The Amazon region occupies parts of seven sovereign nations and is highly heterogeneous both biophysically and socioeconomically. The Amazon of Peru is especially heterogeneous. For example, the forests in the tropical Andes, a region in the western section of the Amazon, by virtue of the nearby mountains, contain more biodiversity than those in other Amazon regions. Exceptionally large numbers of endemic plants (up to 20,000) have been identified in these forests, which are now considered a strong hotspot candidate for conservation support (Myers et al. 2000). The varied topography (200–2000 m above sea level) and the wide range of annual rainfall (1100–5000 mm/yr) provide conditions for very large numbers of different species to thrive.

Alongside this biophysical heterogeneity is a broad array of socio-economic and policy contexts. Multiple decision-making domains coexist in
the region and sometimes overlap. For example, national administrative divisions (e.g., municipalities) exist alongside the domains occupied and managed by indigenous populations that have their own decision-making processes. The combined biophysical, socioeconomic, and policy heterogeneity lead not only to very different resource use strategies and patterns by economic agents but also to a wide range of environmental consequences. Therefore predicting the effects of policy changes on land use patterns is complicated, and foreseeing related effects on the environment is even more so.

Despite this multidimensional and interrelated context, developing the Peruvian Amazon is imperative to the long-term growth of the country. Indeed, the region is undergoing rapid change from increasing economic activity such as timber extraction, slash-and-burn agriculture, livestock production, mineral extraction, and fishing. Although a small human population now lives in the Peruvian Amazon (only about 2.2 million people, or 9 percent of the country’s population), typical economic activities are predictably land-extensive and may have severe consequences for plant and animal biodiversity and the environment in general.

Nearly 60 percent of Peru’s national territory is in the Amazon region. Since the 1980s, government policies such as tax breaks, subsidies, and road building have attempted to speed development in this region as part of a national response to general economic malaise and a growing population (Bedoya Garland 1987). By some accounts, the economic gains associated with these policy actions have been meager (Hecht 1993); by other accounts the gains have been more significant. There is general agreement that the environmental effects have been large and negative.

Yet systematic empirical assessments of the effects of land use change on economic growth and the environment are largely absent. As a result, huge gaps in knowledge limit the efficacy of policy initiatives. To fill some of these knowledge gaps, the Alternatives to Slash and Burn (asb) consortium in Peru undertakes, coordinates, and integrates many research activities in the region. National and international partners conduct both biophysical and socioeconomic research to understand why and how the region is being transformed. Most importantly, lessons are distilled from this research to guide and promote future development activities in the region.

Specific research themes of scientists in the asb consortium in Peru focus on soil and nutrient management, farmer participatory research, environmental–economic tradeoffs, tree genetic resource management, and improved germplasm of tree and agricultural crops. Research also seeks to improve our understanding of the magnitudes and mechanics of pressing local and global environmental issues, including soil degradation, greenhouse gas emissions, and biodiversity loss.

The two central objectives of asb research are to have impact at field level and to generate knowledge, management strategies, and policy options that can be useful outside the Peruvian Amazon. A mix of scientific and other research products, including capacity strengthening, are produced to meet these two objectives.
UNDERSTANDING THE AMAZON: HETEROGENEITY AND CHANGING PATTERNS OF RESOURCE USE

With the hope of earning a better living, settlers migrate to and about the Amazon (Townsend 1983; Aramburú 1984; Barham and Coomes 1995). Yet after forested land is cleared for agricultural use, soil fertility and associated bountiful harvests are short-lived (Nye and Greenland 1960). To maintain production levels, farmers are compelled to cut more forest (Ruthenberg 1976). Therefore there is an apparent tradeoff between preserving the environment and providing basic human needs. At the crux of the environment–economic tradeoff is the fallow period, where vegetative regrowth of 2 to 15 years becomes the nutrient supply for the next agricultural cycle. Although purchased inputs, especially fertilizers, can increase and sustain yields, they are prohibitively expensive for small-scale farmers. Moreover, extensive production techniques are more cost-effective because a hectare of land can cost less than a 50-kg bag of fertilizer (Holland 1999; White et al. 2001). Therefore land use options must be developed with special regard to their financial feasibility and the resource constraints (land, labor, and capital) farmers face.

The Amazon region of Peru is markedly different from the rest of the country. Cooler sierra (mountain) and drier coastal regions are distinct agroecosystems to the hot and humid tropical forests of the Amazon. National policies must be tailored to specific regions of the country. The Peruvian Amazon poses the greatest challenges to policymakers. First, a majority of the national policymakers have little knowledge of this isolated region. Second, the Amazon remains disconnected from the rest of the country, especially the seat of political power and decision making in Lima. Therefore effective policy implementation is difficult and costly in the Amazon. In part because of complexity and costs associated with promoting development, the overall development objectives associated with the region have been pared back.

Despite the lackluster performance of organized settlement programs undertaken when the region was envisioned as a breadbasket (Nelson 1973), Peru continues to formally promote development in the Amazon. In the 1990s, the Peruvian government instituted a series of regional tax relief measures and fuel subsidies. The government also began permitting large tracts of Amazon forest to be logged by national and foreign companies. Other natural resources, such as oil and gas, are being prospected and extracted. Unofficial settlements commonly follow logging or mineral access roads and often encroach into national forests and indigenous community lands. More generally, though, the potential effects of such national policies and settlements on long-term forest cover, the well-being of indigenous communities, or the economic welfare of the region are not known.

