

## Chapter 22

# WEED POPULATION DYNAMICS AND MANAGEMENT ON AMAZONIAN DARK EARTH

JULIE MAJOR<sup>1</sup>, ANTONIO DITOMMASO<sup>1</sup>, LAURA A. GERMAN<sup>2</sup>,  
JOSEPH M. MCCANN<sup>3</sup>

<sup>1</sup>*Department of Crop and Soil Sciences, Cornell University, Ithaca, NY, USA;* <sup>2</sup>*World Agroforestry Center (ICRAF), Kampala, Uganda;* <sup>3</sup>*Division of Social Sciences, New School University, New York, NY, USA*

### 1. IMPORTANCE OF UNDERSTANDING WEED DYNAMICS ON AMAZONIAN DARK EARTH

Our understanding of the role and impact of weeds in tropical agroecosystems is limited by comparison to temperate systems. Most of our knowledge about weeds in tropical regions is based on studies performed on the highly weathered and nutrient impoverished soils that dominate these latitudes (hereafter referred to as background soils, in relation to Dark Earths). The primary objective of this chapter is to address this disparity in knowledge by outlining and elaborating on our current understanding of the role and impact of weeds within the unique and distinctively fertile Amazonian Dark Earths (ADE). ADE are of anthropogenic origin, and are thought to have originated in semi-permanent Amerindian settlements in the prehistoric and early historic periods. Contrary to the vast majority of soils from which they were derived and that surround ADE patches, the latter contain large amounts of organic carbon, phosphorus (P), and calcium (Ca) (Kern and Kampf, 1989; Kern et al., 1999; Woods and McCann, 1999; McCann et al., 2001; Lehmann et al., 2003b).

We review the literature on the effects of important biotic and abiotic factors on weed dynamics and discuss how these factors differ on ADE and background soils. Drawing on the information available about the management of cropping systems on these two soils, we hypothesize how weed dynamics may vary. It is generally accepted that the inherent fertility of Amazonian Dark Earths allows for a more intensive management of these in comparison with most soil types in Amazônia. This distinction is crucial because it results in a substantially lower rate of clearing of mature forest, for the same level of production, as compared to other low-input tropical production systems. For this reason, efforts are underway to better understand the processes that lead to the development of these fertile soils. This knowledge may ultimately allow for more efficient soil fertility management in the

future. If the study of ADE is to yield technology aimed at the development of sustainable tropical agroecosystems, basic information on the ecology and management of weeds on highly fertile soils is required. Moreover, the weed management strategies developed need not only be feasible from an agronomic and economic perspective, but must also be harmonized with the aims and resources of small-scale farmers.

We are not advocating a more widespread or intensive use of ADE soils, since they provide valuable archaeological testimony of early Amerindian societies. In fact, we believe that developing appropriate and sensible weed management strategies can play a significant role in safeguarding the unique physical and chemical properties of these soils, and therefore protecting the cultural heritage of past generations. In this chapter, we focus our discussion primarily on the use of ADE by small-scale farmers for shifting agriculture.

## 2. SOIL FERTILITY

The characteristics of ADE have been reviewed in other chapters of this book. Weed growth and dynamics will be highly dependent on fertility and other soil characteristics of ADE (reviewed by Lehmann et al., 2003a), differences in land use practices (reviewed by Hiraoka et al., 2003), and the resident flora found on these soils (reviewed by Clement et al., 2003). Weed dynamics have been shown to vary greatly at the field scale in both temperate and tropical climates (Staver, 1989b; Fujisaka et al., 1998; Walter et al., 2002). Indeed, ADE soils exhibit large soil variations between and within patches (Kern and Kämpf, 1989; Kern and Lima da Costa, 1995; Woods and McCann, 1999; McCann et al., 2001), and their management is also highly variable. Thus, it is expected that weed control strategies used on ADE soils will also vary widely.

Market access has a significant influence on the types of cropping systems adopted by growers on ADE soils (L. German, unpubl. data). In fact, there exists a gradient from basic subsistence agriculture to mechanized, high-input commercial production on these soils. A shift towards perennial crops is often observed on wealthier farms. Bitter manioc (*Manihot esculenta* Crantz) is the predominant crop grown in low-input production systems on background soils, and is intercropped with low densities of other crops such as cará (*Dioscorea trifida* L.f.), banana (*Musa* sp.), and sweet potato (*Ipomoea batatas* (L.) Lam). In contrast, manioc is often intercropped with maize (*Zea mays* L.), squash (*Cucurbita* sp.), and beans (*Phaseolus* sp., *Vigna* sp.) on ADE. When ADE is used to grow crops such as vegetables for market, these are often monocropped (German 2001). Clearly, the species composition and impact of weeds in these different crop production systems vary considerably, as does their management.

Significant differences exist between cropping cycles on ADE and background soils. Some of these contrasting data are shown in Table 1. All information was collected from small-scale farms, where no external soil amendments were used, and where only manual labor was available.

German (2003) attributes the reduced production time on ADE soils to a combination of factors, including a) more rapid early successional processes and increased weed pressure with increasing swidden maturity, b) higher inherent soil fertility, allowing farmers to clear adjacent young fallow which demands less in terms of labor than clearing old fallow, and c) a preference for high-value, short-cycle crops, a decision based on both labor and economic returns.

*Table 1: The swidden agricultural cycle on Amazonian Dark Earths (ADE) and Ferralsols (background soils).*

<i>Parameter</i>	<i>ADE</i>	<i>Ferralsol</i>
	(months)	(months)
Average Time in Production (with outlier):	10.8	28.0
Average Time in Production (outlier removed) <sup>a</sup> :	6.6	28.0
Average Age of Fallows <sup>b</sup> :	51.5	31.3
% Swiddens Cleared from Mature Forest:	25.6	72.7

<sup>a</sup> *Outliers are two ADE swiddens that were cultivated for far longer than average, leading to severe soil depletion. Data in the second row are therefore more representative of ADE management practices for the region.* <sup>b</sup> *Despite the tendency for Ferralsol swiddens to be cleared from mature forest, this calculation was limited to swiddens cleared from fallow, in order to facilitate comparison with ADE. Adapted from German (2003).*

### 3. WEED GROWTH AND DYNAMICS ON ADE

#### 3.1. The Role of Weeds

It is well documented that weeds can reduce crop yields, harbor pests and diseases, interfere with cropping activities, and reduce crop quality in most cropping systems of the world (Pimentel, 1991). However, the effects of these constraints on crop production in ADE versus adjacent background soil areas are currently not well known. What is known, is that farmers working on ADE perceive weeds to be most detrimental in terms of labor demands (German, 2001). In fact, more labor is required to control weeds on ADE than on background soils. German (unpubl. data) found that while small-scale Dark Earth farmers in the Central Amazon dedicated 30% of their time to weed control, background soil farmers dedicated only 17% of their time to these activities. McCann (unpubl. data) observed a similar situation in eastern Amazônia, where farmers require up to three times as many weedings per cropping cycle on ADE as compared to background soils. Preliminary data on the weed biomass found on ADE and background soils are presented in Fig. 1. Interestingly, on background soil plots, only manioc plants survived, which was not the case on ADE.

Although weeds compete with crops for essential resources, they can also be beneficial in preventing soil fertility decline. For example, weeds might reduce

nutrient losses from surface runoff and leaching (Saxena and Ramakrishnan, 1984). Similarly, weeds can be beneficial in agroecosystems by harboring natural enemies of crop pests or by improving soil physical properties such as drainage and soil aggregation (Hill and Ramsay, 1977).

