Weed control in no-till organic soybean in southern Brazil

by

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GENERAL INTRODUCTION

Organic soybean production is a fast growing enterprise in southern Brazil, particularly in the state of Parana, where 854 farmers harvested 48 thousand metric tons in 2002, or 11 times more tons than in 1997. The expansion of organic farming is welcome in the region because it will demand more labor, generate more income, and improve environmental protection. Coordinated efforts to expand organic agriculture have involved farmers and other non-governmental organizations, government-funded extension and research services, and business agents.

Nonetheless, obstacles to the expansion of organic agriculture are multiple, including those in the organizational, market, regulatory, educational, and biological realms. In this dissertation, I address the control of weeds in organic no-till soybean, the most important of the biological challenges. Although the problems and potential solutions discussed in this dissertation may apply to 400 thousand km$^2$ in southern Brazil, I will focus on the state of Parana. This focus derives from my professional link as a researcher at the Instituto Agronomico do Parana (IAPAR), and from the fact that although Parana occupies only 2.3% of the country surface, it produces 24% of the Brazilian grains.

The outstanding position of Parana, within Brazilian agriculture, results from a combination of natural and man-made conditions, which include governmental policies and technology development. Parana was the cradle of no-till systems in Brazil, and is nowadays one of the most important living laboratories that incubate technologies for organic agriculture in the country. This dissertation represents an attempt to add one more brick to the collective construction of organic agriculture.

Improving the efficiency of weed control in no-till organic soybeans is the ultimate objective of all my efforts in this dissertation. My efforts complement efforts by other sectors of society, including governmental and non-governmental organizations, organic soybean traders, and especially farmers and farmers' organizations that have turned organic soybeans into a growing business, and are now tackling the challenge of no-till, pesticide-free soybean production. My focus is the conversion period from conventional to organic management, when the weed problem is most acute, particularly in no-till systems.
In Chapter 1, I will provide a concise, yet comprehensive, picture of the collective construction of organic agriculture. In the attempt to compromise between comprehensiveness and concision, I first describe the natural setting and the historical occupation of Parana as the background for understanding its present agricultural setting. Second, I locate organic soybean production in the context of the farming systems in which it occurs.

In the following three chapters I address weed control problems and potential solutions. Chapter 2 reports an experiment quantifying the suppression of the weed *B. plantaginoides* by black oat mulch. Black oat mulch was capable of reducing weed infestation so strongly, immediately after mulch application, that, from the point of view of yield loss, manual weeding might even become unnecessary. Heavy black oat mulch “switched off” weed germination. This result drew attention to the necessity of improving the management of black oat as a crop, in order to maximize its biomass production for use as mulch. I also measured *B. plantaginoides* seed production, which was sufficient to maintain heavy weed infestation in subsequent crops, even when, due to heavy mulch, the crop yield was little or even not affected at all.

In Chapter 3, I report experiments quantifying weed seed production in other phases of crop rotation, namely in the maize phase and during a summer fallow period. These experiments revealed that some seeds were produced in maize, even when the crop was kept free of weeds during time periods longer than those currently recommended. One single year of summer fallow, dominated by *B. plantaginoides*, was enough for replenishing the soil seedbank to a level that guaranteed important weed infestation for more than a decade.

The results reported in Chapters 2 and 3, complemented by three experiments reported in the appendix and with information from the literature, allowed me to develop a simulation model, which is presented in Chapter 4. With this model, I addressed questions on the control of *B. plantaginoides* that had not yet been empirically answered, and which might require several years of field experimentation. The most striking result of the modeling was that, contrary to the prevailing idea in no-till systems, continuous, heavy mulch may not be the best strategy to reduce the infestation of *B. plantaginoides*. 
On the one hand, I don't have any false modesty: what we are attempting - to bridge the gap between no-till and pesticide-free production - is, nothing more and nothing less, than perhaps the greatest immediate challenge to sustainable grain production nowadays. On the other hand, I don't have false ideas concerning the importance of the findings presented on this dissertation. I have added a few more bricks, hopefully important ones, to the construction of a more sustainable relationship between mankind and the environment.
CHAPTER 1
THE CONTEXT OF ORGANIC SOYBEAN PRODUCTION IN PARANA

Introduction

Organic soybean production is a fast growing enterprise in southern Brazil, particularly in the state of Parana, where 854 farmers harvested 48 thousand metric tons in 2002, or 11 times more tons than in 1997 (DERAL, 2003). The expansion of organic farming is welcome in the region because it will demand more labor, generate more income, and improve environmental protection. Coordinated efforts to expand organic agriculture have involved farmers and other non-governmental organizations, government-funded extension and research services, and business agents. Nonetheless, obstacles to the expansion of organic agriculture are multiple, including those in the organizational, market, regulatory, educational, and biological realms (Khatounian, 2001).

The State of Parana occupies 2.3% of the country surface, but accounts for 24% of the Brazilian grain production (DERAL, 2003). This outstanding position results from a combination of natural and man-made conditions, which include governmental policies and technology development. Parana was the cradle of no-till systems in Brazil, and is nowadays one of the most important living laboratories that incubate technologies for organic agriculture in the country.

In this chapter, I will provide a concise, yet comprehensive, picture of the collective construction of organic agriculture. I first describe the natural setting and the historical settlement of Parana as the background for understanding its present agricultural setting. Second, I locate organic soybean production in the context of the farming systems in which it occurs. In the other three chapters of this dissertation, I address weed control problems and potential solutions.

The natural setting

Parana is located between latitudes 22°29' and 26°42' S, longitude 49°02' and 59°37' W, and occupies 199.7 thousand km². Plateaus ranging from 300 to 1100 m above sea level

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1 Most of this section is based on Maack (1981).
(a.s.l.), in a rolling relief, dominated the state area. Elevations are highest by the coast, and decrease slowly to the north and the west. The rivers start close to the ocean and flow toward the interior to the Parana River Basin.

Rainfall is distributed throughout the year with no pronounced dry season, although precipitation is higher from October to March. The predominant subtropical position of Parana determines a north-south temperature gradient. This gradient is defined by the lower elevations (300-600 m a.s.l.) in the north, and the higher elevation in the south (up to 1100 m a.s.l.). The combination of temperature and rainfall provide a tropical appearance to northern Parana and the low areas in the west, and a subtropical atmosphere to central and southern Parana. The resulting climatic types are classified as Cfa (north and west) and Cfb (center and south), according to Koeppen’s system. The mean annual temperatures range from 20 to 23 °C in most of the Cfa area, and from 16 to 20°C in the Cfb region. Although temperature per se never prevents plant growth in the area, the frequency of frost -- high in Cfb but rare in Cfa -- has been the major determinant of vegetation type.

In 1500, when the Portuguese first arrived in Brazil, 91.3% of Parana was covered with forests and most of the remaining area was formed by high-altitude, natural prairies (Fig. 1) (SEMA, 2003). The two main types of forests closely matched two climatic domains: the subtropical rain forest and the semi-deciduous tropical forest. The subtropical rain forest (Fig. 2) domain expanded over the frost-hit Cfb climate, at elevations above 700 m a.s.l., and covered 49.8% of the state surface and almost all of its central and southern regions. The dominant tree species in the subtropical rain forest were the Brazilian pine (*Araucaria angustifolia* (Bertol.) Kuntze), and the 'mate' tea (*Ilex paraguaiensis* St. Hil.), an under-story associated tree. The massive and solid 20-25 m high stand of this forest was interrupted, in some places, by natural highland prairies (Fig. 3), which were altogether concentrated in four major areas and occupied 8.4% of the state. The prairies, derived from highly weathered, sedimentary rocks, were associated with shallow and acidic soils and high aluminum content.

The semi-deciduous tropical forest (Fig. 4) occupied the warmer areas of the plateau, at altitudes lower than 600m a.s.l. This forest covered 37.6% of the state area and had an even more solid and continuous stand than the *araucaria* forest. The dominant trees *Ficus* spp. ("figueiras") and *Aspidosperma polyneuron* Muell. Arg. ("peroba") reached 35 m in
height. The domain of this forest matched the Cfa climate, where frost was rare. A third type of tropical forest, which covered the steep coastal side of the plateau, will not be discussed in this paper because it did not play an important role in the economy and history of Parana.

Figure 1. Natural vegetation domains in Parana, Brazil, in 1500. Adapted from SEMA (2003).

The three major vegetation types that covered 95.8% of Parana were associated with three major geological features: a basaltic strip, a sandstone zone, and an area dominated by sedimentary rocks. Parana, as most of the Brazilian plateaus, is part of the very old
geological formation from the time when South America was connected to Africa, in the Gondwana continent. Parana forests, however, were more associated with the continental climate than with its geology.

Figure 2. The subtropical rain forest, dominated by *Araucaria angustifolia*

*Left:* pristine araucaria pine stand, in the back. Notice the flat canopy tops, characteristic of this species. In the foreground, woody shrubby fallow in previous forestland.

*Right:* araucaria forest on the slope and prairie on the hilltop, a common view in southern Brazilian highlands.
Geological differences became evident and gained importance only when the natural vegetation was replaced by agriculture. The Amazon Rain Forest, as well as the Atlantic Forest -- where part of the Parana forests lie -- existed in spite of their soil, and acquired their exuberant aspect 4 million years before European expansion to South America occurred. The Atlantic Forest provided the natural backbone from which and on which the Brazilian economy, culture and national life developed (Dean, 1997).

Figure 3. Altitude prairie in Parana.

Left: Notice the dark green expansions of the araucaria forest and the canyon, common features of the Campos Gerais region.

Right: closer view, at the end of the winter. Photo from Tibagi, 1100 m a.s.l.
The economic occupation of southern Brazil

In the search for an independent route to India, the Portuguese navigator Vasco da Gama crossed the Cape of Good Hope in November 1497, and reached Calicut in May of the following year. After his return to Portugal, the Portuguese king D. Manuel endeavored to organize a second expedition and take commercial advantage of the new westerly route. The new expedition with 13 ships and 1200 men left Portugal in early March 1500, and landed on the Brazilian coast in late April.

Although it remains under debate whether the Portuguese reached Brazil intentionally or by chance, there is no doubt that their main target was to seize the spice-trade route leading to India. Only 30 years later Portugal sent an expedition of settlers to Brazil to guarantee Portuguese domain over the area. Portuguese ruling was founded on the production of sugar. The sugar-plantation economy was centered in the Brazilian Northeast, at the northernmost part of the Atlantic Forest. The sugarcane plantations (engenhos) were located

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1 Most of this section is based on the classic study by Padis (1981).
close to the ocean so that sugar export and the import of African slaves, milling equipment, and luxurious items for the landlords could be conducted more efficiently. Although the engenhos were involved in the international sugar market, they were, to a large extent, self-sufficient in terms of their basic needs.

For dynastic reasons, after the death of the king D. Sebastian, the Portuguese crown was transferred to the Spanish King Phillip II, so that from 1580 to 1640 the physical borders of the two Iberian realms in the New World were blurred. In this period, the sugar economy prospered in the Northeast. The economy of the subtropical southern plateau, however, was going through a depression period, which led the inhabitants of Sao Paulo de Piratininga (presently the city of Sao Paulo) to set forth expeditions into the continent (entradas e bandeiras), in search for gold and to enslave Indians. Most of the present Brazilian territory, including what is now Parana, was secured to the Portuguese crown in this period, as the expeditions founded small settlements on their way to the hinterlands.

In the last decade of the 1600s, the colonial economy underwent a drastic change with the discovery of gold mines in the Minas Gérais plateau. The gold-centered economy dominated the colonial life for the next century (Boxer, 1962). Unlike the self-sufficient sugar cane engenhos, the gold economy had to be supplied with goods and services produced elsewhere. The gold economy was concentrated in relatively large cities within a geographically limited area. As a consequence, an internal market developed in the colony, and distant corners of the Portuguese domain were economically linked for the first time.

**Cattle ranching in the high altitude prairie**

Southern Brazil had been of little interest for the Portuguese crown until gold mines were discovered, mainly because the subtropical climate was not adequate for the tropical crops in demand in Europe at the time. In the 1600s, Portuguese incursions in this area aimed at capturing Indian slaves from the Jesuit missions. Thus the loyalty of the regional populations to either the Spanish or the Portuguese crown was dubious.

The demand for beef in the mining region, however, resulted in the organization of a beef supply chain for the Portuguese incursions that originated in the south. The need for beef increased the already high demand for natural pastures for raising cattle, given the fact
that forests dominated the country. The need for natural pastures led to the first concerted occupation of the southern prairies, both the low-altitude prairies in the far south (pampas) and high-altitude prairies in the southern plateaus (campos). The beef produced on these prairies was salted and dried (charque), and carried to the mining cities on mules, along the more than 1500 km of the Real Caminho de Viamão (the Royal Way of Viamão). The charque economy led to the occupation of the largest area of altitude prairie in Paraná (Fig. 1), called Campos Gerais. The ranches on the Campos Gerais prairies consisted of large areas (sesmarias), where cattle were produced under extensive-grazing systems.

Mule trains traveled 30 to 40 km per day, and stopped at night. In the 1700s, these stopping points evolved into villages, where the immediate needs of the merchants (tropeiros) and their animals were satisfied. The villages so formed gave origin to an incipient urban life, small-scale food and feed production, and craftsmanship along the route between the pampas and the mines. Ponta Grossa (Fig. 1), founded in 1704, became the most important town in the Campos Gerais section of the Royal Way of Viamão. In the second half of the century, the gold economy started to vanish, and the charque economy waned.

The “matte” and the araucaria pine forest
After the decline of the charque cycle, the economy in the region now called Paraná remained stagnant for over a century, until a new product gained importance: the matte. Matte, a tea-like drink used by the Indians since pre-European times, is produced from I. paraguaiensis St. Hil., an understory tree of the araucaria forest. The gaucho, a mestizo population that inhabited the pampas in Brazil, Uruguay and Argentina, adopted the matte as a daily beverage. However, the economically viable stands of the matte tree did not occur in Argentina and Uruguay, and the commercial matte supply came mainly from southern Brazil.

During the last three decades of the 1800s, there was a massive immigration of Europeans to Argentina, Uruguay, and southern Brazil, and the newcomers were rapidly incorporated into the gaucho culture, particularly by developing a taste for matte and beef. The rapid population growth increased the demand for matte, and the araucaria forests (Fig. 1) became the focus of this new economic boom, particularly in the proximity of older settlements. The most important production areas were in the present-day states of Paraná
and Santa Catarina, and the most important markets for *matte* were Argentina and Uruguay. At the beginning of the 1910s, 90 *matte*-processing plants were in operation in Parana.

The *matte* economy was different from the extensive cattle ranching economy in several aspects. First, it relied on the forest whereas ranching relied on the prairie. Second, the *matte* economy was dominated by the commercial capital of processing-plant owners, for whom the most important matter was to be able to count on the harvest of *matte* from trees scattered in the forest; neither land nor forest ownership were sought. Small holders, who lived scattered in the forest, harvested the *matte*. Each family grew crops and raised animals for subsistence, and *matte* collection was their main source of income. A third difference between the charque and the *matte* cycle was that only mestizos (*caboclos*) participated in the *charque* cycle, whereas the *matte* economy included the recently immigrated Polish and Ukrainians, and to a lesser extent, Italians and Germans. These immigrants, particularly the Slavic group, recreated, in southern Parana, the communal animal production system (*faxinal*), characterized by large areas where cattle, pigs, and poultry roamed freely (Chang, 1988). The mestizo peasantry absorbed the *faxinal* concept and the Europeans adopted most of the *caboclo*’s crops and cuisine.

The beginning of the First World War coincides with the crisis of the *matte* economy. When the war was over, *matte* extraction recovered, although its prime position in the Parana economy was lost forever. The fingerprints of the *matte* economy, however, have remained, particularly in the patterns of landownership and land use in central and southern Parana.

*The araucaria pine*

Until the outbreak of World War I, and in spite of immense forest reserves in the country, Brazil's largest cities imported considerable amounts of wood, particularly pine, from Europe. The precarious inland infrastructure for the transportation of wood, and the coastal location of the largest urban centers made importation more efficient. The same was true for Buenos Aires and Montevideo, where the De la Plata River made the importation of wood from Europe easier than the cutting and transporting of wood from inland forests.

Nonetheless, the same war that impaired the *matte* economy also triggered the lumber cycle. The transportation and supply systems that were developed during the *matte* cycle
enabled the extraction of *araucaria* pine for lumber. The commercial exploitation of *araucaria* was not, however, a totally new economic activity in the region: it had existed since the 1870s, when the Curitiba-Paranagua railroad was completed (Fig. 1). From background scenario for the *mate* economy, the *araucaria* forest became the focal point of a flourishing lumber industry, the most important economic activity in Parana from around 1915 to 1940.

Brazilian legislation did not allow logging on public land, so loggers had to purchase land or sign contracts with landowners. After log extraction, the cleared land was either converted into pasture or sold to peasant families, most often the offspring of former *mate* collectors. This process continued as long as there were natural stands of araucaria to be logged. Logging ceased in the 1970s, with the complete depletion of the natural resource. But in the 1940s, before the araucaria cycle was over, another economic cycle was emerging in the northern Parana: the coffee cycle. At the same time, a new wave of settlers reached the southwestern part of the state. Both led to the development of economies, in many aspects different from the preceding cattle, matte and lumber cycles.