The physical characteristics of the Amazon region are diverse, much like its famed plant communities and animal populations. Topography and soils differ throughout the region, ranging from fertile alluvial soils on riverbanks to nutrient-deficient, acidic soils in the upland areas (Sanchez 1976; Denevan 1984; Padoch and de Jong 1992). There-
fore broad generalizations regarding resource endowments or the suitability of agriculture cannot be made. To adequately capture a broad array of biophysical characteristics and understand their roles in determining land use, asb activities take place at two sites: a main benchmark area near Pucallpa and a second smaller site near Yurimaguas.

Pucallpa is located in the Department of Ucayali (figure 15.1), which borders Acre, Brazil, to the east. The department corresponds to an area 80 percent the size of El Salvador but has about 5 percent of that country’s population. Settlement of the Pucallpa area began in the 1940s after construction of a road linking the Ucayali River, a major Amazon tributary, and the capital city of Lima. The current cropping and ranching activity on any given piece of land typically is associated with the number of years since the forest was originally cleared (Fujisaka and White 1998; Labarta 1998; Smith et al. 1999). For example, the amount of area remaining in forest on farms is inversely related to the time since it was first settled. In the more recently settled areas, 59 percent of the rural holdings remain forested, whereas in more mature settlements, forest coverage decreases to 40 percent. Cattle ranches, which tend to dominate the oldest settlements, have an average of 19 percent of their land in forest. Conversely, the land area dedicated to pastures generally increases according to the age of the settlement. The recent settlers have about 10 percent of their holdings in pasture, compared with 19 percent on older farms. Cattle ranches have 66 percent of their land in pasture (Smith et al. 1999). The stocking rate on traditional pastures is approximately 0.6 animal units (aus) per hectare. Land values are low, ranging from us$10 to us$200/ha depending on the quality of road access (Fujisaka and White 1998).

Political instability in the region in the 1990s caused cattle herds to decrease markedly. More than a third of the regional cattle herd was sold or stolen between 1990 and 1995 (Fujisaka and White 1998). The ensuing situation of low stocking rates in the region has led to an oversupply of pasture plant biomass given the size of the regional cattle herd. In some cases, pastures are so overgrown that they become flammable and often permit fire to spread into the surrounding forest (White et al. 2001).

The Pucallpa region has bimodal rainfall pattern, with wet months of February to May and September to November and dry months of June to August and December to January. As in many humid tropical regions, soil infertility is a major factor affecting the production potential of agricultural systems (Nye and Greenland 1960; Ruthenberg 1976). The basic soil constraints are low cation exchange capacity, soil acidity, high aluminum saturation, and low nutrient stocks (particularly phosphorus, nitrogen, and calcium). Soils include more favorable alluvial but less common riverine areas, where pH is about 7.7 and available phosphorus is 15 ppm, and the more common well-drained upland areas of acidic (pH 4.4), low-phosphorus (2 ppm) soils (Loker 1993). Invasive weeds are another factor influencing land use decisions, as discussed later in this chapter.

The Pucallpa site offers two important research advantages. First, the ranges of some key characteristics (e.g., rainfall amounts and patterns, and soil types) are quite similar to those of other broad regions in the Amazon, including the asb research site in Acre, Brazil (IICA 1995). Thus, research outcomes can be compared with, and may
Figure 15.1 Landsat image showing the boundaries of the Pucallpa research site.
be applicable to, larger swaths of the Amazon basin. Second, approximately 50 years of occupation by a steadily growing human population has led to a wide range of deforestation patterns and land uses in this small area (17,000 km$^2$, or 2 percent of the Peruvian Amazon). Although only about 10 percent of the Peruvian Amazon was estimated to be deforested as of 1995, approximately 25 percent of forests in the Pucallpa region had been cleared by then (IIAP 1999). Therefore the Pucallpa experience may offer an important window through which to view, understand, and help manage future deforestation and land use patterns in other areas of the Peruvian Amazon.

The second site, Yurimaguas, adds geographic breadth and a longer-term research context. The Yurimaguas site was home to the North Carolina State/TropSoils Collaborative Research Support Program, where experimental agronomic data have been collected for nearly 30 years. It also provides an interesting comparison with Pucallpa.

![Figure 15.2](image)

*Figure 15.2* Population growth in Yurimaguas and Pucallpa from 1960 to 1995 (INEI 1997).

Table 15.1 Area in Different Land Use Systems, Length of Fallow Period, and Residence Time of Migrants on Farms in Two ASB Peru Research Sites

<table>
<thead>
<tr>
<th></th>
<th>Yurimaguas</th>
<th>Pucallpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average farm size, ha</td>
<td>23.6</td>
<td>28.7</td>
</tr>
<tr>
<td>Primary forest, ha</td>
<td>8.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Fallow, ha</td>
<td>9.4</td>
<td>8.2</td>
</tr>
<tr>
<td>Annual crops, ha</td>
<td>1.9</td>
<td>1.6</td>
</tr>
<tr>
<td>Perennials, ha</td>
<td>0.8</td>
<td>2.3</td>
</tr>
<tr>
<td>Pasture, ha</td>
<td>3.1</td>
<td>7.1</td>
</tr>
<tr>
<td>Average fallow period</td>
<td>3.6 yr</td>
<td>3.2 yr</td>
</tr>
<tr>
<td>Migrants who arrived before 1960</td>
<td>45%</td>
<td>25%</td>
</tr>
</tbody>
</table>

*Source: ASB site characterization survey (Labarta 1998).*
regarding migration in the Amazon. In 1971, Yurimaguas had approximately 20,000 residents, and within 14 years the population doubled. As of 2000, there were about 55,000 inhabitants in Yurimaguas, half of whom were living in rural areas. In contrast, Pucallpa has grown at a much faster rate since 1971 (figure 15.2), and the population has doubled in less than 10 years. Implications of the growing population are seen in the rapidly changing land uses around urban centers. In part because of better market access, land use systems in Pucallpa have shorter fallow periods, and larger areas of cleared land are dedicated to perennial crops and pasture (table 15.1).

