Chapter 4

Weed Management in the Soybean Crop

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1. Introduction

Inadequate weed control is one of the main factors related to decrease in soybean production. Weeds compete with crops by resources (water, light and nutrients). This competition is important mainly in the initial stages of crop development, due to possible losses in production that can be up to 80% or even, in extreme cases, hinders harvest operations [1].

Weeds have traits which confer them great aggressiveness even in adverse environments. High number of seeds, seed dormancy, discontinuous germination, effective dispersal mechanisms and population heterogeneity, are very important for weed establishment during crop development. During this phase, weeds may rapidly capture resources and occupy space; this is often linked to their competitive ability, because rapid growth requires the prompt and efficient conversion of resources into biomass. Thus, the yield is reduced and production costs increase, resulting in a decrease in farmer's income.

Besides reducing crop yield, weeds can cause other problems, like reduce grain quality, cause loss and difficulty during harvesting and serve as hosts of pests and diseases. The role of weeds as alternate hosts for soybean crop pests and diseases and their interference with cultivation operations resulting into higher costs of production must not be over looked. Weeds can also release toxins highly harmful to crop development. However, despite weeds show many negative aspects, they can also show advantages, like: providing food for the wildlife; potential source of germoplasm; recycling nutrients and preventing soil erosion.

Competition is defined as the condition that exists when requirements of one or more organisms living in a community cannot be obtained from available resources. Because competition involves many direct and indirect factors, it is often, preferable to consider it as interference of a plant community on another one, rather than competition. Interference is a natural phenomenon in a plant community where limited resources exist, and tends to be more harmful to competitors as more equal are the environmental demands and vegetative habit between them.

In agricultural ecosystems, weeds show competitive advantages over crop plants, because the aim of crop breeding is to increase the economic productivity, and this is almost always accompanied by a decrease in the competitive potential. Another important aspect in weed interference is the capacity of weeds in reducing or preventing cultivated plants to get access to resources. Thus, when those are limited, weeds almost always stand out, due to its higher efficiency in either capturing or using them. It is up to farmers and agronomists to use weed control methods and cultural practices in order to increase the chances of the crop overcoming weeds in the competition for resources.

Reduction in weed competition is perfectly achievable with the wide spectrum of tools and herbicides existing in the market, but weed management strategies are not related solely to the use of herbicides [2]. Weed control consists in suppressing the development and/or decreasing the number of weeds per area, until an acceptable levels for the coexistence between the species involved is reached, with minimum damages to both. In soybean crop, weed control can be achieved by using one or more control methods that are: preventive, mechanical, chemical, biological and cultural. Farmers can also use the integrated weed management (IWM), in which two or more of these methods are adopted.

The IWM approaches incorporate multiple tactics of prevention, avoidance, monitoring and suppression of weeds, undergirded by the knowledge of the agroecosystem biology [3]. The development of IWM was motivated by a desire to provide farmers with systematic approaches to reduce reliance upon herbicides [4] and, consequently, retard the selection of herbicide-resistant biotypes. The use of integrated control facilitates weed control during all crop cycle. The cultural practices, like soil tillage, fertilization, cultivar choice, sowing time, number of plants per area and crop rotation should be done in order to benefit crop development, and in some cases can reduce or eliminate the need of using other control methods.

The aim of this chapter is to summarize basic information about weed interference and weed management in the soybean crop, subsidizing technicians in the adoption of suitable positions regarding problems with weed control.

2. Competition between weeds and soybean by abiotic and biotic factors

Plants genetically improved by human action, aiming increases in productivity, lost part of their aggressive nature and therefore the ability to survive and compete against adversities imposed by the environment. Thus, most of the weeds show higher extraction capacity and utilization of environmental resources compared to cultivated species. The competition for limited resources or not, directly or indirectly, can be described as: *spatial* competition, which is generated by the physical dominance of a given species over another, simultaneously; a second classification that could be addressed is *temporal* competition, that results from competition over the time in which the crop is under development [5].

The various aspects of competition occurring between weeds and crops may also be named *ecological*, being classified as to their nature in biotic or abiotic [5]. The former are those from the live action elements of the ecosystem, such as predation, parasitism, commensalism, morphophysiological factors among others. The latter is a result of the action of non-living environmental factors, such as climatic and soil factors.

2.1. Competition between soybean and weeds for biotic factors

The biotic factors that determine the increased competitiveness of certain species over others are: plant size and architecture, growth rate, extension of root system, dry mass production, increased susceptibility to environmental elements (such as frost and dry spells), greater leaf area index and greater capacity for production and release of chemicals with allelopathic properties [6].

Morphophysiological traits of plants influence the competitive relationship between crop and weeds. Plant height and development cycle, for example, are features that have been positively associated with competitive ability in soybean; cultivars with higher cycle length and height reduce seeds production and size of weed species due to the increase in competitiveness of the crop [7].

Moreover, yield losses due to competition tend to be higher the more similar are the individuals, i.e. their morphophysiological traits, reaching maximum stress within the same species, because in this case neighboring plants compete for the same resources and occupy the same ecological niche [5].