The cattle, the *mate*, and the lumber cycles were based on resource extraction, and were made possible only because Parana had large reserves of natural resources and a relatively scarce population by that time. In the first decades of the 1900s, Parana became the agricultural frontier of the growing industrial economy based in Sao Paulo, as well as a source of naturally occurring products, particularly lumber. Padis’s (1981) thesis is that the twentieth century dynamics of Parana’s economy is closely linked with the industrialization process in Sao Paulo. The economic cycles based on resource extraction created neither the foundation for a sustained regional development nor a generalized prosperity. These cycles were rather reactions to external forces, and they collapsed when those forces disappeared or when the natural resources were depleted. Furthermore, the emergence of a new cycle did not cause the disappearance of the preceding one. However, the new cycle brought about the loss of importance of the previously dominant product as well as the economic depression of the people and the regions associated with that product.
Southwestern Parana

Although incorporated into the general history of the occupation of the *araucaria* forest, the development of the extreme southwest of Parana was unique in several aspects. Being one of the remotest areas under this forest, loggers reached it only in the 1950s. By that time, the population wave of smallholders coming from European settlements in the states of Rio Grande do Sul and Santa Catarina reached the area from the south. This wave consisted mainly of third and fourth generations of German and Italian settlers, in search of new land to cultivate.

Although most settlers in the cleared pine forest came from the *matte*-centered production systems, the settlers from Rio Grande do Sul and Santa Catarina were mainly producers of grain, pork, and dairy products. In southwestern Parana, these farmers recreated a locally centered economy based on small farms (typically with 5 to 25 ha) with important home and local consumption sectors and well-developed commercial sectors. In these small-farm production systems, cash activities aimed mostly at supplying the Brazilian domestic food market with bean, maize, and pork. The stark smallholder taint of the land tenure pattern led to the development of a locally focused craft sector that included blacksmith shops, and furniture and cutlery factories.

Although founded mostly on modest individual wealth, the regional economy described above became more prosperous than the economies in most other parts of the former pine forest. A key factor for this prosperity was the geology in the region. Most soils in southwestern Parana derive from plant-nutrient-rich basaltic rocks whereas most of the *araucaria* forest grew on soils derived from highly weathered sedimentary rocks. The emergence and flourishing of farmer defense organizations is also claimed as an important reason for this prosperity. In the mid-1950s, misleading contracts written by land retailing companies led affected small farmers to an armed rebellion centered in Francisco Beltrao (Fig.1). The rebellion was finally settled to the benefit of smallholders and is considered the birth of the strong tradition of farmers’ defense association in the region.

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3 In addition to the book by Padis (1981), which supports the entire historical background, the section on southwestern Parana also draws on the publication by Khatounian and Gehlen (1996).
Coffee and the tropical forest

As pine forests were being felled in the higher and cooler plateaus in central and southern Parana, a higher value enterprise was developing in the warmer north: coffee. In the early 1900s, the westward expansion of coffee from the state of Sao Paulo, crossed the Paranapanema River and occupied the fertile basaltic soils of northern Parana, which was then covered with a dense tropical forest. In the first decades of the 1900s, coffee expanded to the east margin of the Tibagi River. In 1935, the railroad bridge over the Tibagi River was inaugurated and launched the fast expansion west of the Tibagi, as coffee could finally be taken easily to Sao Paulo. In the same year, the railroad reached the city of Londrina (Fig. 1), founded in 1934, which eventually became the capital of the coffee economy. Twenty years later, the entire northern region of Parana was connected with the coffee-exporting port of Santos by railroads. Coffee production boomed after the end of World War II and peaked in 1961-62, when 28% of the world coffee production was harvested in northern Parana. In those years, 1.6 million hectares were planted with coffee, or 21% of the area originally covered with the tropical forest.

In addition to occupying a tropical area, the coffee economy differed from the preceding cycles in that it did not rely on the extraction of a naturally occurring product to satisfy national demands, but on cultivation of a crop primarily for the international market. Because coffee was a valuable product, small pieces of land between 10 and 30 ha were enough for a relatively prosperous existence of farmers. A British-controlled colonization company (Companhia de Melhoramentos do Norte do Parana) bought large tracts of land, which were cut into small plots, and the plots eventually were sold to settlers. These settlers were most often former laborers in coffee plantations in the state of Sao Paulo, of Italian, Japanese, or Brazilian ancestry. Eventually, the booming coffee economy attracted people from all corners in Brazil as well a sizeable German and Middle-Eastern contingent. Compared with other regions and economic cycles in Parana, the coffee economy was more cosmopolitan, more affluent, and economically more democratic. The wealth of this area supported a dense urban network, and infrastructure for services and supplies developed. In addition, the region provided a larger tax base upon which the state government drew resources to leverage poorer regions in the state.
By the 1970s, nearly all of the tropical forest in the region, 7.5 million ha, had been replaced with agricultural landscapes dominated by coffee. The region was a mosaic of smallholdings, interspersed with small towns and middle-size cities, under the umbrella of an entrepreneurial and market-oriented mentality.

The decline of the coffee cycle started soon after its peak in 1961-62, due to overproduction, and was accelerated by unfavorable climatic conditions. Although mainly tropical, northern Parana is subjected to occasional frosts whose intensity is associated with topography, latitude, altitude, and long-term climatic cycles. During the coffee-expansion stage, plantations were installed in frost-prone sites and regions, and frost damage was frequent. Aware of the economic and climatic vulnerability of the coffee economy, leaders of northern Parana endeavored to create an agricultural research organization to develop technologies and strengthen the regional economy against climatic and market uncertainties. These efforts resulted in obtaining the necessary federal and state funding to establish the Instituto Agronomico do Parana – IAPAR (Agronomic Institute of Parana), in Londrina, in 1972.

Despite all efforts, the coffee cycle was condemned to end. The final coup occurred in July 1975, when a severe cold spell spread unusually-intense frosts all over southern and southeastern Brazil. The empire of coffee, which once formed a solid and almost uninterrupted stand over 230 km along the main northern Parana road, from Cornelio Procopio to Umuarama, was over. A couple of weeks after the frosts, the solid stands of frost-burned coffee bushes were uprooted like weeds and their dense stems were used as fuel for furnaces of factories of bricks and roof tiles. The green gold, as coffee was called in earlier times, vanished into black smoke. From that time on, coffee retreated to those areas with the lowest risk of frost. The vacuum left by the coffee plantations in most of northern Parana was the fertile terrain for the subsequent expansion of soybean.

The soybean-centered annual-crop economy
Grain production has always been part of the rural economy in Parana. During the charque cycle, maize was produced, and part of it was sold at the overnight stops for the mule trains. During the matte period, maize and bean were the most important subsistence crops for the
families scattered in the *araucaria* forests. After logging the forest, maize and bean were the most important crops for the newly settled smallholders. Even in the international-market-oriented coffee plantations, the inter-rows of coffee were devoted to mainly maize, bean, and rice as annual crops.

After the end of World War II, the industrial boom in Sao Paulo demanded increased amounts of grains, both for human consumption and for pork and poultry production. An increasing proportion of the grain came from the newly-deforested araucaria and tropical forest regions in Parana. However, the grain economy was not the economic focus of Parana until the 1980s, when the state became the leading grain producer in Brazil, a position still held today. Parana occupies 2.3% of the surface of Brazil and, in 2002 it produced 24% of the national total of grains (DERAL, 2003).

The turning point of the Parana economy was the frost of 1975, the last shovel of earth on the hopes for the coffee economy. At that time, soybean, which was already being produced in Parana, became the natural substitute for coffee due to international demand and the soybean-supportive federal policies. In 1974, the federal government founded the Centro Nacional de Pesquisa de Soja (National Soybean Research Center) as part of EMBRAPA*, also in Londrina.

Supported by federal agricultural policies, the available technology, demands by the international market, and the available land, soybean production expanded rapidly, beyond former coffee plantations. Whereas the previous economic cycles required either the more tropical Cfa climate, or the cooler more subtropical Cfb, soybean could be produced in both environments. The impact of soybean on the regional economies, however, depended on the previous dominant activities in each region. In large parts of central, southern, and western Parana, the aftermath of the logging of araucaria forests was weak economies that benefited from the introduction of soybean. The same revitalization process occurred in the natural prairies previously devoted to extensive cattle ranching, where conversion into soybean plantations represented a tremendous economic intensification.

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*EMBRAPA is the acronym for Empresa Brasileira de Pesquisa Agropecuaria (Brazilian Corporation for Agricultural Research), the national organization for agricultural research.*
Nonetheless, profitable soybean production required machinery, and the possession of machinery implied economics of scale. This new situation was considerably different from the coffee plantations in the north and the smallholder, hilly, maize and bean plantations in central and southern Parana, which were farmed mainly with the use of manual tools. Consequently, the expansion of soybean over former coffee land brought about an increase in farm size. The same happened in non-coffee areas, provided the relief was suitable for mechanization.

The consequences of soybean expansion are multifaceted. Contrary to the fast population growth in Parana since the early 1900s, mainly due to immigration, the 1980 census showed the same population as in 1970. Considering the birth rate, the absence of population growth indicated that from 1 to 1.5 million people left Parana between 1970 and 1980. Most of these migrants were originally from the previously labor-intensive coffee regions (Fuentes Llanillo, 1984). Beyond the burning of the coffee stems themselves, the brick-and-roof tile furnaces may have burned the hopes of many of these people, who eventually migrated mostly to the industrial areas in Sao Paulo, or to the then-opening agricultural frontiers in central and western Brazil.

Perhaps the most important positive aspect of the expansion of soybean in Parana was that, for the first time in history, all regions in the state could benefit from the same physical, technological and service infrastructures provided by governmental and private organizations. Soybean research and extension, silos, processing plants, transportation and port facilities, all served the economies of all corners in the state, although not at the same intensity. Furthermore, soybean mechanization resulted in the mechanization of other grain crops, particularly maize and wheat.

The soybean cycle also incited the development of cooperatives. Although farmers' cooperatives existed before the expansion of soybean and the official rural extension efforts in this direction, a rapid increase in number and size of agricultural cooperatives followed soybean expansion. The dependable market of soybean lent economic support for the cooperatives.

In the technological realm, the most outstanding advancement of the grain-based economy was the development of no-till systems. These systems were developed
collaboratively by governmental research organizations (particularly EMBRAPA and IAPAR), cooperatives and industry. The first no-till trials were conducted in the early 1970s, when most of the grain crop area was tilled. No-till production evolved and expanded, and occupied 5 million ha in 2001, or over 90% of the total grain-crop area and almost all of the areas under soybean, maize and wheat (Federacao Brasileira de Plantio Direto na Palha, 2004).

Since the early 1990s, a concentrated research effort at IAPAR has sought to develop no-till equipment for draft animals, aimed at farmers whose spare financial resources and hilly fields do not allow for tractor-based no-till. The equipments developed at IAPAR are produced commercially by regional metal-working industries. The area under draft-animal no-till was 90 thousand ha in 2001 (Federacao Brasileira de Plantio Direto na Palha, 2004), mostly devoted to maize and bean. Compared with conventional tillage, the most important advantages associated with draft-animal no-till at the small farms level are reduced risk of crop failure, increased crop yield, and reduced labor requirements for weed control (Ribeiro and Miranda, 2000).^5^ 

Simultaneous with the expansion of no-till, there has been an ever-increasing dissemination of contract-planting and contract-harvesting, both of which dissociate land ownership from the ownership of machinery. Because most farms in Parana are small -- in 1996, 86% of them were smaller than 50 ha (DERAL, 2003) -- and also because machinery quality is improving rapidly, farmers cannot keep pace with the new technology by owning planters and harvesters themselves. Therefore, a contract-planting and harvesting services sector has emerged, effectively dissociating the ownership of land from that of machinery (Laurenti, 1996). This new scenario of agricultural technology development and equipment ownership in Parana has created new opportunities as well as new constraints. The scenario has also led to the inclusion of the ‘equipment ownership’ and ‘equipment contracting’ criteria in the farm typology of the state. In Parana, a farm-typology was developed and is constantly adapted by joint efforts of governmental research and extension organizations; the typology is also the basis for the development of technology, funding, and policies.

^5^ An illustrated report on this technological innovation was organized by Raunet (2003), under the auspices of the Centre de Coopération Internationale en Recherche Agronomique pour le Développement - CIRAD.
Sharing resources has increased overall return from investments, including in technology, and contributed to bring Parana to a position of leadership in soybean production, processing, and export in the 1980s and 1990s. Leadership in production was lost, however, in 2002, to the state of Mato Grosso, in the Cerrado region. Although the advantage of Mato Grosso is still small and restricted to soybean, it is expected to increase.

Soybean production in central Brazil is the greatest challenge to soybean production in Parana. In spite of recent trends in land concentration in Parana, most soybean producers are relatively small; in 1996, the average total area of soybean farms was 32.4 ha (DERAL, 2003). In contrast, typical soybean farms in central Brazil have several hundred to thousands of hectares. Besides, an estimated 90 million ha are still available for agricultural expansion in the Cerrado region. This is twice the total area presently devoted to annual crops in Brazil. Because economies of scale in soybean production in the Cerrado are likely to increase, prospects for continued small-scale soybean production in Parana are not auspicious.

Nonetheless, the highly favorable climate in Parana, which allows two crops per year without irrigation, and the soils, which are more fertile than those in the Cerrado, may allow Parana to remain as the leader in total grain production. Parana leadership in soybean production, however, is most likely lost forever. The fundamental question for economic, political, and technological agents in Parana State today is to what extent -- if at all -- leadership in total grain production should be pursued.

Urbanization, industrialization, and agricultural differentiation

In the early 1950s, the population in Parana was predominantly rural and engaged mostly in agriculture or extractive activities. Industrial activities were restricted to the immediate processing of primary products, such as matte processing plants, sawmills, slaughterhouses, grain and coffee mills, and small metal-working industries. This situation began to change in the 1970s, as a consequence of the expansion of Sao Paulo's industrial economy, and was intensified in the 1990s, when Parana enacted policies to attract industries. In 2001, industrial products accounted for 56% of Parana's exports.

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6 This section drew mainly on IPARDES (1993), a comprehensive diagnostic of the current social and economic situation in Parana State.
The collapse of the labor-intensive coffee economy and the expansion of fully mechanized soybean-based farming systems, coupled with overall industrialization, contributed to the fact that over 80% of the population lives in urban areas, according to the 2000 population census. In 2001, 24% of the working population was in agriculture, and the remainder mainly in urban-based activities. Although urbanization occurred all over the state, industrialization conveyed human and economic resources to three main regions, particularly the metropolitan area of the capital city, Curitiba, which accounted for 64.5% of the aggregate taxable value. The two other regions are the Londrina - Maringa, and Cascavel - Toledo corridors (Fig. 1).

The impact of these transformations on the rural economy and rural life was enormous. On the one hand, grain production increased from 13 million tons in 1990 to 22 million tons in 2002, on the same area. However, although this gain was achieved with contributions from all corners of the state, inter-regional differentiation accounted for most of the success, particularly from the basaltic area, which is a 120-km-wide strip from the northwest to southwest. In addition, intra-regional differentiation allowed larger farmers to benefit more than small ones.

Besides declining in numbers, the rural population is also aging, and an increasingly larger share of their income comes from non-agricultural activities, being associated with tourism and leisure, manufacturing, and services. The dwindling labor market in agriculture and the concentration of population in nearby towns has also resulted in urban-based jobs being taken by people who live in the countryside. For most of these people, the countryside represents a more economical, residential alternative, because part of the family may remain linked to agricultural activities (Del Grossi and Silva, 2002).

Compared with 30 years ago, the generalization of urban lifestyles and the concentration of the population in three major regions, as well as the generalized improvement in transportation infrastructure and services, has created a new and readily available market for agricultural products. Among these products, the most notable ones are vegetables, fruits, dairy products, ornamental plants, free-range chickens and eggs, brown sugar, honey, and home-style preserves. Between 1990 and 2002, the gross value of
vegetable and fruit production increased 150%. There is also a growing local demand for organic and traditional food products such as brown sugar bricks, salamis, cheese, etc.

None of the products above, alone or as a whole, are demanded in high enough quantities to provide economic opportunities for all 370 thousand farmers in Parana. These products represent, however, market niches that are not being adequately supplied and may be an alternative for a number of farm families. Indeed, the most negative side of the agricultural success in Parana was that it maintained and, in certain areas, exacerbated the marginalization of poor family farms. Although Parana is the sixth richest state in Brazil in terms of gross product, 71% of its rural population lives in municipalities where the Human Development Index (HDI) is below the Brazilian average.

The present agricultural setting

The process leading to the present agricultural setting in Parana was briefly described with regard to its geographic characteristics and historical background in the preceding sections. In this section, I focus on the current agricultural setting.

My first consideration is that the climate in Parana is extremely favorable to agricultural production. The annual average rainfall in most of the state ranges from 1400 mm in the northern border, to 2000 mm in the southern border, and it is distributed throughout the year. The annual mean temperature in most of the state ranges from 16°C to 23°C, and although frost is frequent in some higher altitudes and latitudes, the soil never freezes (IAPAR, 2000). For these reasons, the climate is amenable to crop production the year round, without irrigation, and two or more crops may be harvested every year in most of the state.

Nonetheless, climate determines the best crop options for each region and time, even though the optimum planting times typically stretch over four to eight weeks for most crops. In addition to this flexibility, farmers usually extend planting time beyond the optimum range as regards climate in order to achieve the best crop combinations and land use. As an example, commercial maize crops are planted from early September to late March in northern Parana, so that the same crop may be emerging in a field and being harvested in a neighboring field on the same date. Both the possibility of growing crops throughout the year
and the flexibility in planting dates allow for crop sequences and rotations that are much more diverse and complex than those observed under more rigid climates.

