Instituto de Pesquisas Ecológicas

ESCOLA SUPERIOR DE CONSERVAÇÃO AMBIENTAL E SUSTENTABILIDADE

SEQUESTRO DE CARBONO E SEU POTENCIAL IMPACTO ECONÔMICO EM SISTEMAS AGROFLORESTAIS DE CAFÉ EM SÃO PAULO, BRASIL

CARBON SEQUESTRATION AND ITS POTENTIAL ECONOMIC IMPACT IN COFFEE AGROFORESTRY SYSTEMS IN SÃO PAULO, BRAZIL

Por

NÍCOLAS MORENO GONÇALVES

São Paulo, 2018

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TRABALHO FINAL APRESENTADO AO PROGRAMA DE MESTRADO PROFISSIONAL EM CONSERVAÇÃO DA BIODIVERSIDADE E DESENVOLVIMENTO SUSTENTÁVEL COMO REQUISITO PARCIAL À OBTENÇÃO DO GRAU DE MESTRE

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Àquela quem mais admiro, minha avó Nêna.

Como quem não quer nada você foi chegando.
Como quem não quer nada você foi se instalando.
Como quem não quer nada você foi se insinuando.
Como quem não quer nada você foi me conquistando.
Como quem não quer nada fui me apaixonando.
Como quem não quer nada fomos nos amando.

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RESUMO

Resumo do Trabalho Final apresentado ao Programa de Mestrado Profissional em Conservação da Biodiversidade e Desenvolvimento Sustentável como requisito parcial à obtenção do grau de Mestre

SEQUESTRO DE CARBONO E SEU POTENCIAL IMPACTO ECONÔMICO EM SISTEMAS AGROFLORESTAIS DE CAFÉ EM SÃO PAULO, BRASIL

Por

Nícolas Moreno Gonçalves

Julho, 2018

Orientador: Prof. Dr. Alexandre Uezu

O uso da terra por humanos é o principal fator da perda de biodiversidade. Enquanto que o Código Florestal do Brasil prevê uma dívida de reflorestamento de 21 ± 1 Mha em propriedades privadas. Uma alternativa de reflorestamento e restauração de serviços ecossistêmicos, como o sequestro de carbono, são os sistemas agroflorestais. Assim, objetivamos quantificar o sequestro de carbono e seu potencial impacto econômico na viabilidade econômica de 20 sistemas agroflorestais de café (SACs), dezesseis com dois e quatro com dezesseis anos de idade. A biomassa das árvores foi estimada usando modelos alométricos. Três parâmetros de viabilidade econômica num cenário de 16 anos foram utilizados, Valor Presente Líquido (VPL), Taxa Interna de Retorno (TIR) e *payback period*. A taxa de desconto e o preço médio do carbono aplicada foi de 11% e US$ 5,1 Mg CO2e^{-1}, respectivamente. O estoque médio total de carbono nos SACs jovens e antigos foi de 1,38 ± 0,63 Mg C ha^{-1} e 56,69 ± 32,63 Mg C ha^{-1}, respectivamente. Os SACs apresentaram *payback period* de dois anos, VPL médio de US$ 36.795,69 e TIR média de 97,1%. O impacto da receita do carbono sobre o VPL e a TIR foi de US$ 111,65 e 0,25%, respectivamente. Nossos resultados apontam para os SACs como sendo um modelo uso sustentável e economicamente viável do solo para o cumprimento do Código Florestal Brasileiro. No entanto, o baixo impacto econômico do

sequestro de carbono ressalta o debate em torno da valoração de serviços ecossistêmicos e seus mercados.

ABSTRACT

Abstract do Trabalho Final apresentado ao Programa de Mestrado Profissional em Conservação da Biodiversidade e Desenvolvimento Sustentável como requisito parcial à obtenção do grau de Mestre

CARBON SEQUESTRATION AND ITS POTENTIAL ECONOMIC IMPACT IN COFFEE AGROFORESTRY SYSTEMS IN SÃO PAULO, BRAZIL

By

Nícolas Moreno Gonçalves

July 2018

Advisor: Prof. Dr. Alexandre Uezu

Land use change by humans is the main driver of biodiversity loss. In addition, Brazil's Forest Code forecasts a reforestation debt of 21 ± 1 Mha in private proprieties. Agroforestry is a land use change option for reforesting and restoring ecosystem services, such as carbon sequestration. Therefore, we aimed to quantify carbon sequestration and its potential economic impact in the economic feasibility of 20 Coffee Agroforestry Systems (CAS), sixteen with two-years-old and four with sixteen-years-old. Tree biomass was estimated using an allometric model. Meanwhile, we utilized three economic feasibility parameters in a 16 year economic modeled scenario, Net Present Value (NPV), Internal Rate of Return (IRR) and, payback period. Discount rate and carbon price applied was 11% and US$ 5.1 Mg CO_2e^{-1}, respectively. Total mean carbon stock in young and old CASs was 1,38 ± 0.63 Mg C ha^{-1} and 56.69 ± 32.63 Mg C ha^{-1}, respectively. All CASs presented a payback period of two years, mean NPV of US$ 36.795,69 and mean IRR of 97.1%. Carbon revenue impact on NPV and IRR was US$ 111.65 and 0.25%, respectively. Our results pointed out CASs as a sustainable and economically viable land use model with high potential for Brazilian Forest Code compliance. In the other hand, carbon sequestration economic impact does not encourage the adoption of this type of system, increasing controversies related to ecosystem services valuation and markets.

1. INTRODUCTION

Land use and land use change by humans is the main driver for loss of natural vegetation cover and biodiversity, especially in the Brazilian Atlantic Forest (Myers et al., 2000; Ribeiro et al., 2009). In a scenario where human activities have changed nearly half of earth's ice-free land (Blomqvist et al., 2015), conservation efforts prove to be ever more challenging. Since the expansive Millennium Ecosystem Assessment (2005), much has been debated about the benefits of ecosystem services for our well-being, especially when it comes to the links between ecosystem services and land use.

Ecosystem services are outcomes provided through ecological process that benefit human's survival and well-being. Nelson et al. (2009) showed that there are few tradeoffs between high variety of ecosystem services and high biodiversity in scenarios of land use and land use cover change - such as expansion of monoculture versus crops allied with trees. For this reason, conservation strategies for enhancing ecosystem services allied with biodiversity should be the ideal land use model (Nelson et al., 2009).

Part of these services directly depend on the land use strategy and they can be monetarily evaluated, either at a global scale (Costanza et al., 2014; Jørgensen, 2010), or at a local scale (Ditt et al., 2010; Strassburg et al., 2016). One of the most common global ecosystem services evaluated, mostly because of global-climate change, is carbon sequestration. Carbon sequestration is an important component in agroforestry or similar systems that include trees in their composition (Jose, 2009; Power, 2010; Strassburg et al., 2016).

According to the UN Food and Agriculture Organization definition, agroforestry systems are "[…] dynamic, ecologically based, natural resource management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels" (http://www.fao.org/forestry/agroforestry/80338/en/). Agroforestry has gained much attention due to its capacity to improve productivity, with its agriculture component, while restoring biodiversity and ecosystems services through its native diverse tree component (Jose, 2009; Nair, 1993). This land use model is contemplated by the Land Use, Land Use Change and Forestry (LULUCF), an approach under the United Nations Framework Convention on Climate Change

(UNFCCC), as an afforestation and reforestation strategies for carbon sequestration. Therefore, agroforestry is an option for investment from those countries in need of reducing their greenhouse gas emissions.

Since agroforestry is mostly practiced by family farms in developing countries (Ramachandran Nair, 2014), such as Brazil, the challenge relies in allying environmental and social benefits, inherent to these systems, with economic feasibility (Nogueira and Pereira, 2007; Rodrigues et al., 2007; Santos and Paiva, 2002). In this sense, ecosystem services valuation is important in order to understand its potential economic impact as an instrument of encouragement for those farmers.

In addition, Brazil has its own singularities regarding environmental laws. The actual Brazil's Forest Code forecasts a debt of 21 ± 1 Mha to be restored in private proprieties (Soares-Filho et al., 2014), areas called Legal Reserve (LR) and Areas of Permanent Protection (APPs). The first, according to Brazilian's law could be restored partly with agroforestry systems (Sparovek et al., 2011). Besides that, Brazil has officialized at COP 21 (Paris Agreement) the commitment, as its Nationally Determined Contribution (NDC), in restoring 12 Mha of deforested areas (http://www4.unfccc.int/ndcregistry/Pages/All.aspx). Therefore, understanding how much carbon agroforestry systems stock is essential for underpinning decision makers regarding the country's reality for land use options.

The western portion of São Paulo State, called Pontal do Paranapanema, is located in the Atlantic Forest domain, a domain which is one of the 25 hotspots for conservation efforts (Myers et al., 2000). Recently, a non-governmental organization, called Instituto de Pesquisas Ecológicas (IPÊ), has been working along with local occupier farmers from the Landless Workers' Movement promoting and implementing coffee agroforestry systems in this region.

Adding ecosystem services benefits, sustainable land use and law's requirements, the present work intended to measure carbon sequestration and its potential economic impact on the economic feasibility of coffee agroforestry systems (CAS). By studying 20 coffee agroforestry systems in Pontal do Paranapanema region, three main goals were sought: (i) how much carbon do these 20 areas storage, (ii) are these systems economic feasible, (iii) how much carbon sequestration impact the economic feasibility of these systems.

2. THEORETICAL FRAMEWORK

2.1. Ecosystem services

2.1.1. Brief history of ecosystem services concept

The link between ecosystem functions and processes with its services in benefit for human wellbeing can be found in literature since the 1970's (Gómez-Baggethun et al., 2010). Still different terminologies were applied, like "nature's services" proposed by Walter Westman in 1977 (1977), the concern in raising attention about the dependence of our species in ecosystem functions was the central subject of all works. The term ecosystem services appeared only in 1981 with Ehrlich and Ehrlich work (Ehrlich and Ehrlich, 1981) and, therefore the concept continued raising attention inside scientific community until late 1990's, when it has become a mainstream subject, not only for biologists and economists, but also in politics (Costanza et al., 2017).

Mainstreaming of ecosystem services was due to Gretchen Daily (1997) book and Costanza et al. (1997) published article in *Nature*. The first work with a strong ecological basis and the latter with an economic use perspective have kicked off a wave of research and concern about the unexplored potentials of ecosystem services bridging conservation with economics (Braat and de Groot, 2012).

As an outcome of these two works, two relevant worldwide efforts in assess, raise concern, research and, alerting society and politics were born, Millennium Ecosystem Assessment (Millennium Ecosystem Assessment (Program), 2005) and The Economics of Ecosystem and Biodiversity projects (TEEB, 2010). Both initiatives had great impact on scientific community and politics, contributing even more for the mainstreaming of the theme. The fuss about ecosystem services also triggered in 2012 the foundation of a new scientific journal, *Ecosystem Service Journal* (Braat and de Groot, 2012). Still nowadays, ecosystem services continue as a topic of great interest and in need of ever more research, so human could acquire a broader and better understanding in these natural processes.

2.1.2. Ecosystem services classification and definition

In understanding the ecological concept of ecosystem services, it is common to distinct processes, functions, and services before introducing concept definition. That is why, one can acknowledge that biophysical structures and processes (e.g. vegetation cover, net primary productivity, etc.) contains or are the cause and consequences of ecosystem functions (e.g. biomass and soil retention, etc.). For this reason, one should only consider services, those processes and functions (e.g. carbon sequestration and erosion control, etc.) that benefits directly or indirectly, consciously or un-consciously humans (Costanza et al., 2017).

Braat and de Groot (2012) have done a review work on ecosystem services' concepts and concluded that even though they have reached a consensus definition, the concept would "undoubtedly be further elaborated". Therefore, this work presents one of the first, simplest and yet still in practice concept, present in Costanza et al. (1997) and MA (2005), stated as:

> 'Ecosystem services' (ES) are the ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing: that is, the benefits that people derive from functioning ecosystems. COSTANZA, 2017, p. 3.

By this definition it is clear the rule played by the two actors involved. First, the ecosystem as a producer and distributor of services and second, humans as beneficiaries of the goods offered. Although the concept stands as logically anthropocentric, this is a shallow interpretation and will be further discussed, specially because human also contributes in producing those services.

In addition to this relation, ecosystem services are sometimes referred as natural capital, bridging the notion of services as a source of capital available in nature (Costanza et al., 2017). By doing so, it becomes clear that as capital, ecosystem services can be valued and, also in some cases (e.g. fishery, wood, water purification, etc.), these services only exists when others sources of capital interact, like built or manufactured capital, human capital and social or cultural capital (Costanza et al., 2017).

