# FALLOW LENGTH EFFECTS ON BIOMASS AND SOIL PHOSPHORUS POOLS UNDER FRIJOL TAPADO IN COSTA RICA

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# ABSTRACT

## FALLOW LENGTH EFFECTS ON BIOMASS AND SOIL PHOSPHORUS POOLS UNDER FRIJOL TAPADO IN COSTA RICA

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Many Costa Rican farmers have shortened the fallow period associated with frijol tapado, a slash/mulch bean (*Phaseolus vulgaris* L.) system. This thesis determines the resulting effects on biomass and soil phosphorus (P) pools. The study was conducted on three bean fields, short-fallow cropped for decades, and also on forest and pasture sites. Prior to 1999 seeding, one bean site had been fallowed for nine months, another, for 21, and the third, for 33. Each site had established, dispersed trees. Samples of surface soil (to 30 cm), mulch cover, and living vegetation were collected before slashing, after seeding, and at harvest. Plant material and soil light fraction were analyzed for total P; soils were subjected to sequential P extractions. Soil organic P and labile inorganic P were less after decades of short-fallow frijol tapado, and also after permanent pasture. Nine and 21 month biomass P pools were not statistically different.

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# 1. INTRODUCTION

## 1.1. A brief history of Costa Rica as it pertains to the canton of Acosta

Christopher Columbus made initial contact with Costa Rica, landing in what would become Puerto Límon, on September 18, 1502, during his fourth Trans-Atlantic journey (Rachowiecki, 1997). After a failed Atlantic Coast colonizing attempt in 1506, when the Spanish were vanquished by natives and dense jungle, 16 years would pass before Europeans successfully entered the region now known as Costa Rica. In 1522, an expedition headed by Gil Gonzalez Davila sailed out of newly founded Panama City (1519) to explore the Pacific coast to the north (Perez-Brignoli, 1989). They went as far as Nicaragua, landing in Costa Rica on the way. In the years that followed, European presence in Central America grew, including in what would soon become the province of Costa Rica. Regional conquest and settlement began in the Nicoya Peninsula (the northwest part of present-day Costa Rica) and moved inland (Soley, 1995). Conquistadors found negligible mineral resources in the area, and as a result, their territorial movement was less enthusiastic there than in other parts of Central America. It was not until 1560 that the central valley was settled (Soley, 1995).

Movements from the Central Valley, southward and westward, into the highlands presently known as the cantons of Acosta, Puriscal and Dota, soon followed (Soley, 1995). At that time, the area was inhabited by disperse native communities, linked together, culturally and economically, into "chiefdoms" (Soley, 1995). They practiced subsistence agriculture and their main crops were corn, grown using a slash system, beans, produced with the slash/mulch system now known as frijol tapado, chili peppers and squash (Perez-Brignoli, 1989). Agriculture was practiced in association with hunting, and gathering forest fruits.

## 1.2. Post-colonial history of Acosta

Though there appear to have been few, if any, permanent indigenous settlements within the present-day canton of Acosta, there were two closely associated with it: the "chiefdoms" of Acceri and Pacaca (Soley, 1995). Spanish physical and cultural incursion proved devastating for them—disease, land seizure, physical and economic subjugation, and the undermining of religious and cultural traditions, all contributed to their demise (Soley, 1995). Within 27 years of contact, first made in about 1570, the population of Acceri had dropped from 1000 to 250.

Acosta, formally identified as such in 1910, is said to have remained primarily virgin, mountain forest until well into the 19th century (Soley, 1995). The first major wave of migration from the Central Valley into Acosta occurred between 1821 and 1864. The early Spanish immigrants adopted many indigenous agricultural techniques, including the use of what came to be known as frijol tapado. Hunting continued to be an important activity for about 50 years, after which deforestation effectively eliminated it as a viable means of procuring food (Soley, 1995). The Spanish brought with them new crops, including wheat, sugar cane, different fruits and vegetables, and livestock (Soley, 1995).

After 1864, partially due to a regional agricultural crisis, immigration into the area slowed. By 1892 national demographic movement had shifted toward newly opened agricultural frontiers, though the Acostan population continued to grow (Soley, 1995).

The consequent land pressure translated into more extensive deforestation, excessive land division, over-cropping, and land degradation. Coffee production was introduced to the region in 1900, and it quickly gained popularity, particularly in the northeastern zone (present-day district of San Ignacio), drawing farmers into the cash economy (Soley, 1995).

In the 1940s, a disastrous insect plague decimated food crops for four consecutive years. This, and the disruptive 1948 civil war, left the population in abject poverty. By the 1950s, Acosta was a place of net emigration. Agricultural frontiers held the promise of land, the capital city, of opportunity, and the Atlantic lowland banana plantations, of wages (Soley, 1995). At that time, a series of support programs promoting beef cattle grazing in Acosta were introduced. Large areas of land were put into pasture, and by the 1960s, the problems of land availability and degradation had clearly been exacerbated. Rates of emigration continued to rise (Soley, 1995).

## 1.3. Introduction to frijol tapado and slash/mulch systems

Frijol Tapado, or "covered beans", in English, is a slash/mulch system of edible bean (*Phaseolus vulgaris* L.) production that has been used since pre-Columbian times in the region now known as Costa Rica (Araya and Gonzalez, 1994). Slash/mulch systems are ones in which a crop is sown in direct association with an *in situ* slashed vegetative mulch (Thurston, 1997). They have been used throughout much of humid tropical Central America and northern South America, where copious rainfall inhibits burning, and facilitates, along with warm temperatures, rapid mulch decomposition and nutrient mineralization (Rosemeyer, 1994; Thurston, 1997). Slash/mulch systems are particularly well adapted to the steeply-sloping land, which account for 78% of Central America and 48% of the Andean region, because they provide continuous ground cover which helps limit soil erosion (Thurston, 1994).

Frijol tapado functions as follows: Walkways are slashed through the fallow growth of a selected field with machetes, every 2-3 meters. These paths are then used to transverse the fields while broadcasting bean seed into the standing fallow growth. The remainder of the fallow growth is then slashed and chopped, covering the seed with a mulch layer. The length of time between planting and harvesting is approximately 3 months (more/less depending on the bean variety). At harvest, the bean plants are uprooted, tied into bundles, and hung in the fields to desiccate. When deemed dry enough for safe storage they are thrashed by hand, and the yielded beans are winnowed (Meléndez et al., 1999b).

Frijol tapado is used primarily for subsistence agriculture, and it yields small to medium size crops (normally 200 to 500 kg $ha^{-1}$, though the range is greater) (Meléndez et al., 1996). The average size of a seeded plot is 0.48 ha, ranging from 0.04 to 2.17 ha (Meléndez et al., 1996). As recently as 1982, 38-74% of agriculturalists in the cantons of San Isidro, Upala, Guanacaste, Puriscal and Acosta were producing beans using this system, and 80% of the lands sown to beans in Costa Rica were under frijol tapado (Araya and Gonzalez, 1994). Costa Rican farmers produce beans primarily to satisfy familial protein needs, selling what surplus they might have.

In the literature there appears to be some confusion as to the traditional fallow length. Kettler (1997) states that, as traditionally practiced, a fallow period of two to three years follows three to four years of annual production. Bellows et al. (1996) state that, traditionally, a bean crop was seeded after at least three years of fallow growth. A third claim seems most plausible—fallow length was variable, depending on the nature of climate and soil conditions, and on land availability (Meléndez et al., 1999b). It has been widely acknowledged that farmers have shortened fallow length in response to high land competition and the declining economic viability of hillside bean production (F. Arias, personal communication; Bellows et al., 1996; Kettler, 1995; Meléndez and Szott, 1999).

## 1.4. The strengths of the system

Frijol tapado provides farm families with a reliable, low-input, high-quality source of protein, which, combined with rice, acts as the basis of the traditional Costa Rican diet. Major inputs are limited to land, seed and labour. Labour requirements, though intense while planting and harvesting, are restricted to those periods, allowing farmers to pursue other activities, on or off the farm, at other times (Gonzalez and Araya, 1994). Yields are moderate to low, but according to an economic study by Rumoroso and Torres (1999) the ratio of benefits to costs was highest in zero-input frijol tapado, compared with moderate input frijol tapado, frijol espequeado (a clean cultivation system requiring agrochemical inputs, promoted by the government from the late 1970s to the mid 1980s), and semi-mechanized bean production (in the flatter areas of the country). Amador and Briceño (1999) reported that, compared with espequeado and semi-mechanized, frijol tapado yielded the highest net income. Equally, if not more, important, frijol tapado is a low risk system. According to work by Arias et al. (1999), the probability of economic loss is lower in frijol tapado, compared with espequeado.

In terms of physical sustainability, researchers have found that the high land-use intensity associated with frijol espequeado soon affected substantial erosion, decreased phosphorus availability, promoted pest infestation and diminished yields (Bellows, 1994). Frijol tapado, on the other hand, allows for sustained agricultural production on steeply sloping lands (Jiménez, 1995). Continuous and diverse plant/mulch layers minimize erosion, and simultaneously maintain a moderated and balanced soil microclimate that is conducive to a diverse microbial and microfaunal population (Bellows et al., 1996; Meléndez et al., 1996). The root zone tends to be well aerated, conducive to root proliferation and resistant to pathogenic infestation (Meléndez et al., 1996). Biomass generation is substantial and a diverse population of micro- and macroogranisms are able to process the material into soil organic matter (SOM), and to mineralize nutrients. The mulch cover present during crop growth has the added important advantage of inhibiting raindrop induced soil splash, the primary mode of transference for *Thanatephorus cucumeris*, the causal fungus for web blight, which is considered the most destructive disease for beans in the humid tropics (Thurston, 1990).

## 1.5. Weaknesses of the system

In spite of its strengths, frijol tapado has lost popularity, in relative and absolute terms, particularly in the past two decades. International policies have put intense pressure on governments, particularly those of less developed countries, to improve their balance of payments through structural adjustment and trade liberalization (Amador, 1996). In Costa Rica, this pressure has been coupled with a shrinking gross national product (GNP), wildly fluctuating export crop prices, and inflation (Amador, 1996;

Perez-Brignoli, 1989). The government has responded by encouraging increased export crop production and reducing domestic spending. For subsistence farmers, this response translates in the following way: Financial and technical support programs have been offered for the production of export crops (especially coffee, itabo, citrus, and beef cattle), and support for basic grains has been eliminated (Vernooy et al., 1999). Basic grain receiving and storage facilities, formerly provided by the government, have been closed (Amador, 1996). In 1992, Consejo Nacional de Producción (CNP), the government body formerly charged with supporting basic grain production, lost its role as a marketing board for small farmers. It had traditionally set an annual base price for beans, and had purchased and distributed the entire national crop. In 1992, CNP purchased only 25% of the bean crop and in 1995 CNP's involvement in grain commercialization ended (Araya and Gonzalez, 1994). Land in bean production fell from 35 707 ha in 1994-95 to 22 596 ha in 1995-96 (Vernooy et al., 1999). In Acosta, in 1988, frijol tapado accounted for 50% of the average farm family's income (monetary equivalent). By 1998, it accounted for only 4% (M. Rumoroso, personal communication).

The aforementioned policy changes are the most recent and easily identifiable factors that have diminished the economic viability of frijol tapado, but the assault on the system is by no means a new one. In Acosta, in the 1950s, a growing population and increased beef cattle production intensified competition for land (Soley, 1995). It was already becoming difficult to leave land in fallow for more than a single season. In many parts of the canton today, cattle ranchers rent pieces of land to small land-owners and landless peasants, for frijol tapado, and graze the fields during the supposed fallow period

(Bellows, 1994). Systematic decreases in fallow length, particularly when coupled with cattle grazing, may have serious implications for sustainability.

## 1.6. Acosta today

Overgrazing and land degradation are chronic problems, with land abandonment common. Land ownership has become concentrated in fewer hands—those of the ranchers and coffee growers (Amador et al., 1995; Soley, 1995). Coffee plantations employ a large labour force for harvesting and, to a lesser degree, for pruning, which helps sustain the local population, but cattle ranches employ few workers for short periods (chopping pasture weedy growth). Hence, the reduction in land available for food production has been associated with rising unemployment. Even coffee plantation work is seasonal, and wages fluctuate with the market's vicissitudes. Levels of malnutrition in Acosta are high, availability of health care is low; many areas lack both potable water and electricity (Soley, 1995). It is presently considered to be among the poorest cantons in the country (Vernooy et al., 1999). People continue to emigrate, as they have for decades, to less populated areas, to the city, and to plantations.

## 1.7. The question of fallow length

According to Bellows (1994), few frijol tapado producers presently leave land in fallow for more than nine months. It is unclear just what role fallow length plays in the sustained productivity of frijol tapado. Farmers report negative experiences with shortened fallow length (F. Arias, personal communication), while scientific results are ambiguous. Some researchers have concluded that a shortened fallow period makes frijol tapado less sustainable, and that bean yields are lower when the crop follows a fallow period shorter than three years (Bellows et al., 1996). Others have produced contradictory results. In one study in Acosta, along a series of 1 year fallow sites, yields were higher where biomass was higher, yet the yield from a bean crop following a high-biomass, three year fallow period, was lower than what followed one and two year fallow periods (Meléndez and Szott, 1999). It was suggested that the large quantity of biomass present after three years of fallow growth inhibited seed germination and survival. The site was seeded into beans in the each of two years that followed, and yields where only slightly higher.

According to De la Cruz (1994), a change from long fallow periods (3-5 years) to short (1 year) results in a shift in fallow plant species that causes the system to become unsustainable, eventually leading to land abandonment. Meléndez et al. (1999a) found that the dominant plant species in a 3 year fallow site were considered ideal for frijol tapado (easy to slash; provided thick, uniform mulch; slow re-growth; high macro-nutrient content), while the one that dominated a 1 year fallow site was considered detrimental to the system (rapid re-growth; poor mulcher; short life cycle). Bellows et al. (1996) produced similar results.

Short fallow periods, coupled with cattle grazing, is believed to encourage grassy vegetation, incompatible with frijol tapado. Most evidence for this is anecdotal. Farmers have found that rented land that is grazed during the fallow period tends to become dominated by rhizomous grasses (G. Meléndez, personal communication). The resulting mulch impedes seedling emergence, and the grasses compete too vigorously with the beans. Bellows et al. (1996) found that a short fallow site with such pasture grass mulch had emergence and competition problems. Meléndez et al. (1999a) produced less conclusive results.

## 1.8. The phosphorous problem

It is important to assess the effect that shortened fallow periods may have on the distribution and availability of phosphorus (P) in the system. Approximately 82% of soils in tropical America have levels of plant-available P considered to be limiting to plant growth (Schlather, 1998). Gadea and Briceño (1999) affirmed that P is the primary limiting nutrient for crop production on most frijol tapado soils. Phosphorus deficiency is particularly problematic in the mountainous region in the south, near the Panamanian border, where soils are of volcanic origin, and thus allophane enriched. Allophanes have large surface areas and an affinity for P, and though the soils are often rich in total P, most is strongly adsorbed to the clay minerals, making it effectively unavailable (Schlather, 1998). Oxisols and Ultisols also suffer from a paucity in available P, as a result of protracted leaching and accumulations of aluminum (Al) and iron (Fe) oxides, which have a high affinity for P (Schwertmann and Herbillon, 1992). In P deficient soils, particularly in the absence of an external source, vegetative growth and soil organic matter (SOM) play essential roles in the maintenance of plant-available P.

In Acosta, where this study was conducted, available soil P deficiencies are not as dramatic as in the south of the country. The soils are of a moderate age (10,000 years old), and though they contain volcanic ash, they developed from ancient marine sediments, and are classified as Entisols and Inceptisols (R Matta, personal communication; Matta et al., 1999). However, beans grown on these soils do show a marked response to additions of rock phosphate, without other amelioration, confirming that P is an important limiting factor for crop production (Gadea and Briceño, 1999).

## 1.9. The relative importance of inorganic and organic soil P in plant nutrition

Most P is taken up by plants as orthophosphate ions ($H_2PO_4^-$, $HPO_4^{2-}$ or $PO_4^{3-}$) (Kwabiah, 1997). These may be derived from either organic or inorganic soil pools, from above-ground or below-ground, decomposing biomass, or from fertilizer additions. In weak to moderately weathered soils (i.e. those that make up the vast majority of temperate soils), inorganic phosphorus (Pi) pools make important contributions to the plant-available P pool (Agbenin and Tiessen, 1994). Plant-available P is defined as "all P that is taken up by a plant during a specific period, such as a cropping season, year or growth cycle" (Tiessen and Moir, 1993).

