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Review

Agriculture without burning: restoration of altered areas with chop-and-mulch sequential agroforestry systems in the Amazon region

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Traditional shifting cultivation in the Amazon region has caused negative environmental and social effects due to the use of fire. This type of agriculture has been criticized because it results in emission of large amounts of carbon into the atmosphere and a loss of soil productive potential. Since 1991, Project SHIFT-Tipitamba has researched this type of agriculture and, in a subsequent phase, attempted to propose solutions that could be adopted in northeastern Pará, a region of ancient colonization in Amazon and highly anthropized based on an exclusively slash-and-burn agricultural system for more than 100 years. This paper presents some results obtained over two decades of research on these agricultural systems and proposes a method for the recovery or maintenance of the productive potential of these areas based on sequential agroforestry with secondary vegetation management and chop-and-mulch land preparation.

Keywords: Amazonia, shift cultivation, slash-and-burn,

INTRODUCTION

Shifting cultivation or slash-and-burn agriculture in the Amazon region is an ancient tradition among the indigenous and cabocla populations and represents an extraordinary adaptation to tropical conditions (Shubart, 1983). The slash-and-burn system is perhaps one of the best examples of an ecological strategy used to manage agriculture in the tropics (Altieri, 2002). Despite advantages of this agriculture, it has been considered a problem for some Amazonian ecosystems due to population pressure and changes in the use of natural resources (Nepstad et al.,1999), which result in soils and agricultural systems degradation.

Production system intensification based on secondary vegetation has been the focus of research efforts on finding sustainable alternatives; initiated in 1991, Project Shift (Studies on Human Impact on Forests and Floodplains in the Tropics) is an example of international cooperation between the German and Brazilian governments. The German participants include the Universities of Bonn and George August Göttingen. The Brazilian portion of collaboration has been led by Embrapa Eastern Amazon (Rodrigues et al., 2007); partnerships exist with other institutions, such as the Federal Rural

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University of Amazonia, Federal University of Pará and Emílio Goeldi Museum.

In the initial phase, studies consisted of exploratory research to understand the impacts of traditional agricultural practices on secondary vegetation and to analyze the extent of ecological problems in Eastern Amazon; it was expected that alternative systems would be proposed (Denich et al., 2005).

The alternatives studied included increase the cultivation period (allowing the highest number of annual crops in a fallow/cultivation cycle) with mechanized area preparation (chop-and-mulch), thereby replacing slash-and-burn (Kato et al., 1999).

In early 2000, when Project Shift ended, actions were continued with Project Tipitamba (Rodrigues et al., 2007). Project Tipitamba's main objective is to propose technological, economic and environmentally sustainable alternatives with a focus on the elimination of fire and efficient use of natural resources and agricultural inputs to family farming development.

In this context, this review aims to present some experience obtained over more than two decades of research on alternatives to the use of fire in sequential agroforestry systems in the Amazon region.

The role of secondary vegetation in Amazonian agricultural systems

Studies conducted primarily in recent decades have shown the important environmental and socioeconomic role of secondary vegetation as a component of land use rotational systems adopted by many farmers in the Amazon region, especially in northeastern Pará (Hedden-Dunkhorst et al., 2003).

In the Amazon region, secondary vegetation is important because it provides several beneficial functions for family farming, including biomass and nutrient accumulation, which ensures productivity in the following growing period (Denich, 1991; Denich et al, 2005); the recycling and recovery of nutrients from deep soil layers (Sommer, 2000); erosion control (Denich et al, 2005); weed suppression (Gallagher et al, 1999); timber and firewood supply (Sanchez, 1995) and biodiversity maintenance in agricultural landscapes (Baar, 1997; Denich et al, 2005).

Studies conducted by Baar (1997) in the northeast of Pará state; in 92 secondary vegetation areas aged between 1 and 10 years, 673 plant species were found, of which 316 were trees and shrubs.