Ecosystem services are usually classified into four broad categories (Costanza et al., 2017; Millennium Ecosystem Assessment (Program), 2005; TEEB, 2010) . Therefore, the stated four broad ecosystem services classifications were proposed in Costanza et al. 2017:

> a) Provisioning services – ecosystem services that combine with built, human, and social capital to produce food, timber, fiber, or other "provisioning" benefits. For example, fish delivered to people as food require fishing boats (built capital), fisher-folk (human capital), and fishing communities (social capital).
>
> b) Regulating services combine with the other three capitals to produce flood control, storm protection, water regulation, human disease regulation, water purification, air quality maintenance, pollination, pest control, and climate control. For example, storm protection by coastal wetlands requires built infrastructure, people, and communities to be protected. Regulating services, in general, are not well perceived by individuals.
>
> c) Cultural services combine with built, human, and social capital to produce recreation, aesthetic, scientific, cultural identity, sense of place, or other 'cultural' benefits. For example, a recreational benefit requires a beautiful natural asset (a lake), in combination with built infrastructure (a road, trail, dock, etc.), human capital (people able to appreciate the lake experience), and social capital (family, friends and institutions that make the lake accessible and safe). Even 'existence' and other 'non-use values' require people (human capital) and their cultures (social and built capital) to appreciate. […].
>
> d) Supporting services describe the basic ecosystem processes such as soil formation, primary productivity, biogeochemistry, nutrient cycling and provisioning of habitat. These ecosystem functions contribute indirectly to human wellbeing by maintaining the processes and functions necessary for provisioning, regulating, and cultural services. COSTANZA, 2017, p. 5.

2.1.3. Ecosystem services valuation

Since at least the 1970's, question of how much is worth services offered by nature to human kind are posed. In his work, Westman (1977) debated the stated question, something that it is still one of the main topics surrounding ecosystem services' theme. The answer for this question relies on landscape management and decision-making. Because if services offered by nature affect human well-being, in order to make decisions regarding the environment, decision makers ought to have some value for these services to balance their decisions. Valuing ecosystem services to best underpin sustainable management of natural resources is an important aspect in interdisciplinary ecological economics.

The valuing logic in ecological economics is to attribute value for natural capital, so different sources of capital have a single metric for project analyzes. For example, the construction of a dam, although it has undeniable benefits, it will surely have huge impacts in the environment. Approving or denying such a project not knowing the value of that natural capital impacted would, at least, be an unfair decision. Therefore, acknowledging natural capital and valuing it is a step forward toward a better sense in decision making and sustainable management.

Sustainable management is related to undertaking projects that change the environment. One of the most applied technique for undertaking projects is the Cost-Benefit Analysis (CBA), in which the costs and the benefits are compared and if benefits are bigger than costs, the project usually is accepted (Edwards-Jones, 2006). In the dam construction example, all environmental benefits and costs ought to be valued so the CBA can be made fairly.

There are three distinct sources of value for ecosystem services, recognized in the Millennium Ecosystem Assessment (2003): ecological value, sociocultural value, and economic value. The ecological source of value is attributed to the diversity that distinct ecosystems present, for instance, the capacity of higher carbon sequestration from species or, the capacity of water filtration from aquatic plant species. Ecological value is expressed by indicators such as “species diversity, rarity, ecosystem integrity (health), and resilience” (Millennium Ecosystem Assessment, 2003).

Sociocultural value is related to people’s perspective of a given site. It is expressed by, for example, “designation of sacred species or places, development of social rules concerning ecosystem use (for instance, “taboos”) and inspirational experiences” (Millennium Ecosystem Assessment, 2003).

The last value, economic, is based on the paradigm of value that relates utility with satisfaction. Economic value is traditionally separated in two kinds: use values and non-use values. Both values were well related with ecosystem services in:

> Use values encompass direct consumptive use values such as the value of timber, fish, or other resources that ecosystems provide, and direct, non-consumptive use values such as those related to recreation and aesthetic appreciation. Indirect use values relate to the services provided by nature such as air- and water-purification, erosion prevention and pollination of crops. Non-use value is the importance attributed to an aspect of the environment in addition to, or irrespective of its use values […]. A type of value in between use and non-use is the notion of option value: the value we place on keeping the option open to use ecosystem services in the future, either within our own life time, or for future generations (in the latter case this is called bequest value). The total sum of use and non-use values associated with a resource or an aspect of the environment is called Total Economic Value (TEV). de GROOT ET AL., 2010, p.260

Attributing monetary value or evaluating monetarily an ecosystem service is nor conceptually neither empirically an easy task. De Groot et al. (2010) discussed thoroughly the challenges still remaining and the gaps and possibilities in this modern ecological economics perspective. Five essentials trends in valuing ecosystem services were pointed by the authors, in which important questions still arises that need more research: (i) understanding and quantifying how ecosystems provide services, (ii) valuing ecosystems services, (iii) use of ecosystem services in trade-off analysis and decision making, (iv) use of ecosystem services in planning and management, and (v) financing sustainable use of ecosystem services.

This section, however, will only cover one of the essentials trends, valuing ecosystem services. The focus will retain at economic and non-economic valuation methods. Christie et al. (2008) have summarized economic and non-economic valuation methods brightly in their work (Table 1). Underpinned on their definition, the following valuation methods were postulated.

Table 1 Summary of ecosystem services valuation techniques. Adapted from (Christie et al., 2008).

ECOSYSTEM SERVICES VALUATION TECHNIQUES	
ECONOMIC VALUATION	NON-ECONOMIC VALUATION
A. - Market based approach	F. Consultative methods
A.1. - Market-price approach	F.1. - Questionnaires
A.2. - Market-costs approach	F.2. - In-depth interview
B. - Revealed preference methods	G. - Deliberative and participatory approaches
B.1. - Travel cost method	G.1. - Focus group
B.2. - Hedonic pricing method	G.2. - Citizen's jury
C. - Stated preference method	G.3. - Health-based valuation methods
C.1. - Contingent valuation	G.4. - Q-methodology
C.2. - Choice modelling	
D. - Participatory approaches to valuation	
D.1. - Deliberative monetary valuation	
D.2. - Mediated modelling	
E. Benefit transfer	

A. *Market-based approaches*

A.1. Market-price approaches

This method utilizes applied market-prices to use as a proxy for the environmental good or service valued. This method does not account for the Total Economic Value (TEV), because it does not account for use and/or non-use values.

A.2. Market-costs approaches

Similar with the previous method, although it utilizes the costs of environmental good and/or service as a proxy for valuing. Different manner for calculating costs can be utilized in this method, such as replacement costs – when the cost of replacing an environmental service is used as a proxy – commonly applied in soil erosion valuation. There is also damage cost avoided – utilized, as a proxy, the price of mitigating a certain environmental damage – applied in storm protection services, for example. Finally, there is opportunity costs – based on the value that would be obtained for a foregone activity in order to maintain the current environmental service – applicable in carbon sequestration in different land uses.

B. *Revealed preference methods*

B.1. Travel cost method

This revealed preference method traces data on people's actual behavior in real market toward some environmental good. Generally, the travel cost method is related to costs involved in recreational resources, such as national parks, scenic scenarios, and so on. Two types of travel cost are common. First type, the count model in which valuation are based on the number of travels to a specific site. Second, utility random travel cost, method in which all recreational trips are observed, so valuation is made for an environmental attribute present in the sites observed.

Travel cost method, by definition, does not account for non-use values, meaning it does not consider Total Economic Value (TEV). Another caveat is that the method is unable to value changes in environmental quality without the use of multiple data from other sites.

B.2. Hedonic pricing method

Hedonic pricing is related to non-market environmental good. A variation, Hedonic Property Pricing, is commonly applied when an environmental impact, positive (such as air quality) or negative (such as noise pollution), is attributed to a property value. This method is restricted to localized impacts and for few environmental impacts.

C. *Stated preference methods*

C.1. Contingent valuation

The Contingent Valuation Method (CVM) is a well known stated preference method for non-market valuation. Through different manners, surveys, questionnaires, etc. the Willingness To Pay (WTP) for an environmental good in a hypothetical market or the Willingness To Accept (WTA) to give up an environmental good in a hypothetical market is known from the stakeholders involved. This method is well stablished and practiced, since it can valuate the TEV of goods or services that are not exchanged in markets. In contrast with market-based and revealed preference valuation methods, CVM can also valuate hypothetical changes in scenarios. It is very common technique for valuing biodiversity.

C.2. Choice modelling

Similar to CVM, Choice Modelling (CM) estimates value through a idealized hypothetical market. However, CM's questionnaires and surveys tend to be more robust and complex than CVM. Still, the method works in the same way.

D. *Participatory approaches to valuation*

D.1. *Deliberative monetary valuation*

Deliberative Monetary Valuation (DMV) combines stated preference valuation methods with deliberative processes in a more complex and organized manner. It has risen in response to cover some caveats of stated preference valuation methods, in a way that the process became more participatory, inclusive and deliberative.

D.2. *Mediated modelling*

Models supporting environmental decisions are a common practice in management. Mediated modelling is the process of constructing the model for an environmental question, step by step, involving all stakeholders, such as academic agents, public representants, and public in general.

E. *Benefit transfer*

This technique involves a time frame of the economic information of a specific environmental good and/or service in a place, so it could be used in another place and time. Values estimates can be either monetary or not.

Still it is not a common practiced technique, benefit transfer is a viable approach that only depends on the quality of the reference economic information utilized.

F. *Non-economic consultative methods*

F.1. *Questionnaires*

An inquiry method that is used to record people's perceptions on a given environmental issue. It can have a broad range or be as specific as it needs to be.

The outcome quality, in other words, the value/perception for that given environmental good is directly related to the variables and information required in the questionnaires.

Although questionnaires are widespread and are a good source of knowing how and why people value some place or good, it is not a direct source of economic valuation.

F.2. *In-depth interviews*

Similar to questionnaires, in-depth interviews are an inquiry technique. It works generally in the same way as questionnaires, although it demands more time or effort to have a broad range. Additionally, as interviewed people are free to speak, the method for analyzing the answer and the questions posed should be carefully chosen.

G. Non-economic deliberative and participatory approaches

G.1. Focus group

Focus groups are intended to discover participants position regarding a specific topic. Work in focus group can be carried on different frameworks. Though the important issue is the fact that people express values and preferences, when in groups, in a way that unlikely would happen if interviewed alone.

This technique can be used to obtain any kind of value perception, including monetary value. Although it is usually a non-economic method.

G.2. Citizen's jury

Similar to court scenario, this method aims to obtain, through a rational and underpinned discussion, the opinion of part of the public representatives. The process can be conducted by an organization or other stakeholders involved, where the issue in debate is presented in all its dimension. The outcome is a report with the jury's findings.

Theoretically, the technique can cover all value aspects regarding the issue in question. Moreover, the societal perception and qualitative results are obtained from the whole process.

G.3. Health-based valuation methods

This method is based on the health improvement that certain environmental services can have in people's lives. Through years accompanying previous cases in which the certain services were involved in people's health, a value can be obtained as a proxy.

Besides the method can only be used on those services that have a direct impact on people's health, it is a good method for determining how people values improvement in the environment regarding their health.

G.4. Q-methodology

This method reveals the beliefs and preferences of people. It can generate any kind of value regarding an environmental issue. More than that, the technique goes deeper in the issue in a way that it traces people's understanding, feelings, and solutions, based on psychological techniques.

Q-methodology has been applied in rural studies and it is becoming popular in environmental conflicts and broader environmental and democratic societal questions.

Valuation methods are in constant reviewing process and emergence of new ones. The methods above are utilized in different scenarios and in different cases in developing countries (Christie et al., 2008; da Motta, 1998). However, valuating ecosystem services are far from being a well stablished process (de Groot et al., 2010).

2.1.4. Caveats in ecosystem services valuation

De Groot et al. (2010) emphasized in their work many gaps that still exist in ecosystem services valuation. For example, a Cost-Benefit Analysis (CBA) requires that all costs and benefits are elicited, however around 80% of ecosystem services values are o not captured in markets (Costanza et al., 1997; de Groot et al., 2010). Such incomplete valuation or lack of complete knowledge of the natural capital undermine the whole process of sustainable management, leading to uneven decisions regarding to environmental planning and management.