Primary phosphate minerals, particularly apatite (calcium phosphates), slowly solubilize and release P ions into the soil solution. These are taken up by plants or microbes, are adsorbed to clay colloids, or become associated with secondary mineral compounds (Paul and Clark, 1989). Crystalline, 2:1 clay minerals predominate in most weakly weathered soils, and these loosely adsorb moderate amounts of P, holding the ions in an exchangeable form (Sanchez, 1976).

As soils weather, primary P minerals solubilize and are depleted, and 2:1 layer-silicate clays break down into 1:1 layer-silicates (kaolinites), which have low capacities for P retention (Schwertmann and Herbillon, 1992). Basic cations leach from the system, and biochemical and chemical processes release hydrogen ions ($H^+$); the soil environment becomes more acidic. Under low pH conditions, Al and Fe become more active and form insoluble P compounds, often coated with inert, sesquioxide material (Sanchez, 1976). Iron and Al also undergo hydrolysis, forming small, weakly crystalline Al and Fe hydrous oxide minerals (especially goethite and hematite), furthering the process of soil acidification (by releasing $H^+$) (Sanchez, 1976). The resulting Al and Fe oxides have large surface areas and reactive functional groups, and strongly adsorb large quantities P (Schwertmann and Herbillon, 1992). Overall, Pi resources become less available for plants as soils weather.

Organic phosphorus (Po) is P that is involved in carbon-P compounds. Soil levels of Po and SOM content are very closely connected (Stevenson, 1986). Organic P compounds are released into the soil solution by lysis and secretion, as microbes break down organic material (Tiessen et al., 1994b). Identifiable organic compounds found in the soil, known to release Pi upon further decomposition, are monoesters, such as inositol phosphate (usually 11-30% of Po), and in smaller quantities, nucleic acids and phospholipids (Kwabiah, 1997). At least 50% of soil Po compounds have not been identified (Paul and Clark, 1989). Inositol phosphates, present at much higher relative quantities in the soils than in plants, are believed to be degradation products of other Po molecules. Their relative abundance in soils may be accounted for by the fact that they form insoluble complexes with polyvalent cations, with an orientation that protects the P group from phosphatase activity (Stevenson, 1986; Tiessen et al., 1994b). High molecular weight compounds, such as nucleic acids, are more likely to continue to be involved in biological cycling (Tiessen et al., 1993).

Soil Po compounds are generally thought to play a minor role in contributing to the labile Pi pool in weakly weathered soils when they are used for fertilized agricultural production (Dalal, 1977). However, researchers have found that Po levels were lower in unfertilized, cropped Chernozems, than in fertilized ones, and also lower in sites that were fallowed less frequently (McKenzie et al., 1992). As they decompose, Po compounds may make important contributions to the plant-available P pool in unfertilized, weak to moderately weathered soils that are cultivated.

In highly weathered, cultivated soils, it is clear that Po can play an important role in supplying the plant-available P pool (Agbenin and Tiessen, 1994). According to Sanchez (1976), Po accounts for 60-80% of total P in more weathered topsoils, compared with only 20-50% in less weathered ones. Formerly available Pi has either been leached from the system, fixed by soil minerals (fixation being the process by which soil P becomes less available (Sanchez, 1976)), or has accumulated as Po in SOM and in the biological components of the system (Sanchez, 1976). Studies have shown that Po levels drop significantly when these soils are cropped, but not fertilized, and researchers suggest that mineralized Po may make important contributions to the plant-available P pool (Tiessen et al., 1992; Beck and Sanchez, 1994; Buresh et al., 1997).

## 1.10. The Hedley soil P fractions

The Hedley sequential P extraction, often modified in some way, is frequently used for quantifying soil Pi and Po in terms of availability (Hedley et al., 1982). The original fractionation scheme involved the sequential application of a series of treatments that were increasingly aggressive in extracting P. These were as follows: anion exchange membranes (AEM) (Pi), sodium bicarbonate ($NaHCO_3$) (Pi and Po), sodium hydroxide (NaOH) (Pi and Po), dilute hydrochloric acid (HCl) (Pi), and finally sulfuric acid ($H_2SO_4$) (residual P). The problem with this original extraction procedure was that a large portion of Po was usually allocated to the residual P fraction, where it was not differentiated from Pi (Tiessen and Moir, 1993). A modified Hedley procedure outlined by Tiessen and Moir (1993) included extraction with hot, concentrated hydrochloric acid (HCl) before the final $H_2SO_4$ digestion. Condron et al. (1990) demonstrated this to be an effective means of ensuring that most, if not all, Po had been accounted for before the final digestion step.

The extracted fractions help researchers understand soil P in terms of plant availability, though what they represent is not completely understood. Pi fractions are better understood than Po (Tiessen and Moir, 1993). The AEM Pi is considered the freely exchangeable P (Tiessen and Moir, 1993). The membrane adsorbs Pi that is readily water soluble, including the small amount that enters the solution after it has been depleted. $NaHCO_3$ Pi is thought to be loosely adsorbed to the surfaces of crystalline clays, sesquioxides and carbonates (CAB International, 1989). The AEM and $NaHCO_3$ Pi fractions, combined, are often said to represent the labile Pi in the soil (that which is readily available for plant uptake) (CAB International, 1989; Tiessen and Moir, 1993). NaOH Pi falls into a more ambiguous category. Often classified as "moderately labile", it has been said to be associated with weakly crystalline Fe and Al oxides (CAB International, 1989). In temperate soils, it is believed to be moderately involved in short-term P transformations. In tropical soils, at least one study has indicated that the NaOH Pi fraction is an important participant in maintaining the plant-available Pi pool during the cropping season (Agbenin and Tiessen, 1994). The dilute HCl fraction is representative of the calcium bound Pi (apatite). This fraction becomes less important as soils weather. The concentrated HCl and $H_2SO_4$ Pi fractions include Al and Fe phosphates Pi covered in sesquioxides, and Pi structurally involved in stable secondary minerals (Tiessen and Moir, 1993; Agbenin and Tiessen, 1994). These are considered recalcitrant and highly recalcitrant, respectively, and involved only in long-term transformations.

There is only a vague understanding as to what the Po extracts represent. $NaHCO_3$ Po is defined merely as highly labile and easily mineralizable (CAB International, 1989). Levels have found to be stable over time in cultivated, unfertilized, tropical soils, while NaOH Po levels have been observed to decline within a moderate time period (2-10 years) (Tiessen et al., 1992; Beck and Sanchez, 1994; Buresh et al., 1997). NaOH Po has been defined as an extraction of fulvic and humic acid associated P, moderately labile, involved in microbial transformations (CAB International, 1989; Tiessen et al., 1992). The HCl Po fraction is usually referred to as residual Po. There is no clear sense in the literature as to whether this fraction is different from NaOH Po. Tiessen and Moir (1993) do not preclude the possibility that the residual P ($H_2SO_4$ digestion derived) will include some Po, though they deem it unlikely.

## 1.11. Phosphorus dynamics in forest ecosystems in the humid tropics

In forest ecosystems, the former ecosystems of much of the land used for slash/mulch systems, a number of processes associated with the continuous presence of vegetation are conducive to maintaining a pool of plant-available P in the system.

Through senescence, trees provide continual additions of fresh litter, maintaining a mulch layer and semi-decomposed organic horizon in which superficial roots proliferate and intercept mineralized P before it reaches the mineral soil (Schlather, 1998). Over half of plant-tissue P is water soluble and inorganic, which results in an initial flush of Pi with fresh litter additions (Dalal, 1977; Schlather, 1998). In the subsequent weeks the microbial population decomposes the litter, releasing P, through secretion and cell lysis, into the rhizosphere. There it is sequestered by plant roots, in association with mycorrhizal fungi, and also by other microbes. The cell walls of dead microorganisms (including fungi) become important substrate material for the formation of stable SOM in the mineral soil (Paul and Clark, 1989). Semi-decomposed plant material, as it is mixed into the mineral soil, also serves as an important substrate for the synthesis of stable SOM compounds (Schlather, 1998).

The role that SOM plays in P cycling is complex—in addition to improving soil tilth, porosity and water retention, SOM, specifically humic and fulvic acids, are thought to block P sorption sites on clay minerals and also act as anion exchangers that temporarily hold Pi in an exchangeable form (CAB International, 1989; Pallo, 1993).

The forest system is supplemented by additions of Pi that are sequestered from relatively unavailable soil fractions by tree roots, in association with mycorrhizal fungi (Schlather, 1998).

## 1.12. Phosphorus dynamics in disturbed sites

When forest sites are cleared, and not fertilized, particularly when available Pi pools are small, soil Po mineralization appears to provide plants with an important portion of their required Pi (Tiessen et al., 1994b). It has been widely reported that cleared lands experience a significant decline in SOM, and in Po (Dalal, 1977; CAB International, 1989; Tiessen et al. 1992). This increase in net SOM decomposition and net Po mineralization likely results from smaller overall litter contributions, along with changes in soil conditions, such as warmer temperatures and disturbance-induced aeration, that stimulate microbial activity (Dalal, 1977).

As for the direct P contribution made by slashed biomass to the freshly seeded crop, its importance is great. With the first rainfall after slashing there seems to be a flush of water-soluble Pi released (Kwabiah, 1997; Schlather, 1998). Given that this often comes within hours of seeding, crop uptake is minimal, and is either used for microbial synthesis (eventually contributing to the plant-available P pool through microbial death and cell lysis), is taken up by the slashed plants' root systems or becomes associated with soil minerals. After the initial flush, a stage of net immobilization by microbes translates into a sharp drop in mulch-derived, plant-available P (Kwabiah, 1997). This lasts until microbial death outpaces synthesis, often occurring 2-4 weeks after slashing, though the timing is highly dependent on the initial P content of the mulch material (Kwabiah, 1997; Schlather, 1998). Kwabiah (1997) found that the critical P levels of plant mulch materials ranged from 0.20 to 0.24%, with values below resulting in a net immobilization of P by microbes in the short term (56 days).

One of the major challenges for low-input agriculture is to produce crops without large losses of P (through crop removal and/or soil erosion), and without substantial relocation of potentially available P resources to pools that are effectively unavailable for crop uptake (Buresh et al., 1997). This challenge is inextricably tied to maintenance, or frequent replenishment, of SOM, not only because of the close connection between Po and SOM, but also because of the numerous soil quality factors conferred upon soil by SOM that influence Pi availability (Pallo, 1993). This is particularly relevant in weathered soils but is also an important consideration in other low-input farming situations, where external sources of P are not available.

## 1.13. Frijol tapado and P management

Slash/mulch systems such as frijol tapado were developed, in part, to respond to issues of SOM and P management, though the problem was not understood in those terms until relatively recently. Early farmers found it necessary to leave land in frequent, and relatively extensive (3-4 year), fallow periods in order to sustain yields on the land they worked (Meléndez et al., 1999b). During extended fallow periods, plant species composition progresses from a community of herbaceous, shade-intolerant types of shorter stature, into a bushy thicket of larger, woody shrubs, the leaves of which provide a high quality mulch (Meléndez et al., 1999a). Underground, various root networks develop, breaking apart dense soil masses, and sequestering P from a relatively large soil volume, and from recalcitrant pools (Meléndez and Szott, 1999). The proportion of the system's P in biomass rises. Litter inputs from senescing shrubs and dying plants, along with the lack of physical perturbation, create an environment conducive to building SOM and Po. In a relatively short period, an environment similar to that of a forest is created, and by regularly interjecting cropping practices with fallow periods, the P sequestered by the biomass, and that stored in the SOM, can be repeatedly tapped.

## 1.14. Fallow length and P

There is little data available on the effects of fallow period length on P dynamics and distribution in frijol tapado, and in other slash/mulch systems. Meléndez et al. (1999a) published results that showed bicarbonate Pi (Olsen) to be higher in 1 year fallow sites than in 3 year fallow sites, but it is not clear whether the differences were significant. Meléndez and Szott (1999) found that 3 year fallow sites had more above-ground biomass, before slashing, than 1 year fallow sites did, implying that they also had larger mineralizable, above-ground P pools.

Given what is understood about the nature of P dynamics in undisturbed, and in cleared, forest ecosystems, it would not be unreasonable to hypothesize the following: A shift from long fallow (3-4 years) to indefinitely repeated, short fallow periods (9 months) will result in reduced above-ground biomass, shorter periods of SOM and Po accumulation, and more frequent periods of net SOM decomposition and Po mineralization. A net loss in soil and above-ground Po will result. In weathered and volcanic soils, Pi mineralized from Po will likely accumulate in recalcitrant Pi pools. Tiessen et al. (1994), found that the declining P fertility of a Brazilian Oxisol, cultivated for six years, was primarily a result of mineralization of Po and subsequent mineral fixation. Phosphorus loss associated with annual crop removal may be an additional concern.

The consequence of this hypothesized re-arrangement of P pools, inextricably tied to changes in SOM and related soil physical factors, and ultimately to the entire functioning of the system, would be diminishing productivity, perhaps to some lower equilibrium, or perhaps to the point of land abandonment.

## 1.15. The inclusion of dispersed on-farm trees as a means of improving fallow

There has been substantial evidence that points to the potential of agroforestry to compensate for the intensification of bush fallow systems (Raintree and Warner, 1986; Staver, 1989; Atta-Krah and Kang; 1993). But farmer adoption of researcher developed systems, such as alley cropping, has often been less than expected (Staver, 1989; Kowal, 1999). Raintree and Warner (1986) emphasized that "biologically enriched fallows" were only interesting to farmers if they were also obviously "economically enriching". Kowal (1999) notes that alley cropping requires labour and material inputs that can overwhelm the economic incentives.

Recently, greater attention has been paid to indigenously developed agroforestry systems, with the thought that they may be technologies that farmers in similar situations will find appropriate (Raintree and Warner, 1986; Kass et al., 1993; Hellin et al, 1999; Kowal, 1999). These systems usually have low labour requirements, demand few external inputs, and offer advantages that are obvious to the farmers. Hellin et al. (1999) recorded a wide range of advantages that farmers associated with an indigenous, Honduran agroforestry system, including improved soil moisture retention, decreased erosion, fruit and timber production, lengthier cropping periods between fallow periods, and low labour requirements. Kowal (1999) classified this as a dispersed on-farm tree systems, meaning that trees grew within cropped fields in a dispersed pattern (not in rows). They were pruned at appropriate times so as to ensure minimal competition with crops for light. He noted that systems such as this one, that were developed by the farmers themselves, were spreading through the region with ease.

Kettler (1995) studied the effect that introduced tree species had on short fallow frijol tapado, with results that pointed to the potential of such systems to improve fallow biomass yield, and crop productivity. At least one farmer in Acosta has established dispersed trees within his bean fields and has reported positive results (F. Arias, personal communication).

## 1.16. Research objectives

The objectives of this study were to determine the effects of short-fallow frijol tapado on P pools in the system, and to determine the relative importance of the pools for crop nutrition. The effects of varied fallow length on above-ground biomass, and on P nutrition of the bean crop, were also to be quantified. Finally, the effects of long-term pasturing on soil P pools were to be determined.

# 2. MATERIALS AND METHODS

## 2.1. Site Description

### 2.1.1. Acosta

The canton of Acosta is a sub-region of 34 224 ha situated about 28 km southwest of San José, Costa Rica's capital city (Fig. 2.1). A mountainous area, altitudes range from 500 meters above sea-level (masl) to 2000 masl, and 85% of the land area has slopes greater than 45% (Jiménez, 1995). In 1989, approximately 70% of the land was used for beef cattle grazing, 90% of which had slopes greater than 45%. About 7% of the region was used for perennial crop production (primarily coffee and citrus) and 7% for annual crops (mostly beans and corn) (Jiménez, 1995). The remaining 16%, which included the steepest slopes of the region, supported natural forest growth (Jiménez, 1995). It is certain that the forested area has shrunk since that time (Jiménez, 1995).

### 2.1.2. Bajo Arias

The community of Bajo Arias is situated in the northeastern part of the canton, a few kilometers outside of the regional capital, San Ignacio (9.79N 84.16W) (Fig. 2.1). The population density of the area ranges from 5 to 100 people per km$^2$, except near San Ignacio, where it is as high as 500 people per km$^2$ (Jiménez, 1995). Most farms are 2-4 hectares (ha), though some are as large as 50 ha (Jiménez, 1995). Beef cattle, coffee, citrus, itabo, and basic grains are commonly grown, but due to the relatively moderate slopes in this part of the canton, and its proximity to markets, perennial cash crops (coffee, citrus, itabo) predominate (Amador et al., 1995). The average annual precipitation totals 2700 mm, with a pronounced dry season beginning in mid-December and ending in April (Jiménez, 1995). The main rainy reason extends from mid-August through October. The median temperature is 23°C (Jiménez, 1995).

