sustainability

Article

Improving Farming Practices for Sustainable Soil Use in the Humid Tropics and Rainforest Ecosystem Health

Emanoel Gomes de Moura [1,*], Christoph Gehring [1], Heder Braun [1], Altamiro de Souza Lima Ferraz Junior [1], Fabricio de Oliveira Reis [1] and Alana das Chagas Ferreira Aguiar [2]

[1] Programa de Pós-Graduação em Agroecologia, Universidade Estadual do Maranhão, São Luís 65054-970, Brazil; christophgehing@yahoo.com.br (C.G.); hederbraun@gmail.com (H.B.); altamiro.ferraz@uol.com.br (A.d.S.L.F.J.); fareoli@gmail.com (F.d.O.R.)

[2] Departamento de Biologia, Universidade Federal do Maranhão, São Luís 65080-805, Brazil; alana.aguiar@ufma.br

* Correspondence: egmoura@elo.com.br; Tel.: +55-98-99976-7123

Academic Editor: Tiziano Gomiero
Received: 25 April 2016; Accepted: 19 August 2016; Published: 29 August 2016

Abstract: Unsustainable farming practices such as shifting cultivation and slash-and-burn agriculture in the humid tropics threaten the preservation of the rainforest and the health of the local and global environment. In weathered soils prone to cohesion in humid tropic due to low Fe and carbon content and the enormous amounts of P that can be adsorbed, sustainable soil use is heavily dependent on the availability and efficient use of nutrients. This paper reviews the literature in the field and provides some insights about sustainable soil use in the humid tropics, mainly for the Brazilian Amazonia region. Careful management of organic matter and physical and chemical indicators is necessary to enhance root growth and nutrient uptake. To improve the rootability of the arable layer, a combination of gypsum with continuous mulching to increase the labile organic matter fraction responsible for the formation of a short-lived structure important for root growth is recommended, rather than tillage. Unlike mulching, mechanical disturbance via ploughing of Amazonian soils causes very rapid and permanent soil organic matter losses and often results in permanent recompaction and land degradation or anthropic savannization; thus, it should be avoided. Unlike in other regions, like southeast Brazil, saturating the soil solely with inorganic potassium and nitrogen soluble fertilizers is not recommended. Nutrient retention in the root zone can be enhanced if nutrients are added in a slow-release form and if biologically mediated processes are used for nutrient release, as occurs in green manure. Therefore, an alternative that favors using local resources to increase the supply of nutrients and offset processes that impair the efficiency of nutrient use must be pursued.

Keywords: mulching; organic matter; soil indicators; soil management; sustainability

---

1. Introduction

Sustainable agriculture can be defined as "the management and conservation of the natural resource base, and the orientation of technological change in such a manner as to ensure the attainment of continued satisfaction of human needs for present and future generations. Sustainable agriculture conserves land, water, and plant and animal genetic resources, and is environmentally non-degrading, technically appropriate, economically viable and socially acceptable" [1]. In many regions of the humid tropics, like the Amazonian periphery, inappropriate land management is one of the greatest threats to preserving the rainforest and maintaining a healthy ecosystem, since after degradation of soil in one area, farmers usually consider the lush rainforest vegetation to be an endless source of nutrients. Natural vegetation is cut down and burned as a method of clearing the land for cultivation, and then, when the plot becomes infertile, the farmer moves to a fresh plot and does the same again. This process is repeated over and over by smallholders for staple cultivation or by large landholders for the implementation of extensive pastures. This land use results in a short-lived production because of the rapid depletion of soil nutrients, and produces negative effects for the local and global environment. At the local level, it is leading to the extinction of those species that are most sensitive to burning, allowing for more resistant species to predominate, thereby diminishing the region's biodiversity and impoverishing its ecosystems. In the global context, it is estimated that uncontrolled fires produce 36% of all CO_2 emitted by Brazil, which is one of the world's top five countries in terms of emissions [2].

This continuous process of shifting the cultivated area is now increasingly recognized as a fundamental cause of deforestation and declining food security in small landholder farms in the humid tropic, including the Amazon region and its surroundings [3]. This is mainly because, with the increased population density, this system is no longer capable of feeding the people of the region, and requires larger areas to be used. Therefore, sustainable agricultural soil management is a major challenge for those who care about the health of the rainforest ecosystem [3]. The essence of sustainable agriculture is the management and utilization of the agricultural ecosystem in a way that maintains its biological diversity, productivity, regeneration capacity, vitality, and ability to function, so that it can fulfil—today, and in the future—significant ecological, economic, and social functions at the local, national, and global level, and not harm other ecosystems [4]. A healthy ecosystem must also be defined in light of both its context (the larger system of which it is part) and its components (the smaller systems that compose it) [5].

In the humid tropics, deforestation occurs when areas damaged by improper use with pasture or staple food crops can no longer support production due to loss of the soil quality, which can be defined as the capacity of soil to function within ecosystem and land use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health [6]. Soil quality is assessed with respect to specific soil functions. However, soil functions themselves cannot be directly measured. Selected physical, chemical, and biological properties of the soil are used instead to quantify soil functions related to specific goals. Soil properties such as soil strength, soil organic matter, cation-exchangeable capacity, base saturation percentage, and extractable N-P-K are soil quality indicators. Thus, soil quality indicators are soil measurements that can represent the conditions of the ecosystem or the soil's ability to affect system functions [7].

Among the factors that affect system performance in the humid tropics are P, K, and cation base depletion, a decrease of soil organic matter, and the deterioration of soil rootability. Together, these factors affect biological diversity, biomass productivity, and, consequently, environmental quality [8]. Unfortunately, sustainable soil management by preserving fertility is difficult in most areas of the tropics due to high temperatures and rainfall in soils derived from clastic sedimentary rocks [9].

It is worth highlighting that the extensive agrosystem and monocultural agriculture established for other tropical regions such as southeastern Brazil is not adequate for humid tropic environments because such an agrosystem does not meet the food and income needs of the region's family farmers [2]. Keeping these factors in mind, studies undertaken in this region, mainly by researchers from the Agroecological Program of the State University of Maranhão [10], have shown that many practices recommended for the subsavannah soils of southeast Brazil, such as saturating soils with soluble nutrients, do not raise productivity or ensure the sustainability of land use when applied to agroecosystems of the Amazonian periphery [2]. Certainly, promoting alternative practices relies on knowledge about the processes involved in tropical soil degradation. This paper presents a review of present knowledge of the issue and aims at contributing to a better understanding of how soil management practices may affect the sustainability of soil use and the rainforest ecosystem health of the humid tropics, mainly of the Brazilian Amazonia region.

2. Importance of Soil Physical Attributes to Sustainable Continuous Soil Use under Humid Tropical Soil Conditions

The main requirements that directly affect plants' growth are nutrients, water, air, and space for root growth. The ability of soil to provide these requirements in the root environment is usually referred to as fertility [6]. Pore space, including its size distribution, affects many important physical phenomena, such as storage movement, the availability of water and gases, and ease of root penetration, and these factors in turn influence crop yield [11,12]. Unfortunately, in contrast to chemical fertility indicators, few examples of physical indicators with closed relationships to plant production are known, although the effects of physical indicators on the growth of some plants have been investigated [13].

2.1. Soil Penetration Strength and Soil Rootability

Physical parameters such as the bulk soil density and porosity hold only marginal value as soil quality indicators because the optimal values for these parameters likely vary in different soils, thus making their use problematic for soil-to-soil comparisons. Therefore, Mishra et al. [13], based on Letey [14], suggested that a non-limiting moisture range exists in which physiological plant growth, or dry matter accumulation, is independent of any other physical factors. Additionally, according to Moura et al. [15], neither static nor individual soil indicators relate well to the differences in plant productivity in tropical soil when they are considered separately and dynamic indicators such as penetration strength and water stress days are more suitable for use under experimental or field conditions.

In the humid tropics, most soils derived from clastic sedimentary rocks with low content of free iron and organic carbon levels tend to undergo hardsetting, which decreases the rootable soil volume and impairs nutrient uptake [16]. Combining irregular precipitation with a high potential evapotranspiration rate leads to repeated cycles of wetting and drying, so penetration strength is one of the principal indicators to evaluate soil quality. According to Moura et al. [15], in tropical regions, a decrease in the water potential as the soil dries increases the effective stress, thus causing an increase in strength that hampers root growth. Under these circumstances, nutrient use efficiency is the main factor that affects productive management of agro-systems in the humid tropics due to the low rate of nutrient uptake and the high rate of nutrient loss.

Improving soil rootability conditions and increasing nutrient uptake by crops are crucial to overcoming the challenge of improving profitability and ecological sustainability in a large area of the humid tropics [17]. Unfortunately, under tropical conditions, the improved soil physical conditions that result from tillage are frequently short-lived due to the deterioration of the porous structure and the reconsolidation of the soil at the rootable layer [16]. This process is known as natural reconsolidation, and its rate of occurrence is dependent on the cumulative rainfall and the overall stability of the soil structure. Therefore, compaction of structurally fragile tropical soils in the humid region is a natural process rather than one caused by traffic intensity or a no tillage system.

2.2. Use of Leguminous Residues and Gypsum for Enhancing Tropical Soil Physical Properties

Some authors have recommended enhancing the soil environment for root growth in no-tillage systems and in soil covered with a residue such as mulch [18,19]. This practice has been recommended because a protective layer of mulch absorbs raindrop impact and reduces evaporation from the soil surface, which may delay hardsetting, as reported by Moura et al. [2]. Differences in soil strength caused by mulch from an alley cropping system can be seen in Figure 1.

In addition, the continuous application of residues improves the soil environment for root growth because it promotes the formation of unstable aggregates by increasing the free light fraction of organic matter [18]. Results of Mulumba and Lal [20] confirmed that mulch application increased total porosity, soil aggregation, and moisture content in field moisture capacity. However, the mulch rate effect on soil bulk density was not linear. Mulch rates as low as 2 Mg/ha resulted in dramatic increases in soil porosity compared to no mulch at all. Similarly, beyond 8 Mg/ha of mulch, no significant increases in soil available water capacity were observed. Therefore, the threshold level of the mulch rate for the soil in Mulumba and Lal [20] was 8 Mg/ha.

