite the reduction of planted area with coffee in Paraná State (from 112.000 ha in 2006 to 38.000 ha in 2014) (IBGE, 2009, 2016), virtually the only State with commercial plantations in the Southern Brazil, the agroforestry with this crop is feasible in the region, considering yields and economic return when compared with monocropping (Baggio *et al.*, 1997). The contribution of shading to flavor is a matter of controversy (Rapidel *et al.*, 2015) but some attempts to aggregate value to the coffee from organic agroforestry has been recently carried out in Paraná State (Bronzeri and Bulgacov, 2014). The reduction of pests is also controversial and it can be affected by local factors (Rapidel *et al.*, 2015). However, the use of leguminous shading trees such as *M. scabrella* (Caramori *et al.*, 1996) could offer a significant contribution to the BFN and for reduction of use of industrial fertilizers application.

Horticulture including annual or biannual crops also has been tested in the agroforestry mode here and there. Among these relatively isolated experiences, pineapple is an outstanding case (Figure 4), considering that a mild shading can benefits this crop and pineapple fruits are sensitive to excessive light and temperature in their maturation stage (Liu and Liu, 2012). At agroforestry, Brazilian producers report an expanded period of pineapple fruit maturation than in the full sunlight cultivation, which takes an advantage due to higher commercial values achieved off-season.

Agroforestry as an Ecological Restoration Strategy

Recently, the agroforestry has been utilized in Brazil as a strategy of ecosystem restoration (Vieira *et al.*, 2009), overcoming the paradigm of an inherent conflict between agriculture and ecological restoration and conservation (Figure 4D and 4E). Moreover, the growth of the tree saplings could be higher in the agroforestry than in seedling plantations followed by abandon (Coelho, 2010). The explanation for this could be due to the inhibition of the trees by the herbaceous heliophilous plants, mainly Poaceae (Souza and Batista, 2004; Yu, 2004; Pompéia, 2005; Ziller *et al.*, 2010). In AFS these competitive plants are controlled by the intercropping cultivation, at least during the first years. In addition, fertilizer residues from intercropping cultivation can be captured by tree roots. Moreover, the restoration costs can be partially amortized with the crop yields, similarly to the Taungya system (Rodrigues *et al.*, 2008), in which an intercropping of short cycle crops with timber species can promote a faster economic return and higher cash flow in the first years.

Ecosystem services of the Agroforestry in Southern Brazil

Biological nitrogen fixation

Improvement of nitrogen use efficiency in agriculture can be considered a relevant ecosystem service, face to the growth of human population and food supply demand (Spiertz, 2010). Agroforestry practices can improve the N use efficiency in different ways. First, the trees through their deep root systems can capture the N that would otherwise be lost to the groundwater and the atmosphere (Kremen and Miles, 2012). Secondly, microorganisms associated with plants can transfer N from the atmosphere to the trophic chain through biological fixation. As perennial elements, the trees in the agroforestry systems could represent a low-cost biological N fixation, capturing on average 250 (56-675) kg N ha^{-1} $year^{-1}$ (Nygren *et al*., 2012).

Somarriba and Kass (2001) studied a six-year cycle of a traditional rotation agroforestry with *Mimosa scabrella* at Paraná, Southern Brazil, verifying 356 kg ha^{-1} of N added to the soil and 13.7 kg ha^{-1} $year^{-1}$ of N surplus considering the aboveground biomass (accumulation minus exportation). Certain symbiotic N_2-fixing bacteria strains associated with *M. scabrella* can provide all N required by the plant (Primieri *et al*., 2016). Field evaluation indicates that 90 % of accumulated N in *M. scabrella* is derived from biological N fixation (Coelho *et al*., 2007b).

Several other Fabaceae tree species from Southern Brazil are promising N fixers, standing out those from the genera *Enterolobium*, *Albizia*, *Ateleia*, *Erythrina*, *Machaerium*, *Inga*, *Mimosa*, *Parapiptadenia*, and *Vachellia* (=*Acacia* p. p.). For instance, *Parapiptadenia rigida* (Bentham) Brenan and *A. glazioveana* have been associated with citrus and yerba mate cultivation. The second species present roughly 3.1 % of N content and is well adapted to acid soils with high Al levels (Baggio *et al*., 2002). *P. rigida* presents a lower N content (2.1 % according to Zanella and Coelho, 2014) although is commonly used to shading citrus (Figure 3C) and is very well adapted to acid and rocky soils.