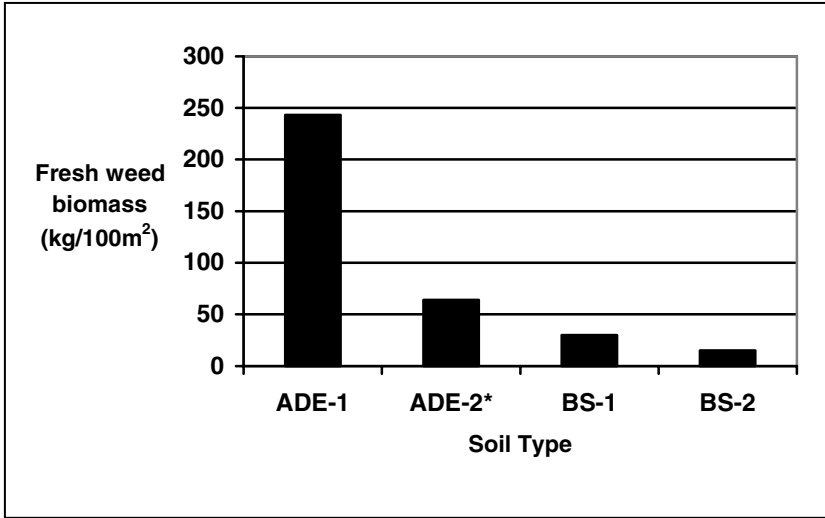


Figure 1: Fresh weight of aboveground non-crop vegetative regrowth on four adjacent swidden plots representing three locally defined soil types: ADE (ADE-1=100 m<sup>2</sup>; ADE-2=280 m<sup>2</sup>) and background soils (BS-1: transitional soil of bamboo forest=400 m<sup>2</sup>), and BS-2: sandy clay oxisols=400 m<sup>2</sup>), located on a riverside plateau at Catarina, Rio Arapiuns, Santarém Municipality, Pará, Brazil. A 10-year-old fallow was cleared and burned according to local practice, and planted to manioc, maize, beans and squash on or about November 11, 1997. Weed biomass was measured on or about Feb. 25 (ADE-1), Feb. 28 (ADE-2), March 8 (oxisol), and March 15 (transitional soil). \*Biomass accumulation in ADE-2 plot is underrepresented due to heavy predation by leaf cutter ants and partial drying of vegetation (McCann, 2003).

Some weed species found on ADE and background soils have important uses as food, medicine, fiber, dye, and construction material (Table 2); however, most of these are treated as weeds due to their competition with economically important crops.

Although these plants are often removed to give more important food and cash crops a competitive advantage, it is important to note that the concept of a “weed” in these subsistence systems is often more ambiguous than in more intensively managed cropping systems (Unruh and Alcorn, 1988). Clearly, ethno-botanical studies are needed to refine the definition of a weed in these systems, so that the development of weed management strategies can better target species that are truly considered “weedy” or problematic by ADE farmers. Despite the additional labor burden, more experienced ADE farmers recognize the inherent value of weeds in

improving soil fertility through green manuring or burning (German 2001). Clement et al. (2003) suggest using weeds of ADE soils as potential indicators of past land use patterns because presumably weeds evolved concomitantly with crops in these systems. In fact, we have found that the species composition of weed populations on ADE swiddens in central and eastern Amazônia differs from that on background soil swiddens.

Table 2. Use and perception of selected volunteer plant species commonly found on ADE swiddens. Data from the Central Amazon (Lower Rio Negro and middle Rio Urubú, collected from 12 farmers, from January 1998 to January 1999 (L. German, unpubl. data).

Common name (English)	Scientific name	Uses	Perceived as a weed?
Quebra-pedra	<i>Phyllanthus orbiculatus</i> LC Rich	medicinal	yes
Malva (Mallow)	<i>Urena lobata</i> L.	fiber	yes
Carirú	<i>Talinum triangulare</i> (Jacq.) Willd.	edible leaf	yes
Goiaba (guava)	<i>Psidium guajava</i> L.	edible fruit	yes
Caiaué (native oil palm)	<i>Elaeis oleifera</i> (Kunth) Cortes	palm wine	yes
Canapum	<i>Physalis angulata</i> L.	edible fruit	yes
Mamão (papaya)	<i>Carica papaya</i> L.	edible fruit	no

### 3.2 Influence of Soil Fertility on Weed Population Dynamics

The availability of nutrients in soil and the ability of plants to acquire these nutrients are fundamental processes that define the growth of all plants and, incidentally, competition between weeds and crops. It is difficult to speculate whether the supply of plant nutrients by ADE soils is comparable to that of fertilizer-amended soils; however it is not unrealistic to expect that fertility differences between ADE and background soils may actually be greater for some nutrients than observed for adjacent fertilized and control plots on the same soil type. For example, available P levels are typically very high on ADE, sometimes several orders of magnitude greater than on background soils. For example, Kern and Lima da Costa (1995) measured 1800 ppm P in ADE compared with 2 ppm in adjacent background soils. Additionally, ADE soils have a greater cation exchange capacity and higher nutrient retention capacity for the same amount of organic carbon than background soils (Sombroek et al., 1993). Because ADE soils are generally recognized to be more fertile than background soils, the following discussion will focus on the effects of soil fertility on various determinants of weed dynamics.

#### 3.2.1. Sexual and Vegetative Reproduction

Weeds growing on more fertile soils have generally shown greater reproductive success than weeds growing on nutrient-impooverished soils, regardless of

reproductive strategy (i.e. sexual or vegetative reproduction, or both). In the case of sexual reproduction, increases in reproductive output with increased fertility have been reported for the annual arable weeds *Centaurea cyanus* L. (Chachulski et al., 1999) and *Senna obtusifolia* (L.) H.Irwin and Barneby (Tungate et al. 2002). Sindel and Michael (1992) reported increased biomass allocation to flower capitula in the weed *Senecio madagascariensis* Poir. (fireweed) with P and potassium (K) addition. When grown in mixture with oats (*Avena sativa* L.), low levels of nitrogen (N) resulted in lower *S. madagascariensis* capitula production than when grown in pure stand, but this effect was reversed as N and P fertility increased (Sindel and Michael, 1992). Therefore, based on previous research, sexual reproduction of weeds on ADE soils is expected to be greater than on background soils, ultimately resulting in larger seedbanks and more intense weed pressure on ADE soils.

Nutrient availability can also influence weed seed germination patterns. The availability of nutrients such as nitrate has been shown to stimulate seed germination in weeds, for example corn spurry (*Spergula arvensis* L.) (Freyman et al., 1989), yellow foxtail (*Setaria glauca* (L.) Beauv.) (Schimpf and Palmblad, 1980), and buckhorn plantain (*Plantago lanceolata* L.) (Pons, 1989). Elevated soil nutrient levels resulted in the production of seeds having lower dormancy (i.e. seeds germinating more readily) in common lambsquarters (*Chenopodium album* L.) (Fawcett and Slife, 1978) and cornflower (*Centaurea cyanus* L.) (Chachulski, 1999) compared with plants grown in low nutrient soils.

Many plant species rely on a combination of sexual and vegetative reproduction for survival. Soil fertility may influence vegetative reproduction as well as seed production and germination. For instance, increased N fertilization led to increased tillering and rhizome bud formation in the perennial weed quackgrass (*Elytrigia repens* (L.) Nevski.), although significant biotype variations were observed (Tardif and Leroux, 1992). Similarly, quackgrass was observed to invade and dominate high-N field plots in Minnesota within three years of the start of the study (Tilman, 1987). de Kroon and Knops (1990) reported fewer dormant rhizome buds with increasing fertility levels in the sedge *Carex flacca* Schreb.

### 3.2.2. Weed-Crop Competitive Interactions

Reports on the effect of increased fertility on weed pressure have been inconsistent, and Barberi (2001) suggests that generalizations may not be appropriate because of variations in pedo-climatic conditions and relative species abundance of weed populations. It is likely that crop density and architecture will play a significant role in competitive outcomes with weeds. On ADE soils, crops as well as weeds may be more competitive than they would be on background soils and thus early growth dynamics may be key in determining competitive outcomes. Ethnographic evidence for rapid early successional processes (German, 2001; German, 2003b) would suggest that this is, in fact, a concern in the management of these soils.

The effect of fertility on weed density has been demonstrated to be variable and species-specific. Everaarts (1992) found that the density of some weed species increased with an increased supply of a given nutrient (e.g. increased density of

*Eleusine indica* L. with K fertilization), while other combinations showed no response (e.g. *E. indica* and N). Research by other workers has shown similar results (Freyman et al., 1989; Hume, 1982), including a reduction in the density of some weed species with increased nutrient availability: *Euphorbia helioscopia* L. densities were reduced by higher P levels (Andeasen et al., 1991). Contrary to these findings, weeds of the family Euphorbiaceae are frequently seen on ADE plots, often at high densities (J. Major, pers. obs.). Studies that have attempted to predict weed densities using soil properties have concluded that variations in weed diversity and density are field-specific, patchy, and often variable between years thereby making generalizations difficult (Medlin et al., 2001; Walter et al., 2002).