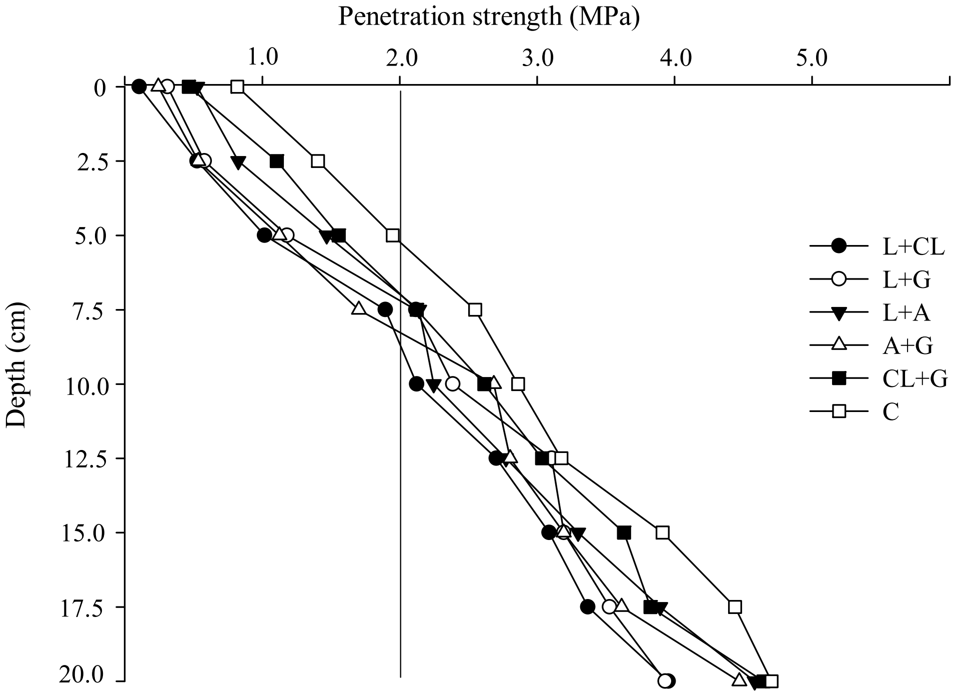

Figure 1. Penetration strength after four days without rain in soil covered with 10 tons/ha of different combinations of leguminous residues. Vertical bars show limiting penetration strength. L + CL = Leucaena + Clitoria; L + A = Leucaena + Acacia; L + G = Leucena + Gliricídia; A + G = Acacia + Gliricidia; CL + G = Clitoria + Gliricídia; C = Control. Adapted of Moura et al. [15].

In no-till systems, improving the soil structure by mulch may primarily result in promoting nutrient uptake, as reported by Moura et al. [21] (Table 1). The variations in the root growth can explain the differences in N and P uptake. The adsorption of N and P by crops is highly dependent on the root development, and root system growth results in greater uptake of N and P and less leaching of N.

Table 1. Nitrogen recovery efficiency (NRE), phosphorus recovery efficiency (PRE), nitrogen agronomic efficiency (NAE), and phosphorus agronomic efficiency (PAE) of maize on uncovered and covered tropical soil. (Adapted of Moura et al. [21].)

	Uncovered Soil		**Covered Soil**	
	Year I	**Year II**	**Year I**	**Year II**
NRE ($kg{\cdot}kg^{-1}$)	26.51 b [1]	11.51 b	47.86 a	41.04 a
PRE ($kg{\cdot}kg^{-1}$)	2.93 b	0.97 b	13.49 a	24.0 a
NAE ($kg{\cdot}ha^{-1}$)	8.21 b	1.83 b	21.22 a	14.09 a
PAE ($kg{\cdot}ha^{-1}$)	6.16 b	1. 14 b	15.92 a	14.09 a

[1] Different letters in the same row indicate a difference at the 5% level per Tukey’s test, in the same year.

It is worth highlighting that the practice of soil covering is effective, in terms of nutrient uptake by crops, only if there are no long intervals between precipitation events [22], mainly because the cover may confine organic matter additions to the upper soil surface and negate a substantial increase of organic matter at a lower soil depth. In this case, improvements in the soil structural properties due to crop residue mulch may only be effective near the soil surface [23]. Additionally, Moura et al. [2]

observed that the direct effect of residues on soil properties did not extend beyond 15 cm below the surface.

To extend rootability improvement to a lower soil depth, some authors recommend the use of gypsum as a "flocculating" agent to improve the soil structure by reducing the dispersion of the clay [24,25]. The action of the dispersed clay in hardening or increasing soil strength is also decreased by the application of gypsum [24]. The improvement in soil structure following gypsum application also involves the creation of a range of different-sized pores. Porous soil facilitates root penetration, thereby allowing plants to more effectively explore the soil volume in search of nutrients and leading to a greater nutrient uptake efficiency and crop growth rate [25].

The effect of gypsum on the reduction of tropical soil strength up to the 20–40 cm layer was observed by Moura et al. [12] when the root length density was twice as much for the gypsum-treated soil as that of the control. The combination of gypsum and residue of leguminous trees dramatically increased the efficiency of phosphorus recovery compared with the application of one of these amendments alone. Given the low mobility of phosphorus in soil, the ability of a plant to take up phosphorus is largely due to plant root distribution relative to the location of the phosphorus in the root zone. Anikwe and Ibudialo [26] also reported a positive effect of gypsum on soil physical and chemical properties from a degraded tropical soil due to effect of Ca^{2+} applied via gypsum to flocculate soil particles thereby creating an enabling soil physical condition, increased P availability and optimum pH for proper growth of cassava. The results of this study showed that soil application of gypsum increased the yield of cassava by more than 50%. On the other hand, Wuddivira and Camps-Roach [27] reported that calcium in addition to organic matter can improve aggregation in tropical sandy-kaolinitic soil, which increases the soil rootability, by increasing aggregate stability resulting from the formation of strong bonds involving Ca^{2+} bridges.

In conclusion, the low Fe and carbon content of tropical soil, by increasing the propensity to cohesion, cause the sustainability of soil use to depend heavily on the careful management of physical properties. To improve the rootability of the arable layer, a combination of mulching with gypsum rather than tillage is recommended, mainly in soils prone to cohesion, as observed by Moura et al. [12].

3. Importance and Dynamics of Soil Organic Matter for Soil Fertility and Land-Use Sustainability in the Humid Tropics

3.1. Relevance of Soil Organic Matter

Soil Organic Matter (SOM) is a key indicator of soil quality in its three dimensions: soil physics, soil chemistry, and soil biology. In the soil physical dimension, SOM content is negatively correlated with bulk soil density [28,29] and positively correlated both with water infiltration [29] and water retention [30,31], as well as pore volume and soil aeration [32]. In the soil chemical dimension, organic forms of nutrients dominate over inorganic forms [33] and SOM is associated with lower P-fixation [34] and reduced Al-toxicity [35] due to the organic complexation of free Al. In contrast, SOM content is not clearly linked to soil pH. Soil biota depends heavily on and is concentrated within the SOM [36] as a consequence of the physico-chemical factors mentioned above and, in turn, decisively affects them. Labile and dissolved organic matter provides energy sources for decomposer organisms, and organic nutrients provide the life basis for macro- and mesofauna [37] and for soil bacteria and fungi [38]. The elevated availability of nutrients in topsoil organic matter promotes intense colonization by plant roots [39], which in turn promotes microbial activity in the "rhizosphere" via root exudation, cell slaying, and dead roots [40].

Compared to the semiarid tropics, the relevance of SOM for soil quality and the soil productive potential is even greater in the soils of the humid tropics [41]; in contrast to the topsoil organic matter, the highly weathered mineral sub-soils have poor nutrient availability and nutrient-retention capacity, and suffer from severe P-fixation [42], often with serious problems of Al- and Mn-toxicity [43]. Consequently, both the SOM and the nutrients it contains, and soil productive potential are almost exclusively concentrated in their "O" and "A" horizons.

3.2. Factors Influencing Organic Matter in Soils of the Humid Tropics

The SOM concentration is a consequence of the balance of C-inputs vs. C-outputs, both of which are very rapid in the humid tropics. C-input via leaf litter is at a record high in mature rainforests (6.66–11.21 $Mg \cdot ha^{-1} \cdot year^{-1}$ [44]). C-inputs via root exudation are believed to represent 1%–10% of net assimilated C-fluxes [45], though estimates are usually based on pot experiments and are therefore insecure for forest ecosystems. Belowground C-inputs from exudation and root sloughing from C4 grasses are high in Brachiaria pastures [46,47], forming the base for SOM-buildup in these systems. The main pathway of C-outputs is via decomposition/respiration of OM and the emission of CO_2 (and small but climate-relevant amounts of methane [48]) to the atmosphere. Leaching of labile organic matter compounds is only of minor importance [49] as such compounds will be readily acquired by microorganisms [50], erosion is virtually absent in densely vegetated mature rainforests in well-drained weathered soils [51], and CO_2 emissions via burning do not occur in dense fire-free mature rainforests (but see [52]). Decomposition dynamics are extremely rapid in Amazonia and the humid tropics as a whole because the constantly favorable temperatures and permanent water availability in central (though not peripheral) Amazonia provide a basis for the high metabolic activity of soil biota [41].

Organic matter decomposition is strongly driven by the chemical composition of the organic matter input from leaves, wood, roots, and exudates, and decomposition duration varies from a few days (for, e.g., sugars and amino acids) to several years [53]. High-quality litter with a low C:N-ratio, a high nutrient-content, and the absence of toxic or repellant substances decomposes quickly, but it contributes little to SOM formation due to high associated soil respiration [54]. By contrast, lignins and high molecular weight polyphenols decompose much more slowly [41,55]. A continuum of continuously more condensed components of SOM are increasingly more stable [36,56] and bind to the surfaces of clay minerals to form "organo-mineral complexes" [57].

Species-specific differences in both the organic matter inputs and their chemical composition and decomposition dynamics can affect the SOM contents [42,58,59], though these effects may be limited to the labile fractions of SOM [60]. Elevated contents of polyphenols and other secondary components in leaf and root tissue retard litter decomposition and nutrient release and favor mycorrhizal fungi in oligotrophic humid tropical vegetation [61]. Plant species differentially affect and occasionally even control the soil microbiota in their surrounding "influence zones" of the litter layer, stemflow, and roots [62–64], and affect the spatial variability of soil physico-chemistry [65].

As with any soil, the SOM concentration in humid tropical soils is positively and approximately linearly correlated with the soil clay and silt content [30,66] and negatively correlated with the (especially coarse) sand content [67], both of which vary systematically along the soil catena. Compared to sandy soils, an increased OM content in clayey/silty soils is due to the protection of SOM decomposition via the formation of "organo-mineral complexes" [68]. Next to the total clay content, clay mineralogy is a key for the formation of such organo-mineral complexes, and inclination of the approximately linear relationship between clay + silt content and SOM is affected by the predominating clay minerals—steepest with high-surface montmorillonite and allophonic clays (both absent in weathered upland soils of the humid tropics) and lowest in low-surface and low-charge 1:1 kaolinite (which predominates in these highly weathered soils) [33,69]. Location of SOM may also impact its decomposability, with deep soil organic matter supposedly more stable/resistant to microbial decomposition [70], likely driven by the lower energy-availability to decomposer communities in the deep soil [71].

Both concentration and stocks of SOM in the tropical rainforest zone are moderate relative to other biomes [72]. In stark contrast to this are the peat soils in some lowlands, notably in Indonesia and Malaysia [73], in which the organic layer occasionally extends to more than 4 m in depth, due to the inhibition of decomposition by a seasonal or continuous anaerobic environment [74,75]. From a global warming perspective, it is of the utmost importance to protect these organic soils from the potentially heavy and disproportionally high C-losses caused by either fire [76–78] or drainage [79]. SOM also is very high in "Indian Blacksoils", due to the resistance of pyrogenic carbon to soil decomposition (see Section 3.4).

3.3. Anthropic Impacts on Amazonian SOM

Amazonian deforestation and transformation to pasture or shifting cultivation as well as the occurrence of repeated fires heavily affect and degrade aboveground organic matter stocks by 7.5—70 Mg $C \cdot ha^{-1} \cdot year^{-1}$ along the arc of deforestation [76,80] and CO_2 emissions caused by above-ground biomass losses account for 76% of Brazil's inventoried GHG emissions [81]. The associated changes in the SOM stock are much smaller and frequently non-significant [82]. Whereas slash-and-burn typically consumes >95% of the aboveground C-stocks directly via burning or immediately thereafter via microbial decomposition of the debris [83], the direct fire-effects on belowground SOM are much less severe and are limited to the first 3 cm of depth, since heat is transmitted upwards and the thermal conductivity in dry soil (in which most fires occur) is low [84,85]. An exception is the potentially devastating effects of long-duration fires on peatland soils, mainly in Southeast Asia [86] but also in parts of Amazonian lowlands.