Bajo Arias was founded about 200 years ago by Rafael Arias, one of the first Spanish immigrants to arrive in the region (F. Arias, personal communication). Approximately 120 people inhabit the village today, 95% of them descendents, or married to descendents, of Rafael. Almost all are agriculturalists. Frijol tapado has been used to provide a reliable source of protein since the community's founding. In recent years, acreage has dropped substantially, partially due to increasing land pressure and decreased economic incentive, and also because of local climatic disruptions. There have been a series of rainy Decembers, the month of bean harvest; as a result, many farmers have been unable to harvest their crops. Little seed was available for sowing in 1999 because of a disastrous harvest in 1998 (F. Arias, personal communication).

The research was conducted on Felipe and Maria del Carmen Arias' farm. Felipe is the great, great grandson of Rafael. With their four children, they grow a wide variety of food and cash crops on about 4 ha. These include coffee, citrus, medicinal plants, beans, corn, squash, peppers, tomatoes, bananas and plantain, all produced without synthetic fertilizers or pesticides.

### 2.1.3. Site descriptions

Soil and plant P pools were studied on five different sites within the boundaries of the farm. Three sites were to be seeded using frijol tapado in August, 1999—all had been in short-fallow (9 month) frijol tapado for decades, but prior to this cropping season, one was in fallow for 9 months (1 yr fallow site), another for 21 months (2 yr fallow site), and a third for 33 months (3 yr fallow site). The fourth site was a virgin forest site, and the fifth had been under pasture for at least 40 years.

The soils on an adjacent farm had been classified as an Andic Dystropepts, tropical Inceptisols of low base content derived from ancient marine sediments, with a covering of volcanic ash (Matta et al., 1999). They had a clay content greater than 48%. The soils within the study area were of the same origin, but due to steeper slopes (63-92% versus 19-27%), were less developed. It was estimated that the areas with slopes greater than 75% had conassociations of approximately 70% Entisols and 30% Inceptisols, and where slopes were less than 75%, proportions of Inceptisols increased (R. Matta, personal communication).

Two weeks prior to the pre-slash sample session, a general reconnaissance mission was undertaken, with maps drawn, and slope, altitude, soil temperature, dimensional and situational measurements taken (Table 2.1). All sites were situated at altitudes greater than 700 masl, with slopes greater than 60%, and faced south-south-east to south-east in order to maximize morning sun exposure. Within the 1 and 2 yr fallow sites were 1700 trees ha$^{-1}$ that were pruned, but not slashed, at seeding time. Some had been planted, others had established themselves during previous fallow periods and had not been slashed. Most were *Albizia adinocephala* (locally known as Gavilancillo), a locally present leguminous tree of moderate stature (2 ½ m after slashing), but there were up to four other species present. These included the leguminous *Diphysa carthagenensis* Jacq. (Guachipelín), *Guazuma ulmifolia* Lam. (Guácimo) and *Litsea glaucescens* HBH (Laurel), the latter two being species that will bear high quality wood. The tree canopy of the 2 yr fallow site was more dense than that of the 1 yr fallow site, and its under-story growth was more sparse, with fewer grass species present. The fallow of the 3 yr site was characterized by even denser tree and shrub growth, and sparser under-story vegetation. *A. adinocephala*, about 6 m tall, were pruned but not slashed at seeding time, and were present at a density of 500 trees $ha^{-1}$.

Composite soil samples were taken from the top 10 cm for fertility analysis. Analysis was performed by the government soil laboratory at the University of Costa Rica, according to established procedures (Table A1). There were sufficient available nutrients for general field crop production at all sites, except that soil zinc content was low, and P, moderately low (Bertsch, 1995). In the 1 and 2 yr fallow sites, traces of yellowish or reddish C horizon were usually present at 26-33 cm. In the 3 yr fallow site, profile development was more variable—evidence of yellowish to greyish C horizon material was sometimes noted within 20 cm from the soil surface, and at other places had not been found by 33 cm.

The forest site occupied slopes running down to a creek. The soils were dark and relatively deep, sometimes without evidence of C horizon material even at 40 cm depths. The traces of C horizon that were present were yellowish and reddish in colour.

In the pasture site there was rarely evidence of the C horizon within the top 33 cm. It tended to be very stony, even at shallow depths. The grass had been grazed to ground level by horses at the start of the season, but had about 5 cm of growth at the final sampling time. There were some large trees in the pasture, but not in the area sampled.

### 2.1.4. Site histories

All three bean sites had been used for frijol tapado since before Felipe Arias, now in his late thirties, was born. His grandfather worked them carefully, until he took ill and was forced to hire help. Subsequent poor management led to weed encroachment, soil degradation and yield reduction. About fifteen years ago, a large, accidental fire consumed the vegetation of all of the sites, and the regrowth was dominated by grasses that were particularly detrimental to frijol tapado (F. Arias, personal communication).

Shortly afterward, Felipe and Maria del Carmen purchased the 1 and 2 yr fallow sites. Faced with weed-infested fields and compacted, infertile soils, they went to work, selecting and promoting weeds and trees that they knew were beneficent to frijol tapado, and working to eliminate the noxious ones. Within two years the fields showed significant improvement. These two bean fields had traditionally been planted every year. Felipe continued doing so, until the fallow period prior to the cropping season covered by the study, in the case of the 2 yr fallow site.

Felipe and Maria del Carmen purchased the 3 yr fallow site five years ago. Despite it particularly steep slope (92%), it had been planted to beans annually until that time. They left it in fallow for 21 months before seeding, and subsequently left it for 33 months, prior to the cropping season involved in this study.

The forest and pasture sites had been managed as such since before Felipe was born. They were purchased by him and Maria del Carmen around the time that the 1 and 2 yr fallow sites were. The forest had never been cleared, though there were occasional, accidental, under-story fires. The most recent burn occurred six years ago. The pasture had not been seeded during Felipe's life, and it sustained two horses on low-yielding native grasses at the time of the study.

The sites had never received fertilizer, synthetic or otherwise, nor had they been treated with pesticides.

## 2.2. Plant, mulch and soil sampling

The first bean site samples were taken about a month before slashing and seeding (August 2nd, 1999) and the first forest and pasture samples were taken on September 2nd, 1999.

Six randomly selected, replicate samples were taken from all but the 3 year fallow site, where four were taken. In the bean sites, the first step of each replicate sampling involved cutting and gathering of standing plant material from within a 0.25 $m^2$ quadrat, including an approximation of the contribution that the trees would make. Next, a 0.125 $m^2$ quadrat was placed within and mulch material was collected. Mulch was defined as any purely organic material on the soil surface. Soil samples were collected using an impact-type, split core sampler with a 33.5 cm depth capacity, and 5.08 cm diameter. The extracted core was divided into four sections: 0-5 cm , 5-10 cm, 10-x cm and x-30 cm. The depths of third and fourth sections were varied in order to attain relatively pure C horizon material, where possible, in the fourth (bottom) layer. The forest and pasture sites were sampled similarly, except that fresh plant material was not taken from the forest because of the difficulty of proper approximation, and neither fresh nor mulch material was present in the pasture (it had been closely cropped by the horses).

The second sampling, taken only from the bean sites, was performed approximately 2 ½ weeks after seeding (Table 2.2), when the seedling bean requirement for P was highest (G. Meléndez, personal communication). Six randomly selected replicate sample sets were taken from each site. Each included a collection of mulch material from within a 0.125 $m^2$ quadrat, and a sample of the top 5 cm of soil, taken with the impact core sampler. The 5 cm sampling depth was chosen based on evidence that the majority of bean plant roots, under frijol tapado, grow in the mulch, in the soil-mulch interface, and in the top 5 centimeters of soil (Matta et al., 1999).

The length of time and quantity of rainfall between seeding and the second sampling was recorded (Table 2.2). Rainfall was measured daily, with a funnel-collection vessel setup and a graduated cylinder. Degree days were not measured, because temperature fluctuations are minimal at that time of year in Acosta (G. Meléndez, personal communication).

The third and final samples were taken at harvest (late November-early December, depending on the respective dates that the fields were seeded). The procedure was similar to that used for the initial sampling. Six randomly selected replicate sample sets were taken from each bean site, which included samples of standing biomass, mulch biomass and soils to 30 cm. Differences in sampling methodology were as follows: 1. An approximated cutting of the trees' new growth was taken separately in the 1 and 2 yr fallow sites, for later P analysis and quantification. The 3 yr fallow site tree shoot growth had to be estimated because tree height and steep incline made sampling impossible. 2. Six bean plants, unthrashed, were taken from each bean site, and the 0.25 $m^2$ quadrant was used to calculate plant densities. 3. The third and fourth soil core depths were divided differently—the purity of the C horizon in the bottom section was less of a priority; instead divisions were made to ensure that both sections were as homogeneous as possible. 4. Soil samples were collected with enough precision so as to allow for bulk density calculations.

Six replicates were taken from the forest, as outlined above, without an approximation of standing biomass. Four replicates were taken from the pasture site. Each replicate included grass clippings from within a 0.125 $m^2$ quadrat, and soil samples.

## 2.3. Laboratory analysis

### 2.3.1. Biomass samples

Biomass samples were oven dried at 80°C for three days, beginning 4-5 hours after sampling. They were then separated into woody and leafy material (where appropriate), weighed, and chopped, using a laboratory mill, to pass a 1 mm screen. Woody samples and large volume leafy samples were then passed through a fine grinder with a 0.5 mm screen, while smaller leafy samples were further ground with a coffee-bean grinder. Samples were digested using hot $H_2SO_4$, with additions of $H_2O_2$, according to the methodology outlined by Thomas et al. (1967). Digestion solutions were analyzed for orthophosphate, colorimetrically, using a Technicon Auto Analyzer II™, using acidified ammonium molybdate and ascorbic acid for color development (Murphy and Riley, 1962; Technicon Instrument Corporation, 1973).

### 2.3.2. Soil samples—P extractions

Immediately after returning from the field, soil samples were mixed and homogenized by hand, and 3.00 g fresh soil sub-samples were measured into centrifuge tubes for a partial Hedley sequential extraction (Anion exchange membrane (AEM) Pi and $NaHCO_3$ Pi extractions) (Tiessen and Moir, 1993). This fresh soil extraction was performed because, according to Schlather (Personal communication), there is an unpredictable change in labile Pi when soil is dried. This is thought to arise from microbial death, lysis and subsequent P release (Tiessen et al., 1994b). A relatively large quantity of soil was used (3.00 g fresh soil compared with the recommended 0.5 g dry soil) because the soils were known to be low in P compared to temperate, fertilized soils (G. Meléndez, personal communication). Pi was determined in the extracts using the Murphy and Riley (1962) colorimetric method (acidified ammonium molybdate, ascorbic acid and antimony potassium tartrate) (Tiessen and Moir, 1993). Dry masses of sub-samples were calculated using the moisture content results from another sub-sample set which was dried at 80°C for 16 hours.

The soils that remained after these initial sub-samples were taken were dried at 55°C for 3 days, and then ground, with a mechanical flail grinder, to pass a 2 mm sieve. Rock fragments and organic material greater than 2 mm were kept only for the harvest sample set, to be weighed and accounted for in bulk density calculations. Soils were re-mixed, and 2.00 g sub-samples of dry soil were treated to a modified Hedley extraction (Tiessen and Moir, 1993). They were treated with $NaHCO_3$, NaOH, dilute HCl, and hot, concentrated HCl. An extract solution volume of 35.0 ml, rather than 30.0 ml, was used in each case. Duplicates were run for the first 40 samples, in order to confirm reliability. Extract solutions were split (except dilute HCl). One portion was acidified, flocculating SOM, so that it could be removed and solution Pi could be analyzed. The other was treated with ammonium persulfate and autoclaved, thus oxidizing SOM and transforming Po into Pi, allowing for the determination of Pt. Po was determined by subtracting Pi from Pt.

Instead of analyzing extract solutions using the manual method described by Tiessen and Moir (1993), solutions were run through a Technicon Auto Analyzer II™

using the methodology described for orthophosphate detection (Technicon Instrument Corporation, 1973). This involved a similar colorimetric approach, using acidified ammonium molybdate and ascorbic acid for colour development (Murphy and Riley, 1962). Sets of standards were prepared with extract solutions, and these were used for both colorimetric calibration and to check for absorption interference. Concentrated, HCl extracts were diluted because of interference, HCl Pi by a factor of 10, and HCl Pt by a factor of 4 (HCl Pt solution was already more dilute due to the associated preceding procedure).

According to the Murphy-Riley method outlined by Tiessen and Moir (1993), extract solutions are brought to volume in flasks. Using the auto-analyzer, this step was not performed, which presented concerns of variable rates of evaporation when solutions were autoclaved for Pt determination. The tubes of solution were covered, but they were allowed to vent so as to avoid explosion. To account for the possibility of variable evaporative loss, extract solutions were weighed after autoclaving (with the tube masses already known), so that their volumes could be precisely determined, and P concentrations adjusted accordingly (extract solution densities were determined by massing replicates of 1.000 ml after autoclaving).

Ammonium persulfate additions to Pt solutions, prior to autoclaving, were increased from the recommended 0.5 g, 0.6 g and 0.4 g, for $NaHCO_3$, NaOH and HCl, respectively (Tiessen and Moir, 1993), to 0.8 g, 1.0 g and 0.6 g, because of incomplete oxidation observed with the lower quantities.

The final step of the Hedley procedure ($H_2SO_4$) was not performed, for time management reasons. Instead, separate sub-samples of dry soil were finely ground (to

~0.18 mm) and digested using $HNO_3$ and $HClO_4$, according to the procedure of Olsen and Sommers (1982), outlined by O'Halloran (1993), to determine Pt.

### 2.3.3. Soil samples—light fraction soil organic matter

The light fraction (LF), which contains most soil macroorganic matter, is defined as the soil material with a density less than 2.0 g/cm$^3$ (soil mineral density is usually greater) (Gregorich and Ellert, 1993). To isolate LF, a density fractionation (floatation), using a sodium iodide solution (NaI) (S.G.=1.7), was performed on oven-dried soil that had been flail ground to pass a 2 mm sieve (Gregorich and Ellert, 1993).

The separated LF was treated with hot $H_2SO_4$, and additions of $H_2O_2$, according to the methodology outlined by Thomas et al. (1967), and colorimetric P analysis of the extract solution was performed using a Technicon Auto Analyzer II™ (Technicon Instrument Corporation, 1973).

## 2.4. Data analysis

Data sets were run through an analysis of variance (ANOVA), and least squared means were compared using a Tukey-adjusted least squared difference (LSD) test, with 95% confidence. Depth and time comparisons were made using concentration values (mg P kg$^{-1}$ oven-dry soil; g LF kg$^{-1}$ oven-dry soil). Site comparisons were made using quantified values per unit area (kg P ha$^{-1}$; Mg LF ha$^{-1}$).

Site comparisons were done with the harvest data set, where sampling procedures permitted bulk density calculations (including and excluding rock fragment content). With that information, the mass of soil contained by a particular volume at a particular depth could be calculated. For the topsoil, because of significant site differences in soil bulk density, it was most appropriate to base P comparisons on equivalent masses of soils (Ellert and Bettany, 1995). A standard mass of 52.0 g was chosen, based on the mass of the top 10 cm of soil in the core of the replicate with the lowest bulk density (excluding rock fragments >2 mm). Fractional P (or LF) values were then calculated by multiplying the P concentrations for relevant depths (0-5 cm, 5-10 cm) by the depth masses that were included in the 52.0 g. Values were adjusted so as to be expressed on a per hectare basis.

For 10-30 cm, similarity in site bulk densities deemed the more simple, fixed sampling depth approach appropriate for P quantification (Ellert and Bettany, 1995). The calculated masses of soil that were contained by the core (<2 mm), between the divisions peculiar to each sample (10-x cm and x-30cm), were multiplied by respective P concentrations (or LF content), and the sum of the products was calculated. Values were adjusted so as to be expressed on a per hectare basis.

Rock fragment content (%) and bulk density (Mg $m^{-3}$) values were compared over profile depth and between sites. Bulk densities were calculated with the masses of rock fragments (>2 mm) included, and also with those masses, and respective volumes (calculated using particle density of these rock fragments), excluded.

The oven-dry mass (Mg $ha^{-1}$) and P content (kg $ha^{-1}$) of above-ground plant material were analyzed in terms of changes during the cropping season and differences between sites.

