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A Comparative Review of Soil Carbon Sequestration Methods in Brazil's Agriculture

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ABSTRACT: Brazil is under unique pressure to adopt sustainable agricultural practices due to its intricate biodiversity and globally dominant agricultural sector. Increasing soil degradation, agricultural land expansion, and rising levels of atmospheric carbon are nationwide concerns that require multifaceted solutions. Integrated agricultural systems, which rehabilitate soils through crop, forage, and livestock rotation as well as biochar—a carbon-rich soil amendment—can address such concerns. These sustainable farming practices improve carbon sequestration and soil fertility; however, uptake remains minimal due to environmental, economic, and policy barriers. Accordingly, this paper proposes a comprehensive model of integrated systems and biochar, in which the benefits of one system can counteract the impediments of the other: biochar can reduce the volatility of integrated systems while integrated systems can reduce the costliness of biochar. This paper will first discuss the environmental impacts of integrated systems and biochar before noting how such impacts are affected in the comprehensive model. The next section will similarly discuss economic impacts in the same manner, and the last section will outline integrated systems policy and the demand for creating biochar policy. This paper offers a holistic review of integrated systems and biochar and encourages further improvements through the combination of both methods.

Introduction

In the past few decades, Brazil has prioritized agricultural profit over environmental preservation. The country became one of the largest food producers in the world, standing as the biggest producer of cattle (Zia, 2019) and the second-largest producer of soybeans (Figueiredo, 2016). Brazil's agricultural sector now makes up 43% of its economy (Carauta et al., 2018). However, this economic success was achieved at the expense of the environment. Booming agribusiness has caused extensive soil degradation, estimated to be 140 million hectares in total and 36 million hectares of pasture land (Klink and Machado, 2005). Degraded soil lowers the efficiency of terrestrial carbon pools, leading to minimal carbon sequestration and excessive greenhouse gas emissions (GHG) (Maia et al., 2008). Such degradation dims the future in the fight against climate change, as it may prevent Brazil from achieving its UNFCCC pledge to reduce 37% of total GHGs by 2025, which was declared at COP26 (Federative Republic of Brazil, 2022). In addition to environmental damage, soil degradation leads to economic loss; households must expand their plots to compensate for reduced soil efficiency. Some livestock ranches operate at stocking rates as low as 0.5 animals per hectare (Gil et al., 2016), which is drastically lower than the global average of 2.6 animals per hectare (Sandhage-Hofmann, 2023). In turn, agricultural land expansion reduces Brazil's rich native vegetation, which houses over 12% of the world's species (Piao et al., 2021). Current practices of the agricultural sector are unsustainable because degraded soil will uproot a series of processes key to the environment and economy, such as soil carbon sequestration, agricultural efficiency, and the maintenance of native vegetation. It is necessary to implement farming methods that simultaneously protect soils and build agri-economic growth. This paper reviews the environmental, economic, and policy impacts of three sustainable farming methods: Integrated crop-livestock systems (ICL), integrated crop-livestock-forestry systems (ICLF), and biochar, as summarized in Table 1.

Environmental Benefits

Integrated systems rehabilitate degraded soil by maintaining crop residue, while biochar acts as a soil amendment through the effects of recalcitrant carbon. Integrated systems are implemented in the form of ICL, which consolidates a cropping and livestock system into a single, multipurpose operation, as well as ICLF, which incorporates forestry alongside cropping and livestock components. While farmers utilize countless variations of ICL and ICLF, what chiefly defines integrated systems is the novel interaction of cropping, livestock, forestry components, and their collective impact on soil (Pezzopane et al, 2017). Factors of carbon sequestration and soil health will first be discussed concerning integrated systems, before shifting these factors concerning biochar. The improvements made by biochar will serve to demonstrate the plausibility of a comprehensive model of integrated systems and biochar, in which the benefits of biochar can improve the limitations of integrated systems.

	ICL: integrated crop-livestock system	ICLF: integrated crop-livestock-forestry system	Biochar
Definition	Intercropping of forage plants, crops, and livestock.	Intercropping of forage plants, crops, livestock, and forestry.	Soil amendment made by burning agricultural waste in a low-oxygen environment.
Environmental impacts	Improves soil health and carbon sequestration, but can be difficult to manage.	Similar to ICL, but includes heightened potential for both carbon sequestration and mismanagement.	Improves soil health and long-term carbon sequestration.
Economic impacts	Increases crop yield, improves livestock quality, and inherently provides crop insurance.	Similar to ICL, but further increases animal stocking rates	High financial and labor costs.
Policy impacts	Incorporated into the ABC Plan, which supported the adoption of ICL through credit lines, but was limited by a lack of technical knowledge for application.	Likewise to ICL.	Lacks governmental support for mainstream adoption.