My second consideration is that Parana was also blessed with fertile red soils (*terras roxas*) derived from basaltic rocks, which cover approximately 40% of the state and account for most of the grain production. The remaining 60% of the state's area is dominated by chemically poor soils, which are, nonetheless, amenable to high grain yields with liming and nutrient supplementation. The limits to using these low fertility soils are, therefore, primarily in the economic realm. To a considerable extent, the outstanding position of Parana within Brazilian agriculture is due to the conjunction of favorable climate, naturally fertile or amenable soils, and the historically determined predominance of family farms. In 2002, Parana was the leading state in the production of maize, bean, wheat, and chicken, and second in the production of soybean, pork, sugarcane (alcohol and sugar), cassava, and barley. Other important products were coffee, milk, beef, tobacco, wood, vegetables, and fruits.

Parana's agriculture can be further understood by analyzing DERAL (2003) figures. In 1996, farmland covered 159 thousand km², 80% of the state area, and was occupied by 1.8 million people. Temporary crops accounted for 5.5 million ha, pastures for 6.7 million ha, and the remainder 3.7 million were devoted to other uses, including roads, buildings, water bodies, and forest reserves. In 2002, the total grain production was 22.4 million Mt, out of which 87% were maize and soybean; the 13% remainder included wheat, bean, rice, and barley among others. Grain-fed animal production was 1.4 million Mt of chicken and 0.3 million Mt of pork, and pasture-based herds comprised 10 million heads beef cattle and 2 million of milk cows. The total agricultural product output was US$ 6.35 billion: 50% from grains, 35% from animal products, 8.3% from wood products, 2.7% from vegetables, and 5% from other products.

Aggregated figures for agricultural land, population, production, and value accrued, resulted from a total of 370,000 considerably diversified farms. Eighty-six percent of the farms were smaller than 50 ha and occupied 28% of the land, and the 7% of farms larger than 100 ha accounted for 61% of the land. Production and income were concentrated in the 26% most affluent farmers, located predominantly on fertile red soils. The poorest 50% are family
farmers on hilly, low-fertility soils. These poor farmers are not only poor, but also live in poor municipalities: 71% of the rural population is in municipalities whose Human Development Indexes are below national averages (IPARDES, 2003).

For poor families engaged in multiple-income activities, so-called pluri-activity farms in the Brazilian rural sociology literature, farming is not a romantic way of life, but a need for survival (Del Grossi, 2002). “The greatest challenge is how to change a pattern of development that has been efficient in increasing production, but that has been equally unable to rescue the majority of the rural population from poverty...” (IPARDES, 2003). This challenge becomes still more difficult to overcome in light of the increasing competition for marketing agricultural products, both from abroad and from other regions within Brazil. At present, it does not seem realistic to expect that a solution for the challenges these poor farmers face will come from changes in the realm of commodity markets. Solutions seem more likely in the realm of pluri-activity. In fact, even the relatively well-off farmers on the most fertile soils and an all-forgiving climate, cannot count on a successful future as long as they persist in the commodity economy.

Rural families are reacting to the above situation differently, according to their perceptions of alternative livelihoods. The most obvious way out, but also the most uncertain, is to abandon rural Parana and either resettle as farmers in the agricultural frontier, or move to a urban area. The first choice requires investments and therefore it is not appropriate for the poorest farmers. These farmers normally become laborers within Parana or in the neighboring states of Sao Paulo or Santa Catarina.

The second alternative is to remain in place and engage in pluri-activity systems, balancing low-income agricultural activities with other sources of income (Del Grossi and Silva, 2002). The third alternative, which does not exclude the second one, is to convert the system into more profitable enterprises, such as the vegetables, fruits, farm-based dairy, and free-range chickens, which are usually associated with processing and direct marketing. Although field observations show that all these activities are increasing, reliable statistics are available only for vegetables and fruits, which together increased from 2% to 5% of the gross agricultural product in Parana between 1990 and 2002. An additional step for more profitable enterprises is the conversion to organic agriculture.
Organic agriculture in Parana

Compared with other livelihood strategies under the unfavorable macro-economic environment in rural Parana, organic agriculture has two important advantages. First, instead of changing to new products with which farmers might not be familiar, farmers can benefit from the knowledge they have and only change the way activities are conducted. The second advantage is that farmers do not need to engage personally in marketing, as long the organic premiums remain high. It seems that these are probably the main reasons for the rapid expansion of organic agriculture in the state (Fig. 5).

In addition to farmers' reasons to engage in organic agriculture, two macroeconomic factors support its expansion: the existence of 320 thousand small-scale, diversified farms, that are amenable to organic production, and the comprehensive infrastructure of transportation. And last, but certainly not least, there is considerable social capital among the smallholders' organizations created over the last 40 years. In fact, the first pole from which organic production radiated in Parana was exactly the region with the highest social capital in smallholders' organizations, i.e., the southwestern region of the state.

The development of organic production has benefited from a fluid relationship between non-governmental and governmental organizations. In the 1970s, both the extension and research services were mainly oriented towards the use of industrial inputs. However, the economic hardship of the entire Brazilian economy from the 1980s onwards, led to a search for low-input techniques. This atmosphere contributed to the insertion of organic techniques into the extension and research agendas. At the same time, farmers' organizations and related non-governmental initiatives started demanding technologies that emphasized the concern for desirable social and environmental impacts of changes.

This flexible and adaptable fluid relationship between governmental and non-governmental organizations in organic agriculture was founded on a group of mostly young professionals from across these organizations who shared a core of social and environmental concerns. The philosophical affinity among these professionals buffered the usual clash between the rather conservative bent of governmental organizations and the transformative impetus of the social and environmental organizations.
Figure 5. Evolution of total production and number of farmers in organic agriculture in Parana. Adapted from DERAL (2003)

The expansion of organic agriculture was also due to the lack of importance of chemical inputs in many of the smallholdings. Many of these farmers did not use, or used insignificant amounts of chemicals, simply because they could not afford them. There were other farmers who, although less numerous, had never used chemicals because of health concerns. This group has increased with the intensification of information on pesticide
intoxications, broadcasted since the 1990s. The expansion of organic agriculture was also facilitated by the relatively fresh memories of high yields without chemicals after forest clearing, which in most of the state occurred only a couple decades ago (Fig. 6).

Figure 6. Deforestation in Parana from 1895 to 1995. The dotted uppermost line represents the total state area. Adapted from IAP (2000).

On the basis of these memories, most people identify organic farming with the technologies used in the 1950s and 1960s. In fact, the most dynamic sectors of the agricultural economy in Parana at that time were pesticide-free, but relied on the rapid consumption of the fertility accumulated in the forest ecosystem over millennia. In the areas with fragile geological bases, such as the sandy northwestern region, the degradation from exuberant forest to low quality pasture occurred in less than 30 years. In areas with more resilient red soils, the decline was slower and is still under way. To bridge the cognitive gap between pesticide-free but fertility-consuming farming and pesticide-free and fertility-
building land management is presently the greatest challenge to sustainable production in the area (Khatounian, 2001).

Although I have so far concentrated on the agricultural aspects of organic farming, the major force that triggered its development was essentially urban: consumer demand for pesticide-free food. It took a long time for farmers to perceive this tendency as actual demand, and some still have not. Once the demand was recognized, the second step was to bridge the gap between production, which is dispersed throughout the countryside, and demand, concentrated in urban markets. Two main strategies have been adopted: the direct or semi-direct commercialization in farmers’ markets, mainly for fresh produce in major cities, and the aggregation of production by wholesale dealers.

The largest initiative in farmers’ markets is that of AOPA (Associacao de Agricultura Organica do Parana), in Curitiba. AOPA works mainly with fresh produce and counted over 300 farmers in 2003. Marketing of organic soybean started after the pioneer work of Terra Preservada, the first soybean wholesale dealer founded in 1993, when 410 Mt of soybean were bought from 87 producers. By the end of 2002, there were five wholesale dealers competing for organic soybean in Parana, and 854 farmers who produced 16,282 Mt (DERAL, 2003).

Organic soybean production in Parana

Organic soybean production was instrumental in giving social visibility to organic agriculture. The agribusiness community either was ignorant of the organic option, or, at best, viewed it derogatorily as “backyard” production. This growing social visibility contributed not only to expanding the market for organic products but also drew the attention of governmental agencies and the business community to organic agriculture. In addition, organic soybean production had immediate repercussions in the production of other grains such as maize, wheat and bean, included in the crop rotation.

Characterization of the agricultural systems with organic soybean

A considerable diversity exists among the agricultural systems in which organic soybean is produced. Much of the diversity is associated with the history of the regional economic
occupation, the natural resource endowment, and the social capital accumulated in the area. As a first approach, the systems may be grouped in macro geographic regions, as depicted in Figure 7. The immediate criterion for this grouping was geographic location, but as geographic location in Parana is associated with historical, ethnic, and land-tenure factors, these factors were also factored in the grouping.

Figure 7. Number of organic soybean farmers per agricultural macro-region in Parana, as of the 2001-2002 season. For the sake of visual quality, the number was omitted for regions with less than 20 farmers.
Table 1. Organic soybean production macro regions in Parana: number of farmers, area, production, mean grain yield, and mean area per-farm, 2001-2002 season.
Adapted from DERAL (2003).

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of farmers</th>
<th>Area in the region (ha)</th>
<th>Production in the region (Mt)</th>
<th>Mean grain yield (Mt/ha)</th>
<th>Mean area per farm (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-south</td>
<td>444</td>
<td>4877</td>
<td>2490</td>
<td>1.96</td>
<td>5.6</td>
</tr>
<tr>
<td>West</td>
<td>188</td>
<td>5486</td>
<td>2736</td>
<td>2.01</td>
<td>14.6</td>
</tr>
<tr>
<td>Southwest</td>
<td>166</td>
<td>4931</td>
<td>1964</td>
<td>2.51</td>
<td>11.8</td>
</tr>
<tr>
<td>North</td>
<td>56</td>
<td>988</td>
<td>411</td>
<td>2.40</td>
<td>7.3</td>
</tr>
<tr>
<td>Entire state</td>
<td>854</td>
<td>16282</td>
<td>7601</td>
<td>2.14</td>
<td>8.9</td>
</tr>
</tbody>
</table>

**Organic soybean macro-regions**

The central-southern region (Fig. 7) accounted for 444 out of 854 organic soybean producers in the state and for almost a third of the crop area and production (Table 1). The mean soybean area per farm was 5.6 ha, the smallest among Parana organic soybean regions. The modal area is considerably lower because the average includes a few large farms as well as a many smallholdings. The large farms date from the charque cycle, in the 1700s, whereas the small farms stem mostly from the matte cycle. The soils are acidic and chemically poor, and the relief varies from flat to hilly. Smallholdings are usually in the hilliest areas, most of which were formerly covered with the araucaria pine forest (Fig. 1). Large farms are mostly on flat or rolling relief. The average organic soybean yield, 1.96 Mt/ha, is the lowest in the Parana, due to weeds and to unfavorable chemical characteristics of the soil. To some extent, the low yield is also due to the novelty of soybean for most small holders, for whom the traditional cash crops were maize and bean.

Western Parana (Fig. 7) ranked second in number of farmers, area, and production in 2002. The mean crop size was 14.6 ha and the mean yield 2.01 Mt/ha. Western Parana was the region where the migration waves from the south and the expansion of coffee met, in the 1960s. The region contained the last pieces of araucaria forest to be cut down, and part of the
region was also covered with the semi-deciduous tropical forest. The fertile red soils derived from basalt predominate and the relief is rolling. Large farmers are rare. The mean area with organic soybeans is 14.6 ha, and is likely to reflect the modal crop size. The yield of 2.01 Mt/ha, however, is low, considering that the regional average for conventional soybean is approximately 3 Mt/ha. The difference may be associated with the fact that most organic producers in the area are newcomers in organics, and even more important, they are being resettled from areas affected by the construction of dams. Resettlement per se poses several problems, which disturb the concentration of efforts on production. Weed control is the major biological problem.

Southwestern Parana, the pioneer in organic soybean production, harvested the first certified organic soybeans in 1993. In 2002, 166 farmers harvested organic soybean in this region, with an average yield of 2.51 Mt/ha and 11.8 ha of organic soybean per farm. Organic soybean in this region originated from the long-term work of ASSESAR, a regional farmer-managed, non-governmental organization, which conducts projects on rural education, agroecology, and political empowerment in rural communities. From these communities, organic production spread rapidly soon after the wholesale company Terra Preservada started its operation in the region. Attracted by the boom of organic soybean, particularly in the municipalities of Planalto and Capanema, other dealers soon arrived in the region. For the first time, small farmers in the region felt in possession of a product over which dealers were fighting among themselves, a situation that farmers took advantage of. The social capital accumulated in this area also resulted in several brown sugar projects and some pork projects as well, typically by groups of ten farmers (Khatounian and Gehlen, 1996). To enhance sales, these groups operate one regional and several municipal wholesale centers, with connections to major markets in Brazil. Most systems that produce organic soybean in this region previously grew bean as their main cash crop and an important food product in the Brazilian domestic market. The higher stability of soybean yield and price, compared with those of bean, improved farmers' economy.

Organic soybean production in the northern region counted 58 farmers and 988 ha in the 2001-2002 season, but yield was 2.4 t/ha, close to that of the pioneering southwest. Soils are fertile, and the main bottleneck in organic soybean production is the control of weeds.
Incidence of stinkbugs is usually more pronounced than in the other regions (Hoffman-Campo et al., 2000). Most farms are smallholdings stemming from the coffee cycle, which engaged in organic production in an attempt to increase farm income. Some farms produced conventional soybean before converting into organic management, whereas others introduced soybean only recently. This region still lacks facilities to receive, dry, clean, and sort and pack organic grains, probably because organic soybean production is new in this region. Thus, most of the regional production is presently shipped to facilities in Ponta Grossa.

**Socio-economic farm types in organic soybean**

The criteria currently used for the socio-economic characterization of farm systems in Parana (Doretto et al., 2001) include labor source, gross product value, total area, and use of contracted operations. The term family farm is used for farms where no labor is hired, which accounted for 66% of the farms. When hired labor represented less than 50% of the total labor used, the farm was classified as employer-family farm (*familiar empregador*), which accounted for 24% of the farms in 1995. Non-family farms were those where more than 50% of the labor force was hired, which represented 10% of farms in 1995. On the basis of the gross product value threshold of R$ 27,500, used by the federal government as the upper limit for family-farm loans, 98% of family farms and 87% of the employer-family farms would qualify for loans (Doretto et al., 2001). These data imply that farmers in these categories were predominantly low-income.

Specific statistics for organic soybean growers are not available. Our observations indicate that the majority of these farmers are in the employer family-farm group. The data on mean yield and mean acreage (Table 1), combined with average soybean prices, place these farmers below the federal threshold levels in all producing regions, if only the gross product of soybean is considered. Contrasting with this general picture of small production area and frugal income, there are also a few farms with hundreds of hectares of organic soybean, and farms with several tens of hectares are not rare. An accurate picture of the systems in which organic soybean is grown is still to be compiled.
Technological characterization in organic soybean production

During my study trips to the organic soybean regions in Parana, my focus was the technology used in organic soybean production. I visited many farms and talked with agents involved in extension, trade, education, politics, and farmers' organization, so as to have a comprehensive view of technological patterns and to understand the contexts in which these patterns are adopted. Qualitatively, the systems I visited may be placed in two categories: conventional tillage with conventional cultivation, and no-till with cover crops and manual hoeing.

Figure 8. Organic soybean fields under conventional tillage and conventional cultivation.

Left: fully mechanized tillage and cultivation. In the leftmost part of the photo, the crop was already cultivated with a tractor, and will still receive a complementary manual pass with hired labor. Engenheiro Beltrao.

Right: tillage, planting and cultivation using draft animals. The complementary manual pass is done with family labor.
Conventional tillage with conventional cultivation is the dominant technological pattern in southwestern Parana. The soil is tilled with tractors or draft animals (Fig. 8), seeds are planted with tractor planters, weeds are controlled with draft animals and complementary manual hoeing, and harvest is either mechanical or manual. If farmers use no-till, weed control with draft animals is hindered, and more time for complementary manual weeding is required. Another obstacle for no-till is the presence of stones in the soil.

People involved with agricultural technology in Parana, as well as many farmers, agree that -- for a state where over 90% of the grain area is no-tilled -- the persistence of conventional tillage is undesirable. However, the economic constraints of these farmers force them into more cash grain crops, leaving little room for cover crops. When winter cover crops are planted, mainly black oat, it is usually grazed, so little mulch is left for the succeeding summer crop. Nonetheless, the southwest is the region where weeds normally cause the least damage to the crop, essentially because of careful weed control. I visited farms that were under organic management for over 20 years, where weeds could hardly be found.

Although not as prevalent as in the southwest, conventional tillage with conventional cultivation is also practiced in western and northern Parana. In these cases, the use of draft animals is less common, and mechanized cultivation is used instead, complemented with manual hoeing.

No-till with cover crops and manual hoeing is prevalent in central-southern Parana, but is also practiced in all other organic soybean regions. A winter cover crop, most often black oat or ryegrass (*Lolium multiformum* Lam), is planted to produce mulch, into which soybean is no-till planted in the following summer. Although this system has been used across a variety of farm sizes and crop and livestock combinations, it has crucial limitations, namely the dependence on a cool and moist winter and the impossibility of growing a cash crop in the winter.

In the central-southern plateau under the Cfb climate, the winter is normally cool and moist enough for a good vegetation of both black oat and ryegrass, so either may be used for mulching. Ryegrass is a better choice for pasture than black oats, but it becomes a noxious
weed in winter crops eventually planted in the field. For this reason, mulching with ryegrass is usually associated with animal production in the farm.

Figure 9. No-till organic soybean fields.

Left: no-till organic soybean over ryegrass. Photo from mid November. In three weeks, ryegrass (vertical green lines) will die, and soybean will take over. Due to heavy mulch, few weeds are expected in this area. Ponta Grossa.