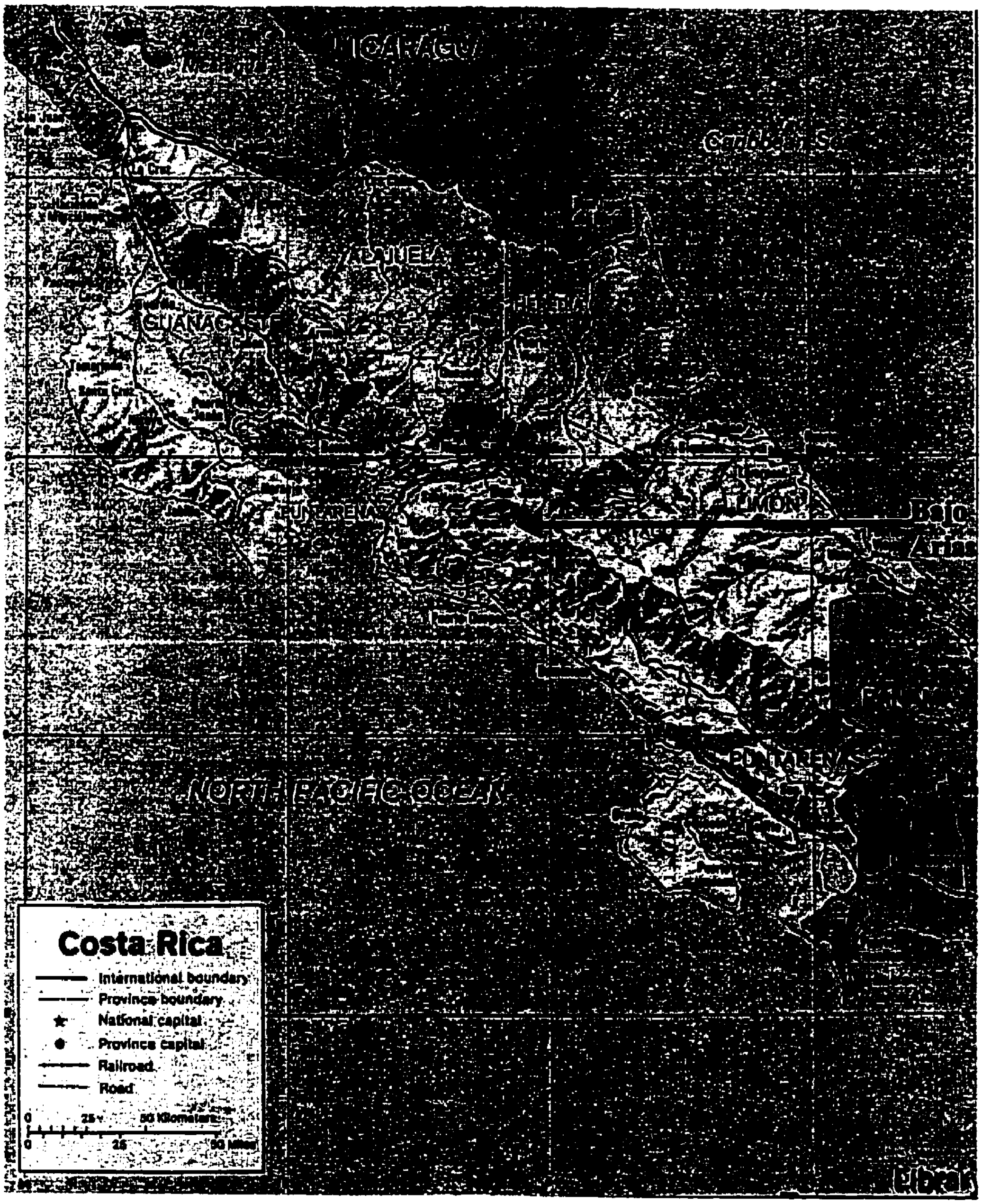


Fig. 2.1. Location of Bajo Arias, Acosta

Adapted from CIA map

Table 2.1. Physical characteristics of study sites

| Site | Area<br>($m^2$) | Slope<br>(%) | Altitude<br>(masl) | Slope Facing | Soil Temp.†<br>(°C) | Tree density<br>(trees $ha^{-1}$) |
|---|---|---|---|---|---|---|
| 1 yr fallow | 775 | 66 | 752 | SSE | 22.8 | 1700 |
| 2 yr fallow | 192 | 66 | 752 | SSE | 24.2 | 1700 |
| 3 yr fallow | 1250 | 92 | 791 | SE | n.d.‡ | 500 |
| Forest | 750 | 63 | 703 | SSE | n.d. | n.d. |
| Pasture | 800 | 65 | 806 | SSE | n.d. | n.d. |

† Mean of five replicates taken at 5 cm, before slashing, at 8:00 a.m.

‡ Not documented

Table 2.2. Time and rainfall between pre-slash and post-seed sampling times

| Site | Time<br>(days) | Rainfall<br>(mm) |
|---|---|---|
| 1 yr fallow | 18 | 318.8 |
| 2 yr fallow | 20 | 350.1 |
| 3 yr fallow | 17 | 228.5 |

# 3. RESULTS

## 3.1. Rock fragment volume and soil bulk density

The volume occupied by rock fragments (>2 mm) was notably low in top 5 cm of soil in the forest and 3 yr fallow sites, compared with the others, which were not different from each other (Fig. 3.1 and Table B1). At 5-10 cm, the rock fragment contents of these two sites were similar to those of the others (except for the 1 yr fallow site). Below 10 cm, the 1 yr fallow soil rock fragment volume was significantly greater than all other soils.

The soil bulk density of the forest (excluding rock fragments) was significantly less than all other sites at depth 0-5 cm, and it remained low at 5-10 cm (Fig. 3.2 and B2). The soil bulk density of the 1 yr fallow site was also low (though only significantly less than the 3 yr fallow soil). Soil bulk densities were greater at 5-10 cm, and below that depth the forest and 2 yr fallow soil bulk densities continued to increase, while those of the 1 yr and 3 yr fallow sites did not change, and that of the pasture decreased.

## 3.2. Initial fresh soil Pi extraction

Due to problems with the calibration curves, the values obtained from the initial, fresh soil extraction were not meaningful. It was observed, though, that Pi was extracted by the AEM, and that none was extracted by the $NaHCO_3$ treatment that followed.

## 3.3. Phosphorus concentrations over soil profiles

In all sites, P concentration decreased with depth (Table 3.1). Inorganic P concentrations decreased at 10 cm, and usually remained statistically unchanged below that depth. $NaHCO_3$ extractable Pi concentrations decreased between depth 1 (0-5 cm) and 2 (5-10 cm), any change below 10 cm being insignificant (except in the forest soil, where the statistically significant decline continues to depth 3 (10-x cm)). The decrease between depth 1 and 2 was particularly marked in the forest soil. NaOH Pi concentrations and dilute HCl Pi concentrations decreased to depth 3. The hot, concentrated HCl Pi extract concentration did not decrease significantly with soil depth in 2 yr fallow, 3 yr fallow and forest sites, and decreased slightly, but significantly, in the 1 yr fallow and pasture sites. Residual P concentrations decreased between depth 2 and 3 in the 1 yr and 2 yr fallow sites, and between depth 1 and 2 in the 3 yr fallow site. In the forest and pasture, residual P concentrations decreased with profile depth, particularly between depth 1 and 2, but also deeper into the profiles.

Organic P concentrations decreased with soil depth (Table 3.1). In the forest site, there were particularly marked decreases in $NaHCO_3$ and HCl Po concentrations at depth 2.

It is interesting to note that across all sites there was a tendency for P to accumulate in the topsoil, and that that accumulation occurred in both Pi and Po fractions. This contradicts research by Tiessen et al. (1994a). They found that an Oxisol supporting mixed forest vegetation had accumulations of carbon and Po in the topsoil, but that Pi became more concentrated with depth, as did total P. Agbenin and Tiessen (1994) found that a brush vegetated, hillside tropical Inceptisol had higher levels of Po and labile Pi (AEM, $NaHCO_3$ and NaOH) in the A horizon, and lower levels of non-labile Pi (conc. HCl and residual), compared with the B and C horizons.

## 3.4. Soil P concentrations during the cropping season

Almost all significant changes during the cropping season occurred in the Po fractions. In the top 5 cm of the 1 yr and 2 yr fallow soils there were significant decreases in NaOH Po concentrations 2 ½ weeks after seeding (Tables 3.2 and 3.3). Concentrations had increased at harvest time, to levels either equivalent to (2 yr site), or somewhat less than (1 yr site) initial levels. At 5-10 cm in the 1 and 2 yr fallow sites, NaOH Po concentrations were lower at harvest than at seeding (not significantly so for 2 yr fallow site). In the lower depths there were no measured differences in NaOH Po between seeding and harvest. The $NaHCO_3$ Po and HCl Po concentrations of the 1 and 2 yr fallow soils at 0-5 cm had increased 2 ½ weeks after seeding, and they remained higher at harvest (except 2 yr fallow $NaHCO_3$ Po, which did not increase significantly until harvest). 1 yr and 2 yr fallow $NaHCO_3$ Po and HCl Po concentrations were also greater at harvest at depths 5-10 cm and 10-x cm (except 2 yr HCl Po, which did not change).

In terms of Pi, concentrated HCl Pi changed in the 1 yr fallow soil, apparently increasing in the surface soil at the post-seeding sampling time, and decreasing at harvest, and also decreasing in the lower sections of the profile at the end of the season. In the 2 yr fallow soil, the only changes in Pi fractions occurred in the dilute HCl Pi concentration at 5-10 cm, which decreased by the end of the season, and residual P, which was greater at harvest at 10-x cm.

The 3 yr fallow site exhibited few discernable changes over the length of the season. In terms of Po, $NaHCO_3$ concentrations in the top 5 cm were significantly lower at harvest, compared with at post-seeding, and the combined Po fraction concentration at depth 2 was lower at harvest compared to at seeding (Table 3.4). Dilute HCl Pi increased over the season, though the change was only significant at 10-x cm.

The forest soils, unlike the 1 and 2 yr fallow sites, did not exhibit a change in NaOH Po concentration over the length of the season (Table 3.5). In the top 10 cm, $NaHCO_3$ Po and concentrated HCl Po were more concentrated by the end of the season, the rise in HCl Po being particularly impressive. Below 10 cm, HCl Po did not change, and $NaHCO_3$ Po increased at 10-x cm. An increase in residual P by harvest time, at 5-10 cm, was the only statistically significant Pi-related change during the cropping season.

In the pasture soil, the only statistically significant change in fractional P concentrations occurred at 10-x cm, where $NaHCO_3$ Po had increased by the end of the season (Table 3.6).

## 3.5. Relative sizes of site P pools

$NaHCO_3$ Pi was present in equivalent quantities in the topsoil (top 52.0 g) of all three cropped sites, with greater amounts in the forest soil, and none present in the pasture (Table 3.7). This fraction was the smallest, but its significance should not be underestimated, given that it is a labile pool and is representative of the P made available from other soil and biomass fractions. In terms of NaOH Pi, the 1 yr fallow, 2 yr fallow and pasture soils had equivalent amounts, and the 3 yr fallow and the forest soils had less than the 1 year fallow. The dilute HCl Pi extractions were highly variable within sites, and the only site difference was between the pasture, which had none present, and all of the other sites. The 1 yr fallow, 2 yr fallow, 3 yr fallow and forest soils all contained similar amounts of concentrated HCl Pi, and the pasture contained less (significantly less than the 1 and 2 yr fallow soils). The forest topsoil contained the most residual P, statistically more than all others.

All topsoils, except that of the 3 yr fallow, contained equivalent quantities of $NaHCO_3$ extractable Po (Table 3.7). The 2 yr fallow, 3 yr fallow, forest and pasture topsoils had similar amounts of NaOH Po, while the 1 yr fallow soil a larger pool. The forest topsoil had the largest HCl Po pool, and the pasture, the smallest. The bean sites fell in between these two extremes, with the 3 yr fallow soil yielding the largest quantity of HCl Po, the 2 yr the smallest, and the 1 yr fallow soil content was considered statistically equivalent to both.

Overall, the forest topsoil had significantly more P than any other site; the 1 yr fallow soil was also notably P rich (statistically more so than 3 yr fallow and pasture sites).

The forest subsoil (10-30 cm) contained more P than all other soils (which were statistically equivalent). This was largely a result of high Po levels (Table 3.8). It yielded the most NaOH and HCl extractable Po, statistically more, in both cases, than all other sites. The other sites had statistically equivalent NaOH Po values, and also HCl Po values (except for the somewhat larger 3 yr fallow subsoil HCl Po pool). In terms of $NaHCO_3$ Po, the bean subsoils had statistically equivalent quantities, the pasture soil had more, and the forest soil had more than only the 3 yr fallow site.

As in the topsoil, the forest subsoil was notably high in $NaHCO_3$ Pi, though it had statistically more than only the 2 yr fallow and pasture sites (Table 3.8). $NaHCO_3$ Pi quantities were statistically equivalent in all other subsoils. The 3 yr fallow subsoil had the largest NaOH Pi pool, though it was only significantly greater than that of the 1 yr fallow site. All other subsoils had statistically equivalent NaOH Pi pools. The 3 yr fallow subsoil also had a notably large dilute HCl Pi pool, larger than all but the forest. The others had dilute HCl Pi pools of similar sizes. In terms of concentrated HCl Pi, the 1 yr fallow and the pasture subsoils yielded less than the forest and 2 yr fallow sites did. The 3 yr fallow content was statistically equivalent to all sites. As for residual P, the forest subsoil contained much more than any of the others, and the pasture and 2 yr fallow sites contained more than the 1 and 3 yr fallow sites.

## 3.6. Light fraction

All sites exhibited a significant decrease in LF (g $kg^{-1}$ oven-dry soil) between depth 1 and depth 2, with an insignificant (3 yr fallow, forest, pasture), or a slight, significant decrease (1 and 2 yr fallow) below 10 cm (Fig. 3.3 and Table B3). The forest soil exhibited a particularly large decrease in LF content from depth 1 to depth 2 . Light fraction P concentrations (mg $kg^{-1}$ oven-dry soil) behaved similarly, with only the 3 yr fallow site exhibiting a significant decrease below 10 cm (Fig. 3.3 and Table B4).

Over the cropping season, the 1 yr fallow, 3 yr fallow and pasture soils experienced no significant change in LF or LF P at any depth. The LF in the top 5 cm of forest and 2 yr fallow soil increased significantly (Fig. 3.4 and Table B5). The forest LF P at 5-10 cm increased significantly.

The topsoil of the forest site contained the largest quantity of LF and LF P (Table 3.9). There were no differences between cropped sites. The pasture topsoil had significantly less LF than the forest and 1 yr fallow sites. There were no differences between sites in LF or LF P in the subsoil (Table B9).

## 3.7. Above-ground biomass

Before slashing and seeding, the 1 and 2 yr fallow sites apparently had equivalent quantities of standing biomass material and P (Table 3.10); but the significant increase in above-ground biomass in the 2 yr site, at the post-seed sampling time (Table 3.11) suggests that its tree component was initially under-assessed. Assuming the post-seed sampling time to be a more accurate representation, above-ground biomass may have increased with fallow period length, but the only statistical differences were between the 1 and 3 yr fallow leafy biomasses, and between the 3 yr fallow woody and other bean site woody biomasses (Table 3.12). Pre-slash mulch layers were not statistically different. The 3 yr fallow site mulch, though numerically greater than the 1 and 2 yr fallow sites, was highly variable and thus not different from the others.

The biomass values recorded for the 3 yr fallow site 2 ½ weeks after slashing and seeding do not contradict the pre-slash standing biomass numbers, nor do the 1 yr fallow site's. It can thus be concluded that the 3 yr fallow site had approximately the same quantity of standing leafy material as the 1 yr site, and more woody material. The aforementioned difference between the two sites, in terms of leafy biomasses, is a result of the cumulative effects of pre-slash standing leafy and mulch leafy material.

Standing biomass was not accounted for in the forest, but the forest floor mulch layer alone contained as much P as did the entirety of the above-ground biomass in the cropped sites (not including dispersed tree trunks).

There were no detectable losses in P from above-ground biomass 2 ½ weeks after seeding (3.12). This result is not reliable because of the aforementioned underestimation of tree biomass. Site differences in mulch biomass and P, 2 ½ weeks after seeding, were minor (statistically), partially as a result of high ground cover variability (Table 3.12). The 3 yr fallow site did have statistically more mulch than the 1 yr fallow site.

By harvest, the P contents of the leafy mulch of all three fallow sites and the forest had decreased significantly from those at the post-seed sampling time (Tables 3.13). The woody matter P did not change significantly over the length of the season at any of the sites. The mulch biomass of the 3 yr fallow site decreased particularly substantially (Table 3.11); initially the largest of the bean site mulches, by the end it was the smallest (though it was only significantly smaller than the 1 yr fallow site) (Table 3.14). Of the bean sites, the 3 yr fallow site had the most new standing growth (excluding the bean crop and tree growth). *A. adinocephala* regrowth was considerable in the 1 and 2 yr fallow sites, and shoots had high P contents (Table 3.15) compared with the overall fresh leafy material P content before slashing (Table 3.10).

