# Taking Stock of the Brazilian "Zero-Till Revolution": A Review of Landmark Research and Farmers' Practice

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Two decades of extensive research and experimentation with zero-till methods has allowed "ideal" zero-till systems to emerge in Brazil, involving no soil turning, maintenance of a permanent vegetative cover, and rotations of both cash and cover crops. By exploiting rapid successions of suitable crops, for example, as well as through careful temporal and spatial planning, Brazilian examples show that it is possible to continuously cover soil, gradually increase soil organic matter (SOM) stocks, integrate livestock, move surface-applied lime through the soil profile, break compact soil layers, and reduce reliance on agrochemicals in zero-till, all under a variety of edaphic and climatic conditions, and levels of mechanization/farm sizes. Various such technologies and systems are reviewed in this chapter. However, we also note that among smallholder zero-till farmers, for example, the adaptations of "ideal" zero-till systems are manifold and complex, partial adoption of certain components and technologies rather than full adoption of zero-till systems being the norm. By examining farmers' experiences and practice, we ascertain that in many cases there is perhaps a divorce between the ideal, originating mainly from individual technology research on agricultural research stations, and farmers' reality, given the complexity of socioeconomical constraints facing the latter. We conclude that although there is a wealth of valuable zero-till experience and technologies precipitating from the Brazilian zero-till "revolution," numerous challenges in zero-till research, especially in respect to resource-poor smallholder farmers, still remain, and perhaps more holistic, participatory and adaptive on farm-research is necessary in future. 

# ABBREVIATIONS

| | |
|---|---|
| **APDC** | Zero-till Organization of the Cerrado |
| **CEC** | Cation exchange capacity |
| **CIRAD** | French Agricultural Development Corporation |
| **EMATER** | Government agricultural extension services |
| **EMBRAPA** | Brazilian Agricultural Research Corporation |
| **EPAGRI** | Agronomic Institute of Santa Catarina |
| **FEBRAPDP** | Brazilian Federation for Direct Planting into Straw |
| **GTZ** | German Development Corporation |
| **IAPAR** | Agronomic Institute of Paraná |
| **ICI** | Imperial Chemical Industries |
| **IPEAME** | Agricultural Research Institute of Southern Brazil |
| **IPW** | Integrated weed management |
| **POM** | Particulate organic matter |
| **SOC** | Soil organic carbon |
| **SOM** | Soil organic matter |

# I. INTRODUCTION

Effectively brought about with the commercial release of the herbicides atrazine and paraquat and the subsequent production of the first mechanized zero-till planters by "Allis Chalmers" in the late 1950s and early 1960s (Hill *et al.*, 1994; Séguy *et al.,* 1996), modern zero-till, defined in this chapter as the planting of crops in previously unprepared soil by opening a narrow slot, trench, or band of sufficient width and depth to obtain proper seed coverage, without performing any other soil preparation (Phillips and Young, 1973), has become increasingly recognized as a means of improving agricultural soil and water conservation, of gradually building soil fertility, of reducing labor/fuel requirements and machinery wear, and concomitantly increasing overall farm profitability (Belvins and Frye, 1993; Borlaug, 2000; FAO, 2001). However, under certain circumstances, such benefits may only accrue partially or not at all, while some drawbacks may precipitate. Given the lack of mechanical weed and pest habitat clearing, for example, as well as the slower soil organic matter (SOM) mineralization and consequent nutrient release in unplowed compare to plowed soils, zero-till is also commonly associated with heavy reliance on agrochemicals and biocides to replace some of the functions of plowing. Furthermore, it is frequently maintained that zero-till entails sophisticated machinery capable of seeding through residues into unworked soil and evenly spreading harvest trash, as well as advanced managerial skills in order to optimize machinery, input, labor, and crop use (Brunner *et al.*, 1998; Dijkstra, 2002; Russel, 1998), thereby potentially being less suitable for asset-restricted smallholder farmers, farmers who often suffer most from the consequences of poor soil fertility and soil degradation. Additionally, zero-till is commonly assumed problematic or unfeasible in areas with shallow, acidic, or extreme-textured soils (sands or heavy clays) with a propensity to compact, without good internal drainage (Derpsch, 2001), on hilly topography, and/or in areas without sufficient rainfall for ample biomass production (Brunner *et al.*, 1998; Lal, 1993).

Nevertheless, despite such challenges and owing to its significant and well-documented advantages in a host of different regions, zero-till has become progressively more widespread throughout the world, most notably in countries such as the United States, Brazil, Argentina, Canada, and Australia, expanding to an area of over 72 million hectares globally according to some of the most recent estimates (Derpsch and Benites, 2004). Brazil in particular, where the area estimated under zero-till-type land management has exploded from less than 1000 ha in 1973/1974 to nearly 22 million hectares in 2003/2004 (FEBRAPDP, 2004) is a case *par excellence* of successful zero-till dissemination and adoption [*N.B.*, these adoption data are the only available and a result of a compilation of information provided by extension services and zero-till associations in individual Brazilian states, and, as Ribeiro *et al.* (2005) further point out may also include systems where cover crop seed is broadcast and incorporated with a disc harrow rather than drilled, and so on].

Although zero-till adoption in Brazil initially started on mechanized farms in humid subtropical Southern Brazil, on medium-textured, well-fertilized, and limed soils on flat to undulating land with low-weed pressure, it has since spread and reportedly proved successful on a large range of soil textures (from <10% to >70% clay) (Amado and Reinert, 1998; Amado *et al.*, 2006), on lithic or gravelly land with steep slopes (Freitas, 2000; Pieri *et al.*, 2002), for farmers without expensive machinery and capital inputs (Freitas, 2000; Heiden, 1999; Melo, 2000; Samaha *et al.*, 1996, 1998) or agrochemical outlays (Petersen *et al.*, 1999; Saturinino and Landers, 1997), and in regions that encompass the elevated, year-round humid subtropics to the acidic, seasonally dry tropical savannah plateau (cerrado) of Central Brazil. Forty-five percent of total cultivated land in Brazil is now estimated to be managed with zero-till (Scopel *et al.*, 2004), although in Southern Brazil, this figure is reported to exceed 80% (Amado *et al.*, 2006) or even 90% in the case of land cropped by smallholders (<50 ha) (Denardin and Kochhann, 1999). Among the leading zero-till nations, Brazil is purportedly the only one with both substantial zero-till in the tropics, as well as, importantly, a significant amount of smallholder zero-till farms (Ralisch *et al.*, 2003; Wall and Ekboir, 2002). The latter is perhaps of particular significance, as, contrary to zero-till spread in general, the adoption of true (permanent rather than sporadic) zero-till systems by smallholder farmers worldwide has been poor, remaining relatively marginal outside Brazil, Paraguay (where appropriate systems spread to from Southern Brazil), and small parts of Central America, where similar systems were already traditional (Buckles *et al.*, 1998). While the opportunity cost of labor and land and/or residues is often viewed as a stumbling block to smallholder zero-till, Berton (1998) suggests that the main reasons for smallholder farmers in Southern Brazil to adopt zero-till practices include labor and time savings, erosion control, greater income, and higher yields. Ribeiro and Milléo (2002) concur, specifying that labor savings and less drudgery, once plowing and mechanical weeding are discontinued, are the major incentives expressed by smallholder farmers.

In summary, numerous reports highlight a large diversity of highly productive, profitable, and labor-reducing farms in Brazil, ranging in size and scope from low-capital, family operated, semisubsistence smallholdings (<50 ha) to large, capital-intensive, and commercially orientated agricultural enterprises (Ambrosi *et al.*, 2001; Berton, 1998; Darolt, 1998a; Fontaneli *et al.*, 2000; Rego, 1998; Ribeiro and Milléo, 2002; Scopel *et al.*, 2003; Wall, 1993), and therefore ostensibly a wealth of diverse zero-till experiences that could potentially prove useful in other parts of the world has accumulated across Brazil, both at agricultural research stations and universities, but also among Brazilian farmers, some of which are now into their third decade of practicing zero-till-type land management. However, although much of this knowledge and experience is intrinsic in Brazil and neighboring countries, a large amount remains locked in local literature and conference proceedings rather than being published internationally, due partially to the Portuguese–English language barrier. Some recent English-language reviews do exist, but these either focus on certain specific aspects of Brazilian zero-till (Bernoux *et al.*, 2006; Machado and Silva, 2001, on soil management; on soil carbon sequestration and erosion), are intended to give a general overview rather than agronomic/technical detail (Scopel *et al.*, 2004), or focus on a certain region within Brazil (Freitas, 2000, on smallholders in Santa Catarina State). The broad objective of this chapter is consequently to first review some of knowledge precipitating from Brazilian zero-till experiences, this mainly coming from empirical research, and then, where possible given the relative dearth of truly analytical data in this respect, critically take stock of it by putting it into the context of farmers' practice. The particular focus of the chapter is on overcoming some of the major agroecological challenges associated with productive zero-till systems, such as effectively managing permanent soil cover, soil fertility, weeds and pests without all-out reliance on agrochemicals, integrating livestock, and suitable equipment for various soils, slopes, and levels of mechanization. Special emphasis will be granted to the context of resource-poor smallholder farmers.

## II. HISTORICAL BACKGROUND

The history of the Brazilian zero-till "revolution" is well documented in the literature. Calegari (1998b), Derpsch (1998), Landers (2001), Steiner *et al*. (2001), and Ekboir (2002), among others, provide recent and comprehensive English-language accounts of the development of zero-till in Brazil. In brief (more detailed histories are provided in a later section), zero-till development precipitated out of the widespread soil degradation in the 1960/1970s in subtropical Southern Brazil (especially Paraná), and spread from here to Paraguay and the tropical Brazil in the early 1980s (Fig. 1).

### A. Zero-Till Development in Subtropical Southern Brazil

During the 1960s, a significant expansion of the area under soybean (*Glycine max* L. Merr) and winter wheat (*Triticum aestivum* L.) occurred in Southern Brazil. The intensive plowing and disking, residue burning and

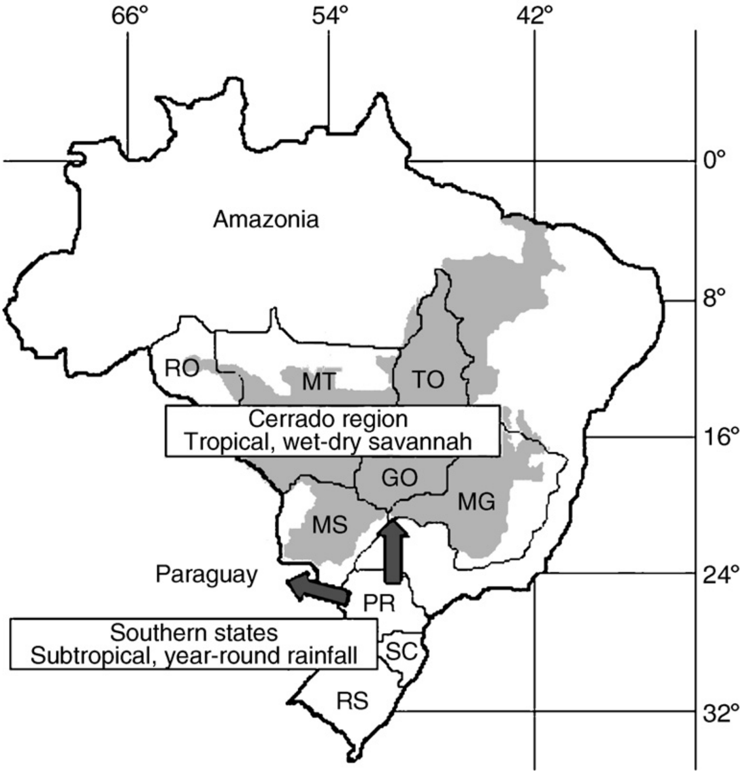



**Figure 1** Map of Brazil showing the subtropical southern states of Paraná (PR) and Rio Grande do Sul (RS), where Brazilian zero tillage originated and then spread west and north (indicated by arrows) to Paraguay and the tropical "cerrado" savannah region (shaded). RO, Rondônia; MT, Mato Grosso; TO, Tocantins; GO, Goiás; MG, Minas Gerais; MS, Mato Grosso do Sul; SC, Santa Catarina. Typically, farms in the cerrado region are large and mechanized, while in Southern Brazil a great variety of farm sizes and levels of mechanization exist.

downhill seeding regimes widely adopted with these crops exposed bare soils to intensive rainfall, which in turn led to extensive soil erosion and concomitant economic losses throughout large tracts of Southern Brazil (Borges, 1993; Cogo *et al.*, 1978; Gianluppi *et al.*, 1979; Mielniczuk and Schneider, 1984). Cassol (1984) estimated that during the 1980s, two-thirds of agricultural land in Southern Brazil showed some form of degradation, often manifested in the loss of SOM, poor rainfall infiltration, structural degradation and compaction, and a reduction in plant available water, but also in the pollution of waterways through runoff and erosion and even the abandonment of farms (Amado and Reinert, 1998; Pöttker, 1977). Although farmers frequently put up terraces and contours in an attempt to check runoff and topsoil loss, this rarely curtailed erosion sufficiently, and Mielniczuk (2003) estimated that for each kilogram of soybeans harvested, 10 kg of soil were lost. In response, concerned farmers and researchers gradually began to shift their production paradigm toward promoting better *in situ* soil conservation. The first scientific zero-till trial was initiated in 1969 by the Federal University of Rio Grande do Sul on a 1-ha plot, but discontinued in the second season due to the accidental destruction of the zero-till planter used for the trial (Borges Filho, 2001). New trials were established in 1971 at research stations in Londrina and Ponta Grossa in the state of Paraná by the Agricultural Research Institute of Southern Brazil (IPEAME, later EMBRAPA) in collaboration with the GTZ and subsequently also ICI (Derpsch, 1998; Steiner *et al.*, 2001). Impressed by the results of a zero-till demonstration plot set up on his farm, Herbert Bartz, a farmer in Rolândia, northern Paraná, visited zero-till research facilities at the ICI headquarters in Fenhurst, UK, and Harry Young in Kentucky. Bartz subsequently returned to Brazil with a zero-till planter and planted his first zero-till soybean crop in October 1972. His success in controlling erosion and reducing production costs quickly inspired some neighbors to adopt similar technologies. The successful diffusion of zero-till systems on a broader scale, however, remained erratic throughout the 1970s, due mainly to the lack of suitable techniques to effectively control weeds, as well as of planters able to work with high amounts of residues, of appropriate cover crop options, of technical assistance and studies clearly demonstrating the advantages of zero-till (Amado and Reinert, 1998; Bernoux *et al.*, 2006). Derpsch (1998) elaborates that the first Brazilian-built planters (available from 1975/1976 and based on a rotary hoe) were slow and cumbersome, while the only the herbicides 2,4-D and paraquat were available for weed management.