Reduction of the aboveground vegetation implies a lower aboveground organic matter input in pastures, shifting cultivated fields and degraded or young secondary forests, but this is partially compensated for by the slower organic matter decomposition that is caused by less favorable microclimatic conditions [87] and sometimes by reduced litter "quality" (less nutrients, higher lignin and polyphenol content) in degraded land. Agroforestry legumes can build up and maintain SOM relative to degraded areas [88], via continual inputs of leaf/twig (and root) litter and of pruning. Plant tissues with slow decomposition dynamics caused by low "litter quality" (high content of lignins and other secondary plant compounds, wide C:N and C:P-ratios) are more efficient in SOM-buildup and maintenance, whereas fast-decomposing green manures fail to increase SOM [54]. On the other hand, the inclusion of N_2-fixing legume trees in restoration efforts has been shown to increase SOM buildup and SOC sequestration [89,90]. Mechanical disturbance via ploughing of weathered humid tropical upland soils causes very rapid and permanent SOM losses and often even results in permanent land degradation or anthropic savannization [91].

High inputs by root exudation and root slowing of C4-grasses (in Amazonia mainly *Brachiaria brisantha*, *B. humidicola*, and *Panicum maximum*) inject substantial amounts of C into the soil which compensate or frequently even over-compensate for initial SOM-losses caused by deforestation, as revealed in many $\delta^{13}C$ isotopic studies [92,93]. However, this holds true only for well-managed pastures, preferably also containing a legume component [94], whereas degraded *Brachiaria* pastures do not sequester SOC [95]. In a meta-analysis of 21 Amazonian studies on the effects of deforestation on 0–20 cm SOM stocks depicts (i) small increases (+6.8% or +2.2 Mg $C \cdot ha^{-1}$) in pastures and (ii) losses (−8.5% or −4.5 Mg $C \cdot ha^{-1}$) in annually cropped lands (with unclear land-use history) relative to soil in paired mature rainforests [82]. Such estimates are far lower than the anthropic effects on aboveground organic matter. Soil organic matter stocks of successional forests (secondary regrowth following pastures or shifting cultivation) or of plantation forests differ only marginally and mostly non-significantly relative to paired mature rainforest sites [96–98].

3.4. Biochar and Indian Blacksoils

The "Indian Black Soils" (*terra preta de índio*) mentioned above are geographically very limited but are nevertheless a fascinating exception to the low-fertility Amazonian Oxisols and Ultisols, with a very deep organic matter layer (occasionally several meters) that is nutrient-rich [99] and with its soil biology [100] forming the basis for very high agronomic productivity. Advanced analytical methods (^{13}C-NMR) have demonstrated the pyrogenic origin of this SOM [101]. Rather than burning organic matter and its transformation into CO_2, carbonization under reduced O_2 causes the formation of biochar/"black carbon" via pyrogenic chemical transformations/molecular condensation. The very large organic matter content and stocks in Indian Black Soil are due to the retarded decomposition of biochar because the predominating aromatic and aliphatic compounds they contain are relatively stable, notably highly condensed soot can be resistant to microbial decomposition for thousands of years [102]. Typically, more than 50% of the newly formed biochar has long-term (decades or centuries) resistance to microbial decomposition [103]. Large-scale application of biochar in agriculture has been proposed as a promising technology for long-term C-sequestration and underground storage [104,105]. At the same time, much research and many (though not all) experimental applications of charcoal have demonstrated positive effects of black carbon on soil physical properties, including pore space; bulk density; water retention and infiltration [102,106,107]; soil chemical characteristics, such as a long-term increase in the cation exchange capacity [108,109], nutrient retention [110], improved P availability [111,112] (but frequently reduced N-availability [113], and reduced methane and nitrous oxide emissions [114–116] (but see [117,118]). Biochar applications have also been reported beneficial for soil biology, such as increases in mycorrhizal fungi [119] and in biological N_2-fixation [120] (but see [121] and increases in overall diversity of the microbiota [103,122,123], despite the possible toxic nature of some biochar compounds [124]. In many (though not all) cases, experimental charcoal application has significantly increased agronomic productivity [123]. The effects of charcoal application vary widely with the vegetal origin, carbonization conditions [124] and quantity of the charcoal tested, and they are most pronounced and positive in combination with organic nutrient input (manure, for example, in horticulture) or inorganic nutrients [125], and in combination with earthworms [126].

The negative effects of high fire frequency and short fallow periods on the secondary forest biomass are among the most pressing socioecological issues concerning degrading shifting cultivation systems throughout the humid tropics [127,128] and in Amazonia [129]. An under-researched aspect of frequent fires in slash-and-burn shifting cultivation is the repeated inputs of 2%–3% of the total aboveground biomass in the form of charcoal with each slash-and-burn cycle [83]. Little is known about the effects of such constant black-C inputs on the SOM in regions with a long-term shifting cultivation history, though these could potentially serve as a long-term carbon sink [130–132] and could potentially improve the soil's physicochemical properties.

4. Soil Chemical Indicators, Availability, and Nutrient Use Efficiency in Humid Tropical Soil Affect Sustainability

Establishing and maintaining low-input agricultural systems suitable for small holdings in the humid tropics will require a reduction in cost and an increase in the efficiency of nutrient use [21]. Therefore, agricultural researchers find it extremely difficult to establish low-input agricultural systems suitable for smallholders without resorting to environmentally harmful slash-and-burn practices [2]. Challenges arise from a combination of factors that increase the rate of nutrient removal from the profile and reduce crop nutrient use efficiency, including the low cation-retention capacity of these weathered soils and the high rainfall during the humid period. The land use and management affect the soil quality and sustainability of production systems [133]. Thus, soil quality has been defined as the soil's capacity or fitness to support plant growth without resultant soil degradation or other environmental damage or, more simply, as fit for purpose [134].

4.1. Soil Chemical Indicators and Tropical Land Degradation

The physical, chemical, and biological properties of soil are called soil quality indicators. Soil quality has been defined as "the capacity of a soil to function within ecosystem and land-use boundaries, to sustain biological productivity, maintain environmental quality and promote plant and animal health" [134,135]. Soil quality may display resilience when, for example, an indicator returns to the initial conditions or to conditions similar to those at the start of agricultural production. If a parameter is different from that prior to agricultural disturbance (altered and worsened condition), the degradation of the soil quality is indicated. Soil conservation measurements by chemical indicators are easily interpreted, and the soil quality may occasionally be increased by agricultural practices such as liming and/or fertilization. Due to agricultural practices by farmers, soil chemical attributes have presented a positive linear correlation lower than 0.5 ($p < 0.05$) with sugarcane yield [136] and beans yield (*Phaseolus vulgaris* L.) [137]. Soil chemical indicators can also be useful when considering a soil's capacity for maintaining high yield and sustainability, nutrient cycling, plant biomass, and organic matter [133].

The availability and uptake efficiency of crop nutrients is a fundamental consideration in any attempt to achieve sustainability and productivity in many tropical agricultural systems. Thus, crop potential productivity is not achieved due to low soil chemical fertility being a primary constraint in tropical regions [6]. Low soil chemical fertility is becoming increasingly recognized as the fundamental cause of deforestation and declining food security in smallholder farms both in and around the Amazon region, where farmers nearly always consider forest vegetation to be a nutrient source after burning [3].

The soil pH, cation exchange capacity (CEC), organic matter, and nutrient levels are the main chemical attributes used for soil quality assessment, especially when considering a soil's capacity for supporting high yield crops [133,138]. These chemical indicators are sensitive to soil management and natural disturbance [19]. Soil pH is a principal chemical indicator because it correlates directly with nutrient availability and solubility in soil [139,140]. Evidence from experimental manipulations was reported by Stark et al. [140] showing that low soil pH limits microbial growth and extracellular enzyme activities. Zhao et al. [141] reported that liming application resulted in a 10-fold increase in bacterial growth rates compared with the control. These authors also reported that soil pH had a greater impact on soil microbial community composition. Rousk et al. [142] reported that soil pH is very important for the two principal decomposer groups in soil, fungi and bacteria, and they concluded that all microbial functions were inhibited below pH 4.5, likely due to the inhibitory effects induced by increased aluminum availability. The tillage system also affects soil pH as reported by Busari and Salako [143]. These authors showed that the no-tillage system pH was higher than in the conventional tillage.

The causes of land degradation in humid tropical areas include loss of basic cations, decreased SOM, and P depletion. Together, these factors result in decreased soil quality, biodiversity and, consequently, biomass productivity [6]. In the humid tropics, highly weathered tropical soil has a very low cation exchange capacity (CEC), which results in low nutrient retention and high nutrient removal rates. Nutrient removal results in a lower amount of cations in the profile (including K, Ca, Mg, and Na) and a lower proportion of the CEC occupied by basic cations. A relatively high CEC base saturation should be maintained to achieve the most sustainable cropping system. Low base saturation levels (<50%) result in very acidic soils with potentially toxic cations, such as Al and Mn, that can be released from the soil [144]. Soil acidity affects morphological, physiological and biochemical processes in plants and thus N uptake and use efficiency [145]. In contrast, high base saturation results in greater Ca, Mg, and K availability, buffers the soil pH, and decreases P availability [146].

4.2. Nitrogen, Phosphorus, and Potassium Use Efficiency

Highly weathered tropical soils can adsorb large amounts of P and remove P from the soil solution, which limits the availability of inorganic P for plants regardless of whether P is already present in the soil or is added as fertilizer. Lynch [147] and Kochian [148] reported that about 30%–50% of soil worldwide shows a high phosphate-fixing capacity. Due to the high phosphate-fixing large amounts of P fertilizer must be applied to overcome the limitations of P-fixation. However, for most farmers in tropical regions, mineral phosphate fertilizer is an expensive input and many farmers lack the financial resources to purchase phosphorus fertilizers [149]. One possibility for circumventing these problems is growing plant varieties with high P use efficiency.

Soil P occurs in various organic and inorganic forms that are important P sources for plants. The P organic rarely represents a major portion of soil P. In soil, inorganic P can be found in labile and non-labile forms and according to the degree of stability or solubility. P inorganic can be found in soil solution and fixed through adsorption, with oxides of Fe and Al (of clay fraction) [150]. This process establishes either weak adsorption (labile P) or strong adsorption (moderately labile P) with these oxides and, precipitated with Al, Fe, and Ca, establishes insoluble forms (non-labile P) [150]. Changes in the soil-P pools are affected by chemical and biological processes. Thus, it is important to understand the soil intervention practices that minimize the P-flow out from the cycle (through "fixation" reactions) and maximize the P-flow via dynamic pools that are accessible absorption by plant roots.