An indirect effect of nutrient additions in agroecosystems is the increased production of plant biomass, leading to increased shading and competition for light (King and Purcell, 1997). If crop growth was favored over that of weeds on more fertile soil, crops would have a clear competitive advantage because they would likely out compete weeds for essential resources such as light. Jornsrgard et al. (1996) observed this effect in a field experiment in Denmark. At low N levels, the growth of cereal crops was depressed compared with high N plots thus increasing weed biomass because of a greater proportion of light reaching the weeds. These findings suggest not only that some weed species may be more light- than N-limited, but that competitive interactions, more so than direct N effects on weeds, dictate the outcome of fertilization on weed-crop dynamics in this system (Jornsrgard et al., 1996).

Shortly after seed germination, weed species often accumulate soil nutrients more efficiently than crops. This derives from differences in seed weight (and seed reserves for growth) between weeds and crops, where weed seeds tend to be many orders of magnitude smaller than crop seeds (Liebman and Davis, 2000). This leads to a greater reliance, by weeds, on soil nutrients for early growth. If early weed growth is not controlled adequately on ADE, weeds may produce more biomass more rapidly than on background soils, and compete strongly with crops that may be slower to establish.

Fertilization has been observed to benefit weeds more than crops in some studies (Liebman, 1989; Sindel and Michael, 1992; Ampong-Nyarko and Datta, 1993;). This is believed to be the result of an increased ability of weeds to take up nutrients (Qasem, 1992), which leads to greater weed competitive ability. However, with increased soil quality (i.e. high nutrient and water availability, good structure, etc.), crops may grow more vigorously and be more tolerant of certain levels of weed infestation. Gallagher et al. (1999) found that while maize yields were dependent on weed infestation in systems managed with chemical fertilizers only, a relationship was less evident when maize followed a legume cover crop or manure applications (Gallagher et al., 1999). Similarly, in a field experiment in Québec by Légère et al. (1994), increased P fertilization had detrimental effects on the competitiveness of several weeds in the presence of spring barley (*Hordeum vulgare* L.). Variable effects of P fertility on weed competitiveness were observed in field surveys carried out by Andreasen et al. (1991) in Denmark. The frequency of some weed species increased (e.g., *Solanum nigrum* L. ssp. *nigrum*), decreased (e.g., *Chenopodium album*), or was unaffected (e.g., *Euphorbia helioscopia*) by increasing

soil P levels. It can be hypothesized that nitrogen availability may be most limiting in ADE soils such that weed (or crop) species that are more efficient at producing above-ground biomass at these low nitrogen levels will capture a greater share of light and out compete other, less efficient species. Similarly, leguminous weed or crop species capable of fixing atmospheric nitrogen are expected to be more abundant on ADE soils than on adjacent background soils that have low levels of both N and P (see section on legumes). However, these hypotheses remain to be tested under field conditions.

The strong interaction between increased nutrient availability and the density of weeds and crops can have a substantial impact on weed-crop competition. In pot experiments, Shrefler et al. (1994) investigated the competitiveness of the annual weed spiny amaranth (*Amaranthus spinosus* L.) and lettuce (*Lactuca sativa* L.) at two P levels. P addition was found to interact with plant density such that at lower plant densities, P addition resulted in lettuce being just as competitive as spiny amaranth, while at higher densities, spiny amaranth was found to be significantly more competitive than lettuce, regardless of the P level added. Similarly, Carlson and Hill (1986) observed that spring wheat (*Triticum aestivum* L.) yield increased with increasing N fertilization only when the density of wild oats (*Avena fatua* L.) was below 1.6 percent of total plant density.

### 3.2.3. Community Composition and Diversity

Suarez et al. (2001) observed that field sites in grasslands of Rio de la Plata, Argentina with above average crop yields also exhibited greater weed species diversity. On the other hand, Pysek and Leps (1991) observed decreased weed biodiversity and altered distribution of growth forms with N fertilization in a barley field in the Czech Republic. Nutrient addition studies conducted in natural, nutrient-poor ecosystems such as heathlands, have reported increases in plant diversity following fertilization (Heil and Diemont, 1983; Helsen et al., 1983). However, other studies on unaltered ecosystems and abandoned old-fields have reported opposite effects (Tilman, 1987; Hobbs et al., 1988). In agricultural systems, weed species adapted to high fertility levels (especially N) that are not usually found in the successional system can invade and dominate for a time (Tilman, 1987; Odum et al., 1994). Changes in species composition with different nutrient availability levels can arise from differences in the competitive ability of the species present in the system (Aerts and Berendse, 1988; DiTommaso and Aarssen, 1989). Certain species adapted to low fertility levels may be unable to survive under conditions of higher fertility. For example, this was observed for arctic plant species, where it was hypothesized that high N levels were either toxic or might have inhibited winter hardening (Russell, 1973).

Dieleman et al. (2000) reported an association between weed species distribution and several soil fertility properties in maize fields under continuous cultivation in Nebraska, USA. They found that more fertile soils were associated with annuals, while less fertile soils were associated with perennial weeds. Tilman (1987) reported similar observations in fertilized experimental plots within

temperate old-fields in Minnesota, USA and speculated that the observed trends in plant species dominance might be due to differences in initial growth rates between annuals and herbaceous perennials. The faster growth rate of annual species during the first year of fertilizer addition allowed annuals to be dominant on the test plots (Grime and Hunt, 1975). However, in subsequent years of nutrient addition, perennials were favored because they invested more resources to vegetative structures such as rhizomes thereby growing more rapidly at the beginning of the season compared with annuals, which reproduce and establish from seed (Tilman, 1987). These findings suggest that herbaceous perennial weeds may be more abundant and problematic on ADE soils than herbaceous annual weeds, especially if disturbance is limited.

In summary, soil fertility alone may not predict the structure and diversity of future weed communities accurately in a given area. This inability to arrive at generalizations is likely due to the wide differences in climate, site history, and management of the studies used in the literature. It is possible that, on a localized scale, weed species abundance could be linked to soil fertility. For example, Ugen and Wortmann (2001) proposed that Ugandan farmers use the density of weeds to assess the fertility of their fields. The principle behind this strategy is the differential response of weeds to the availability of various plant nutrients. Thus, weed species could serve as good indicators of adequate or deficient nutrient levels in cropping systems. For example, a relative density of more than 20% for *Cyperus* spp. (nutsedges) in an annual cropping system indicates that N availability is likely inadequate. Additionally, some farmers in Costa Rica consider that the weeds *Sida rhombifolia* L., and *Piper* sp., which are found on ADE, are indicative of good soil fertility (de la Cruz, 1994). Whether differences in weed biodiversity on ADE soils are observed may depend on the ability of particular weed species to colonize these areas. The proximity of ADE sites to rivers and human activity may facilitate weed dispersal and establishment (Clement et al., 2003).

#### 3.2.4. Nutrient Availability and Timing of Application

The timing and placement of nutrient application can have a significant effect on the outcome of weed-crop competition (DiTomaso, 1995). Fertilization strategies should thus be designed to benefit crop species by ensuring that crops are better able to secure added nutrients when and where they are provided, thus making them unavailable to weeds. This approach may not be possible in complex, polycultural cropping systems, or when the nutrient requirements of weeds overlap those of crops, in terms of both nutrient levels and timing of uptake. This tactic is highlighted by the planting of fire tolerant sweet potatoes by the Kayapó Indians of the Amazon basin before forested areas are fully cut down, in order to take full advantage of the nutrient flush made available immediately after residual plant material is burned following the cutting of forest (Hecht and Posey, 1989). Hence, weeds that are not established at this time of relatively high nutrient availability would be at a relative disadvantage compared with this crop.

### 3.2.5. Legumes

Weedy legumes may be more common on ADE than on background soils, because of the increased availability of nutrients other than N, for example P. It is plausible that at low fertility and organic matter levels, legumes would be favored over non-leguminous species. However, it is likely that the presence of large pools of nutrients other than N (e.g., as is the case on ADE) would also allow legumes to be more competitive by alleviating other fertility constraints. In fact, low P availability often prevents optimum biological N fixation (Giller and Cadish, 1995). In ADE, N availability is likely low, and the availability of other nutrients, especially P, can be much greater than in background soils (Lehmann et al., 2003a). In pot experiments, Lehmann et al. (2003b) observed that the high C:N ratio of ADE soils reduced soil N uptake by the legume *Vigna unguiculata* (L.) Walp (cowpea) to levels below those observed on a non-fertilized Ferralsol (background soil). This occurred despite a greater total N content of the ADE soil (4.96 g N kg<sup>-1</sup> soil), compared with the background soil (3.17 g N kg<sup>-1</sup> soil). Nonetheless, total biomass production of cowpea was greater on the ADE than on the background soil. This suggests that other soil characteristics influenced overall fertility, allowing the legume to compensate for low soil nitrogen availability with atmospherically derived nitrogen.