BIOPHYSICAL RESEARCH

The biophysical component examines how different land uses are associated with changes in biodiversity, carbon stocks, and greenhouse gas emissions. The asb also seeks to identify geographic patterns of genetic variation in tree species. The ultimate objective is to provide practical policy guidance for improved land management.

Above-Ground and Below-Ground Biodiversity

Slash-and-burn creates spatially diverse sets of land uses that can complicate traditional methods of vegetation classification and limit their usefulness for characterizing above-ground plant biodiversity. Two different approaches were used to assess the effects of land use on above-ground biodiversity. Gillison and Alegre (2000) used a plant functional attributes approach to measure the diversity of plants (chapter 4, this volume). Fujisaka et al. (2000) used an ecological approach, combined with an ethnographic component that addressed farmers’ understanding of and preferences for different plants, including weeds. A third study of below-ground animal biodiversity examined soil macrofauna in different land uses and their links to soil quality.

For the species richness and plant functional types approach, twenty-one 40- by 5-m transects were used to sample a range of land use types and chronosequences in Yurimaguas. The highest species and functional type richness were recorded in a forest logged 40 years previously, 20-year abandoned gardens, and 2-year successional fallows dominated by plants from the Asteraceae or the daisy family. Multistrata agroforests showed moderate degrees of species and plant functional attribute richness, and improved pastures were least rich, with only four plant species and functional types (Gillison and Alegre 2000). Initial analysis of the data revealed close associations between plant-based classifications, land use type, and vegetation succession but generally weak correlations between these same classifications and soil physical and chemical characteristics. The most significant correlations of soil attributes arose between vegetation structure, plant functional attributes, and ratios of richness of plant species to functional types.
Fujisaka et al. (2000) examined the sequence of interactions between farmers and ecosystems to examine how farmers manage biodiversity. In samples taken across a chronosequence in Pucallpa, 235 plant species were recorded in the forest, of which 143 were not found in any successive land use. Plants not existing in the forest colonized both cropland fields and fallow areas. In total, 595 species were identified across the land uses. Changes in plant communities generally reflected the replacement of shade-tolerant plants and plants for which seeds are dispersed by bats, other mammals, ants, and larger birds. Pioneer plants were those adapted to conditions of more direct sunlight and produced larger numbers of small seeds dispersed by smaller birds or the wind. Each form of land use contained 7 to 25 percent of the original forest species plus thirteen to sixty-six new plant species adapted to that land use.

As field conditions changed over time, different sets of more competitive weeds emerged. In response, farmers adapted agricultural product mix and management strategies, relegated weed-infested plots to fallow, and cleared more forest. Farmers were most concerned about *Rottboellia cochinchinensis* (Lour.) Clayton in fields after fallow and *Imperata brasiliensis* Trin., both of which serve as indicators of soil degradation. Farmers identified useful species across treatments, but counts of these species were very low, suggesting high levels of human intervention in the forest and heavy pressure on such species in all land uses. Although fallowed areas regained some of the original forest-like plant species, valuable shade-tolerant, slow-growing hardwood trees did not reappear in fallow areas, perhaps because of their short duration. Perhaps because many settlers were new to the region, they did not use indicator species to identify fertile forest areas or signal decreased soil productivity after cropping (Fujisaka et al. 2000).

The below-ground soil macrofauna diversity was significantly affected by land use in Yurimaguas (table 15.2). As intensity of land use increased, macrofauna numbers decreased significantly. The number of taxonomic units identified in a traditional tree-based fallow area (thirty) was nearly twice that of low-input annual cropping system with a legume-based cover crop fallow (sixteen). By this measure, the multistrata agroforestry system contained the most biodiversity. However, more detailed analysis revealed that 95 percent of the total biomass of the multistrata system (55.7 g/m²) corresponded to the exotic earthworm species *Pontoscolex corethrurus* Muller (Alegre et al. 2001). Thus even though this agroforestry system helped conserve (or rebuild) below-ground biodiversity, the emerging composition was quite different from that of the original forest. Research into the functional consequences for agricultural productivity and other ecosystem functions of this shift in the composition of below-ground biodiversity is under way.

**Carbon Stocks**

Scientists from the Instituto Nacional de Investigación Agraria (INIA), Universidad Nacional del Ucayali (UNU), Tropical Soil Biology and Fertility Programme (TSBF),
National Perspectives and International Centre for Research in Agroforestry (icraf) evaluated the above- and below-ground carbon stocks in land use chronosequences near Pucallpa and Yurimaguas. The evaluation was accomplished using the procedural guidelines developed by the tsbf for asb (chapter 2, this volume). This report includes only the above-ground carbon stocks, not the time-averaged carbon stocks for the entire rotation as reported in chapter 2.