Replicates were not taken from the bean crop itself, so yield values have not been analyzed statistically. Bean yields at the 1 and 2 yr fallow sites were greater than at the 3 yr fallow site (Table 3.15).

The total above-ground biomass P in the 1 and 2 yr fallow sites was larger at harvest than before slashing (Table 3.16) and had not changed in 3 yr fallow site.

By the end of the cropping season the forest mulch layer P pool was smaller than at the beginning (Table 3.13), but it was still larger those of the other sites (Table 3.14). The forest standing biomass was not accounted for. The pasture had visibly more vegetative material by the end of the season than it had at the beginning.

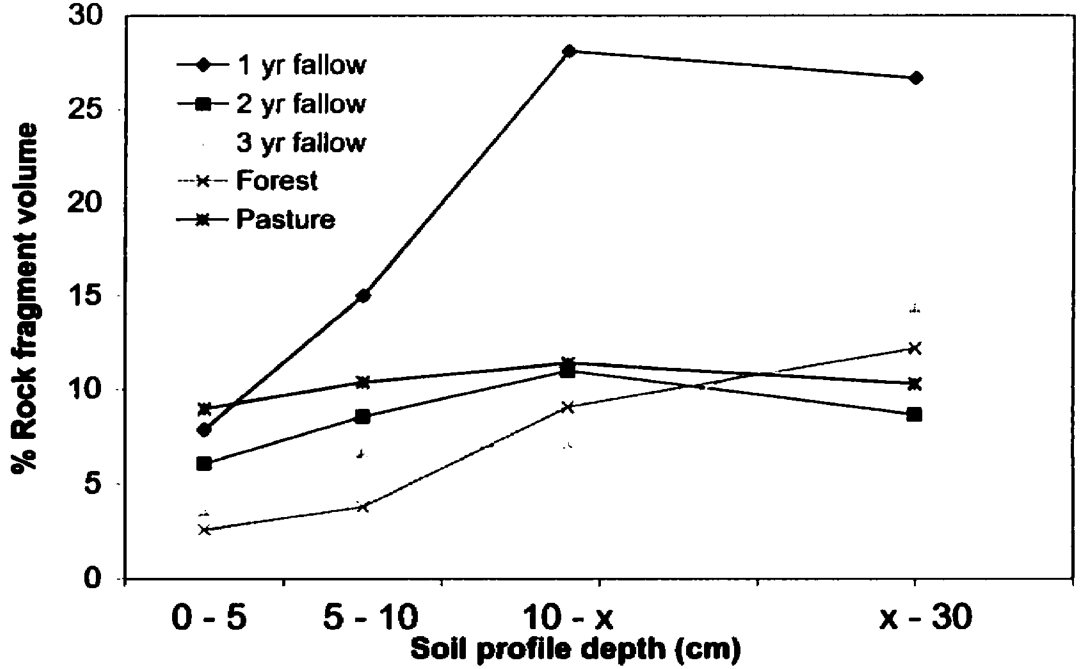


Fig. 3.1. Rock fragment (>2 mm) content of the soils (% volume)

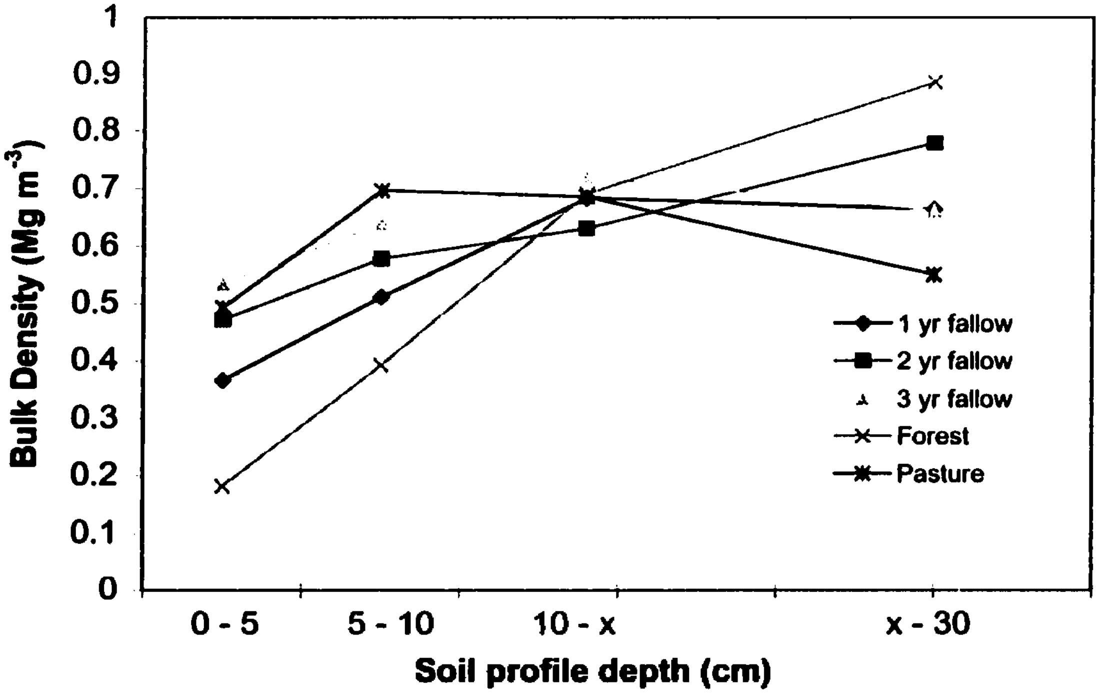


Fig. 3.2. Soil bulk density (excluding rock fragments (>2 mm))

Table 3.1. Phosphorus concentrations of soil

| Depth | Pi | | | | Po | | | Residual P |
|---|---|---|---|---|---|---|---|---|
| | $NaHCO_3$ | NaOH | DilHCl | HCl | $NaHCO_3$ | NaOH | HCl | |
| (cm) | mg kg$^{-1}$ | | | | | | | |
| **1 yr fallow** | | | | | | | | |
| 0-5 | 1.85b†‡ | 33.8c | 19.9c | 154b | 18.2d | 127c | 33.1c | 114b |
| 5-10 | 0.22a | 24.5b | 11.2b | 141b | 13.4c | 117c | 21.0b | 94.6b |
| 10-x | 0.02a | 15.6a | 2.94a | 119a | 8.10b | 80.4b | 13.5a | 49.4a |
| x-30 | 0.000a | 11.5a | 0.73a | 105a | 2.68a | 50.6a | 7.14a | 30.1a |
| **2 yr fallow** | | | | | | | | |
| 0-5 | 0.61b | 23.6c | 11.7c | 157a | 16.8d | 104c | 21.0c | 77.8b |
| 5-10 | 0.03a | 16.6b | 4.58b | 137a | 13.2c | 91.0c | 14.8b | 68.6b |
| 10-x | 0.00a | 11.2a | 1.14a | 138a | 5.24b | 62.7b | 9.85b | 48.8a |
| x-30 | 0.00a | 7.82a | 0.45a | 154a | 0.00a | 42.8a | 1.16a | 42.0a |
| **3 yr fallow** | | | | | | | | |
| 0-5 | 2.96b | 21.5b | 25.4b | 131a | 11.0c | 78.8b | 44.4c | 77.4b |
| 5-10 | 0.67a | 19.2ab | 20.5ab | 126a | 6.35b | 70.0b | 35.6bc | 45.0a |
| 10-x | 0.20a | 15.3a | 11.1a | 112a | 3.16ab | 54.0a | 25.1ab | 41.6a |
| x-30 | 0.07a | 15.4a | 8.12a | 106a | 1.95a | 41.4a | 16.4a | 21.8a |
| **Forest** | | | | | | | | |
| 0-5 | 9.42c | 22.6b | 27.6b | 125a | 25.5c | 93.8b | 81.5c | 181c |
| 5-10 | 3.17b | 18.6ab | 17.9ab | 128a | 12.6b | 83.0ab | 55.5b | 137b |
| 10-x | 0.66a | 15.6a | 10.2a | 114a | 5.40a | 69.7ab | 40.1ab | 116ab |
| x-30 | 0.40a | 13.7a | 11.8a | 104a | 2.79a | 56.2a | 26.3a | 92.9a |
| **Pasture** | | | | | | | | |
| 0-5 | 0.18b | 22.6b | 3.71b | 104b | 19.9c | 99.5b | 16.3b | 108c |
| 5-10 | 0.00a | 18.2b | 2.27ab | 91.5ab | 16.7c | 88.1b | 7.94a | 86.3b |
| 10-x | 0.00a | 11.5a | 1.01a | 85.2ab | 8.80b | 63.5a | 4.30a | 64.2a |
| x-30 | 0.00a | 11.6a | 0.66a | 81.3a | 2.80a | 51.4a | 2.33a | 56.6a |

† Least squared means of all samples, calculated by SAS

‡ Numbers in each column, within a given treatment, and followed by the same letter, are not significantly different (Tukey LSD, $P<0.05$)

Table 3.2. Changes in P concentrations in the 1 yr fallow soil during the cropping season

| Time | Pi | | | | Po | | | Residual P |
|---|---|---|---|---|---|---|---|---|
| | $NaHCO_3$ | NaOH | Dil. HCl | HCl | $NaHCO_3$ | NaOH | HCl | |
| | mg kg$^{-1}$ | | | | | | | |
| | | | | | **0-5 cm** | | | |
| Pre-slash | 1.40a†‡ | 33.6a | 19.4a | 159a | 13.7a | 136c | 22.8a | 83.8a |
| Post-seed | 2.93a | 36.1a | 20.0a | 178b | 21.6b | 99.5a | 42.3b | 142a |
| Harvest | 2.19a | 34.0a | 21.1a | 149a | 22.0b | 118b | 44.1b | 117a |
| | | | | | **5-10 cm** | | | |
| Pre-slash | 0.00a | 25.0a | 10.5a | 148a | 9.53a | 128b | 16.9a | 76.0a |
| Harvest | 0.33a | 23.9a | 11.0a | 134a | 16.9b | 105a | 30.2b | 79.1a |
| | | | | | **10-x cm** | | | |
| Pre-slash | 0.00a | 14.5a | 2.56a | 116a | 4.44a | 83.4a | 5.76a | 42.0a |
| Harvest | 0.03a | 16.7a | 3.74a | 118a | 12.0b | 77.4a | 21.2b | 31.4a |
| | | | | | **x- 30 cm** | | | |
| Pre-slash | 0.00a | 11.4a | 0.948a | 119b | 1.37a | 51.8a | 4.71a | 24.5a |
| Harvest | 0.00a | 10.7a | 0.572a | 90.0a | 4.36b | 49.5a | 9.57a | 8.80a |

† Least squared means calculated by SAS

‡ Numbers in each column, at a given soil depth, followed by the same letter, are not significantly different (Tukey LSD, $P<0.05$)

Table 3.3. Changes in P concentrations in the 2 yr fallow soil during the cropping season

| Time | Pi | | | | Po | | | Residual P |
|---|---|---|---|---|---|---|---|---|
| | $NaHCO_3$ | NaOH | Dil. HCl | HCl | $NaHCO_3$ | NaOH | HCl | |
| | mg $kg^{-1}$ | | | | | | | |
| **0-5 cm** | | | | | | | | |
| Pre-slash | 0.240a†‡ | 23.3a | 12.3a | 158a | 12.4a | 115b | 9.28a | 64.6a |
| Post-seed | 0.677a | 24.7a | 8.99a | 152a | 16.3ab | 70.4a | 23.0b | 88.6a |
| Harvest | 0.975a | 24.4a | 11.3a | 152a | 21.2b | 88.6b | 30.3b | 80.6a |
| **5-10 cm** | | | | | | | | |
| Pre-slash | 0.003a | 16.1a | 6.26b | 145a | 9.69a | 103a | 5.57a | 54.2a |
| Harvest | 0.058a | 16.0a | 2.89a | 129a | 16.8b | 77.2a | 22.3b | 74.9a |
| **10-x cm** | | | | | | | | |
| Pre-slash | 0.00a | 11.5a | 2.12a | 142a | 3.20a | 73.4a | 2.64a | 22.0a |
| Harvest | 0.002a | 10.8a | 0.165a | 133a | 7.20b | 50.4a | 15.5a | 68.6b |
| **x-30 cm** | | | | | | | | |
| Pre-slash | 0.00a | 7.97a | 0.00a | 138a | 0.00a | 53.8a | 1.23a | 28.0a |
| Harvest | 0.00a | 8.03a | 0.00a | 157a | 0.00a | 31.6a | 4.14a | 45.4a |

† Least squared means calculated by SAS

‡ Numbers in each column, at a given soil depth, followed by the same letter, are not significantly different (Tukey LSD, $P<0.05$)

Table 3.4. Changes in P concentrations in the 3 yr fallow soil during the cropping season

| Time | Pi | | | | Po | | | Residual P |
|---|---|---|---|---|---|---|---|---|
| | $NaHCO_3$ | NaOH | Dil. HCl | HCl | $NaHCO_3$ | NaOH | HCl | |
| | mg kg$^{-1}$ | | | | | | | |
| | | | | | **0-5 cm** | | | |
| Pre-slash | 3.59a†‡ | 21.0a | 21.5a | 125a | 13.2ab | 74.6a | 42.6a | 110a |
| Post-seed | 2.96a | 26.4a | 8.06a | 148a | 14.9b | 75.2a | 46.0a | 107a |
| Harvest | 2.06a | 23.0a | 26.8a | 132a | 9.40a | 85.8a | 43.4a | 110a |
| | | | | | **5-10 cm** | | | |
| Pre-slash | 1.09a | 16.8a | 12.6a | 123a | 7.77a | 75.6a | 38.5a | 46.2a |
| Harvest | 0.28a | 22.0a | 23.8a | 126a | 5.51a | 70.8a | 31.9a | 46.2a |
| | | | | | **10-x cm** | | | |
| Pre-slash | 0.31a | 14.1a | 10.2a | 116a | 4.25a | 58.5a | 25.1a | 62.5a |
| Harvest | 0.15a | 18.5a | 13.3b | 133a | 2.48a | 55.9a | 24.4a | 62.5a |
| | | | | | **x-30 cm** | | | |
| Pre-slash | 0.13a | 13.8a | 2.68a | 95.5a | 3.76a | 55.1a | 14.8a | 6.75a |
| Harvest | 0.13a | 18.7a | 11.2a | 110a | 0.00a | 40.5a | 15.5a | 2.52a |

† Least squared means calculated by SAS

‡ Numbers in each column, at a given depth, followed by the same letter, are not significantly different (Tukey LSD, $P<0.05$)

Table 3.5. Changes in P concentrations in the forest soil during the cropping season

| Time | Pi | | | | Po | | | Residual P |
|---|---|---|---|---|---|---|---|---|
| | $NaHCO_3$ | NaOH | Dil. HCl | HCl | $NaHCO_3$ | NaOH | HCl | |
| | mg $kg^{-1}$ | | | | | | | |
| | | | | | **0-5 cm** | | | |
| Pre-slash | 8.06a†‡ | 23.1a | 29.6a | 111a | 22.0a | 101a | 66.0a | 149a |
| Harvest | 10.8a | 22.1a | 25.7a | 138a | 31.4b | 86.6a | 96.7b | 209a |
| | | | | | **5-10 cm** | | | |
| Pre-slash | 3.31a | 18.5a | 22.3a | 112a | 11.3a | 79.1a | 41.3a | 103a |
| Harvest | 3.03a | 18.7a | 13.5a | 144a | 14.9b | 86.7a | 69.8b | 173b |
| | | | | | **10-x cm** | | | |
| Pre-slash | 0.80a | 13.5a | 13.8a | 93.8a | 3.85a | 59.2a | 28.5a | 91.1a |
| Harvest | 0.52a | 16.5a | 5.12a | 135a | 8.23a | 80.2a | 53.5a | 141a |
| | | | | | **x-30 cm** | | | |
| Pre-slash | 0.76a | 11.9a | 11.7a | 80.4a | 1.76a | 39.7a | 12.6a | 81.4a |
| Harvest | 0.00a | 14.9a | 9.80a | 127a | 5.14a | 72.8a | 41.1a | 123a |

† Least squared means calculated by SAS

‡ Numbers in each column, at a given soil depth, followed by the same letter, are not significantly different (Tukey LSD, $P<0.05$)