Fertilization can differentially affect the competitive abilities of plant species depending on their N-fixing capabilities. For instance, Liebman and Mohler (2001) showed that the competitive outcome between a legume crop (*Pisum sativum* L.) and a non-leguminous weed (*Brassica hirta* Moench) in the field was dependent on N fertilization. When both species were grown in mixture, the legume crop produced 185% more aboveground biomass when no fertilizer was added than when ammonium sulfate was supplied. Ammonium is rapidly oxidized to nitrate in most soils, and this anion inhibits atmospheric N fixation (Voisin et al., 2002). It is possible that, in this case, the legume crop was less competitive for mineral N than was the non-leguminous weed. In contrast, Hume (1982) found no effect of fertilization on the density of a weedy vetch (*Vicia* sp.) in cereal cropping systems of western Canada.

### 3.3. Influence of Natural Succession Processes and other Biotic Factors

When discussing weed dynamics in shifting cultivation systems, it is valuable to consider natural plant succession following slash-and-burn land preparation. Weeds are in fact pioneer species that respond to ecosystem disturbances, and therefore play a key role in plant succession dynamics.

In the context of swidden agriculture, volunteer species (whether referred to as weeds, pioneers or successional species) are an integral component of each phase of crop and fallow management. The primary objective of farmers is to manipulate natural succession for a given period to allow the harvest of planted crops and useful volunteer species. Subsequently, when soil nutrients are depleted and/or weed pressure is excessive, farmers in shifting agricultural systems rely on this same volunteer vegetation to restore soil fertility after the cropping cycle. During the cropping phase, early successional plants are subject to management activities such

as slashing, hoeing and high frequency burning that do not typically occur under natural successional processes. Such practices likely modify the course of natural succession. Nevertheless, cropping and fallow periods should be viewed as key points along a continuum of plant community development rather than as two distinct phases, because farmers often continue to harvest useful species after swidden “abandonment” (Denevan et al., 1984; Padoch, 1988; Szott et al., 1994; Hammond et al., 1995; Lambert, 1996; Coomes et al., 2000; Steininger, 2000; Kammersheidt, 2002), and because annual and perennial weeds often play a central role during fallow periods (Ahn, 1979).

### 3.3.1. Natural Plant Succession Processes

Using field surveys in the state of Acre in the Brazilian Amazon, Fujisaka et al. (1998) observed that the total density of non-crop plants decreased by half as “natural” forests on background soils were cleared, but increased sharply in subsequent cropping seasons because of colonization by shrubs and herbaceous species. Working on background soils in the Peruvian Amazon, Staver (1989a) also reported increasing plant cover of non-crop species in fields planted to crops following slash-and-burn. Fields that had been slash-and-burned for at least 34 months had substantially greater weed cover (58%) than young fields of 2-4 months (19%).

Changes in dominant weed life forms or species over time may not always be apparent. Dominant life forms can vary substantially in crop production fields (Staver, 1989b; Fujisaka et al., 1998), where different management practices are often used. In a field experiment in Costa Rica for example, Harcombe (1977) observed different successional outcomes on non-fertilized versus fertilized background soil plots cleared from old-growth forest. In non-fertilized plots, shrubs eventually replaced forbs as the dominant life form within one year, but in fertilized plots the forb *Phytolacca rivinoides* Kunth and Bouché was dominant one year after land preparation (Harcombe, 1977). These findings suggest that differences in successional patterns are likely to occur between ADE and the less fertile background soils, and this hypothesis is corroborated through ethnoscientific evidence for distinctive successional processes on ADE and background soils (German, 2003b). Over time, fallowing can reduce total plant density (Uhl et al., 1982; Fujisaka et al., 1998) and suppress herbaceous weeds present during cropping, as woody vegetation colonizes the site (Uhl et al., 1982; Staver, 1989b; Roder et al., 1997).

These changes in the life form and composition of weedy vegetation in slash-and-burn agriculture are strongly linked to the potential of weeds to successfully colonize and become established in disturbed sites.

### 3.3.2. *Seeds and Weed Colonization*

Seeds capable of withstanding fires often play a critical role in the colonization of newly disturbed areas. While investigating plant regeneration following the slash-and-burn of a mature forest on a background soil in the Amazon basin, Uhl et al. (1981) found that on-site seed regeneration was of greater importance for successional tree species than for herbaceous grasses and forbs. That is, grasses and forbs were more likely to re-colonize a disturbed site after a fire from nearby areas than through active recruitment from the post-burn seedbank. The relatively smaller seeds produced by forbs and grasses are more easily dispersed by wind than the larger seeds of successional trees, which are dispersed primarily by birds and bats. Interestingly, once these early weed colonizers were established in the site, their densities did not increase substantially until they began to produce seeds regardless of whether they were trees, grasses or forbs.

Given these observations were obtained on plots that had been cleared of mature forest, one might hypothesize that the seedbank of areas at earlier stages of succession (i.e., that have more recently been cleared and left to regenerate) should contain more seeds of herbaceous life forms. Clearly, if these species are not killed by fire, a distinctive colonization pattern emerges. For instance, Fujisaka et al. (2000) working on background soils in the Peruvian Amazon found a 20% greater plant density in plots cropped after fallow than in plots cropped after the removal of a mature forest. Additional evidence for the buildup of weed seedbanks under more intense crop production is provided by data showing that labor requirements for weeding increase when fallow periods decrease (Roder et al., 1995). The size and increase of weed seedbank populations are highly dependent on the seed output of the component species and the degree of dormancy of seeds.

### 3.3.3. *Seed Longevity*

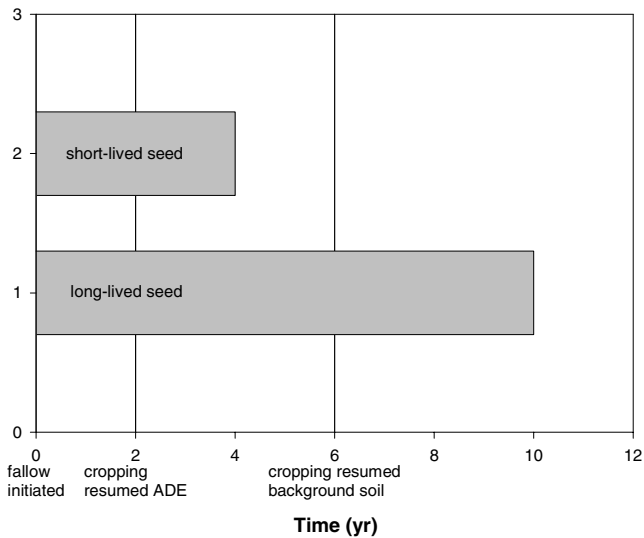
Seed dormancy represents an important ecological adaptation of weedy species in temperate climates, and often plays a significant role in determining the type and efficacy of weed management strategies used (Baskin and Baskin, 1998). Seed dormancy may not be as common for weedy species in tropical regions as in temperate areas since environmental conditions favorable to seedling establishment may be more prevalent in the tropics. For example, the absence of winters during which plant growth is inhibited precludes the need for cold stratification. Nonetheless, seeds of some tropical weedy species do exhibit dormancy, primarily physiological (i.e., a physiological inhibiting mechanism of the embryo that prevents radicle emergence (Baskin and Baskin, 1998).) In tropical regions, the occurrence of forest gaps is necessary for the establishment and growth of successional species. Hence, many of these species exhibit a light requirement for breaking seed dormancy. In fact, in many tropical successional species, seed germination can be induced by exposure to direct sunlight and fluctuating temperatures (Holthuijzen and Boerboom, 1982; Uhl and Clark, 1983).