The above-ground carbon stocks for natural forests in the Yurimaguas area were almost twice those of the forests in Pucallpa (table 15.3). This difference in forest biomass could be a result of the higher rainfall and less disturbance of the forest from a lower population density in Yurimaguas. Not surprisingly, when forest is converted to agricultural uses, above-ground carbon is reduced; in fact, the 15-year-old fallows in each location attained about 70 percent of the biomass of the primary forest. The natural fallows had carbon accumulation rates as high as 10 t C/ha/yr (table 15.3), as high as or higher than those reported in chapter 2. Among the managed, tree-based systems, the carbon content ranged from 41 t C/ha for oil palm (Elaeis guineensis Jacq.) plantations to 74 t C/ha for rubber (Hevea brasiliensis [A. Juss.]) plantations (Pucallpa), whereas that of multistrata agroforestry system in Yurimaguas was intermediate at 59 t C/ha. Rubber plantations and multistrata systems have a permanent understory of tropical kudzu (Pueraria phaseoloides [Roxb.]), which increased the carbon stocks by 2 to 5 t C/ha (Alegre et al. 2002; Palm et al. 2002).

### Table 15.2 Taxonomic Richness, Mean Abundance, and Biomass of Macroinvertebrates in Different Land Use Systems in Yurimaguas, Peru

<table>
<thead>
<tr>
<th>Land Use System</th>
<th>Shifting Agriculture</th>
<th>High-Input Cropping</th>
<th>Low-Input Cropping</th>
<th>Multistrata Agroforestry</th>
<th>Peach Palm Plantation</th>
<th>Secondary Forest Fallow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of taxonomic units²</td>
<td>22</td>
<td>16</td>
<td>16</td>
<td>31</td>
<td>22</td>
<td>30</td>
</tr>
<tr>
<td>Population density/m²ᵇ</td>
<td>151</td>
<td>171</td>
<td>175</td>
<td>557</td>
<td>115</td>
<td>806</td>
</tr>
<tr>
<td>Biomass (g/m²)ᵇ</td>
<td>21.8</td>
<td>22.4</td>
<td>23.3</td>
<td>55.9</td>
<td>35.5</td>
<td>42.9</td>
</tr>
</tbody>
</table>

Land use systems are defined as follows:
- Shifting agriculture: 1-yr annual cropping alternated with a 7-yr fallow.
- High-input cropping: mechanized maize–soybean continuous rotational cropping over 7 yr with high nutrient input from fertilizers and lime.
- Low-input cropping: 2-yr rotational cycle of annual crops with fallow of tropical kudzu (*Pueraria phaseoloides*). Multistrata agroforestry: a diversified production system with timber, pole, and fruit trees (tornillo, *Cedrelinga catenaeformis* D. Duck; coffee, *Coffea canephora* Pierre ex Fröhner; bolaina blanca, *Colubrina glandulosa*; peach palm, *Bactris gasipaes* Kunth; araza, *Eugenia stipitata* McVaugh; and *Inga edulis* Mart.), annual crops in the first 2 yr, followed by a *Centrosema macrocarpum* Benth. understory, forming different strata in the system.
- Peach palm plantation: peach palm planted at 5 by 5 m with a *Centrosema macrocarpum* Benth. understory.
- Secondary forest fallow: maintenance of a secondary forest fallow, 7 yr old in 1985.

²Includes earthworms, termites, ants, Coleoptera, Arachnida, Myriapodes, and others.

ᵇFresh weight.

*Source: Alegre et al (2001).*
<table>
<thead>
<tr>
<th>Site and Land Use</th>
<th>Above-Ground Carbon (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Yurimaguas</strong></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td></td>
</tr>
<tr>
<td>Moderately logged (&gt;40 yr)</td>
<td>294</td>
</tr>
<tr>
<td>Fallow</td>
<td></td>
</tr>
<tr>
<td>15 yr</td>
<td>185</td>
</tr>
<tr>
<td>5 yr</td>
<td>44</td>
</tr>
<tr>
<td>3 yr</td>
<td>19</td>
</tr>
<tr>
<td>Agricultural crops</td>
<td></td>
</tr>
<tr>
<td>Rice</td>
<td>17</td>
</tr>
<tr>
<td>Pasture</td>
<td></td>
</tr>
<tr>
<td>Degraded (30 yr)</td>
<td>2</td>
</tr>
<tr>
<td>Improved (w/ <em>Brachiaria</em>)</td>
<td>5</td>
</tr>
<tr>
<td>Agroforestry</td>
<td></td>
</tr>
<tr>
<td>Multistrata&lt;sup&gt;b&lt;/sup&gt;</td>
<td>59</td>
</tr>
<tr>
<td><strong>Pucallpa</strong></td>
<td></td>
</tr>
<tr>
<td>Forest</td>
<td></td>
</tr>
<tr>
<td>Primary (untouched)</td>
<td>162</td>
</tr>
<tr>
<td>Residual (logged)</td>
<td>123</td>
</tr>
<tr>
<td>Fallow</td>
<td></td>
</tr>
<tr>
<td>15 yr</td>
<td>126</td>
</tr>
<tr>
<td>3 yr</td>
<td>21</td>
</tr>
<tr>
<td>Agricultural crops</td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>8</td>
</tr>
<tr>
<td>Cassava</td>
<td>3</td>
</tr>
<tr>
<td>Plantain</td>
<td>16</td>
</tr>
<tr>
<td>Pasture</td>
<td></td>
</tr>
<tr>
<td>Degraded</td>
<td>3</td>
</tr>
<tr>
<td>Perennial crops</td>
<td></td>
</tr>
<tr>
<td>Rubber (30 yr) with kudzu</td>
<td>74</td>
</tr>
<tr>
<td>Oil palm with grasses</td>
<td>41</td>
</tr>
</tbody>
</table>

<sup>a</sup>Includes standing trees and dead and fallen logs.