N fixing effectiveness and efficacy of native leguminous trees from southern Brazil need further investigation in order to promote the economic use and conservation of native biodiversity.

Figure 4. Silvopasture and other agroforestry systems at Southern Brazil. A. Silvopasture with remnant native trees in Guatambu, SC, 2015; B. Agroforestry with pineapple, orange and banana with native shading trees in Nova Laranjeiras, PR; C. beans intercropping with *Trema micrantha* (L.) Blüme and *Mimosa scabrella* Bentham in Catuípe, RS, 2007; D-E. agroforestry for forest restoration with cassava, maize and pumpkins associated with native tress such as *Handroanthus albus* (Cham.) Mattos and *Peltophorum dubium* (Spreng.) Taub. on left, *Cedrela fissilis* Vell. and *Heliocarpus americanus* L. on right, in Doutor Maurício Cardoso, RS, 2003.

Carbon sequestration with agroforestry

Carbon sequestration *via* AFS presents low costs when compared with other strategies (Verchot *et al.* 2005) and can incorporate 2.0-5.8 Mg C ha^{-1} $year^{-1}$ (Concha *et al.*, 2007). If compared to wild rainforests or afforestation (Allen *et al.*, 2009), AFS can maintain between 60-80 % of the methane absorption capability, which could be explained by the reduction of the bulk soil density and the increase of porosity and O_2 availability in soils (Mutuo *et al.*, 2005).

The soil changes promoted by the agroforestry include an increment in the amount of total organic matter and recalcitrant organic matter ((Hawke and O'Connor, 1993; Muñoz *et al.*, 2007; Haile *et al.*, 2008). Concomitantly, AFS reduce pH due to cation transference from the soil to the aboveground biomass and/or increased levels of acidic organic matter (Hawke and O'Connor, 1993; Sharma *et al.*, 2009). AFS increase the nutrient cycling due to growing litter production, which is related to tree aging and basal area (Bhojvaid and Timmer, 1998; Kumar, 2008). On the other hand, it should be stressed that litter production in agroforestry could change by a magnitude of 20 depending on the tree species, and the pioneer and early secondary species present the higher values (Benvenuti-Ferreira *et al.*, 2009). Nutrient cycling is also enhanced as a function of a higher microbiological activity under AFS (Vallejo *et al.*, 2010).

Aforementioned changes in the soil observed in AFS resembles those modifications observed along the aging of afforested sites (Berthrong *et al.*, 2009; Wen-Jie *et al.*, 2011) and of secondary spontaneous succession in subtropical and tropical forest ecosystems (Feldpausch *et al.*, 2004; Coelho *et al.*, 2011; Schwiderke *et al.*, 2012) since the growth of trees is the key driver of the changes in the soil properties in these ecosystems. The presence of shading trees also contributes expressively to reducing erosive processes (Rodríguez and García, 2009; De Aguiar *et al.*, 2010), which constitutes one of the main ecosystem services of agroforestry, for example the protection of water sources and soil fertility. Moreover, AFS tends to present great soil porosity and water retention (Silva *et al.*, 2011b), promoting a more sustainable use of water resources.

CH_4 and N_2O greenhouse gases emissions

Agroforestry potential for reduce the emission of methane from ruminating animals due to the reduction of heat stress and the increase in pasture quality has been hypothesized. Preliminary results obtained at Southern Brazil (Pontes *et al.*, 2014) indicate a reduction of near 40 % in methane emission, although the difference between treatments was not statistically significant due to the small sample. On the other hand, in experiments in controlled stable conditions an inverse correlation between methane emission and temperature in a 5-20 ºC interval was observed (Ngwabie *et al.*, 2011). Mechanistic evolving methane emission is highly complex (Allard *et al.*, 2007; Knapp *et al.*, 2014) and further field investigations are needed to validate whether the silvopastures could present such additional effect in the carbon cycle. Notwithstanding, silvopastoral systems can reduce methane emissions as a result of changes in the physicochemical properties of the soil, which are promoted by the presence of trees (Allard *et al.*, 2007; Knapp *et al.*, 2014). The increase of the soil porosity in agroforestry (and also in forests and riparian buffers) is a key factor to increment the CH_4 oxidization, producing a net uptake from the atmosphere (Rowlings *et al.*, 2012; Kim *et al.*, 2016).