Additionally, there is an important assumption in a CBA that, when applied to natural capital, is not well accepted, the substitutability assumption. Substitutability refers to the assumption that if one gives more for one good it can compensate the loss of another. In other words, it means that money can compensate for the loss of specific habitat, or that money can make up for the loss of a species. This substitutability assumption, if taken into account in a CBA regarding a natural capital, can lead to bad decision-making (Edwards-Jones, 2006).

Many works have stated the benefits and caveats in the ecosystem approach to conversion (Haines-Young and Potschin, 2010; Redford and Adams, 2009; Schwartz et al., 2000). However, there is a trend in ecosystem literature that undermines the essence of ecosystem approach, in which it states the problems in treating ecosystem services as natural capital, the green economics (Boehnert, 2016). In her work, Boehnert (2016) has precise arguments on how environmental economics, ecological economics and the recently launched green economy project (UNEP, 2011) are wrong in capitalize nature-commons. By attributing economic value to nature, in contradiction with green economics assumptions, it will subordinate nature to the economic logic, when the opposite relation is the desirable one.

Finally, this mainstream nature capital-based logic can lead to another phenomenon known as “green grabbing”, consequence of the commodification of ecosystem services (Fairhead et al., 2012). This phenomenon implies that when nature, treated as assets, is traded it creates a shift of ownership, an appropriation, in which it usually goes from the poor (usually poor people or entity) to the powerful (Fairhead et al., 2012). Accounting for this phenomenon as real, in a long term, a possible scenario could be the monopolization over nature by few, as it happens with todays market wealth concentration, where less than 1% of global population owns 46% of such wealth (Credit Suisse Research Institute, 2017).

2.1.5. Final considerations

Although many are the caveats surrounding the ecosystem approach, and many are the economic approaches that are under debate in how to treat nature, the relevance of ecosystem services for human well-being are undeniable. It is important to state that the present work did not intended to support the commodification of the ecosystem service addressed, carbon sequestration. However, underpinned in ecological economics assumptions, the work explored the economic potential of carbon sequestration in the agroforestry context, as to measure its relevance for the adoption of agroforestry, a sustainable land-use practice.

3. METHODS

3.1. Study area

The study was conducted in the western portion of the Pontal do Paranapanema (henceforth Pontal) region, which is in the western tip of São Paulo State, Brazil. The cities/municipalities involved are Euclides da Cunha, Mirante do Paranapanema, and Teodoro Sampaio (Figure 1).

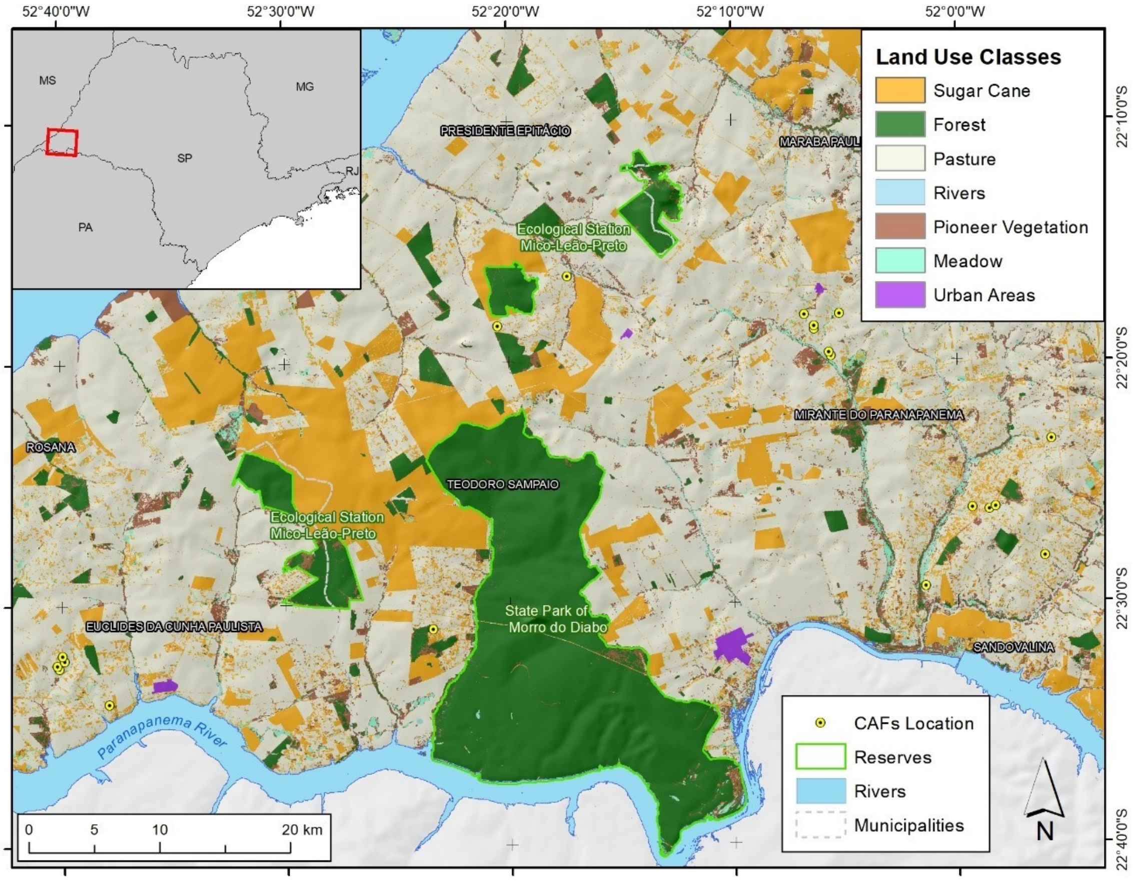

Figure 1 Pontal do Paranapanema region displaying coffee agroforestry systems locations represented by the yellow spots, and the legal Conservation Units of the region.

Mean annual temperature and rainfall registered for this region, in the past 40 years, was 22.9°C and 1230 mm, with rainfall varying from 50 mm, in the driest months, up to 200 mm in summer months (Braido and Tommaselli, 2010). This portion of Pontal is composed mainly of red latosol with deep sandy soil, high drainage and low fertility, giving this region a relatively low agricultural potential (de Oliveira et al., 1999; Ditt, 2002; Veloso et al., 1991). The natural vegetation is classified as tropical semi-deciduous forest, characterized by two distinct climatic seasons, one tropical with heavy summer rains followed by a drought period, another sub-tropical with no dry period, but with physiologic dry period caused by low temperatures (Veloso et al., 1991). The tropical semi-deciduous forest belongs to the domain of the Atlantic Forest in Southwest portion of Brazil (Figure 1).

Pontal has a recent fragmentation history. Since the late 1940s, up to 95% of the region natural coverage was reduced to no more than 20% of its native vegetation (Ferrari Leite, 1998; Uezu and Cullen Junior, 2012). Most of what is left is located in the two conservation units, Estação Ecológica Mico-Leão-Preto and Morro do Diabo State Park (Uezu and Metzger, 2016). As consequence, the region landscape turned into a matrix of pasture and sugar cane plantation (Table S1).

After the 1990s, the Landless Workers' Movement started its land occupation adding a new complexity to the region (Fernandes and Ramalho, 2001). A process of land fragmentation started, due to the movement's success, the big properties was divided into several small family core properties, in which those occupy up to 30% of rural areas in municipalities like Mirante do Paranapanema (Fernandes and Ramalho, 2001). For the last two decades, efforts have been made to change the dominant pasture matrix of the region's landscape, by connecting natural fragments with forest corridors, and stepping stones, supporting coffee agroforestry systems as a land use change.

3.2. Description of coffee agroforestry systems

Twenty coffee agroforestry systems present in the region were studied in this research, each of approximately 1 ha. They are distributed across three municipalities in the studied region (Figure 1). All the coffee agroforestry systems are essentially shade coffee producers, although they typically have some different additional agriculture in the system. Table 2 displays the agricultural composition of each coffee agroforestry system studied.

A total of 95 trees species were found in the coffee agroforestry systems (Table S2), in different proportions and compositions, with only four exotic species. Trees were, in the majority of the coffee agroforestry systems, planted at a spacing of 8m × 2m, with two coffee lines between trees lines, totaling approximately 500 trees per ha. There were a variable number of coffee plants

Table 2 Coffee agroforestry systems composition (CAS). Acronyms stands for the municipalities where the CASs are located. EC – Euclides da Cunha, MP – Mirante do Paranapanema, TS – Teodoro Sampaio.

Coffee agroforestry	Coffee trees	Pineapple	Banana	Jackfruit	Lemon	Orange	Pearl orange	Avocado	Coconut	Soursop	Lychee	Papaya	Persimmon	Native trees
EC 1	4,000	1,000	39	19	16	16	37	0	3	19	19	20	14	390
EC 2	1,248	1,100	39	19	16	16	37	0	3	0	19	0	0	500
EC 3	3,744	1,000	39	19	16	16	37	0	3	0	19	0	0	500
EC 4	4,000	1,000	39	19	16	16	17	0	0	0	19	0	0	500
EC 5	2,492	1,000	39	19	16	16	27	0	0	0	19	0	0	500
MP 1	1,872	1,000	39	19	16	16	39	0	0	19	10	39	19	700
MP 2	2,496	1,100	39	19	16	16	37	0	0	19	19	0	0	650
MP 3	624	1,100	39	19	16	16	17	0	0	19	19	39	11	600
MP 4	1,248	1,100	39	19	16	17	16	4	4	19	19	39	11	600
MP 5	1,872	1,100	39	19	16	16	17	4	4	19	19	39	0	600
MP 6	624	1,100	39	19	16	16	32	0	0	19	19	0	0	850
MP 7	624	1,250	39	19	16	16	17	3	3	19	29	39	11	600
MP 8	624	1,100	39	19	16	16	17	4	4	19	19	39	11	500
MP 9	2,496	1,100	35	19	21	10	10	4	3	19	19	40	19	500
MP 10	1,248	1,100	35	19	10	10	10	0	0	0	19	40	19	500
MP 11	624	1,100	39	19	16	16	17	4	4	19	19	39	0	500
MP 12	2,496	1,100	35	19	20	10	10	4	3	19	19	40	19	500
TS 1	1,248	1,100	35	19	17	16	17	4	3	19	19	0	0	500
TS 2	1,248	1,100	35	19	16	16	16	4	3	19	19	0	0	550
TS 3	624	1,100	39	19	17	16	17	4	4	19	19	0	0	580

due to the fact that those farmers, up to the date of the study, received/planted different quantities of coffee saplings. There were six coffee agroforestry systems implemented in Legal Reserves – a 20% property's area reserved for native forest under the Brazilian Forest Code. Therefore, an additional line of native trees was planted to increase the proportion of native trees inside the reserve in accordance with Brazilian's law.

The coffee agroforestry systems in this study were originally designed and implemented by the Brazilian non-governmental organization IPÊ - Instituto de Pesquisas Ecológicas. The IPÊ organization has a long history of conservation projects in the region and constructed a long-term relation with local producers, which led to these standardized coffee agroforestry systems across the region.

At the time of field inventories of the coffee agroforestry systems, 16 were two years old and four were 16 years old with one of these proprieties having coffee agroforestry systems areas of both ages. Additionally, all the coffee agroforestry systems studied meet the characteristics of family farming (Garner and de la O Campos, 2014), where all the operation and management are reliant on the family's labor, linking the family and the farm's economic, environmental, cultural, and social functions. Therefore, the coffee agroforestry systems can present different degrees of quality, reflecting its productivity and development due to the families' involvement.

3.3. Tree measurements, biomass estimation and carbon stock

Trees were sampled according to the following systematic method: measurements were taken every five trees, starting from the first individual until 20% of total trees inside the area were measured. Dead trees were counted aiming to estimate the total number of dead and alive trees. Coffee plants were sampled with a similar method: measurements were taken every eight coffee plants, starting from the first individual until 12.5% of total living trees were measured, which meant that dead coffee plants were not counted. A greater proportion of native trees were measured because of the higher variance in tree sizes and development compared to coffee, which was relatively small and uniform by comparison. Because of the low variability in coffee plants, rather than individual coffee agroforestry system estimates, a mean biomass estimation was used for coffee plants obtained from three young and two old coffee agroforests.

Field measurements were conducted in October 2017 and a total of 1295 trees and 777 coffee plants were measured. For the two-year-old coffee agroforestry systems sites, diameter at 30 cm height (D30) and total tree height (H) of the individuals sampled were measured. Tree biomass of young coffee agroforestry systems were estimated using an allometric model proposed for trees in a six-year-old restoration site (Table 3, (Ferez et al., 2015). This model seemed more suitable because of the age proximity and because in their work, Ferez et al. (2015) generated this model through destructive samples of the same semi-deciduous forest trees present in the studied area.