<sup>b</sup>Peach palm (*Bactris gasipaes* Kunth), tornillo (*Cedrelinga catenaeformis* D. Ducke), Inga edulis Mart., bolaina blanca (*Colubrina glandulosa* Perkins), and coffee (*Coffea arabica* L.) with cover crop of *Centrosema macrocarpum* Benth.

*Source: Alegre et al. (2002).*
The amount of carbon in annual cropping systems is very low (3–17 t C/ha). The upland rice (*Oryza sativa* L.) system in Yurimaguas showed carbon stocks similar to those of the biennial plantain system in Pucallpa, but much of that was the carbon still held in the remaining unburned logs from the clearing. Pastures contained the lowest quantities of carbon. Of note, as with the forests, carbon stocks were greater in similar land use systems in Yurimaguas than in Pucallpa. This is probably a result of the lower levels of agricultural intensification and higher rainfall in Yurimaguas (Fujisaka et al. 1998; Alegre et al. 2002).

**Greenhouse Gas Emissions**

In addition to net carbon emissions, deforestation and resulting land use can lead to the release of other greenhouse gases, including methane (CH₄) and nitrous oxide (N₂O). Although tropical soils can provide sinks for atmospheric CH₄, they are also reputed to be a major source of N₂O gases (Keller et al. 1997). Evidence suggests that the CH₄ sink strength of well-drained upland tropical soils diminishes as the intensity of land use increases. Early analyses of tropical forest conversion to pasture indicated a large positive flux (4.18 µg/cm²/h) of N₂O into the atmosphere (Luizao et al. 1989). More recent studies suggest that such emission increases are temporary and that the rates may eventually decrease to less than those of the nearby undisturbed forest (Keller and Reiners 1994; Erickson and Keller 1997). Because few studies on trace gas emissions in the tropics have been undertaken in areas other than natural forests and pastures, a goal of ASB was to sample and compare fluxes from the full spectrum of land uses ranging from natural forests to degraded pastures (see chapter 3, this volume).

A strategy of intensive sampling of N₂O and CH₄ fluxes in fewer, well-characterized locations was adopted for sites in Peru and Indonesia. Similar land use categories were and continue to be monitored in both Pucallpa and Yurimaguas, representing the entire range of land uses from forest to pasture.

In Yurimaguas, monthly measurements were taken over the course of 2 years, 1997 to 1999, in a long-term experiment comparing different land uses (Palm et al. 2002). Five of the six land use systems were established 13 years previously by slashing and burning of a 10-year-old shifting cultivation forest fallow. In 1985, a portion of the 10-year fallow was slashed and burned and the following five treatments were installed: traditional shifting agriculture system, high-input cropping with fertilization and liming, low-input cropping, a multistrata agroforestry system, and a peach palm (*Bactris gasipaes* Kunth) plantation (table 15.2). These five treatments were all compared with the original forest fallow that was 23 years old at the time gas measurements were taken.

Average monthly N₂O fluxes ranged from 0.6 to 0.9 kg N/ha/yr in the tree-based systems, were almost twice as high in the low-input cropping system, and reached 2.3 kg N/ha/yr in the high-input cropping system. The fluxes in the nonfertilized systems
(tree-based and low-input cropping) are similar to those on the acid, infertile soils in the Indonesia ASB site in Jambi (chapter 3, this volume).

Methane fluxes also showed differences across treatments, with the high-input cropping system actually switching to a net source of CH$_4$ of +1.3 kg C/ha/yr (Palm et al. 2002). All of the other systems maintained a net CH$_4$ sink, showing decreasing sink strength with increasing land use intensity (e.g., –2.6 kg C/ha/yr in the 23-year-old forest fallow and –1.6 kg C/ha/yr in the low-input cropping). The differences in CH$_4$ flux are related primarily to increased soil bulk density and corresponding increased water-filled pore space. These methane consumption rates are similar to those reported from the Jambi site in Indonesia (chapter 3, this volume).

These preliminary results demonstrate that agroforestry systems maintain CH$_4$ sink and have low N$_2$O emissions, and as land use intensification increases, CH$_4$ sink strength decreases and N$_2$O emissions increase if nitrogen fertilization and tillage are practiced.

An analysis of the net global warming potential (GWP), which includes the net radiative forcing effects of CO$_2$, N$_2$O, and CH$_4$, of the different land use systems in Yurimaguas indicated that the CO$_2$ released from the vegetation as a result of biomass burning from deforestation (75 mol C/m$^2$/yr; dashed line in figure 15.3; Palm et al. 2004) exceeded any subsequent emissions of CO$_2$, N$_2$O, and CH$_4$ from the soils. Carbon dioxide emissions from the decomposition of soil organic matter after deforestation, 0 to 8 mol C/m$^2$/yr, were as high as or higher than the combined GWP of N$_2$O and CH$_4$ fluxes, despite the higher net radiative forcing values for the latter two gases, 21 for CH$_4$ and 310 for N$_2$O (Watson et al. 2000). The GWP from CH$_4$ production in

Figure 15.3 Sources of the net global warming potential (GWP) over a 25-yr period for the different land use systems in Yurimaguas in the Peruvian Amazon. The dashed line represents the GWP resulting from deforestation and biomass burning (adapted from Palm et al. 2004).
the high-input cropping system or consumption in the other systems were undetectable in comparison to the $\text{gwp}$ from CO$_2$.

The establishment of tree-based systems reduced the initial $\text{gwp}$ as a result of deforestation by 11 to 35 percent (figure 15.3); this decrease resulted from carbon sequestered in the vegetation. In contrast, establishment of the two cropping systems increased the initial $\text{gwp}$ by more than 20 percent through losses of soil carbon and, in the case of the high-input cropping system, higher $\text{N}_2\text{O}$ losses and net $\text{CH}_4$ production. Efforts to mitigate this dominating effect of the release of CO$_2$ from the slash-and-burn process should focus on reducing rates of deforestation or establishing tree-based land use systems that sequester more carbon in the vegetation and soil than annual cropping systems and pasture.