However, these effects are not yet sufficiently studied and a definitive explanation is not yet available (Allen *et al.*, 2009). Further investigations are urgently needed considering that the direct emissions from the cattle reach 64 % of the emissions from the agriculture in Brazil (Brasil, 2016).

The influence of agroforestry adoption on the emission of N_2O present conflicting results and no significant difference to other agricultural land uses was observed (Kim *et al.*, 2016). On the other hand, N_2O emissions from agroforestry reported by these authors (1.3 to 10.1 kg N_2O ha^{-1} $year^{-1}$) are in the range of tropical and subtropical forest emissions (5.1-74.5 kg N_2O ha^{-1} $year^{-1}$; Rowlings *et al.*, 2012), which indicates that agroforestry *per se* does not enhance N_2O release for atmosphere. The increment in the N_2O emissions in agroforestry could be associated with the biological N fixation by leguminous trees (Kim *et al.*, 2016). However, comparisons between biological N fixation and synthetic N fertilizers as a source of N in agriculture indicate that the synthetic sources present higher N_2O emissions (Bayer *et al.*, 2015). Again, agroforestry in itself could not be the driver of N_2O emission elevation. N management (leguminous trees, residues incorporation, green and animal manure) would be the focus for strategies of N_2O reduction.

Agroforestry and biological control

When compared to monocultures, agroforestry tends to reduce weeds, disease and herbivory. However, results are highly context-dependent. Factors such as pest and tree species identity and crop type may play a major role (Schroth *et al*., 2000; Pumariño *et al*., 2015). Interplanting of *Citrus* with *Psidium guajava* at Vietnam reduced the incidence of the bacteria *Candidatus liberibacter* (greening disease) only for one year, after what the effect was null (Ichinose *et al*. 2012). However, interplanting with other fruit trees of the same stature should not be considered equivalent to the agroforestry orchards observed in Brazil (Figure 3A and 3C) where the shading trees perform a dossel over the citrus plants. Moreover, since the agroforestry citrus plantings in Southern Brazil are not isolated from other contaminated orchards, it could be hypothesized that a kind of increased resistance to the fungi and bacterial diseases is established. Similar beneficial effects were observed in cacao and coffee, for what microclimate modifications due to shade can control pathogenic fungi and bacteria (Avelino *et al*., 2011). In spite of the relative high number of studies on the relationship between agroforestry management and disease and insect pests (Philpott and Ambrecht, 2006; Tscharntke *et al*., 2011), investigations on citrus and yerba mate agroforestry are surprisingly scarce.

On the other hand, the biological control effectiveness on agroforestry could be related to factors of landscape scale. For example, distance from remnant forest patches can interfere with the pest and enemies populations (Tscharntke *et al*. 2008, De la Mora *et al*. 2015). Some taxa may be more sensitive to landscape effects. For instance, Lepidoptera increased in abundance on sites located at higher distances from the primary forest in Cacao agroforestry (Maas *et al*., 2013) but different Lepidoptera species could present opposite responses to landscape variables in coffee agroforestry (Muriel *et al*., 2014). Notwithstanding, landscape effect biological controls and pest and disease incidence on agroforestry is poorly studied around the world, and studies from Brazil are lacking.

Economic trade-offs of agroforestry adoption in Southern Brazil

Despite the environmental contribution, the economic balance is a key factor in the adoption of AFS. Broadly, the economic advantages come from a higher productivity of the set of cultures, with an equivalent area ratio higher than 1.0, indicating complementarities in the use of resources by the different cultures and a low competition level (Van der Werf *et al.*, 2007; Martin and Van Noordwijk, 2009). In addition, economic advantages can come from indirect advantages obtained with costs reduction or quality increment, for instance through biological fixation of nitrogen, protection against climatic extremes or reduction of pests and diseases (Baggio *et al.*, 1997; Nygren *et al.*, 2012; Maas *et al.*, 2013), even when the main culture experiences a yield decrease.