Table 1. Definition and Summary of Each Method and their Respective Impacts

ICL

Increased crop residue and the practice of no-tillage are factors of ICL that increase the soil carbon sink. ICL increases crop residue by diversifying crops, and their accordingly diverse spatial and temporal characteristics. The cropping component consists of grain, cereals, and legumes, while the livestock component uses perennial forage crops, and cattle or sheep for livestock (Carvalho et al., 2010). These two systems can be rotated every two to four years, every summer and winter, or intercropped (Brewer and Gaudin, 2020; Alves et al., 2019). While the range in rotation length, crop composition, and layout of intercropping encompasses countless variations of ICL, the practice of no-tillage is a common denominator. No-tillage, a method in which soil is not tilled before planting, improves soil by lowering rates of erosion, leaving crop residue to decompose slowly (Duyck and Petit, 2016), and extending the period in which carbon remains in the soil. No-tillage and crop diversity lead to effective sequestration largely by increasing soil organic matter (SOM), particularly soil organic carbon, which is 58% of SOM (Lal, 2004; Post and Kwon, 2000). Carbon then remains within the soil for longer when compared to conventional systems. Greater carbon pools in ICL are highlighted by Carvalho et al. (2010) conducted from 1999 to 2007, in which a rate of 1.16 megagrams per hectare per year of carbon stocks was reported. The increase was recorded as total organic carbon (TOC) instead of as a carbon particulate fraction, making the reported rate unusually high, especially for a period lasting less than 10 years (Carvalho et al., 2010). Salton et al. (2013) support this finding in their comparison of ICL and conventional tillage (CT) among other systems; TOC was measured at approximately 22.49 g/kg for ICL, and approximately 15.89 g/kg for CT over the course of 17 years. ICL expands soil carbon sink capacity in a relatively short period, helping to capture atmospheric carbon and reduce GHG emissions.

Additionally, ICL improves soil health by increasing SOM, CEC (cation exchange capacity), microbial activity, and organic phosphorus. SOM, a collection of organic content such as C, K, Ca, N, and Mg (Alves et al., 2019), improved in the aforementioned study by Salton et al. (2013), which compared ICL and CT. Calculated through SOM lability, or the fraction of soil in which carbon levels are most volatile (Benbi et al., 2015), SOM was approximately 12.12% in ICL, as compared to 9.22% in CT (Salton et al., 2013). In terms of CEC, which retains cations for plant absorption and stabilizes soil pH (Alves et al., 2019), ICL continued to show greater benefits. Salton et al. (2013) highlight increased CEC in ICL at approximately 14.72 centimole positive charge per dm^3, as compared to 12.820.18 gulcentimole positive charge per dm^3 in CT. Microbial activity follows suit, as basal respiration was 24.2 carbon converted to carbon dioxide per gram (C-CO2/g) of soil per day for ICL and 14.1 C-CO2/g of soil per day for CT. No tillage within ICL is largely responsible for this increased microbial activity because it reduces soil disturbances. Lastly, organic phosphorus, which is fundamental for root growth via plant cell division (Gul and Whalen, 2016), was reported to be higher in ICL. Organic P in ICL was 31.32.05 mg/kg as compared to 26.45.03 mg/kg in CT (Salton et al., 2013), and this is likely a result of the presence of livestock (Alves et al., 2019). Through greater crop residue and no-tillage, ICL improves both sequestration potential and soil fertility.

ICLF

While ICL demonstrates remarkable soil improvements, ICLF can sequester more carbon than ICL because it holds a closer resemblance to forests, which retain more soil carbon than pasture land. Crops lack the deep rooting capacity of trees, which helps stimulate greater levels of microbial activity and provide recalcitrant carbon that slows carbon decomposition (Abril, 2013). Eucalyptus is most commonly used for the forestry component, as it matures quickly and accumulates a substantial amount of carbon (Behera et al., 2020). Results of increased carbon were highlighted in a study by Conceição et al. (2017), which compared ICLF, ICL, and a eucalyptus plantation. Though both ICL and ICLF were reported to have more soil carbon relative to the eucalyptus plantation, the increase in ICLF was far more drastic. Soil carbon increased by 7.8% in ICLF after three years. On the other hand, ICL increased only by 0.6% (Conceição et al., 2017). Furthermore, Barsotti et al. (2020) found greater carbon storage in ICLF, having measured carbon fixation across a conventional pasture and two ICLF systems. Carbon fixation is similar to carbon sequestration as it measures organic carbon, though only in relation to inorganic carbon and not atmospheric carbon. One ICLF plot was set at a high density of 357 trees per hectare, and the other at a low density of 227 trees per hectare. Carbon fixation of high-density ICLF was 20.09 tons of carbon per hectare, while the low-density ICLF was 11.07 tons of carbon per hectare (Barsotti et al., 2020).

However, such improvements in soil carbon pool capacity must be taken with caution as research involving SOM can be contradicting. Bieluczyk et al. (2020) found that ICLF led to no additional SOM improvement when compared to ICL. The presence of eucalyptus trees likely caused competition for nutrients, evident in the reduction of grass biomass and root volume when compared to the same plot two years prior. Although there is substantial research noting the positive impacts of ICLF, it is necessary to definitively conclude the greater carbon sequestration of ICLF.