Right: no-till soybean in poor oat mulch, after a dry winter. High weed infestation is likely to occur. Capanema.

Black oat tolerates higher temperature and resists drought better than ryegrass and is, for these reasons, the most common winter cover crop for mulch in soybean in the regions under the Cfa climate, namely the west, the north, and part of the southwest. However, biomass production of black oat decreases as temperature and water deficit increase. For this
reason, black oat biomass production tends to be lower in northern than in southern Parana, particularly when the winter is drier than usually. Nevertheless, black oat is the best choice at present, combining adaptation to the region, providing stability in biomass production and a strong allelopathic effect on regional weeds, particularly on *Brachiaria plantaginea* (Almeida, 1991), the most noxious weed during conversion to organic agriculture.

When black oat is used, operations for a soybean crop include rolling the oat, no-till planting, manual weeding, and harvesting. Except for manual weeding, all operations are usually mechanized and contracted operations are usual. Depending on the crop area, manual weeding is conducted by the family, day laborers, or both. Moderately infested crops require 8.3 man-days per hectare, but the labor requirement for weeding declines considerably as weed infestation decreases. The immediately consequence of reduced weed infestation is that the same laborer can weed more land per day. Moreover, if weed infestation is low enough as to inflict little pressure on the crop yield, the removal of weeds can be spread over a longer period of time, aiming rather at reducing weed seed production. Ultimately, reduced weed infestation results in lower risk of crop loss, more flexibility in the timing of weeding, and better distribution of labor-demand over time.

**A final remark**

While writing this long introduction, I wondered several times if so much was necessary to provide the reader with the context within which the other chapters of this dissertation become small parts, little stones in a big mosaic. And I still don’t know whether there were too many details or still too few of them. If the length of this introduction bothers you reader, I sincerely beg you to forgive me. But if you feel you now know how the present situation of organic soybean production in Parana was constructed and what its future may look like, then I achieved my goal. Overall, this chapter was meant to enable the reader to see which pieces the next chapters are adding to the puzzle.
References


CHAPTER 2
BLACK OAT MULCH CONTROLS WEEDS
BUT DOES NOT PREVENT WEED SEED PRODUCTION
To be submitted to Pesquisa Agropecuaria Brasileira
Carlos A. Khatounian, Matt Liebman and Jose A. Soler
Index terms: Avena strigosa, Brachiaria plantaginea, conversion, organic agriculture, no-till, Brazil

Abstract
To facilitate the conversion into organic no-till soybean production, we studied the effects of black oat (Avena strigosa Schreb.) mulch on soybean and on the weed Brachiaria plantaginea (Link.) Hitchc. in Londrina, Brazil, during two field seasons. Treatments comprised a zero-mulch control and 2, 4, 6, 8, or 10 t/ha mulch, either evenly distributed or concentrated over the planting furrow. Subplots did or did not receive complementary weed control. When weeds were controlled, mulch did not affect soybean biomass and yield. Increasing mulch reduced weed populations exponentially, both within and between crop rows. Concentrating mulch over the planting furrow reduced the in-row weed population, but this reduction did not result in higher crop biomass or yield. Increasing mulch reduced weed biomass linearly from 8.66 to 0.76 t/ha, and increased linearly both soybean biomass production, from 2.35 to 6.75 t/ha, and soybean grain yield, from 0.71 to 2.81 t/ha. Increasing mulch quantity reduced weed seed production exponentially, from 1085 to 41.5 kg/ha, equivalent to 26.7 and 1.02 thousand seeds/m², with over 95% viable. Increasing black oat biomass production may reduce the need for manual weeding in no-till organic soybean.

Introduction
Organic soybean production is a fast growing enterprise in Parana State, Brazil. In 2002, 854 farmers harvested 48 thousand metric tons, 11 times more than in 1997, and further conversion from conventional into organic agriculture is both expected and highly desirable for its positive impact on the environment, on human health, and on the local economy. The conversion period is characterized by a series of changes in farming practices, comprising regulatory, biological, educational, and economic aspects (Khatounian, 2001).
In the biological realm, the main aspects for most crops involve the management of nutrients, insect pests, and weeds. For soybean, symbiotic N-fixation has facilitated nutrient management, and biological control techniques have kept insect-pest populations at or below acceptable levels, particularly the caterpillar *Anticarsia gemmatalis* Hübner (Hoffman-Campo *et al.*, 2000). In this paper, we discuss weed control, which has been the most limiting biological obstacle to the expansion of organic soybean production, particularly in no-till systems.

Erosion used to be a major problem in Parana State, but its importance decreased significantly in the last 20 years as no-till grain crop production expanded to occupy presently almost the entire area devoted to grain crops. The present challenge is to develop no-till and pesticide-free systems, and mulching with winter cover crops seems to be the keystone for such systems. In addition to reducing soil erosion, such systems may qualify for organic premiums in the marketplace.

Since the late 1970s, winter cover crops and their effects on summer-crop weeds have been studied in the region in order to promote the adoption of zero tillage production systems (Almeida, 1991). From these studies, black oat stood out in both mulch production and weed suppression. Compared with other species, black oat was the most stable in biomass production, produced seeds easily and was a nutritious forage crop. For these reasons, black oat became the most important winter cover crop in most of southern Brazil, particularly in organic farms.

The weed flora during the conversion period from conventional to organic production reflects previous management practices, and is often dominated by *Euphorbia heterophylla* L. and *B. plantaginea*, the latter being more aggressive and leading to greater losses in crop yield. Vidal *et al.* (1998) and Theisen *et al.* (2000) studied the suppressive effect of black oat mulch on *B. plantaginea*, with and without herbicides, in no-till soybean. Black oat mulch alone did suppress the weed, but weed suppression was not sufficient to achieve the yield obtained with mulch and herbicides. The yield gap in mulch-alone treatments was due to the remaining weed population, which was higher in the crop rows, i.e., emerging from planting furrows, than in the inter-rows (Theisen, 2000). Liebman and Mohler (2001) suggested that concentrating mulch over the planting furrow might improve the control of in-row weed
populations.

Weed infestation over years depends on weed seed production, but no assessment of *B. plantaginea* seed production has been reported in the scientific literature. Theisen et al. (2000) suggested that *B. plantaginea* seed production might be enough to replenish the soil seed bank, even when soybean was mulched with 10.5 t/ha of black oat and crop yield was little affected by weed competition.

To facilitate weed management in organic no-till soybean production, we conducted an experiment to determine whether covering planting furrows with mulch would reduce in-row weed population density and thus improve weed control. If this were true, less manual labor would be required in the conversion period from conventional to organic no-till production. We also measured *B. plantaginea* seed production, an essential piece in the assessment of future weed infestation.

**Materials and Methods**

The experiment was arranged in a randomized block design with split-plots, and involved 11 treatments and five replications. The main-plot treatments comprised a no-mulch control plus a factorial of five quantities of *A. strigosa* mulch (2, 4, 6, 8, and 10 t/ha) and two mulch placement patterns, namely evenly distributed over soil or concentrated over the planting furrow. In the latter case, 2 t/ha out of the total mulch was placed over the planting furrow, in a 20-cm-wide strip. Plots were split into subplots with or without complementary manual weed control. Main plots comprised nine 8-m-long soybean rows at a 50-cm spacing (36 m²). Subplot experimental areas consisted of the central 2-m-long segment of the three central soybean rows (3 m²).

The experiment was conducted in soybean seasons 2001-2002 and 2002-2003 in two fields highly infested with *B. plantaginea*. Both fields had previously been under conventional management. The experiment thus simulated the conditions of the first year of the conversion period from conventional to organic production. The fields are located at the experimental farm of Instituto Agronomico do Parana in Londrina, Brazil (23°22' S, 51°10' W), 585 m above sea level. The local soil is an acortox, classified as “Latossolo Roxo Distrofico” in the Brazilian Soil Classification System (Empresa Brasileira de Pesquisa
The local climate is classified as “Cfa, with hot summers and mild winters and no defined dry season” (Instituto Agronomico do Paraná, 2000). In both seasons, black oat was planted in April, in the winter preceding experimentation. In early November, the mature oat stand was rolled down with a “rolo faca”, and mulch quantities were adjusted to fit experimental design by shifting straw among plots to achieve desired levels. To reduce unintended effects on weeds that resulted from shifting straw, glyphosate was applied at 0.54 kg/ha of the active ingredient. Soybean cv. BRS-133 was then no-till planted with 50 cm between rows and 18 seeds/m, and maintained according to international organic standards (International Federation of Organic Agriculture Movements, 2002).

In the 2001-2002 cropping season, soybean was planted on 7 Nov. 2001 and harvested on 5 Apr. 2002. In this period, precipitation was 942 mm, and the averages of minimum, mean and maximum daily temperatures were, respectively, 19.2 °C, 24.0 °C, and 30.1 °C. In the season 2002-2003, soybean was planted on 9 Nov. 2002 and harvested on 27 Mar. 2003. In this period, precipitation was 808 mm, and the averages of minimum, mean and maximum daily temperatures were, respectively, 19.7 °C, 24.3 °C, and 30.2 °C. Total rainfall and temperature range in both years were considered normal for the region.

In weed-controlled subplots, infestation was checked weekly and weeds were hoed manually whenever necessary until crop canopy closure, 50 days after planting. We measured inter-row and in-row weed population densities, and biomass and seed production for both soybean and weeds. Weeds were counted 12 days after planting soybeans, three counts per subplot. For the inter-row population, we used a 50 x 46 cm² rectangle, placed so as to keep a distance of 2 cm from each adjacent crop row. For the in-row population, a 50 x 4 cm² rectangle was used, laid longitudinally to cover 2 cm at each side of the crop row.

Biomass and seed produced by both soybean and B. plantaginea were assessed at crop harvest, by cutting standing plants at the soil level and drying the material to constant weight at 60 °C. For soybean, abscised leaves were added to biomass, and seed production was obtained by threshing the dried material.

Brachiaria plantaginea seed production was assessed in three out of the five replications by brushing the seeds from soil surface in the experimental area. Recovered seeds were first passed through an air-screen seed cleaner and then subjected to manual
selection, until samples reached at least 99% purity in weight. To assess the ability of weed seeds to infest following crops, we used 5 g cleaned seeds of each treatment to make a composite sample, which was stored at 22 °C for two months. Seeds were then germinated under an alternating regime of 16 h at 20 °C without light, and 8 h at 30 °C with light, and were considered viable if they either germinated or remained firm when pressed with tweezers.

All data were subjected to ANOVA, using the general linear procedure in SAS (SAS Institute Inc., 1998), and Tukey's Studentized Range (HSD) Test at P = 0.05. The t-test was used for the contrast between evenly distributed mulch and concentrated mulch. Regression analyses were conducted to quantify the relationships between mulch quantity and the studied variables.

Results and Discussion

The most salient outcomes of our experiment were (1) the suppression of *B. plantaginea*, but not of soybean, by black oat mulch, and (2) the reduction of in-row weed population density by mulch concentration over the planting furrow. However, while the overall suppression of *B. plantaginea* resulted in increases in soybean yield, the reduction of in-row weed population density did not affect crop yield. When manual hoeing was not applied, weed seed production was sizeable at all mulch levels. Regression analyses showed that, except for in-row weed population density, the studied variables were more dependent on the inter-row than on the total mulch quantity. Therefore, except for in-row weed population density, we focused attention on the inter-row mulch quantity in the discussion.

Weed population density

In both years, the inter-row weed population density decreased exponentially in response to increasing quantities of mulch (Fig. 1, P<0.0001) and *B. plantaginea* accounted for at least 95% of weed plants. Although weed density 12 days after planting was higher in 2001-2002 than in 2002-2003 (P<0.0001), the curves of response to mulch quantity followed the same pattern (Fig.1). The reasons for lower weed populations in 2002-2003 are not known. We speculate that *B. plantaginea* seeds may have been subjected to black oat allelochemicals
(Almeida, 1991) to a greater extent in 2002-2003 than in 2001-2002. While few and intense rains followed soybean planting in 2001-2002, there was an 11-day almost continuous rainy period in 2002-2003, which might have favored more consistent allelochemical extraction from black oat mulch, but might as well have leached the allelochemicals from the weed germination zone.

In spite of differences in weed population densities between seasons, there were large reductions in inter-row weed population density from zero to 6 t/ha of mulch in both seasons, and more modest reductions from 6 to 10 t/ha of mulch (Fig. 1). Vidal et al. (1998) and Theisen et al. (2000) obtained similar results in Eldorado do Sul, Brazil, under a slightly cooler Cfa climate and different soil conditions. Therefore, 6 t/ha may be the black oat mulch threshold for successful control of *B. plantaginoides*, irrespective of soil, under the Cfa climates of southern Brazil.

The in-row weed population density was affected by the interaction of mulch quantity and mulch concentration over the planting furrow \((P=0.0035)\). There were also interactions between mulch treatment and year \((P=0.0029)\), with weed suppression by mulch being greater in 2002-2003 than in 2001-2002 (Fig. 2). However, the response of in-row weed density to mulch level followed the same pattern in both seasons. Although these results supported the hypothesis that concentrating mulch over the planting furrow would reduce in-row weed population density, reductions of in-row weed population density were not reflected in higher crop production. We attributed this lack of response in crop production to two different factors, depending on mulch quantity. At mulch levels of 2 and 4 t/ha, the decrease in in-row weed population density was accompanied by an increased inter-row weed density, because the 2 t/ha mulch concentrated over the crop row was taken from crop inter-rows. At mulch levels of 6 t/ha and above, the overall weed pressure was low, so the reduction in in-row weed density was of little importance (Fig. 2).

Nevertheless, mulch concentration over the planting furrow may be an alternative when little mulch is available, because the mechanical control of weeds is easier and more effective between crop rows than within rows. The strategy of concentrating mulch requires further studies concerning equipment design for mulch movement and no-till cultivation, and may be limited to situations where mulch disturbance by the wind is not likely to occur.
Crop and weed biomass production

When weeds were controlled, soybean biomass production was not affected by mulch quantity, mulch concentration, or year (Fig. 3). When weeds were not controlled, however, biomass production of both soybean and weeds was affected by the interaction of mulch quantity by year (P=0.0081). Increasing mulch quantity increased weedy soybean biomass and decreased total weed biomass (Fig. 3), B. plantaginea accounting for at least 98.3% of the latter. Minor weed species were Echinochloa crusgalli var. crusgalli (L.) P. Beauv., Euphorbia heterophylla L., Commelina benghalensis L., Ipomoea spp, and Digitaria spp. The responses of soybean and weed biomass production to mulch followed the same trends in both seasons, but the intensity of the effects varied with the season. Without weed control, each additional 1.0 t/ha of mulch increased soybean biomass by 0.23 t/ha in 2001-2002, but by 0.64 t/ha in 2002-2003. Concerning weeds, each additional t/ha of mulch reduced biomass production by 0.51 t/ha in 2001-2002, but 1.08 t/ha in 2002-2003.

While mulch caused an exponential decrease in weed population density (Fig.1), the decrease in weed biomass was linear and less abrupt (Fig. 3), indicating the ability of B. plantaginea to compensate for reductions in the number of individuals with increased individual growth. We observed a high phenotypic plasticity in this species, one single plant producing tillers to densely cover 1 m² of soil, or a tiny 10-cm-long single-stemmed plant. Passini (2001) observed a similar plasticity in this species in Piracicaba, Brazil.

If the regressions in Fig. 3 were extrapolated, 11 t/ha mulch would produce full crop biomass and zero weed biomass. Typical mulch quantities in farmers’ fields are currently between 4 and 6 t/ha, but black oat biomass production above 11 t/ha has been recorded under experimental conditions in the region (Sa et al., 2002). Because little attention is presently devoted to black oat as a crop, we believe that improved growing techniques may realistically increase biomass production to 6-8 t/ha, at which level the weed problem would be strongly reduced (Fig. 3). In addition, our experimental fields were chosen for their high infestation with B. plantaginea, beyond typical infestation in production fields. Therefore the positive impact of 6 - 8 t/ha of black oat mulch in production fields may result in relatively higher crop production and lower weed production than in our experimental site. This hypothesis requires verification, given the high phenotypic plasticity of B. plantaginea.
An intriguing question arose from contrasting the effects of mulch on weed population density and on soybean biomass production in 2001-2002, with the same effects in 2002-2003 (compare Fig. 1 with Fig. 3). Despite the fact that weed population densities were higher in 2001-2002 than 2002-2003, weeds inflicted greater losses to the crop in 2002-2003. For zero mulch, soybean biomass production was 3.59 t/ha in 2001-2002, with 900 weed plants/m², compared with 0.95 t/ha in 2002-2003, with 342 weed plants/m². We speculate that this contradiction may result from the different ways the climate affects the crop and the weed. In 2001-2002, in the beginning of the crop cycle, there were heavy rains spaced five to seven days apart, which provided enough moisture to the 5-cm-deep planted soybean seed, and conversely subjected B. plantaginoides seedlings to desiccation or hindered their early growth. In 2002-2003, there was also a dry and hot spell from day 30 to 76 after crop planting, during which time the C-4 B. plantaginoides developed much faster than the C-3 soybean crop. Together, these facts may explain why higher weed densities ended up with lower weed biomass in 2001-2002, as compared with 2002-2003. However, this explanation requires further experimental verification.

Soybean grain yield
The effects of complementary weed control, and of mulch quantity and concentration on soybean biomass (Fig. 3) were reflected in their effect on soybean grain yield (Fig. 4). When weeds were controlled, soybean grain yield was not affected by mulch quantity and concentration, but was affected by the season (P<0.0001).