**Genetic Variation in Tree Species and Its Role in Promoting Sustainable Land Use**

The asb research program on tree domestication takes discoveries regarding spatial and temporal variation within tree species and uses them to promote on-farm productive diversity and improved tree germplasm. Farmers in the lowland jungle of the Peruvian Amazon depend on more than 250 agroforestry tree species for construction material, fenceposts, firewood, charcoal, fibers, resins, fruits, medicines, and service functions such as soil conservation and shade (Sotelo Montes and Weber 1997). These trees contribute significantly to the income and food security of resource-poor farmers (Labarta and Weber 1998) and provide environmental services at local, national, and global levels.

It is widely known that deforestation and logging decrease the abundance of tree species around many rural communities in the tropics (Pearce and Brown 1994). As a result, these communities have fewer natural resource options for economic development in the future. Less widely recognized but equally important is that genetic variation within tree species may also be decreasing around rural communities (Ledig 1992). If this continues unchecked, communities may have even fewer opportunities for sustainable economic development in the future because reduced variation within tree populations is likely to decrease production stability and yield over time. Therefore it is imperative that domestication projects focus not only on increasing the number of valuable tree species on farm but also on managing the genetic resources of these species (O’Neill et al. 2001).

Intraspecific genetic variation in tree species is fundamental for the improvement of agroforestry systems. Through appropriate selection strategies, significant improvements can be made in timber tree form, fruit quality, and other commercially important traits (Simons et al. 1994). The presence of intraspecific genetic variation not only creates opportunities for selection but also provides an adaptive buffering capacity to changing user needs and environmental pressures.

One challenge for asb was to quickly and cheaply identify the most productive germplasm for different agroforestry systems. Farmers consistently cite the lack of
high-quality tree germplasm as a major obstacle to diversifying and expanding their agroforestry practices, and traditional tree improvement methods are too slow and expensive to meet their needs (Simons 1996). Nontraditional approaches involving farmers as collaborators in the research and development process are needed (Weber et al. 2001), and asb has taken steps to develop and implement them. An example follows.

In the Pucallpa region, farmers want more productive germplasm of bolaina blanca (*Guazuma crinita* Mart.), capirona (*Calycophyllum spruceanum* Benth.), and other timber trees (Sotelo Montes and Weber 1997). In 1996, researchers and farming communities worked together to collect seed from eleven natural populations of bolaina blanca and capirona and established on-farm provenance trials in 1998. These were the first genetics trials of native tree species in the Peruvian Amazon. The principal objective of the trials was to identify the most promising provenances as seed sources for reforestation in different environmental conditions in the Peruvian Amazon. The trials were established on farms in the Aguaytía watershed (near Pucallpa), which is representative of many watersheds in the western Amazon Basin. Farmers participate in the evaluation of growth and other characteristics and provide useful information about their selection criteria for tree germplasm.

Preliminary results of the on-farm provenance trials illustrate the potential gains in productivity that farmers can realize from an early selection of provenances of fast-growing timber trees (Sotelo Montes et al. 2000). In both bolaina blanca and capirona there was significant variation in average height between provenances in the nursery and after 6 and 12 months in the field (*p* < .001). In the case of bolaina blanca, after 12 months in the field the local provenance from the Aguaytía watershed (Von Humboldt) was 13 percent taller than the average height of the other provenances combined (*p* < .05). Capirona did not grow as rapidly as bolaina blanca during the first few years.

Traditional studies of variation in provenance trials provide essential information about the adaptive and commercial value of germplasm from different regions (Morgenstern 1996), but they cannot fully quantify the underlying diversity and genetic constitution of tree populations. Molecular methods can provide this information and are being used to complement traditional approaches. Molecular methods provide insights into the origin of tree populations, and the relationships between these populations—essential information for management of tree genetic resources. For example, molecular techniques were used to identify diverse populations of capirona for cultivation and for in-situ and on-farm conservation in the Peruvian Amazon (Russell et al. 1999).

Accelerating the delivery of high-quality tree germplasm to farmers is the second principal objective of participatory tree domestication. A traditional forestry approach involves many steps: species selection trials, provenance trials to identify the best seed sources of each species, progeny tests to identify the best mother trees within each selected site, collection of seeds or vegetative material from the best mother trees to establish seedling or clonal seed orchards, and finally the production of high-quality seed for dissemination. Using this slow and costly process, government and nongov-
ernment organizations cannot meet the growing demand for high-quality germplasm, particularly when formal institutions and networks break down.

Involving farmers in germplasm selection, production, and dissemination can accelerate delivery of high-quality germplasm. On-farm genetics trials, like the prov-enance trials just mentioned, can be transformed directly into seed orchards. Farmers with on-farm genetics trials are being organized into networks for the production and commercialization of high-quality seed, seedlings, and timber. These seed orchards are a new form of small business enterprise in Peru and also serve as ex situ conservation sites.

Provisional guidelines were determined for seed transfer within the region based on geographic patterns of genetic similarity between populations. In general, one should try to match the environment conditions of the seed source with those of the plantation. This entails characterizing the environmental conditions of potential plantation sites and seed sources. In the absence of such characterization data, seeds should be collected from trees that grow near the plantation site and have desirable phenotypic characteristics. Using seeds from geographically distant regions should be avoided unless there is evidence from genetic trials that such seedlots are adapted to local environmental conditions.