Table 3 Allometric models for trees and coffee plants employed for biomass estimation. **AGB** = aboveground biomass; **BGB** = belowground biomass; **CR** = coarse roots biomass; **C** = crown biomass; **DBH** = diameter at breast height (in cm); **D15** = diameter at 15 cm (in cm); **SA** = sectional area (in m^2); **H** = total height (in m); ***p*** = wood specific density.

CAF's Age	Component	Model	Source
Old CAFs	Aboveground	$AGB = 0.0673 \times (p \times DBH^2 \times H)^{0.976}$	Chave et al. 2014
	Belowground	$BGB = \exp(-1.3267 + 0.8877 \times \ln(AGB) + 0.1045 \times \ln(A))$	Cairns et al. 1997
Old CAFs	Aboveground	$AGB = 0.2035 \times DBH^{2.3196}$	Pearson et al. 2005
	Belowground	$BGB = \exp(-1.3267 + 0.8877 \times \ln(AGB) + 0.1045 \times \ln(A))$	Cairns et al. 1997
Young CAFs	Aboveground	$AGB = 6.039 + 0.945 \times \ln(SA) + 0.961 \times \ln(H) + 1.022 \times \ln(p)$	Ferez et al. 2015
	Coarse roots	$CR = -0.288 + 0.742 \times \ln(AGB)$	
	Crown	$C = 0.384 + 0.123 \times AGB - 0.086 \times CR$	
Young and Old Coffe Trees	Aboveground	$\log_{10}(AGB) = -1.113 + 1.578 \times \log_{10}(D15) + 0.581 \times \log_{10}(H)$	Segura et al. 2006

In old coffee agroforestry systems sites, two field measurements were taken, diameter at breast height (DBH) - determined at 1.3 m above ground surface - and total tree height. Aside from those two measurements, wood specific gravity was obtained from literature (Chave et al., 2006; Reyes et al., 1992). For these older areas, an allometric model developed by Chave et al. (2014) was employed for estimating tree biomass (Table 3). This pantropical model was generated from a global database of 58 tropical sites. As a premise of this employed model trees with DBH < 5 cm were not included - three individuals in the present study.

Because differences in estimates can be found according to the model employed, especially for high DBH trees (Schmitt-Harsh et al., 2012), an alternative model proposed by Sandra Brown and colleagues in Pearson et al. (2005) was employed for tree biomass estimation (Table 3). However, due to the results found, only the model proposed by Chave et al. (2014) was utilized for our objectives, since these results proved to be more suitable with similar cases (see discussion section). Comparative data of the two different models was shown in supplementary materials (Figure S1 and Table S3).

Both models estimate only aboveground biomass, lacking the belowground component. Therefore, the model proposed by Cairns et al. (1997) was employed for estimating belowground biomass (Table 3).

In both young and old areas, coffee plant diameter at 15 cm height (D15) and total tree height (H) were measured for estimating biomass. A model proposed by Segura et al. (2006) in shade agroforestry coffee areas was employed for estimating coffee plants biomass (Table 3). This model was the fittest for our agroforestry system because its similarity and also because it usually includes managements, such as pruning, a common practice in this system.

For field measurements, a tape measure was used for diameters and an iron measuring stick used for heights. Wood specific gravity values were mostly obtained from Chave et al. (2006), only three species (3%) were obtained from Reyes et al. (1992), and one (1%) from an unpublished work of IPÊ (Table S2). For those species (23%) that wood specific gravity values were not found, hence the genus mean value was employed from the same database of Chave et al. (2006).

Total carbon stock was measured as 50% of the estimated biomass for all trees and coffee plants (IPCC et al., 2003; Pearson et al., 2005). For each site, carbon stock per hectare was obtained by dividing total carbon stock estimated by the coffee agroforestry systems area.

3.4. Economic feasibility parameters and agricultural prices

The finance model applied in this study was developed from a project called VERENA (Portuguese acronym for Economic appreciation of native trees reforestation). VERENA's finance model accounts for both economics and ecosystem services of agroforestry systems. The model's goal is to return economic parameters of agroforestry project feasibility, such as Net Present Value (NPV), Internal Rate of Return (IRR) and, payback period. Quantitative data to input into the model was obtained through field interviews with each of the 20 coffee agroforestry systems' farmers regarding revenues, productivity, and costs in these systems. A 16 year scenario was simulated for the economic feasibility assessment, since it is the time for the first pruning coffee cycle and it was the age of the oldest areas.

Net Present Value (NPV) is a common economic approach for measuring profit in agroforestry projects (Bentes-Gama et al., 2005; Rodrigues et al., 2007; Santos and Paiva, 2002). NPV measures profit by subtracting a time series of cash inflows (revenues) from a time series cash outflows (costs), with a discount rate applied in each time series, resulting in a present value of a future investment. Therefore, positive NPVs in projects result in net profit. The discount rate applied in this study was 11%, a discount rate predetermined by the model regarding the country's reality. NPV is calculated according to the formula:

$$NPV = \sum_{t=0}^{T} \frac{R_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

Where:

R_t is the net cash inflows during the period t,
C_t is the net cash outflows during the period t,
r is the discount rate,
t is the number of periods in years and T is the total number in years.

Internal Rate of Return (IRR) is another economic metric that measures how desirable a project could be, because it represents the expected rate of a project's growth. IRR is a discount rate that makes NPV equal to zero, which means that it is calculated when the difference between the time series of cash inflows (revenues) and the time series of cash outflows (costs) is zero. In general, the higher the IRR of a given project the better from an economic perspective, however it is only necessary an IRR higher than the applied discount rate (r) for a project to profit.

Slow rates of return and high net present values are possible to occur in the same project. It all depends on the timing of the cashflows – how many periods of cashflows – and the size of the project - the amount of cash invested and obtained.

Payback period is a measure, in years, in which the initial invested capital takes to return. Payback period disregards the time value of money - meaning it does not account for depreciation of money - such as the two above economic parameters. Therefore, payback period is a more straight and simple method of assessing an investment. The longer it takes to return the initial invested capital, the worse it is from an economic perspective.

Table 4 displays retail prices applied for the agricultural products that were obtained mostly from the National Supply Agency (Portuguese acronym, CONAB), a national public agency that provides annual reports for underpinning the country's Minimum Price Guarantee Policy. This policy states the minimum retail prices practiced for agricultural products in the country. Another retail prices source consulted was the Company of General Warehouses of São Paulo (Portuguese acronym, CEAGESP), a state company that underpin retail prices applied in the state.

Table 4 Prices and productivity for each agricultural product in the coffee agroforestry systems.

Crops	Productivity (Kg/plant)	Productivity source	Price (US$/Kg)	Price source
Café	0.3	Bulletin 200	2.25	CEPEA/ESALQ
Abacaxi	1.0	Bulletin 200	0.65	CONAB
Banana nanica	20.0	Bulletin 200	0.58	CONAB
Jaca dura	210.0	Gomes et al. 2001	0.58	CONAB
Limao taiti	70.0	De Almeida et al. 2007	0.89	CONAB
Laranja lima	70.0	Mattos Júnior et al. 2005	0.89	CONAB
Laranja pera rio	70.0	Mattos Júnior et al. 2005	0.43	CONAB
Abacate	50.0	Vale 2017	0.77	CONAB
Coco	50.0	Bulletin 200	0.18	CONAB
Graviola	15.0	Pagliarini et al. 2013	1.78	CONAB
Lichia	20.0	Matos 2012	1.81	CEAGESP
Mamão Papaia	15.0	Silva et al. 2014	0.61	CEAGESP
Caqui Chocolate	20.0	Bulletin 200	1.08	CONAB

Regarding the main commodity in the coffee agroforestry systems, coffee retail prices was obtained from the Center for Advanced Studies in Applied Economics (Portuguese acronym, CEPEA), a study center of the University of São Paulo which creates retail prices indicators for agricultural commodities. For this reason, we utilized the mean coffee retail price for October 2017 with a 15% discount - for conservative purposes - in the economic modeling (Table 4).

Aside from retail prices, productivity from agricultural yields had to be inputted into the economic model. Therefore, productivity data was obtained mainly from the 200 Bulletin (2014) a sourcebook produced by the Agronomic Institute of São Paulo State (ACI-SP) containing practices and information regarding the main agricultures farmed in the State, including productivity (Table 4). Complementary data, when needed, was obtained from specific works in literature (De Almeida et al., 2007; Gomes et al., 2001; Matos, 2012; Mattos Júnior et al., 2005; Pagliarini et al., 2013; Silva et al., 2004; Vale, 2017).

Finally, costs related to saplings, labor and agricultural inputs were explicated in Table 5. Compared to other regions in the State, labor hour prices were low, which increase overall profit. Currency exchange rate applied was US$ 1 equivalent to R$ 3.25.

Table 5 Costs related to crops saplings, inputs and labor hours.

Crops/Inputs/labor	Saplings price (US$/unit)	Crop Costs* (US$/plant)	Crops inputs (US$/Kg)	Labor price (US$/hour)
Coffee	0.2	0.23		
Pineapple	0.1	0.02		
Banana	1.0	0.46		
Jackfruit	0.9	2.31		
Lemon	2.7	1.11		
Orange	2.7	1.11		
Pear Orange	2.6	1.11		
Avocado	2.5	10.15		
Coconut	2.5	1.05		
Soursop	0.9	1.29		
Lychee	2.3	1.85		
Papaya	0.8	0.31		
Persimmon	3.4	1.94		
Native trees	0.2			
Phosphate (P)			0.30	
Calcium (Ca)			0.05	
Manual				2.31
Semi-mechanized				3.23
Mechanized				3.54

* Crop costs includes implementation, maintenance and harvest costs.

3.5. Carbon stock, prices, and productivity

Carbon stock value in economic analyses was obtained from the Chave et al. (2014) model. A mean value for carbon stock obtained from the four old coffee agroforestry systems was utilized for all studied sites, since the economic scenario was 16 years. Moreover, payments for carbon was stipulated at every four years – while usually they are stipulated at five years – so payment could fit in the 16 years scenario. Since the carbon sequestration rate was unknown, the mean value obtained was split into four for each payment period. Lastly, because carbon transacted in markets are usually in CO_2e, a conversion rate of 3.67 was applied for converting carbon stock to carbon dioxide equivalent.

Besides carbon dioxide equivalent, in order to input it in cash flows, carbon needs to be priced. In carbon markets, carbon is an offset, which means that a project's carbon is calculated, measured, and verified by standard bodies that are, usually, non-profit organizations. Offsets are transacted in compliance markets and/or voluntary markets. Compliance markets are regulated by government agency, while in voluntary markets standard bodies are responsible for regulating transactions. For this and other market reasons, carbon prices varied greatly worldwide from US$ 0.5 Mg CO_2e^{-1} to US$ 50 Mg CO_2e^{-1} in 2017 accordingly to the Ecosystem Marketplace initiative report (Hamrick and Gallant, 2017). The average carbon price found more adequate for coffee agroforestry systems was those offsets transacted in the forestry and land use category. Therefore, the average carbon price applied in this contribution was US$ 5.1 Mg CO_2e^{-1}. An alternative best scenario was also evaluated and for this reason the highest value registered (US$ 50 Mg CO_2e^{-1}) for CO_2e transactions was utilized. Despite the distance from the usual value for CO_2e (US$ 5.1 Mg CO_2e^{-1}) transacted in forestry and land use category, this best scenario showed the maximum economic impact of CO_2 applied in agroforestry systems.

Since costs related to carbon certification are not related with the size of the property and, because all coffee agroforestry systems studied are small (1 ha each), these costs were not applied so it did not bias the result.

3.6. Data analyses

All models for biomass estimation employed and statistical analyses required were done using R! Software v.3.2.3 (R Core Team, 2015). Confidence intervals calculated for the estimates were conducted at the 95% confidence level.

4. RESULTS

4.1. Young coffee agroforestry systems

A total of 73 trees species were registered across the 16 young coffee agroforestry systems studied. Individual tree biomass ranged from 0.38 to 130.85 kg with a mean of 7.37 ± 2.34 kg tree^{-1}. The most important species regarding biomass were *T. micrantha*, *G. ulmifolia*, *C. floribundus*, *C. pachystachya*, *C. urucurana*, *A. polyphylla*, *I. vera*, which together accounted for 26% (270) of the total sampled individuals and presented over 4.14 Mg (51%) of the total biomass (Figure 2). For coffee plants, biomass of individual plants ranged from 0.001 to 0.348 kg with a mean of 0.065 ± 0.046 kg tree^{-1}.