When weeds were not controlled, increasing mulch quantity increased soybean grain yield (P<0.0001), but the rate of increase varied with the year (Fig. 4, P<0.0001). In 2001-2002, each additional 1.0 t/ha of black oat mulch increased grain yield by about 110 kg/ha, compared with approximately 310 kg/ha in 2002-2003. In addition, the range of soybean yield in weedy plots was considerably narrower in 2001-2002 (means between 1.28 and 2.40 t/ha) than in 2002-2003 (means between 0.25 and 2.90 t/ha). Nonetheless, the regressions of soybean biomass and yield using weed biomass as the independent variable (Fig. 5), combining data from both seasons, showed that the differences between seasons may be primarily attributed to differences in weed biomass. In Eldorado do Sul, Brazil, Theisen et al.
(2000) observed a yield increase of around 160 kg/ha for each additional 1.0 t/ha of black oat mulch, which is within the range we obtained in our experiment.

Although increasing black oat mulch increased soybean yield by reducing weed biomass (Fig 3. and Fig. 5), soybean yield with mulch alone was never as high as that obtained with manual hoeing. The highest mulch-alone yields were obtained with 10 t/ha of mulch, and represented 86%, in 2001-2002, and 90%, in 2002-2003, of the yield of achieved with manual hoeing. In experiments where black oat mulch was complemented with herbicides, Vidal et al. (1998) and Theisen et al. (2000) obtained maximum mulch-alone soybean yields of 73% and 59% of those from mulch plus herbicides. In both these experiments and the present study, maximum mulch-alone soybean yields were obtained with highest mulch quantities, which were 10.5 t/ha for Vidal et al. (1998), and 9 t/ha for Theisen et al. (2000). The gaps in soybean yield were caused by the existence of a residual weed population, which causes two additional problems for organic soybean production. The first is a reduction in crop value due to grain staining during the harvest. When the harvest machine breaks the standing plants, both crop and weeds, sap from green weeds and dust adheres to the grains, resulting in stains that are not removable by grain selecting and cleaning machines. This problem is particularly important in red oxisols, which predominate in several Brazilian soybean-producing zones, because iron oxides are potent pigments. For this reason, maximum economic benefit requires complementary weed control practices, which presently means manual hoeing. Increasing mulch production by applying improved cultural practices for black oat seems to be a possible alternative to reduce the labor required for manual hoeing. The second problem associated with the residual weed population is weed seed production, which contributes to the infestation of future crops.

**Brachiaria plantaginosa seed production**

Seed production of *B. plantaginosa* (Fig.6) was affected by the interaction of mulch quantity by season (P=0.0028). Without mulch, *B. plantaginosa* produced 11.2 thousand seeds/m² (0.45 t/ha) in 2001-2002, and 42.4 thousand seeds/m² (1.72 t/ha) in 2002-2003. Although mulch reduced these figures exponentially in both years, seed production at 10 t/ha mulch was still sizeable, reaching 1.7 and 0.4 thousand seeds/m², respectively, in 2001-2002 and
2002-2003. The differences in seed production between seasons were primarily associated with weed biomass (Fig. 7). The fraction of biomass directed to seeds increased as weed biomass increased, probably because the lower the weed population, the greater the competitive pressure imposed on weeds by the crop.

After two-month storage, seed viability was 92.1% (88.2% germinated plus 3.9% hard) in 2001-2002, and 93.3% (54.7% germinated + 38.6% hard) in 2002-2003. With the seemingly achievable 6-8 t/ha mulch, seed production ranged between 2.5 and 7.0 thousand viable seeds/m², which makes an important contribution to soil weed seed bank. Present knowledge of the dynamics of B. plantaginea seeds on and in the soil is limited to a few studies on the effect of tillage and mulch on seedling emergence and seed survival and longevity. In a ten-year experiment in which weed seed production was prevented, Skora Neto (2001) observed an exponential decrease in the emergence of B. plantaginea, and the decrease was faster under no-till than under conventional tillage. However, even after ten years of no seed addition, there still were 0.2 plants/m², five thousand plants/ha, of B. plantaginea emerging in early November, before weed control practices were applied. The potential weed emergence was probably higher, because this weed emerges throughout the year (Rodrigues et al., 2000), which provides ample opportunity for replenishing the soil weed seed bank. Within the soil seed bank, the longevity of B. plantaginea seeds is longer if they are buried at the depth of 10 cm than at 2 cm (Barbosa et al., 1995; Theisen and Vidal, 1999; Rodrigues et al., 2000). In a study focusing on the longevity of B. plantaginea seeds under different tillage systems, Voll et al. (1995) observed life times of 11.5 to 12.2 years under conventional tillage, and 5.2 years under no-till with pesticides. Because more organisms feeding on seeds are presumed to be present in pesticide-free systems (Liebman and Mohler, 2001), the decay in weed seed banks may be faster in organic no-till, but this remains to be confirmed. Nevertheless, on the basis on current knowledge, the control of the mulch-surviving weed populations is fundamental to optimize crop yield (Fig. 5) and to reduce weed infestation in subsequent crops.
Conclusions

Increasing black oat mulch from 0 to 10 t/ha strongly affects *B. plantaginoides*, reducing its population density exponentially and its biomass decreases linearly. The intensity of these reductions varies between growing seasons. From 0 to 6 t/ha mulch, the reductions in weed population density are rapid, but reductions are less marked from 6 t/ha upwards. Concentrating mulch over the planting furrow reduces in-row weed population density, but these reductions in weed density do not improve crop production.

The effect of black oat mulch on soybean depends on whether other complementary weed control practices are applied. When weeds are hoed manually, mulch quantity does not affect soybean biomass or grain yield. However, when black oat mulch is the only weed control practice, varying mulch from 0 to 10 t/ha linearly increases soybean biomass and grain yield. Soybean biomass and grain yield decreases linearly as a function of *B. plantaginea* biomass.

Weed seed production decreases exponentially with increasing levels of mulch, but the intensity of the decrease depends on the season. Seed production is proportionally greater as weed biomass production increases. However, even at the lowest levels of weed biomass production, with 10 t/ha black oat mulch, weed seed production is still greater than 1000 seeds/m², making complementary weed control techniques necessary to reduce weed infestation in subsequent crops. We conclude that increasing black oat biomass production can improve weed control, but is not sufficient to maximize crop yield and commercial quality. Integrated approaches are necessary.

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Figure 1. Effect of black oat (*Avena strigosa* Schreb.) inter-row mulch quantity on inter-row weed population density. Londrina, Brazil, seasons 2001-2002 and 2002-2003. Points for 10 t/ha mulch are means of five experimental units, other points are means of ten experimental units.

Figure 2. Effect of concentrating 2 t/ha of black oat (*Avena strigosa* Schreb.) mulch over the planting furrow on weed population density in the crop row. Londrina, Brazil, seasons 2001-2002 and 2002-2003. Points are means of five experimental units.

Figure 3. Effect of black oat (*Avena strigosa* Schreb.) inter-row mulch quantity and complementary manual hoeing on the biomass production of soybean cv. ‘BRS-133’ and weeds. Londrina, Brazil, seasons 2001-2002 and 2002-2003. For 10 t/ha mulch, points are means of five experimental units, other points are means of ten experimental units.

Figure 4. Effect of black oat (*Avena strigosa* Schreb.) inter-row mulch quantity and complementary manual hoeing on soybean BRS-133 grain yield. Londrina, Brazil, seasons 2001-2002 and 2002-2003. For 10 t/ha mulch, points are means of five experimental units, other points are means of 10 experimental units.

Figure 5. Effect *B. plantaginea* (Link) Hitchc. biomass on soybean BRS-133 biomass and grain yield. Londrina, Brazil, seasons 2001-2002 and 2002-2003. Each point is the mean of 20 experimental units from either 2001-2002 or 2002-2003.

Figure 6. Effect of black oat (*Avena strigosa* Schreb.) inter-row mulch quantity on *B. plantaginea* (Link) Hitchc. seed production. Londrina, Brazil, seasons 2001-2002 and 2002-2003. Each point is the mean of six experimental units.

Figure 7. Effect *B. plantaginea* (Link) Hitchc. biomass on its seed production. Londrina, Brazil, seasons 2001-2002 and 2002-2003. Each point is the mean of six experimental units from either 2001-2002 or 2002-2003.
Figure 1

Inter-row weed population (plants/m²)

- \( y = 1618e^{0.23x} \)
  - \( r^2 = 0.96 \)
- \( y = 421e^{0.62x} \)
  - \( r^2 = 0.95 \)

2001-2002
2002-2003
Figure 2

2001-2002
mulch evenly distributed \( y = 1562e^{-0.22x} \) \( r^2 = 0.98 \)
mulch concentrated \( y = 570e^{-0.18x} \) \( r^2 = 0.82 \)

2002-2003
mulch evenly distributed \( y = 1356e^{-0.62x} \) \( r^2 = 0.78 \)
mulch concentrated \( y = 365e^{-0.47x} \) \( r^2 = 0.92 \)
Figure 3

2001-2002

\[ y = 6.98 \]
\[ y = 3.96 + 0.23x \]
\[ r^2 = 0.89 \]

2002-2003

\[ y = 6.79 \]
\[ y = 0.73 + 0.64x \]
\[ r^2 = 0.96 \]

\[ y = 10.9 - 1.08x \]
\[ r^2 = 0.94 \]

- □ soybean, manually hoed
- △ soybean, mulch alone
- ○ weeds
Figure 4

2001-2002

\[ y = 2.80 \]

\[ y = 1.35 + 0.11x \]

\[ r^2 = 0.95 \]

2002-2003

\[ y = 3.22 \]

\[ y = 0.08 + 0.31x \]

\[ r^2 = 0.95 \]
Figure 5

![Graph showing the relationship between weed biomass and soybean grain yield. The graph includes data points and lines of regression for two years: 2001-2002 and 2002-2003. The equations for the lines are:

- 2001-2002: \( y = 7.09 - 0.55x \) with \( r^2 = 0.96 \)
- 2002-2003: \( y = 2.99 - 0.26x \) with \( r^2 = 0.97 \)]

Figure 6

![Graph showing the relationship between mulch application and seed production. The graph includes data points and lines of regression for two years: 2001-2002 and 2002-2003. The equations for the lines are:

- 2001-2002: \( y = 10e^{-0.17x} \) with \( r^2 = 0.90 \)
- 2002-2003: \( y = 72e^{-0.43x} \) with \( r^2 = 0.87 \)]
Figure 7

\[ y = 0.02 + 0.04x + 0.35x^2 \]

\[ r^2 = 0.89 \]

Seed production (1000 seeds/m²)

Biomass production (t/ha)

2001-2002
2002-2003
CHAPTER 3
SEED PRODUCTION OF Brachiaria plantaginea (Link.) Hitchc.
EMERGING AT DIFFERENT TIMES AS A WEED
IN A MAIZE CROP OR IN A PURE STAND
To be submitted to Pesquisa Agropecuaria Brasileira
Carlos A. Khatounian, Matt Liebman and Jose A. Soler

Index terms: Zea mays, Glycine max, conversion, organic agriculture, Brazil

Abstract
Brachiaria plantaginea is a noxious summer weed in southern Brazil, particularly important in the conversion period from pesticide-based to organic soybean production systems. Organic soybean systems typically include maize every third summer, and sometimes include summer fallow after short-cycle crops. The control of weeds is usually stricter in soybean than in other phases of the rotation, in which weeds produce seeds, and thus contribute to infestation of subsequent crops. In order to quantify B. plantaginea seed production when the weed infests maize and when it grows in virtually pure stands in fallow land, we conducted two experiments during two summer seasons, in Londrina, Brazil. In the maize/B. plantaginea experiment, treatments consisted of four weed-free periods (0, 20, 40, and 60 days) after the maize planting date, after which the weed developed freely. In the pure stand experiment, we tested four weed emergence dates, coinciding with those used for the maize/B. plantaginea experiment. Seed production of maize-infesting B. plantaginea decreased exponentially as the weed-free period increased, and was affected by an interaction between the season and weed-free period, varying from 6.94 to 0.01 thousand seeds/m². In pure stands, B. plantaginea seed production was affected by an interaction between weed emergence date and season, and varied from 47 thousand to 4.6 thousand seeds/m². Based on B. plantaginea seed survival data from other studies in the same region, one cycle of the weed in a pure stand may produce enough seeds to infest the area for up to 17 years.
Introduction

Organic production is a fast growing sector in Brazilian agriculture, and in 2001 soybean was the most important product (Ormond et al., 2002). Organic soybean production is concentrated in Rio Grande do Sul, Santa Catarina, and Parana States, the latter being the biggest producer. In the 2001-2002 season, 854 farmers planted 7.6 thousand hectares and harvested 16.3 thousand Mt of organic soybeans (Departamento de Economia Rural, 2003).

Given the attractive prices of organic products in general (Ormond, 2002), and particularly those of organic soybean, further conversion of land from pesticide-based into organic agriculture is expected. Conversion to organic agriculture is also highly desirable for its positive impacts on the environment, human health, and the local economy. The conversion period from conventional to organic production is characterized by a series of changes in farming practices, comprising regulatory, biological, educational, and economic aspects (Khatounian, 2001).

In the biological realm, the main constraint for the production of organic soybean is the control of weeds. The weed flora during the conversion period is dominated by Euphorbia heterophylla L., Digitaria spp, and B. plantaginea, the latter being the species which is most aggressive and responsible for the greatest losses in crop yield. Brachiaria plantaginea is known to suppress other weed species (Cunha et al., 1997) as well as crops, which may be one of the reasons it is the dominant weed species in several cropping systems in southern and southeastern Brazil (Lorenzi, 2000), particularly under conventional tillage and the first years of no-till.

Crop rotations based on organic soybean in southern Brazil typically include maize every third summer, and black oat (Avena strigosa Schreb.), wheat, and annual ryegrass (Lolium multiflorum Lam.) as winter crops. Depending on the local climate and on market opportunities, crops like bean, rye, and triticale may be included. The field may also be left in fallow for the entire winter or for part of the summer. Soybean is the most profitable crop in the rotation, so weed control is usually stricter in soybean than in the other crops. Although the emergence of B. plantaginea is greater in the summer, it was observed to emerge during all months of the year in Parana (Rodrigues et al., 2000). Therefore, the relatively lax weed control in crops other than soybean may provide ample opportunity for B. plantaginea to
produce seeds and replenish the soil weed seed bank, and thus render weed control more difficult in succeeding crops.

Visual observation of *B. plantaginoides* growth and seed production during the winter season suggests that it is quantitatively less important than in the summer. In the winter, *B. plantaginoides* emergence is considerably lower than in the summer (Rodrigues et al., 2000), and the competitive edge shifts from the weed to the winter crop. Conversely, *B. plantaginoides* emergence peaks in the hot and humid summer months (Rodrigues et al., 2000), in which period it is a noxious weed in maize and other summer crops, and dominates fields in fallow after short-cycle spring crops, particularly after bean. The quantification of *B. plantaginoides* seed production under these situations is a keystone for the development of strategies to control this weed in subsequent crops.

In this paper, we report on experiments to assess *B. plantaginoides* seed production in association with maize and in pure stands simulating summer fallow. We also explore the potential consequences of seed production in subsequent years.

**Materials and Methods**

We conducted two experiments to assess *B. plantaginoides* development and seed production, both repeated in the 2001-2002 and the 2002-2003 seasons. Experiment 1 focused on the weed while infesting a maize stand, and Experiment 2 addressed it as pure stand simulating fallow land. Experiment 1 was arranged in a completely randomized design with four treatments and four replications. The treatments comprised different weed-free periods (0, 20, 40, and 60 days, counted from maize planting date), after which weeds were allowed to grow freely. Each plot measured 7.2 m x 4 m (eight 4-m long rows of maize, spaced 0.9 m). The experimental area for maize was the central 2-m segment of the two central rows (1.8 m x 2 m = 3.6 m²). The inter-row space between the maize experimental rows (0.9 m x 2 m = 1.8 m²) was the experimental area with *B. plantaginoides*. The 16 plots of the experiment were placed in a strip containing 12 rows of maize, with a 5-m long border zone at each end.
Experiment 2 was arranged as Experiment 1 and with the same randomization, in a 6-m-wide strip adjacent to Experiment 1, but without maize. Thus, there were four emergence dates spaced at 20-day intervals in the pure stands of *B. plantaginina*.

The experiments were conducted in two fields at the experimental farm of the Instituto Agronomico do Parana (IAPAR) in Londrina, Brazil (23°22' S, 51°10' W, 585 m above sea level). The local soil is acrotex, classified as “Latossolo Roxo Distrofico” in the Brazilian Soil Classification System (Empresa Brasileira de Pesquisa Agropecuaria, 1999). The local climate is classified as “Cfa, with hot summers and mild winters and no defined dry season” (Instituto Agronomico do Parana, 2000).

In both years, the experimental fields had a history of high infestation with *B. plantaginina* and were left in fallow in the preceding summer to guarantee high weed pressure in the experimental season. Both fields were previously under conventional tillage and pesticide-based management, in order to simulate the conditions of the first year of the conversion to organic production. In both seasons, black oat was planted in April, in the winter preceding experimentation. Mulch levels at the time of maize planting were 4.2 t/ha in 2001-2002 and 4.6 t/ha in 2002-2003. In early October, the mature oat stand was rolled down with a “rolo faca”. To reduce unintended effects of weeds that germinated after straw was rolled and before maize was planted, glyphosate was applied at 0.54 kg/ha of the active ingredient. Open-pollinated maize IPR 114 was no-till planted on 9 November 2001 and on 8 November 2002, and fertilized with 300 kg/ha of 8-28-16 formulation (N-P₂O₅-K₂O). Insect pests were controlled with products approved by the International Federation of Organic Agriculture Movements (IFOAM, 2002). Weeds were hoed manually every five to ten days, and the last control operation was done on the last day of the weed-free period of each treatment. In both seasons, the climate during the maize cycle was normal, totaling 896 mm of precipitation and averaging 24.0°C of mean daily temperature in 2001-2002, and 808 mm and 24.2 °C in 2002-2003.