Seed dormancy in weedy tropical grasses has been shown to be relatively complex and highly variable between populations (Groves, 1991). Selected seeds of

successional grasses, forbs, shrubs and trees remained viable after one year under a forest canopy in southern Venezuela (Uhl and Clark, 1983). However, after 15 months of burial in southeastern Nigeria, only 5 of 15 weed species had seeds with 50% or more viability (primarily species in the Cyperaceae and Lamiaceae families). Interestingly, seeds of several species in the Asteraceae were non-viable after only one month of burial (Marks and Nwachuku, 1986). In a long-term experiment in a lowland tropical forest of Surinam, buried seeds of weedy trees within the genus *Cecropia* exhibited a high degree of viability after more than five years (Holthuijzen and Boerboom, 1982). Similarly, Juliano (1940) observed that buried seeds of eleven of 23 herbaceous weed species in the Philippines retained viability after 6 years of burial in glass jars.

Nevertheless, weed seed dormancy does appear to be less common in tropical regions than temperate regions (Marks and Nwachuku, 1986) and for this reason, seedbank numbers have been observed to be lower (by about one order of magnitude) in tropical climates (Garcia, 1995).

Given that fallow periods are typically shorter on ADE, weed species with low seed dormancies should be more common during cropping phases on these soils. Alternatively, on background soils where longer fallow periods are generally used, seeds of species that maintain viability for longer periods should be most common. This concept is illustrated in Figure 2.



*Figure 2: Conceptualized relationship between seed dormancy and length of fallow period. While longer fallow periods on background soils allow for reductions in seedbank numbers, declines in the seedbank may be less important on ADE soils because the fallow period interval is shorter.*

### 3.3.4. *Effect of Fallows on Weeds and Seedbanks*

During fallow, the decline in herbaceous weed biomass occurs gradually. Firstly, growth and subsequent shading by trees, lianas, and shrubs leads to a reduction in the number of weedy species adapted to open habitats (Akobundu et al., 1999). This causes declines in seed production and seedbank size as some seeds germinate, some are lost to predation while others lose viability through decay (Garcia, 1995).

In Nigeria, three consecutive years of fallow were required after one year of cropping before substantial declines in the weed seedbank occurred (Akobundu, 1999). In contrast, research by Staver (1991) in the Peruvian Amazon demonstrated that the size of the weed seed bank, in that setting, begins to decline immediately after cropping ceases. Likewise, the total number of species present in the seedbank decreased over a 10-year period largely because of declines in the number of seeds of herbaceous species.

The fallow period is generally completed by slashing and burning, with fire reducing seedbank size in direct proportion to its intensity (Monaco, 1998). On ADE, there is a tendency to clear fallow of a younger age (earlier stage of succession) (German 2003a), and often during rainy months when only young fallow will burn effectively (German, 2001). This suggests that burns on background soils are generally more intense than on ADE, and lead to greater declines in seedbank numbers. The ethno-scientific data presented by German (2001) further supports the need for a more intense burning event on background soils to effectively restore soil fertility. Over time, these divergent management practices should lead to disproportionate increases in seedbank size on ADE versus background soils, thereby magnifying weed management problems on ADE soils.

### 3.3.5. *Tree Coppicing*

Tree and shrub regeneration via coppicing (or sprouting) are favored by short cropping and long fallow periods. ADE soils are more fertile, generally allowing for shortened fallow periods within shifting agricultural systems (German, 2001, 2003a). While this may lead to decreased pressure from sprouting vegetation through time, the length of the cropping period may also be shorter in some ADE systems, thereby confounding any clear trend of regeneration through coppicing on ADE.

In the previous section, we emphasized the important role of trees, shrubs and lianas for suppression of weeds during fallow. Plants from these life forms can originate from seed but, often, perennial species can establish and persist from one fallow period to the next via sprouting. In fact, biomass arising from tree, liana, and herbaceous sprouting can represent a significant portion of the live plant material present in an area following slashing. For instance, three months following the slashing of a mature forest area in southern Venezuela, 87% of plants had originated from tree stump sprouts (Uhl et al., 1981). Stocker (1981) reported that of 82 trees species found in an old-growth forest area in Northern Australia that had been cleared and burned, 90% coppiced from stumps, 12% of species produced root suckers, and 41% of the species reproduced by seed. While several of the tree

species reproduced exclusively by vegetative means, most reproduced both vegetatively and by seed (Stocker, 1981). Tropical weedy trees of the genus *Cecropia* and palms are particularly well known for their ability to reproduce by sprouting (Kauffman, 1991). However, cropping can substantially alter sprouting patterns. Over a three year cropping cycle in the Ivory Coast, de Rouw (1993) found that the proportion of biomass from resprouting herbaceous species declined while that of lianas increased from 18 to 75% during this same period.

An effective method of preventing and killing sprouts is burning, provided that high enough temperatures are reached (Uhl et al., 1981; Kauffman, 1991; de Rouw, 1993). Uhl et al. (1981) observed dramatic reductions in the level of tree sprouting in slash four months after burning. After slash-and-burn, the weeding frequency may have a stronger impact on the biomass of sprouts than on their density (Staver, 1991; de Rouw, 1993). de Rouw (1993) also noted that during the first and second years of cropping, initial fire intensity had a greater impact on sprout density than did weeding frequency, and suggested that plants capable of withstanding a severe fire event are less affected by subsequent weeding. Interestingly, after three years of cropping, sprout densities were similar among all four fire-intensity and weeding treatment combinations. Although de Rouw (1993a) observed a rapid decrease in the diversity of sprouting plant species, no significant differences in total sprout density were found on fields cleared from primary forest, secondary forest, or from fallows 6 to 16 years old.

Tree species reproducing by seed eventually disappear from weeded plots because they are generally not allowed to set seed. Therefore, woody vegetation found in cropped areas and at the onset of a fallow originates largely from sprouting stumps and roots (Stromgaard, 1986), and this life form dominates during the fallow period (Kellman, 1980). However, intensive manual weeding or mechanical tillage can lead to the elimination of sprouting vegetation (Kellman, 1980). Tree species that remain in ADE cropping systems will influence the vegetational composition of fallows (Kellman, 1980), as well as seedbank size and weed pressure in subsequent cycles.

### *3.3.6. Influence of Management on Weed Dynamics*

Weed management prior to abandonment and the duration of the fallow period before the next cropping cycle strongly influence weed population dynamics. A solid understanding of these processes is fundamental for addressing the importance of weeds in shifting agricultural systems. Moreover, weed population dynamics will likely vary substantially between ADE and background soils due to strongly divergent site histories and management practices.

Continued cropping and weeding of swiddens modifies the composition and density of the weed community. As weeding exhausts reserves of sprouting woody species and seedlings are removed, the seedbank of these species is severely depleted. Fujisaka et al. (2000) observed fewer trees in areas cropped after fallow than in areas cropped after the cutting of a forest. Grasses and forbs are capable of colonizing and dominating open areas such as agricultural fields because they can

rapidly produce large numbers of easily dispersible seeds (Uhl, 1982). Persistent cosmopolitan weeds such as the grasses *Imperata brasiliensis* Trin. (Fujisaka et al., 1998), *Paspalum* sp., *Panicum* sp., and *Rottboellia cochinchinensis* (Lour.) W.D. Clayton (Fujisaka et al., 2000) can be introduced or selected for by the intensification of cropping and weeding practices.

Some ADE sites in the Amazon Basin have reached a level of agricultural intensification that is quite unique to these soils. Thus, weed dynamics in these sites may differ widely from those in shifting agricultural sites, whether on ADE or background soils. One possible difference is the dominance of cosmopolitan weeds on these intensively managed ADE soils which may alter weed seedbank dynamics and eventual fallow vegetation, but this remains to be verified.

In a slash-and-burn agricultural system, Staver (1991) observed that the timing of weed control (frequent, early, and late in the cropping cycle) had no significant effect on weed biomass two years post-burning. Nonetheless, manioc and plantain yields did respond differently to the various weeding regimes. Early weed pressure in plots subjected to the late weed control treatment reduced yield in cassava but not in plantain. The duration of fallows and fallow dynamics may have a greater effect on weed pressure during cropping cycles than weeding regimes. In Amazonian Peru, Staver (1991) observed that plots having the lowest weed biomass at maize harvest were under fallow the longest (up to 12 years), regardless of the number of times plots were weeded during the cropping cycle. Because ADE sites are fallowed for shorter periods of time, and weed growth and reproduction may increase on these soils, weed establishment from the seedbank may be a more important feature of recruitment than for less fertile background soils. If the fallow period is relatively short and if adequate fallow vegetation does not develop due to poor tree species regeneration, management of the resident vegetation may be especially problematic.