SOCIOECONOMIC RESEARCH

Farmers in the Amazon, like their counterparts worldwide, face many agronomic and marketing challenges: Yields are uncertain, market prices typically are low and can fluctuate wildly, and transportation to major markets is expensive. In the case of the Peruvian Amazon, however, transportation costs are much higher than those faced by agriculturalists in other areas; to reach international markets, products must be transported down one of the longest rivers or over some of the highest mountains in the world. Such conditions make farming (and hence farmers) uncompetitive in all but local markets for most of their products, and these markets suffer from severe seasonal gluts. Political and social instability also complicate production and marketing activities, putting farmers in the region at a further competitive disadvantage even compared with their Amazonian counterparts in Brazil and Bolivia. For example, unrest in the late 1980s led to a severe decline in livestock herd sizes in the Pucallpa region (Fujisaka and White 1998). Contributing to the slow and ongoing recovery is the drastic reduction of agricultural support programs (e.g., product price subsidies and subsidized credit) in the 1990s (Hopkins 1998; Yanggen 2000a).

In an effort to improve smallholder welfare in the region, numerous land use alternatives have been developed, ranging from improved traditional annual cropping systems to new multistrata agroforestry systems. Though agronomically suited to the region, improvements in income and food security based on these new systems have been limited by several factors, some of which are beyond the reach of any policymaker. For example, in 1999 perennial crops such as coffee (Coffea spp.), palm oil, and cocoa
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*(Theobroma cacao* L.) suffered price declines ranging from 25 to 50 percent. Despite a large set of well-funded activities to promote exotic Amazonian fruits and forest products (Clay and Clement 1993; Toledo 1994), citrus and achiote (*Bixa orellana* L.) have failed commercially. Consequently, farmers near Pucallpa continue to sell citrus and other perennial tree crops at low prices in local markets. Despite these failures, new projects that encourage the production of other Amazonian agricultural goods, such as camu-camu (*Myrciaria dubia* [Kunth] McVaugh) and uña de gato (*Uncaria tomentosa* [Willd.] DC), are under way. Although these products provide an opportunity to diversify production, demand for these specialty products is uncertain.

The ASB socioeconomic research also addressed the issue of how government policies could best promote sustainable production systems, improve smallholder welfare, and reduce the impact of agriculture on deforestation (Yanggen 2000b). More specifically, the research analyzed how changes in Peruvian agricultural policies, including those of structural adjustment in the 1990s, affected use of cleared land and forest cover. Analysis based on a 1998 household survey revealed that upon provision of subsidized agricultural credit and guaranteed minimum prices for agricultural products in the latter half of the 1980s, 94 percent of farmers increased production (predominantly of rice and maize [*Zea mays* L.]), 90 percent of farmers hired more labor, but only 11 percent of farmers increased capital input use. These government policies led farmers to increase output by hiring more labor for slash-and-burn production of annual crops. A sharp increase in forest clearing resulted; 75 percent of farmers reported clearing more primary forest for agricultural use. When subsidized credit and guaranteed prices were eliminated in the context of structural adjustment, production levels and deforestation sharply declined in the region around Pucallpa (Yanggen 2000a). Satellite images confirmed this decrease in deforestation rates over a broader area (IIAP 1999).

The econometric component of this research analyzed the dynamics of agriculture’s impact on deforestation at three levels: how economic and policy incentives and other factors (e.g., biophysical conditions) affect farmer decisions concerning choice of production technology, product mix, and the amount of land cultivated and how these decisions, in turn, affect rates of deforestation. (figure 15.4).

The regression model results showed a clear evolution of land use patterns. Annual crop production was most strongly associated with early frontier development and led to deforestation at the forest margin. Pasture and cattle tended to occupy land previously used for annual cropping, and also displaced secondary forest fallows. These results confirm those of Fujisaka and White (1998) and Smith et al. (1999). Area dedicated to perennial tree crops stagnated over the period covered by the sample, primarily because the profitability of these activities was undermined by steep declines in product prices.

Regression results also confirm the key role of labor as a constraining factor of production. Farmers with above-average amounts of family labor produced more of all the principal outputs: annual crops, perennial tree crop products, and livestock products. Greater overall labor availability (both hired labor and family labor) led to
greater amounts of primary and secondary forest clearing. Farm households engaged in above-average amounts of off-farm employment activities reported significantly lower annual and perennial crop production. Clearly, reducing labor availability can reduce the pressure on forests.

These models also capture the key role of financial capital in determining product mix, technology choice, and deforestation. The use of credit was positively correlated with the use of purchased inputs and hired labor. Credit was negatively correlated with labor- and capital-saving technologies, such as kudzu-improved fallows and *Brachiaria*-improved pastures. Although the impacts of these specific inputs and technologies on deforestation were not uniform, it is clear that access to credit played a key role in determining the farmers’ decisions regarding scale of operation and product mix, and these decisions did affect deforestation.