The floristic diversity found in secondary vegetation harbors a considerable number of species with different abilities to accumulate essential nutrients that can sustain plants during cultivation. This functional diversity was studied by Denich (1991) in northeastern of Pará state; in that study, the concentration of 11 bioelements (N, P, K, Ca, Mg, Mn, Fe, Zn, Cu, Na and Al) was evaluated in leaves and ligneous material of 81 species. This study revealed sixteen groups of species with similar concentrations of nutrients in their leaves through a cluster analysis of 80 secondary vegetation species.

The accumulation of biomass by secondary vegetation (Denich et al., 2004) is fundamental to slash-and-burn system because this accumulation of nutrients (Denich, 1991; Sommer, 2000; Denich et al., 2004) is necessary for the cultivation phase, when the nutrients are made available to plants in ashes remaining from vegetation burning during area preparation. Low amounts of phosphorus accumulate in secondary vegetation biomass, and this nutrient is one of the most limiting in tropical regions.

The composition and nutrient concentration of litter formed by secondary vegetation species (Cattanio, 2002) influences organic matter availability because the composition of this material influences the diversity and concentration of mesofauna in soil (Denich, 1991) and processes mediated by the mesofauna.

When primary forest is converted to pasture or agricultural areas using the slash-and-burn technique, soil nutrients and carbon are vulnerable to loss through various mechanisms including combustion, faster soil organic matter decomposition, soil chemical and microclimatic changes, and changes in the quality and quantity of nutrient cycles in forest replacement systems (Juo & Manu, 1996). In seven years of secondary vegetation burning in the Bragantina region, northeastern Pará, 21.5 Mg carbon and 372.0 kg nitrogen ha^{-1} were estimated to have been lost (Sommer, 2000). In addition, between 45 and 70% of typically less volatile cations, such as potassium (K), calcium (Ca) and magnesium (Mg), are lost. Most of this loss occurs through particle transport in smoke, and the most worrying feature is the export of 63% of phosphorus (P) stock, corresponding to 1.0 kg ha^{-1} (Sommer, 2000).

In secondary vegetation aged 7 years and with 31 $Mg.ha^{-1}$ of dry matter, Hölscher (1995) and Hölscher et al. (1997) suggests losses of 98% of accumulated carbon in biomass (143,78.0 kg $C.ha^{-1}$), 96% of nitrogen (199.2 to 205.0 kg $N.ha^{-1}$), 48% of potassium (35.1 to 39.0 kg $K.ha^{-1}$), 47% of phosphorus (4.0 to 4.3 kg $P.ha^{-1}$), 35% of calcium (102.0 to 107.0 kg $Ca.ha^{-1}$), 40% of magnesium (17.1 to 18.0 kg $Mg.ha^{-1}$), 76% of sulfur (34 kg $S.ha^{-1}$) and 30% of sodium (5.6 to 6.0 kg $Na.ha^{-1}$).

After several slash-and-burn cycles in the same area, this type of agriculture exhibits a decrease in sustainable levels, particularly when the fallow period is reduced (usually the result of an increase in population pressure and a reduction or elimination of secondary forest areas) [Zarin et al., 2005; Lawrence et al., 2010]. The biomass accumulation per cycle change is significantly lower in young forests that have gone through a shorter fallow period (Lawrence et al., 2010). Similarly, the nutrient contribution to annual crops provided by secondary vegetation is reduced (Kanashiro & Denich, 1998).

In recent decades, farmers have reduced fallow periods

Figure 1. The chopping sequence for secondary vegetation. Stage 1: Reversed operation (a), (b) and (c). Stage 2: Forward operation (d), (e) and (f). (g) Mulch resulting from stage 1. (h) Mulch resulting from stage 2. (i) Aboveground mulch.

from 20 to approximately 5 years, limiting accumulation of plant nutrients needed to sustain crop productivity (Joslin et al., 2011). The predominant adoption of increasingly shorter fallow periods is associated with nutrient losses during burning and is endangering the system stability of both private lands and the wider landscape because when fallow periods were long (7-10 years), systems based on secondary vegetation management were sustainable.