The release of glyphosate in Brazil in the mid-1970s changed this situation significantly, and toward the beginning of the 1980s, farmers began to organize themselves into zero-till-promoting associations, such as the "Clube da Minhoca" ("Earthworm Club") and the "Clubes Amigos da Terra" ("Friends of the Soil" clubs), as well as private research institutions, such as the "Fundação ABC" (ABC Conglomerate of Farmers' Cooperatives), thereby becoming more apt at voicing concerns within the public arena. The provincial agricultural research institution of Paraná, IAPAR, became the first government institution to intensify and spearhead systematic research into zero-till systems (Borges Filho, 2001; Dijkstra, 2002). Gradually, zero-till development received increased backing from multinational agrochemical corporations, international development agencies, local seed, and agricultural machinery companies (Busscher, 1996), as well as the national Brazilian Agricultural Research Corporation, EMBRAPA, who established breeding programs to enhance various crops' suitability to zero-till conditions (Scopel *et al.,* 2004).

The local government extension service, EMATER, however, did not support and recommend zero-till technologies until the late 1980s, and the initial expansion drive of the zero-till was in essence led by pioneer farmers, who also organized the first Brazilian zero-till conference in 1981 (Steiner *et al.*, 2001). Zero-till technologies and systems subsequently spread fairly rapidly from Paraná to other Southern Brazilian states and neighboring Paraguay, where similar environmental conditions existed.

## B. Zero-Till Development in Tropical Brazil

During the 1980s, the tropical, wet-dry savannah region (cerrado) of Central Brazil emerged as the fastest growing agricultural frontier zone of Brazil, experiencing a boom of continuous soybean and cotton monocultures due to favorable world market prices for these crops (Séguy *et al.*, 1996). However, similar to Southern Brazil, conventional agricultural practices in this region led to significant soil degradation. Séguy *et al.* (1996) report yield potential declines in degraded soils despite the increased use of chemical inputs and the replacement of monocropping by crop rotations, while in some regions SOM stocks were being depleted by as much as 30–50%. A steady interregional migration of farmers from Southern Brazil to tropical Brazil brought a transfer of the basic zero-till principles in its wake, but the different agro-ecological conditions of humid subtropical Southern Brazil compared to those of frost-free, seasonally dry, tropical Brazil, as well as the often quite different scale of large cerrado farms compared to generally smaller farms in the South meant that zero-till systems still had to be undergo considerable modification before being effective in the latter region (Spehar and Landers, 1997). The first records of mechanized zero-till in the tropics of Brazil, and probably worldwide, were in the state of Goiás dating from 1981/1982 (Landers *et al.*, 1994), although Landers (1998) does recount that smallholder farmers in the state of Rondônia, Center-West Brazil, were zero-tilling beans (*Phaseolus sativa* L.) with manual jab planters into rice straw after managing weeds with paraquat already in about 1980. The French Agricultural Development Corporation, CIRAD, collaborating with pioneer farmers and local organizations, became instrumental in the process of developing suitable zero-till systems for the cerrado region from around 1986 (Landers, 1998). Working simultaneously on improving the cropping system and crop germplasm, CIRAD and its partners in Mato Grosso state, for example, were able to develop several highly productive rain-fed rice cultivars suitable for zero-till, such as CIRAD 141 and Sucupira (Séguy and Bouzinac, 2001), as well as devising systems that could successfully integrate livestock herds with cropping enterprises (Séguy *et al.*, 1996). With the results from the CIRAD-led research, as well as official and private sector herbicide research and new developments in zero-till planters, enough information specific to the cerrado was generated to allow zero-till to be promoted on a general level throughout the region (Landers, 1998). The cerrado region is now the major expansion area of zero-till in Brazil, with over 6 million hectares estimated under zero-till in 2002 (APDC, 2005). Landers (1998) contends that possible future zero-till expansion will encompass agricultural areas in the Amazon region, while Bernoux *et al.* (2006) report that enticed by high-potential profit margins, ranchers in Amazonia have already started converting pasture into soybean/millet (*P. americanum* L.) zero-till cropping systems.

### C. Development of Smallholder Zero-Till Systems

Up until the mid-1980s, Brazilian zero-till research was almost exclusively directed toward medium to large-scale (>100 ha), mechanized farms, especially as these contributed most to the erosion process (Steiner *et al.*, 2001). Although smallholder (<50 ha) farmers in Southern Brazil also frequently expressed concern about soil erosion, the availability of zero-till technologies and equipment suited to their situations, as well as a technical support and farmer training, was limited at this stage (Berton, 1998). In the second half of the 1980s, IAPAR started focusing research efforts on resource-poor farmers, and in cooperation with the newly established Brazilian Federation for Direct Planting (FEBRAPDP) and the government extension service EMATER commenced a drive to introduce zero-till technologies on smallholder farms through demonstrations, seminars, field courses and training days. Light-mechanization (minitractors) and animal-drawn zero-till equipment was developed and trialed on various soils and topography by IAPAR and its equivalent in the state of Santa Catarina, EPAGRI (Table I), and gradually more and more smallholder farmers started adopting zero-till technologies.

However, as the results of a recent survey in the Irati region of Paraná indicate, unlike their more commercially orientated larger-scale counterparts, smallholder zero-till farmers without sufficient means to buy recommended external inputs and consequently often a high degree of risk-adverseness, as well as high-opportunity costs for land, labor, and crop biomass, still resort to a range of intermediate-tillage systems rather than adopting complete or "ideal" zero-till models promoted by research and extension (Palmans and van Houdt, 1998; Ribeiro *et al.*, 2005). Many such farmers fall back on disc harrowing before/after certain crops in order to check weeds and pests and incorporate lime, while sometimes neglecting cover and main crop rotations that could potentially optimize the functioning of zero-till systems. As Ribeiro *et al.* (2005) further conclude, contrary to

**Table I**
**The Development, Testing and Trialing, and Dissemination and Adoption Process of Zero-Till Technologies for Smallholder Farmers in Santa Catarina State, Southern Brazil (from Freitas *et al.*, 1994)**

| | | |
|---|---|---|
| 1984/1985 | 1986 | 1987 |
| Facilitation of farmer excursions to relevant research and experimental sites<br>Formation of microcatchment commissions | Establishment of a green manure observation unit and identification of potential cover crop green manure systems | Establishment of the first crop through zero-till with animal traction |
| 1988/1990 | 1991/1992 | 1993/1994 |
| Period of testing and adapting agricultural equipment, especially equipment for zero-till with animal traction and light mechanization | Farmers start to adopt zero-till practices (5% adoption rate)<br>Continuous research and adaptation of zero-till equipment | Increase in the area under zero-till<br>Acquisition of equipment by individuals and farmer groups |

some perhaps overly enthusiastic reports on the success of zero-till in Brazil, and although some very-well functioning "ideal" smallholder zero-till farms do exist, numerous challenges in respect to resource-poor smallholder zero-till on a general level still remain. As Calegari (2002) argues, such challenges, but also innovations and advances in terms of smallholder systems (e.g., equipment and fertility changes) need to be continuously evaluated and monitored in testing/validation processes that involve the smallholders themselves. We will elaborate on such challenges and partial adoption issues under the relevant sections.

## III. INDIVIDUAL ISSUES, INNOVATIONS, AND CHALLENGES

### A. Permanent Soil Surface Cover

In regions that experience high-intensity rainfalls and support undulating terrain and/or erosive soils, protecting the soil from raindrop impact through sufficient vegetative mulch is conceivably one of the best safeguards against excessive runoff and erosion (Amado, 1985; Calegari, 2000, 2002; Erenstein, 2003; Wildner, 2000). Not plowing, in turn, means that a protective biomass cover or mulch from previous crops or spontaneous plants can be maintained on the soil surface. Beyond immediate erosion and runoff control, a soil cover is also important for improving soil moisture maintenance by reducing evaporation from bare soil (Amado *et al.*, 1990a; Stone and Moreira, 1998, 2000), for mediating soil temperature extremes (Derpsch *et al.*, 1986), for providing a buffer against compaction under the weight of heavy equipment or animals (Séguy *et al.*, 2003), for smothering weeds (Darolt, 1997; Kumar and Goh, 2000), creating a favorable environment for beneficial soil fauna and flora (Balota *et al.*, 1996) and preventing soil and water contamination from pesticides and fertilizers leaching (Scopel *et al.*, 2004), but may also make the planting process more complicated, allow pests and pathogens to reproduce and spread longer in close proximity to crops (Forcella *et al.*, 1994), protract the warming up of soil after cold periods, induce erratic crop germination, and decrease the efficiency of fertilizers and herbicides (Banks and Robinson, 1982; Rodrigues, 1993). Nevertheless, zero-till in itself, without soil cover (for example, if residues are burnt, grazed, or otherwise exported from the field), can lead to worse soil degradation and crop productivity than plowing. Especially where soils are sandy and/or have high-bulk densities/low-total porosities and hence a tendency to form crusts upon wetting and drying, leaving land unplowed and uncovered means that it actually may lose more water and topsoil through runoff than if it were plowed (Bailey and Copeland, 1961; Laryea *et al.*, 1991; Nicou and Chopart, 1979; Scopel and Findeling, 2001; Seganfredo *et al.*, 1997; Shaxton and Barber, 2003; Unger, 1992). The amount of surface sealing or crusting resulting from raindrop impact during a rainfall event is in turn inversely proportional to the amount of vegetation or residues covering the soil, as are consequently infiltration rates over the course of a shower (Calegari, 2002; Roth, 1985; Roth *et al.*, 1987). Infiltration studies with a rainfall simulator in Paraná showed that regardless of tillage system, 100% water infiltration only occurred when soils were completely (100%) covered with plant residues, while bare soils only measured between 20% and 25% water infiltration (Derpsch, 1986). A residue cover of about 4–6 t of dry matter per ha is commonly proposed as adequate for erosion control (Lal, 1982, 1993; Mannering and Meyer, 1963; Roose, 1977), as this is assumed to cover close to 100% of the soil and ensure complete infiltration of rainfall, although this depends on crop species, flatness of the residues, rainfall intensity and duration, soil physical conditions (texture, permeability) and the land slope (Meyer *et al.*, 1970). In Londrina, Paraná, Roth *et al.* (1988) reported that about 7 t of soybean or 4–5 t of wheat residue dry matter per ha would provide 100% soil cover. They further remarked that in Southern Brazil, the average quantities of wheat or soybean residue left on the field after harvest amount to about 1.5 and 2.5 t $ha^{-1}$, respectively, which would amount to an average degree of cover of only about 60%. Thus, they put forward, in order to control erosion thoroughly, a change from conventional tillage to zero-till in this region must be accompanied by the integration of mulch producing crops or cover crops.

Apart from the physical amount of biomass produced as mulch, two other aspects are important to consider. First, the mulch should be evenly distributed over the plot, with most of above-ground crop residues ideally remaining anchored in the soil. In mechanized systems, harvesting machines should consequently have a device to spread residue trash evenly over the entire cutting edge, but, as Derpsch (2001) laments, this is seldom properly understood by machine manufacturers, the result often being an uneven distribution of plant residues, which in turn exacerbates poor performances of herbicides and seeding equipment. Second, it is also important that the mulch continues functioning as a cover at least until the following crop has itself developed a sufficient canopy to protect the soil. The mulch's degree of resistance to decomposition within a given climatic and edaphic context is in turn chiefly governed by its carbon (C) to nitrogen (N) ratio, but also to a lesser extent by its degree of lignification and its polyphenolic content (Calegari, 2002; Palm and Sanchez, 1991; Seneviratne, 2000), meaning that less mature crop stands and legumes are generally less suited for long-lasting (6-week or more) complete cover. Séguy *et al.* (1992) found that while maize (*Zea mays* L.) and rice (*Oryza sativa* L.) residues still maintained a soil cover of about 20–30% four months after the first rain at the end of the dry season in tropical Brazil, soybean residues had completely disappeared after the third month (Table II).

Rather than rely purely on crop residues from a main crop to provide adequate and permanent soil cover, especially in regions where the climate favors rapid decomposition of residues, one of the major Brazilian adaptations of zero-till has been the strong emphasis on integrating fast-growing winter cover crops and summer crop rotations into zero-till cropping systems. Such crops can be intercropped prior or planted immediately after the harvest of the main crop and rapidly produce abundant mulch, consequently allowing a succession of enhanced, year-round biomass accumulation. This can compensate for residue decomposition, as well as offsetting potential

**Table II**
**Loss of Soil Cover After the Start of the Rainy Season in Western Brazil (Tropical Humid Cerrado Region) (Data from Séguy *et al.*, 1996)**

| | Soil cover (%) | | |
|---|---|---|---|
| Days after first rain | Maize | Rice | Soybeans |
| 30 | 82 | 85 | 35 |
| 60 | 54 | 46 | 16 |
| 90 | 30 | 38 | 7 |
| 120 | 22 | 26 | 0 |

opportunity costs of residues in their grazing value, for example. Due to the high amount of mulch left on the soil surface at seeding time, Brazilian farmers hence commonly refer to zero-till as "*plantio direto na palha*" or "planting directly into straw" (Amado *et al.*, 2006), and Derpsch (2001) and Steiner *et al.* (2001) argue that the complete integration of cover crops into zero-till cropping systems is probably the single most fundamental key to the success of such systems in Brazil.