Table 3.6. Changes in P concentrations in the pasture soil during the cropping season

| Time | Pi | | | | Po | | | Residual P |
|---|---|---|---|---|---|---|---|---|
| | $NaHCO_3$ | NaOH | Dil. HCl | HCl | $NaHCO_3$ | NaOH | HCl | |
| | mg $kg^{-1}$ | | | | | | | |
| **0-5 cm** | | | | | | | | |
| Pre-slash | 0.27a†‡ | 22.8a | 4.01a | 112a | 19.1a | 88.8a | 18.4a | 106a |
| Harvest | 0.00a | 25.6a | 0.00a | 107a | 20.2a | 83.4a | 9.62a | 111a |
| **5-10 cm** | | | | | | | | |
| Pre-slash | 0.00a | 18.4a | 2.02a | 96.2a | 14.9a | 76.5a | 9.38a | 81.5a |
| Harvest | 0.00a | 22.8a | 2.89a | 106a | 18.1a | 72.6a | 5.91a | 93.6a |
| **10-x cm** | | | | | | | | |
| Pre-slash | 0.00a | 11.4a | 0.371a | 93.7a | 5.49a | 46.8a | 4.38a | 59.2a |
| Harvest | 0.00a | 18.3a | 0.00a | 89.8a | 13.0b | 78.4a | 5.43a | 66.8a |
| **x-30 cm** | | | | | | | | |
| Pre-slash | 0.00a | 11.3a | 0.323a | 86.0a | 1.66a | 36.9a | 4.68a | 51.7a |
| Harvest | 0.00a | 19.6a | 0.612a | 86.8a | 3.98a | 49.1a | 2.28a | 45.1a |

† Least squared means calculated by SAS

‡ Numbers in each column, at a given soil depth, followed by the same letter, are not significantly different (Tukey LSD, P<0.05)

Table 3.7. Fractional P content of site topsoils† at harvest

| Site | Pi | | | | Po | | | Residual P | Po |
|---|---|---|---|---|---|---|---|---|---|
| | $NaHCO_3$ | NaOH | Dil HCl | HCl | $NaHCO_3$ | NaOH | HCl | | |
| | kg $ha^{-1}$ | | | | | | | | (%) |
| 1 yr fallow | 0.486ab‡§ | 7.53b | 4.87ab | 37.3b | 5.28b | 29.5b | 9.63bc | 27.8b | 35.9 |
| 2 yr fallow | 0.212ab | 6.12ab | 2.53ab | 38.0b | 5.28b | 22.4ab | 7.47b | 21.0b | 34.5 |
| 3 yr fallow | 0.675b | 5.48a | 7.11b | 33.0ab | 2.26a | 19.7a | 12.0c | 28.3b | 36.6 |
| Forest | 1.31c | 4.93a | 3.39ab | 36.5ab | 4.83b | 22.0a | 20.3d | 47.2c | 32.7 |
| Pasture | 0.00a | 6.28ab | 0.00a | 27.2a | 5.28b | 19.6ab | 2.27a | 26.1b | 33.4 |

† Top 52.0 g (256 Mg $ha^{-1}$)

‡ Least squared means calculated by SAS

§ Numbers in each column with the same letter are not significantly different (Tukey LSD, $P<0.05$)

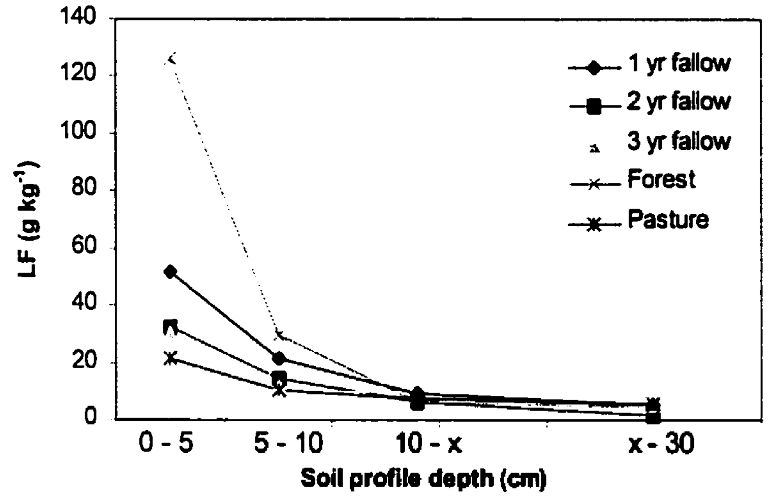
Table 3.8. Fractional P content of site subsoils† at harvest

| Site | Mass of soil in core | Pi |  |  |  | Po |  |  | Residual P | Po |
|---|---|---|---|---|---|---|---|---|---|---|
|  |  | $NaHCO_3$ | NaOH | Dil HCl | HCl | $NaHCO_3$ | NaOH | HCl |  |  |
|  | (g) | kg ha$^{-1}$ |  |  |  |  |  |  |  | (%) |
| 1 yr fallow | 180a‡§ | 0.0350ab | 11.7a | 1.75a | 81.3a | 5.60ab | 54.1a | 12.3a | 12.4a | 40.9 |
| 2 yr fallow | 245a | 0.00a | 11.1ab | 0.128a | 175b | 4.28ab | 45.0a | 11.7a | 58.6b | 19.9 |
| 3 yr fallow | 260a | 0.0510ab | 25.0b | 28.3b | 148ab | 3.18a | 70.4a | 30.7b | 35.3ab | 35.7 |
| Forest | 276a | 0.300b | 21.2ab | 5.62ab | 177b | 7.53bc | 102b | 62.6c | 189c | 29.6 |
| Pasture | 232a | 0.00a | 18.8ab | 0.00a | 101a | 9.71c | 58.8ab | 2.16a | 55.2b | 28.4 |

† 20-30 cm

‡ Least squared means calculated by SAS

§ Numbers in each column with the same letter are not significantly different (Tukey LSD, $P<0.05$)



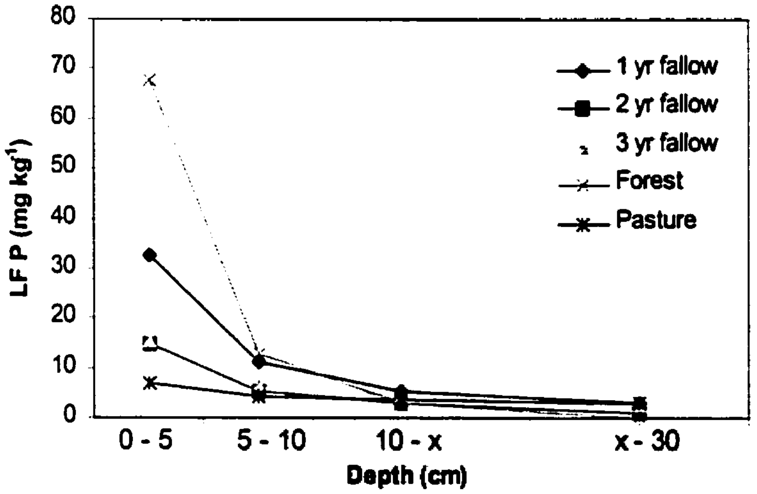


Fig. 3.3. Light fraction SOM and LF P content in soil profiles at different sites

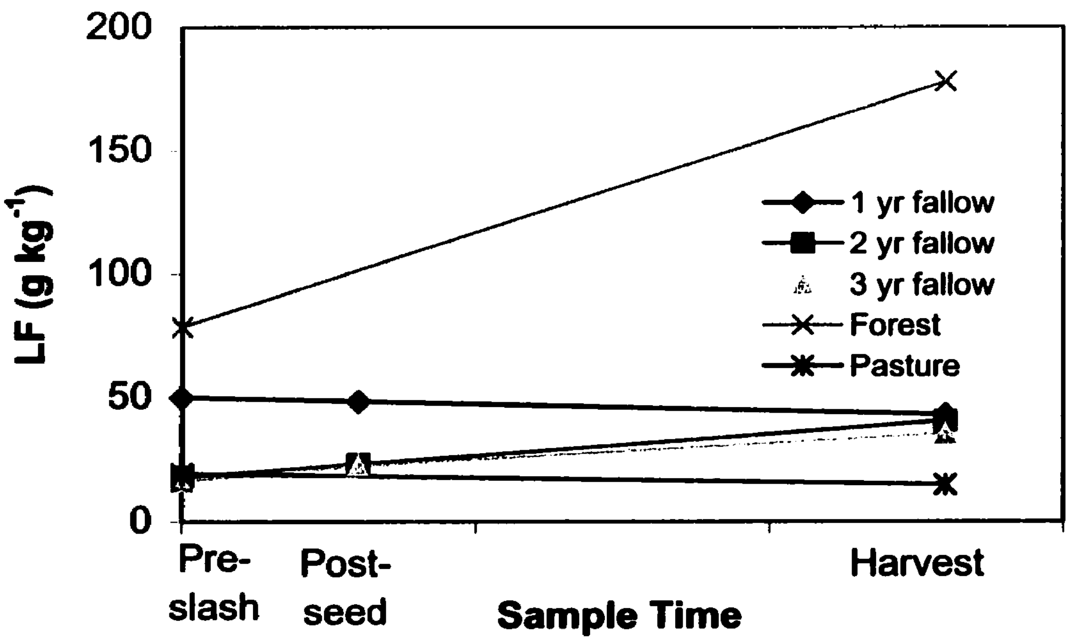


Fig. 3.4. Light fraction SOM at 0-5 cm depth during the cropping season at different sites

Table 3.9. Light fraction SOM and LF P in different site topsoils† at harvest

| Site | LF | P |
|---|---|---|
| | (Mg ha$^{-1}$) | (kg ha$^{-1}$) |
| 1 yr fallow | 11.9a‡§ | 7.14b |
| 2 yr fallow | 9.43a | 4.47ab |
| 3 yr fallow | 9.82a | 4.18ab |
| Forest | 25.2b | 13.3c |
| Pasture | 3.81a | 1.53a |

† Top 52.0 g

‡ Least squared means calculated by SAS

§ Numbers in each column with the same letter are not significantly different (Tukey LSD, $P<0.05$)

Table 3.10. Above-ground biomass and P before seeding

| Site | Biomass | | | P | | |
|---|---|---|---|---|---|---|
| | Standing Leafy | Standing Woody¶ | Mulch Leafy | Standing Leafy | Standing Woody¶ | Mulch Leafy |
| | Mg $ha^{-1}$ | | | kg $ha^{-1}$ | | |
| 1 yr fallow | 2.41a†‡ | 0.00a | 1.98a | 3.08a | 0.00a | 4.05a |
| 2 yr fallow | 1.96a | 0.403ab | 2.21a | 2.69a | 0.551b | 3.32a |
| 3 yr fallow | 2.52a | 2.80b | 8.96a | 3.95a | 2.52c | 9.97b |
| Forest | n.d.§ | n.d. | 21.1b | n.d. | n.d. | 21.46b |

† Least squared means calculated by SAS

‡ Numbers in each column with the same letter are not significantly different (Tukey LSD, $P<0.05$)

§ Not determined

¶ Not including dispersed tree trunks

Table 3.11. Changes to the slashed biomass during the cropping season

| Time | 1 yr fallow | 2 yr fallow | 3 yr fallow | Forest‡ |
|---|---|---|---|---|
| | | Mg ha$^{-1}$ | | |
| Pre-slash | 6.32a§¶ | 6.50a | 16.2b | 20.0a |
| Post-seed | 8.93a | 16.5b | 22.6b | n.d.# |
| Harvest† | 6.58a | 5.78a | 4.90a | 7.90a |

† Harvest values represent the mulch material that remained at the end of the season

‡ Mulch P only

§ Least squared means calculated by SAS

¶ Numbers in each column with the same letter are not significantly different (Tukey LSD, $P<0.05$)

# Not determined

Table 3.12. Mulch biomass and P 2½ weeks after seeding

| Site | Biomass | | P | |
|---|---|---|---|---|
| | Leafy | Woody | Leafy | Woody |
| | ——Mg ha$^{-1}$—— | | ——kg ha$^{-1}$—— | |
| 1 yr fallow | 6.18a†‡ | 0.00a | 8.93a | 0.00a |
| 2 yr fallow | 11.1ab | 1.83a | 8.05a | 0.809b |
| 3 yr fallow | 17.1b | 5.95b | 14.1a | 3.47c |

† Least squared means calculated by SAS

‡ Numbers in each column with the same letter are not significantly different (Tukey LSD, $P<0.05$)

Table 3.13. Changes to the slashed biomass P during the cropping season

| Time | 1 yr fallow | | 2 yr fallow | | 3 yr fallow | | Forest |
|---|---|---|---|---|---|---|---|
| | Leaf | Wood | Leaf | Wood | Leaf | Wood | Total‡ |
| | | | | kg $ha^{-1}$ | | | |
| Pre-slash | 7.50b§¶ | 0.00a | 6.07ab | 0.562a | 13.4b | 1.88a | 21.7b |
| Post-seed | 8.64b | 0.00a | 8.42b | 0.514a | 14.0b | 3.45a | n.d.# |
| Harvest† | 3.72a | 2.00b | 2.23a | 1.40a | 2.12a | 0.786a | 6.16a |

† Harvest values represent the P that remained in the mulch at the end of the season

‡ Mulch P only

§ Least squared means calculated by SAS

¶ Numbers in each column with the same letter are not significantly different (Tukey LSD, P<0.05)

# Not determined

Table 3.14. Above-ground biomass and P at harvest†

| Site | Biomass | | | P | | |
|---|---|---|---|---|---|---|
| | Standing Leafy | Mulch Leafy | Mulch Woody | Standing Leafy | Mulch Leafy | Mulch Woody |
| | Mg ha$^{-1}$ | | | kg ha$^{-1}$ | | |
| 1 yr fallow | 0.912ab‡§ | 3.77c | 2.76a | 1.69ab | 3.84cd | 2.25b |
| 2 yr fallow | 0.600a | 2.79bc | 2.17a | 0.954a | 2.37bc | 1.34b |
| 3 yr fallow | 1.27bc | 1.69b | 2.02a | 2.58b | 1.55b | 1.64b |
| Forest | n.d.¶ | 6.83d | 2.81a | n.d. | 5.12d | 1.43b |
| Pasture | 1.71c | 0.00a | 0.00a | 2.00ab | 0.00a | 0.00a |

† Not including crop or trees

‡ Least squared means calculated by SAS

§ Numbers in each column with the same letter are not significantly different (Tukey LSD, $P<0.05$)

¶ Not determined

Table 3.15. Bean yield, trash, and fresh tree shoot biomass and P content at harvest

| Site | Biomass | | | P content | | | % P in tree shoots |
|---|---|---|---|---|---|---|---|
| | Bean yield | Trash | Tree† | Bean yield | Trash | Tree† | |
| | Mg ha$^{-1}$ | | | kg ha$^{-1}$ | | | (%) |
| 1 yr fallow | 3.38 | 2.88 | 0.370 | 14.69 | 2.43 | 1.71 | 0.462 |
| 2 yr fallow | 3.21 | 2.30 | 0.292 | 11.93 | 1.77 | 0.793 | 0.272 |
| 3 yr fallow | 1.60 | 1.49 | 0.109 | 6.83 | 1.50 | 0.502 | n.d.‡ |

† *A. adinocephala* fresh shoot material

‡ Not determined—3 year fallow tree material was calculated based on the 1 yr fallow site tree shoot P concentration

Table 3.16. Changes in total above-ground P during the cropping season

| Time | 1 yr fallow† | 2 yr fallow† | 3 yr fallow† | Forest‡ | Pasture |
|---|---|---|---|---|---|
| | kg ha$^{-1}$ | | | | |
| Pre-slash | 7.88a§¶ | 6.57a | 15.4a | 21.7b | n.d. |
| Post-seed | 8.51a | 9.61a | 17.1a | n.d.# | n.d. |
| Harvest | 25.6b | 19.3b | 14.4a | 6.16a | 1.39 |

† Not including dispersed tree trunks

‡ Not including trees

§ Least squared means calculated by SAS

¶ Numbers in each column with the same letter are not significantly different (Tukey LSD, P<0.05)

# Not determined

# 4. DISCUSSION

## 4.1. Relative P fertility of the soils in this study

The relative P fertility of these soils can be assessed by comparing their concentration values with those of other soils. This approach is imperfect, since it does not take into account soil bulk density and its effects on nutrient concentration, but it does offer a common unit for comparison (Ellert and Bettany, 1995). Pt in the top 5 cm of these soils ranged from 371 to 510 mg kg$^{-1}$. Tiessen and Moir (1993) present values of 503 mg kg$^{-1}$ and 745 mg kg$^{-1}$ for Canadian Mollisol Pt concentrations, and 127 mg kg$^{-1}$ and 138.5 mg kg$^{-1}$ for Brazilian Oxisols. These suggest that the Pt pools of this study's soils were relatively large. It is interesting to note that Agbenin and Tiessen (1994) studied a Brazilian Inceptisol with a Pt concentration of 2340 mg kg$^{-1}$. This high value illustrates the effect of parent material on the P content of the soil (parent material in that study was syenite, with a concentration of 5500 mg P kg$^{-1}$).