Fire-free land preparation using the chop-and-mulch system

Sustainability is threatened by proliferation of pastures on family farms. Attempting to practice cattle ranching and semipermanent mechanized crops increase, such as passion fruit and black pepper, compromises the regeneration of most species in secondary vegetation, precluding the subsequent use of these areas for agriculture. Unless high-cost techniques are adopted, the situation becomes generally unfeasible for small farmers.

To reduce these limitations, family farming systems in this region, which are dominated by secondary vegetation of different ages, have been developed and validated; agricultural interventions in eastern Amazon include the replacement of slash-and-burn practices by the use of chop-and-mulch during land preparation phase (Denich et al., 2005).

Manual chopping of vegetation started with the use of tools that are typically available in family production units. For secondary vegetation with little biomass, forage harvesters has also been tested. Despite its advantages, this type of work was adopted at low levels due to the need for highly intensive labor and difficulty experienced in execution, which is arduous and unattractive to farmers. It was necessary to develop a solution that could decrease the rejection rate and facilitate adoption of the proposed technology. Then, the mechanization process began (Kato et al, 2009).

Current mechanized land preparation uses a branch chopper, also known as a forestry mulcher trailer, which is attached to a wheeled tractor (Denich et al, 2004). The vegetation is chop to 5-10 cm of aboveground, so as not to disturb the soil (a no-tillage system) and avoid damaging the main regeneration system of secondary vegetation (stumps and roots that remain intact in the area, ensuring natural vegetation regrowth).

Two operations are required for adequate area preparation (Figure 1). In first operation, secondary vegetation is slashed, and vegetal material is partially chopped; in second operation, large material is chopped, and a soil mulch layer is standardized (Block, 2004).

Fallow vegetation performs an important role in maintaining and restoring soil productivity in Amazonian slash-and-burn agricultural systems. However, the intensity of land use is dramatically reduced during the fallow period. Therefore, soil quality must be restored more rapidly (Cattanio, 2002).

Research has shown that chop-and-mulch and no-tillage systems ensure secondary vegetation regeneration because they avoids damage to root systems, and 70% regeneration is guaranteed by the regrowth of stumps and roots (Stevens, 1999).

Rodrigues et al. (2007) conducted a comparative study of flora in areas under traditional slash-and-burn and alternative chop-and-mulch systems and found no significant differences in terms of the total number of individuals and species richness, but in an alternative system, a greater number of individuals and species richness was found in the upper stratum (> 1.5 m high), demonstrating faster regeneration and development.

This technique has shown positive economic and financial results in northeast Pará (Mburu et al, 2007). However, other solutions based on low external input standards are required before this agriculture becomes viable for small farmers (Costa, 2012).

This technology was also tested on semi-permanent and permanent cultures in experiments (Kato et al., 2001) and on cattle livestock subsystem for family farms (Bittencourt et al, 2009).

Based on Projects Shift and Tipitamba results, three options sequences for more sustainable land use were available to farmers: 1) Land preparation with secondary vegetation chop-and-mulch systems → annual crops → perennial fruit crops in agroforestry; 2) Land preparation with secondary vegetation chop-and-mulch systems → annual crops → fallow with natural secondary vegetation regeneration, and 3) Land preparation with secondary vegetation chop-and-mulch systems → annual crops → fallow enriched with fast growth species.

Aspects of fire-free land preparation in agricultural production

Denich et al. (2000); Tippmann (2001) and Sommer (2001) presented important data regarding above- and below-ground carbon stocks in young secondary vegetation in northeastern Pará. Denich (1991) demonstrated that groups of secondary vegetation species have the functional ability to accumulate major nutrients, whereas Sommer (2000) offered evidence for a protective role played by secondary vegetation roots (safety net) in reducing nutrient losses resulting from lixiviation and in reducing aquifer contamination (Wickel et al., 2002).

Regarding the sustainability of agricultural practices for Amazonian agroecosystems, Leal (2002) demonstrated that land preparation for cultivation using fire dramatically reduces species richness; consequent increased fire frequency can cause savannization, producing a landscape predominantly comprising graminoids and herbs, and reducing the presence of trees.

The development and maintenance of soil fertility is a major challenge for researchers dedicated to sustainable agricultural systems implementation in the humid tropics because highly weathered soils with low cation retention capacities coexist with a pluviometric index of more than 2.000 mm per year (Moura et al., 2008).