## B. Cover Crops, and Crop Rotations and Associations

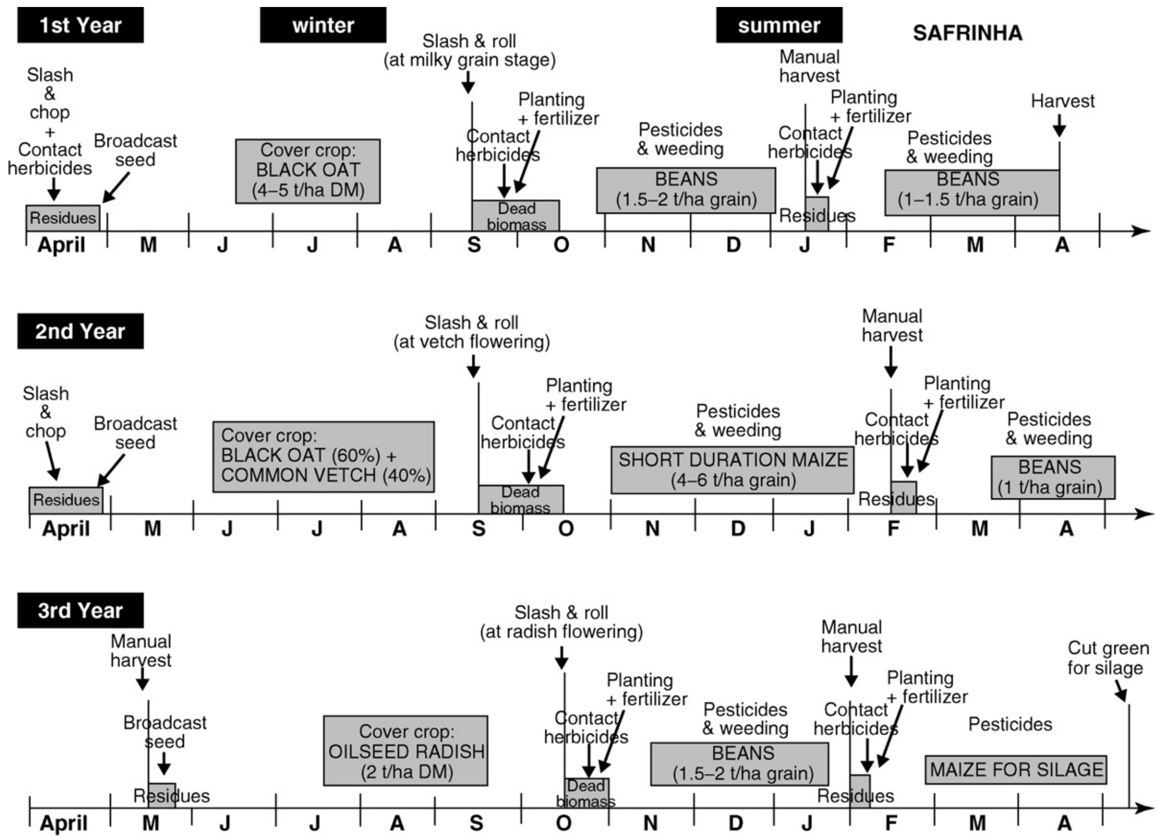
Although the primary function of cover crops is to produce biomass and soil cover during periods when available resources are too limited or too irregular for a commercial crop, most cover crops used in Brazil fulfill multiple agronomic, ecological, or economic functions in concert with those performed by the main crops (Anderson *et al.*, 2001; Calegari, 2002; Florentín *et al.*, 2001). Such general functions of cover crops broadlys include: (1) providing additional fodder, forage, food, and secondary commercial or subsistence products for livestock and humans, (2) directly adding or sparing N to/from the soil through symbiotic $N_2$ fixation from the atmosphere, (3) converting otherwise unused resources, such as sunlight and residual soil moisture, into additional biomass and concomitantly, upon the breakdown of their residues, increasing the build-up of SOM, (4) capturing and recycling easily leachable nutrients (nitrates, K, Ca, and Mg) that would otherwise be lost beyond the rooting zone of commercial crops, (5) ameliorating soil structure and buffering against compaction by creating additional root channels that differ from those of the main crops and by stimulating soil biological activity through, *inter alia*, the release of root exudates, (6) improving the management of acidic soils by releasing various products that can mobilize lime movement through the soil profile, decarboxylize organic anions, function in ligand exchange and add basic cations to the soil, (6) facilitating weed management by competing against or smothering weeds that would otherwise become noxious in the main crop cycle, and (7) breaking the cycle of certain pests and diseases that could otherwise build-up in continuous monocropping systems. On the other hand, integrating cover crops into existing cropping systems generally incurs extra costs in form of seed and agrochemicals (e.g., herbicides to terminate the crop before the next main crops), but also in form of extra labor and managerial skill required to establish and maintain the crop, as well as the opportunity cost of the land and equipment, while the rewards of cover crops may well take time to properly manifest themselves. Some of the major cover crops used in Brazil, together with their main advantages/functions and drawbacks, are presented in Table III, although we would like to draw

**Table III**
**Some of the Major Cover Crops Grown in Brazil[a]**

| | | Species | Soil and climatic requirements | Days to flowering | DM (t ha$^{-1}$ year$^{-1}$) | Advantages and limitations |
|---|---|---|---|---|---|---|
| Winter | Nonlegumes | *Avena strigosa* (Schreb.) | S–C; LF-MF | 120–160 | 2–11 | AF; WC; decrease soil root diseases (*Fusarium* spp., and so on); FASM |
| | | *Lolium multiflorum* (L.) | S–C | 120–150 | 2–6 | AF; WC |
| | | *Raphanus sativus* ssp. oleiferus Metzg. | S–L; A– | 90–110 | 3–9 | High-nutrient recycling capacity; BP; WC; FASM |
| | | *Secale cereale* (L.) | S–C; LF; A+; Wlog–; DT | 100–120 | 4–8 | BP; WC; controls some soil diseases |
| | Legumes | *Lathyrus sativus* (L.) | S–C; MF | 100–120 | 2.5–4 | AF; HF; mech. harvesting difficult; sensitive to aphids and diseases |
| | | *Lupinus albus* (L.) | S–C; MF; Wlog– | 120–140 | 3.5–5 | AF; HF; BNF; BP; sensitive to diseases (*Fusarium* spp., and so on) |
| | | *Lupinus angustifolius* (L.) | S–C; A+; Wlog– | 120–140 | 3–6 | AF; HF; BNF; BP; sensitive to diseases (*Fusarium* spp., and so on); FASM |
| | | *Lupinus luteus* (L.) | S–C; LF; A+; Wlog– | 130–150 | 3–4 | Recommended for restoring depleted soils (sandy and clay) |
| | | *Pisum arvense* (L.) | S–C; A– | 100–130 | 2.5–7 | AF; FEG; BNF; sensitive to aphids and some diseases |
| | | *Vicia sativa* (L.) | S–C; HF; A–; Wlog– | 120–150 | 3–5 | AF; BNF |
| | | *Vicia villosa* Roth. | S–C; LF; A+; WL– | 140–180 | 3–5 | AF; BNF; WC |
| Summer | Nonlegumes | *Brachiaria* spp. | S–C; A+ | n.a. | >4 | AF; BP; high biomass; SOM |
| | | *Helianthus annuus* (L.) | S–C; A+; LF; DT | 70–120 | 4–8 | FEG, high nutrient recycling; WC |
| | | *Pannicum maximum* (L.) | S–C; WD; DT; A+; Wlog– | n.a. | >20 | FEG; AF; BP; SOM |
| | | *Paspalum notatum* Flugge | S; DT; CT | n.a. | 3–8 | AF; SOM |

| | | | | | |
|---|---|---|---|---|---|
| | *Pennisetum americanum* (Schum.) | S; A+; LF; DT | 90–120 | 3.5–21 | AF; BP; SOM; WC; FASM |
| | *Setaria italica* (L.) | S–C; WD; MF; DT | 45–60 | 2.5–8.5 | AF; FEG; FASM; high-seed production |
| | *Sorghum bicolor* (L.) Moench | S–C; WD; MF; DT | 60–110 | 3.5–18.5 | AF; BP; SOM |
| Legumes | *Cajanus cajan* (L.) (dwarf variety) | S – L; LF; Wlog– | 70–85 | 2–6.5 | AF; NC; high-seed production |
| | *Cajanus cajan* (L.) Millsp. | S–C; LF; Wlog– | 140–180 | 3–7.5 | AF; BP; BNF + nutrient recycling, NC |
| | *Calopogonium mucunoides* Desv. | L–C | n.a. | 4–10 | WC; GC |
| | *Canavalia ensiformis* (L.) DC. | S–C; LF; DT | 100–120 | 5–6 | WC (allelopathic effects against *Cyperus* spp. and *Cynodon dactylon*) |
| | *Crotalaria juncea* (L.) | S–C; MF | 110–140 | 3–8.5 | BNF; WC; NC; efficient in nutrient cycling |
| | *Dolichos lablab* (L.) | S–C; LF; A+; DT; WD | 75–150 | 4–13 | AF; HF |
| | *Macroptilium atropurpureum* (DC.) Urb. | S–C; WD; A+; MF; DT | n.a. | 3–6.5 | AF; SOM; WC |
| | *Mucuna pruriens* (L.) DC. | S–C; LF | 130–150 | 2–5 | FEG; GC; BNF; NC |
| | *M. pruriens* (L.) DC. (dwarf varieties) | S–C; LF | 80–100 | 2–4 | NC; FASM; rain during harvesting period can damage the seeds |
| | *Pueraria phaseloides* (L.) | L; WD; Wlog–; DT | n.a. | 3.5–8 | AF; GC |
| | *Stylosanthes* spp. | S–C; A+, LF; DT | n.a. | n.a | AF; BP; SOM |
| | *Vigna radiata* (L.) | S–C; DT; WL– | 60–80 | 3.5–6.5 | AF; HF; high seed production |
| | *Vigna unguiculata* (L.) | S–C; L/MF; A+; WL– | 70–110 | 2.5–5.7 | AF; HF |

[a]n.a., Data not available; S, light-textured (sandy) soil; L, medium-textured (loamy) soil; C, heavy-textured (clayey) soil; L/M/H, low/medium/high fertility; WD, well-drained soil; Wlog–/+, intolerant/tolerant of waterlogging; A–/+, intolerant/tolerant of soil acidity; DT, drought tolerant; AF, animal forage; HF, human food; BNF, high-N fixation; GC, produces good cover; WC, weed suppression; BP, biological plowing; SOM, good SOM builder; FASM, facilitates acid soil management; FEG, fast early growth; NC, nematode control.



1st Year
winter
summer
SAFRINHA
Slash & chop + Contact herbicides
Broadcast seed
Residues
Cover crop: BLACK OAT (4–5 t/ha DM)
Slash & roll (at milky grain stage)
Contact herbicides
Planting + fertilizer
Dead biomass
Pesticides & weeding
BEANS (1.5–2 t/ha grain)
Manual harvest
Contact herbicides
Planting + fertilizer
Residues
Pesticides & weeding
BEANS (1–1.5 t/ha grain)
Harvest
April M J J A S O N D J F M A
2nd Year
Slash & chop
Broadcast seed
Residues
Cover crop: BLACK OAT (60%) + COMMON VETCH (40%)
Slash & roll (at vetch flowering)
Contact herbicides
Planting + fertilizer
Dead biomass
Pesticides & weeding
SHORT DURATION MAIZE (4–6 t/ha grain)
Manual harvest
Contact herbicides
Planting + fertilizer
Residues
Pesticides & weeding
BEANS (1 t/ha grain)
April M J J A S O N D J F M A
3rd Year
Manual harvest
Broadcast seed
Residues
Cover crop: OILSEED RADISH (2 t/ha DM)
Slash & roll (at radish flowering)
Contact herbicides
Planting + fertilizer
Dead biomass
Pesticides & weeding
BEANS (1.5–2 t/ha grain)
Manual harvest
Contact herbicides
Planting + fertilizer
Residues
Pesticides
MAIZE FOR SILAGE
Cut green for silage
April M J J A S O N D J F M A

attention to the fact that cover crops are commonly also grown in mixtures rather than alone by Brazilian farmers. The function of certain cover crops in terms of building SOM, enhancing nutrient management, alleviating soil compaction, and facilitating soil acidity and weed management are elaborated in the relevant Section III.C–H.

### 1. Cover Crops in Subtropical Southern Brazil

As there is generally sufficient year-round moisture in most parts of Southern Brazil, temperature is the main limiting factor to crop production, frosts being frequent between late April and early September (Grodzki, 1990), making the summer the most important growing season. In general, however, the Southern Brazilian climate allows up to three crops a year, and formulaic Southern Brazilian zero-till systems comprise planting a commercial summer crop of maize, soybean, common bean, tobacco, onions, and so on, into the mulch of a winter cover crop that has previously been killed with either a knife-roller or herbicides or both. A second, shorter-duration crop or summer cover crop (referred to as "safrinha" crop) is then immediately planted into the residues of the first commercial crop in order to take advantage of the warm temperatures at the end of summer (Ribeiro *et al*., 2005), and a winter cover crop is subsequently planted into the residues of the safrinha crop. Such a cropping sequence over 3 years for a maize/bean system in Southern Brazil is shown in Fig. 2, while Darolt (1998b) and Ribeiro *et al*. (2000) further detail different possible crop rotations suited for zero-till systems in Southern Brazil involving tobacco, dairy cattle, and soybeans, sorghum (S*orghum bicolor* L. Moench), and beans or onions as the main commercial components, and using mixtures of common cover crops such as black oat (*Avena strigosa* Shreb) and hairy vetch (*Vicia villosa* Roth), ryegrass (*Lolium* spp.), oilseed radish (*Raphanus sativus* var. Oleiferus Metzg.), corn spurry (*Spergula arvensis* L.), and mucuna (*Mucuna* spp.) as winter or safrinha cover crops.

Results obtained with winter cover crops in Southern Brazil indicate that significant yield increases can be attained if the proper cover crop is included in crop rotations (Bairrão *et al*., 1988; Calegari, 1995, 2000, 2002; Calegari

**Figure 2** Schematic representation of a model zero-till maize–bean rotational system for Southern Brazil. Safrinha refers to the short growing season following summer which Southern Brazilian farmers commonly use in order to utilize residual summer warmth before planting winter crops or cover crops. "Slash & chop" implies cutting down and shredding residues after harvest, while "slash & roll" implies slashing and laying flat an unharvested cover crop (e.g., using an animal-drawn knife-roller). "DM" refers to the amount of dry matter that can be harvested from the system as food, fodder, or fuel rather than the amount of residues remaining on the field. Information based on Darolt (1998b).

and Alexander, 1998; Calegari *et al.*, 1993, 1998a; Medeiros *et al.*, 1989). Although over a hundred different species and varieties of cover crop were screened tested and trialed throughout Southern Brazil in the 1980s (Derpsch, 2003), and many different cover crops are being used by both large and small-scale farmers in Southern Brazil (Calegari, 1998b), black oats, vetches (both *V. villosa* and *V. sativa* L.) oilseed radish, ryegrass, rye (*Secale cereale* L.), and white or blue lupines (*Lupinus albus* L. and *L. angustifolius* L.), grown alone or in mixtures, have emerged as the most common winter cover crop species (Calegari, 2002; Schomberg *et al.*, 2006). Prior to 1977, black oat, for example, was planted on a very small scale, but with the diffusion of zero-till systems, is now grown on over 3 million hectares in Paraná and Rio Grande do Sul alone (Steiner *et al.*, 2001). Data from participatory assessment of smallholder farmers' preferences regarding cover crop species in a region of Paraná indicated that farmers choice was based on criteria such as biomass production, resistance to decomposition, speed of soil cover, ease of planting the subsequent crop with animal-drawn planters, and weed suppression (Ribeiro *et al.*, 2005).