#### 4. WEED MANAGEMENT TECHNIQUES CURRENTLY USED ON AMAZONIAN DARK EARTHS

Shifting agriculture is itself a powerful weed management tactic. Indeed, burning reduces weed seed numbers on or near the soil surface and damages vegetatively produced plant structures such as tillers and sprouts. During the cropping phase, labor is a primary constraint to crop production on ADE soils (German, 2001). As discussed, small-scale farmers in the Central Amazon invest 23% more time weeding on ADE soils than on background soils (L. German, unpubl. data). While less experienced smallholder ADE farmers manage residues and weeds much like they would on background soils (e.g., by infield burning), more experienced farmers actively experiment with new weed management tactics. Examples include the establishment of long rows of slash that decompose and “prepare” the soil for planting (German, 2001). Similarly, weeds have been used for mulching and burning by the Kayapó Indians of the Amazon basin (Hecht and Posey, 1989). Other forms of weed management may also be found, yet many farmers lack experience with these practices and knowledge of “what works” is only incipient (German, 2003b). These management strategies may be especially beneficial when weeds are used to

capture nutrients that could otherwise be lost from the system after the addition of ashes or fertilizers, for example.

## 5. FUTURE PROSPECTS AND CHALLENGES

There is a critical need for the development of sustainable agroecosystems in the Amazon, and we believe that the promotion of effective, economically and socially acceptable weed management strategies is an especially important element of this challenge. ADE soils are highly fertile and weed pressures on them are greater than on background soils. These soils are currently farmed using a wide range of management techniques and input levels. The dynamic manner in which they are managed is dependent on demographic, economic, and cultural factors. If fertile soils could eventually be developed from the nutrient-impoverished soil types that predominate in the Amazon, effective weed management techniques would be required to fully take advantage of these more productive soils. The paucity of information relating to weeds on ADE soils strongly suggests the need for a greater research effort in this area. Beyond the research currently underway on biodiversity and crop yield reduction potential of weeds in ADE systems, future research should focus on developing and implementing effective weed management options for crops grown on ADE soils. This research should consider actual farmer resource endowments, constraints and priorities.

Intensive, market-oriented management of crop production systems on ADE soils uses techniques similar to those found in other intensive commercial farming areas of the world and may include monocropping, irrigation, pesticide application, mechanized tillage, and the use of soil amendments such as inorganic fertilizers and manures. While some of these strategies can be used effectively to manage weeds, they can also have detrimental effects on soil health and the sustainability of cropping practices (German, 2003a). In order to maintain the fertility and overall health of ADE soils, an integrated weed management approach is required that employs multiple control tactics, possibly including crop rotation, cover cropping, increased crop diversity, and mulching, for example.

On less intensively managed agricultural land, fallow management for weed control is critical. Traditional strategies of weed control have made use of bush fallow, a practice that allows volunteer vegetation to establish prior to being slashed, when labor is available. Short-term managed fallows may be an alternative option for reducing fallow periods while still allowing acceptable levels of weed control and improving soil fertility. Improved fallow systems that have made use of leguminous species have been widely adopted throughout the tropics (Sanchez, 1999). In these systems, the establishment of natural vegetation is encouraged but desirable herbaceous and/or woody species can also be planted (Gallagher et al., 1999). Gallagher et al. (1999) review the potential role of improved fallows for weed management in tropical agroecosystems. Improved fallows can reduce weed pressure by modifying the soil environment (e.g. largely through their effect on soil temperature), thus promoting losses of weed seeds from the seedbank through germination, decay, and predation. Allelochemicals represent an additional tactic

that can be used to inhibit weed seed germination and seedling growth. However, much work is required to effectively incorporate this management option into current crop production systems in the tropics (Gallagher et al., 1999). Agroforestry techniques may be additional tools for managing weeds (Staver, 1989; Becker and Johnson, 1999; Akobundu and Ekeleme, 2002). However, this approach may require additional labor and access to seeds of non-traditional plants (or the collection of seeds) for the planting and establishment of the fallow vegetation (Staver, 1989). A favorable market climate that provides economic returns throughout the year is another necessary feature of this approach (Anderson and Ioris, 1992). The use of native and introduced weeds of the Asteraceae family, such as *Chromolaena odorata* (L.) King and Robinson and *Tithonia* sp., may also be simple yet valuable options for improved fallows. These species are very efficient nutrient accumulators, but may become problematic during crop production because of their invasive nature (Gallagher et al., 1999).

The objectives of active fallow management need not be restricted to soil fertility restoration and/or weed pressure reduction but may also include increased economic returns through diversification of the system. For example, the harvesting of firewood and timber (Akobundu and Ekeleme, 2002), and forage for animals (Ahn, 1979) could comprise key components of the production system. The optimum duration of a fallow is then determined not only by soil and weed management considerations, but also by these additional economic factors.

Managed fallows may prove to be useful weed management tools on ADE and background soils of the Amazon. However, for this approach to be successfully employed, a sound understanding and appreciation of local knowledge as it relates to ecological, economical, and cultural aspects of crop production will be required.

## 6. REFERENCES

- Aerts, R., & Berendse, F. (1988). The effect of increased nutrient availability on vegetation dynamics in wet heathlands. *Vegetatio*, 76, 63-69.
- Ahn, P.M. (1979). The Optimum Length of Planned Fallows. In H.O. Mongi, & P.A. Huxley (Eds.), *Soils Research in Agro-forestry* (pp. 15-39). Nairobi, Kenya: International Council for Research in Agroforestry.
- Akobundu, I.O., & Ekeleme, F. (2002). Weed seedbank characteristics of arable fields under different fallow management systems in the humid tropical zone of southwestern Nigeria. *Agroforestry Systems*, 54, 161-170.
- Akobundu, I.O., Ekeleme, F., & Chikoye, D. (1999). Influence of fallow management systems and frequency of cropping on weed growth and crop yield. *Weed Research*, 39, 241-256.
- Ampong-Nyarko, K., & Datta, S.K.d. (1993). Effects of nitrogen application on growth, nitrogen use efficiency and rice-weed interaction. *Weed Research*, 33, 269-276.
- Anderson, A.B., & Ioris, E.M. (1992). Valuing the rain forest: Economic strategies by small-scale forest extractivists in the Amazon estuary. *Human Ecology*, 20, 337-369.
- Andreasen, C., Streibig, J.C., & Haas, H. (1991). Soil properties affecting the distribution of 37 weed species in Danish fields. *Weed Research*, 31, 181-187.
- Barberi, P. (2001). Weed management in organic agriculture: are we addressing the right issues? *Weed Research*, 42, 177-193.
- Baskin, C.C., & Baskin, J.M. (1998). *Seeds: Ecology, Biogeography, and Evolution of Dormancy and Germination*. San Diego, California: Academic Press.
- Becker, M., & Johnson, D.E. (1999). The role of legume fallows in intensified upland rice-based systems of West Africa. *Nutrient Cycling in Agroecosystems*, 53, 71-81.