Biochar

Biochar was inspired by Amazonian Dark Earth (DE), a soil created by pre-Hispanic indigenous civilizations containing high levels of organic matter, which often came from charred, woody biomass (Leach et al., 2020). Biochar reaches similarly high levels of organic matter from burning organic waste, such as forage, crop, and agroforestry residue, in a low-oxygen environment known as anaerobic pyrolysis (Qambrani et al., 2017). Typically added to soils as an amendment, biochar effectively improves carbon sequestration and the health of particularly poor soil.

As charred organic matter, biochar takes much longer to decompose when compared to uncharred organic matter (Cheng et al., 2008). 97% of the carbon in biochar is recalcitrant, a form of carbon that is up to five times more stable than labile soil carbon (Gross et al., 2021). Recalcitrant carbon, or black carbon, has a strong affinity for aromatic compounds, which are particularly resistant to microbial decomposition (Qambrani et al., 2017). Biochar then establishes efficient sequestration, evident in a study by Lefebvre et al. (2020) that compared increments of biochar application (100%, 50%, 25%) across sugarcane plots; the biochar was created from bagasse, a type of organic waste from sugarcane production. The plot applied with 100% of the available biochar sequestered the most carbon, as its sequestration rate was 13.5 Mt of C per hectare per year[1], while the sequestration rate for the plot with 25% biochar was only 6.75 Mt of C per hectare per year. Biochar unmistakably increases carbon sequestration potential; this is further supported by a number of studies (Pandit et al., 2017; Rittl et al., 2015; Major et al., 2005).

Similarly to integrated systems, biochar provides improvements in organic phosphorus, pH, aluminum saturation, and SOM. Major et al. (2005) report higher P and pH levels as well as lower Al saturation in a study comparing DE with oxisols and ultisols. Results from this study are comparable to biochar because DE demonstrates similar effects on soil, and Latossolos exemplify a typical farm soil that is nutrient-poor and has an acidic pH. Biochar's affinity for phosphate groups at the molecular level increases organic P (Zhao et al., 2022), while pH levels improve due to a negative charge that exists on biochar's surface, which prevents acidic soil from developing (International Biochar Initiative, n.d.). Additionally, biochar lowers Al saturation by attracting non-polar compounds, which absorb chemicals detrimental to soil fertility, such as Al (Qambrani et al., 2017). In terms of SOM, Bruun and El-Zehery (2012) found slower rates of SOM mineralization with biochar; decreased mineralization rates translate to slower decomposition and an extended retainment of organic matter. They compared two plots of soil covered in straw residue: one with biochar and one without. Biochar applied at 15.5 g/kg reduced SOM mineralization to 5.7% of 20 g of soil, whereas it was 6.6% in the plot without biochar (Bruun and El-Zehery, 2012). Biochar's inherent chemical properties positively impact soil characteristics in a similar manner to integrated systems, creating yet another viable option for rehabilitating soil health.

Biochar and integrated systems

The addition of biochar in integrated systems can provide extended sequestration rates and strengthen soil resilience. When compared to soil organic carbon in integrated systems, biochar carbon has an exponentially longer residence time, or the period in which carbon is present in soil. The average residence time of recalcitrant biochar carbon pools is 556 years (Latawiec et al., 2019), and through radiocarbon dating, has even been shown to remain in soil for up to 10,000 years (Leach et al., 2010). On the other hand, integrated systems often have TOC residence rates of 10 to 20 years (Assmann et al., 2014; Brewer et al., 2023; Latawiec et al., 2019). Furthermore, a substantial proportion of soil carbon in integrated systems is stored in the labile fraction, in which the average residence time is 108 days (Salton et al., 2013). Additionally, ambiguity regarding sequestration length in integrated systems arises due to gaps in research (de Moraes et al., 2013; Carvalho et al., 2010; Vinholis et al., 2020); such ambiguity creates an opportunity for biochar to mend these types of setbacks. Biochar's extensive sequestration is a core strength that can compensate for integrated systems' sequestration rates, which are significantly shorter than biochar when mentioned by studies, but largely remain inconclusive. The combination of biochar and integrated systems creates an even more appealing framework for policymakers to adopt and ultimately can secure long-term carbon targets through biochar's extensive sequestration rates.

Biochar can also stabilize soil bulk density within integrated systems. Similarly to other soil characteristics in integrated systems, bulk density is inherently volatile because of the contrasting components of livestock, crop, and forestry (de Moraes et al., 2014). Mismanagement of integrated systems, particularly overgrazing, easily increases soil bulk density due to extended pressures on soil from livestock weight. However, low soil bulk density is critical for healthy soil as it promotes water retention, porosity, and SOM retainment (Blanco-Canqui, 2017). Biochar can provide low soil bulk density and counteract the risk of increased soil compaction from overgrazing. Biochar naturally has a lower bulk density than soil; biochar's average bulk density is 0.6 g/cm^3, while clayey and sandy soils are about 1.1 g/cm^3 and 1.5 g/cm^3 respectively, both of which are characteristics of typical farm, nutrient-poor soil (Fontana et al., 2023). The effect of biochar on bulk density is evident in a study by Carvalho et al. (2020), in which biochar was applied to Latossolos at increasing rates of 0 megagrams per hectare, 6.25 megagrams per hectare, 12.5 megagrams per hectare, and 25 megagrams per hectare. Results highlighted that biochar applied at 25 megagrams per hectare successfully decreased bulk density by 63% when compared to the control group of 0 megagrams per hectare (Carvalho et al., 2020). Biochar can stabilize the sensitivity of soil by maintaining low bulk density, as it can be difficult to achieve optimal stocking rates for healthy soil in integrated systems. The inherent properties of biochar fittingly compensate for the inherent volatility of integrated systems; the combination of both methods is arguably more desirable than its parts.