However, although the above-presented combinations of multiyear winter cover crops and summer crop rotations represent an ‘‘ideal'' model for approaching permanent soil cover, soil fertility build-up, and productive farming in Southern Brazilian zero-till systems, and although it is possible to find many farmers resorting to such cropping systems on large tracts of their land, Ribeiro *et al.* (2005) argue that this does not necessarily represent the reality on the ground for the majority of resource-poor smallholder farmers. The results of a survey of 60 smallholder zero-till farmers conducted in 2004 in the Irati region of Paraná, for example, indicate that about 70% actually grew winter cover crops on any of their plots, and that, despite of the efforts of researchers and extension worker promoting the diversification of the cover crop species, few of the surveyed farmers grew anything else than black oat and ryegrass, mainly due to the better market availability and lower price of the seeds of these species compared to others, exacerbated by the fact that very few farmers produced their own seeds. Among the farmers who did grow a winter cover, most held dairy cattle, which explains the dominance of black oat and ryegrass, both species suited for animal forage. Calegari (2002) notes that a soil cover option employed by smallholder farmers in Paraná who do not plant a specific cover crop is the use of spontaneous vegetation as cover, which in Paraná is predominantly composed of alexandergrass (*Brachiaria plantaginea*). Alexandergrass which develops late in the maize season and hence does not complete with maize during its critical growth period can be killed with herbicides before the planting of the subsequent crop, thereby producing an important mulch cover (4–7 t of dry matter) into which beans, maize, cotton, or soybeans, for example, can be planted (Calegari, 2002). Alternatively, Calegari (2002) also describes how mixtures of mucuna, planted at maize flowering, and spontaneously emerging alexandergrass can be used as a cover before both species are killed by winter frosts or by "knife-rolling" prior to the planting of tobacco.

Also, rather than rotate crops on a given plot as the ideal model system prescribes, a large proportion of farmers surveyed in Ribeiro *et al.* (2005)'s report chose to repeat the same crops over two or three of the annual cropping seasons, attempting to maximize profit rather than sustainability in the lack of any external subsidies. Palmans and van Houdt (1998) observed similar trends. Evaluating all cropping systems in the Jahu Microcatchment, northern Paraná, they found great variability in zero-till adoption levels, some farmers practicing zero-till without any crop rotations at all, others only rotating either cover or cash crops but not both, and only a small minority of farmers at the microwatershed level combining both zero-till with full rotation of cash and cover crops.

## 2. Cover Crop Systems in the Tropical Cerrado Region

As much of the cerrado is agricultural frontier land, and land prices are considerably lower than in Southern Brazil, most farms are consequently large (>100 ha) and mechanized. As the seasonality of rainfall in the cerrado region does not allow continuous cropping without irrigation, it is common for farmers to establish fast-growing, drought-tolerant cover crops immediately after harvest of the main crop, thereby allowing the cover crop to produce enough biomass on residual soil moisture stored under the mulch layer. The most common cover crop to be used in this way in the cerrado is millet (*P. americanum* L.), but other drought-tolerant cereals or pasture and forage species are also frequently used. Séguy *et al.* (1996) describe systems where farmers plant millet at the beginning of the rainy season rather than at the end, desiccating the millet with glyphosate 45–80 days later and planting soybeans into the millet residues. The advantage of this system compared to planting soybean first is that the millet grows much more rapidly than soybean, its roots extending at a rate of around 3 cm a day to a depth of about 1.5–2.4 m. This allows the millet to function as a pump for nutrients in deep soil strata, thereby utilizing more mobile nutrient, such as nitrates, that would otherwise be lost with the mineralization and leaching after soil wetting and drying cycles at the break of the season (Birch, 1958), but also means that more biomass and a different rooting pattern are added to the soil. Alternatively, Séguy *et al.* (2003) detail continuous zero-till systems with sequences of cover crops that remain throughout the 3- to 5-month dry season of the cerrado region, regrowing very rapidly after the first rains of the following rainy season or after sporadic dry season rain and thereby ensuring a permanent soil cover. Such systems consist of one commercial crop (soybean, rain-fed rice, maize, or common beans) grown during the rainy season and followed by a second crop of fast-growing cereals or cover crops [millet, maize, sorghum, finger millet (*Eleusine coracana* L. Gaertn.) or sunnhemp (*Crotalaria juncea* L.)] intercropped with forage species (*Brachiaria, Stylosanthes, Axonopus*, *Stenotaphrum*, and *Cajanus* spp., as well as *Pannicum maximum* var. Tanzania, *Cynodon dactylon* var. Tifton, various varieties of *Paspalum notatum* and *Pennisetum clandestinum* and the legumes *Calopogonium mucunoides*, *Arachis pintoi*, *A. repens*, *Lotus uliginosus*, *L. corniculatus*, *Trifolium semipilosum*, *Tephrosia pedicellata*, *Stizolobium aterrinum*, and *Pueria phaseoloide*, grown alone or in mixtures) at the end of the rainy season, the latter enduring throughout the dry season after the cereal has been harvested (Scopel *et al.*, 2004; Séguy *et al.*, 1996). The forage species/pasture can then be knocked back with split rates of glyphosate and later controlled with reduced rates of selective herbicides before the planting and throughout the cycle of the next commercial crop, thereby giving the latter a competitive edge but maintaining a continuous undergrowth or "carpet" of forage species. Alternatively, the forage species can be completely terminated with full rates of glyphosate before the seeding of the commercial crop, as at this stage it has already produced sufficient mulch. Such combinations of cereals and forage species planted at the end of the rainy season allow receding soil moisture, as well as sunlight to be used efficiently during the dry season, while concomitantly producing large amounts of biomass which can be either grazed or used as green manure. Séguy *et al.* (2001) observed that under irrigation or in wetter areas (>1500 mm rainfall per year), total above and below ground annual dry matter production increased from an average of 4–8 t $ha^{-1}$ in systems with a single annual commercial crop to an average of around 30 t $ha^{-1}$ in the most efficient zero-till systems using, for example, *Brachiaria* species (*B. mutica*, *B. decumbens*, *B. arrecta*, *B. brizantha*, or *B. humidícola*). Some farmers in the cerrado with large livestock herds and sufficient land at their disposal leave part of their land under pasture for 3–4 years, before recommencing a 3- to 4-year cycle of zero-till grain cultivation, as this minimizes the reestablishment costs of the pasture and the need for selective herbicides, while allowing effective SOM build-up (Séguy *et al.*, 1996).

### C. Soil Organic Matter Build-Up

In soils rich in high-activity clays, the effect of a loss of SOM on soil aggregation, cation exchange, and water-holding capacity may not be very detrimental to overall soil fertility. However, in areas where soil mineralogy is dominated by low-activity clays and sesquioxide material, the soil's fertility and integrity is much more SOM dependent. In some tropical Brazilian soils, 70–95% of cation exchange capacity (CEC) is founded in SOM (Bayer and Mielniczuk, 1999). In such soils, SOM maintenance or build-up is crucial to ensuring good crop productivity, and is often postulated as the single most important element of the soil restoration process associated with Brazilian zero-till regimes. In principle, both decreased erosive losses of SOM-rich topsoil (Lal, 2002; Rasmussen and Collins, 1991) and slower SOM mineralization rates in zero-till soil compared to plowed soil suggest that zero-till may provide more favorable conditions for SOM build-up than conventional tillage. Not turning the soil, for example, means that: (1) less soil macroaggregates are disrupted, consequently leading to the increased formation of stable microaggragates that occlude and protect particulate organic matter (POM) from microbial attack (Amado *et al.*, 2006; Feller and Beare, 1997; Lal *et al.*, 1999; Six *et al.*, 1998, 1999, 2000), that (2) there is less stimulation of short-term microbial activity and concomitant release of $CO_2$ in response to enhanced soil aeration (Bayer *et al.*, 2000a,b; Bernoux *et al.*, 2006; Kladivko, 2001), and that (3) there is less mixing of residues deeper into the soil where conditions for decomposition are often more favorable than on the soil surface (Blevins and Frye, 1993; Karlen and Cambardella, 1996). In this context, Mielniczuk (2003) estimated the rate of SOM mineralization under conventional tillage regimes in Southern Brazil to be on average 5–6% per year compared to an average of about 3% per year in zero-till soils.

Although the actual amount of SOM storage potential in a given soil is in turn largely determined by climate and the capability of soils to stabilize and protect SOM, this itself generally being largely determined by soil texture, soil mineral surface area, and soil mineralogy, with soil parameters such as water-holding capacity, pH, and porosity acting as rate modifiers (Baldock and Skjemstad, 2000; Six *et al.*, 2002b), the large majority of Brazilian literature does indeed suggest that SOM accumulation in zero-till soils above that of plowed soils occurs, and that this is the case over a range of soil textures, from sandy loams (Amado *et al.*, 1999, 2000, 2001, 2002, 2006; Bayer *et al.*, 2000a,b, 2002) to heavy clay (>60% clay) soils (Amado *et al.*, 2006; De Maria *et al.*, 1999; Perrin, 2003), both in Southern Brazil (Muzilli, 1983; Sá *et al.*, 2001a,b; Zotarelli *et al.*, 2003), as well as in the cerrado region (Corazza *et al.*, 1999; Freitas *et al.*, 1999; Resck *et al.*, 1991, 2000; Scopel *et al.*, 2003). Bernoux *et al.* (2006) recently reviewed some 25 published and unpublished data sets on the rate of C (SOM ~58% C) accumulation in Brazilian zero-till soils and observed that reported C accumulation rates in excess of those found in comparable plowed soils vary from around 0.4–1.7 t C $ha^{-1}$ $year^{-1}$ for the 0- to 40-cm soil layer in the cerrado region and between −0.5 and 0.9 t C $ha^{-1}$ $year^{-1}$ in Southern Brazil. They further noted that average rates of C storage amounted to about 0.6–0.7 t of C $ha^{-1}$ $year^{-1}$

in all reported regions of Brazil when the soil surface layer was considered (0–20 cm), although these values combine different soil and crop types, and the actual site-to-site/experiment-to-experiment variation was high. We found over 40 published articles relating to SOM dynamics in Brazilian zero-till regimes (with very few exceptions all from experimental stations or trial plots rather than farmers' fields), but reviewing them in more detail reveals a varied picture, which is compounded by the fact that relevant reports originate from various climates and soils with diverse tillage, cropping and fertility management histories, as well as often being sampled to different depths and based on analytical and calculation methods of varying accuracy. Freitas *et al.* (1999), for example, observed increases in SOM in coarse particle-size fractions (200–2000 μm) down to 20-cm depth compared to similarly cropped but plowed land in a clayey cerrado Oxisol already after only 4 years of zero-till, while other work reported a decrease in SOM compared to plowed soil down to a depth of 10 cm after 3 years in a Oxisol in Toledo (Riezebos and Loerts, 1998), to a depth of 20 cm after 11 years of zero-till in an Oxisol in Passo Fundo (Machado and Silva, 2001), to a depth of 40 cm after 10 or 22 years of zero-till in either a well drained, Typic Hapludox Oxisol in Tibagi (Sá *et al.*, 2001a) or an Oxisol in Londrina (Machado and Silva, 2001), respectively, and Sisti *et al.* (2004) and Castro Filho *et al.* (2002) found no significant increase in SOM down to 30-cm depth in a clayey Typic Hapludox Oxisol after 13 years of zero-till in Passo Fundo or down to 40-cm depth even after 21 years of zero-till in a Typic Haplorthox Oxisol in Londrina, respectively.

Sampling depth is an important issue in terms of SOM accumulation studies in Brazil, and results are strongly influenced by the pattern of SOM storage. In the absence of soil inversion and mixing, zero-till soils have highly stratified SOM stocks, SOM being most concentrated near the surface and gradually decreasing with depth (Machado and Silva, 2001; Sá *et al.*, 2001a,b). Additionally, and importantly in this context it is essential to note that direct comparisons in absolute SOM storage between plowed and zero-till soils are inappropriate if soil depths less than 20 cm are considered, as conventional soil tillage homogenizes SOM down to 20 cm (Bernoux *et al.*, 2006; Reicosky *et al.*, 1995). Deeper samples, however, also show different trends. Studies performed in the cerrado region by Centurion *et al.* (1985) and Corazza *et al.* (1999) showed that while soil C stocks under zero-till were higher than under plowed soils in the surface 20 or 30 cm, extending sampling depth to 100 cm evened out global differences in SOM between tillage systems due to lower C content under ZT in the 30- to 100-cm depth interval. Sisti *et al.* (2004), on the other hand, found much larger differences in total SOM between zero-till and plowed soil if soils were sampled down to a depth of 100 cm, the 30- to 100-cm depth interval containing between 50% and 70% of the extra C in zero-till compared to tilled soil. This, they reasoned, could possibly be explained by the greater root density at depth under zero-till compared to the plowed soil in their study, while the acidic subsoil in the studies by Centurion *et al.* (1985) and Corazza *et al.* (1999) in the cerrado region may have inhibited much rooting at depth. We found no other Brazilian literature that reports SOM storage at depths greater than 40 cm.

Brazilian research data also indicate that the pattern and quality of SOM in zero-till soils differs to that of plowed soils. Various research has also found that the relative amount of free labile or more recent (e.g., POM) rather than humified and occluded SOM fractions is higher in zero-till soils compared to plowed soils, which is in turn has important ramifications for soil structure, nutrient cycling and as a source of energy for soil microbial biomass. Using a particle-size fractionation technique combined with electron spin resonance, Bayer *et al.* (2000b), for example, observed that soil organic C (SOC) associated with sand and silt fractions in zero-till soils was less humified and therefore younger than that associated with finer fractions, while Sá *et al.* (2001a) reported that although they also found higher SOC concentrations in the finer particle-size fractions ($<20$ μm) under zero-till compared to conventional tillage, the percentage of SOC derived from crop residues, as assessed by $^{13}C$ natural abundance, was generally greater in the coarse ($>20$ μm) fractions than in the finer ones. Similarly, Amado *et al.* (2006), investigating SOM storage in four long-term trials in a range of light ($<9\%$ clay) to heavy ($>70\%$ clay) soils in Southern Brazil, noted that free light fraction SOM was on average 3.5 times higher under zero-till than in tilled soil, stipulating that this was probably a consequence of lower soil temperatures and residue-soil contact in zero-till soils compared to plowed soils. They therefore conclude that physical protection of SOM was important in zero-till, especially in sandy soils, but that in contrast to neighboring soils under native vegetation, soil texture played a less important role in short-term SOM stabilization.