In the yerba mate case, the yields do not are reduced in moderate shading (Coelho *et al.*, 2007a). However, the optimal shading level is little known and should vary between regions and growth conditions. Nevertheless, it is possible to introduce shading trees with high timber value, increasing the economic income without reducing yerba mate yields (Baggio *et al.*, 2011). The high trading value of the raw material from shaded cultivation can also aggregate value.

Regarding citrus, the moderate shading does not reduce and could even increase the productivity (Gonzatto, 2009). However, the greatest economic benefit of shaded orchards is the reduction of fungal and bacterial diseases. This also applies to the cultivation of bananas.

For silvopastoral systems, the situation is no different. The economic evaluations indicate that the silvopastures present higher economic incomes when compared to the forestry or conventional cattle farming (Paciullo *et al.*, 2011; De Souza *et al.*, 2015).

As an overall conclusion, there is no evidence of economic conflict in the adoption of agroforestry systems in Southern Brazil. As with other innovations, agroforestry adoption and permanence is influenced by several social, economic, and biophysical factors (Mercer, 2004). Land tenure, age, education level, self-efficacy, attitudes, social regulation, availability of credit and markets, labor resources, public policies (or lack thereof), among others, are the variables significantly associated with agroforestry adoption (Pattanayak *et al*., 2003; McGinty *et al*., 2008; Miccolis *et al.*, 2011; Meijer *et al*., 2016). However, discrepancies among theoretical framework, methodologies, and selection of variables have led to a scientific puzzle (Mercer, 2004). A theoretical synthesis and even a rank of the relative importance of the different factors remain unavailable. In Southern Brazil, the public policies and government initiatives towards agroforestry development are still scarce, and usually, the few official programs are restricted to consortia of *Eucalyptus* (or other exotic species) and cattle. Almost all the successful cases related here are isolated developments derived from landowners' experience or projects of NGOs and small cooperatives. Nevertheless, they would be models for future expansions and research. For example, NGOs were able to establish innovative approaches such as participatory design and partnerships, fostering the technical improvement of agroforestry systems in the Northern Atlantic Forest (Cardoso *et al*., 2001; Souza *et al*., 2012). In the Rio Grande do Sul State, cooperatives and NGOs have promoted a greater commercial value of native fruit species in agroforestry systems (Tonin *et al*., 2017).

Beyond the scarcity of public initiatives, restriction laws to the economic use of native species in Brazil (Coelho, 2012; Chaimsohn and Chiquetto, 2013), following the example of similar legal barriers in other countries (Detlefsen and Somarriba, 2015; Nath *et al*., 2016), constitute an additional factor which can inhibit agroforestry expansion, at least high diverse agroforestry with native biodiversity. Other factors remain to be clarified considering the scarcity of studies on the adoption of agroforestry in Brazil.

CONCLUSIONS

Agroforestry systems can offer many ecosystem services, for example carbon uptake and global warming mitigation, biodiversity conservation, biological controls and reduction of pesticides application, erosion control, biological fixation of nitrogen and nutrient cycling, reducing the dependence of industrial fertilizers. Most of its services are related directly to soil changes: increase of carbon, porosity, and flux of nutrients. In the Southern region of Brazil several innovative initiatives on agroforestry, mostly designed by the own farmers, have demonstrated feasibility not only in terms of increasing yields or economic return, but also by providing ecosystem services. The main productive categories which present well-established experiences and also the great potential for the successful conversion from conventional cultivation to agroforestry systems in Southern Brazil are silvopastures, *Citrus* orchards, and banana plantations, mainly due to the great extent of these activities in Brazil. In both activities, ecological and economic advantages are convergent and recognized also at academic level. Other agroforestry systems such as yerba mate (*I. paraguariensis*) and açaí-juçara (*E. edulis*) could also offer ecosystem services, despite the need of further investigations to elucidate some controversial questions, for instance the contribution to biological controls and the adequate level of shading. In addition, the impact of the conversion of remnant forests to agroforestry also deserves further attention. A great challenge to the region is to qualify the extension initiatives to improve the adoption of the agroforestry systems, at least for the crops to which there are better scientific bases.

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