Alternatives biomass management strategies have been studied, for example, the planting of fast-growing leguminous and nitrogen-fixing trees in secondary vegetation (Brienza Junior, 1999). Studies using techniques based on this principle have been developed in the Amazon region and have introduced species, usually leguminous plants, in fallow enrichment techniques using fast-growing species (Brienza Junior, 1999; Borges et al., 2011; Rangel-Vasconcelos et al., 2012), green manure (Aragão et al., 2012) and alley cropping (Moura et al., 2008).

Nutrient cycling (the transfer of mineralized elements in soil-plant systems) is effectively realized by leguminous plants due to ability of these species to absorb nutrients from deeper layers of soil and to promote their release at the surface by roots decomposition , litter and pruning waste (Alegre et al., 2000). More efficient nutrient cycling during fallow periods contributes to ensuring production during the shifting cultivation period.

Soil management is unquestionably important to the development of agriculture in the tropics; however, there are many limitations to achieving sustainable development. One of the major limitations is related to distance between researchers and small farmers, who have low financial resources.

Only recently have researchers formed groups that work more directly with small farmers. This allows the consolidation of small producers confidence, providing adequate information to supply their needs. Conversely, deficiencies in research or in the adaptation of technology that enables the use of sustainable production systems that emphasize the maintenance of soil fertility with less chemical input are limitations that need to be determined and resolved.

Development of food crops in chop-and-mulch systems

Land preparation using chop-and-mulch system does not reduce production compared to slash-and-burn systems with fertilization. A tendency toward increases in production with crop intensification is observed in areas that are not burned (Kato et al, 1999). When fertilizer is not used, the first crop in burned areas is always greater than areas

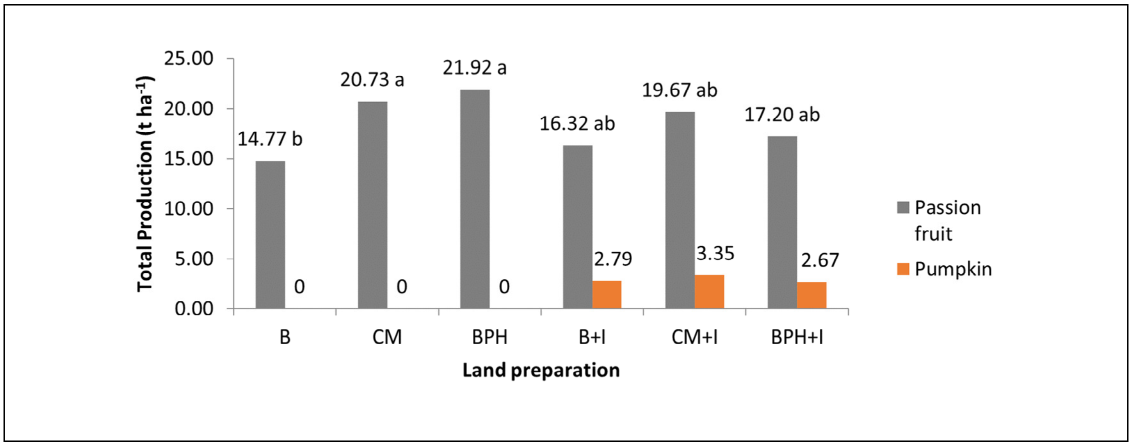

Figure 2. Aggregate production of three harvest periods (2001/2002) of passion fruit cultivation (adapted from Cardoso Jr. et al. [2007]) and pumpkin (unpublished data), according on land preparation method. CM - chop-and-mulch, BPH - burning, plowing and harrowing, B - burning, I - intercropping with pumpkin. Means followed by same letter do not differ based on the Tukey test at 5% probability.

without burn. This difference between systems is due to positive effect of ash in burned areas and nutrients immobilization by decomposing mulch microorganisms (which initially reduces nutrient availability) in unburned areas (Cattanio, 2002). However, there is greater production stability in lands that have been prepared using chop-and-mulch land (especially for cassava roots).