Finally, and most importantly in terms of actually managing SOM build-up, the increase in plant biomass per unit of land and time through fast-growing cover crops typical for Brazilian zero-till systems means that more fresh organic matter is added to soils than under traditional double-cropping plow regimes. Although physicochemical characteristics inherent to different soil may partially limit increase in SOM with increased organic inputs, various studies suggest that SOM responds linearly to increasing rates of residue addition over a variety of soils and climates (Bayer, 1996; Black, 1973; Burle *et al.*, 1997; Rasmussen and Collins, 1991; Testa *et al.*, 1992; Teixeira *et al.*, 1994). Burle *et al.* (1997), for example, obtained a close relationship between SOC in the 0- to 17.5-cm soil layer and residue quantity added by 10 different zero-till cropping systems. Results obtained by Bayer (1996) stipulated that after 9 years of zero-till with high-residue addition

(14 t of dry matter per ha per year), SOC content increased by 11 t ha$^{-1}$ in the top 17.5 cm of soil compared to conventional cropping systems that only yielded additions of 6.5 t of residues ha$^{-1}$ year$^{-1}$. In Southern and tropical Brazil, with average annual temperatures close to or above 20°C and concomitantly high-decomposition rates, it is therefore probably necessary to annually add between 8 and 10 t of residue dry mass ha$^{-1}$ year$^{-1}$ in order to maintain the SOM stocks under zero-till, which, as Mielniczuk (2003) postulates is only really feasible if both suitable high-biomass cover crops and main crops are resorted to. Especially fodder grasses, as used as dry season cover crops in the cerrado (Section III.B.2), but also cereal cover crops, such as millet, sorghum, and black oat, or crucifers, such as oilseed radish and legumes such as vetches and lupines (Calegari, 1998c), can produce high amounts of biomass (Table III), and in combination with high-residue producing main crops, such as maize rather than soybean or wheat, can help boost SOM stocks. Importantly also in this context, it is essential to consider below-ground biomass of crops and cover crops, especially as the C added in roots can be close to double that of shoots (Mielniczuk, 2003) and, as discussed earlier, Sisti *et al.* (2004) found increased roots under zero-till compared to plowed soils well below plowing depth.

De Maria *et al.* (1999) compared SOM stocks after 9 years of either maize or soybean in summer and oat in winter both under zero- and conventional tillage. Despite the fact that maize produced much larger biomass quantities, these did not increase SOM under either tillage type, and SOM actually decreased over the study period in all treatments. As the net N balance (fertilizer N – grain N export) was only about 20 kg of N per hectare, the lack of SOM accumulation under either tillage treatments may be related to the lack of sufficient external N input to the system. Sisti *et al.* (2004) and Amado *et al.* (2006) further studied the role of N additions in SOM build-up under zero-till in Brazil, and both found that where rotations with $N_2$-fixing legumes were included, much more SOM was accumulated, hence highlighting the fact that for there to be an accumulation of SOM there must be not only a C input from crop residues, but a net external input of N. Sisti *et al.* (2004) observed that where hairy vetch was planted as a winter cover crop in rotations that included common oat and wheat in winter and maize or soybean in summer, soil C stocks were increased by approximately 10 t ha$^{-1}$ down to a depth of 100 cm after 13 years of zero-till, soil C being 17 t higher in this soil layer than in comparable plowed soils. They further postulated that where net N balance was close to zero over the whole crop rotation, little SOM accumulation was to be expected. Amado *et al.* (2006) reported that pigeonpea and mucuna cover crops integrated into zero-till maize cropping systems had the highest C accumulation rates under zero-till and that intensive cropping systems, including mixes of black oat with hairy vetch in winter and maize with cowpea in summer, as well as rotations of oilseed radish and ryegrass, among other crops, effectively increased zero-till C accumulation rates compared to more conventional double-crop systems used by many farmers.

In summary, a large body of Brazilian work corroborates the fact that SOM accumulates under zero-till in excess of that under plowed land, and that farmers can in theory influence SOM build-up through astute crop rotations and appropriate liming and fertilization regimes. The amount and rate of SOM build-up is, however, less clear. This complexity of data on Brazilian SOM accumulation make it hard to draw any firm conclusions about a possible timeframe for which SOM levels significantly increase. However, Six *et al.* (2002a), reviewing literature on SOM dynamics in tropical and temperate zero-till soils around the world, remarked that there commonly is a relative increase in SOM in the upper 40 cm of zero-till soil after 6–8 years when compared to tilled systems under similar cropping regimes, and this pattern could potentially hold true for a large amount of the Brazilian data.

## D. Nutrient Management

Possibly one of the most important immediate nutrient effects of zero-till is the potential of the residue cover to restrict N availability. Residues with a high C to N ratio, such as black oat, wheat, maize, sorghum, and ryegrass, commonly induce N immobilization in soil surface strata during decomposition, although the magnitude of this effect is dependent on residue quantity and quality, as well as the mineral status of the soil. Sá (1999) suggests that the immobilization process is most intense during the first years of zero-till, but after 5 or more years, gradually diminishes due to the increased surface concentration of SOM acting as an N source and thereby effectively counteracting N limitations induced by residues. Especially as zero-till increases the POM stock, which is strongly correlated to potentially mineralizable N, soil N availability under long-term zero-till is suggested to increase over time when compared to conventional tillage (Sá *et al.*, 2001a,b). During the first few years of zero-till, however, cereal response to N fertilization is high, and generally N-fertilization is recommendable or necessary (Calegari, 2002), although care should be taken to distance fertilizer deposition as far as possible from the mulch in order to avoid fertilizer immobilization (Wiethölter, 2002).

An option of adding N to the system and alleviating immobilization-induced N constraints under zero-till is by rotating legumes with non-legumes, as well as mixing legume swards with nonlegume stands. Residues with a low C to N ratio as common vetch, lupine species, soybean, oilseed radish, mucuna, jackbean (*Canavalia ensiformis* L. DC.), or pigeonpea can increase N availability. Much work has been conducted on the nutrient content and residual effects of common cover crops in Southern Brazil, Paraguay, and Uruguay (Amado *et al*., 1990b; Calegari, 1989, 1990, 1995; Calegari *et al*., 1993; Derpsch and Calegari, 1992; Derpsch and Florentin, 1992; Igue, 1984; Jucksch *et al*., 1984; Kage, 1984; Lovadini *et al*., 1972; Monegat, 1991). Relating to the results of trials conducted over 2 years at IAPAR in Londrina, Derpsch *et al*. (1986), for example, reported that maize fertilized with P and potassium (K) produced highest yields after preceding crops of white lupine and hairy vetch, when compared to yields after grasspea (*Lathyrus sativus* L.), cereals, and sunflower. This can be explained by the fact that appropriate legume residues can decrease maize mineral N requirement by about 60–90 kg $ha^{-1}$ (Amado *et al*., 2000; Calegari, 1995; Sá, 1999). Both in tropical and subtropical Brazil, legume residues left on the soil surface decompose rapidly and provide a prompt N release, sometimes so fast that it causes asynchronies with maize demand (Acosta, 2005; Giacomini, 2001; Vinther, 2004). Common vetch residue left on soil surface in Santa Maria, for example, released 60 kg of N per hectare in only 15 days (Acosta, 2005). Derpsch *et al*. (1986) also noted high-maize yields after oilseed radish in the same trials, which they explained as a consequence of the high amount of N (135 kg $ha^{-1}$) in the plant shoots and roots at harvesting time. Muzilli *et al*. (1983), Calegari (1985), Amado *et al*. (1990b), Derpsch and Calegari (1992), and Debarba and Amado (1997) all also reported positive effects of N supply provided by legume cover crops such as white lupine and hairy vetch in Southern Brazil, while Carvalho *et al*. (1996) noted that pigeonpea and sunnhemp fulfilled a similar function in the cerrado region. Sisti *et al*. (2001) actually found that legumes grown under zero-till symbiotically fixed a higher proportion of their N requirements compared to legumes sown to plowed soil, which is presumably a consequence of the lower rates of N mineralization and concomitant higher dependency on fixation when soils were not turned. Acosta (2005), using $^{15}N$ labeling, found that common vetch symbiotically fixed 50–90% of its N requirement in a zero-till trial in Santa Maria, Rio Grande do Sul. Burle *et al*. (1997) trialed mixed stands of cover crops over 10 years and found maize unfertilized with N to respond best to a preceding mixture of black oats and hairy vetch compared to nine other cover crop combinations planted prior to maize (Table IV). This is most probably a result of the maize profiting both from the beneficial effects of lasting soil cover and large C inputs generated and gradually laid down by the fast-growing oat, as well as the symbiotically fixed N from the vetch. Giacomini *et al*. (2003) also found mixtures of black oats or oilseed radish and hairy vetch to be the most efficient way of combining both physical soil protection through long-lasting residues and high-biomass production with N fixation in Southern Brazilian zero-till systems.

**Table IV**
**Maize Yields on a Zero-Tilled Oxisol in Southern Brazil After 10 Years of One of Seven Cropping Regimes and Fertilized with Either 0 kg ha$^{-1}$ N or 120 kg ha$^{-1}$ N[a]**

| Cropping systems studied | | Grain yields (t ha$^{-1}$) | |
|---|---|---|---|
| Winter | Summer | 0 kg ha$^{-1}$ N | 120 kg ha$^{-1}$ N |
| *Avena strigosa* | Maize | 2.0 a A | 7.1 B |
| *A. strigosa* + *Vicia sativa* | Maize + *Vigna unguiculata* | 6.6 b B | 7.6 B |
| *A. strigosa* + *Trifolium subteraneum* | Maize | 5.4 b B | 7.0 B |
| *Macroptilium atropurpeum* (8 years) | Maize (5th and 10th year) | 5.7 b A | 8.3 B |
| *Cajanus cajan* | Maize + *C. cajan* | 5.4 b B | 7.2 B |
| Fallow | Maize | 1.1 a A | 6.5 B |
| *Digitaria decumbens* (8 years) | Maize (5th and 10th year) | 1.3 a A | 6.8 B |

[a]Means followed by the same small letter down rows or capital letter across columns are not significantly different using the Tuckey test at $p = 0.05$ (data from Burle *et al.*, 1997).

For zero-till maize production in Southern Brazil, variations in traditional mineral N fertilization regimes have also been tested. The use of part of maize N fertilization in the black oat cover crop had a positive effect in terms of increasing black oat residue quantity and quality (lower C:N ratio), but this in turn had a fairly limited effect on N supply to the following maize crop (Amado *et al.*, 2003). Another zero-till fertilizer strategy is to use the total rate of mineral N at cover crop termination (approximately 15 days before the seeding the main crop) or at maize seeding time rather than apply N in split applications, assuming that the residue mulch will temporarily bind added N and thereby partially prevent leaching losses of N, as this eliminates the need for an additional field operation. However, in terms of maize yields, this strategy was only efficient in years with light rainfall during maize growth (Basso and Ceretta, 2000; Pöttker and Wiethölter, 2002; Sá, 1999). In years with high rainfall, the traditional strategy of applying one-third of N at seeding and the remaining two-thirds as a top dressing after 6 weeks was more efficient (Ceretta *et al.*, 2002; Pöttker and Wiethölter, 2002).

As N fertilizer is not thoroughly mixed into the soil, concerns about N volatization in zero-till are frequent (Blevins and Frye, 1993). Cabezas *et al.* (1997), for example, evaluated the efficiency of broadcasting of urea, the most common mineral fertilizer source of N in Brazil, on mulch, and found that about 80% of N was lost through volatilization. In this context, however, we would like to stress that this result was obtained under hot and dry conditions common in the cerrado, and under wet winter conditions in Southern Brazil, Wiethölter (2002) found that only about 5% of broadcast urea-N was lost by volatilization in a wheat crop. The discrepancy between the results most likely is explained by the differences in weather conditions. A light rain after broadcast urea in zero-till can reduce the N volatilization.

As with N, P has been shown to accumulate in soil surface strata under zero-till regimes (Sá, 1999), due to the management effect of broadcasting or row applying P fertilizer rather than incorporating it, but also due to decomposition of P-containing residues on the soil surface and the slow movement of P through the soil profile. As this corresponds to soil strata that is richest in SOM under "mature" zero-till, P phytoavailability has been shown to improve, due both to lower P sorption on clay particles and iron and aluminum sesquioxides surface, as well as due to increased biological activity in this strata (Afif *et al.*, 1995; De Maria and Castro, 1993; Falleiro *et al.*, 2003; Fontes *et al.*, 1992; Lopes *et al.*, 2004; Muzilli, 1985; Reinert, 1982; Sá, 1999; Selles *et al.*, 1997; Sidiras and Pavan, 1985; Silva *et al.*, 1997). This effect is exacerbated by the fact that there is generally also a higher concentration of surface roots under zero-till compared to plowed soils (Holanda *et al.*, 1998; Stone and da Silveira, 1999). Gassen and Gassen (1996), for example, reported that after some years, demand for fertilizer P is up to 50% lower under zero-till compared to crops with the same P uptake in plowed soil. Furthermore, Sá (1999) found that organic P made up 70% of total P in the 0- to 20-cm soil strata under zero-till, consequently suggesting that organic P in zero-till could play an important role in maintenance of the P equilibrium in the soil solution as it is more mobile than inorganic P. Lopes *et al.* (2004), however, only found organic P in an Oxisol to amount to 25–35% of total P, and Oliveira *et al.* (2002) argue that, similarly to N, P in the first years of zero-till is immobilized in the organic matter that is being built up, the SOM therefore acting as a temporary P drain before the beneficial effects of SOM on P phytoavailability become evident.

Similar to N and P, but also calcium (Ca) and magnesium (Mg) (Calegari, 2002), K has a higher concentration in topsoil (0–10 cm) than in deeper soil layers under zero-till, but, due to its high-soil mobility, its stratification is not as extreme as that of P. The significant increase of CEC as a result of increased surface SOM concentrations under zero-till, especially in low activity or sandy soils, has also been shown to greatly reduce K leaching under zero-till compared to plowed soil (Bayer, 1996). Furthermore, crop rotations have proved particularly important in the maintenance of K under zero-till, with cover crops, such as millet and oilseed radish oil having a high potential to absorb and hence recycle K, hence functioning as K catch crops and thereby reducing K leaching losses. In the cerrado region, where many soils have low K, the combined use of K fertilizers and cover crops with zero-till showed an increase in soil K above that of conventional tillage (Lopes *et al.*, 2004).