Braos et al. [150] reported that the contribution of soil organic P (Po) to increase available P (labile P) can be more relevant when organic fertilization or other practices that increase the SOM content are part of the soil management. However, plant and microbial strategies need to be further improved, particularly the uptake of residual soil P (from applied fertilizers and manures) and subsoil P uptake [151]. Some management strategies have positive effects on the availability and P use efficiency in highly weathered soils that are included the use of crop rotations, the presence of cover catch crops, crop breeding [152], no tillage system [153], and leguminous residues or alley cropping [8]. For example, the increase in P use efficiency occurs mainly due to the P adsorbed on various clays and Al/Fe oxides can be released by desorption reactions [154]. The desorption of P has a direct relationship with the content of P-sorbed [155]. Strategies for improving P efficiency in soil and reducing P adsorption to soil particles involve applying organic substances. Humic acids contain large numbers of negative charges and carboxyl and hydroxyl groups, which compete for the adsorption sites with P inorganic [156]. Additionally, legumes modify the distribution of soil-P among various pools when trees take up a portion of the inorganic P and transform it into organic P. This transformation results in the buildup of organic P in the soil and prevents a portion of the P from becoming fixed by the soil [133].

The efficiency of nitrogen and potassium usage is a major factor for the successful management of low input agrosystems in soils in the periphery of Amazonia, which are susceptible to cohesion and subject to high nutrient leaching. Unlike in other regions of Brazil, the sole use of inorganic potassium (K) and nitrogen (N) fertilizers is not recommended here because it does not allow a crop to reach its greatest productivity potential [15]. Nutrient retention in the root zone can be enhanced where nutrients are added in a slow release form and biologically mediated processes are utilized for nutrient release, as with green manure [17]. These approaches may sustain agrosystems in the humid tropics better than saturating the soil solution with soluble nutrients [156]. The loss of N fertilizer in cereal production can be attributed to the combined effects of denitrification, volatilization, and leaching. The uptake of N by crops is closely related to rootability conditions in the soil: higher root length densities lead to higher NO_3^- uptake and less leaching. When fertilizers such as urea are applied to the surface without incorporation as in no tillage systems, N losses can exceed 40%, and these losses are generally greater with increasing temperature, soil pH, and surface residues [19,157,158]. Therefore, for cereal crops grown under tropical conditions, the steady release of N from organic sources during the crop cycle, including the post-flowering stage, is important to complement the early and rapid availability of N from synthetic fertilizer. In most tropical soils that have a low buffering capacity in which K^+ ions do not interact strongly with the soil matrix, the application of K fertilizer results in a higher K concentration in the soil solution that might be leached under tropical humid conditions [159]. Because of the weak bond between K^+ ions and soil constituents, a reduction in the K concentration may also occur due to replacement with other cations, especially calcium after liming. K uptake is highly dependent on root development and requires a vigorously growing root system to intercept and absorb the available K. The response to the K supply at the final stage of cereal development suggests that the constant availability of K must be carefully considered to increase the productivity and sustainability of cropping systems under humid tropical conditions. A strategy for increasing the efficiency of nutrient use in a cohesive soil in the humid tropics must include enhancing root growth by improving the soil environment, adding nutrients in slow-release forms, and ensuring that at the flowering stage, nutrient demand and release are synchronized.

5. Organic Management of Tropical Soil Taking Advantage of Local Resources to Overcome the Challenges of Sustainability

5.1. Tropical Environment and Conventional versus Organic Agriculture Systems

The high temperature and humidity conditions and the prevalence of low fertility soils in the humid tropics prevent the use of an agricultural model based on monoculture, intensive mechanization and extensive plantation to support the sustainability of the agrosystem. Under these circumstances, the use of the biological diversity and the synergism between the main components of the organic farm systems can ensure the sustainability of food production, in contrast to agricultural practices such as saturating the soils with soluble fertilizers that are recommended in other regions in intensive agricultural practices [1]. Organic agriculture refers to a farming system that bans the use of agrochemicals such as synthetic fertilizers and pesticides and the use of Genetically Modified Organisms (GMO), as well as many synthetic compounds used as food additives (e.g., preservatives, coloring) [160]. In addition to the high rate of nutrient removal from the soil profile due to high rainfall, the use of highly soluble fertilizer can release nutrients that are not synchronized with crop uptake mechanisms and may affect the soil biota, surface and subsurface water, and greenhouse gas emissions [161], especially in tropical environments that have high temperatures and high humidity. Soluble fertilizer, mainly nitrogen, may also affect the susceptibility of plants to insect pests by altering the nutrient levels in plant tissue or tissue fractions. For example, nitrogen fertilizer increases free amino N in several crops [162]. This biochemical imbalance affects both herbivore damage and the ability of a plant to recover from herbivory [163]. Therefore, organic agriculture is more adequate in the humid tropics by adopting a set of farming practices that emphasize ecological sustainability, principally diversification that optimizes the use of local resources and the synergism between their components [156]. This is a food production style that mimics the structure and function of tropical natural agro-ecosystems.

5.2. Alternative Local Resources for Organic Soil Management

In contrast to conventional management, Altieri et al. [163] claim that plants would be expected to be less prone to insect pests and diseases if organic soil amendments (e.g., organic compost) were used because they generally result in lower N concentrations in plant tissue. The use of residues such as wood ash, biofertilizer, and powdered rocks may be another low cost alternative to increase soil fertility without affecting the imbalance of nutrients [162]. Biofertilizer consists of liquid fermented manure that can be produced at a local farm, and it has been identified as an alternative to chemical fertilizer to increase soil fertility and crop production in sustainable farming [163]. It protects plants by providing micronutrients, growth-promoting substances, and N_2-fixing organisms. In experiments conducted in humid tropic soils [164], biofertilizer application reduced the damage caused by Spodoptera frugiperda in maize leaves and promoted a weight increase in pumpkins [165]. Organic management uses other strategies to optimize the nutritional status of crops such as mulching, no-tillage, intercropping and agroforestry systems. In a tropical environment, the major goal is to produce organic matter in abundance on a farm to avoid the high cost of organic manure, considering the high rate of decomposition of soil organic matter.

Crowder and Reganold [166] analyzed 55 organic and conventional farming practices on five continents and concluded that organic farming is more profitable than conventional farming, which has been attributed to better ecosystem services provided by organic management, although the yield is lower. Therefore, organic management has a greater potential for global expansion. The enhancement of ecosystem services like preservation of soils and renewal of their fertility, pollination of crops and natural vegetation, cycling and movement of nutrients, maintenance of biodiversity, is due to the substitution of monoculture for greater variability in crop rotation, intercropping, agroforestry systems associated with the exclusion of pesticides, highly soluble inorganic fertilizer, and genetically modified crops [167,168].

5.3. Harm and Risks of Agrochemical Use in Tropical Agrosystems

Agrochemicals entail a high risk of occupational pesticide exposure and environmental contamination, and serious poisoning problems and chronic illnesses result from pesticide exposure among agriculture workers [169]. Another problem is that the leaching of agrochemicals used in conventional agriculture systems (such as Glyphosate ((N phosphonomethyl) glycine) seems to be mainly determined by the soil structure and rainfall [170]. Tropical soils normally have good structure and receive intense rainfall. Pesticides can disrupt the equilibrium between pests and natural enemies. Pesticides are important in large monocultures but are prohibitive in organic management. The high complexity of organic systems introduces more diversity into agroecosystems, which are characterized by more beneficial organisms, natural enemies and "biocontrol plants" that provide food or shelter for biocontrol agents [171,172]. Under organic management, leguminous trees *Clitoria fairchildiana* increased in arbuscular mycorrhizal spores near hedgerows [173]. In another experiment, we observed that the addition of leguminous residue promoted the enhancement of the arthropod population in pumpkins cultivated in an alley cropping system under organic management [174].

International organic regulations and certification rules in many countries (such as Brazil and the USA) prohibit high solubility fertilizers, agrochemicals and GMOs [175]. Although they may seem retrogressive to some, the legal impediments established by organic certification systems aim to prevent a variety of harmful outcomes. Organic farming cannot use GMOs due to (i) potential environmental risk (exotic invasive species, pesticide resistance); (ii) risk to human health (allergic response); (iii) inaccessibility to small holders; and (iv) creating dependence on seed companies.

6. Current and Future Developments

Substituting traditional systems such as shift agriculture, slash-and-burn, and predatory extensive pasture with other environmentally more suitable practices in the humid tropics is recommended, firstly due to the pressing need to increase agricultural productivity, and secondly due to the urgency of reducing the environmental impact of slash-and-burn techniques and deforestation [2]. This challenge also provides a great opportunity to adopt agrosystems that enhance soil fertility while reducing the impact of atmospheric CO_2 emissions, reducing emissions from biomass burning or decomposition, and retaining C within the soil organic matter.

Unfortunately, alternatives that replicate systems like extensive and monocultural agriculture established for the south/southeast regions of Brazil based on soil tillage and soil nutrient saturation do not ensure crop productivity or agrosystem sustainability in the humid tropics. In this region, to improve and maintain soil fertility in this region, no-tillage farming and mulching are more important than are other common practices such as plowing and chiseling because they contribute to the formation of a litter layer that reduces evapotranspiration [6,20]. This may delay soil drying and hardening during periods without rain. In contrast, the continuous use of mulch may increase the labile organic matter fraction responsible for the formation of an ephemeral structure that, in turn, is important for root growth. Thus, overall, this process may enhance soil rootability, uptake, and nutrient use efficiency [16]. Although the use of mulching and the increasing organic matter affect the primary sustainability issues in tropical agrosystems, their effects are limited to the surface layer and have little effect on nutrient availability. In the future, alternatives that favor the use of the local resources to increase the nutrient supply and attenuate the processes that impair the efficiency of its use must be sought.

7. Conclusions

Weathered tropical soils are prone to cohesion and hardsetting, as well as being acidic, low in cation availability, and prone to strong P-fixation. Traditional slash-and-burn practices degrade soil productivity because of the increasingly high frequency of fires and reduced fallow periods, causing a loss of biodiversity and ultimately rural poverty. Application of conventional soil management of the temperate zones fails in these soils, as ploughing causes catastrophic losses in soil organic matter and permanent savannization, and chemical fertilizers are rapidly lost and therefore inefficient. This calls for the development of alternative strategies, promising avenues for a more sustainable management of tropical soils including biological nitrogen fixation and P-solubilization, slow-release fertilizers and local alternative inputs, the application of gypsum for improvement of soil rootability, and black carbon for the restoration and maintenance of soil organic matter.

Acknowledgments: The authors wish to thank CNPq (National Council for Scientific and Technological Development), CAPES (Coordination for the Improvement of Higher Level Personnel), and FAPEMA (Foundation of Research and Development Scientific and Technological of Maranhão, Brazil) for their support. Academic English Solutions revised the English of the manuscript (http://www.academicenglishsolutions.com/AES/home.html).