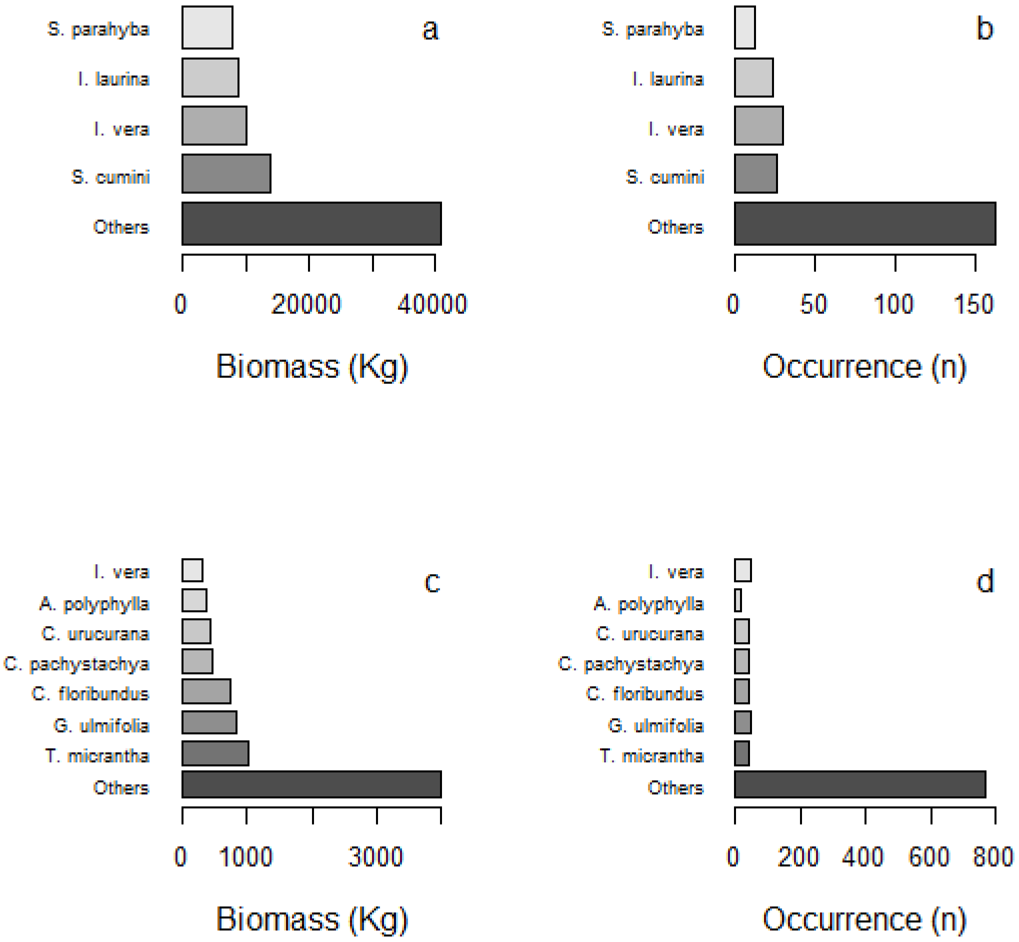

Figure 2 Biomass and frequencies for the most important species found in the CASs. **a** – biomass of the species in old CASs; **b** – frequencies of the species in old CASs; **c** – biomass of the species in young CASs; **d** – frequencies of the species in young CASs.

Mean tree carbon stock for all 16 coffee agroforestry systems presented a mean of 1.35 ± 0.62 Mg C ha^{-1}, while the mean carbon stock for coffee plants was 0.029 ± 0.014 Mg C ha^{-1}. Moreover, total mean carbon stock – tree carbon stock plus coffee plant carbon stock – for each coffee agroforestry system ranged from 0.24 to 4.8 Mg C ha^{-1} with a mean of 1,38 ± 0.63 Mg C ha^{-1} (Table 6). The highest and lowest values presented a difference of more than twenty-fold.

Table 6 Total mean carbon stock for each young CAS studied and the mean carbon stock value – with 95% confidence. Acronyms stand for the municipalities where the CASs are located. **EC** - Euclides da Cunha, **MP** - Mirante do Paranapanema.

CAF site	Total mean C stock (Mg C ha^{-1})	CAF site	Total mean C stock (Mg C ha^{-1})
MP 7	4.80	MP 9	0.88
MP 2	3.49	EC 3	0.85
MP 1	2.50	MP 5	0.71
MP 4	1.88	MP 3	0.70
MP 8	1.47	EC 1	0.56
MP 11	1.24	MP 12	0.40
MP 6	1.12	MP 10	0.36
EC 5	1.06	EC 4	0.24
Mean			1.38 ± 0.63

4.2. Old coffee agroforestry systems

A total of 48 trees species were registered considering all four old coffee agroforestry systems studied. Tree biomass ranged from 1.75 to 4600.14 kg with a mean of 349.5 ± 175.42 kg/tree. The most important species regarding biomass were *S. cumini*, *I. vera*, *I. laurina*, and *S. parahyba*, which grouped accounted for 36% (91) of the total sampled individuals and represented over 40.82 Mg (50%) of the total biomass (Figure 2). Coffee plant biomass ranged from 0.19 to 15.47 kg with a mean of 2.07 ± 0.26 kg tree^{-1}.

Mean tree carbon stock for the four coffee agroforestry systems was 58.57 ± 31.76 Mg C ha^{-1}. Meanwhile, mean carbon stock for coffee plants was 1.12 ± 0.87 Mg C ha^{-1}. For each of the four old coffee agroforestry systems, total mean carbon stock – tree carbon stock plus coffee plant carbon stock– ranged from 38.18 to 107.55 Mg C ha^{-1}, a difference of approximately two-and-a-half-fold (Table 7). Thus, total carbon stock mean for the old coffee agroforestry systems was 56.69 ± 32.63 Mg C ha^{-1} (Table 7).

Table 7 Total mean carbon stock for each CAS studied and the mean carbon stock value – with 95% confidence intervals. Acronyms stand for the municipalities where the CASs are located. **EC** - Euclides da Cunha, **TS** - Teodoro Sampaio.

CAF site	Total Mean Carbon Stock (Mg C ha^{-1})
EC 2	107.55
EC 3	46.64
TS 1	47.36
TS 2	38.18
Mean	59.69 ± 32.63

4.3. Economic feasibility

All the 20 coffee agroforestry systems presented a payback period of two years. Net Present Value (NPV) for all coffee agroforestry systems in the 16 years modeled scenario ranged from US$ 30.375,67 to US$ 43.393,98 (Figure 3). Internal Rate of Return (IRR) between all coffee agroforestry systems in the 16 years modeled scenario ranged from 75.62% to 126.11% (Figure 3).

Besides coffee, in general the two most relevant crops for the economic results were pineapple and jackfruit, mainly because of pineapple high density and the high productivity in jackfruit trees. All specific costs and revenues for each coffee agroforestry systems were displayed in supplementary materials (Table S4 and S5).

The difference between NPV in the 16 years modeled scenario for the base case – without carbon revenue – and NPV accounting with carbon revenue was US$ 111.65 (Table 8). Considering the best scenario – in which carbon price was the highest registered (US$ 50 Mg CO_2e^{-1}) – the same difference raised to US$ 1,107.21 (Table 8). The difference in the 16 years modeled scenario between the base case IRR and for the IRR with carbon revenue was 0.25%. The same difference for the best scenario simulated raised to 2.49% (Table 8).

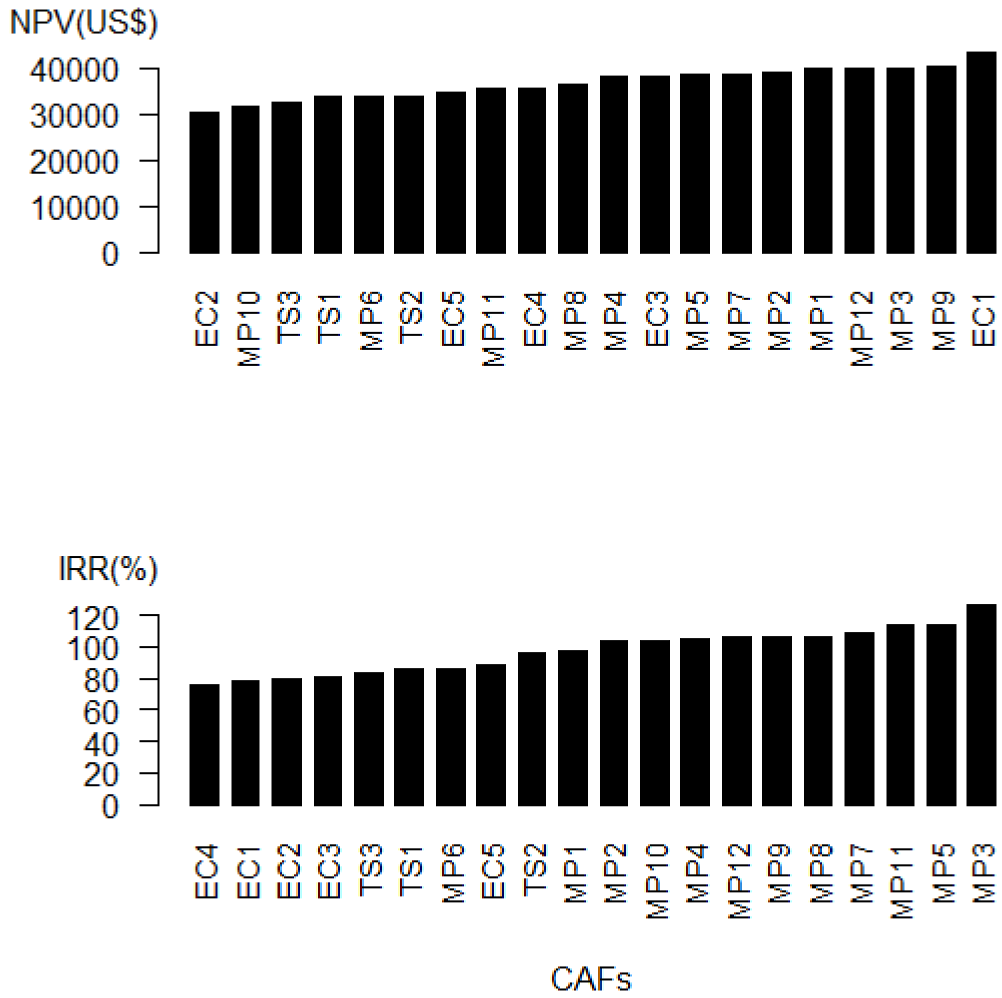

Figure 3 Economic feasibility results for two parameters, respectively net present value (NPV) and internal rate of return (IRR), for all coffee agroforestry systems. Acronyms stand for the municipalities where the CASs are located. **EC** - Euclides da Cunha, **MP** - Mirante do Paranapanema, **TS** - Teodoro Sampaio.

Table 8 Mean net present value (NPV) and internal rate of return (IRR) for all coffee agroforestry systems. First without carbon revenue, second with carbon revenue and the respectively delta (Δ) – difference between both situations.

Carbon Price	IRR	IRR+CO_{2e}	Δ	NPV	NPV+CO_{2e}	Δ
US$5.1 Mg CO_{2e}^{-1}	97.10%	97.36%	0.25%	$36,795.69	$ 36,907.34	$ 111.65
US$50 Mg CO_{2e}^{-1}	97.10%	99.59%	2.49%	$36,795.69	$ 37,902.90	$ 1,107.21

5. DISCUSSION

5.1. Carbon stock

Results obtained for total mean carbon stock for the old coffee agroforestry systems (59.69 ± 32.63 Mg C ha^{-1}) were similar to values found by another authors in coffee agroforestry systems with similar age and within the tropical zone: in South Mexico 39.4 Mg C ha^{-1} and 46.3 Mg C ha^{-1} (Soto-Pinto et al., 2010), in Guatemala 75.6 Mg C ha^{-1} (Schmitt-Harsh et al., 2012) and, in Southwestern DR Congo 82 Mg C ha^{-1} (Dossa et al., 2008). Hence, our results corroborated the high potential for carbon sequestration in coffee agroforestry systems.