- Carlson, H.L., & Hill, J.E. (1986). Wild oat (*Avena fatua*) competition with spring wheat: effects of nitrogen fertilization. *Weed Science*, 34, 29-33.
- Chachulski, L., Janakowski, S., & Golinowski, W. (1999). Effects of fertility, weed density and crop competition on biomass partitioning in *Centaurea cyanus* L. *Acta Societatis Botanicorum Poloniae*, 68, 69-77.
- Clement, C.R., McCann, J.M., & Smith, N.J.H. (2003). Agrobiodiversity in Amazonia and its Relationships with Dark Earths. In J. Lehmann, D.C. Kern, B. Glaser, & W.I. Woods. (Eds.), *Amazonian Dark Earths: Origin, Properties, Management* (pp. 159-177). The Netherlands: Kluwer Academic Publishers.
- Coomes, O.T., Grimard, F., & Burt, G.J. (2000). Tropical forests and shifting cultivation: secondary forest fallow dynamics among traditional farmers of the Peruvian Amazon. *Ecological Economics*, 32, 109-124.
- de Kroon, H., & Knops, J. (1990). Habitat exploration through morphological plasticity in two chalk grassland perennials. *Oikos*, 59, 39-49.
- de la Cruz, R. (1994). The usefulness of weed diversity in slash/mulch bean production: difficulties in herbicide use. In H.D. Thurston, M. Smith, G. Abawi, & S. Kearle (Eds.), *Tapado slash/mulch: How Farmers Use It and What Researchers Know About It* (pp. 233-237). Ithaca, NY: Cornell International Institute for Food, Agriculture, and Development (CIIFAD).
- Denevan, W.M., Treacy, J.M., Alcorn, J.B., Padoch, C., Denslow, J., & Paitan, S.F. (1984). Indigenous agroforestry in the Peruvian Amazon - Bora Indian management of swidden fallows. *Interciencia*, 9, 346-357.
- de Rouw, A. (1993). Regeneration by sprouting in slash and burn rice cultivation, Tai rain forest, Côte d'Ivoire. *Journal of Tropical Ecology*, 9, 387-408.
- Dieleman, J.A., Mortensen, D.A., Buhler, D.D., & Ferguson, R.B. (2000). Identifying associations among site properties and weed species abundance. II. Hypothesis generation. *Weed Science*, 48, 576-587.
- DiTomaso, J.M. (1995). Approaches for improving crop competitiveness through the manipulation of fertilization strategies. *Weed Science*, 43, 491-497.
- DiTommaso, A., & Aarssen, L.W. (1989). Resource manipulations in natural vegetation: a review. *Vegetatio*, 84, 9-29.
- Everaarts, A.P. (1992). Response of weeds to application of nitrogen, phosphorus and potassium on low-fertility acid soils in Suriname. *Weed Research*, 32, 385-390.
- Fawcett, R.S., & Slife, F.W. (1978). Effects of field applications of nitrate on weed seed germination and dormancy. *Weed Science*, 26, 594-596.
- Freyman, S., Kowalenko, C.G., & Hall, J.W. (1989). Effect of nitrogen, phosphorus and potassium on weed emergence and subsequent weed communities in south coastal British Columbia. *Canadian Journal of Plant Science*, 69, 1001-1010.
- Fujisaka, S., Escobar, G., & Veneklaas, E.J. (1998). Plant community diversity relative to human land uses in an Amazon forest colony. *Biodiversity and Conservation*, 7, 41-57.
- Fujisaka, S., Escobar, G., & Veneklaas, E.J. (2000). Weedy fields and forests: interactions between land use and the composition of plant communities in the Peruvian Amazon. *Agriculture, Ecosystems and Environment*, 78, 175-186.
- Gallagher, R.S., Fernandes, E.C.M., & McCallie, E.L. (1999). Weed management through short-term improved fallows in tropical agroecosystems. *Agroforestry Systems*, 47, 197-221.
- Garcia, M.A. (1995). Relationship between weed community and soil seed bank in a tropical agroecosystem. *Agriculture, Ecosystems and Environment*, 55, 139-146.
- German, L.A. (2001). *The Dynamics of Terra Preta: An Integrated Study of Human-Environmental Interaction in a Nutrient-Poor Amazonian Ecosystem*. Unpublished Ph.D. thesis, University of Georgia, Athens, GA, USA.
- German, L.A. (2003a). Historical contingencies in the coevolution of environment and livelihood: contributions to the debate on Amazonian Black Earth. *Geoderma*, 111, 307-331.
- German, L.A. (2003b). Ethnoscience understandings of Amazonian Dark Earths. In J. Lehmann, D.C. Kern, B. Glaser, & W.I. Woods. (Eds.), *Amazonian Dark Earths: Origin, Properties, Management* (pp. 179-201). The Netherlands: Kluwer Academic Publishers.
- Giller, K.E., & Cadish, G. (1995). Future benefits from biological nitrogen fixation: an ecological approach to agriculture. *Plant and Soil*, 174, 255-277.
- Grime, J.P., & Hunt, R. (1975). Relative growth-rate: its range and adaptive significance in a local flora. *Journal of Ecology*, 63, 393.

- Groves, R.H. (1991). The physiology of grassy weeds in tropical agriculture. In F.W.G. Baker & P.J. Terry (Eds.), *Tropical Grassy Weeds* (pp. 39-51). Wallingford, Oxon, UK: CAB International.
- Hammond, D.S., Dolman, P.M., & Watkinson, A.R. (1995). Modern Ticuna swidden-fallow management in the Colombian Amazon - Ecologically integrating market strategies and subsistence-driven economies. *Human Ecology*, 23, 335-356.
- Harcombe, P.A. (1977). The influence of fertilization on some aspects of succession in a humid tropical forest. *Ecology*, 58, 1375-1383.
- Hecht, S.B., & Posey, D.A. (1989). Preliminary results on soil management techniques of the Kayapó Indians. *Advances in Economic Botany*, 7, 174-188.
- Heil, G.W., & Diemont, W.H. (1983). Raised nutrient levels change heathland into grassland. *Vegetatio*, 53, 113-120.
- Helsper, H.P.G., Glenn-Lewin, D.C., & Werger, M.J.A. (1983). Early regeneration of *Calluna* heathland under various fertilization treatments. *Oecologia*, 58, 208-214.
- Hill, S.B., & Ramsay, J. (1977). *Weeds as indicators of soil conditions*. Ecological Agriculture Projects Publication 67. Retrieved October 11, 2002, from the World Wide Web: <http://www.eap.mcgill.ca/>
- Hiraoka, M., Yamamoto, S., Matsumoto, E., Nakamura, S., Falesi, I.C., & Baena, A.R.C. (2003). Contemporary use and management of Amazonian Dark Earths. In J. Lehmann, D.C. Kern, B. Glaser, & W.I. Woods (Eds.), *Amazonian Dark Earths: Origins, Properties, Management* (pp. 387-406). The Netherlands: Kluwer Academic Publishers.
- Hobbs, R.J., Gulmon, S.L., Hobbs, V.J., & Mooney, H.A. (1988). Effects of fertilizer addition and subsequent gopher disturbance on a serpentine annual grassland community. *Oecologia*, 75, 291-295.
- Holthuijzen, A.M.A., & Boerboom, J.H.A. (1982). The *Cecropia* seedbank in the Surinam lowland rain forest. *Biotropica*, 14, 62-68.
- Hume, L. (1982). The long-term effects of fertilizer application and three rotations on weed communities in wheat (after 21-22 years at Indian Head, Saskatchewan). *Canadian Journal of Plant Science*, 62, 741-750.
- Jornsgard, B., Rasmussen, K., Hill, J., & Christiansen, J.L. (1996). Influence of nitrogen on competition between cereals and their natural weed populations. *Weed Research*, 36, 461-470.
- Juliano, J.B. (1940). Viability of some Philippine weed seeds. *Philippine Agriculturist*, 29, 313-326.
- Kammersheidt, L. (2002). Perspectives on secondary forest management in tropical humid lowland America. *Ambio*, 31, 243-250.
- Kauffman, J.B. (1991). Survival by sprouting following fire in tropical forests of the Eastern Amazon. *Biotropica*, 23, 219-224.
- Kellman, M. (1980). Geographic patterning in tropical weed communities and early secondary successions. *Biotropica*, 12, 34-39.
- Kern, D.C., & Kämpf, N. (1989). Antigos assentamentos indígenas na formação de solos com terra preta arqueológica na região de Oriximiná, Pará. *Revista Brasileira de Ciencia do Solo*, 13, 219-225
- Kern, D.C., & Lima da Costa, M. (1995). *Distribuição geoquímica do fósforo em sítios arqueológicos com terra preta: o exemplo de Caxiuanã (Pará)*. Paper presented at the V Congresso Brasileiro de Geoquímica e III Congresso de Geoquímica dos Países de Língua Portuguesa, Niterói, RJ, Brazil.
- Kern, D.C., Lima da Costa, M., & Frazão, F.J. (1999). *Geoquímica de sítio arqueológico com terra preta no centro da cidade de Quatipurú-PA*. Paper presented at the VI Symposium on Geology of the Amazon, Manaus, AM, Brasil.
- King, C.A., & Purcell, L.C. (1997). Interference between hemp sesbania (*Sesbania exaltata*) and soybean (*Glycine max*) in response to irrigation and nitrogen. *Weed Science*, 45, 91-97.
- Lambert, D.P. (1996). Crop diversity and fallow management in a tropical deciduous forest shifting cultivation system. *Human Ecology*, 24, 427-453.
- Légère, A., Simard, R. R., & Lapierre, C. (1994). Response of spring barley and weed communities to lime, phosphorus and tillage. *Canadian Journal of Plant Science*, 74, 421-428.
- Lehmann, J., Kern, D. German, L., McCann, J., Martins, G.C., & Moreira, A. (2003a). Soil fertility and production potential. In J. Lehmann, D.C. Kern, B. Glaser, & W.I. Woods (Eds.), *Amazonian Dark Earths: Origin, Properties, Management* (pp. 105-124). The Netherlands: Kluwer Academic Publishers.
- Lehmann, J., Pereira da Silva, J., Steiner, C., Nehls, T., Zech, W., & Glaser, B. (2003). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil*, 249, 343-357.