Author Contributions: The individual contribution and responsibilities of the authors were as follows: Emanoel Gomes de Moura conceived the need for this review paper and contributed to the review of soil physical indicators. Christoph Gehring contributed to the review of soil organic matter. Heder Braun and Fabricio de Oliveira Reis contributed to the review of soil chemical indicators. Altamiro de Souza Lima Ferraz, Junior contributed to the review of organic management of tropical soil. Alana das Chagas Ferreira Aguiar helped draft, edit, and revise the manuscript. The discussion was a team task. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Food and Agriculture Organization of the United Nations (FAO). *Report of the Council of FAO*; FAO: Washington, DC, USA, 1988.
2. Moura, E.G.; Sena, V.G.L.; Correa, M.S.; Aguiar, A.F.C. The Importance of an Alternative for Sustainability of Agriculture around the Periphery of the Amazon Rainforest. *Recent Pat. Food Nutr. Agric.* **2013**, *5*, 70–78. [CrossRef] [PubMed]
3. Aguiar, A.C.F.; Freitas, I.C.; Carvalho, C.S.; Monroe, P.H.M.; Moura, E.G. Efficiency of an agrosystem designed for family farming in pre-Amazon region. *Renew. Agric. Food Syst.* **2011**, *26*, 24–30. [CrossRef]
4. Stirling, G.R. Soil ecosystems management in sustainable agriculture. In *Biological Control of Plant-Parasitic Nematodes*; CABI: London, UK, 2014.
5. Lu, Y.; Wang, R.; Zhang, Y.; Su, H.; Wang, P.; Jenkins, A.; Ferrier, R.C.; Bailey, M.; Squire, G. Ecosystem health towards sustainability. *Ecosyst. Health Sustain.* **2015**, *1*, 1–15. [CrossRef]
6. Aweke, M.; Gelaw, R.; Singh, R.; Lal, R. Soil Quality indices for evaluating smallholder agricultural land uses in Notthern Ethiopia. *Sustainability* **2015**, *7*, 2322–2337.
7. Viana, R.M.; Ferraz, J.B.S.; Neves Junior, A.F.; Vieira, G.; Pereira, B.F.F. Soil quality indicators for different restoration stages on Amazon rainforest. *Soil Tillage Res.* **2014**, *140*, 1–7. [CrossRef]
8. Aguiar, A.C.F.; Candido, C.S.; Carvalho, C.S.; Monroe, P.H.M.; Moura, E.G. Organic matter fraction and pools of phosphorus as indicators of the impact of land use in the Amazonian periphery. *Ecol. Indic.* **2013**, *30*, 158–164. [CrossRef]
9. Doré, T.; Makowski, D.; Malézieux, E.; Munier-Jolain, N.; Tchamitchian, M.; Tittonell, P. Facing up to the paradigm of ecological intensification in agronomy: Revisiting methods, concepts and knowlegde. *Eur. J. Agron.* **2011**, *34*, 197–210. [CrossRef]
10. Moura, E.G.; Marques, E.S.; Silva, T.M.B.; Piedade, A.; Aguiar, A.C.F. Interactions among leguminous trees, crops and weeds in a no-till alley cropping system. *Int. J. Plant Prod.* **2014**, *8*, 441–456.
11. Lordan, J.; Pascual, M.; Fonseca, F.; Villar, J.M.; Rufat, J. Use of rice husk to enhance peach tree performance in soils with limiting physical properties. *Soil Tillage Res.* **2013**, *129*, 19–22. [CrossRef]
12. Moura, E.G.; Sena, V.G.L.; Sousa, C.C.M.; Silva, F.R.; Coelho, M.J.A.; Macedo, V.R.A.; Aguiar, A.C.F. Enhancement of the rootability of a structurally fragile tropical soil using gypsum and leguminous residues to increase the maize yield. *Soil Use Manag.* **2016**, *32*, 118–126. [CrossRef]
13. Mishra, A.K.; Aggarwal, P.; Bhattacharyya, R.; Das, T.K.; Sharma, A.R.; Singh, R. Least limiting water range for two conservation agriculture cropping systems in India. *Soil Tillage Res.* **2015**, *150*, 43–56. [CrossRef]

14. Letey, J. Relationship between soil physical properties and crop production. *Adv. Soil Sci.* **1985**, *1*, 277–294.
15. Moura, E.G.; Oliveira, A.K.C.; Pinheiro, K.M.; Aguiar, A.C.F. Management of a cohesive tropical soil enhance rootability and increase the efficiency of nitrogen and potassium use. *Soil Use Manag.* **2012**, *28*, 370–377. [CrossRef]
16. Daniells, I.G. Hardsetting soils: A review. *Soil Res.* **2012**, *50*, 349–359. [CrossRef]
17. Moura, E.G.; Serpa, S.S.; Santos, J.G.D.; Costa Sobrinho, J.R.S.; Aguiar, A.C.F. Nutrient use efficiency in alley cropping systems in the Amazonian periphery. *Plant Soil* **2010**, *335*, 363–371. [CrossRef]
18. Duval, M.E.; Galantini, J.A.; Iglesias, J.O.; Canelo, S.; Martinez, J.M.; Wall, L. Analysis of organic fractions as indicators of soil quality under natural and cultivated systems. *Soil Tillage Res.* **2013**, *131*, 11–19. [CrossRef]
19. Moura, E.G.; Aguiar, A.C.F.; Piedade, A.R.; Rousseau, G.X. The contribution of legume tree residues and macrofauna to the improvement of abiotic soil properties in the eastern Amazon. *Appl. Soil Ecol.* **2015**, *86*, 91–99. [CrossRef]
20. Mulumba, L.N.; Lal, R. Mulching effects on selected soil physical properties. *Soil Tillage Res.* **2008**, *98*, 106–111. [CrossRef]
21. Moura, E.G.; Monroe, P.H.M.; Coelho, M.J.A.; Costa Sobrinho, J.R.S.; Aguiar, A.C.F. Effectiveness of calcined rock phosphate and leucaena prunings as a source of nutrients for maize in a tropical soil. *Biol. Agric. Hort.* **2013**, *29*, 132–144. [CrossRef]
22. Twum, E.K.A.; Nii-Annang, S. Impact of soil compaction on bulk density and root biomass of *Quercus petraea* L. at Reclaimed Post-Lignite Mining Site in Lusatia, Germany. *Appl. Environ. Soil Sci.* **2015**. [CrossRef]
23. Johan, A.; Hakansson, I. Response of different crops to soil compaction—Short-term effects in Swedish field experiments. *Soil Tillage Res.* **2014**, *138*, 56–63.
24. Sumner, M.E. Gypsum improves subsoil root growth. In Proceedings of the International Symposium Root Reseacher and Aplications, Viena, Austria, 2–4 September 2009.
25. Nora, D.D.; Amado, T.J.C.; Bortolotto, R.P.; Ferreira, A.O.; Reichardt, K.; Santi, A.L. Subsoil chemical amelioration and crop yields under continuous long-term no-till in a subtropical Oxisol. *Afr. J. Agric. Res.* **2014**, *9*, 3338–3349.
26. Anikwe, M.A.N.; Eze, J.C.; Ibudialo, A.N. Influence of lime and gypsum application on soil properties and yield of cassava (*Manihot esculenta Crantz.*) in a degraded Ultisol in Agbani, Enugu Southeastern Nigeria. *Soil Tillage Res.* **2016**, *158*, 32–38. [CrossRef]
27. Wuddivira, M.N.; Camps-Roach, G. Effects of organic matter and calcium on soil structural stability. *Eur. J. Soil Sci.* **2007**, *58*, 722–727. [CrossRef]
28. Chaudhari, P.R.; Ahire, D.V.; Ahire, V.D.; Chkravarty, M.; Maity, S. Soil bulk density as related to soil texture, organic matter content and available total nutrients of Coimbatore soil. *Int. J. Sci. Res. Publ.* **2013**, *3*, 1–8.
29. Blanco-canqui, H.; Shapiro, C.A.; Wortmann, C.S.; Drijber, R.A.; Mamo, M.; Shaver, T.M.; Ferguson, R.B. Soil organic carbon: The value to soil properties. *J. Soil Water Conserv.* **2013**, *68*, 129A–134A. [CrossRef]
30. Manns, H.R.; Berg, A.A. Importance of soil organic carbon on surface soil water content variability among agricultural fields. *J. Hydrol.* **2014**, *516*, 297–303. [CrossRef]
31. Yang, F.; Zhang, G.L.; Yang, J.L.; Li, D.C.; Zhao, Y.G.; Liu, F.; Yang, R.M.; Yang, F. Organic matter controls of soil water retention in an alpine grassland and its significance for hydrological processes. *J. Hydrol.* **2014**, *519*, 3086–3093. [CrossRef]
32. Zaffar, M.; Lu, S.G. Pore size distribution of clayey soils and its correlation with soil organic matter. *Pedosphere* **2015**, *25*, 240–249. [CrossRef]
33. Blume, H.P.; Brümmer, G.W.; Fleige, H.; Horn, R.; Kandeler, E.; Kögel-Knabner, I.; Kretzschmar, R.; Stahr, K.; Wilke, B.M. Soil Organic Matter. In *Scheffer/Schachtschabel Soil Science*; Springer: Berlin, Germany; Heidelberg, Germany, 2016; pp. 55–86.
34. Flores, J.C.M.; Realpe, I.B.; Montoya, J.C. Retention and availability of phosphorus associated with organic matter in a typic melanudands of Cauca Department, Colombia. *Acta Agron.* **2014**, *62*, 261–267.
35. Hagvall, K.; Persson, P.; Karlsson, T. Speciation of aluminum in soils and stream waters: The importance of organic matter. *Chem. Geol.* **2015**, *417*, 32–43. [CrossRef]
36. Dungait, J.A.J.; Hopkins, D.W.; Gregory, A.S.; Whitmore, A.P. Soil organic matter turnover is governed by accessibility not recalcitrance. *Glob. Chang. Biol.* **2012**, *18*, 1781–1796. [CrossRef]