This research distinguished between the clearing of primary and secondary forests. Primary forests are areas that have never been felled (but often selectively logged); vegetative regrowth on fallow land becomes secondary forests. A common perception is that once primary forest deforestation has occurred, the forest (and all the services it provides) is lost forever. However, research by the Food and Agriculture Organization (fao 1996) estimated that in 1990 there existed 165 million ha of secondary forest in Latin America; hence, the potential exists for recouping at least some of the forest services via increases in area in secondary fallow. In the Pucallpa area, farmers maintain nearly equivalent areas of secondary and primary forest, 30 and 31 percent of the average operational holding, respectively (Yanggen 2000a). Econometric analysis showed that use of kudzu-improved fallows, purchased inputs (e.g., fertilizer, improved seed, and herbicides), and alluvial soils increased the amount of secondary forest cleared on farms but decreased the amount of primary forest cleared. Increases in land productivity in these cases seemed to mitigate declines in soil fertility linked to annual crop production, thereby enabling farmers to reuse secondary forest fallows, which decreased the need to clear primary forest (Yanggen and Reardon 2001).
A central conclusion of this research is that the production of annual crops using shifting slash-and-burn agriculture is a key driver of deforestation in the Pucallpa research area. Greater labor availability increased these extensive production systems and deforestation. One general policy objective, then, is to reduce the labor available for shifting annual crop production. One option is to promote off-farm income opportunities that siphon labor away from annual cropping and other agricultural activities. Development of a nonagricultural economic sector therefore may be key to removing pressures on forests. This implies the need for a broad-based development strategy including other sectors such as industry, tourism, and other services. In addition, research and policy initiatives must promote more sustainable annual cropping practices. The use of productivity-enhancing inputs such as improved seeds, fertilizer, and pesticides intensified land use and reduced clearing of primary and secondary forests in our sample of farmers from the Pucallpa area. However, given low product prices and poor transportation infrastructure, agricultural research must redouble efforts to identify product and technology packages that are affordable to and profitable for smallholders.

One option is to intensify pasture production systems. Indeed, kudzu-improved fallows and *Brachiaria*-improved pastures have been widely adopted by farmers because they increase returns to the labor. However, these systems use less labor per hectare, thereby freeing labor for deforestation and other uses; analysis revealed that the adoption of kudzu-improved fallows increased secondary forest clearing, and the adoption of *Brachiaria*-improved pastures increased clearing of all types of forests (Yanggen 2000b). The challenge is to identify production practices that both increase returns to labor and decrease pressure on primary and secondary forests. Labor-intensive production of high-value perennial crops can do this by absorbing labor while still providing high returns to labor. Agroforestry techniques that incorporate trees with high-value products into pastures and fallow areas have the potential to do this. Therefore, integrating perennial tree crops into production systems should be a research priority. In addition, on-farm processing of agricultural products into oils, preserves, flour, and other products can dramatically lower the transportation costs relative to unit value of output, and refined products also tend to suffer less price turbulence than do primary products. Finally, policies that promote forest-based processing can help promote sustainable production of nontimber forest products.

This research proposed a series of strategies to encourage more intensive and sustainable agricultural production practices. However, this research also pointed out that if new practices or crops were sufficiently profitable, farmers would invest in labor-saving equipment or simply hire more labor to expand production and would do so at the expense of forests. Thus more intensive forms of cultivation may promote deforestation. Therefore there is a need to complement the promotion of intensive cropping systems with policies that restrict access to forests. Options such as reductions in new road construction and enforceable regulations limiting the clearing of primary forest merit consideration.

Recent geographic information system analysis by the International Center for Tropical Agriculture (CIAT) used high-detail images to identify the ASB Pucallpa
benchmark area of the Aguaytía watershed while identifying and coding land uses. Complementary research by the Instituto de Investigacion de la Amazonia Peruana (IIAP) delineated and estimated the rates of deforestation from 1955 to 1995. This work has served as an input to policy planning (e.g., road construction and agricultural development projects) according to environmental and economic criteria (IIAP 1999).

CAPACITY STRENGTHENING, ASB IMPACT, AND FUTURE RESEARCH PRIORITIES

In 1998, national and international organizations working in Pucallpa held a workshop on participatory planning by objective to define research priorities. Using the logical framework method, participating organizations selected biodiversity research, research on and development of markets for Amazonian products, and the refinement and application of farmer participatory research methods as priority issues. The establishment of a Training and Information Center also was deemed necessary.

The 1998 workshop yielded quick results for ASB and its collaborators. National research partners and universities began to include agroforestry in their research portfolios and curricula and also began to refine and replicate research methods, such as tree domestication processes and the measuring of carbon stocks in production systems. Training in tree domestication and genetic resource management has motivated INIA, the Instituto Nacional de los Recursos Naturales, and the Reforestation Committees to include similar projects in their research portfolios, thereby expanding the overall impact of ASB research in Peru. In addition, the government of Peru is incorporating recommendations regarding tree genetic resource management in its new national forestry laws.

The ASB collaborators are involved in participatory, farm-based research on the management of pastures and secondary forests. Tropileche, a research consortium involving CIAT, IIAP, and the Instituto Veterinario de Investigaciones Tropicales y de Altura (IVITA) aims to improve pasture quality and productivity for milk and beef (dual-purpose) cattle production systems (Holmann 1999; White et al. 2001). The Secondary Forest Project collaborates with institutions in Peru (Centre for International Forestry Research [CIFOR], INIA, Universidad Nacional Agraria la Molina), Brazil (Empresa Brasileira de Pesquisa Agropecuária), and Nicaragua to characterize secondary forest use, examine the biophysical dynamics of secondary fallow systems, and identify management options for enriching and otherwise improving secondary falls (Smith et al. 2001).

Planned future research and outreach efforts include expanding efforts to distill practical policy messages from field-based research results, with special attention paid to policies likely to affect smallholder land use decisions and welfare. Examples include more careful assessments of the affects of policy changes on smallholders; help in prioritizing spending on agricultural research and extension, and greater efforts
to identify and transfer to Peru relevant policy lessons learned from other ASB sites, especially Brazil.

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