The above cited Mollisols had combined AEM and $NaHCO_3$ fractions of 27 and 95 mg kg$^{-1}$, respectively, while the Oxisols contained 7 and 7.5 mg kg$^{-1}$ (Tiessen and Moir, 1993). The values of this study's soils ranged from 0.240-10.8 mg kg$^{-1}$ in the top 5 cm. In other words, they had relatively small labile P pools. Dilute HCl Pi concentrations, which represent apatite Pi, were 216 and 218 mg kg$^{-1}$ for the Mollisols, and 2 and 3 mg kg$^{-1}$ for the Oxisols. In this study, values were 4.01-29.6 mg kg$^{-1}$, indicating that substantial weathering had occurred.

In terms of recalcitrant Pi, 9-13% of Mollisol P, and 60-63% of Oxisol P, was included in the concentrated HCl and $H_2SO_4$ extracts (Tiessen and Moir, 1993). In this study, 52-62% of P was concentrated in those fractions.

Po contents in the top 5 cm of these soils accounted for 34-37% of Pt (when calculated on a concentration basis). According to Sanchez (1976), in weak to moderately weathered soils, 20-50 % of Pt is in organic form, whereas Po may account for 60-80% of Pt in highly weathered soils. The examples of Mollisols cited by Tiessen and Moir (1993) support this, but the Oxisols do not (only 15-22% Po).

This preliminary comparison of soils gives evidence that, in spite of their moderate profile development, the Inceptisols in this study had experienced significant weathering—low dilute HCl Pi, high fixed Pi and low labile Pi concentrations, along with relatively large Po pools, all support this hypothesis. However, total P concentrations were relatively high, which indicates that P losses from the soil profile have been low, or that parent material P concentration was high.

## 4.2. Frijol tapado soil P resources

The P pools of the 1 and 2 yr fallow soils were not significantly different, except for subsoil HCl Pi and residual P, which were both lower in the 1 yr fallow site. The high rock fragment content of the subsoil of the 1 yr fallow site, resulting in a low soil mass used for P calculations, ought to be remembered in interpreting these differences. This rocky subsoil nature may affect the fertility of the site, but given the common cropping history of the 1 and 2 yr fallow sites, it is unlikely that it is a product of site management. Their shared cropping history, common physical characteristics (Table 2.1), and relatively similar chemical properties (Table A1) partially explain their similarity in soil P resources. It was expected that the recent longer fallow of the 2 yr fallow site would have increased topsoil Po. It appears that, when dispersed trees are included, short fallow

(9 month) replenishes P pools to the same degree that longer fallow (21 month) does.

There were more differences between 3 yr fallow site and the other two bean sites—the 3 yr fallow topsoil had relatively small NaOH Pi and $NaHCO_3$ Po pools. On the other hand, subsoil NaOH Pi, dilute HCl Pi, and HCl Po pools in the 3 yr fallow site were relatively large. A high subsoil bulk density influenced these latter results, though that does not appear to account for them entirely. It may be that this soil formed from different parent material, or that it has been less severely weathered. Either possibility is supported by the relatively large quantities of apatite P. Initial fertility data (Table A1) indicated relatively high levels of exchangeable Ca, low levels of exchangeable Fe, and a higher pH and lower acid saturation than the other bean sites, further supporting both possibilities.

The 3 yr fallow site had a slope almost 50% greater than the other sites. The incline may have made the soil more vulnerable to erosive forces, particularly after slashing. Its physical instability, relative to the other sites, was notable even when moving about the field. In the initial field description, it was observed that the 3 yr fallow soil profile exhibited highly variable depths to C horizon intrusions, suggesting physical movement of soil within the field. If such processes occurred, to a greater degree than in the other bean sites, less-weathered former subsoil may have been frequently present in the topsoil.

LF contents of all three bean site topsoils were high, compared with those of Mollisols in unfertilized fallow-wheat rotations (2.7-7.2 g LF $kg^{-1}$ soil) and canola-fallow rotations (10.1-12.3 g LF $kg^{-1}$ soil) (Janzen et al., 1992). They were higher than almost all of the rotations, fertilized and unfertilized, in that study. This might be attributed to high annual biomass production in the humid tropics, compared with in temperate grassland zones, resulting in larger additions of organic material to the soil.

LF and LF P contents were statistically equivalent in all bean site topsoils. It was expected that they would have been higher in the 3 yr fallow site, which had a relatively large quantity of mulch material, before and after slashing. The similarity can be partially attributed to the high variability of the LF, particularly in the 3 yr fallow topsoil (standard error of adjusted mean was 3.32).

## 4.3. Comparison of forest soil P resources with frijol tapado

The forest topsoil had relatively large $NaHCO_3$ Pi, HCl Po and residual P pools. It also had more LF. The relatively large $NaHCO_3$ Pi pool may be the result of inputs from the decomposing mulch layer, and perhaps also from the LF. The smaller HCl Po pools in the bean sites suggest that this pool decreases in size under protracted, short-fallow frijol tapado production. The high residual P content of the forest soil is surprising; Tiessen and Moir (1993) state that this fraction probably contains only highly recalcitrant Pi, but they do not state, unequivocally, that it cannot contain Po. Noting that, even after being treated with concentrated HCl, the forest topsoil had a surprisingly dark coloration, it might not be unreasonable to assume that a part of the residual P was composed of Po. On that basis, the smaller residual P pools in the bean sites suggest an additional loss of Po as a result of cropping.

The forest and bean field topsoil NaOH Po levels were not clearly different. Tiessen et al. (1992) and Beck and Sanchez (1994) both concluded that NaOH Po levels decreased over a moderate time-frame (6-10 years) when fallow lands were brought into unfertilized or moderately fertilized cultivation. These studies were carried out on fields that had been continuously cropped for extended periods (6-18 years). In this study, similar NaOH Po values suggest that short-fallow frijol tapado does not deplete that particular pool. This will be discussed in terms of dynamics during the cropping season in the next section.

The forest subsoil contained more NaOH Po and HCl Po than all bean site subsoils did, and it had significantly more $NaHCO_3$ Pi and Po, and concentrated HCl Pi than one of the bean sites (it varied which one). Decades of continuous erosion losses from the cropped sites, while not superficially evident, may have resulted in a shallower A horizon, which would account for the low concentrations of Po at relatively shallow depths. It is also possible that the forest site had accumulated topsoil that had been eroded from up-slope coffee fields.

Relatively large annual litter additions in the forest, and the related high LF content in the surface soil, may also have affected the forest subsoil Po content. As microbes decompose organic material, they release Po molecules through lysis and secretion. Po is known to be more vertically mobile in the soil profile than Pi, and may have leached into, and accumulated in, the subsoil (Dalal, 1977). A third factor contributing to the large subsoil Po pool may have been the greater number of deeper rooting trees, which exude and slough off organic compounds, in the forest. Finally, a rise in soil temperature may have been associated with post-slashing solar exposure in the bean sites, encouraging microbial activity deep in the soil profile and resulting in net Po mineralization (Dalal, 1977).

## 4.4. Comparison of pasture soil P resources with the forest

Pasture P content was low, particularly in terms of HCl Po and residual P, in the topsoil and in the subsoil. HCl Po was more depleted in the pasture than in the bean sites. It appears that decades of biomass removal by grazing animals, and negligible litter inputs, resulted in a net mineralization of soil Po. Subsoil HCl Pi resources were also depleted, perhaps as a result of root uptake by pasture grasses.

## 4.5. Relative importance of soil Pi and Po during the cropping season

Organic phosphorus accounted for less than 41% of Pt in all soils. According to Sanchez (1976), it is common for weak to moderately weathered soils to contain 20-50% Po, whereas in highly weathered soils it may account for up to 80% of Pt. Almost all detected changes in soil P during the cropping season were concentrated in the Po pool. Changes in Pi were minor and followed no clear pattern.

The 1 and 2 yr fallow soils both experienced a decrease in NaOH Po concentration after seeding, and a partial recharge at harvest. In the forest soil, on the other hand, there was no significant difference between pre-slash and harvest NaOH Po levels. The literature confirms these findings, pointing to NaOH Po as an important source of plant-available P in unfertilized cropping systems, particularly on weathered soils (McKenzie et al., 1992; Tiessen et al., 1992; Beck and Sanchez, 1994; Buresh et al., 1997). Tiessen et al. (1992) and Beck and Sanchez (1997) found that soils continuously cropped without fertilizer experienced a decrease in NaOH Po over a moderate time-frame (6-10 years). The data from this study suggests that NaOH Po is a relatively dynamic pool, with a portion quickly mineralized after land clearing, and a partial replenishment occurring during the frijol tapado cropping season, as slashed material decomposes. This surprisingly dynamic nature may be related to the high volume of rainfall, and the warm temperatures, associated with these sites (1409 mm of rain fell over the length of this study). Similar quantities of NaOH Po in forest and bean sites (Section 4.3), indicate that this fraction, in spite of its easily mineralizable nature, was not depleted by frijol tapado.

Tiessen et al, (1994b) concluded that $NaHCO_3$ Po concentrations, in some tropical soils, are constant over time and across treatments. In this study, levels were constant across sites (except for the low value in the 3 yr fallow site), but increased significantly over the length of the season, well into the soil profile. This may have been an indicator that microbial activity and the quantity of mineralizable material was greater at harvest than before slashing.

HCl Po concentrations were greater at the end of the cropping season in the 1 yr fallow, 2 yr fallow and forest soils, to a depth of at least 10 cm. Given HCl Po in the bean sites did not decrease after slashing, this extract appears to represent a fraction less easily mineralized than NaOH Po. The increase at harvest may have represented an accumulation of more stable SOM molecules. HCl Po and NaOH Po have not been well differentiated in the literature.

The bean soils had less HCl Po than the forest (Section 4.3). As such, it would be expected that that fraction would decrease during the cropping season. Perhaps, under the former, unimproved, short-fallow system, HCl Po pools were depleted, and with the relatively recent inclusion (ten years ago) of dispersed trees, that trend was had been reversed. Or perhaps there are changes in SOM occurring over the year that result in a decrease in HCl Po at another time.

Seasonal P dynamics in the 3 yr fallow soil were unlike those in the other bean sites. $NaHCO_3$ Po was slightly lower at harvest than at post-seed; all other changes, in Po and Pi, were negligible. The decomposing mulch seemed to have provided virtually all of the P taken up by the crop.

Changes in soil P pools over the cropping season were negligible in the pasture.

## 4.6. Above-ground biomass P in frijol tapado sites

Pre-slash, above-ground biomass increased with the age of the fallow (assuming that the post-seed numbers are more reliable indicator than the pre-slash ones), but only differences between the 1 yr and 3 yr fallow sites were significant. The 2 yr fallow site did not have significantly more leafy or woody material, standing or mulch, than the 1 yr site, according to both the pre-slash and post-seed data. The presence of dispersed trees in both sites is likely to have moderated the difference between them. The 3 yr fallow site did not have more standing leafy material than other bean sites, but it did have more standing woody material, and also more pre-slash, leafy mulch material (although the cover was highly variable). The differences between it and the others may have been moderated by their more intensive dispersed trees systems.

At the post-seed sampling date, though some P would have been lost from the mulch (Schlather, 1998), that loss was not detected. The post-seed, mulch biomass of the 3 yr fallow site was high, but the P content was more moderate, probably because of the weathered nature of the original mulch material.

By harvest, all mulch layers in the bean sites were smaller. The change was particularly notable in the 3 yr fallow site.

It is important to note that the regrowth of *A. adinocephala*, the dominant dispersed tree, accounted for approximately 30% of the new biomass, and close to 50% of the fresh plant P, in the 1 and 2 yr fallow sites (not including the bean plants). Tree shoot P content for the sites were 0.46% and 0.27%, respectively (Table B13). Kwabiah (1997) determined critical P concentration for plant material to be 0.20-0.24%, concentrations below resulting in short-term (at least 56 days) net immobilization of P. According to the data from the pre-slash sampling time, the standing, leafy material consistently had a P concentrations below 0.20% (Table B10). *A. adinocephala* may have the capacity to provide P-enriched biomass additions, which would raise the P concentration of the mulch at seeding.

## 4.7. Mulch biomass in the forest

The forest mulch biomass was smaller at the end of the cropping season. During the preceding dry season there had probably been increased leaf senescence and a slowed rate of decomposition, resulting in biomass accumulation. During the rainy season, decomposition outpaced litter additions. It is interesting to note that LF accumulated in the forest topsoil during the cropping season, indicating that a certain amount of the decomposing mulch was incorporated into the soil as particulate organic matter.

## 4.8. Bean crop yields

The recorded crop yields were much higher than normal yields for frijol tapado (Meléndez et al. 1996). These may result from the relatively fertile soils, and the careful associated management, but they may also be overestimates.

Crop yields for the 1 and 2 yr fallow sites were similar. In terms of crop production, P was not more limiting in the 1 yr fallow than in the 2 yr fallow site; the soil and biomass P data support this result. The yields of the 3 yr fallow site were much lower than those of the other sites. Meléndez and Szott (1999) attributed relatively low yields, following a 3 year fallow, to the negative effect that large quantities of mulch had on seedling germination and survival. In this study, the predominant tree and bush vegetation in the 3 yr fallow site produced a highly variable much cover, thick in places and absent in others, which may have inhibited crop establishment and development. Completely different P dynamics in the 3 yr fallow soil severely limited the quantity of P supplied to the beans.

## 4.9. Interactions between the soil and the above-ground biomass P pools in the frijol tapado sites

The total above-ground biomass P was greater at harvest in the 1 and 2 yr fallow sites. A substantial quantity of P had been sequestered from soil P pools. NaOH Po is likely to have contributed a large portion of that. Changes in soil total P were not detectable, because they were small relative to Pt. Accumulations in the soil HCl Po pool during the cropping season where likely derived from decomposing, above-ground biomass material.

In the 3 yr fallow site, the total above-ground biomass P pool was not different in size at harvest. Detected changes in soil P pools over the cropping season were few. Soil P contribution to biomass growth was smaller at this site; the decomposing mulch provided the majority of plant-available P.

None of the soil P fractions was larger in the bean sites than in the forest. It can be concluded from that there had not been a detectable redistribution of mineralized Po to other soil pools. Rather, mineralized Po was taken from the system in annual bean crops. In an Oxisol, Tiessen et al. (1992) found that removal of P with the harvested crop was minor compared with the amount of mineralized Po that accumulated as fixed Pi. Oxisols have much higher Al and Fe oxides contents than do Inceptisols, fixing large quantities of P as a result. This accounts for the substantial redistribution of P that was associated with the Oxisol, but was not observed in these soils.

# 5. CONCLUSIONS AND FURTHER RESEARCH

## 5.1. Conclusions

Decades of short-fallow frijol tapado can result in depletions of stable soil Po. In this study, HCl Po pools in every bean site top- and subsoil were smaller than those in the forest. The residual P pool, which probably included some quantity of Po, was also smaller in all bean site top- and subsoils. In soils with moderate P fixing capacities, P removal in harvested crops accounts for a larger portion of net Po loss than redistribution of P among the soil pools does.

Short-fallow frijol tapado production also results in a decrease in $NaHCO_3$ Pi. This pool is directly influenced by contributions from soil and biomass Po, and reduced quantities of both in cropped sites account for the smaller pool.

Of the soil P fractions, NaOH Po makes the most important contribution to plant nutrition during the cropping season. Unlike the more stable HCl Po pool, a portion of the NaOH Po was mineralized shortly after slashing, providing the freshly seeded bean crop with a source of available Pi. The pool was replenished relatively quickly.

Above-ground biomass supplies the bean crop with a substantial portion of its required P, under frijol tapado. In this study, on particularly steep slopes (92%), most P taken up by the crop was derived from above-ground biomass. On more moderate slopes, both the soil and the biomass made important contributions.

Fallow periods of nine months, and of 21 months, which include dispersed trees, supply frijol tapado crops with statistically equivalent quantities of biomass P, and affect soil P pool sizes and dynamics in similar ways. On particularly steep slopes (92%), physical instability of soil may necessitate longer fallow periods.

Long-term pasturing results in decreases in top- and subsoil HCl Po and residual P, and in subsoil HCl Pi. In this study, the pasture soil often had less P than the bean sites had.