- Liebman, M. (1989). Effects of nitrogen fertilizer, irrigation, and crop genotype on canopy relations and yields of an intercrop/weed mixture. *Field Crops Research*, 22, 83-100.
- Liebman, M., & Davis, A.S. (2000). Integration of soil, crop and weed management in low-external-input farming systems. *Weed Research*, 40, 27-47.
- Liebman, M., & Mohler, C.L. (2001). Weeds and the soil environment. In M. Liebman, C.L. Mohler, & C.P. Staver (Eds.), *Ecological Management of Agricultural Weeds* (pp. 210-268). Cambridge, UK: Cambridge University Press.
- Marks, M.K., & Nwachuku, A.C. (1986). Seed-bank characteristics in a group of tropical weeds. *Weed Research*, 26, 151-157.
- McCann, J.M., Woods, W.I., & Meyers, D.W. (2001). Organic matter and anthrosols in Amazonia: interpreting the Amerindian legacy. In R.M. Rees, B.C. Ball, C.D. Campbell, & C.A. Watson (Eds.), *Sustainable Management of Soil Organic Matter* (pp. 180-189). Wallingford: CAB International.
- Medlin, C.R., Shaw, D.R., Cox, M.S., Gerard, P.D., Abshire, M.J., & Wardlaw III, M.C. (2001). Using soil parameters to predict weed infestations in soybean. *Weed Science*, 49, 367-374.
- Monaco, L.M. (1998). *O Efeito Do Fogo Sobre A Regeneração De Espécies Pioneiras Na Amazônia Central*. Unpublished Masters thesis, Instituto Nacional de Pesquisas da Amazônia-Universidade do Amazonas, Manaus, AM.
- Qasem, J.R. (1992). Nutrient accumulation by weeds and their associated vegetable crops. *Journal of Horticultural Science*, 67, 189-195.
- Odum, E.P., Park, T.Y., & Hutcheson, K. (1994). Comparison of the weedy vegetation in old-field and crop fields on the same site reveals that fallowing crop fields does not result in seedbank buildup of agricultural weeds. *Agriculture, Ecosystems and Environment*, 49, 247-252.
- Padoch, C. (1988). The economic importance and marketing of forest and fallow products in the Iquitos region. *Advances in Economic Botany*, 5, 74-89.
- Pimentel, D. (1991). *CRC Handbook of Pest Management in Agriculture*. Boca Raton, Florida: CRC Press.
- Pons, T. L. (1989). Breaking of seed dormancy by nitrate as a gap detection mechanism. *Annals of Botany*, 63, 139-143.
- Pysek, P., & Leps, J. (1991). Response of a weed community to nitrogen fertilization: a multivariate analysis. *Journal of Vegetation Science*, 2, 237-244.
- Roder, W., Phengchanh, S., & Keoboulapha, B. (1995). Relationship between soil, fallow period, weeds and rice yield in slash-and-burn systems of Laos. *Plant and Soil*, 176, 27-36.
- Roder, W., Phengchanh, S., & Maniphone, S. (1997). Dynamics of soil and vegetation during crop and fallow period in slash-and-burn fields of northern Laos. *Geoderma*, 76, 131-144.
- Russell, E.W. (1973). *Soil Conditions and Plant Growth* (10th ed.). New York: Longman Group Ltd.
- Sanchez, P.A. (1999). Improved fallows come of age in the tropics. *Agroforestry Systems*, 47, 3-12.
- Saxena, K.G., & Ramakrishnan, P.S. (1984). Herbaceous vegetation development and weed potential in slash and burn agriculture (Jhum) in N.E. India. *Weed Research*, 24, 135-142.
- Schimpf, D.J., & Palmblad, I.G. (1980). Germination response of weed seeds to soil nitrate and ammonium with and without simulated overwintering. *Weed Science*, 28, 190-193.
- Shrefler, J.W., Shilling, D.G., Dusky, J.A., & Brecke, B.J. (1994). Influence of phosphorus fertility on intra- and interspecific interference between lettuce (*Lactuca sativa*) and spiny amaranth (*Amaranthus spinosus*). *Weed Science*, 42, 574-578.
- Sindel, B.M., & Michael, P.W. (1992). Growth and competitiveness of *Senecio madagascariensis* Poir. (fireweed) in relation to fertilizer use and increases in soil fertility. *Weed Research*, 32, 399-406.
- Sombroek, W.G., Nachtergaele, F.O., & Hebel, A. (1993). Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. *Ambio*, 22, 417-426.
- Staver, C. (1989a). Shortened bush fallow rotations with relay-cropped *Inga edulis* and *Desmodium ovalifolium* in wet central Amazonian Peru. *Agroforestry Systems*, 8, 173-196.
- Staver, C. (1989b). Why farmers rotate fields in maize-cassava-plantain bush fallow agriculture in the wet Peruvian Amazon. *Human Ecology*, 17, 401-426.
- Staver, C. (1991). The role of weeds in the productivity of Amazonian bush fallow agriculture. *Experimental Agriculture*, 27, 287-304.
- Steininger, M.K. (2000). Secondary forest structure and biomass following short and extended land-use in central and southern Amazonia. *Journal of Tropical Ecology*, 16, 689-708.
- Stocker, G.C. (1981). Regeneration of a North Queensland rain forest following felling and burning. *Biotropica*, 13, 86-92.

- Stromgaard, P. (1986). Early succession on abandoned shifting cultivator's plots in the Miombo of South Central Africa. *Biotropica*, 18, 97-106.
- Suarez, S.A., Fuente, E.B.d.l., Ghersa, C.M., & Leon, J.C. (2001). Weed community as an indicator of summer crop yield and site quality. *Agronomy Journal*, 93, 524-530.
- Szott, L.T., Palm, C.A., & Davey, C.B. (1994). Biomass and litter accumulation under managed and natural tropical fallows. *Forest Ecology and Management*, 67, 177-190.
- Tardif, F.J., & Leroux, G.D. (1992). Response of three quackgrass biotypes to nitrogen fertilization. *Agronomy Journal*, 84, 366-370.
- Tilman, D. (1987). Secondary succession and the pattern of plant dominance along experimental nitrogen gradients. *Ecological Monographs*, 57, 189-214.
- Tungate, K.D., Susko, D.J., & Rufty, T.W. (2002). Reproduction and offspring competitiveness of *Senna obtusifolia* are influenced by nutrient availability. *New Phytologist*, 154, 661-669.
- Ugen, M.A., & Wortmann, C.S. (2001). Weed flora and soil properties in subhumid tropical Uganda. *Weed Technology*, 15, 535-543.
- Uhl, C., Clark, H., Clark, K., & Maquirino, P. (1982). Successional patterns associated with slash-and-burn agriculture in the Upper Rio Negro region of the Amazon basin. *Biotropica*, 14, 249-254.
- Uhl, C., & Clark, K. (1983). Seed ecology of selected Amazon basin successional species. *Botanical Gazette*, 144, 419-425.
- Uhl, C., Clark, K., Clark, H., & Murphy, P. (1981). Early plant succession after cutting and burning in the upper Rio Negro of the Amazon basin. *Journal of Ecology*, 69, 631-649.
- Unruh, J., & Alcorn, J.B. (1988). Relative dominance of the useful component in young managed fallows at Brillo Nuevo. In W.M. Denevan, & C. Padoch (Eds.), *Swidden-fallow Agroforestry in the Peruvian Amazon* (pp. 47-52). New York, NY, USA: The New York Botanical Garden.
- Voisin, A.S., Salon, C., Munier, J.N.G., & Ney, B. (2002). Quantitative effects of soil nitrate, growth potential and phenology on symbiotic nitrogen fixation of pea (*Pisum sativum* L.). *Plant and Soil*, 243, 31-42.
- Walter, A.M., Christensen, S., & Simmelsgaard, S.E. (2002). Spatial correlation between weed species densities and soil properties. *Weed Research*, 42, 26-38.
- Woods, W.L., & McCann, J.M. (1999). The anthropogenic origin and persistence of Amazonian Dark Earths. *The Yearbook of the Conference of Latin American Geographers*, 25, 7-14.