## E. Soil Compaction

Soil compaction is another contentious issue in Brazilian zero-till, which, if severe, can potentially both curtail infiltration rates, as well as restricting crop root development, which in turn is especially important in areas prone to periods of in-season drought and poor soil fertility. While soil compaction is a natural process, the cohesion between aggregates tending to decrease under the flux of water in soil, this process is counterbalanced in natural ecosystems by intensive biological activity throughout the soil profile. In cultivated land, on the other hand, compaction is often accentuated by the random traffic of machinery, animals, or humans (McGarry, 2003). Plowing is in turn commonly used to remedy compacted soil, at least to 20-cm depth, while in Brazilian zero-till, activating and enhancing biological activity is the key to avoiding natural or man-induced compaction, as is the case in natural ecosystems (Scopel *et al.*, 2003). In theory, bulk density may well increase over time under zero-till, but infiltration rates remain reasonable due more favorable porosity, pores being continuous and vertical, postulate McGarry (2003) and Scopel and Findeling (2001). Farmer experiences with soil compaction published in the Brazilian literature, however, are somewhat conflicting. Sá (2000) gives soil compaction and resulting yield declines, especially during dry periods, as a reason for some Southern Brazilian farmers to abandon zero-till and returning to conventional cultivation. Ribeiro *et al.* (2005), relying on data from a survey of 60 farmers in southern Paraná, elaborate on this, maintaining that farmers justify the use of chisel ploughs for soil decompaction or for breaking soil crusts, the latter occurring specially in soils with high amounts of silt. Conversely, however, Derpsch (2001) argues that compaction does not translate in reduced soybean yields, while researchers in Rio Grande do Sul further reason that soil compaction there is not big issue, despite the high sand and silt content making soils very prone to compaction, because suitable planter-rippers are able to break the shallow soil compaction induced by cows over the winter period.

In more detail in terms of experimental trials, Derpsch *et al.* (1986) found that after 7 years of zero-till, bulk density at 0- to 20-cm depth in a clayey Oxisol in Southern Brazil was greater than under conventional tillage, whereas the plowed soils had more or less pronounced "plow pans" at 20- to 30-cm depth. Furthermore, total and macropore volume was considerably lower under zero-till, while mesopore space was higher and micropore space unchanged between tillage systems. Corsini and Ferraudo (1999), on the other hand, found that although during the first 3 years of zero-till on a clayey Oxisol soil macroporosity and root development was lower under zero-till than in an adjacent tilled plot, the long-term benefits of continuous zero-till on soil macroporosity kicked in during the fourth year. After this, macroporosity and root development values increased and matched corresponding levels of freshly plowed soils in the experimental area during the eighth year. Similarly, Machado and Silva (2001) and Oliveira *et al.* (2003) remarked that bulk density at 0- to 20-cm depth after 11 or 20 years of zero-till on an Oxisol was not greater than bulk density under conventional tillage on the same soil. At 20–30 cm, however, bulk density of the plowed soil was greater than of the zero-till soil.

Part of the relative ‘‘ecompaction’’ process is undoubtedly due to the effects of gradual increases of SOM on soil structure and integrity. SOM has a direct impact on soil bulk density (or inversely on the porosity), both because the particle density of organic matter is considerably lower than that of mineral soil, but also because SOM is often associated with increased aggregation and permanent pore development as a result of increased soil biological activity (Franzluebbers, 2002). Various Brazilian authors have pointed at the beneficial influence of increased surface SOM levels under zero-till on soil structural stability and aggregate size and stability (Campos *et al.*, 1995; Carpenedo and Mielniczuk, 1990; Castro Filho *et al.*, 1998; Silva *et al.*, 2000), although the degradation and the opposite process—restoration of structural stability under zero-till—have been shown to be very dependent on soil texture and are much faster in sandy soils than in clayey soils. Borges *et al.* (1997), for example, observed that zero-till on sandy (>70% sand) soil restored water aggregate stability to near 70% of original levels of undisturbed soil after 3 years, whereas Da Rós *et al.* (1996) found that in clayey soil, where SOM storage potential was much greater, similar values were only achieved after 9 years of zero-till. Castro Filho *et al.* (1998) further reported that soil aggregation had a tendency to increase when crop rotations included plant species such as maize, whose residues had high C to N ratios. Roth *et al.* (1988) concluded that even though porosity was lower in soils after 7 years of zero-till compared to tilled soil, this was offset by a higher aggregate stability under zero-till, so that in the end no significant differences in infiltrability were found between tilled and untilled soils, even when neither soils were covered by adequate amounts of residues.

Additionally to the effect on soil aggregation, the increase in SOM in surface layers under zero-till may also affect plant-available moisture levels, as SOM has a greater water-holding capacity than mineral soil (Franzluebbers, 2002), and even if roots growth is restricted, this may be compensated by the fact that roots need to explore less soil volume to get water. Another explanation for the absence of yield decreases even in soils of high bulk density is that, as put forward earlier in this section, roots and water may exploit continuous biopores and channels generated by previous plants or soil fauna (Ehlers, 1975). Using suitable crops to break through compacted soil layers and create biopores is a feasible strategy to circumvent compaction problems. Kemper and Derpsch (1981) argue that crop rotations involving deep-rooted cover crops, such as hairy vetch, sunflower, castor bean (*Ricinus communis*), pigeonpea, or oilseed radish, may promote biological loosening of compact soils. Machado and Silva (2001) showed that if hairy vetch and maize were included in zero-till rotations of soybean and wheat, soil bulk density actually tended to be lower than in plots only cultivated with soybean and wheat. Especially a bulbless variety of oilseed radish is often reported as an outstanding example of biological plowing in Brazil, while Séguy *et al.* (2003) maintain that plant species, such as *Brachiaria*, *Eleusine*, or *Cynodon* species, are very efficient in restoring the soil structure both thanks the abundance of roots they develop in the first 0–40 cm of soil, as well as their overall strong root systems.

### F. Soil Acidity and Aluminum Toxicity

The control of soil acidity is often viewed as one of the most controversial aspects of effective zero-till. Due to the absence of soil inversion under zero-till systems, applied sources of lime are not physically mixed into deeper soil strata, and different approaches are required in order to tackle soil acidity problems. The most conventional approach is to rectify soil acidity before commencing zero-till, and Derpsch (2001) and Aghinoni (1989) recommend applying lime the year before entering into zero-till, thereby making use of the opportunity to incorporate lime. In general, if crop residues are thereafter returned to the soil, acidification should not present a problem due to the decarboxylization of organic anions, ligand exchange, and the addition or retention of basic cations (Miyazwa *et al.*, 1993; Yan *et al.*, 1996). Research by Kretzschmar *et al.* (1991), for example, showed that millet straw left on fields increased pH from 4.5 to 5.7 over 6 years. Long-term tillage and crop rotation experiments on acidic soils in Brazil have indicated that zero-till may increase pH, KCl-exchangeable Ca and Mg, and Mehlich-1 P, and decreased KCl-exchangeable Al (Calegari, 1995; Calegari and Pavan, 1995; Sidiras and Pavan, 1985) compared to conventional tillage (Machado and Gerzabek, 1993; Muzilli, 1983; Sidiras and Pavan, 1985).

Another approach is to broadcast lime or dolomite on the soil surface and allow it time to leach (Caíres *et al.*, 1996; Lopes *et al.*, 2004). Work by Sá (1993) indicated that surface application of lime after 270 days was superior to its incorporation to 20-cm depth with zero-till on distrophic red-yellow and dark red Oxisols in Paraná, while Lopes *et al.* (2004) agree that when the level of soil P is satisfactory, it is possible to achieve highly productive cultures in zero-till soils by applying calcareous material to the soil surface without incorporation, the quantity of material needed for this being lower than when the material is incorporated into the soil, although the maximum effect on soil acidity is limited to the 0- to 10-cm soil layer. The actual mobility of lime through the soil profile to date still appears to be rather uncertain. Results of both laboratory and field studies using Brazilian soils indicate little or no downward movement beyond the point of placement, limiting the effectiveness of the surface-applied lime to the top 5–10 cm (Gonzalez-Erico *et al.*, 1979; Miyazawa *et al.*, 2002; Pavan *et al.*, 1984; Ritchey *et al.*, 1980), while other work reports fairly rapid movement of lime through the soil profile (Chaves *et al.*, 1984; Morelli *et al.*, 1992; Oliveira and Pavan, 1996; Wright *et al.*, 1985). In a field experiment over 5 years on a clayey Oxisol in Paraná, Oliveira and Pavan (1996) surface applied various rates of lime and found that one quarter of the lime (dolomite) rates required to achieve 60% base saturation applied annually over 4 years increased soil pH significantly down to a depth of 40 cm over the experimental period, and that this resulted in improved soybean yields similar to those achieved when dolomite was incorporated to a depth of 20 cm, as compared to no liming. They argued that the apparent contradictions between mobility rates in other research could be an artifact of the differing soil management and cropping conditions, allowing for more or less complete reaction of the lime at the point of placement. In the studies of Gonzalez-Erico *et al.* (1979), Ritchey *et al.* (1980), Pavan *et al.* (1984) and Miyazawa *et al.* (2002), surface soil pH remained low and lime reacted completely at the point of placement with little pH change being evident deeper in the soil. Oliveira and Pavan (1996) also postulate that dolomite may possibly have followed old weed and crop root channels in the undisturbed soil to react with acidity at greater depths, as well as being transported by water or organic residue decomposition products through the well-drained, porous, and highly structured zero-till Oxisol they conducted field experiments on, as opposed to disturbed soils which were used in other experiments. Machado and Silva (2001) further maintain that channels made by macroarthropods and annelids could also influence lime movement, while Kaminski *et al.* (2000) proposed that crops grown on zero-till land suffered less from aluminum toxicity as their roots often followed the channels produced by insects or the decay of previous roots in the soil profile, such channels having lower levels of aluminum, higher levels of exchangeable Ca and Mg, raised available P and K, more organic matter, and higher pH than the adjacent soil. Some Brazilian zero-till farmers corroborate this view by claiming that after a number of years of zero-till, the soil has both a good enough structure to allow surface-applied lime to percolate into deeper layers even without plowing and that their crops do not suffer from the usual effects of low pH/aluminum toxicity.

The downward movement of Ca and Mg from the dolomite to deeper layers as a result of the formation of hydrosoluble organic compounds present in plant residues has recently gained more attention within the same group of researchers from IAPAR (Cassiolato *et al.*, 1998; Franchini *et al.*, 1999a,b, 2001; Meda *et al.*, 2001; Merten and Fernandes, 1998; Miyazawa *et al.*, 2002; Ziglio *et al.*, 1999). Low-molecular weight organic acids, such as malate and citrate, produced during decomposition of blue lupine and oilseed radish on an Oxisol were able to form stable Al complexes (Franchini *et al.*, 1998, cited in Machado and Silva, 2001). Miyazawa *et al.* (2002) used leaching columns of disturbed acid soil in a greenhouse experiments to evaluate the effect of plant residues on the mobility of surface-applied calcite lime through the soil profile. They applied black oats, rye, mucuna, leucaena (*Leucaena leucocephala*), and wheat straw at a rate of 40 t of dry matter per hectare to the soil surface in combination with 3 t $ha^{-1}$ of lime and an irrigation program equivalent to 1500-mm rainfall per year, and found that while the effect of lime without plant residues was limited to the upper 10-cm profile, lime combined with plant residues increased pH deeper in the soil, as well as generally increasing Ca and decreasing free Al concentrations in the soil profile compared to an untreated control. The efficiency of plant residues on lime mobility differed between species, black oats inducing the largest effect, followed by rye, mucuna, and leucaena, respectively, with the wheat residue treatment not differing from the sole lime application. Miyazawa *et al.* (2002) explained the results through the presence of carboxyl and phenolic compounds in the decomposition products of the residues, which acted as ligands forming uncharged or negatively charged metal–organic complexes with Ca, thereby facilitating the movement and leaching of Ca through the negatively charged clay soils. The difference in amounts of these carboxyl and phenolic compounds in the decomposition products of the residues of different species would subsequently explain species differences, with the minimal effect of wheat residues on lime mobility in soil due to their low concentrations of organic acids. Putting Miyazawa *et al.* (2002) results into a farmers' field context, 40 t of residues probably more than most farmers would produce. However, combined with the potential of lime movement through the porous structure of an undisturbed soil, as well as the movement of the lime in the decomposition products, this indicates that farmers potentially can control subsoil acidity with surface-applied lime and appropriate cover crops. Machado and Silva (2001), however, raise concerns that in systems where fertilizers are applied, surface liming may also reduce the efficiency of surface applied N (by volatilizing $NH_3$) and P (by complexing P with $Ca^{2+}$) and furthermore, that promising cover crop species, such as sunnhemp and pigeonpea, may not produce organic acids capable of forming stable Al complexes. More research in this respect is, therefore, potentially still necessary.

## G. Weed Management

One of the primary reasons for tillage is to control weeds. In the absence of soil inversion to bury and/or induce premature germination of weed seeds, or sever the roots and storage organs of annual and perennial weed species, and instead relying to a greater extent on herbicides, crop rotations, and hand weeding, the weed spectra in zero-till systems commonly differ from those under conventional tillage practices. Furthermore, as soil characteristics, such as bulk density and cover, are changed, these can have a direct influence on weed seedling emergence (Moyer *et al.* 1994). Small seeds of alexandergrass [*Brachiaria plantaginea* (Link) A. S. Hitchc.], for example, although they generally emerge from deeper soil layers in cultivated than in uncultivated soils due to changed bulk density (Lorenzi, 1984), are commonly incapable of germinating and emerging from soil deeper than 1 cm (Roman and Dinonet, 1990), hence being favored by zero-till and having become a major weed species in Southern Brazilian zero-till systems (Derpsch, 2003). A 6-year field study to evaluate the effects of tillage systems on weed density and species composition in rotations including wheat, soybean and maize in Argentina revealed that the weed spectrum changed rapidly in zero-till plots (Tuesca *et al.*, 2001). In wheat, annual broad-leaved species showed higher populations in plowed soils in 4 out of 6 years, while grassy annuals and perennial species showed an erratic response to tillage systems. In summer crops, broad-leaved weeds were higher in plowed soil than in zero-till for the last 5 years in the wheat/soybean rotation and for the last 4 years in the maize/soybean rotation. Over time, grassy annual populations increased in the maize/soybean rotation, and wind-dispersed weed populations increased in the wheat/soybean rotation, but perennial weeds maintained inconsistent behavior in relation to tillage type in the maize/soybean rotation. Machado *et al.* (2005) observed that purple nutsedge (*Cyperus rotundus*) remained the most important species in plowed maize systems after a 4-year trial on a clayey Ultisol in the State of Minas Gerais that had originally been infested with that weed species, but that the broad-leaved weed species (*Amaranthus deflexus*, *Bidens pilosa*, *Euphorbia heterophylla*, *Galinsoga parviflora*, and *Ipomoea grandifolia*) rather than purple nutsedge became dominant in zero-till maize. Roman and Dinonet (1990) observed a decrease in annual weed populations in a long-term double cropping system on farmers' fields that involved wheat, maize, and soybeans in Southern Brazil, while there was no indication that biennial weed densities increase in zero-tillage systems. Moyer *et al.* (1994) conclude that it is difficult to predict the type of weed population that emerge in cropping sequences that include several crops, especially under different edaphic and climatic conditions and if several different herbicides for weed control are used.