By contrast, total mean carbon stock found (107.65 ± 55.93 Mg C ha^{-1}, Table S3) utilizing the alternative model (see methodology section) seemed to overestimate our result, when compared to the others coffee agroforestry systems, which lead to its exclusion from the main result. Although similarities like, matching altitude, age, vegetation and rainfall levels could be found among the previous cited works and our work, carbon stock variation can be attributed to elements such as stage of development, proportion of trees and coffee trees, soil quality, nutrient availability and management in agroforestry systems (Häger, 2012; Nair et al., 2009). Regarding carbon sequestration for two years-old coffee agroforestry systems, no comparable data was found.

In addition, comparing total mean carbon stock from old coffee agroforestry systems with the two remaining forest patches in the study region, both conservation units, our obtained total mean carbon stock (59.69 ± 32.63 Mg C ha^{-1}) was higher than the 40.7 Mg C ha^{-1} in the Ecological Station Mico-Leão-Preto and, lower than the 110.9 Mg C ha-1 in the State Park Morro do Diabo (IPÊ 2017, unpublished data). This high carbon stock found for the coffee agroforestry systems presents a viable alternative for carbon sequestration, especially suitable to Brazil's Paris Agreement commitment in restoration, the Nationally Determined Contributions (NDC).

At last, the difference between the carbon stock of the old coffee agroforestry systems (59.69 ± 32.63 Mg C ha^{-1}) and the young coffee agroforestry systems (1.38 ± 0.63 Mg C ha^{-1}) was up to fifty-fold. A plausible reason relies on the generic simulated biomass increment curve (Figure S1), based on Brown's model. This exponential like curve suggests that for higher DBH values, the higher the impacts on biomass accumulation, which could explain the fifty-fold difference in carbon stock. It also means a great potential in carbon sequestration for short to medium terms, again reinforcing the suitability of coffee agroforestry systems' importance for restoration and Brazil's NDC.

5.2. Economic feasibility

All the 20 coffee agroforestry systems studied presented high economic feasibility, according to both economic parameters, net present value (NPV) and, internal rate of return (IRR, Figure 3). Bernasconi et al. (2016) calculated the opportunity cost, based on the land price, for the Pontal region and the rest of the state. The opportunity cost for the region varied from approximately $ 300 to $ 1.500. Considering our mean annual revenue ($ 2.306,71 a.a.), obtained from the annualized mean NPV, the difference between the revenue from the coffee agroforestry systems and the opportunity cost were one-and-a-half up to seven-fold higher, corroborating the high economic feasibility of this system.

Comparatively with others agroforestry systems (AFS), twelve different types of AFSs in different regions of Brazil were analyzed with VERENA economic model, in which the mean IRR found was 14.4% (VERENA, unpublished data). Thereby, our mean IRR found for the coffee agroforestry systems studied (97.1%) had an economic performance six times higher than those other AFSs (Table 8). Although the causes of such difference were not covered in this work, elements such as low price of labor and land in the region along with the diversity of crops – which leads to a diversity of income in a time scale – could provide insights for an explanation.

Besides the favorable economic parameters, the variability in NPV and IRR found in each coffee agroforestry system were a consequence of the composition of each coffee agroforestry system and the costs and revenues derived from it (Table 2, S4 and S5). For example, the highest NPV found – in EC1 coffee agroforestry system US$ 43.393,98 (Figure 3) – reflected the great number of coffee trees in addition with the presence of all other crops, increasing the overall income. However, the high number and density of crops in EC1 raised the costs, reducing its IRR to the lower value found for all coffee agroforestry systems. This logic of high costs involved in crops abundance associated with the potential income mainly explained the general variability in NPV and IRR for all the coffee agroforestry systems studied.

5.3. Role of agroforestry systems in Forest Code compliance

Brazil’s Forest Code states that properties above four fiscal modules – which are areas of approximately 80 ha for Sao Paulo state’s rules- are obliged to preserve 20% of their area (Bernasconi et al., 2016; Soares-Filho et al., 2014). The Forest Code also dictates that the 20% preserved area – an area called Legal Reserve (LR) – is eligible to be half composed by agroforestry systems (Sparovek et al., 2011). Therefore, our results supported coffee agroforestry systems as a profitable (Figure 3), with social and environmental benefits, productive system for complying with Brazil’s Forest Code (Nogueira and Pereira, 2007; Rodrigues et al., 2007).

In addition, for those properties under four fiscal modules, i.e. properties that do not have to reforest their LR as an indebtedness, coffee agroforestry systems could be used as a surplus and traded as forest certificates for those properties in debt (Soares-Filho et al., 2016), i.e. for those properties ranging more than four fiscal modules (>~80 ha) with a deforested LR. Soares-Filho et al. (2016) calculated that in the best market scenario, the forest certificates market could reach US$ 9.2 ± 2.4 billion. Accordingly to Uezu and Cullen Junior (2012) the Pontal has a LR debt of 58,171 ha, demonstrating the great potential for forest certificates’ market in the region.

5.4. Economic impact of carbon sequestration

Carbon sequestration estimated, valuated and economic modeled in this study has presented a mean NPV and IRR increment on the economic feasibility results of only US$ 111.65 and 0.25%, respectively (Table 8). Even when the best carbon price was applied (US$ 50 Mg CO_{2e}^{-1}) the increment raised NPV to only US$ 1,107.21 and 2.49% for IRR (Table 8). Thereby, the economic impact of carbon sequestration in the economic feasibility of the coffee agroforestry systems was positive as expected, considering that it was an additional revenue. However, it was near to irrelevant to the overall economic feasibility of this production system.

Our work has not explored all carbon pools, for instance, soil dead organic matter and dead biomass, which would increase the overall carbon stock. However, Noordwijk et al. (2002) have estimated in 82 Mg C ha^{-1} the carbon stock in living and dead biomass and soil organic matter for shade coffee plantation in tropical zone of Indonesia. Even If that result were applied for our coffee agroforestry systems sites, the NPV and IRR increment of US$ 176.06 and 0,40%, respectively, would still be low regarding the overall economic feasibility of the coffee agroforestry systems (Table S6).

Our results have shown that, in this 16 year economic modeled scenario, little was the economic impact of carbon sequestration on the economic feasibility of coffee agroforestry systems, even in the absence of certificate costs. However, we have underestimated the carbon sequestration, as previously discussed, and also recognize the existence of others ecosystem services in agroforestry systems in general (Costanza et al., 1997; Jose, 2009). Future investigations adding those other ecosystem services could yield higher incomes for those systems, hence promoting a powerful argument for sustainable land uses, such as coffee agroforestry systems. However, there are some caveats that coupled with our results suggest otherwise, as discussed in this next section.

5.5 Pontal land use and land use change

The current land use of Pontal region is pasture and cane sugar plantation (Uezu and Cullen Junior, 2012). However, the promotion of coffee agroforestry systems by the IPÊ's work has been a great effort for land use change in the region (Beltrame et al., 2006). By doing so, those coffee agroforestry systems will serve as stepping stones, which will improve the connectivity of the landscape (Beltrame et al., 2006). Thefore, the high profitability of those systems shown in this work will help underpin future IPÊ's actions.

Although there was no evident economic benefit derived from ecosystem services, more specifically carbon sequestration, the land use change underway is important for perpetrating other ecosystem services values. Despite the following statements were not evaluated with a scientific accuracy and, hence they were only not standardized observational statements. Aesthetic benefits were the most perceived benefit followed by a sense of place when we confronted the farmers about their own perceptions. Therefore, a land use change would probably not only enhance the landscape, but also increase the welfare of farmers.

5.6. Caveats in payments for environmental services and ecosystem services valuation

Payments for environmental services (PES) is a recent conservation approach intended to bridge ecosystem services providers, mainly landowners, with direct beneficiaries and, it has gained much attention in specialized literature (Engel et al., 2008; Pattanayak et al., 2010; Wunder, 2005). Carbon sequestration, for instance, is one of the environmental services involved in these PES schemes, in which a landowner, for example a shade coffee producer, could get monetary compensation in exchange of his/her carbon offset produced. Although there is no PES scheme in action for the Pontal region, the economic exercise explored in this work with carbon sequestration provided initial data for interested PES stakeholders, such as NGO’s and government agencies. This contribution is important, specially because our results were obtained with field data in small properties, both elements with few records in literature (Engel et al., 2008).

Montagnini and Finney (2011) have assessed PES schemes for agroforestry systems in Costa Rica and found that these schemes “can be a tool to finance reforestation, restoration, conservation, and changes in land use that enhance rural development”. Similar positive impacts were found for others agroforestry systems in Costa Rica and Mozambique (Cole, 2010; Hegde and Bull, 2011). However, the authors reported caveats in PES schemes, like differential income by gender (Hegde and Bull, 2011), and lack of technical support for landowners (Cole, 2010).

Meanwhile Montagnini and Finney (2011) pointed out eight other limitations that can occur in PES schemes. First, most of the others ecosystem services provided are difficult to quantify and, therefore be included in a PES scheme. Second, some indicators for environmental services are imperfect, for instance biodiversity indicator may present different results accordingly to the species used. Third, markets must be established and, fourth, also systems must be established such as laws and regulations. Fifth, transactions cannot be low to optimize benefits. Sixth, undesirable consequences could occur due to PES presence, for example an intended deforestation of an area in order to be eligible for a PES. Seventh, the delivery of environmental services could be interrupt after the termination of the PES contract. Eighth and last, PES eventually conflicts economic efficiency, environmental effectiveness, and equitability, which should not happen.

In these sense, a thorough review in PES schemes undertaken by Pattanayak et al. (2010) indicated that is to soon – because of most PES schemes ages - to assert that these payments will secure conservation. In addition, because of the high profitability of the coffee agroforestry systems presented and the inherent offer of ecosystem services in this land use – i.e. a win-win situation for landowner and services beneficiaries – Engel et al. (2008) argued that a PES schemes in this situation would lack additionality, meaning that the resource invested would be inefficient, since it is already a desirable option for landowners.

Moreover, Gómez-Baggethun and Ruiz-Pérez (2011) see monetary valuation of ecosystem services as a short-term strategy to demonstrate the importance of biodiversity in a political and economic. The authors argued that in a long-term, economic valuation of ecosystems services could lead to its commodification (Gómez-Baggethun and Ruiz-Pérez, 2011). This commodification of ecosystem services was argued by Boehnert (2016) that would stablish an economic logic in decision making over the environment, in which markets would stipulate conservation priorities.

In face of all possible downsides in payments for environmental services and ecosystem valuation and, also considering the low potential economic impact of carbon sequestration for coffee agroforestry systems explored in this work, neither ecosystem services markets nor PES schemes should be the ideal model for fomenting this sustainable land use option. High economic viability and the provisioning of plenty ecosystem services inherent to coffee agroforestry systems should provide enough arguments for conservation strategies in a landscape scale for interested private and public stakeholders.

6. CONCLUSION

Our results, along with literature data presented in this work, showed that agroforestry systems are also viable from an economic perspective. This is especially true for coffee agroforestry systems in the Pontal do Paranapanema region. These systems presented revenues higher than the land opportunity costs for the region and, profitability higher than others agroforestry systems. Hence, agroforestry systems in general are profitable sustainable land use option for landowners.

Prices applied in carbon markets generates low income for those with carbon credit, which turns not to be an economic driver of sustainable land use. The low economic impact of carbon is especially true for high profitable sustainable productive system, such as coffee agroforestry systems. Therefore, sustainable land use change for producers are disconnected with the potential income provided by ecosystem services. The high profitability in the coffee agroforestry systems studied, along with non-market environmental and social benefits inherent to agroforestry systems are the best argument for sustainable land use change.

Nonetheless, agroforestry systems, more specifically coffee agroforestry systems are land use alternatives that stock large quantities of carbon, comparable even with forest patches. At the same time, these systems can be used for restoration and afforestation projects that aim to comply with Brazilian’s law or even for Brazil’s NDC. The previous arguments coupled with high economic viability showed in this work, present coffee agroforestry systems ever more as a viable option from an economic, social, and environmental perspective that should be fomented regardless of the monetary ecosystem services values, but still because of ecosystem services non-market values for human welfare.

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SUPPLEMMENTARY MATERIALS

Table S1 Land use distribution for Pontal do Paranapanema region. Adapted from Uezu and Cullen Junior (2012). Obs.: Exposed soil in its majority is being prepared to be planted, specially with more sugar cane.

Land use	Area (Mha)	Percentage (%)
Rivers	1.02	16.62
Natural vegetation	0.87	14.23
Wetlands	0.12	2.02
Pasture	3.09	50.39
Sugar cane	0.61	9.90
Exposed soil	0.40	6.60
Urban areas	0.01	0.24
Total	6.13	100

Table S2 Trees species list found in the coffee agroforestry systems with its wood specific density.