Environmental Setbacks

Despite the large steps taken in integrated systems and biochar research, limitations that cannot be resolved with a comprehensive model continue to persist. Setbacks in integrated systems are rooted in the unique requirements of the cropping, livestock, and forestry components, which make integrated systems highly sensitive to agricultural mismanagement. Meanwhile, biochar has potential harmful effects when applied to neutral or alkaline soil, which, therefore, limits its application to acidic soil.

Integrated systems

While biochar can reduce the likelihood of poor soil bulk density observed in integrated systems, decreased crop residue still persists as a symptom of poor grazing control. Ribeiro et al. (2020) highlight this finding in a study comparing light, moderate, and heavy grazing intensities, set at pasture heights of 10 cm, 20 cm, and 30 cm. Moderate grazing had the highest carbon sequestration rate at an average of 4.92 megagrams CO2 equivalents per hectare per year after 3.5 years, while light and heavy grazing intensities had average rates of 1.84 Mg CO2 eq. per hectare per year. As reduced crop residue is a result of both light and intense grazing, it is incredibly difficult for integrated systems to find the optimal level of moderate grazing. Without this information, suboptimal results lead households to falsely believe that integrated systems are ineffective (de Moraes et al., 2014).

Pertaining to ICLF, cramped tree spacing decreases crop yield through excessive shading, which reduces sunlight. Pezzopane et al. (2017) measured PAR (photosynthetically active radiation) across an ICL plot and four ICLF plots, which had an incremental forestry-crop spacing of 1.5 m, 3.75 m, 7.5 m, and 11.25 m. ICL served as a baseline of 100%. For the crop component, ICLF-1.5 m demonstrated only 39.7% as much sunlight as ICL, while ICLF-3.75 m demonstrated 89.5%. For the pasture component, ICLF-1.5 m had 35.1% sunlight, in comparison to ICLF-11.25 m, which had 79.4%. Lower PAR becomes significant in crop output; the dry matter yield of Piatã grass, a type of pasture grass, was 2226.2 kg per hectare for ICLF-1.5 m, while dry matter yield for ICLF-7.5 m was 3707.1 kg per hectare (Pezzopane et al., 2017). Most of the dry matter is distributed among the three plots of 3.75 m, 7.5 m, and 11.25 m, while ICLF-1.5 m consistently has a lower dry matter yield. Similarly, tree spacing exemplifies another delicate factor that can reduce crop yield. ICLF can have trouble succeeding due to its highly specific requirements, requiring attentive planning and knowledge that may lead to reluctance in the adoption of integrated systems.

Research into integrated systems tends to lack in-depth information needed for practical application at the household level. Current research tends to repeat crop type and region, limiting conclusions to be applicable for highly specific circumstances. ICLF research overemphasizes eucalyptus as the forestry component, leaving the impact of other trees unknown. While trees native to a region could be especially attractive for increasing biodiversity, their characteristics are yet to be studied. Similarly, research in ICL focuses on the few plant species of oats, perennial ryegrass, and *Brachiaria brizantha*, overlooking the effects of other potential crops (de Moraes et al., 2014). Additionally, much research occurs in regions that are not primarily used for livestock and crops common to integrated systems. Figure 1 indicates the primary land usage of each biome region. As highlighted by the *Farming* and *Agriculture mosaic* land covers in Figure 1, most agricultural activity occurs in the lower half of Brazil; however, the majority of experiments are conducted in the Amazon and Cerrado regions (de Moraes et al., 2013).

The diverse climate and geography of Brazil make research in these regions much less applicable for households operating