37. Whalen, J.K. Managing soil biota-mediated decomposition and nutrient mineralization in sustainable agroecosystems. *Adv. Agric.* **2014**, *2014*, 1–13. [CrossRef]
38. Cotrufo, M.F.; Wallenstein, M.D.; Boot, C.M.; Denef, K.; Paul, E. The microbial efficiency-matrix stabilization (mems) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Glob. Chang. Biol.* **2013**, *19*, 988–995. [CrossRef] [PubMed]
39. Hinsinger, P.; Bengough, A.G.; Vetterlein, D.; Young, I. Rhizosphere: Biophysics, biogeochemistry and ecological relevance. *Plant Soil* **2009**, *321*, 117–152. [CrossRef]
40. Jones, D.L.; Nguyen, C.; Finlay, R.D. Carbon flow in the rhizosphere: Carbon trading at the soil–root interface. *Plant Soil* **2009**, *321*, 5–33. [CrossRef]
41. Lal, R. Challenges and opportunities in soil organic matter research. *Eur. J. Soil Sci.* **2009**, *60*, 158–169. [CrossRef]
42. Gama-Rodrigues, A.C.; Sales, M.V.S.; Silva, P.S.D.; Comerford, N.B.; Cropper, W.P.; Gama-Rodrigues, E.F. An exploratory analysis of phosphorus transformations in tropical soils using structural equation modeling. *Biogeochemistry* **2014**, *118*, 453–469. [CrossRef]
43. Cristancho, R.J.A.; Hanafi, M.M.; Syed Omar, S.R.; Rafii, M.Y. Aluminum speciation of amended acid tropical soil and its effects on plant root growth. *J. Plant Nut.* **2014**, *37*, 811–827. [CrossRef]
44. Chave, J.; Navarrete, D.; Almeida, S. Regional and seasonal patterns of litterfall in tropical South America. *Biogeosciences* **2010**, *7*, 43–55. [CrossRef]
45. Jones, D.L.; Hodge, A.; Kuzyakov, Y. Plant and mycorrhizal regulation of rhizodeposition. *New Phytol.* **2004**, *163*, 459–480. [CrossRef]
46. Souza Braz, A.M.; Fernandes, A.R.; Alleoni, L.R.F. Soil attributes after the conversion from forest to pasture in Amazon. *Land Degrad. Dev.* **2013**, *24*, 33–38. [CrossRef]
47. Anderson-Teixeira, K.J.; Wang, M.M.H.; McGarvey, J.C.; LeBauer, D.S. Carbon dynamics of mature and regrowth tropical forests derived from a pantropical database (TropForC-db). *Glob. Chang. Biol.* **2016**. [CrossRef] [PubMed]
48. Skinner, C.; Gattinger, A.; Muller, A.; Mäder, P.; Flieβbach, A.; Stolze, M.; Ruser, R.; Niggli, U. Greenhouse gas fluxes from agricultural soils under organic and non-organic management—A global meta-analysis. *Sci. Total Environ.* **2014**, *468–469*, 553–563. [CrossRef] [PubMed]
49. Craswell, E.T.; Lefroy, R.D.B. The role and function of organic matter in tropical soils. *Nutri. Cycl. Agroecol.* **2001**, *61*, 7–18. [CrossRef]
50. Zech, W.; Senesi, N.; Guggenberger, G.; Kaiser, K.; Lehmann, J.; Miano, T.M.; Miltner, A.; Schroth, G. Factors controlling humification and mineralization of soil organic matter in the tropics. *Geoderma* **1997**, *79*, 117–161. [CrossRef]
51. Labrière, N.; Locatelli, B.; Laumonier, Y.; Freycon, V.; Bernoux, M. Soil erosion in the humid tropics: A systematic quantitative review. *Agric. Ecosyst. Environ.* **2015**, *203*, 127–139. [CrossRef]
52. Bonal, D.; Burban, B.; Stahl, C.; Wagner, F.; Hérault, B. The response of tropical rainforests to drought—Lessons from recent research and future prospects. *Ann. For. Sci.* **2016**, *73*, 27–44. [CrossRef] [PubMed]
53. Dias, T.; Oakley, S.; Alarcón-Gutiérrez, E.; Ziarelli, F.; Trindade, H.; Martins-Loução, M.A.; Sheppard, L.; Ostle, N.; Cruz, C. N-driven changes in a plant community affect leaf-litter traits and may delay organic matter decomposition in a Mediterranean maquis. *Soil Biol. Biochem.* **2013**, *58*, 163–171. [CrossRef]
54. Qiao, N.; Xu, X.; Hu, Y.; Blagodatskaya, E.; Liu, Y.; Schaefer, D.; Kuzyakov, Y. Carbon and nitrogen additions induce distinct priming effects along an organic-matter decay continuum. *Sci. Rep.* **2016**. [CrossRef] [PubMed]
55. Talbot, J.M.; Yelle, D.J.; Nowick, J.; Treseder, K.K. Litter decay rates are determined by lignin chemistry. *Biogeochemistry* **2012**, *108*, 279–295. [CrossRef]
56. Lehmann, J.; Kleber, K. The contentious nature of soil organic matter. *Nature* **2015**, *528*, 60–68. [CrossRef] [PubMed]
57. Hättenschwiler, S.; Vitousek, P.M. The role of polyphenols in terrestrial ecosystem nutrient cycling. *TREE* **2000**, *15*, 238–243. [CrossRef]
58. Russell, A.E.; Raich, J.W. Rapidly growing tropical trees mobilize remarkable amounts of nitrogen, in ways that differ surprisingly among species. *Proc. Nat. Acad. Sci. USA* **2012**, *109*, 10398–10402. [CrossRef] [PubMed]

59. Vesterdal, L.; Clarke, N.; Sigurdsson, B.D.; Gundersen, P. Do tree species influence soil carbon stocks in temperate and boreal forests? *For. Ecol. Manag.* **2013**, *309*, 4–18. [CrossRef]
60. Gentile, R.; Vanlauwe, B.; Six, J. Litter quality impacts short- but not long-term soil carbon dynamics in soil aggregate fractions. *Ecol. Appl.* **2011**, *21*, 695–703. [CrossRef]
61. Hättenschwiler, S.; Coq, S.; Barantal, S.; Handa, I.T. Leaf traits and decomposition in tropical rainforests: Revisiting some commonly held views and towards a new hypothesis. *New Phytol.* **2011**, *189*, 950–965. [CrossRef] [PubMed]
62. Schmidt, M.W.I.; Torn, M.S.; Abiven, S. Persistence of soil organic matter as an ecosystem property. *Nature* **2011**, *478*, 49–56. [CrossRef] [PubMed]
63. Germer, S.; Zimmermann, A.; Neill, C.; Krusche, A.V.; Elsenbeer, H. Disproportionate single-species contribution to canopy-soil nutrient flux in an Amazonian rainforest. *For. Ecol. Manag.* **2012**, *267*, 40–49. [CrossRef]
64. Austin, A.T.; Vivanco, L.; Gonzáles-Arzac, A.; Pérez, L.I. There's no place like home? An exploration of the mechanisms behind plant litter–decomposer affinity in terrestrial ecosystems. *New Phytol.* **2014**, *204*, 307–314. [CrossRef] [PubMed]
65. Parsons, S.A.; Congdon, R.A.; Shoo, L.P.; Valdez-Ramirez, V.; Williams, S.E. Spatial variability in litterfall, litter standing crop and litter quality in a tropical rain forest region. *Biotropica* **2014**, *46*, 378–386. [CrossRef]
66. Desjardins, T.; Barros, E.; Sarrazin, M.; Girardin, C.; Mariotti, A. Effects of forest conversion to pasture on soil carbon content and dynamics in Brazilian Amazonia. *Agric. Ecosyst. Environ.* **2004**, *103*, 365–373. [CrossRef]
67. Feller, C.; Beare, M.H. Physical control of soil organic matter dynamics in the tropics. *Geoderma* **1997**, *79*, 69–116. [CrossRef]
68. Feng, W.; Plante, A.F.; Aufdenkampe, A.K.; Six, J. Soil organic matter stability in organo-mineral complexes as a function of increasing C loading. *Soil Biol. Biochem.* **2014**, *69*, 398–405. [CrossRef]
69. Wattel-Koekkoek, E.J.W.; Buurman, P.; van der Plicht, J.; Wattel, E.; van Breemen, M. Mean residence time of soil organic matter associated with kaolinite and smectite. *Eur. J. Soil Sci.* **2003**, *54*, 269–278. [CrossRef]
70. Chaopricha, N.T.; Marín-Spiotta, E. Soil burial contributes to deep soil organic carbon storage. *Soil Biol. Biochem.* **2014**, *69*, 251–264. [CrossRef]
71. Stone, M.M.; Plante, A.F. Relating the biological stability of soil organic matter to energy availability in deep tropical soil profiles. *Soil Biol. Biochem.* **2015**, *90*, 162–171. [CrossRef]
72. Padmanabhan, E.; Eswaran, H.; Reich, P.F. Soil carbon stocks in Sarawak, Malaysia. *Sci. Total Environ.* **2013**, *465*, 196–204. [CrossRef] [PubMed]
73. Couwenberg, J. Greenhouse gas emissions from managed peat soils: Is the IPCC reporting guidance realistic. *Mires Peat* **2011**, *8*, 1–10.
74. Page, S.E.; Rieley, J.O.; Banks, C.J. Global and regional importance of the tropical peatland carbon pool. *Glob. Chang. Biol.* **2011**, *17*, 798–818. [CrossRef]
75. Cochrane, M.A. Fire science for rainforests. *Nature* **2003**, *421*, 913–919. [CrossRef] [PubMed]
76. Couwenberg, J. Emission Factors for Managed Peat Soils. An Analysis of IPCC Default Values. Wetlands International, 2009. Available online: http://www.imcg.net/media/download_gallery/climate/couwenberg_2009a.pdf (accessed on 20 September 2015).
77. Page, S.E.; Siegert, F.; Rieley, J.O. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* **2002**, *420*, 61–65. [CrossRef] [PubMed]
78. Hooijer, A.; Page, S.; Canadell, J.G. Current and future CO_2 emissions from drained peatlands in Southeast Asia. *Biogeosciences* **2010**, *7*, 1505–1514. [CrossRef]
79. Nogueira, E.M.; Yanai, A.M.; Fonseca, F.O.R.; Fearnside, P.M. Carbon stock loss from deforestation through 2013 in Brazilian Amazonia. *Glob. Chang. Biol.* **2015**, *21*, 1271–1292. [CrossRef] [PubMed]
80. Ministry of Science and Technology (MCT). Brazilian Inventory of Anthropogenic Emissions by Sources and Removals by Sinks of Greenhouse Gases Not Controlled by the Montreal Protocol. *Brazil's Initial National Communication*; MCT: Brasilia, Brazil, 2004. Available online: http://www.mct.gov.br/upd_blob/0005/5163.pdf (accessed on 13 December 2003).
81. Fujisaki, K.; Perrin, A.S.; Desjardins, T.; Mernoux, M.; Balbino, L.C.; Brossard, M. From forest to cropland and pasture systems: A critical review of soil organic carbon stocks changes in Amazonia. *Glob. Chang. Biol.* **2015**, *21*, 2773–2786. [CrossRef] [PubMed]