Nevertheless, weed management in the absence of plowing is a contentious issue in Brazilian zero-till, as it does commonly necessitate increased reliance on herbicides. In their survey of 31 smallholder farms in Paraná using mainly animal traction for drought and where weed control in conventional systems is mostly based on plowing, Samaha *et al.* (1998) noted that herbicide expenditures in conventional smallholder systems amount to about 2% or 5% of total production costs for either maize or beans respectively, but increase to 11% and 12% in similar zero-till systems. Rego (1993), also resorting to smallholder data from Paraná, corroborates this trend by stating that zero-till on average induces an increase of 17% in the use of herbicides when compared with conventional tillage in general, while conversely Silva (2002) argues that over time, successful zero-till systems in the cerrado tend to reduce the amounts of herbicides that are necessary (due mainly to decreased seed banks and weed-smothering properties of cover crops and residue mulches), but also, importantly, there being a change from preemergent herbicides with long residual times in the soil to postemergent herbicides, which are rapidly broken down in the environment. Scopel *et al.* (2004) also argue the latter point, stating that all the facts on the actual use of herbicides and other pesticides (products, rates, frequency of applications) for zero-till should be weighed and compared with that of the conventional systems they are displacing. For example, they argue, whereas rates of 4–5 liter $ha^{-1}$ of atrazine and simazine-based preemergent herbicides were used in conventional maize management in the cerrado region, now, these same types of herbicides are used postemergence in zero-till systems, at early stages of maize development and at rates of 1–2 liter $ha^{-1}$. Moreover, in the case of soybean, for example, they elaborate, very stable preemergent products have been substituted with more rapidly degraded postemergent ones.

In various calculations of global labor use in zero-till systems compared to conventional systems, based on smallholder farmer surveys in Paraná (Ribeiro *et al.*, 1993; Samaha *et al.*, 1993, 1996, 1998), for example, some of the most significant labor reductions in zero-till are reportedly due to the decrease in time spent on manual weeding and plowing, these operations being replaced by the use of herbicides. There is therefore a tradeoff between the use of herbicides and manual weeding. In a more recent survey among 60 smallholder zero-till farmers in Paraná, Ribeiro *et al.* (2005) found that farmers cultivating labor-intensive crops, such as tobacco, often applied herbicides fairly late and hence witnessed low-herbicide efficacy. Especially farmers that needed to control critical densities of *Spermacoce latifolia* after tobacco and perennial species such as *C. ferax*, *Paspalum* species and *Vernonia polyanthes* commonly resorted to disc harrowing or plowing rather than maintain zero-till, restarting zero-till after weed densities had been effectively reduced. Although herbicides are available and technically effective for control of these species (Lorenzi, 1994; Rodrigues and Almeida, 1998), Ribeiro *et al.* (2005) further stated that mechanical weeding was considered more effective and less costly than herbicide used by interviewed farmers.

In general, their high-relative costs (Petersen *et al.*, 1999), the difficulties experienced by smallholder farmers with herbicide formulation and handling combined with the dearth of farmers resorting to protective clothing for such procedures (Amado and Reinert, 1998; Berton, 1998; Merten, 1994), the presence in zero-till rotations of weed species difficult to control with herbicides and the increasing number of cases of weed resistance (Christoffoleti *et al.*, 1994), and the often negative environmental impacts associated with pesticide use has led to a heightened research of alternative weed management methods on smallholder zero-till farmers in Southern Brazil. Adegas (1998) describes a study of an integrated weed management (IPW) program on 58 farms in Paraná, observing that after 3 years, if optimal recommendations are followed, weed control costs decreased on average by 35% with herbicide reductions of 25%. Ruedell (1995) also details the results of an IPW program in Rio Grande do Sul, where, over an average of 34 areas there was a reduction of 42% in weed control costs assuming farmers follow optimal weed management practices. Such results potentially demonstrate that in theory IPW can prove agronomically, economically, and ecologically beneficial, although it was not clear from these reports if farmers did indeed apply IPW practices themselves under normal circumstances, and if not, why not.

Possibly the major tool in Brazilian IPW under zero-till systems is the use of cover crops. Cover crops are important in weed management mainly for two reasons: first, because they can compete against weeds during their development, and second, after termination of their cycle, their mulch can suppress weed emergence (Almeida *et al.*, 1984; Kliewer *et al.*, 1998; Petersen *et al.*, 1999; Skóra Neto, 1998; Tardin *et al.*, 1998; Thiesen *et al.*, 2000). Considering the first aspect, several winter and summer cover crops have been shown to suppress weeds through their fast growth pattern (Calegari *et al.*, 1993). Favero *et al.* (2001), for example, observed reduction of 22–96% of weed biomass in the presence of summer cover crops varying according the species. Using appropriate cover crop species in a rotation, Skóra Neto and Campos (2004) also noted a weed population reduction of 93% after 3 years. Vasconcelos and Landers (1993) report experiences of planting grain crops into permanent cover crops, of which maize into siratro (*Macroptilium atropurpureum* L. urb.) was the most successful, allowing the complete elimination of the selective maize herbicide. Fernandes *et al.* (1999) observed that *C. breviflora*, *C. spectabilis*, and pigeonpea plots had reduced densities of weeds, while Skóra Neto (1993a) also noted that pigeonpea grown as a companion crop to maize decreased weed infestation at and after the harvesting time; research that was later corroborated by Severino and

Christoffoleti (2004), who remarked that sunnhemp and pigeonpea were effective as smother crops against numerous weed species.

The mulch remaining on the soil can also improve weed management, both through its physical presence on the soil surface and by controlling N availability (Kumar and Goh, 2000) or by direct suppression due to allelopathy (Almeida, 1988; Caamal-Maldonado *et al.*, 2001; Rodrigues, 1997; Skóra Neto and Müller, 1993). Trials at IAPAR showed that black oat, rye, and common vetch residues were capable of suppressing weed emergence after 100 days between 30% and 50% (Table V). Roman (1990) performed similar on-station trials in Passo Fundo, recording the incidence of alexandergrass, arrowleaf sida (*Sida rhombifolia*), and blackjack (*B. pilosa*) infestation through the mulch of 14 common cover crop species after 40 days, finding that black oat, common oat, and ryegrass mulches suppressed all weed species very strongly, while oilseed rape, barley, rye, and a mixture of black oats and common vetch was effective against alexandergrass and blackjack, but not against arrowleaf sida. In general, cover crops species that

**Table V**
**Weed Emergence (Individual Species or General) in Plots Covered with Residues of Various Cover Crop Species, Expressed as Percentage of Weed Emergence in Uncovered Control Plots in Southern Brazil**

| | Emergence of individual weed species after 40 days at Passo Fundo, PR (Roman, 1990) | | | |
|---|---|---|---|---|
| Cover crop residue | *Sida rhombifolia* | *Brachiaria plantaginea* | *Bidens pilosa* | Weed emergence after 100 days, Ponta Grossa, PR (Skóra Neto, 1993b) |
| *Avena sativa* | 23 | 0 | 0 | |
| *Avena strigosa* | 22 | 0 | 0 | 53 |
| *Hordeum vulgare* | 100 | 17 | 22 | |
| *Lathyrus cicera* | 87 | 50 | 20 | |
| *Linum usitatissimum* | 100 | 60 | 90 | |
| *Lollium multiflorum* | 17 | 0 | 0 | |
| *Lupinus angustifolius* | | | | 97 |
| *Ornithopus sativus* | 72 | 55 | 10 | |
| *Raphanus raphanistrum* | | | 96 | |
| *Raphanus sativa* | 80 | 12 | 0 | |
| *Secale cereale* | 100 | 11 | 0 | 56 |
| *Tritico cereale* | 100 | 32 | 0 | |
| *Triticum aestivum* | 100 | 24 | 70 | |
| *Vicia sativa* | 100 | 40 | 40 | 66 |
| *A. strigosa* + *V. sativa* | 32 | 7 | 0 | |
| Fallow | 100 | 100 | 100 | |

produce high amount of residues with a high C to N ratio (i.e., less rapidly decomposed) are more efficient in suppressing weed emergence.

At farm level, the situation is generally more complex, and mulching alone is often only sufficient to minimize weed competition adequately under certain conditions. Skóra Neto *et al.* (2003), for example, recording all inputs and outputs of farmers in five regions of Paraná over 3 years, verified that zero-till crop production without herbicides was possible and economically feasible, but performances were very variable, the best results being obtained only with a combination of good soil fertility, high-cover crop dry matter production, correct main crop populations, and spacing, good timing, and precise planting, while the major drawback or constraint was the amount of labor required for weed control. Jackson (1997) also adds that it is necessary to have implements that allow the farmers to harvest and plant one crop after another nearly simultaneously, thereby encouraging early establishment and competitively of the following crop, but also stresses that having farm labor available to do spot weeding as a management practice is essential. Kliewer *et al.* (1998) reported farm trials conducted in the Alto Paraná region of Paraguay, which, using suitable cover and main crops in rotations over a 3-year period, managed to completely do away with the need for herbicides. They noted that the traditional double-cropping of wheat and soybeans required 11 herbicide applications for adequate weed control, costing over US$200 per ha. Including cover crops in a 2-year rotation (1st year: sunnhemp–wheat–soybean; 2nd year: white lupine–maize), "rolling" the cover crops with a "knife roller" about 50–60 days after seeding and subsequently seeding into the stubble with a zero-till planter improved the situation. This cropping system only required four herbicide applications to manage weeds, which amounted to a total cost of just over US$180 per ha including the cost of cover crop seed and management. A 3-year crop rotation including three cover crops (1st year: sunflower–black oats–soybean; 2nd year: wheat–soybean; 3rd year: lupine–maize) not only eliminated the need for herbicides altogether but also reduced the total cost of weed management to about US$150 per ha. The main reasons for such decreases of weed infestation over time are reductions in weed seed banks, and Skóra Neto (1998), for example, showed an exponential reduction in weed populations when weeds were controlled before seed-set and not allowed to produce seeds.

In summary, empirical results from farmers and researchers have shown that using adequate integrated strategies and cover crops, successful weed management in zero-till is possible with low levels of inputs. The reality on the ground for farmers in Brazil, however, is often more varied and, as, for example results from Skóra Neto *et al.* (2003) and Ribeiro *et al.* (2005) suggest, the great majority of the farmers, especially smallholders in Southern Brazil, still struggle with weed problems and rely on high-herbicides use or resort to sporadic disc harrowing or even plowing, often not being able to apply the "optimal" recommendations of cover crop and weed control timings proposed by research.

### H. Pests and Disease Management

Increased problems with pest and disease "over wintering" in residues are often cited as a major drawback of zero-till: the residues left on the soil surface directly provide a food source and habitat for insects and pathogens in proximity to current or future crop stands, while the indirect effects of residues on soil moisture or temperature may allow certain pests and pathogens to reproduce and spread for longer (Bianco, 1998; Forcella *et al.*, 1994; Nazareno, 1998). Nevertheless, research on the putative effects of zero-till on plant diseases and pests has been rather limited in Brazil (Freitas *et al.*, 2002). Scopel *et al.* (2004), however, note that disease control is a major weak point in zero-till systems in the cerrado region, while they further contend that fungal diseases in wheat, for example, are commonly viewed as problematic by zero-till farmers in Southern Brazil. Breeding programs established by EMBRAPA are focusing on disease resistance in new soybean, rice, wheat, cotton, and maize cultivars exclusively bred for zero-till conditions, and varieties resistant to some of the major disease and pest problems are becoming increasingly available, although, as Freitas *et al.* (2002) argue, these are often not being used by farmers, as susceptible varieties sometimes have other superior agronomic traits. In this context, however, it is important to bear in mind that a residue mulch not only harbors pests and diseases, but also their natural enemies, and the wisest way to tackle pest problems is arguably to apply integrated pest management techniques, for example, where necessary applying carefully considered amounts of inorganic and organic pesticides, resorting to resistant crop species and cultivars, boosting natural pest–predator populations, where possible adjusting sowing date to avoid early infection, avoiding planting susceptible varieties on compact and consequently potentially improperly drained soils, superficial seeding, treating seeds with fungicides, using crops to attract or repel pests, breaking the surface area of a monocrop through intercropping, and, once again, rotating crop species and integrating cover crop species that may help to break pest and disease cycles and/or act as traps for insects and viral vectors. Santos *et al.* (2000), for example, found that sufficient crop rotation, including vetches, black oats, sorghum, soybean, and maize, was efficient in reducing the incidence of root diseases in zero-till maize in Rio Grande do Sul, while Ribeiro *et al.* (2005) state that among a surveyed group of smallholder farmers in Paraná, those farmers growing tobacco faced the most serious challenges in respect to pests and diseases, and hence were also those that rotated crops most frequently. Yorinori (1996) observed a reduction of *Diaporthe phaseolorum* ssp. *meridionalis* dispersion in soybean by the use of millet as zero-till cover crop, while black oats have been noted to decrease root rot diseases, such as *Fusarium* species, and pigeonpea or sunnhemp have been shown successful in controlling nematodes (Caligari, 1998a,b,c). Viedma (1997) also reported that including vetches mixed with oats into a zero-till rotation relying only on wheat and oats nearly completely eliminated the incidence of *Heliminthrosporium* and *Drechslera* species. Conversely, however, higher incidence of snails and slugs have been noted after crucifers, more thrips after graminae, *Diabrotica* species after hairy vetch (Buntin *et al.*, 1994), caterpillars (*Pseudalentia* spp.) after oats, stemborers (*Listronotus* spp.) after ryegrass (Gassen, 2000), and insects acting as vectors for soybean viruses after a cover crop of *Arachis pintoï* (Scopel *et al.*, 2004), so these crops should be avoided if the associated pest is potentially a threat. A residue mulch may in itself draw insect pests away from growing crops, and Gassen (1999), for example, reported that white grubs (*Cyclocephala flavipennis*), even when present in numbers exceeding 100 larvae $m^{-2}$ did not cause damage to crops as long as sufficient soil cover for them to feed on was present. Freitas *et al.* (2002) also noted that residue mulch decreased the impact of rain drops in dispersing potential pathogen propagules, thereby resulting in less spread of inoculum of, for example, *Diaporthe phaseolorum* ssp. *meridionalis* in the cerrado region. If pests that are restricted in their mobility pose a problem, removing residues from the row and areas of high risk of occurrence may also provide a partial solution.

In summary, although the use of increasingly available crop cultivars resistant to a range of major pests and diseases, as well as astute crop rotation, planting densities, dates and other integrating pest management practices are being used successfully by some farmers in the cerrado and Southern Brazil, pest and disease problems do remain a major challenge in Brazilian zero-till systems and merit further research, both in terms of integrated pest management practices, but also, as Scopel *et al.* (2004) suggest, in terms of the different biocide behavior under zero-till and mulched soils compared to plowed soils.