Kato et al. (1999) observed that rice and cowpea production was decreased in chop-and-mulch system when compared to land prepared with fire; this is unacceptable for small farmers. The solution is to use fertilizers to compensate for production losses. Due cassava is an undemanding crop with a cycle of greater than 12 months, it benefits from nutrient release from biomass in mulch form.

Fire-free land preparation wastes ted for passion fruit culture intercropped with pumpkin cultivation. A significant difference was observed between treatments regarding the total production of passion fruit obtained from two crops in the same year. Passion fruit production was higher in both chop-and-mulch system and burning, plowing and harrowing (Figure 2).

Intercropping reduced passion fruit production, possibly due to competition with pumpkin crop for water and nutrients. However, in burned areas and in areas that used chop-and-mulch land preparation, intercropping allowed greater aggregate production (passion fruit + pumpkin), obtaining 19.11 and 23.02 t ha^{-1}, respectively.

In slash and burn shifting cultivation, cassava is traditionally the last crop, and more demanding crops, such as rice, maize and cowpea, are planted immediately after land preparation at the beginning of the rainy season to utilize nutrients deposited by the ash produced by vegetation burning. In systems that do not use burning, soil fertility is not increased immediately after land preparation, and use of fertilizer is recommended to compensate for low nutrient availability in the initial phase (Kato et al., 1999).

The natural fertility of Amazonian soils is low, and nutrients in slash-and-burn systems come from secondary vegetation biomass. In chop-and-mulch systems, the release of nutrients from secondary vegetation biomass depends on decomposition of chopped vegetal material. Chopped biomass is formed of ligneous material, and the C/N ratio is high, indicating relatively slower decomposition. Thus, in the initial phase after chopping occurs, the decomposition of immobilized nutrients begins, initiating decomposition of organic material deposited on soil as mulch (Cattanio, 2002).

With low soil natural fertility and because nutrients remain immobilized during the initial phase, fire-free systems require the addition of nutrients as fertilizer to neutralize this initial negative effects. Kato et al. (1999) and Bunemann (1998) demonstrated that phosphorus is the most limiting element in Amazonian soils (levels are below 1 mg dm^{-3}), and a small amount is present in secondary vegetation biomass (Denich, 1991). Although applying small amounts of phosphate fertilizer produces a great response in maize production.

When it is impossible to acquire fertilizer for application, it is recommended to initiate the system with a cassava crop because this crop demands less nutrients and exhibits no productivity loss during the initial phase of chop-and-mulch system. After growing cassava, when mulch decomposition is more advanced and soil nutrient availability is higher, more demanding crops, such as rice, maize or cowpea are recommended.

The incidence of weeds in chop-and-mulch systems is lower due to cover formed from chopped material deposited on the ground. This coverage inhibits seed germination, especially that of herbs and grasses. The more secondary vegetation biomass is present, greater is weed suppression. Weeds that emerge in these areas are the initial regrowth of secondary vegetation species from stumps and roots that remain intact in the soil.

Soil changes using the chop-and-mulch system

In humid tropical regions as Amazonia, which are characterized by high pluviometric precipitation and high temperatures, the use of chop-and-mulch systems based on secondary vegetation should allow the efficient maintenance of OM levels.

Thus, the maintenance of agroecosystem productivity depends mainly on OM decomposition and, consequently, on microbial biomass (Gama-Rodrigues, 1999), which functions as an OM transformation agent in the nutrient cycle and energy flows (Wardle, 1993).

Ground mulch formation is the main aspect that differentiates chop-and-mulch from slash-and-burn systems. Mulch has an important role in soil functioning (Sayer, 2006) and positively affects physical, chemical and biological soil properties.