82. Fearnside, P.M.; Imbrozio Barbosa, R.; Alencastro Graça, P.M.L. Burning of secondary forest in Amazonia: Biomass, burning efficiency and charcoal formation during land preparation for agriculture in Apiau´, Roraima, Brazil. *For. Ecol. Manag.* **2007**, *242*, 678–687. [CrossRef]
83. Giovannini, C.; Lucchesi, S.; Giachetti, M. Effects of heating on some chemical parameters related to soil fertility and plant growth. *Soil Sci.* **1990**, *149*, 344–350. [CrossRef]
84. Raison, R.; Woods, P.; Jakobsen, B.; Bary, G. Soil temperatures during and following low-intensity prescribed burning in a *Eucalyptus passiflora* forest. *Soil Res.* **1986**, *24*, 33–47. [CrossRef]
85. Turetsky, M.R.; Benscoter, B.; Page, S.; Rein, G.; van der Werf, G.; Watts, A. Global vulnerability of peatlands to fire and carbon loss. *Nat. Geosci.* **2015**, *8*, 11–14. [CrossRef]
86. Guimarães, D.V.; Gonzaga, M.I.S.; Silva, T.O.; Silva, T.L.; Silva Dias, N.; Matias, M.I.S. Soil organic matter pools and carbon fractions in soil under different land uses. *Soil Tillage Res.* **2013**, *126*, 177–182. [CrossRef]
87. Rosenstock, T.S.; Tully, K.L.; Arias-Navarro, C.; Naufeldt, H.; Butterbach-Bahl, K.; Verchot, L.V. Agroforestry with N_2-fixing trees: Sustainable development's friend or foe? *Curr. Opin. Environ. Sustain.* **2014**, *6*, 15–21. [CrossRef]
88. Prescott, C.E. Litter decomposition: What controls it and how can we alter it to sequester more carbon in forest soils? *Biogeochemistry* **2010**, *101*, 133–149. [CrossRef]
89. Chaer, G.M.; Resende, A.S.; Campello, E.F.C.; Faria, S.M.; Boddey, R.M.; Schmidt, S. Nitrogen-fixing legume tree species for the reclamation of severely degraded lands in Brazil. *Tree Physiol.* **2011**, *31*, 139–149. [CrossRef] [PubMed]
90. Martins, P.F.S.; Cerri, C.C.; Volkoff, B.; Andreux, F.; Chauvel, A. Consequences of clearing and tillage on the soil of a natural Amazonian ecosystem. *For. Ecol. Manag.* **1991**, *38*, 273–282. [CrossRef]
91. Bowling, D.R.; Pataki, D.E.; Randerson, J.T. Carbon isotopes in terrestrial ecosystem pools and CO_2 fluxes. *New Phytol.* **2008**, *171*, 24–40. [CrossRef] [PubMed]
92. Rouw, A.; Soulileuth, B.; Huon, S. Stable carbon isotope ratios in soil and vegetation shift with cultivation practices (Northern Laos). *Agric. Ecosyst. Environ.* **2015**, *200*, 161–168. [CrossRef]
93. Guan, X.K.; Turner, N.C.; Song, L.; Gu, Y.J.; Wang, T.C.; Li, F.M. Soil carbon sequestration by three perennial legume pastures is greater in deeper soil layers than in the surface soil. *Biogeosciences* **2016**, *13*, 527–534. [CrossRef]
94. Silva, J.E.; Resck, D.V.S.; Corazza, E.J.; Vivaldi, L. Carbon storage in clayey Oxisol cultivated pastures in the "Cerrado" region, Brazil. *Agric. Ecosyst. Environ.* **2004**, *103*, 357–363. [CrossRef]
95. Schedlbauer, J.L.; Kavanagh, K.L. Soil carbon dynamics in a chronosequence of secondary forests in northeastern Costa Rica. *For. Ecol. Manag.* **2008**, *255*, 1326–1335. [CrossRef]
96. Marín-Spiotta, E.; Sharma, S. Carbon storage in successional and plantation forest soils: A tropical analysis. *Glob. Ecol. Biogeogr.* **2013**, *22*, 105–117. [CrossRef]
97. Fialho, R.C.; Zinn, Y.L. Changes in soil organic carbon under Eucalyptus plantations in Brazil: A comparative analysis. *Land Degrad. Dev.* **2014**, *25*, 428–437. [CrossRef]
98. Glaser, B.; Birk, J.J. State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). *Geochim. Cosmochim. Acta* **2012**, *82*, 39–51. [CrossRef]
99. Lima, A.B.; Cannavan, F.S.; Navarrete, A.A. Amazonian Dark Earth and plant species from the Amazon region contribute to shape rhizosphere bacterial communities. *Microb. Ecol.* **2014**, *69*, 855–866. [CrossRef] [PubMed]
100. Novotny, E.; Hayes, M.B.; Azevedo, E.; Bonagamba, T. Characterisation of black carbon-rich samples by 13C solid-state nuclear magnetic resonance. *Naturwissenschaften* **2006**, *93*, 447–450. [CrossRef] [PubMed]
101. Lu, W.; Ding, W.; Zhang, J.; Li, Y.; Luo, J.; Bolan, N.; Xie, Z. Biochar suppressed the decomposition of organic carbon in a cultivated sandy loam soil: A negative priming effect. *Soil Biol. Biochem.* **2014**, *76*, 12–21. [CrossRef]
102. Ameloot, N.; Graber, E.R.; Verheijen, F.G.A.; Neve, S. Interactions between biochar stability and soil organisms: Review and research needs. *Eur. J. Soil Sci.* **2013**, *64*, 379–390. [CrossRef]
103. Smith, P. Soil carbon sequestration and biochar as negative emission technologies. *Glob. Chang. Biol.* **2016**, *22*, 1315–1324. [CrossRef] [PubMed]
104. Sohi, S.P.; Krull, E.; Lopez-Capel, E.; Bol, R. Review of biochar and use and function in soil. *Adv. Agron.* **2010**, *105*, 47–82.

105. Novotny, E.H.; Hayes, M.H.B.; Madari, B.E. Lessons from the Terra Preta de Índios of the Amazon region for the utilization of charcoal for soil amendment. *J. Braz. Chem. Soc.* **2009**, *20*, 1003–1010. [CrossRef]
106. Novotny, E.H.; Maia, C.M.B.F.; Carvalho, M.T.M.; Madari, B.E. Biochar: Pyrogenic carbon for agricultural use—A critical review. *Rev. Bras. Cienc. Solo* **2015**, *39*, 321–344. [CrossRef]
107. Laird, D.; Fleming, P.; Wang, B.; Horton, R.; Karlen, D. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma* **2010**, *158*, 436–442. [CrossRef]
108. Agegnehu, G.; Bass, A.M.; Nelson, P.M.; Muirhead, B.; Wright, G.; Bird, M.I. Biochar and biochar-compost as soil amendments: Effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia. *Agric. Ecosyst. Environ.* **2015**, *213*, 72–85. [CrossRef]
109. Ding, Y.; Liu, Y.-X.; Wu, W.-X. Evaluation of Biochar Effects on Nitrogen Retention and Leaching in Multi-Layered Soil Columns. *Water Air Soil Pollut.* **2010**, *213*, 47–55. [CrossRef]
110. Nelson, N.O.; Agudelo, S.C.; Yuan, W.; Gan, J. Nitrogen and Phosphorus Availability in Biochar-Amended Soils. *Soil Sci.* **2011**, *176*, 218–226. [CrossRef]
111. Borchard, N.; Ladd, B.; Eschemann, S.; Hegenberg, D.; Möseler, B.M.; Amelung, W. Black carbon and soil properties at historical charcoal production sites in Germany. *Geoderma* **2014**, *223–224*, 236–242. [CrossRef]
112. Clough, T.J.; Condron, L.M.; Kammann, C.; Mueller, C. Review of biochar and soil nitrogen dynamics. *Agronomy* **2013**, *3*, 275–293. [CrossRef]
113. Sousa, A.M.B.; Soares Santos, R.R.; Gehring, C. Charcoal in Amazonian paddy soil—Nutrient availability, rice growth and methane emissions. *J. Plant Nutr. Soil Sci.* **2013**, *177*, 39–47. [CrossRef]
114. Xu, G.; Lv, Y.; Sun, J.; Shao, H.; Wei, L. Recent advances in biochar applications in agricultural soils: Benefits and environmental implications. *CLEAN Soil Air Water* **2012**, *40*, 1093–1098. [CrossRef]
115. Zhang, A.; Cui, L.; Pan, G. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agric. Ecosyst. Environ.* **2010**, *139*, 469–475. [CrossRef]
116. Gurwick, N.P.; Moore, L.A.; Kelly, C.; Elias, P. A Systematic review of biochar research, with a focus on its stability in situ and its promise as a climate mitigation strategy. *PLoS ONE* **2013**. [CrossRef] [PubMed]
117. Liu, J.; Shen, J.; Li, Y.; Su, Y.; Ge, T.; Jones, D.L.; Wu, J. Effects of biochar amendment on the net greenhouse gas emission and greenhouse gas intensity in a Chinese double rice cropping system. *Eur. J. Soil Biol.* **2014**, *65*, 30–39. [CrossRef]
118. LeCroy, C.; Masiello, C.A.; Rudgers, J.A.; Hockaday, W.C.; Silberg, J.J. Nitrogen, biochar, and mycorrhizae: Alteration of the symbiosis and oxidation of the char surface. *Soil Biol. Biochem.* **2013**, *58*, 248–254. [CrossRef]
119. Mia, S.; van Groenigen, J.W.; van de Voorde, T.F.J.; Orama, N.J.; Bezemer, T.M.; Mommer, L.; Jeffery, S. Biochar application rate affects biological nitrogen fixation in red clover conditional on potassium availability. *Agric. Ecosyst. Environ.* **2014**, *191*, 83–91. [CrossRef]
120. Quilliam, R.S.; Deluca, T.H.; Jones, D.L. Biochar application reduces nodulation but increases nitrogenase activity in clover. *Plant Soil* **2013**, *366*, 83–92. [CrossRef]
121. Warnock, D.; Lehmann, J.; Kuyper, T.; Rillig, M. Mycorrhizal responses to biochar in soil—Concepts and mechanisms. *Plant Soil* **2007**, *300*, 9–20. [CrossRef]
122. Lehmann, J.; Rillig, M.C.; Thies, J.; Masiello, C.A.; Hockadayd, W.C.; Crowley, D. Biochar effects on soil biota—A review. *Soil Biol. Biochem.* **2011**, *43*, 1812–1836. [CrossRef]
123. Solaiman, Z.M.; Murphy, D.V.; Abbott, L.K. Biochars influence seed germination and early growth of seedlings. *Plant Soil* **2012**, *353*, 273–287. [CrossRef]
124. Jeffery, S.; Verheijen, F.G.A.; van der Velde, M.; Bastos, A.C. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agric. Ecosyst. Environ.* **2011**, *144*, 175–187. [CrossRef]
125. Ponge, J.F.; Topoliantz, S.; Ballof, S. Ingestion of charcoal by the Amazonian earthworm *Pontoscolex corethrurus*: A potential for tropical soil fertility. *Soil Biol. Biochem.* **2006**, *38*, 2008–2009. [CrossRef]
126. Dube, O.P. Linking fire and climate: Interactions with land use, vegetation, and soil. *Curr. Opin. Environ. Sustain.* **2009**, *1*, 161–169. [CrossRef]
127. Styger, E.; Rakodrondamasi, H.M.; Pfeffer, M.J.; Fernandes, E.C.M.; Bates, D.M. Influence of slash-and-burn farming practices on fallow succession and land degradation in the rainforest region of Madagascar. *Agric. Ecosyst. Environ.* **2007**, *119*, 257–269. [CrossRef]
128. Alencar, A.A.C.; Brando, P.M.; Asner, G.P.; Putz, F.E. Landscape fragmentation, severe drought and the new amazon forest fire regime. *Ecol. Appl.* **2015**, *25*, 1493–1505. [CrossRef] [PubMed]