In Experiment 1, biomass and seed production of both maize and *B. plantaginina* were measured at maize harvest time on 5 April 2002, and on 31 March 2003. In Experiment 2, *B. plantaginina* biomass and seed production were determined when the plants matured, which varied from simultaneous with maize in the earliest emerging treatments, to 40 days later for
the latest emergence dates. Biomass of both maize and *B. plantaginea* were assessed by cutting standing plants at the soil level, and drying the material to constant weight at 60 °C.

*Bracharia plantaginea* seed production was determined by collecting the seeds both from the soil surface and from standing plants. The seeds were passed through an air-screen seed cleaner and subjected to manual selection, until samples reached at least 99% purity in weight. To assess the ability of weed seeds to infest following crops, 5 g of cleaned seeds of each treatment were used to make a composite seed sample, which was stored at 22 °C for two months. Seeds germinated under an alternating regime of 16 h at 20 °C without light, and 8 h at 30 °C with light, and were considered viable if they either germinated or remained firm when pressed with tweezers.

All data were subjected to ANOVA, using the general linear procedure in SAS (SAS Institute Inc., 1998), and Tukey's Studentized Range (HSD) Test at P = 0.05. Regression analyses were conducted to explore the relationship between weed-free periods and *B. plantaginea* seed production.

**Results and Discussion**

The most important outcome from Experiment 1 was that *B. plantaginea* seed production may be substantial even when the weed does not affect maize production. From Experiment 2, we learned that, although delaying emergence for as much as 60 days reduced seed production in a pure stand of *B. plantaginea*, the weed still produced several thousand seeds/m² at the latest emergence date.

Weed emergence occurred 8 to 12 days after the last control operation. Therefore, while interpreting the results, weed-free periods can also be considered as emergence dates approximately ten days later.

*Effect of the weed-free period on maize and B. plantaginea biomass production, and on maize grain yield*

In the maize/*B. plantaginea* experiment, the results of the two seasons were very similar in terms of maize biomass and yield and weed biomass, with no interactions between years and treatments. When no weed control was applied after maize planting, maize biomass was
substantially reduced (P < 0.0001) compared with when weeds were controlled (Fig. 1). However, there was no statistically significant difference between weed-free periods of 20, 40, and 60 days. The effect on maize grain yield was similar to that on maize biomass (Fig. 1), and yield levels were within the usual range for maize without side-dressed N in the region.

The weed flora was dominated by *B. plantaginea*, which accounted for at least 98.6% of the weed biomass, followed by *Commelina benghalensis* L. Biomass production of *B. plantaginea* was reduced as the weed-free period increased (Fig. 1), but most of the reduction (84%) occurred from 0 to 20 weed-free days. The abrupt reduction in weed biomass from 0 to 20 weed-free days was attributed to the competitive edge gained by weed-free maize seedlings over later emerging weeds, a phenomenon that is commonly observed in studies of the dynamics of competition between annual crops and annual weeds (Mohler, 2001).

The effects on both maize and the weed confirm the established knowledge in the region that, from the maize production perspective, weeds have to suppressed effectively during at least the first month of the crop cycle. In the more specific condition of no-till maize in black oat mulch, the impact of non-controlled *B. plantaginea* on maize yield observed in our experiments was similar to that obtained by Spader & Vidal (2000) in Eldorado do Sul, Brazil. In our experiment, maize yield was reduced by 82% when weeds were not controlled, while Spader & Vidal observed reductions of around 80% with *B. plantaginea* densities at or above 100 plants/m². However, maize yields in Spader & Vidal’s (2000) study ranged from 2 to 10 t/ha of grain, while we harvested from 0.8 to 4.5 t/ha, on a 12% moisture basis. We believe that the major reason for the differences in the yield is the higher fertilization rates used by Spader & Vidal, which amounted to 600 kg/ha of 5-20-20 (N-P₂O₅-K₂O), plus 250 kg/ha of side-dressed N, compared with 300 kg/ha of 8-28-16 (N-P₂O₅-K₂O) in our study.

*Effect of the emergence date on B. plantaginea biomass production in a pure stand*

The weed flora emerging in pure stands adjacent to maize plots was also dominated by *B. plantaginea*, which accounted for at least 98.3% of the total weed biomass. The remaining 1.7% or less came from *Commelina benghalensis* L. Biomass production of *B. plantaginea*
(Fig. 2) was affected by the interaction of emergence date and season ($P = 0.0023$). In the 2001-2002 season, no consistent trend between the weed-free period and weed biomass was observed (Fig. 2). In the 2002-2003 season, however, *B. plantaginea* biomass production decreased linearly at a rate of 0.15 t/ha/day ($r^2 = 0.95, P = 0.016$) as the emergence was delayed.

**Effect of the weed-free period on *B. plantaginea* seed production infesting maize or in a pure weed stand**

Seed production of *B. plantaginea* infesting maize (Fig. 3) was affected by the interaction of weed-free period and season ($P = 0.0023$). Although in both seasons seed production decreased exponentially as the weed-free period increased, seed production was higher in 2001-2002. The difference between seasons was especially apparent when no weed control was applied (Table 1), seed production being 23 times greater in 2001-2002 than in 2002-2003. The difference between seasons tended to decrease as the weed-free period increased (see Fig. 3 and Table 1). In both seasons, maize-infesting *B. plantaginea* that emerged after 40 weed-free days produced 50 seeds/m$^2$ or less.

After a two-month storage period, the viability of seeds produced by maize-infesting *B. plantaginea* plants was 90.3% (87.1% germinated plus 3.2% hard) in 2001-2002, and 92.0% (63.1% germinated plus 28.9% hard) in 2002-2003.

Seed production of *B. plantaginea* in pure stand (Fig. 4) was also affected by the interaction of weed-free period and season ($P=0.0045$). In both years, weed seed production decreased exponentially as emergence date was delayed, but the rate of decrease and maximum production varied (Fig. 4). Pure-stand seed production of *B. plantaginea* ranged from 4.6 to 15.5 thousand seeds/m$^2$ (185 – 513 kg/ha, dry matter) in 2001-2002, and from 8.9 to 47.1 thousand seeds/m$^2$ (320 – 1700 kg/ha, dry matter) in 2002-2003. Thus, *B. plantaginea* seed production in a pure stand was 100 to 1000 times higher than in adjacent maize plots, for cohorts that emerged at the same date. The viability of pure-stand seeds was 89.3% (86.0% germinated plus 3.3% hard) in 2001-2002, and 91.7% (53.4% germinated plus 38.3% hard) in 2002-2003. These values are very similar to those of the seeds from the maize-infesting populations.
From the perspective of controlling *B. plantaginea* in production fields, the results of our experiments have to be seen as a starting point for potential answers rather than the ultimate answer. Given the lack of studies on *B. plantaginea* seed production, we do not know the extent to which our results can be extrapolated to other sites in the vast expanse (perhaps greater than 600,000 km\(^2\)) where this species is a noxious weed. Supposing that the seed production levels that we obtained are representative, the next question would be how such seed quantities would affect *B. plantaginea* infestation in subsequent crops. We explored this question in two ways: for weed seed production from a pure weed stand, and from a weed-infested maize field.

In a pure *B. plantaginea* stand, our maximum measured seed production was 47 thousand seeds/m\(^2\). If all these seeds were uniformly incorporated into the top 20-cm soil layer, and if those seeds within the topmost 2-cm (Barbosa et al., 1995; Theisen and Vidal, 1999; Rodrigues et al., 2000) would germinate as a cohort in the next season, and the germination rate were our measured 63.1%, then the weed density in the next season would be around 3 thousand plants/m\(^2\). Using the same reasoning for the lowest measured pure-weed-stand seed production, namely 4.6 thousand seeds/m\(^2\), the next-season weed density should be around 0.4 thousand plants/m\(^2\). These are conservative figures, because seed losses due to predation, pathogens and physiological decay would certainly occur. However, given the lack of studies quantifying these processes, we opted for the conservative approach in exploring our data.

In order to explore what the densities might be in subsequent seasons, we used the equations that Skora Neto (2001) obtained in a 10-year experiment. In his experiment, which examined both conventional tillage and zero tillage systems, weed seed production was prevented, corn was the summer crop, and there always were winter cover crops, alternating legumes (*Lupinus angustifolius* L. and *Vicia sativa* L.) and a grass (*Avena strigosa* Schreb.). Skora Neto observed that weed density decreased exponentially over time, and that the weed density was always higher with conventional tillage.

Using his equations, we calculated how many years would be necessary to achieve a weed density of 10 plants/m\(^2\) or less. After our minimum pure-weed-stand seed production (4.6 thousand seeds/m\(^2\)), it would take three years with no-till and six years with
conventional tillage to achieve the threshold of 10 weed plants/m². For our maximum measured weed seed production, 47 thousand seeds/m², it would take 10 years with no-till and 18 years with conventional tillage to cross the 10-plant/m² threshold. This threshold was defined arbitrarily to keep a balance between the higher *B. plantaginoides* densities tolerated by maize (Spader & Vidal, 2000) and lower densities tolerated by soybean (Khatounian, unpublished data).

Concerning the effect of *B. plantaginoides* seed production in maize stands on subsequent crops, our results only indicate that the annual contribution to the soil weed seed is limited, because weeds are usually controlled up to the sixth week after planting in production fields. However, *B. plantaginoides* seed production in association with maize is limited if compared with the seed production of pure stands of the weed. Nevertheless, depending on the longevity of these seeds, small annual contributions may sum up to considerable amounts. In a five-year study on summer soybean – winter wheat, Voll et al. (1995) observed *B. plantaginoides* seed longevities of 5.2 years for no-till, and 11.5 to 12.2 years for different types of conventional tillage equipment. In addition, although the emergence of *B. plantaginoides* is concentrated in summer months, seedlings emerge the year round in the region (Rodrigues et al., 2000), which provides ample opportunity for producing new seeds. Contrary to the preceding reasoning, it is also possible that those 50 *B. plantaginoides* seeds/m², observed with 40 or more weed-free days while in association with maize, are not enough to threaten future crops. Seed predation and natural death may indeed reduce seed numbers, so that the weed would not threaten future crops. Experimentation is necessary to resolve this issue.

Although our results may be used for both conventional and organic production, our immediate focus was weed control in organic no-till soybean-based systems. However, given the lack of research on organic no-till worldwide, as well as in the region, the discussion of the results in this paper relied on studies conducted in no-till systems with pesticides. For this reason, we may have overestimated both the period of time to achieve the 10-plants/m² threshold, and seed longevity in organic-soybean based production systems. Several aspects of the soil environment can be more favorable to weeds in conventional than in organic
agriculture (Liebman & Mohler, 2001), but the extent to which this applies to soybean production systems in southern Brazil remains to be assessed.

Conclusions

When *B. plantaginea* is not controlled, maize biomass production and grain yield suffer a loss of 80% compared with weed-free conditions. Extending the weed-free period from 20 to 60 days after planting maize does not affect maize biomass and yield. Biomass production of *B. plantaginea* infesting maize is maximal when it emerges with maize, and decreases as the weed-free period increases. In a pure *B. plantaginea* stand, emergence date between mid-November and mid-January does not consistently affect biomass production.

Seed production of *B. plantaginea* is higher in a pure weed stand than in association with maize. In both situations, however, seed production decreases exponentially as the emergence is delayed. The rate of the exponential decrease depends on the year. The quantity of seeds produced by one cycle of pure stand of *B. plantaginea* seems to be enough to infest the area for several subsequent years.

Acknowledgements

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Table 1. Seed production of the weed *Brachiaria plantaginoides* infesting maize, emerging after different weed-free periods. Londrina, 2001-2002 and 2002-2003 seasons. In each column, values not followed by the same letter are different by Tukey Studentized test, at P=5%.

<table>
<thead>
<tr>
<th>Weed-free period preceding weed emergence (days after planting maize)</th>
<th><em>B. plantaginoides</em> seed production (1000 seeds/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.94 a</td>
</tr>
<tr>
<td>20</td>
<td>0.36 b</td>
</tr>
<tr>
<td>40</td>
<td>0.05 c</td>
</tr>
<tr>
<td>60</td>
<td>0.01 c</td>
</tr>
</tbody>
</table>

Figure 1. Effect of the weed-free period after planting maize on maize biomass and grain yield, and on biomass of the weed *B. plantaginoides* infesting maize. Londrina, 2001-2002 and 2002-2003 seasons. Points are means of eight experimental units. Tukey's Studentized LSD values at P= 5% are 1.2 for maize biomass, 0.6 for maize yield and 0.5 for *B. plantaginoides* biomass.

Figure 2. Effect of the weed-free period after planting maize on *B. plantigena* biomass production in a pure stand adjacent to maize. Londrina, 2001-2002 and 2002-2003 seasons. Points are means of four experimental units. Tukey's Studentized LSD values at P= 5% are 1.7 for 2001-2002, and 2.1 for 2002-2003.

Figure 3. Effect of the weed-free period after planting maize on seed production of *B. plantaginoides* infesting maize. Londrina, 2001-2002 and 2002-2003 seasons. Points are means of four experimental units.
Figure 4. Effect of the weed-free period after planting maize on *B. plantaginea* seed production in a pure stand adjacent to maize. Londrina, seasons 2001-2002 and 2002-2003. Points are means of four experimental units. Tukey’s Studentized LSD at $P= 5\%$ are 2.1 for 2001-2002, and 3.2 for 2002-2003.

Figure 1

![Biomass and grain yield graph](image1)

Figure 2

![Biomass graph](image2)
Figure 3

2001-2002: $y = 4.7e^{-0.1x} \quad r^2 = 0.98$

2002-2003: $y = 0.2e^{-0.04x} \quad r^2 = 0.79$

Figure 4

2002-2003: $y = 36e^{-0.03x} \quad r^2 = 0.85$

2001-2002: $y = 16e^{-0.02x} \quad r^2 = 0.71$
CHAPTER 4
CRITICAL QUESTIONS AND POTENTIAL ANSWERS CONCERNING WEED CONTROL DURING THE CONVERSION FROM CONVENTIONAL TO ORGANIC NO-TILL SOYBEAN PRODUCTION
To be submitted to Pesquisa Agropecuaria Brasileira
Carlos A. Khatounian, Matt Liebman and Jose A. Soler

Index terms: modeling, Brachiaria plantaginea, Parana, Brazil

Abstract

Organic soybean production is a fast growing enterprise in southern Brazil, but its expansion is limited by the difficulty in controlling weeds, among which Brachiaria plantaginea is the most problematic species. Although several previous investigations have addressed the control of this weed, a number of questions remain concerning its control in no-till organic soybean-based systems. We developed a model to address such questions, with the software Stella 7.0.3. Various simulations were run to cover a range of potential situations in terms of crop sequence, mulch mass, and weed control efficacy. Regarding the crop sequence during the conversion period to organic production, maize/maize or soybean/maize led to approximately the same level of weed infestation in the first certified organic soybean crop. Heavy mulch strongly reduced weed emergence immediately after application, but also protected weed seeds in the soil. When the goal was to deplete the soil weed seedbank, a combination of no mulch and complete weed elimination was the best strategy. Alternating heavy mulch in the soybean years with no mulch and total weed control in the maize year was more advantageous, in terms of weed control, than continuous heavy mulch. Modeling analyses indicated that the density threshold of B. plantaginea necessary to regulate the population over the long term was 64 times smaller than the “tolerable” infestation level when only the current crop yield was considered.
Introduction

Organic soybean production is a fast growing enterprise in southern Brazil, and Parana is the leading state both in total production and number of producers. In 2002, 854 farmers harvested 48 thousand metric tons of certified organic soybean, 11 times more seed than in 1997 (DERAL, 2003), and further expansion is expected. To achieve the “certified organic” status and qualify for organic premiums, fields must pass through a two-year conversion period, during which time management practices must comply with organic standards. This conversion period is characterized by a series of changes in farming practices, comprising regulatory, educational, economic, and biological aspects (Khatounian, 2001). In the biological realm – which is our sole concern in this paper - the most critical bottleneck during the conversion period is the control of weeds. In no-till organic systems, weed control has been accomplished by a combination of manual hoeing and mulching. Mulch is produced on-site from winter cover crops, typically black oat (*Avena strigosa* Schreb.) or annual ryegrass (*Lolium multiflorum* Lam.). The most common rotation of summer crops is soybean—soybean—maize.

During the conversion period, the weed flora reflects previous management practices and is often dominated by *Euphorbia heterophylla* L. or *Brachiaria plantaginea* (Link.) Hitchc. We have observed that *E. heterophylla* is the dominant weed species in systems with a previous history of soybean monoculture, most often in no-till soybeans. *Brachiaria plantaginea* usually dominates systems previously subjected to conventional tillage. The latter weed species is more aggressive, leads to greater losses in crop yield, and is frequently associated with minor populations of *Digitaria* spp., *Echinochloa* spp. or both.

Failures to control weeds during the conversion to organic production are not uncommon, particularly in areas infested with *B. plantaginea*, and the challenge of managing pesticide-free no-till systems profitably is enormous. Given the scarcity of research on the biology of *B. plantaginea*, farmers have attempted to control the weed mainly by trial-and-error initiatives. In addition, the few pieces of research on the biology of *B. plantaginea* (Voll et al., 1995; Voll et al., 1996; Theisen and Vidal, 1999; Rodrigues et al., 2000; Theisen et al., 2000; Skora Neto, 2001) were conducted in pesticide-based production systems. Therefore, the extrapolation of results obtained in pesticide-based to pesticide-free systems may be
inappropriate. The puzzle of efficacious and efficient weed control in organic, no-till soybean comprises numerous questions, including: (1) does the crop sequence during the conversion period affect weed infestation?; (2) how does mulch affect weed seedling density and the soil weed seedbank?; (3) what is the best mulch/weed management strategy combination during the conversion period?; and (4) is it necessary to eradicate B. plantaginea or is there a tolerable density?