The absence of burning and mulch formation in chop-and-mulch systems should increase soil carbon (C) concentration and storage. However, after 2 cultivation cycles, there were no significant differences in C concentration between secondary vegetation (4 and 10 years old), slash-and-burn and chop-and-mulch systems (Denich et al., 2004). In another study conducted in a long-term experiment at Igarapé-Acu, Pará state, after 2 cultivation cycles, total C concentration was significantly higher at shallow depths (0-5 and 5-10 cm) in a chop-and-mulch (C_{0-5} = 2.70%, C_{5-10} = 1.86%) than in a slash-and-burn system (C_{0-5} = 1.65%, C_{5-10} = 1.47%); in layers at 10-20 and 20-30-cm depths, no significant differences were observed between treatments (Sampaio, 2008). In same study, the C stock at a 0-30-cm depth was greater in a chop-and-mulch system (56.6 t C ha^{-1}) than in a slash-and-burn system (50.7 t C ha^{-1}) [Sampaio, 2008], suggesting the potential storage of C in soil in the system without burning.

The high contribution of biomass in chop-and-mulch land preparation systems can negatively affect greenhouse gas emissions from soil. For example, high inputs of C and N and higher soil moistures in chop-and-mulch systems can generate favorable scenario for methanogenesis and nitrification, stimulating the production of methane (CH_4) and nitrous oxide (N_2O) emissions, respectively, from soil (Davidson & Schimel, 1995). In fact, the levels of N_2O and CH_4 emissions produced by chop-and-mulch systems are higher than those produced by slash-and-burn systems (Davidson et al, 2008). However, calculating the total balance of CO_2 equivalents emitted during crop cycles, considering CO_2 emissions from vegetation burning (in slash-and-burn system) and fuel consumption in mechanized chopping system, shows that the chop-and-mulch system produces at least 1/5 of the CO_2 equivalent emissions as those produced by slash-and-burn system (Davidson et al., 2008).

Rangel-Vasconcelos (2012), studying enriched fallow systems, affirmed that the use of a chop-and-mulch system in 23-month-old fallow vegetation, with fallow enrichment, increases free light organic matter (F-LOM) and improves soil quality.

Comte et al. (2012) compared the effects of traditional slash-and-burn agriculture to crops and pastures, a crop chop-and-mulch system with an enriched fallow period using leguminous trees and a pasture chop-and-mulch non-enriched fallow system; the authors observed that the enriched chop-and-mulch system conserved soil density and increased nutrient and organic matter concentrations significantly compared to slash-and-burn and forest control methods. In pastures, the use of chop-and-mulch non-enriched fallow had minor impacts on the physical and chemical properties of soil, with the exceptions of water retention capacity and total P stock.

Despite the expected soil compaction due to tractor weight, this effect was not observed by Comte et al. (2012), possibly because the use of a large amount of biomass as mulch reduced the effect of raindrops and because the presence of organic matter promoted more stable aggregates, resulting in soil density recovery over the two years between analyses.

Chop-and-mulch systems support the maintenance of soil moisture and prevent extreme fluctuations in soil temperature compared to slash-and-burn systems. In addition, increased soil OM content and improvements in soil physical properties provided favorable environments for soil fauna. Rousseau et al (2010) studied soil macrofauna in environments with 20- and 40-year-old secondary forests, chop-and-mulch systems with crops or pasture, and traditional slash-and-burn systems with crops or pasture; the authors observed that the Macrofauna Index of Soil Health (MISH) was higher in a chop-and-mulch system with agricultural crops; in particular, sub-indices related to the presence of earthworms and other invertebrates in the studied systems were high. These results demonstrated that chop-and-mulch systems exist closer to equilibrium, similar to a 40-year-old secondary forest.

CONCLUSION

Fire-free agriculture based on secondary vegetation management is an alternative to slash-and-burn agriculture that allows the possibility of recovering sustainability that has been affected by the loss/reduction of nutrients in agroecosystems as the result of fire and reduced fallow periods. The results obtained thus far indicate the possibility of substantial change in family farming systems, particularly in the region targeted in this study; such change would allow farming without the use of fire and based on secondary vegetation management, thus ensuring a higher production of biomass and bioelements and a period of time appropriate for current land use pressures. At the same time, it can offer additional value aggregation in the case of woody species that can also be used partly for other purposes (e.g., as energy sources) that are currently in demand due to the disappearance of wood and coal sources in the Amazon region and increases in petroleum derivatives prices.

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