Scientific name	Common name	Wood specific density	Source
Acacia mangium	acácia-mangium	0.73*	Chave et al. 2006
Acacia polyphylla	monjoleiro	0.64	Chave et al. 2006
Aegiphila sellowiana	tamanqueiro	0.66*	Chave et al. 2006
Albizia hasslerii	farinha-seca	0.53*	Chave et al. 2006
Albizia lebbeck (L.)	albizia	0.53*	Chave et al. 2006
Alchornea triplinervea	tapiá	0.47	Chave et al. 2006
Alibertia Edulis	marmeleiro	0.76	Chave et al. 2006
Aloysia virgata	lixeira	0.70	Chave et al. 2006
Anacardium occidentale	cajueiro	0.44	Chave et al. 2006
Anadenanthera colubrina	angico-preto	0.88	Chave et al. 2006
Anadenanthera macrocarpa	angico-vermelho	0.9*	Chave et al. 2006
Anadenanthera peregrina	angico-branco	0.93	Chave et al. 2006
Anonna cacans	araticum	0.70	Chave et al. 2006
Apeiba tibourbou Aubl.	pau-jangada	0.28*	Chave et al. 2006
Apuleia leiocarpa	garapa	0.77	Chave et al. 2006
Aspidosperma parvifolium	gatambu	0.78	Chave et al. 2006
Astronium graveolens	guaritá	0.85	Chave et al. 2006
Bastardiopsis densiflora	jangada-brava	0.65	Chave et al. 2006
Bixa orellana L.	urucum	0.36	Chave et al. 2006
Caesalpinia ferrea (var. leiostachya)	pau-ferro	1.17	Chave et al. 2006
Campomanesia eugenioides	gabiroba	0.84	Chave et al. 2006
Cariniana legalis (Mart.) Kuntze	jequitibá-rosa	0.49	Chave et al. 2006
Carpotroche brasiliensis	cutieira	0.52	Chave et al. 2006
Caryocar brasilense	pequizeiro	0.65	Chave et al. 2006
Casearia gossypiosperma	espeteiro	0.68*	Chave et al. 2006
Casearia sylvestris	guaçatonga	0.71	Chave et al. 2006
Cecropia pachystachya	embaúba	0.41	Chave et al. 2006
Cedrella fissilis	cedro-rosa	0.49	Chave et al. 2006
Ceiba speciosa	paineira-rosa	0.39	Chave et al. 2006
Citharexylum myrianthum Cham	pau-viola	0.70	Chave et al. 2006
Colubrina glandulosa Perkins	saguaragi	0.74	Chave et al. 2006
Copaifera langsdorffii	copaíba	0.65	Chave et al. 2006
Cordia americana	guajuvira	0.51*	Chave et al. 2006
Cordia ecalyculata	café-de-bugre	0.51*	Chave et al. 2006
Cordia superba	babosa-branca	0.69	Chave et al. 2006
Cordia trichotoma	louro-pardo	0.60	Chave et al. 2006
Croton floribundus	capixingui	0.60	Chave et al. 2006
Croton urucurana	sangra-d'água	0.55	Chave et al. 2006
Cybistax antisyphilitica	ipê-verde	0.59	Chave et al. 2006
Dictyoloma vandellianum	tingui	0.49	Unpublished IPÊ's work
Enterolobium contortisiliquum	tamboril	0.44	Chave et al. 2006
Eugenia florida	pitanga-preta	0.75	Chave et al. 2006
Eugenia uniflora	pitanga	0.83	Chave et al. 2006
Ficus guaranitica	figueira-branca	0.41*	Chave et al. 2006
Ficus luschnathiana	figueira-preta	0.41*	Chave et al. 2006
Ficus carica	figueira	0.41*	Chave et al. 2006
Gallesia integrifolia	pau-d'alho	0.55	Chave et al. 2006
Genipa americana	genipapo	0.63	Chave et al. 2006
Gliricidia sepium	gliricídea	0.58*	Chave et al. 2006
Gochnatia polymorpha	candeia	0.76	Chave et al. 2006
Guazuma ulmifolia	mutambo	0.7	Chave et al. 2006
Hymenaea courbaril	jatobá	0.77	Chave et al. 2006
Inga laurina	ingá-liso	0.65	Chave et al. 2006
Inga sesselis	ingá-de-macaco	0.43	Chave et al. 2006
Inga vera	ingá-do-brejo	0.58	Chave et al. 2006

*wood specific density obtained from the mean genus or family.

Table S2 (cont.) Trees species list found in the coffee agroforestry systems with its wood specific density.

Scientific name	Common name	Wood specific density	Source
Jacaranda brasiliana	jacarandá-mimosa	0.65	Chave et al. 2006
Jacaranda cuspidifolia	caroba	0.48*	Chave et al. 2006
Jacaratia spinosa	jaracatiá	0.42*	Chave et al. 2006
Lafoensia pacari	dedaleiro	0.80	Chave et al. 2006
Lithraea molleoides	aroeira-brava	0.47	Chave et al. 2006
Lonchocarpus muehlbergianus	feijão-cru	0.66	Chave et al. 2006
Luehea candicans	açoita-cavalo-graúdo	0.5*	Chave et al. 2006
Luehea divaricata	açoita-cavalo-miúdo	0.56	Chave et al. 2006
Mabea fistulifera	mamoninha	0.70	Chave et al. 2006
Machaerium villosum Vogel	jacarandá	0.78	Chave et al. 2006
Mangifera indica	mangueira	0.52	Reyes et al. 1992
Myracrodruon urundeuva	aroeira-preta	1.00	Chave et al. 2006
Myroxylon peruiferum	cabreúva	0.83	Chave et al. 2006
Nectandra fistulifera	canelinha	0.52*	Chave et al. 2006
Parapiptadenia rigida	angico-verdadeiro	0.81*	Chave et al. 2006
Peltophorum dubium	canafístula	0.74	Chave et al. 2006
Poecilanthe parviflora	coração-de-negro	0.99	Chave et al. 2006
Pouteria torta	abiu	0.77	Chave et al. 2006
Psidium guajava	goiabeira	0.74	Chave et al. 2006
Psidium sartorianum	araçá	0.79	Chave et al. 2006
Pterogyne nitens	amendoim-do-campo	0.69	Chave et al. 2006
Sapindus saponaria	sabão-de-soldado	0.69	Chave et al. 2006
Schinus terebinthifolius	aroeira-pimenteira	0.62*	Chave et al. 2006
Schizolobium parahyba	guapuruvu	0.41	Chave et al. 2006
Solanum mauritianum	fumo-bravo	0.42*	Chave et al. 2006
Syzygium cumini	jambolão	0.70	Reyes et al. 1992
Tabebuia aurea	ipê-amarelo-do-cerrado	0.76	Chave et al. 2006
Tabebuia chrysotricha	ipê-amarelo	1.04	Chave et al. 2006
Tabebuia heptaphylla	ipê-roxo	0.89	Chave et al. 2006
Tabebuia impetiginosa	ipê-rosa	0.92	Chave et al. 2006
Tabebuia insignis	ipê-branco-do-brejo	0.53	Chave et al. 2006
Tabebuia roseoalba	ipê-branco	0.57*	Reyes et al. 1992
Tabernaemontana hystrix Steud	leiteiro	0.48*	Chave et al. 2006
Tapirira guianensis Aubl.	peito-de-pombo	0.45	Chave et al. 2006
Terminalia triflora	amarelinho	0.75	Chave et al. 2006
Trema micrantha	candiuva	0.35	Chave et al. 2006
Triplaris americana L.	pau-formiga	0.49	Chave et al. 2006
Vochysia tucanorum	pau tucano	0.70	Chave et al. 2006
Zeyheria tuberculosa	ipê-tabaco	0.77	Chave et al. 2006

*wood specific density obtained from the mean genus or family.

Table S3 Total mean carbon stock for each old CAS studied and the mean for the four CASs analyzed by different models. Acronyms stand for the municipalities where the CASs are located. **EC** - Euclides da Cunha; **TS** - Teodoro Sampaio.

	Mean Carbon Stock (Mg C ha^{-1})	
CAF site	Chave et al. (2014)	Pearson et al. (2005)
EC 2	107.55	174.58
EC 3	46.64	131.080
TS 1	47.36	73.33
TS 2	38.18	52.56
Mean	59.69 ± 32.63	107.65 ± 55.93

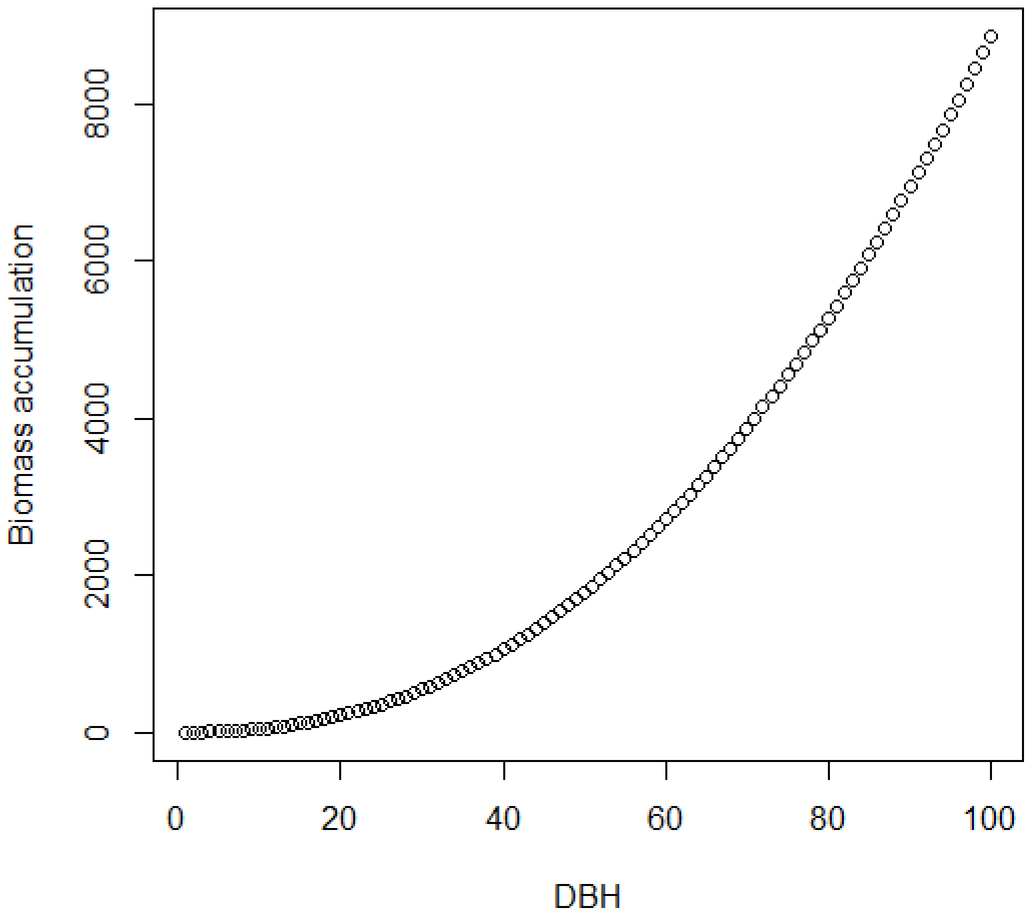

Figure S1 Biomass accumulation curve for Brown's model in Pearson et al. (2005).

Table S4 Costs of each variable for each CAS with its respectively percentage. Acronyms stand for the municipalities where the CASs are located. **EC** - Euclides da Cunha; **MP** – Mirante do Pontal de Paranapanema. **nr** – not relevant or displayed cost in the model.