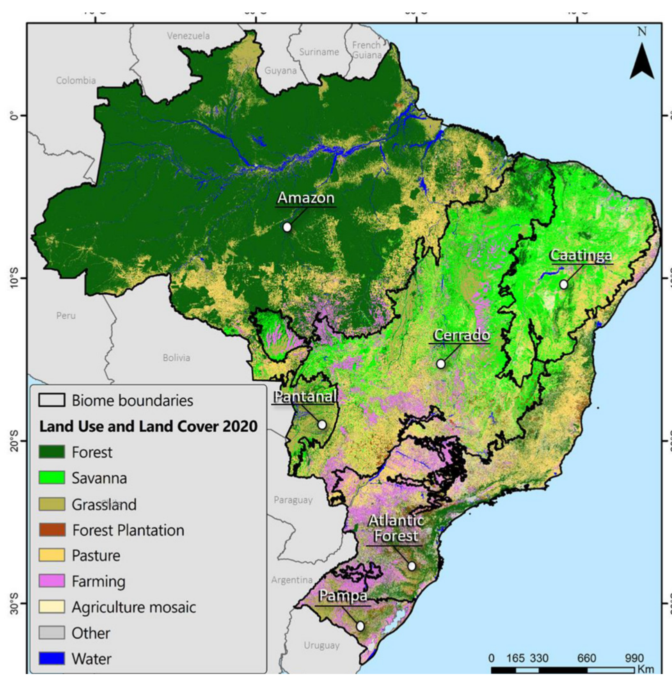

Figure 1. Map portraying primary land usage in Brazil's biomes (Alencar et al., 2022)

elsewhere. Soil weathering, flooding patterns, and clay content are a few of the factors that vary regionally, yet highly affect agriculture (Fontana et al., 2023; Padmanabhan et al., 2023; Holzman and Rivas, 2016). Lastly, there is likely overlooked research potential into the individual components of integrated systems as opposed to the interaction between such components (de Moraes et al., 2014). Much attention is channeled into the singular factor of cropping, rarely discussing livestock. Detailed research entailing proper planning of integrated systems is needed to avoid ineffective circumstances, such as cramped tree spacing and overgrazing, as well as the provision of accessible, location-specific knowledge for household application.

Biochar

The positive effects of biochar are limited when applied to non-acidic soil. The aforementioned Lefebvre et al. (2020), in which biochar application was conducted using either 100%, 50%, or 25% of all onsite biochar, the study highlights this effect in sugarcane plots. These proportions were replicated three times to also vary priming levels of 0%, 21%, and 91% (Zimmerman and Ouyang, 2019). Priming is the process of applying fresh organic matter to stimulate carbon decomposition and establishes an average pH of 6.5–7, when soil is less acidic and nutrient-poor (Liu et al., 2020; Wang et al., 2016). Figure 2 highlights that at all percentages of biochar application, biochar's sequestration ability decreased for the priming level of 91%, and was 13.9–25.3% lower than the plot with 0% priming.

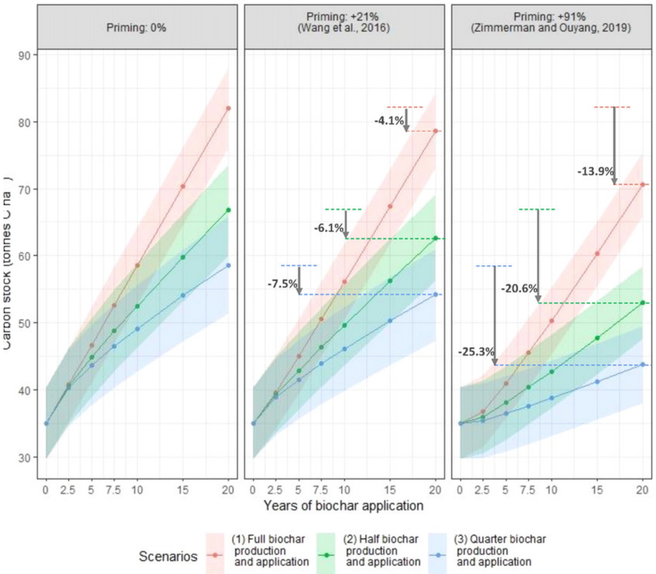

Figure 2. This graph highlights the decreases in sequestration at increasing levels of priming (Lefebvre et al., 2020)

When soil is already within a desired pH range, such as through priming, biochar becomes less effective; it is only helpful for acidic soil since it tends to increase the soil pH (Zhang et al., 2019). Soil pH greatly impacts the resulting carbon sequestration and overall GHG reduction, making it critical to fully comprehend the characteristics of the soil prior to biochar application.

Economic Impact

Integrated systems are profitable compared to both conventional farming systems and isolated biochar applications. These economic provisions would therefore be useful in a comprehensive model of biochar and integrated systems by compensating for the minimal profit of isolated biochar application.

Integrated systems

ICL increases livestock quantity, widens profit margins, and provides market insurance. Increased livestock quality is a result of healthy forage crops, which come from enhanced soil fertility. Carvalho et al. (2007) demonstrated this by comparing carcass weight gain in ICL against a continuous grazing system. Livestock in ICL showed an average weight gain of 540 kg per hectare, while continuous grazing showed an average weight gain of 439 kg per hectare. ICL then offers households additional income via increased carcass weight. ICL also widens profit margins by increasing revenue and decreasing cost. Higher crop yield secures more revenue, as exemplified by Salton et al. (2013), which recorded soybean yields under optimal and poor rainfall in two systems, ICL and a conventional system (CS). ICL produced an average of 3544 kg per hectare and 2882 kg per hectare in optimal and poor rainfall, respectively. CS produced an average of 2984 kg per hectare and 1642 kg per hectare, respectively (Salton et al., 2013). ICL not only produces more but is more resilient as it still outproduces CS under poor rainfall. Greater crop yield is further supported by Figure 3, which graphs twenty-three different studies to contrast grain yield between ICL and conventional systems. The 23 ICL experiments are represented by the various shapes, though maize is depicted in a graph separate from soybean, bean, and wheat. The dotted line strictly represents crop systems in which soil is ungrazed. In addition to increasing revenue, ICL lowers costs by using less external fertilizer, as soils already have nutrients from crop residue. Lastly, ICL's crop diversification creates a financial cushion against market price fluctuations, a risk insurance that monocropping systems do not have. This is particularly useful against frequent summer crop failures and low winter prices, especially pertaining to grain (Carvalho et al., 2010).