## I. Integrating Livestock and Crops

Small to medium-scale zero-till systems that integrate livestock, both for milk and meat production, but also as a source of drought power, are common in Southern Brazil and typically include high-yielding forage cover crops, such as black oat, common vetch, and ryegrass in winter, or fodder sorghum and mucuna in summer, while large-scale commercially orientated crop and livestock farms are common in the cerrado. In order to not jeopardize cover crop biomass production, animals on Southern Brazilian smallholder farms are either only permitted onto the fields during strictly controlled periods that allow cover crops to recover and resprout after grazing, or alternatively, the crops are made into hay, silage, or mixed food rations in a cut-and-carry system (Jackson, 1997; Lara Cabezas and Freitas, 2000; cited in Pieri *et al.*, 2002; Ribeiro *et al.*, 2002). Planting contour ridges of vegetative grasses or fodder plants through fields (ideally these should remain vegetative so that they do not set seed in the crop fields), which then serve the dual purpose of providing erosion and runoff control, as well as animal feed, is another common strategy (Darolt, 1998b; Freitas, 2000; Sabourin *et al.*, 2000), and in their proposed steps to facilitate conversion from conventional to zero-till on smallholder farms, IAPAR researchers suggest farmers first initially increase the amount of vegetative grasses grown on contours and set aside land throughout the farm, which would then serve to feed livestock and thereby decrease grazing pressure on residues, subsequently evaluating different spatial arrangements and planting densities over the whole farm before abandoning tillage and moving toward proper zero-tillage. Common contour species in Southern Brazil include elephant, king or cameroon dwarf and giant varieties of napier grass (*P. purpureum*), phalaris (*Phalaris hibrida*), sugarcane (*Sacharum officinarum*), lemon grass (*Cymbopogon citratus*), pigeonpea, or sometimes vetiver grass (*Vetiveria zizanioides*), which is reportedly particularly efficient in erosion control (World Bank, 1990), the type of vegetation chosen by farmers for contouring depending mainly on the number of animals that have to be fed, the labor available to manage it and other agricultural production priorities on the property. For the seasonally dry cerrado region, Séguy *et al.* (1996) suggest planting napier grass, bana grass (a sterile hybrid of napier grass and *P. typhoides*), or *Tripsacum laxum* on contours. If land for cropping is at a premium, intensive fodder banks or gardens on small plots of land either set aside or on marginal parcels and strips that are unsuitable for annual cropping, such as along fence lines or around cattle pens, and so on, are used. Especially in the semiarid northeast of Brazil, such feed gardens or *capineiras* of napier grass, forage cactus (*Opuntia* spp.), or gliricidia (*Gliricidia sepium*) are widespread on smallholder farms (Menezes *et al.*, 2002; Sabourin *et al.*, 2000).

In the seasonally dry cerrado region, ley systems, where forage land is set aside and grazed for 3–4 years, are common. When the unfertilized pasture becomes nitrogen deficient, the land is bought back into legume or fertilized crop production, and a new parcel of land set aside for grazing. *Brachiaria* and *Stylosanthes* species have been shown to be both efficient in recycling nutrients and as good forage species in the cerrado (Scopel *et al.*, 2004). If grown as cover crops toward the end of the rainy season, they can be grazed as soon as at the beginning of the following dry season. Moreover, due to their large biomass production, successions of *Brachiaria* and *Stylosanthes* species with commercial crops offer the possibility building SOM levels and rehabilitating degraded pastures at basically no installation costs (Scopel *et al.*, 2004), while Broch *et al.* (1997) found that such systems can support soybean yield increases over a number of years. Kluthcouski *et al.* (2000) describe the "Santa Fé" cropping system in the cerrado, which mixes a maize crop and a brachiaria pasture. The brachiaria is made to germinate and emerge later than the maize, either by delaying its planting or by planting it deeper. During the whole maize cycle, the brachiaria is shaded by maize plants and remains minimally competitive to the maize, but at maize harvest, the pasture is already in place, and grows very quickly over the maize residues. The brachiaria is then killed with a desiccant herbicide, with rates varying from about 2 liter $ha^{-1}$ of glyphosate on *B. ruziziensis* to over 4 liter $ha^{-1}$ on *B. brizantha*, with *B. decumbens* at an intermediate level, and soybean is planted directly into the dead/dying brachiaria sward, the zero-till planter breaking through the superficial compaction layer (8–10 cm) of the pasture (Landers, 1998). Similar types of systems have been devised in Southern Brazil, including a rotation of ryegrass used as pasture during winter followed by a soybean crop planted directly on the chemically desiccated ryegrass (Scopel *et al.*, 2004). This tight integration between forage and grain crops generally leads to a better use of total farm land and a more intensive use of the pastures, with shorter turnover and less pasture degradation.

### J. Suitable Equipment for Resource-Poor Farmers

As the first Brazilian-built zero-till planters were only commercially available from 1975, many pioneer farmers started zero-till by transforming their conventional equipment, and a great variety of equipment evolved (Derpsch, 2001). Today, however, about 15 companies in Brazil build zero-till equipment (Derpsch, 2001), some of which are now among the world leaders in the production of zero-till equipment. A large variety of equipment for various operations, farm sizes, soils, crops, and levels of mechanization exists. However, while some of the more sophisticated machinery is in principle similar to that produced elsewhere in the world and a detailed description thereof beyond the scope of this chapter, what is perhaps unique in Brazil is the large variety of implements suited for smallholder farmers, designed for light mechanization, animal drawing, or hand operation. Although many Southern Brazilian farmers may purchase expensive equipment in group or associations, subsequently sharing its cost and use (Freitas, 2000), examples of smallholder operations in Southern Brazil demonstrate that zero-till and cover crop management can be practiced by individual farmers at all levels of mechanization and without extensive capital outlays. While much of such equipment is detailed in IAPAR publications (IAPAR, 1981, 1993, 1998), we would like to refer interested readers to Freitas (2000) or Pieri *et al.* (2002), for example, where a variety of relatively low-cost zero- and minimum-till planters, crop rollers, and sprayers are presented in English-language publications, instead restricting our review here to the principles behind animal-drawn or hand-operated zero-till planters and knife-rollers that have been developed in Brazil.

Especially important for Brazilian-type zero-till are implements that allow for timely planting of crop in order to optimize early growth and minimize competition from weeds, as well as maximize the crop's weed-smothering potential at the appropriate time. Probably the best-known and best-proven zero-till implement for smallholder farmers on steep land is the hand-held, V-shaped jab planter, known as "matraca" in Southern Brazil. This simple utensil has now been in use for decades in South America for the manual seeding of large areas (Steiner, 1998), can easily be adapted for various conditions and seed types, and exists in versions that include a fertilizer holder, thereby allowing fertilizer granules to be applied at the time of seeding (Araújo Almeida, 1993). More sophisticated planters include a series of animal-drawn zero-till planters derived from the "Gralha Azul" prototype, originally conceived by IAPAR. Basically, these planters are equipped with weighted discs that cut through trash to open narrow seed furrows, as well as a seeding and fertilizer element and seed and fertilizer containers. The seed is placed behind the discs directly into the furrows, usually together with fertilizer in a way that it does not come into direct contact with the seed, while the soil is subsequently recompacted by the rubber wheels that follow the seeding elements and allow the working depth to be controlled. Drilling or banding the fertilizer close to the seed means that germinating seed can get its radicle to the fertilizer in relatively short time, and in the case of nutrients that are important very early in the crop's life cycle, also means that the crop seed will get a head start over weeds in a low-fertility system. In general, direct subsurface placement of fertilizer also greatly increases fertilizer efficiency and decreases amounts required by avoiding excessive volatization or adsorption of fertilizer nutrients onto soil particles. The "Gralha Azul"-type of planter has proved especially popular in the Southern Brazilian states of Santa Catarina and southern Paraná, where the often hilly topography restricts mechanization, thereby making the use of animal traction and manual labor frequent (FAO/INCRA, 1995). There are now over 10 models of the "Gralha Azul," which differ in their suitability to heavy or light soils, residue amounts, steepness of the topography, and so on (Ribeiro, 1998). Darolt (1998b) suggests that animal traction can be used on land with a slope of up to 30%, while steeper slopes are more suited for planting using a matraca. A similar type of zero-till planter now produced by four manufacturers in Brazil is well suited to stony soils (Ribeiro *et al.*, 2000).

Another implement innovation that has been refined through adaptive experimentation and trialing by Brazilian farmers is the “knife-roller” (“rolo faca” or small Argentine roll) designed to crush or break and roll cover crops. Although a knife roller commonly comprises a cylinder with blades to be drawn by an animal or a small tractor, versions in Brazil range from simple weighted pieces of wood that crush plant stands when towed through them (mainly useful when plant biomass is not very high), to complex cylinder-and-disc systems attached to the front or rear of tractors (Araújo *et al.*, 1993, 1998; Freitas, 2000). Apart from reducing the reliance on herbicides to terminate cover crops, rolling also has the advantage that residues are knocked down in the direction of rolling, thereby facilitating planting, but also, as described previously (Section III.A), that the whole plant remains intact and attached to the soil, thereby preventing dispersal of loose residue by wind and during planting operations, and decreasing residue decomposition rate, consequently extending the effectiveness of the residue cover to suppress weed growth. The timing of the rolling operation is however crucial to its success, as most plant species can regenerate if they are rolled or slashed prematurely, while mature seeds of the cover crop or weeds may set and germinate if elimination is carried out too late (Skóra Neto, 1998; Skóra Neto and Darolt, 1996). Trials to this respect indicate that the best time to roll grasses is at the milky grain phase, while in legumes this is best done at the beginning of pod formation or full flowering, depending on the species (Ashford and Reeves, 2003; Calegari, 1998a).

## IV. CONCLUDING REMARKS

A great wealth of zero-till technologies applicable to a variety of scenarios has accumulated in Brazil, and some of the basic stereotypical zero-till systems of Brazil are presented in Table VI.

Two decades of extensive adaptive research and experimentation with reduced tillage methods has allowed farmers and researchers to mature zero-till into a holistic intertwining of soil and crop management techniques, involving no soil turning, rigorous maintenance of a permanent vegetative cover, and judicious rotations of both cash and cover crops, thereby giving rise to “ideal” zero-till systems suited to a variety of conditions. Brazilian research clearly demonstrates that under the right conditions, it is possible to practice successful zero-till on a variety of soils commonly deemed

**Table VI**
**Stereotypical or "Model" Brazilian Zero-Till Systems (Partially Based on Calegari, 2002; Scopel *et al.*, 2004)**

| Systems | Physical conditions | Basic cropping regimes | Reported advantages | Reported challenges |
|---|---|---|---|---|
| Large-scale farms in the Cerrado (>100 ha) Mechanized grain and livestock production | Seasonally dry, humid tropics; Deep, acidic Oxisols; Flat to undulating topography | During rainy season: soybean, maize, rice, cotton, or beans At end of rains/over dry season: deep-rooted cereals, such as millet, maize, sorghum, often in combination with an undersown, drought tolerant fodder or forage cover crop | | Technical management of certain crops (rice, cotton); Disease control |
| Large-scale farms in Southern Brazil Mechanized grain and livestock production | Humid subtropics; Clayey Oxisols and Alfisols to sandy Ultisols; Undulating topography, sometimes with steep slopes | In spring/summer (main growing season): commercial crops such as maize and soybean In the "safrinha"/winter season: black oats, wheat, ryegrass, common or hairy vetches, oilseed radish, rye, white or blue lupines, grown alone or as mixes | Erosion control; Nutrient recycling; Increase in SOM; Organization of farm activities | Disease control; Negative effects of certain rotations (e.g., allelopathic effects on succeeding crop, and so on) |
| Smallholder farms in Southern Brazil (<50 ha) Low levels of mechanization and external input use, commonly animal traction. Crop and livestock production | | In spring/summer: maize, beans, tobacco, onion, garlic, potatoes, rice, cotton, and soybean In the "safrinha"/winter season: black oats, common or hairy vetches, oilseed radish, rye, white or blue lupines, and ryegrass, grown alone or as mixes. Many fallow fields if they cannot afford cover crop seed, while some grow wheat as cash crop | Labor and external input savings; Erosion control; Increased crop yields | Weed control; timely labor and input management; No markets for diversifying crop rotations; Cover crops seed production or affordability |

unsuitable for zero-till, and that by exploiting rapid successions of suitable summer and winter crop and cover crops, in combination with careful temporal and spatial planning, it is possible to continuously cover soil, gradually build-up SOM, benefit from residual nutrient effects, successfully integrate livestock, move surface-applied lime through the soil profile without plowing, and break up compact soil layers, among other things. Suitable rotations, timing, spacing, and fertility conditions in combination with implements, such as zero-till planters and knife-rollers of various levels of sophistication, have further been shown to allow herbicide and pesticide use to be reduced or even, in the best case scenarios, to be eliminated over a certain timeframe.

However, such systems represent the "ideal," and in order for farmers to effectively reap the full benefits of zero-till, appropriate systems must simultaneously combine and integrate many of the different ideal technologies and components. Rather than resort to the complete combination of all such technologies, most Brazilian farmers on the ground, on the other hand, incorporate the various zero-till components into their practices to a greater or lesser extent according to their socioeconomic, cognitive, and biophysical situation: although farmers practicing ideal or model zero-till systems certainly exist, this is probably not true for the majority of farmers, especially not for the majority of resource-poor smallholder farmers in Southern Brazil, who struggle to afford cover crops seed or herbicides, who resort to periodical plowing to combat mounting weed pressure or incorporate lime, who may not be able to employ the right amount of labor at the right time, or who are simply limited to growing sequences of cash crops rather than optimal rotations of main and cover crops due to economic necessity in the lack of subsidies or other income-generating activities, for example. In this context, we stress that although Brazilian zero-till harbors many useful lessons on how to surmount obstacles commonly associated with zero-till, many challenges to successful zero-till remain.

Additionally, although undoubtedly numerous advances in zero-till research has accrued in Brazilian research over the past 20 years, much of this research has been based on experimental conditions in optimal settings, studying individual technologies rather then more complex whole-farm systems with all the flaws such a setting may bring with it. Consequently, there is somewhat of a divorce between some of the research innovations and results and farmers' reality. Although researching ideal technologies is undoubtedly invaluable in formulating general guidelines for what method induces what effect, future research should perhaps increasingly also consider the effects of less optimal but more realistic intermediate systems that may include periodical plowing or suboptimal rotations when the need arises.

In conclusion, the wealth of high-quality research data and farmers' experience on various Brazilian zero-till techniques precipitating out of the Brazilian zero-till revolution can certainly inspire and afford us potential guidelines along which we can seek solutions and directions for successful zero-till in many other parts of the globe. We must, however, bear in mind the true context of these innovations and technologies in order to realistically assess them in the right light.

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