		Costs																			
Variable	Unit	EC 1		EC 2		EC 3		EC 4		EC 5		MP 1		MP 2		MP 3		MP 4		MP 5	
Coffee	$\$\ \text{ha}^{-1}$	9,600.00	54%	2,995.20	28%	8,985.60	54%	9,600.00	55%	5,559.08	46%	4,492.80	37%	5,989.54	45%	1,497.60	27%	2,995.20	28%	4,492.80	38%
Pineapple	$\$\ \text{ha}^{-1}$	55.38	1%	60.92	2%	55.38	1%	55.38	1%	55.38	1%	55.38	2%	60.92	2%	60.92	2%	60.92	2%	60.92	2%
Banana	$\$\ \text{ha}^{-1}$	40.56	1%	40.56	2%	40.56	1%	40.56	1%	40.56	2%	40.56	2%	40.56	2%	40.56	2%	40.56	2%	40.56	2%
Jackfruit	$\$\ \text{ha}^{-1}$	17.25	3%	17.25	5%	17.25	3%	17.25	3%	17.25	4%	17.25	4%	17.25	4%	17.25	5%	17.25	5%	17.25	4%
Lemon	$\$\ \text{ha}^{-1}$	42.83	1%	42.83	2%	42.83	1%	42.83	1%	42.83	1%	42.83	1%	42.83	1%	42.83	2%	42.83	2%	42.83	1%
Orange	$\$\ \text{ha}^{-1}$	42.83	1%	42.83	2%	42.83	1%	42.83	1%	42.83	1%	42.83	1%	42.83	1%	42.83	2%	45.51	2%	42.83	1%
Pearl orange	$\$\ \text{ha}^{-1}$	95.63	2%	95.63	4%	95.63	2%	43.94	1%	69.78	2%	100.80	3%	95.63	3%	43.94	2%	41.35	2%	43.94	1%
Coconut	$\$\ \text{ha}^{-1}$	nr	-	nr	-	nr	-	-	-	-	-	-	-	-	-	-	-	nr	-	nr	-
Soursop	$\$\ \text{ha}^{-1}$	17.54	1%	-	-	-	-	-	-	-	-	17.54	2%	17.54	2%	17.54	2%	17.54	2%	17.54	2%
Lychee	$\$\ \text{ha}^{-1}$	43.26	2%	43.26	3%	43.26	2%	43.26	2%	43.26	3%	22.77	2%	43.26	3%	43.26	4%	43.26	3%	43.26	3%
Papaya	$\$\ \text{ha}^{-1}$	16.30	0%	-	-	-	-	-	-	-	-	31.80	1%	-	-	31.80	2%	31.80	1%	31.80	1%
Persimmon	$\$\ \text{ha}^{-1}$	46.95	2%	-	-	-	-	-	-	-	-	63.72	3%	-	-	36.89	2%	36.89	2%	-	-
Avocado	$\$\ \text{ha}^{-1}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	9.85	4%	9.85	4%
System Costs	$\$\ \text{ha}^{-1}$	1,085.54	9%	749.68	11%	749.68	7%	848.00	7%	809.88	10%	642.63	8%	306.17	4%	471.26	7%	584.98	8%	373.91	5%
Land Leasing	$\$\ \text{ha}^{-1}\ \text{year}^{-1}$	293.54	21%	293.54	36%	293.54	23%	293.54	22%	293.54	30%	293.54	31%	293.54	29%	293.54	39%	293.54	36%	293.54	32%

Table S4 (cont.) Costs of each variable for each CAS with its respectively percentage. Acronyms stand for the municipalities where the CASs are located. **MP** – Mirante do Pontal de Paranapanema; **TS** - Teodoro Sampaio. **nr** – not relevant or displayed cost in the model.

		Costs																			
Variable	Unit	MP 6		MP 7		MP 8		MP 9		MP 10		MP 11		MP 12		TS 1		TS 2		TS 3	
Coffee	$\$\ \text{ha}^{-1}$	1,497.60	17%	1,497.60	16%	1,497.60	17%	5,990.40	45%	2,995.20	31%	1,497.60	17%	5,990.40	45%	2,995.20	28%	2,995.20	29%	1,497.60	16%
Pineapple	$\$\ \text{ha}^{-1}$	60.92	2%	69.23	3%	60.92	2%	60.92	2%	60.92	2%	60.92	2%	60.92	2%	60.92	2%	60.92	2%	60.92	2%
Banana	$\$\ \text{ha}^{-1}$	40.56	3%	40.56	2%	40.56	2%	36.40	1%	36.40	2%	40.56	2%	36.40	1%	36.40	2%	36.40	2%	40.56	2%
Jackfruit	$\$\ \text{ha}^{-1}$	17.25	6%	17.25	5%	17.25	5%	17.25	4%	17.25	5%	17.25	5%	17.25	4%	17.25	4%	17.25	5%	17.25	5%
Lemon	$\$\ \text{ha}^{-1}$	42.83	2%	42.83	2%	42.83	2%	56.22	2%	26.77	1%	42.83	2%	53.54	2%	45.51	2%	42.83	2%	45.51	2%
Orange	$\$\ \text{ha}^{-1}$	42.83	2%	42.83	2%	42.83	2%	26.77	1%	26.77	1%	42.83	2%	26.77	1%	42.83	2%	42.83	2%	42.83	2%
Pearl orange	$\$\ \text{ha}^{-1}$	82.71	4%	43.94	2%	43.94	2%	25.85	1%	25.85	1%	43.94	2%	25.85	1%	43.94	2%	41.35	2%	43.94	2%
Coconut	$\$\ \text{ha}^{-1}$	-	-	nr	-	nr	-	nr	-	-	-	nr	-	nr	-	nr	-	nr	-	nr	-
Soursop	$\$\ \text{ha}^{-1}$	17.54	3%	17.54	3%	17.54	3%	17.54	2%	-	-	17.54	3%	17.54	2%	17.54	2%	17.54	2%	17.54	3%
Lychee	$\$\ \text{ha}^{-1}$	43.26	4%	66.03	6%	43.26	4%	43.26	3%	43.26	4%	43.26	4%	43.26	3%	43.26	3%	43.26	3%	43.26	4%
Papaya	$\$\ \text{ha}^{-1}$	-	-	31.80	2%	31.80	2%	32.62	1%	32.62	2%	31.80	2%	32.62	1%	-	-	-	-	-	-
Persimmon	$\$\ \text{ha}^{-1}$	-	-	36.89	3%	36.89	3%	63.72	3%	63.72	4%	-	-	63.72	3%	-	-	-	-	-	-
Avocado	$\$\ \text{ha}^{-1}$	-	-	-	3%	9.85	5%	9.85	3%	-	-	9.85	5%	9.85	3%	9.85	4%	9.85	4%	9.85	4%
System Costs	$\$\ \text{ha}^{-1}$	802.34	14%	608.92	10%	587.38	10%	456.05	5%	501.91	8%	448.68	8%	455.75	5%	698.52	10%	467.85	7%	788.88	13%
Land Leasing	$\$\ \text{ha}^{-1}\ \text{year}^{-1}$	293.54	44%	293.54	41%	293.54	42%	293.54	28%	293.54	39%	293.54	42%	293.54	28%	293.54	35%	293.54	36%	293.54	40%

Table S5 Revenues of each variable in each CAS with its respectively percentage. Acronyms stand for the municipalities where the CASs are located. **EC** - Euclides da Cunha; **MP** – Mirante do Pontal de Paranapanema.

		Revenue																			
Variable	Unit	EC 1		EC 2		EC 3		EC 4		EC 5		MP 1		MP 2		MP 3		MP 4		MP 5	
Coffee	\$ ha^{-1}	7,085	14%	- 15	0%	6,785	15%	7,366	18%	3,303	8%	1,812	4%	3,911	9%	3,129	7%	180	0%	2,130	5%
Pineapple	\$ ha^{-1}	4,800	10%	5,280	15%	4,800	11%	4,800	11%	4,800	12%	4,800	11%	5,280	12%	5,280	12%	5,280	13%	5,280	12%
Banana	\$ ha^{-1}	3,333	7%	3,333	10%	3,333	8%	3,333	8%	3,333	9%	3,333	7%	3,333	8%	3,333	8%	3,333	8%	3,333	8%
Jackfruit	\$ ha^{-1}	11,146	22%	11,146	32%	11,146	25%	11,146	27%	11,146	28%	11,146	25%	11,146	25%	11,146	25%	11,146	26%	11,146	26%
Lemon	\$ ha^{-1}	4,688	9%	4,688	14%	4,688	11%	4,688	11%	4,688	12%	4,688	10%	4,688	11%	4,688	11%	4,688	11%	4,688	11%
Orange	\$ ha^{-1}	4,688	9%	4,688	14%	4,688	11%	4,688	11%	4,688	12%	4,688	10%	4,688	11%	4,688	11%	4,981	12%	4,688	11%
Pearl orange	\$ ha^{-1}	5,135	10%	5,135	15%	5,135	12%	2,359	6%	3,747	10%	5,413	12%	5,135	12%	2,359	5%	2,221	5%	2,359	6%
Coconut	\$ ha^{-1}	137	0%	137	0%	137	0%	-	-	-	-	-	-	-	-	-	-	183	0%	183	0%
Soursop	\$ ha^{-1}	2,375	5%	-	-	-	-	-	-	-	-	2,375	5%	2,375	5%	2,375	5%	2,375	6%	2,375	6%
Lychee	\$ ha^{-1}	3,315	7%	178	1%	3,315	8%	3,315	8%	3,315	8%	1,745	4%	3,315	8%	3,315	7%	3,315	8%	3,315	8%
Papaya	\$ ha^{-1}	1,335	3%	-	-	-	-	-	-	-	-	2,602	6%	-	-	2,602	6%	2,602	6%	2,602	6%
Persimmon	\$ ha^{-1}	1,537	3%	-	-	-	-	-	-	-	-	2,086	5%	-	-	1,207	3%	1,207	3%	-	-
Avocado	\$ ha^{-1}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	602	1%	602	1%
Carbon	\$ ha^{-1}	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%

Table S5 (cont.) Revenues of each variable for each CAS with its respectively percentage. Acronyms stand for the municipalities where the CASs are located. **MP** – Mirante do Pontal de Paranapanema; **TS** - Teodoro Sampaio.

		Revenue																			
Variable	Unit	MP 6		MP 7		MP 8		MP 9		MP 10		MP 11		MP 12		TS 1		TS 2		TS 3	
Coffee	$ ha-1	- 1,777	-5%	- 1,548	-4%	- 1,523	-4%	3,733	8%	278	1%	- 1,359	-3%	3,733	8%	45	0%	319	1%	- 1,762	-5%
Pineapple	$ ha-1	5,280	14%	6,000	14%	5,280	13%	5,280	12%	5,280	15%	5,280	13%	5,280	12%	5,280	14%	5,280	14%	5,280	14%
Banana	$ ha-1	3,333	9%	3,333	8%	3,333	8%	2,991	7%	2,991	9%	3,333	8%	2,991	7%	2,991	8%	2,991	8%	3,333	9%
Jackfruit	$ ha-1	11,146	30%	11,146	26%	11,146	28%	11,146	25%	11,146	32%	11,146	28%	11,146	25%	11,146	29%	11,146	29%	11,146	30%
Lemon	$ ha-1	4,688	12%	4,688	11%	4,688	12%	6,153	14%	2,930	8%	4,688	12%	5,860	13%	4,981	13%	4,688	12%	4,981	14%
Orange	$ ha-1	4,688	12%	4,688	11%	4,688	12%	2,930	7%	2,930	8%	4,688	12%	2,930	7%	4,688	12%	4,688	12%	4,688	13%
Pearl orange	$ ha-1	4,441	12%	2,359	6%	2,359	6%	1,388	3%	1,388	4%	2,359	6%	1,388	3%	2,359	6%	2,221	6%	2,359	6%
Coconut	$ ha-1	-	-	137	0%	183	0%	137	0%	-	-	183	0%	137	0%	137	0%	137	0%	183	0%
Soursop	$ ha-1	2,375	6%	2,375	6%	2,375	6%	2,375	5%	-	-	2,375	6%	2,375	5%	2,375	6%	2,375	6%	2,375	6%
Lychee	$ ha-1	3,315	9%	5,060	12%	3,315	8%	3,315	7%	3,315	9%	3,315	8%	3,315	7%	3,315	9%	3,315	9%	3,315	9%
Papaya	$ ha-1	-	-	2,602	6%	2,602	6%	2,669	6%	2,669	8%	2,602	7%	2,669	6%		-		-		-
Persimmon	$ ha-1	-	-	1,207	3%	1,207	3%	2,086	5%	2,086	6%	-	-	2,086	5%		-		-		-
Avocado	$ ha-1	-	-	452	1%	602	1%	602	1%	-	-	602	2%	602	1%	602	2%	602	2%	602	2%
Carbon	$ ha-1	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%	114	0%

Table S6 Economic modeled scenario accordingly to Noordwijk et al. (2002) measured carbon stock (82 Mg C ha-1). Internal Rate of Return (IRR) and Net Present Value without and with carbon revenue and, the respectively delta – difference between both situations.

Carbon Price	IRR	IRR+CO_{2e}	Δ	NPV	NPV+CO_{2e}	Δ
US$5.1 Mg CO_{2e}^{-1}	97.10%	97.50%	0.40%	$ 36,795.69	$ 36,971.75	$ 176.06