ICLF has arguably greater profit margins than ICL due to its forestry component, which prompts more efficient stocking rates. Barsotti et al. (2014) compared rates in conventional pasture, low-forestry ICLF, and high-forestry ICLF. The average stocking rate for conventional pasture was 0.9 Animal Units per hectare, while the average stocking rate for ICLF at low density was 1.7 Animal Units per hectare, and 1.8 Animal Units per hectare at high density (Barsotti et al., 2014). ICLF maximizes stocking rates efficiency and profit margins accordingly without sacrificing soil health. Environmental benefits of integrated systems are economically rewarding by creating sustainable returns on profit.

Biochar

Like integrated systems, biochar increases crop yield by improving soil fertility. However, it does not often lead to similar profitability, as revealed by research on biochar's financial and labor costs. In a study by Latawiec et al. (2019) concerning *Brachiaria* and *Panicum* forage grasses, the recorded cost of biochar application was $6,410 USD, while the cost of standard fertilizer application was $893. Priced at more than six times the amount of fertilizer, it is financially illogical for households to use biochar. Additionally, 15 megagrams per hectare of biochar was applied in contrast to 0.6825 megagrams per hectare of fertilizer, showing that exponentially more biochar is needed to be effective. Intense demands of biochar increase demands in labor and therefore labor costs. Latawiec et al. (2019) determined that 150 to 583 stoves and 75 to 210 stove operators are required to produce

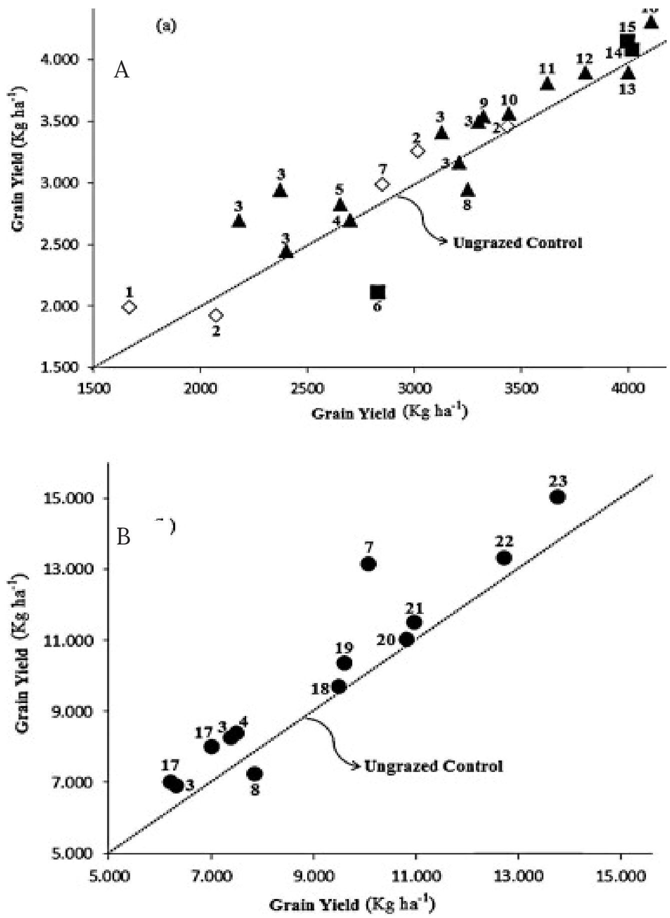

Figure 3. Graph plotting various studies to depict differences in grain yield of ICL and conventional systems (de Moraes et al., 2013)

the minimum effective quantity of 15 megagrams per hectare. The manual labor behind biochar production is immense, making it highly unappealing for small-scale farmers. On the other hand, Pandit et al. (2017) discuss kilns as a replacement for stoves. Being underground conical pits, flame curtain kilns require low cost, labor, and maintenance and also provide a quality of biochar similar to that of stoves. Kilns make biochar more accessible by offering an opportunity for implementation at the small-scale, household level. However, little research has been written on flame curtain kilns, and more research on production costs is needed before biochar can be efficiently used on a large scale.