We answered these questions in part with the experimental research reported in Chapters 2 and 3 of this dissertation, but important pieces of them remained unanswered. Consequently, to develop answers to these questions, we developed a simulation model based on information available in the literature and on our own previous research and field experience in Parana State. Here, we describe the model and discuss its results with regard to more effective weed management in organic, no-till soybean-based systems in southern Brazil.

Materials and Methods

The life cycle of B. plantaginea in a no-till organic soybean-based rotation was simulated in a model (Fig. 1) built using Stella 7.0.3 (High Performance Systems, 2001) to describe the following situation. Every year, a fraction of the seed population in the soil suffers natural death and another fraction germinates, emerging as seedlings in a crop stand. Mulching may reduce the fraction that emerges. In Parana, most of the emerged seedlings will be eliminated by manual hoeing each year, but some seedlings will mature and become reproductive adults. The reproductive adults will in turn produce seeds in the crop stand of either soybean or maize. Seed predators will eliminate a fraction of the seed produced, but the remaining seeds will be added to the soil weed seedbank, from which the next cycle initiates.

In order to assign values to the parameters in the model, we relied on research reported in the literature, on the experiments reported in Chapters 2 and 3 of this dissertation, and on the experiments reported in the Appendix. In the case of parameters for which no specific information was available, we used values based on our best current knowledge. The
sources of information, parameter values, assumptions, and equations used in the model are reported in the following section.

**Soil seedbank.** Seed depth is a critical factor in the definition of the soil weed seedbank. The total number of seeds and the percentage of seeds that emerge as seedlings depend directly on seed burial depth. Maximum soil depth for *B. plantaginea* seeds to emerge has not been reported in the literature. Nonetheless, Barbosa et al. (1995) and Theisen and Vidal (1999) observed higher germination rates for seeds at a depth of 2 cm than for seeds at 10 cm. If the soil is not tilled, seeds positioned at depths from which they are not able to germinate do not emerge. For our model, we relied on data from Rodrigues et al. (2000) and considered 4 cm as the lowest depth limit for the soil seedbank. As a basis for simulations, the initial number of seeds in the soil was set at 1000 seeds/m², a fairly high infestation according to Skora Neto (2001), Voll et al. (1996), and our own observations. For very high and more normal infestations, we used 4000 seeds/m² and 250 seeds/m², respectively. While performing the calculation of seedbank status, the seed input from the previous season was added, and seeds that died or germinated were subtracted. The order of calculations was subtraction of dead seeds, addition of seed input, and subtraction of seeds that emerged to seedlings.

**Seed death.** The number of dead seeds was calculated by multiplying the number of seeds in the soil by the seed death rate. In each cycle of the model, the number of dead seeds was subtracted from the density of seeds in the soil seedbank prior to calculating emergence.

**Seed death rate.** We assumed an annual death rate of 19%, based on data reported by Voll et al. (1995) obtained from a summer soybean - winter wheat system managed with pesticides.

**Emergence.** We calculated emergence as the product of soil seedbank density and emergence rate, applied as a pulse function in the first of every three time-steps of the model.

**Emergence rate.** We calculated the emergence rate as the product of potential emergence and the mulch factor. The potential emergence was 40%, taken from Rodrigues et al. (2000) and based on a soil seedbank depth of 4 cm.

**Mulch factor.** A reduction in *B. plantaginea* emergence caused by a mulch of *Avena strigosa* Schreb. was incorporated into the model by means of the "mulch factor". This reduction in emergence was represented as a graphic function (Fig. 2) based on two-year averages of
weed seedling density, at mulch levels varying from 0 to 10 t/ha dry weight according to the data obtained from the experiment reported in Chapter 2.

**Mulch quantity.** Mulch quantity was adjusted to suit the various scenarios explored in the simulations, being set at 3 t/ha for “low” mulch, 5 t/ha for “regular” mulch, and 7 t/ha for “high” mulch.

**Seedlings.** Seedlings were calculated as the product of soil seedbank and emergence rate, as a pulse in the second of every three time-steps.

**Weed control efficacy.** This was the percentage of seedlings killed by weed control measures with a basic value of 99%.

**Maturation.** Maturation referred to the development of seedlings into reproductive adults, and was calculated as the product of seedling number and seedling survival \([1 - \text{weed control efficacy}]\). For simulations with cultivation-escaped weed density thresholds, this equation was complemented with a graphic function, the threshold being the maximum density of escaped weeds developing into reproductive adults.

**Seedling death.** This is an artifact of emptying the seedling stock every cycle; otherwise, the software accumulates seedlings from one cycle to the next. Thus, after the number of seedlings surviving the control was sent to maturation, the total number of seedlings was subtracted from the seedling stock.

**Reproductive adults.** This was the number of plants that survived the seedling stage and became reproductive, contributing seeds to the next weed cycle.

**Adult death.** Similar to seedling death, adult death was an artifact of emptying the stock of reproductive adults in each model cycle.

**Seed production.** Seed production occurs in a stand of either maize or soybean, the only summer crops in the rotation. Because maize imposes harsher competition on *B. plantaginea* than soybean, the same number of cultivation-escaped reproductive adults produces fewer seeds in a stand of maize than of soybean. An if/else statement was used to define the time steps in the rotation when each crop was grown, so that the appropriate seed production was selected for the next step of calculations. In our model, we did not consider seed production in the winter for two reasons. First, because germination in winter months is very limited (Rodrigues *et al.*, 2000). Second, because being a warm season grass, *B. plantaginea* tends to
be out-competed by winter crops. For these reasons, weed seed production associated with winter crops is probably negligible compared with seed production in summer crops. Empirical confirmation of this assumption is, however, necessary.

*Seed production when soybean is grown.* In this case, seed production was defined as a graphic function relating cultivation-escaped reproductive adults with seed production (Fig. 3), based on the experiment reported in the Appendix.

*Seed production when maize is grown.* Maize seed production was also defined as a graphic function (Fig. 3), and the empirical data are in the Appendix.

*Seed predation rate.* To our knowledge, there has been no research concerning losses of *B. plantaginea* seeds to granivores. Nonetheless, earthworms, crickets, ants, beetles, birds, mammals, and other organisms may actively feed on seeds and thus eliminate considerable amounts of weed seeds. We assumed a cumulative seed predation rate of 50%, based on data available from the United States and Europe (Liebman, 2001).

*Seed input.* Seed input was the net amount of seeds added to the soil bank after predation occurred. It was calculated as the product of seed production and seed survival of predation \(1 - \text{seed predation rate}\). The seed input was added to the seedbank before restarting each cycle.

While running the model, the values assigned to some of the parameters were altered to explore different potential situations. The parameter values used in each situation are specified in the discussion of results. In most situations, our focal variables were the soil seedbank and/or the seedling density. While the seedbank is an indicator of the potential weed threat, the density of seedlings is of immediate concern for the present crop. Seedling density influences both the total amount of labor time required per unit of land and the critical period for weed control. We have observed that when *B. plantaginea* seedling density is above 100 plants/m², the first cultivation has to be done in the first two to three weeks after planting the crop, depending on climatic conditions. For normal infestation levels in the region, 8.3 man-days are required per hectare, but fewer man-days are necessary as weed density decreases.

When weed density is so low as to inflict little pressure on the crop yield, the control of weeds aims at reducing weed seed production and can be spread over a longer period of
time. For this reason, low seedling densities relieve the time constraint for weed removal and reduce the need for numerous weeding teams, from 8.3 man-days to less than 1 man-day per ha. For the purpose of our simulation, the low seedling density goal was set at 10 plants/m\(^2\), as a compromise between a realistically achievable weed density and a tolerable yield loss at the production field level. However, the relationship between weed density, timing of control, and crop yield loss remains to be quantified.

**Results and Discussion**

Modeling provided insight into the population dynamics of the weed *B. plantaginea* in the context of organic soybean production. Some so-far overlooked aspects of the life cycle of this weed became visible and opportunities for improved management strategies became apparent. The most important of these aspects was the trade-off between reducing seedling density with mulch and reducing the weed seedbank. The model also revealed research gaps that once fulfilled might improve our ability to understand and control this weed, particularly as related to seed predation and other forms of seed mortality. These findings are presented in detail while discussing the answers to each of the questions that led us to build the model.

**Does crop sequence during the conversion period affect weed infestation?**

The rationale for this question is that soybean and maize inflict different competitive pressure on the weed as well as different levels of difficulty to the control of weed seedlings. Maize is more competitive than soybean, causing weed fecundity to be lower than in a soybean stand (see Appendix). In addition, wide inter-rows in maize - around 0.9m, twice as much as for soybean - facilitate the elimination of weed seedlings. From a commercial point of view, crops cannot be sold as organic during the two-year conversion period. For this reason, the third year is usually devoted to soybean, because it then qualifies for organic premiums and commands the highest profits among organic grains.

We tested the effect of two crop sequences during the conversion period, combined with two weed control efficacies, on the seedbank status at planting time of the first certified organic soybean crop. The crop sequences were (1) maize – maize and (2) soybean – maize,
with either 99 or 100% weed control efficacy. With 99% efficacy in seedling control the seedbank increased in both crop sequences, although the increase was slightly more rapid when soybean was the first crop (Fig. 4). Regardless of the crop sequence, if all weed seedlings were eliminated, the seedbank declined from one thousand to 0.6 thousands seeds/m². Thus, the efficacy of weed control is more important than crop sequence per se. In practice, however, total seedling elimination is more likely to be achieved in maize than in soybean.

How does mulch affect seedling density and the soil seedbank?

We knew from previous research that increasing the quantity of black oat mulch mass decreased weed seedling density exponentially (Chapter 2) and thus facilitated weed control. We did not know, however, how mulching would affect the status of the soil seedbank. As a first approach, we simulated the effects of 0, 3, 5 and 7 t/ha of black oat mulch on the soil seedbank and on weed seedling density, assuming 100% weed control to avoid the confounding effect of seedbank replenishment.

Decline of the soil weed seedbank was fastest with no mulch and slowest with the maximum mulch quantity (Fig. 5), which at first seemed surprising. However, a closer examination of the factors determining the decline of the soil seedbank demonstrated the consistency of these results. In each crop cycle, the soil seedbank was depleted as seeds germinated or died. Although mulch quantity did not affect seed death rate in the model, increasing mulch quantity reduced germination rate, so that more seeds remained in the soil. With 0 t/ha of mulch, 40% of the seeds germinated every year compared with only 4.5% germination with 7 t/ha of mulch. These results were consistent with empirical results obtained by Theisen and Vidal (1999), who observed that mulching with black oat increased the survival of B. plantaginea in the soil. Those seeds that did not germinate remained in the soil and contributed to infestation in the future. Therefore, if the main objective is to exhaust the soil seedbank, the best option is no mulch, provided that there is no weed seed production.

Regarding the seedling density, it was around ten times greater with no mulch than with 7 t/ha mulch at the beginning of the conversion period (Fig. 6). However, seedling
density decreased fastest with no mulch, because germination accounted for a 40% decline in the seedbank in each model cycle. On the other hand, the seedling density at 7 t/ha of mulch was consistently low and decreased at a lower pace. In the fourth year there were 18 seedlings/m² for no mulch and 16 seedlings/m² for 7 t/ha of mulch, both densities relatively low and tractable. The simulated reductions in seedling density with intermediate mulch levels were comparable to those obtained empirically by Skora Neto (2001). These comparable results lent support to the outcomes of simulation, because the parameters used for the seedbank decline came from studies other than that by Skora Neto.

Our results revealed a tradeoff between the immediate reduction of seedling density - obtained with heavy mulching - and the longer-term reduction in the soil weed seedbank. Reducing seedling density makes weed control more tractable in the immediate season, whereas exhausting the soil seedbank reduces the overall weed threat in the future. For the sake of simplicity, our simulations assumed no weed seed production, which seems to be a realistic objective only for a short period of time.

**Best mulch/weed management strategy during the conversion period**

In order to make the preceding simulation more realistic, we attempted to facilitate weed management by taking advantage of the biological phenomena involved in the aforementioned tradeoff. We envisioned a weed control strategy consisting of a seed-bank-decreasing phase during the two-year conversion period, followed by an emergence-suppressing phase in the fully certified organic production period. In the first phase, no mulch was used in order to maximize germination from the seedbank, and weed control was total. In the second phase, high mulch quantities of 7 t/ha were used and a residual weed population was considered. Because mulch hinders mechanical weed control, total weed control is more realistic without mulch and heavy mulch is usually associated with a control-escaped weed population.

Weed control in no-till organic soybean in the region consists of manual hoeing and the operator is not supposed to leave weed plants behind. To a major extent, the residual population depends on the visual screening and on the ability of the person doing the job. For this reason, we used absolute maximum values for the residual weed population instead of
defining the residual population as a function of seedling density. The maximum control-escaped population densities for medium and strict control were, respectively, 0.25 and 0.0625 plants/m² (or 2500 and 625 plants/ha). These maxima were incorporated into the model by replacing the equation in maturation with a graphic function, which had a ceiling at the desired residual weed density.

The results of the simulation (Fig. 7) showed that, as far as seedbank depletion is concerned, the two-year-no-mulch-total-control strategy was more effective than continuous heavy mulch. After the two years of no-mulch and total control, the seedbank decreased from 1 to 0.21 thousand seeds/m², but only from 1 to 0.8 thousand seeds/m² with continuous heavy mulch and 625 escaped weed plants/ha. However, the decreased seedbank - resulting from two years of total weed control – started to recover because of the control-escaped weed population associated with heavy mulch. The pace of seedbank recovery increased with increased weed residual population. Seed banks stabilized around year 15 (Fig. 7) at around 2.1 thousand seeds/m² for 2500 residual plants/ha, and at about 0.53 thousand seeds/m² for 625 plants/ha. In contrast, the seedbank continued decreasing under continuous heavy mulch with 625 plants/ha, to stabilize at the same level as that of 625 plants/ha preceded by two years of total control (Fig.7).

Despite the fact that the calculated values for residual weed population and seedbank inherently bear errors embedded in the assumptions of model, the simulation revealed keystones for the design of strategies to control weeds in organic no-till soybean. First, that continuous heavy mulch may be less desirable than it has been historically assumed to be. In the situation we are focusing upon, it seems most realistic and effective to alternate phases of no or little mulched maize coupled with total weed control, with phases of heavily mulched soybean and some inevitable residual weed population. The alternation may also contribute to disruption of the selection of the weed flora associated with heavy mulch. In addition to the benefits in weed management, the alternation provides space for low-mulch-yielding winter cash crops such as wheat.

However, the success of the alternation relies on very shallow cultivation, so deeply buried weed seeds are not brought to the surface. This is not a problem with traditional manual hoeing practices in the region, where the hoe blade is fixed at the handle so that it
works almost parallel to the soil surface, seldom reaching the depth of 1 cm. However, if tractor or draft animal cultivators are used, a new wave of weed infestation is likely to be triggered. The results on Fig. 7 also indicate that the seedbank may be building up even when crop yield is not being affected. This aspect will be explored in the following section.

*Is it necessary to eradicate this weed or is there a tolerable density?*

Although this question seems to be trivial, it relies on a cloudy concept of “tolerable” density. In the shortest-term approach, yield reduction may be the criterion for being tolerable. However, if the objective is to reduce the seedbank to an amenable level, in a long-term approach, then the tolerable weed density may be considerably lower. To explore this question, we set the initial seedbank at 4000, 1000, or 250 seeds/m², representing very high, fairly high and normal infestation levels. To these initial seedbanks, 5 t/ha of mulch were applied and the system was subjected to three levels of control-escaped weed densities, namely 1, 0.25, or 0.0625 escaped-plants/m², respectively, for lax, regular, and strict weed control.

These simulations revealed that the residual weed density defined the size of equilibrium seedbank, regardless of the initial size of the seedbank (Fig. 8). The order of magnitude of the equilibrium seedbank was visible around the tenth year and amounted to 7.3, 1.9, or 0.5 thousand seeds/m² for lax, regular or strict weed control, respectively. These equilibrium seedbanks were associated with annual weed seed production of 3.9, 1.0, and 0.24 thousand seeds/m², and with seedling densities of 620, 150, and 40 plants/m². In terms of weed management, *B. plantaginoides* infestations of 620 and 150 seedlings/m² require control soon after the crop emerges, complemented with a careful second pass, just to prevent yield losses (see Appendix). The 40 seedlings/m² emerging from the lowest seedbank might not require a second pass, although 40 seedlings/m² does not allow for delays in the first pass. In order to achieve a tractable seedling density of 10 plants/ha, the maximum control-escaped weed population would be 156 plants/ha (0.0156 plants/m²), associated with a soil seedbank of 100 seeds/m² and with the annual production of 60 seeds/m².

In regard to the question of the “tolerable” weed density, these results point at contrasting conclusions, depending on how tolerable is understood. If the current crop yield
is the criterion, even the lax-control residual population of 10000 plants/ha may be considered “tolerable”, because yield losses at this infestation level were only 0.5% in maize and 2.7% in soybean (see Appendix). However, the seedbank (3.9 thousand seeds/m²) and seedling density (620 plants/m²) associated with this control level would condemn the field to a high and eternal threat of crop failure. If, for reasons such as wet weather or labor shortage, weed control cannot be accomplished soon after crop emergence, crop losses are inevitable.