129. Lehmann, J.; Gaunt, J.; Rondon, M. Bio-char Sequestration in Terrestrial Ecosystems—A Review. *Mitig. Adapt. Strateg. Glob. Chang.* **2006**, *11*, 395–419. [CrossRef]
130. Steiner, C.; Teixeira, W.; Zech, W. Slash and Char: An Alternative to Slash and Burn Practiced in the Amazon Basin. In *Amazonian Dark Earths: Explorations in Space and Time*; Glaser, B., Woods, W., Eds.; Springer: Heidelberg, Germany; Berlin, Germany, 2004; pp. 183–193.
131. Turcios, M.M.; Jaramillo, M.M.A.; Vale, J.E.F.; Fearnside, P.M.; Barbosa, R.I. Soil charcoal as long-term pyrogenic carbon storage in Amazonian seasonal forests. *Glob. Chang. Biol.* **2016**, *22*, 190–197. [CrossRef] [PubMed]
132. Cardoso, E.J.B.N.; Vasconcellos, R.L.F.; Bini, D.; Miyauchi, M.Y.H.; Santos, C.A.; Alves, P.R.L.; Paula, A.M.; Nakatani, A.S.; Pereira, J.M.; Nogueira, M.A. Soil health: Looking for suitable indicators. What should be considered to assess the effects of use and management on soil health? *Sci. Agric.* **2013**, *70*, 274–289. [CrossRef]
133. Oliver, D.P.; Bramley, R.G.V.; Riches, D.; Porter, I.; Edwards, J. Soil physical and chemical properties as indicators of soil quality in Australian viticulture. *Aust. J. Grape Wine Res.* **2013**, *19*, 29–139. [CrossRef]
134. Doran, J.W.; Parkin, T.B. Defining and assessing soil quality. In *Defining Soil Quality for a Sustainable Environment. Soil Science Society of America*; Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A., Eds.; American Society of Agronomy: Madison, WI, USA, 1994; pp. 3–21.
135. Karlen, D.L.; Andrews, S.S.; Doran, J.W. Soil quality: Current concepts and applications. *Adv. Agron.* **2001**, *74*, 1–40.
136. Cerri, D.G.P.; Magalhães, P.S.G. Correlation of physical and chemical attributes of soil with sugarcane yield. *Pesqui. Agropecu. Bras.* **2012**, *47*, 613–620. [CrossRef]
137. Montanari, R.; Passos e Carvalho, M.; Silva Junior, C.A.; Rodrigues Corrêa, A.; Dalchiavon, F.C.; Paz González, A. Relations between the yield of bean (*Phaseolus vulgaris* L.) and chemical attributes of an Acrustox under no-tillage. *J. Soil Sci. Plant Nutr.* **2013**, *13*, 367–379. [CrossRef]
138. Zhao, J.; Dong, Y.; Xie, X.; Li, X.; Zhang, X.; Shen, X. Effect of annual variation in soil pH on available soil nutrients in pear orchards. *Acta Ecol. Sin.* **2011**, *31*, 212–216. [CrossRef]
139. Jiao, F.; Shi, X.-R.; Han, F.-P.; Yuan, Z.-Y. Increasing aridity, temperature and soil pH induce soil C-N-P imbalance in grasslands. *Nature* **2016**, *6*, 1–9.
140. Stark, S.; Männistö, M.K.; Eskelinen, A. Nutrient availability and pH jointly constrain microbial extracellular enzyme activities in nutrient-poor tundra soils. *Plant Soil* **2014**, *383*, 373–385. [CrossRef]
141. Zhao, C.; Fu, S.; Mathew, R.P.; Lawrence, K.S.; Feng, Y. Soil microbial community structure and activity in a 100-year-old fertilization and crop rotation experiment. *J. Plant Ecol.* **2015**, 1–10. [CrossRef]
142. Rousk, J.; Brookes, P.C.; Bååth, E. Contrasting Soil pH Effects on Fungal and Bacterial Growth Suggest Functional Redundancy in Carbon Mineralization. *Appl. Environ. Microbiol.* **2009**, *75*, 1589–1596. [CrossRef] [PubMed]
143. Busari, M.A.; Salako, F.K. Effect of tillage, poultry manure and NPK fertilizer on soil chemical properties and maize yield on an Alfisol at Abeokuta, south-western Nigeria. *Niger. J. Soil Sci.* **2013**, *23*, 206–218.
144. Nduwumuremyi, A.; Ruganzu, V.; Mugwe, J.N.; Rusanganwa, A.C. Effects of unburned lime on soil pH and base cations in acidic soil. *ISRN Soil Sci.* **2013**. [CrossRef]
145. Marschner, H. *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Academic Press: London, UK, 2011.
146. Fageria, N.; Baligar, V. Enhancing nitrogen use efficiency in crop plants. *Adv. Agron.* **2005**, *88*, 97–185.
147. Lynch, J.P. Root phenes for enhanced soil exploration and phosphorus acquisition: Tools for future crops. *Plant Physiol.* **2011**, *156*, 1041–1049. [CrossRef] [PubMed]
148. Kochian, L.V. Rooting for more phosphorus. *Nature* **2012**, *488*, 466–467. [CrossRef] [PubMed]
149. Yang, X.; Post, W.M. Phosphorus transformation as a function of pedogenesis: A synthesis of soil phosphorus data using Hedley fractionation method. *Biogeosciences* **2011**, *8*, 2907–2916. [CrossRef]
150. Braos, L.B.; da Cruz, M.C.P.; Ferreira, M.E.; Kuhnen, F. Organic phosphorus fractions in soil fertilized with cattle manure. *Rev. Bras. Cienc. Solo* **2015**, *39*, 140–150. [CrossRef]
151. Richardson, A.E.; Lynch, J.P.; Ryan, P.R.; Delhaize, E.; Smith, F.A.; Smith, S.E.; Harvey, P.R.; Ryan, M.H. Plant and microbial strategies to improve the phosphorus efficiency of agriculture. *Plant Soil* **2011**, *349*, 121–156. [CrossRef]

152. Rodrigues, M.; Pavinato, P.S.; Withers, P.J.; Teles, A.P.; Herrera, W.F. Legacy phosphorus and no tillage agriculture in tropical oxisols of the Brazilian savanna. *Sci. Total Environ.* **2016**, *15*, 1050–1061. [CrossRef] [PubMed]
153. Shen, J.; Yuan, L.; Zhang, J.; Li, H.; Bai, Z.; Chen, X.; Zhang, W.; Zhang, F. Phosphorus dynamics: From soil to plant. *Plant Physiol.* **2011**, *156*, 997–1005. [CrossRef] [PubMed]
154. Pinto, F.A.; de Souza, E.D.; Paulino, H.B.; Curi, N.; Carneiro, M.A.C. P-sorption and desorption in Savanna Brazilian soils as a support for phosphorus fertilizer management. *Ciênc. Agrotecnol.* **2013**, *37*, 521–530. [CrossRef]
155. Drinkwater, L.E.; Snapp, S.S. Nutrients in Agroecosystems: Rethinking the Management Paradigm. *Adv. Agron.* **2007**, *92*, 163–186.
156. Sustainable Agricultural Systems in the 21st Century. Available online: http://dels.nas.edu/resources/static-assets/materials-based-on-reports/reports-in-brief/Systems-Ag-Report-Brief.pdf (accessed on 15 December 2015).
157. Meena, S.K.; Rakshit, A.; Meena, V.S. Effect of seed bio-priming and N doses under varied soil type on nitrogen use efficiency (NUE) of wheat (*Triticum aestivum* L.) under greenhouse conditions. *Biocatal. Agric. Biotech.* **2016**, *6*, 68–75. [CrossRef]
158. Kolahchi, Z.; Jalali, M. Effect of water quality on the leaching of potassium from sandy soil. *J. Arid Environ.* **2007**, *68*, 624–639. [CrossRef]
159. Gehring, C.; Moura, E.G.; Santos, R.R.S.; Aguiar, A.C.F.; Sousa, A.M.B.; Boddey, R.M. Ecological intensification of rice production in the lowlands of Amazonia—Options for smallholder rice producers. *Eur. J. Agro.* **2013**, *46*, 25–33. [CrossRef]
160. Gomiero, T.; Pimentel, D.; Paoletti, M.G. Environmental impact of different agricultural management practices: conventional vs. organic agriculture. *Crit. Rev. Plant Sci.* **2011**, *30*, 95–124. [CrossRef]
161. Niggli, U. Sustainability of organic food production: Challenges and innovations. *Proc. Nutr. Soc.* **2015**, *74*, 83–88. [CrossRef] [PubMed]
162. Comadira, G.; Rasool, B.; Karpinska, B.; Morris, J.; Verrall, S.R.; Hedley, P.E.; Foyer, C.H.; Hancock, R.D. Nitrogen deficiency in barley (*Hordeum vulgare*) seedlings induces molecular and metabolic adjustments that trigger aphid resistance. *J. Exp. Bot.* **2015**, *2*, 1–17. [CrossRef] [PubMed]
163. Altieri, M.A.; Ponti, L.; Nicholls, C.I. Biodiversity and insect pests: Key issues for sustainable management. In *Soil Fertility, Biodiversity and Pest Management*; Gurr, G.M., Wratten, S.D., Snyder, W.E., Read, D.M.Y., Eds.; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2012; pp. 72–84.
164. Sampaio, L.R.; Araújo, J.R.G.; Sousa, E.H.S.; Ferraz Júnior, A.S.L.; Araujo, A.M.S. Cultivo de abóbora, suplementada com biofertilizante, em aléias de leguminosas arbóreas. *Hortic. Bras.* **2015**, *33*, 40–44. [CrossRef]
165. Mondego, J.M. Resistência Induzida em Milho à Spodoptera Frugiperda (J.E. Smith, 1797) (Lepidoptera: Noctuidae). Ph.D. Thesis, Universidade Federal da Paraíba, Areia, Paraíba, 2014.
166. Crowder, D.; Reganold, J. Financial competitiveness of organic agriculture on a global scale. *Proc. Natl. Acad. Sci. USA* **2015**. [CrossRef] [PubMed]
167. Sands, D.C.; Pilgeram, A.; Morris, C.E. Development and marketing of perennial grains with benefits for human health and nutrition. In *Perennial Crops for Food Security Proceedings of the FAO Expert Workshop*; Batello, C., Wade, L., Cox, S., Pogna, N., Bozzini, A., Choptiany, J., Eds.; FAO: Rome, Italy, 2013; pp. 208–220.
168. Muhammed, D.; Serkan, A. Intercropping of legumes with cereal crops in particular with the perennials to enhance forage yields and quality. In *Perennial Crops for Food Security Proceedings of the FAO Expert Workshop*; Batello, C., Wade, L., Cox, S., Pogna, N., Bozzini, A., Choptiany, J., Eds.; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2013; pp. 221–228.
169. Tsimbiri, P.F.; Moturi, W.N.; Sawe, J.; Henley, P.; Bend, J.R. Health impact of pesticides on residents and horticultural workers in the Lake Naivasha Region, Kenya. *Occup. Dis. Environ. Med.* **2015**, *3*, 24–34. [CrossRef]
170. Gan, Y.; Hamel, C.; O'Donovan, J.T.; Cutforth, H.; Zentner, R.P.; Campbell, C.A.; Niu, Y.; Poppy, L. Diversifying crop rotations with pulses enhances system productivity. *Sci. Rep.* **2015**. [CrossRef] [PubMed]
171. Parolin, P.; Bresch, C.; Poncet, C.; Desneux, N. Introducing the term 'Biocontrol Plants' for integrated pest management. *Sci. Agric.* **2014**, *71*, 77–80. [CrossRef]

172. Khalil, M.A.; Al Assiuty, A.L.; van Straalen, N.M.; Al Assiuty, B.A. Changes in soil oribatid communities associated with conversion from conventional to organic agriculture. *Exp. Appl. Acarol.* **2015**, *67*, 1–14. [CrossRef] [PubMed]
173. Nobre, C.P.; Ferraz Júnior, A.S.L.; Goto, B.T.; Berbara, R.L.L.; Noqueira, M.D.C. Fungos micorrízicos arbusculares em sistema de aléias no Estado do Maranhão, Brasil. *Acta Amazon.* **2010**, *40*, 641–646. [CrossRef]
174. Oliveira, N.N.F.C. Efeito de um Sistema de Cultivo em Aléias em Diferentes Consórcios de Leguminosas Arbóreas Sobre Grupos de Artrópodes. Master's Thesis, Universidade Estadual do Maranhão, São Luís, Brazil, 2013. (In Portuguese)
175. Restrictions on Genetically Modified Organisms. Available online: https://www.loc.gov/law/help/restrictions-on-gmos/restrictions-on-gmos.pdf (accessed on 15 December 2015).