Biochar and integrated systems

As biochar is a novel method with uncertain production costs, it lacks economic benefits as an independent system. When incorporated with integrated systems, the profits from integrated systems may be able to counterbalance the economic setbacks of biochar. As mentioned by Latawiec et al. (2019), biochar pyrolysis is an expensive process but only when produced for direct sale or direct fertilizer application. Profits would only cover 8–22% of costs unless farmers produced biochar for charcoal instead of fertilizer purposes. Through this method, they could make an additional $30–$85USD per month. This will likely dissuade farmers from using biochar as an amendment, and only as a means for profit through charcoal. However, the application of biochar in integrated systems would allow farmers to make profits sufficient to continue sustainable soil practices. Carauta et al. (2018) measured economic resilience in ICL through a bioeconomic simulation for 10 years. They found that an annual average income of approximately $1300 is associated with the optimal stocking rate of 5.8 Animal Units per hectare(Carauta et al., 2018). At $108 per month, integrated systems can provide greater profits than biochar production for charcoal. Profits from the adoption of integrated systems would only grow from biochar application, considering costs would remain low from biochar's long-term retention of carbon, and would therefore result in SOM and overall soil health improvement. The combination of these two systems creates strong financial incentives that are sustained through environmental benefit, though such conclusions are theoretical and would require practical trials.

Policy Impacts

Integrated systems were nationally adopted through the policy of the ABC Plan. Though it encountered several limitations, its success was substantial enough to set up a framework for the creation of biochar policy, which is currently lacking at the national level.

Integrated systems benefits

The ABC Plan, known as "Agricultura de Baixo Carbono" in Portuguese or Low-Carbon Agricultural Plan, is committed to providing financial, technological, and informational support for nationwide integrated systems adoption from 2010 to 2020 (Carauta et al., 2018). It prioritized GHG mitigation, land rehabilitation, and technician training, among the other goals of waste management and tree planting (Vinholis et al., 2020). The ABC Plan successfully increased the adoption of integrated systems with rural credit and institutional oversight, even exceeding some of its target numbers. Uptake was especially true for ICLF (Carauta et al., 2018), which was lesser-known than ICL before the ABC Plan. However, the success of the ABC Plan was not absolute. The distribution of rural credit and institutional support was severely mismanaged due to a lack of local input, heavily hindering adoption for rural areas. Rural credit encouraged the adoption of integrated systems by removing financial barriers. Rural credit had especially advantageous grace periods and loan terms as well as exceptionally low interest rates, which were annually set to seven percent lower than the national interest rate from the Central Bank of Brazil (Vinholis et al., 2020; Carauta et al., 2018). Offering cushioned loans recognized and reduced the inherent risk of adopting any new system. Farm Purchase Bonds (CPR) were also implemented, and allowed for crops to be purchased before they were grown, which gave farmers the finances to purchase the necessary equipment (Spolador and Ponchio, 2005). Rural credit proved effective in the agricultural year of 2012–13 when 2800 contracts were signed (Piao et al., 2021), nearly doubling the area of integrated systems in 2013.

Formal networks, consisting of bank and governmental institutions, conducted these credit contracts, acting as a decentralized form of financial subsidization and technical support. Bank of Brazil and BNDES (Brazilian Development Bank) managed contracts through local bank managers, who determined households' eligibility for credit (Carauta et al., 2018). The MAPA (Ministry of Agriculture, Livestock and Food Supply) organized technician programs in which EMBRAPA was responsible for managing technician–farmer relations (Piao et al., 2021). Technical support was dispersed through smaller chains known as rural extension services, while credit lines were accessed through technological reference units (Vinholis et al., 2020). Technical and financial support from formal networks proved to be successful; 6 million hectares of integrated systems were implemented, which was two million hectares more than the targeted four million hectares (Piao et al., 2021; Bragança et al., 2022).

Integrated systems setbacks

Dispersal of such resources among formal networks was unevenly distributed. Access to credit contracts and technical support were largely available only in southern regions. The north and northeast regions made up 4% and 4.5% of total credit contracts respectively, while the south and southeast regions had 46% and 30% each in the agricultural year of 2012–13 (Gurgel et al., 2013). Northern regions are notably more deficient in infrastructure and technology (Piao et al., 2021), and therefore should have received a concentrated investment of resources. This was likely overlooked by the standardized, top-down management. Future policies can learn to recognize the varying needs of each region to provide fair opportunities for credit. Unequal distribution of formal networks was likely due to the lack of attention given to heterogeneous knowledge between and within regions. Each region specializes in different types of farming and requires different types of technicians, bank managers, and overall assistance. For example, southern Brazil has a long history in crop farming, whereas the central-west is more familiar with cattle ranching (Jepson, 2006). When knowledge varies from region to region, formal networks are only partially effective because they cannot address gaps between a region's specific area of expertise and the government's standardized treatment. This plants a hesitancy and unwillingness for an integrated adoption of systems (Hardaker et al., 2015; Gil et al., 2016). However, informal networks can be used to complement formal networks by covering knowledge gaps between the federal and regional levels. Informal networks are built on social capital, which prioritizes mutual trust among households to regulate future relationships (Lyon, 2000), and are often rooted in interactions specific to a community's environment (Bragança et al., 2022). Since formal networks alone cannot adapt to local knowledge, informal networks are necessary for the success of future policies. In regards to research, available data for the ABC Plan remains vague, making improvements for future agricultural policy difficult. While the majority of research speaks highly of credit contracts, its application at the household level is rarely mentioned. Little is known about household responses to credit contracts, despite heterogeneous knowledge and its accordingly varied responses to credit efficiency (Carauta et al., 2018). Even contracts themselves are vague, as qualifications for contracts are limited by the inherently broad, nonspecific definition of integrated systems itself. Such vagueness can cause skepticism about the accuracy of nationwide statistics, as the lack of definitiveness forces highly approximated data of credit uptake (Carauta et al., 2018). Additionally, remarks regarding technical programs were drawn only at the national level, in which articles shared the same disappointed sentiment of short-staffed and unequally distributed technicians (Hochstetler, 2021; de Magalhães and Lima, 2014; Vinholis et al., 2020), but did not address any regional and household perspectives. While household-level data may simply not be available yet, considering the ABC Plan recently ended in 2020, the delay in available data undeniably hinders the success of future policies. Without understanding household-level responses to policy, it will be difficult to establish equitably distributed success.