If “tolerable” comprises reducing risk and if a tractable density of 10 seedlings/m² is pursued, then the tolerable escaped-weed density would be 156 plants/ha. This implies a further reduction of 98.4% in the “tolerable” control-escaped density based on losses to the crop yield. But even at the level of 156 control-escaped B. plantaginifera plants/ha, careful weed control remains a necessity, because every year 100 thousand seedlings/ha will be emerging and will have to be reduced to 156 plants. The fecundity of B. plantaginifera (Fig. 3) is such that the soil seedbank may be replenished with several thousand seeds/m² in a single season if seedlings are not reduced to the 156-plants/ha level.

Our last considerations make the no-weed-seed-production threshold proposed by Norris (1999) particularly interesting. His proposal is based on the idea that environmentally-friendly weed control is more likely to be achieved if weeds are eradicated by the complete depletion of the soil seedbank. The eradication of B. plantaginifera is certainly difficult to achieve, as demonstrated by Skora Neto (2001), who reported that 5000 seedlings/ha were still emerging after 10 years in which seed production was prevented. Another consideration is whether the eradication of this weed is desirable, when the whole system is analyzed. First, although B. plantaginifera is usually regarded as a noxious weed, it also has provided important services and products to the farming systems of southern Brazil. Its fast growth and natural reseeding has contributed to a reduction in soil erosion in crop fields, particularly in hilly areas (Kranz, 2001). Second, B. plantaginifera is also a valuable forage crop (Lancanova et al., 1988) that has been explored in the region as a spontaneous pasture plant after maize production. Considering these facts, harnessing the biological potential of B. plantaginifera may be a more realistic and desirable goal than eradicating it. To harness its biological potential and at the same time avoid it as a noxious weed, two prerequisites have to be met:
to reduce the seedbank to a tractable size, and to use heavy mulch as a switch to regulate germination as desired.

**How would model assumptions, if inappropriate, affect the results?**

In order to lend confidence to our model, most parameters were initially drawn from empirical sources from experiments conducted under the same soil and climate conditions. The only exception was seed predation rate, for which no empirical evidence was available. However, even empirical data have limits to their applicability, given the specificity of any datum to the conditions in which it was produced. In our case, a general question was to which extent the parameters produced in pesticide-based systems could be extrapolated to organic systems. We were particularly concerned with seed predation rate and seed death rate, for both play crucial roles in the dynamics of the soil seedbank. Because more organisms feeding on seeds are presumed to be present in pesticide-free systems (Liebman and Mohler, 2001), the values used in our model may have underestimated the annual loss of seeds.

In a long-term study comparing conventional, biodynamic and organic management in winter wheat in Switzerland, Pfiffner and Niggli (1996) found that the population of beneficial arthropods was around 90% higher in pesticide-free management. We explored the effect of organic management by assuming that both seed predation and other forms of seed mortality would increase by 50% due to the removal of pesticides from the system. This was an arbitrary value, still to be refined with empirical studies in the region.

The simulation (Fig. 9) showed that the equilibrium soil seedbank with fair weed control (2500 escaped-plants/ha) and 5 t/ha of mulch fell from 1.8 thousand seeds/m², with our basic parameters, to 0.7 thousand seeds/m², with the enhanced seed loss due to organic management. For the purpose of comparison, we also included in Fig. 9 a line representing the simulation with the basic parameters for seed predation and death rate, but strict (625 escaped-plants/ha) - instead of fair - weed control. The equilibrium seedbank with strict weed control was around 0.5 thousand seeds/m². Thus, the results in Fig. 9 show that organic management may reduce the labor time in manual hoeing if natural mechanisms enhance
seed removal from the seedbank. The extent of these losses remains to be examined in future research.

Nevertheless, there is a generalized observation in the region that, when changing from conventional tillage to no-till, the infestation of *B. plantaginea* decreases. We speculate that the decrease in the infestation with this weed may be due to enhanced seed predation, because with no-till most seeds remain on the soil surface, where they are more likely to be found by predators. But this, as well as enhanced predation and natural seed death, remains to be confirmed.

**Final remarks on the model and on the results**

The model we used can be seen as a set of equations centered on the seedbank, all other elements being intermediate stages ultimately stemming from or contributing to the seedbank. Thus, it is not surprising that variables affecting the seedbank directly, such as annual seed input, natural seed death rate, and germination/emergence exert a direct influence on the model results. Only two factors defined the seed input, namely, weed fecundity and weed seed predation. Fecundity had an overwhelming influence because of the extraordinary capacity of *B. plantaginea* to produce seeds abundantly at very low plant densities (Fig. 3). While fecundity was determined empirically in the region (see Appendix), predation was estimated based on available data from different sites. Even if predation were much higher, as discussed in the previous section, its influence would be felt only after some time (Fig. 9), because a few seeds escaping predation would be enough for massive contributions to the seedbank if seedlings were allowed to reproduce. Therefore, although predation has the net effect of reducing fecundity in the previous season, the inherent high fecundity of *B. plantaginea* in the current season buffers its previous effect. For this reason, continuous weed control was necessary even at very low seedbank densities. Seed death rate is different because it works as a residence time, so that the net effect of increased death rate is the acceleration of the rate of decline in the seedbank.

When defining the basic parameters in the model, we opted to remain on the conservative side, always working in the extreme of the parameter-value range more favorable to the weed. This decision certainly affected the results in our simulations and
provided them with a security margin. The most important security measures refer to assuming that *B. plantaginea* seeds were reintroduced into the soil, and to predation and natural death rates. In fact, seeds are no reintroduced into the soil, but rather sit on the soil surface, where predation and natural death are likely to be more intense. For these reasons, weed control in real organic conditions may be less demanding than our simulations indicated.

**Conclusions**

For practical purposes, the crop sequences maize/maize or soybean/maize during the two-year conversion period do not lead to distinct levels of weed infestation in the first certified organic soybean crop. However, maize may be a better choice if advantage is taken of the wider spacing of maize rows to conduct more efficacious control.

Although mulch is a potent tool to reduce weed emergence immediately after mulch is applied, it brings along a tradeoff of providing better protection of the soil weed seedbank. When the goal is to deplete the weed soil seedbank, no mulch and complete weed seedling elimination is the best strategy. For these reasons, alternating heavy mulch in the soybean years with no mulch and total weed control in the maize year is more advantageous, in terms of weed control, than continuous heavy mulch.

The “tolerable” *B. plantaginea* control-escaped population for a tractable seedling infestation is 64 times smaller than the tolerable infestation when only protection of the current crop yield is considered. Strategies to reduce the pressure of this weed on crops and at the same time benefit from its forage value and erosion control properties require the maintenance of a small seedbank in the soil.

**Acknowledgements**

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References


Figure 1. Stella-TM model developed to explore *B. plantaginea* population dynamics.

Figure 2. Graphical function converting mulch quantity into mulch factor.

Figure 3. Graphical functions converting *B. plantaginea* reproductive adults into seed production in a stand of soybean or maize.

Figure 4. Effects of crop sequence and weed control on *B. plantaginea* soil seedbank during the two-year conversion period. Mulch quantity was 5 t/ha, seed predation rate 50%, and seed death rate 19%.

Figure 5. Decline in *B. plantaginea* soil seedbank under different quantities of mulch, with prevention of seed production. Seed predation rate was 50%, and seed death rate 19%.

Figure 6. Decline in *B. plantaginea* seedling density under different quantities of mulch, with prevention of seed production. Seed predation rate was 50%, and seed death rate 19%.

Figure 7. Evolution of the soil seedbank under either continuous 7 t/ha mulch with 625 *B. plantaginea* (Bp) escaped plants/ha, or no-mulch and total weed control in the first two years, followed by 7 t/ha mulch and 625 or 2500 escaped plants/ha.

Figure 8. Effect of the initial value of the soil seedbank combined with control-escaped weed populations on the evolution of the soil seedbank. Mulch quantity was 5 t/ha.

Figure 9. Effect of enhanced seed predation rate and natural death rate on *B. plantaginea* seeds in the soil with 2500 escaped plants/ha. For comparison, the effect of normal predation and death rates with 625 escaped-plant/ha was included. Mulch was 5 t/ha. P stands for predation, ND for natural death.
Figure 1

Figure 2
Figure 3

<table>
<thead>
<tr>
<th>Reproductive adults (plants/m²)</th>
<th>Seed production (1000 seeds/m²)</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>50</td>
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</tr>
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</table>

in soybean: \( y = \exp(3.5 - \exp(0.87 - 0.40x)) \)
\( r^2 = 0.99 \)

in maize: \( y = \exp(2.6 - \exp(1.2 - 0.98x)) \)
\( r^2 = 0.97 \)

Figure 4

<table>
<thead>
<tr>
<th>Time under organic management (years)</th>
<th>Soil seedbank (1000 seeds/m²)</th>
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</thead>
<tbody>
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<td>0</td>
</tr>
<tr>
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<td>2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

- soybean - maize, 99% weed control
- maize - maize, 99% weed control
- any sequence, 100% weed control
Figure 5

Soil seedbank (seeds/m²) vs. Time under organic management (years)

- 7 t/ha mulch
- 5 t/ha mulch
- 3 t/ha mulch
- 1 t/ha mulch
- no mulch

Figure 6

Seedlings (plants/m²) vs. Time under organic management (years)

- no mulch
- 3 t/ha mulch
- 5 t/ha mulch
- 7 t/ha mulch
Figure 7

- total control, then 2500 plants/ha
- total control, then 625 plants/ha
- 625 plants/ha, all the time

Figure 8

- 10000 escaped plants/ha
- 2500 escaped plants/ha
- 625 escaped plants/ha
Figure 9

Soil seedbank (1000 seeds/m²)

- 50% P + 19% ND, 2500 escaped plants/ha
- 75% P + 28.5% ND, 2500 escaped plants/ha
- 50% P + 19% ND, 625 escaped plants/ha

Time under organic management (years)
GENERAL CONCLUSIONS

The studies reported in this dissertation allowed for a deeper insight on the control of the weed *B. plantaginea* in no-till organic soybean. Knowledge advanced in three major areas: quantification of the suppressive effect of black oat on the weed, quantification of weed seed production under distinct crop environments, and development of weed control strategies based on combinations of mulch and weed control.

Quantification of the suppressive effect of black oat on *B. plantaginea*

The increase in black oat mulch from 0 to 10 t/ha reduced population density of *B. plantaginea* exponentially and the weed biomass linearly. The intensity of weed reduction varied between growing seasons. From 0 to 6 t/ha mulch, reductions in weed population density occurred rapidly and less so at 6 or more t/ha. Concentrating mulch on the planting furrow reduced the density of in-row weed population, but the reductions did not improve crop production. The effect of black oat mulch on soybean depended on the use of other complementary weed control practices. When weeds were hoed manually, mulch quantity did not affect soybean biomass or grain yield. However, when black oat mulch was the only weed control practice, varying mulch from 0 to 10 t/ha increased both soybean biomass and grain yield linearly.

Weed seed production under distinct crop environments

When growing in association with soybean, seed production of *B. plantaginea* decreased exponentially with increasing levels of mulch, but the pace of decrease in seed production varied between years. Seed production increased proportionally to increases in weed biomass production. However, even at the lowest levels of weed biomass associated with 10 t/ha of black oat mulch, weed seed production was still above one thousand seeds/m², and complementary weed control was required to reduce weed infestation in subsequent crops.
When associated with maize, the weed seed production increased as the weed-free period increased from 0 to 60 days after planting maize. Without control, the weed produced up to seven thousand seeds/m², and caused an 80% loss in maize yield. Weed plants that emerged after the 40-day weed-free period produced at the very most 50 seeds/m².

Seed production was highest in pure weed stands and decreased as emergence was delayed, but production varied between years. *Brachiaria plantaginea* stands emerging in mid November, at the same time as maize, produced up to 47 thousand seeds/m². In mid January, the latest emerging time, maximum seed production was nine thousand seeds/m².

**Weed control strategies combining mulch and weed control**

For practical purposes, increasing black oat biomass in winter, for use as mulch in summer, seemed to be central in the general strategy to control the weed. The need for complementary manual weeding in the summer crop diminishes to the extent that mulch suppresses the emergence of *B. plantaginea*.

Although mulch was a potent tool to reduce weed emergence immediately after being applied, the technique brings a tradeoff for better protection of the soil weed seedbank. When the goal is to deplete the soil weed seedbank, no mulch and complete weed seedling elimination may be a better strategy than continuous heavy mulch.
APPENDIX

Effect of *Brachiaria plantaginea* (Link) Hitchc. population density on its seed production in a pure stand, and in association with maize or soybean

In order to support the model discussed in Chapter 4, three experiments were conducted to quantify the relationship between the weed density and its seed production in a pure stand, and in association with maize or soybean. The experiments were planted in adjacent areas, in the same location as the activities reported in Chapters 2 and 3, in the 2002-2003 season.

As a pure stand or associated with maize, the densities of *B. plantaginea* were 0, 2, 4, 16, and 48 plant/m², with three replications. In the association with soybean, the weed densities were 0, 1, 2, 4, 8, and 48 plant/m², with 6 replications. All weed densities were achieved by thinning to the desired levels the weed cohort that emerged soon after the crops were planted. Plot size, experimental area, dates of planting harvest, and cultural practices were the same as reported in Chapter 2, for soybean, and in Chapter 3, for both maize and pure stand *B. plantaginea*. Measurements included seed production of the weed and of the crops.

Results

For the sake of brevity, data for seed production of *B. plantaginea* in all three experiments are presented together (Figure 1). Although the curves cannot be compared in the strict statistical sense, the fact that they were produced in adjacent areas sharing the same characteristics allows some comparison, for the purpose of our modeling.

For all three situations, 2 plants/m² produced about half as many seeds as 48 plants/m², and 4 plants/m² produced three fourths as many as 48 plants/m² (Fig.1). The maximum weed seed production was affected by growing environment, although the fact that the experiments were independent precludes conclusions based on statistics.
Figure 1. Seed production of *B. plantaginea* as a function of its population density in a pure stand, or associated with maize or soybean. Londrina, Brazil, 2002-2003 season. Vertical bars are standards deviations of the means.

\[
y = \exp(3.9 - \exp(0.96 - 0.71x)) \quad r^2=0.99
\]

pure stand: \( y = \exp(3.9 - \exp(0.96 - 0.71x)) \quad r^2=0.99 \)

with soybean: \( y = \exp(3.5 - \exp(0.87 - 0.40x)) \quad r^2=0.99 \)

with maize: \( y = \exp(2.6 - \exp(1.2 - 0.98x)) \quad r^2=0.97 \)

Figure 2. Grain yield of soybean as a function of *B. plantaginea* population density in the crop. Londrina, Brazil, 2002-2003 season.

\[
y = 3.4 - 0.062x \quad r^2 = 0.99
\]
Grain yield of both soybean and maize decreased as weed density increased. In the case of soybean, the decrease was linear (Fig. 2), while for maize (Fig. 3) the decrease was hyperbolic. As regards soybean, my focus was on the effect of low densities of the weed, so I prioritized the range from 0 to 8 plants/m$^2$, to simulate different levels of control-escaped weed densities. However, the absence of weed densities in the wide interval between 8 and 48 plants/m$^2$ in soybean hindered the reliability of regression, because the crop might produce a non-linear response to weed density in this interval.

Figure 3. Grain yield of maize as a function of $D. pfanagmea$ population density in the crop. Londrina, Brazil, 2002-2003 season. Points are means of three replications.

\[ y = \frac{1}{0.29 + 0.0096x} \]
\[ r^2 = 0.91 \]

Definition of the low density goal for simulation purposes

In our simulations, we worked towards reducing the weed seedling density so as to reduce the risk of yield loss and alleviate the time constraint to weeding operations. For regular weed infestations, most farmers presently spend, on average, 8.3 man-days/ha in
manual hoeing for soybean, but there are farmers spending less than one man-day/ha, in fields with very low weed densities. These low weed densities typically result from concentrated efforts in preventing seed production for several years, and, in some cases, for more than one farmer generation. Under low weed densities, the removal of weeds aims at preventing weed multiplication rather than at safeguarding crop yield.

In order to define a working level of “low” weed density for the simulations, I had to find a compromise between an acceptable level of yield loss and a realistic time frame to reduce weed infestation. If the low density were set too low, the time necessary to achieve it would be disproportionally long. On the other hand, if the low density were set at a too high level, the risk of crop loss would increase.

Figure 4. Soybean crop with eight *B. plantaginea* plants/m², 40 days after planting. Londrina, Brazil, 2003. At this weed density, and at this time, there seems to be very little effect of the weed on the crop.
Our field observations indicated that a density of 8 *B. plantaginea* plants/m² would cause minimum or even no yield loss if weeds were removed up until the sixth or seventh week after soybean planting date (Fig. 4). In fact, even the pure stand of the weed in a density of 16 plants/m², in a cohort emerging simultaneously with the crop, had not closed its canopy 40 days after soybean planting date (Fig. 5).

Figure 5. Pure stand of *B. plantaginea* at the density of 16 plants/m². The plants emerged on the same date as those in Figure 4, in an adjacent field. Londrina, Brazil, 2003.

On the basis of these observations, for simulation purposes, I assumed that a density of up to 10 seedlings/m² might be weeded as late as six weeks after planting the crop, with little, if any, loss in crop yield. However, if these weeds were not removed, the yield loss caused by 10 weed plants/m², calculated with the regressions in Fig. 2 and 3, would be 18% for soybean and 33% in maize. This implies that 10 seedlings/m² may reasonably be assumed to be a tractably low weed density, but is still not a tolerable infestation level.
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