## 5.2. Further research

Further research into the potential of dispersed on-farm trees as means of enhancing short-fallow slash/mulch systems is required. Shortened fallow periods are an unavoidable reality of many contemporary farming situations. Soil Po levels are being depleted, and system adjustments that would increase above ground biomass P, and soil Po pools, would improve productivity and sustainability. Preliminary results indicate that indigenous agroforestry systems, such as dispersed trees, do have considerable potential to improve biomass production and quality, without requiring prohibitively high labour inputs.

Further research into the nature and dynamics of soil Po is also necessary. It is clear that soil Po plays an essential role in supplying crops with P in many low-input situations. Yet, its nature and dynamics are inadequately understood, and attempts at managing the pools continue to be without certain direction. An improved understanding would help farmers and researchers adjust management systems so as to make the utilization of P resources more efficient.

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# APPENDIX A

Table A1. Chemical properties of site soils†

| Site | | Exchangeable | | | | | Exchangeable | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | pH | Ca | Mg | K | Acid sat. | CEC | P | Cu | Fe | Mn | Zn |
| | | cmol(+) $L^{-1}$ | | | | | mg $L^{-1}$ | | | | |
| 1 yr. | 5.4 | 6.40 | 1.82 | 0.45 | 3.02 | 8.94 | 9.4 | 2.3 | 114 | 8.4 | 0.6 |
| 2 yr. | 5.1 | 5.73 | 2.23 | 0.30 | 7.19 | 8.90 | 8.5 | 2.7 | 160 | 12.6 | 0.8 |
| 3 yr. | 5.6 | 14.50 | 3.32 | 0.40 | 0.87 | 18.38 | 7.6 | 1.9 | 85 | 14.3 | 0.7 |
| Forest | 6.0 | 32.40 | 7.00 | 0.51 | 0.47 | 40.10 | 3.9 | 0.9 | 31 | 10.2 | 1.9 |
| Past | 5.3 | 7.00 | 3.40 | 0.08 | 7.66 | 11.35 | 3.3 | 2.8 | 287 | 11.2 | 0.5 |
| Crit. Level‡ | | 4 | 1 | 0.2 | <10 | | 10 | 1 | 10-500 | 5-100 | 2 |

† 0-10 cm

‡ Critical level for bean production (F. Bertsch, personal communication)

# APPENDIX B

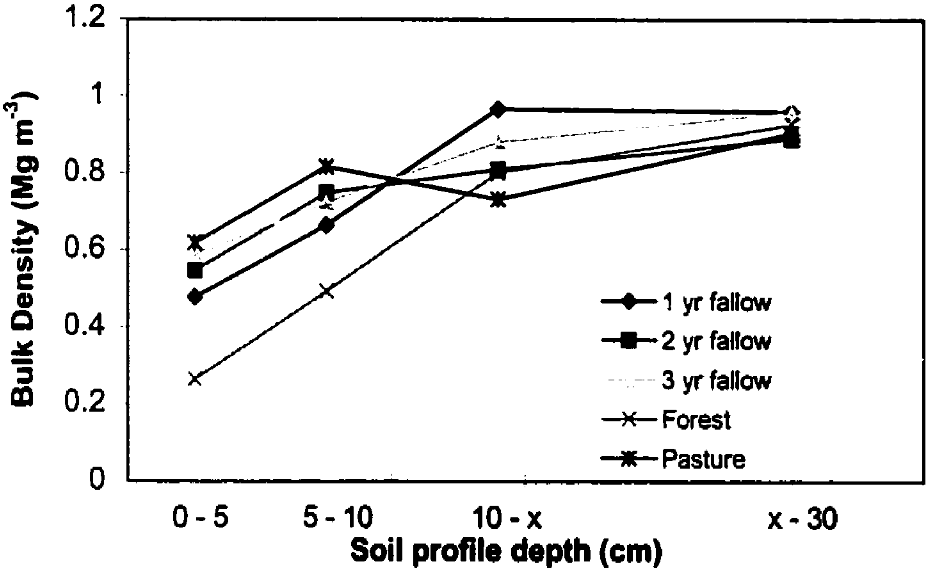

Fig. B1. Bulk density including rock fragments (>2 mm)

Table B1. Rock fragment (>2 mm) content of soil (% volume)

| Site | 0-5 cm | 5-10 cm | 10-x cm | x-30 cm |
|---|---|---|---|---|
| | | (%) | | |
| 1 yr fallow | 7.86c†‡ | 15.0b | 28.1b | 26.7b |
| 2 yr fallow | 6.15bc | 8.61ab | 11.0a | 8.67a |
| 3 yr fallow | 3.64ab | 6.73a | 7.19a | 14.4ab |
| Forest | 2.60a | 3.83a | 9.11a | 12.2a |
| Pasture | 9.01c | 10.4ab | 11.4a | 10.3a |

† Least squared means calculated by SAS

‡ Numbers in each column with the same letter are not significantly different (Tukey LSD, P<0.05)

Table B2. Soil bulk density, with rock fragment (>2 mm) mass and volume included and excluded

| Treatment | without rock fragments | | | | with rock fragments | | | |
|---|---|---|---|---|---|---|---|---|
| | 0-5 cm | 5-10 cm | 10-x cm | x-30 cm | 0-5 cm | 5-10 cm | 10-x cm | x-30 cm |
| | | | | $g\ cm^{-3}$ | | | | |
| 1 yr fallow | 0.366b†‡ | 0.512ab | 0.683a | 0.664ab | 0.478b | 0.666ab | 0.968 b | 0.961a |
| 2 yr fallow | 0.472bc | 0.579bc | 0.631a | 0.779ab | 0.548b | 0.749b | 0.810 ab | 0.890a |
| 3 yr fallow | 0.534c | 0.640bc | 0.719a | 0.662ab | 0.588b | 0.725b | 0.882 ab | 0.960a |
| Forest | 0.182a | 0.393a | 0.690a | 0.886b | 0.265a | 0.494a | 0.802 ab | 0.928a |
| Pasture | 0.493bc | 0.696c | 0.685a | 0.551a | 0.620b | 0.817b | 0.734 a | 0.904a |

† Least squared means calculated by SAS

‡ Numbers in each column with the same letter are not significantly different (Tukey LSD, P<0.05)

Table B3. Light fraction SOM content of soil profiles at different sites

| Depth | 1 yr fallow | 2 yr fallow | 3 yr fallow | Forest | Pasture |
|---|---|---|---|---|---|
| (cm) | | | $g\ kg^{-1}$ | | |
| 0-5 | 51.6c†‡ | 32.4c | 30.8b | 126b | 21.5b |
| 5-10 | 21.7b | 14.4b | 12.4a | 29.6a | 10.3a |
| 10-x | 9.29ab | 6.67ab | 7.94a | 6.38a | 7.27a |
| x-30 | 5.15a | 1.64a | 5.17a | 4.92a | 5.79a |

† Least squared means calculated by SAS

‡ Numbers in each column with the same letter are not significantly different (Tukey LSD, P<0.05)

Table B4. Light fraction SOM P content of soil profiles at different sites

| Depth | 1 yr fallow | 2 yr fallow | 3 yr fallow | Forest | Pasture |
|---|---|---|---|---|---|
| (cm) | | | $mg\ kg^{-1}$ | | |
| 0-5 | 32.5b†‡ | 14.8b | 15.4c | 67.9b | 7.06b |
| 5-10 | 11.2a | 5.38a | 6.54b | 12.9a | 4.22a |
| 10-x | 5.28a | 3.12a | 4.33ab | 3.12a | 3.59a |
| x-30 | 2.98a | 1.07a | 2.48a | 0.00a | 2.87a |

† Least squared means calculated by SAS

‡ Numbers in each column with the same letter are not significantly different (Tukey LSD, P<0.05)

Table B5. Light fraction SOM (g kg$^{-1}$) and LF P (mg kg$^{-1}$) at 0-5 cm depth during the cropping season at different sites

| Time | 1 yr fallow | | 2 yr fallow | | 3 yr fallow | | Forest | | Pasture | |
|---|---|---|---|---|---|---|---|---|---|---|
| | LF | P | LF | P | LF | P | LF | P | LF | P |
| Pre-slash | 49.8a†‡ | 29.4a | 18.0a | 6.93a | 16.2a | 7.77a | 78.6a | 39.1a | 19.2a | 7.50a |
| Post-seed | 48.3a | 23.5a | 23.2a | 14.0ab | 22.4a | 13.7a | n.d.§ | n.d. | n.d. | n.d. |
| Post-harvest | 43.0a | 33.5a | 40.6b | 19.5b | 35.6a | 15.7a | 178b | 98.7a | 14.8a | 5.76a |

† Least squared means calculated by SAS

‡ Numbers in each column with the same letter are not significantly different (Tukey LSD, P<0.05)

§ Not determined

Table B6. Light fraction SOM (g kg$^{-1}$) and LF P (mg kg$^{-1}$) at 5-10 cm depth during the cropping season at different sites

| Time | 1 yr fallow | | 2 yr fallow | | 3 yr fallow | | Forest | | Pasture | |
|---|---|---|---|---|---|---|---|---|---|---|
| | LF | P | LF | P | LF | P | LF | P | LF | P |
| Pre-slash | 18.0a | 12.2a | 13.3a | 4.40a | 10.3a | 5.56a | 14.0a | 7.14a | 9.88a | 4.08a |
| Post-harvest | 25.1a | 9.82a | 15.8a | 6.14a | 13.4a | 7.78a | 45.3a | 18.6b | 5.53a | 2.88a |

Table B7. Light fraction SOM (g kg$^{-1}$) and LF P (mg kg$^{-1}$) at 10-x cm depth during the cropping season at different sites

| Time | 1 yr fallow | | 2 yr fallow | | 3 yr fallow | | Forest | | Pasture | |
|---|---|---|---|---|---|---|---|---|---|---|
| | LF | P | LF | P | LF | P | LF | P | LF | P |
| Pre-slash | 4.17a | 2.71a | 5.85a | 2.69a | 7.19a | 3.49a | 6.08a | 3.24a | 4.80a | 3.37a |
| Post-harvest | 14.4b | 7.86b | 8.35a | 4.03a | 7.73a | 4.77a | 6.67a | 3.01a | 8.46a | 3.98a |

Table B8. Light fraction SOM (g kg$^{-1}$) and LF P (mg kg$^{-1}$) at x-30 cm depth during the cropping season at different sites

| Time | 1 yr fallow | | 2 yr fallow | | 3 yr fallow | | Forest | | Pasture | |
|---|---|---|---|---|---|---|---|---|---|---|
| | LF | P | LF | P | LF | P | LF | P | LF | P |
| Pre-slash | 3.32a | 1.78a | 1.95a | 0.690a | 3.94a | 2.10a | 5.13a | 2.32a | 3.97a | 2.13a |
| Post-harvest | 7.62a | 4.40a | 2.93a | 1.79a | 4.45a | 2.47a | 4.70a | 2.84a | 6.08a | 3.54a |

Table B9. Light fraction SOM and LF P in different site subsoils† at harvest

| Site | LF | P |
|---|---|---|
| | (Mg $ha^{-1}$) | (kg $ha^{-1}$) |
| 1 yr fallow | 7.54a‡§ | 4.94a |
| 2 yr fallow | 6.73a | 3.61a |
| 3 yr fallow | 7.01a | 4.56a |
| Forest | 7.63a | 3.94a |
| Pasture | 8.26 a | 4.38 a |

† 10-30 cm

‡ Least squared means calculated by SAS

§ Numbers in each column with the same letter are not significantly different (Tukey LSD, $P<0.05$)

Table B10. Biomass P and nitrogen (N)† content before slashing

| Site | Standing Leafy | | Standing Woody‡ | | Mulch Leafy | |
|---|---|---|---|---|---|---|
| | (%P) | (%N) | (%P) | (%N) | (%P) | (%N) |
| 1 yr fallow | 0.127§ | 1.29 | n.d. | n.d. | 0.103 | 1.69 |
| 2 yr fallow | 0.148 | 2.18 | 0.103 | 0.803 | 0.0778 | 1.41 |
| 3 yr fallow | 0.162 | 1.79 | 0.0969 | 0.638 | 0.0838 | 1.30 |
| Forest | n.d.¶ | n.d. | n.d. | n.d. | 0.0914 | 1.75 |

† Determined using methodology of Thomas et al. (1967)
‡ Not including tree trunks
§ Mean values
¶ Not determined

Table B11. Biomass P and N content after planting

| Site | Mulch Leafy | | Mulch Woody† | |
|---|---|---|---|---|
| | (%P) | (%N) | (%P) | (%N) |
| 1 yr fallow | 0.0854‡ | 0.978 | n.d.§ | |
| 2 yr fallow | 0.0666 | 1.34 | 0.0427 | 0.728 |
| 3 yr fallow | 0.0743 | 0.960 | 0.0503 | 0.560 |

† Not including tree trunks
‡ Mean values
§ Not determined

Table B12. Biomass P and N content at harvest

| Site | Standing Leafy | | Mulch Leafy† | | Mulch Woody | |
|---|---|---|---|---|---|---|
| | (%P) | (%N) | (%P) | (%N) | (%P) | (%N) |
| 1 yr fallow | 0.147‡ | 1.48 | 0.0992 | 1.46 | 0.0671 | 0.933 |
| 2 yr fallow | 0.165 | 1.91 | 0.0904 | 1.70 | 0.0464 | 0.913 |
| 3 yr fallow | 0.187 | 1.54 | 0.0925 | 1.18 | 0.0590 | 0.710 |
| Forest | n.d.§ | n.d. | 0.0708 | 1.76 | 0.0370 | 1.25 |
| Pasture | 0.0979 | 0.994 | n.d. | n.d. | n.d. | n.d. |

† Not including tree trunks
‡ Mean values
§ Not determined

Table B13. Bean, trash and fresh tree shoot† P and N content at harvest

| Site | Bean | Bean | Trash | Trash | Tree | Tree |
|---|---|---|---|---|---|---|
| | (%P) | (%N) | (%P) | (%N) | (%P) | (%N) |
| 1 yr fallow | 0.435‡ | 3.91 | 0.0845 | 1.08 | 0.462 | 3.86 |
| 2 yr fallow | 0.370 | 3.92 | 0.0772 | 1.02 | 0.272 | 3.54 |
| 3 yr fallow | 0.427 | 3.73 | 0.100 | 1.12 | n.d.§ | n.d. |

† *A. adinocephala*
‡ Mean values
§ Not determined

# APPENDIX C

Table C1. Total P concentrations of soil

| Depth | 1 yr fallow | 2 yr fallow | 3 yr fallow | Forest | Pasture |
|---|---|---|---|---|---|
| (cm) | | | mg kg$^{-1}$ | | |
| 0-5 | 504d†‡ | 401d | 391c | 594c | 368c |
| 5-10 | 435c | 341c | 328bc | 486b | 308b |
| 10-x | 296b | 273b | 283ab | 397a | 238a |
| x-30 | 218a | 228a | 211a | 338a | 214a |

† Least squared means calculated by SAS

‡ Numbers in each column with the same letter are not significantly different (Tukey LSD, P<0.05)

Table C2. Changes in total P concentrations during the cropping season

| Time | 1 yr fallow | 2 yr fallow | 3 yr fallow | Forest | Pasture |
|---|---|---|---|---|---|
| | | | mg kg$^{-1}$ | | |
| | | | **0-5 cm** | | |
| Pre-slash | 460a†‡ | 390a | 421a | 544a | 369a |
| Post-seed | 539a | 377a | 432a | n.d.§ | n.d. |
| Harvest | 517a | 413a | 318a | 629a | 360a |
| | | | **5-10 cm** | | |
| Pre-slash | 422a | 351a | 352a | 440a | 296a |
| Harvest | 402a | 345a | 280a | 527b | 317a |
| | | | **10-x cm** | | |
| Pre-slash | 279a | 276a | 339a | 344a | 221a |
| Harvest | 274a | 287a | 226a | 456b | 271b |
| | | | **x-30 cm** | | |
| Pre-slash | 228a | 220a | 138a | 277a | 210a |
| Harvest | 182a | 238a | 214a | 427b | 198a |

† Least squared means calculated by SAS

‡ Numbers in each column, at given soil depths, followed by the same letter, are not significantly different (Tukey LSD, P<0.05)

§ Not determined

Table C3. Total P content of topsoils† and subsoils‡ at harvest

| Site | Topsoil Pt | Subsoil Pt |
|---|---|---|
| | ——kg $ha^{-1}$—— | |
| 1 yr fallow | 124b§¶ | 176a |
| 2 yr fallow | 102ab | 305a |
| 3 yr fallow | 92.9a | 292a |
| Forest | 144c | 580b |
| Pasture | 81.2a | 248a |

† Top 52.0 g (256 Mg $ha^{-1}$)

‡ 10-30 cm

§ Least squared means calculated by SAS

¶ Numbers in each column with the same letter are not significantly different (Tukey LSD, $P<0.05$)