Biochar

Policy is needed to regulate the growing interest in biochar among corporations, as it is an increasingly attractive asset for biofuel production, particularly as carbon emissions policies grow more restrictive. Corporations may seek to manage a growing number of field sites for industrial biomass production; however, this can put households, particularly small-scale farms, at risk of losing their land, potentially leaving farmers displaced and in poverty — a phenomenon also known as green grabs (Piao et al., 2021). As Brazil's agricultural sector makes up almost half the economy (Leach et al., 2010), its entire economy will likely be negatively affected if enough farms are repurposed into biochar sites for overseas purposes. The mass economic potential for biochar within Brazil reflects great urgency to protect its farmers from land grabs through policies detailing proper subsidization, production, and distribution of biochar.

> "Booming agribusiness has caused extensive soil degradation, estimated to be 140 million hectares in total and 36 million hectares of pasture land."

Policy delays are likely due to the inability to transition action from scientific institutions to government institutions. Within the realm of science, biochar has already been credited by UNCCD (United Nations Convention to Combat Desertification) as an effective solution for land degradation, carbon sequestration, and improving soil (Carauta et al., 2018). There are several notable initiatives, such as the IBI (International Biochar Initiative) and Biochar Fund, that offer comprehensive lists of various types of biochar applications. EMBRAPA, one of Brazil's largest government-funded institutions, is also responsible for the growing number of biochar resources, particularly regarding ADE (Amazonian Dark Earth), soil fertility, and climate change mitigation. While state-owned, EMBRAPA has had no involvement in national policy. However, such knowledge remains embedded in science, as the Brazilian government appears more focused on decreasing deforestation than on sequestering soil carbon stocks (Rittl et al., 2015). The government's lack of interest is stark when compared to EMBRAPA, which participated in 15.3% of biochar activity from 2006-2010, while the government participated in 4.2% and only reduced engagement from 2011-2013 (Leach et al., 2010). Such resistance may cause Brazil to fall behind other countries such as Eswatini, Zambia, and Australia, where biochar has already been implemented in agriculture, fuel, and the fight against global warming (Rittl et al., 2015).

The relative success of the ABC Plan can be used as a framework for initiating biochar policy. Through the ABC Plan, integrated systems successfully transitioned from the research and development sector to mainstream adoption largely because of financial aid policies such as rural credit. Carauta et al. (2018) explain that adoption of integrated systems would have only been found among 11% of farmers without the ABC Plan, versus the realized 27%. Additionally, the ABC Plan pushed forth integrated systems even when researchers knew little about certain components, such as crop type and crop-livestock interactions. This logic can apply to biochar: Although doubts exist in the research and development sector regarding biochar performance, demonstrated benefits in soil are arguably sufficient for policy actions to be taken. Prospective biochar policy can also learn from the shortcomings of the ABC Plan. As local, heterogeneous knowledge was not acknowledged, diverse backgrounds can be incorporated into future policy by subsidizing multiple farming methods of both integrated systems and biochar.

Conclusion

Integrated systems and biochar are sustainable alternatives that can replace conventional agricultural practices. Integrated systems manage crop schedules to simultaneously rehabilitate degraded soil and maximize profit, offering environmental protections without having to sacrifice economic gains. Biochar improves soil fertility and reduces agricultural waste, but requires policy initiatives to perpetuate economic gains and protect Brazil's soil at a national level. The comprehensive hypothesis of both systems is worth exploring in future research, as the benefits of one method can compensate for the setbacks of another. Biochar can strengthen integrated systems through long-term sequestration and greater crop yield, while integrated systems can help make the cost of biochar more accessible. It is in the interest of Brazil to continually push forth the agenda of biochar and integrated systems, as the consequences of conventional agricultural methods demand immediate solutions.

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Author Biography

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