2.1.1. Plant traits indicators of higher competitive ability

The competitive ability of crops can be expressed according to the crop ability to compete with weeds, reducing the production of seeds and dry mass accummulation by weeds, which is called *suppressive ability*. There is also the crop ability to *tolerate competition* with weeds, when under competition the crop is capable of maintaining yields almost unchanged [8, 9]. For Jordan [10], the suppressive ability should be preferred because it reduces seeds production by weeds and its benefits remain for subsequent growing seasons, while tolerance to weeds limits its benefits only to the current growing season. It is worth noting that in case crops do not have the ability to suppress weeds, the probability of yield reduction is increased, regardless of crop tolerance to competition.

Olofsdotter [11] remarks that several traits which confer competitive ability are genetically changeable, and can be manipulated by plant breeding, as they are elucidated by research. According to the author, it is necessary to identify one or more traits as well as their genetic variability in the crop. After demonstrating its variability, studies are needed to indicate the mechanisms involved and the environmental effect on the expression of these traits. Finally, it is necessary to involve geneticists and breeders in the identification of genes coding for the desired trait, as well as to evaluate the usefulness of indicators in the selection, i.e. if the character can be selected.

Differences in competitive ability between soybean cultivars with weeds have been reported by Bussan et al. [12]; Jannink et al. [9]; Lamego et al. [13]; Bianchi et al. [14] and Fleck et al. [15]. Suitable conditions for crop planting, such as moist soil, proper and uniform planting depth, close contact between seed and soil, as well as certified quality seeds, are essential to ensure competitive advantage to the crop by promoting the rapid emergence and establishment of uniform populations. In a study with soybeans, higher size of seeds resulted in seedlings with higher hypocotyl expansion rates, which may constitute a favorable feature in adverse conditions of emergence as in the case of soil crusting following heavy rainfalls [16].

2.1.2. Exploring competitive traits

The use of cultural methods for weed management can minimize weeds interference on soybean. Among the most efficient management practices for the suppression of weeds, the population density of the crop can be highlighted, as well as equal plants arrangement, development cycle and root growth of the crop.

2.1.3. Population density

In areas of agricultural production, the density of cultivated plants is kept constant along the field while weeds density varies with the degree of infestation, which is determined by the soil seed bank richness [17, 5]. According to these authors a variation occurs in the crop/weeds density ratio, making important to understand in competition studies not only the influence of density in the competition process – additive studies, but also the influence of the variation in the species proportion in the population - substitutive studies [5].

The duration of the period planting-emergence is also affected by seeding rate, temperature and soil moisture, planting depth and seed traits [18]. The duration of this period changes seedling height and subsequently, the intra-specific competitive ability. According to this author, the effects on the duration of this period are more evident under high plant densities.

2.1.4. Emergence speed

The use of high vigor seeds, which provide immediate plant emergence after planting, is important for the cultural management of weeds. In the dispute for limited environmental resources, the advantage is granted for plants that exhibit early establishment. A growing plant must quickly seize space and other resources, and its competitive success depends on the anticipated use of them. Plants stop growing when its area is restricted by competitors, so that the last individuals appear to grow very little due to shading. Thus, a fast emergence is often more important than the spatial arrangement of individuals in determining the competitiveness of the population [19].

Plants that have rapid and uniform emergence can compete more effectively for environmental resources [13]. These authors reported that the emergence rate is positively correlated with the ability of soybean cultivars to compete with weeds. In this sense, Fischer & Miles [19] formulated theoretical principles in which the greater the rate of development of a plant, the higher the shoot and edaphic volume explored. The first seedlings to emerge, probably present higher yields because they have priority in using water, light and nutrients, i.e., they occupy the niche early [20].

Plants that use resources earlier will shade the others, reducing the amount and quality of light available for the neighbors [20]. Weeds which establish before the crop, with big size and high number of seeds, will increase its frequence in the soil seed bank and keep infesting subsequent crops [6]. Another problem resulting from the establishment of crops later in relation to weeds is the need for increasing herbicide rates for their control [21].

Ecologically, weeds are less demanding in true growth factors in relation to crop plants, which confers great competitive ability for them [6]. In a study conducted by Carranza et al. [22], it was found that the relative intraspecific competition (yield loss per weed unit) decreased when weed population increased. According to the authors, plants that emerged earlier were 1.5 times more competitive than those who had delayed emergence.

Crop management practices such as use of high quality seeds, appropriate management of soil and planting at the recommended time and depth significantly increase chances of crop plants to be more competitive. The adoption of these practices, along with the use of cultivars with fast establishment, are key points to accelerate crop growth and focus on their success in competition with weeds.

2.1.5. Soybean plants arrangement and its relationship with weeds

The better arrangement of crop plants may be more important for those species with less potential for branching or tillering. The increase in grain yield of soybean with narrow row spacing has been demonstrated in several studies [23, 24, 16]. Positive results are obtained with this practice especially in wet years with the use of early maturing cultivars [16], in soil well supplied with nutrients [24], and also with late planting [25].

In the case of planting soybean after the recommended period, Board et al. [25] found that the reduced spacing resulted in higher dry mass of branches of plants at maturity (R8), which was highly correlated with grain yield. They also observed that the yield components of the branches, such as number, length and number of nodes in the branches, were higher in the smaller spacing, justifying the greater yield in reduced spacing system in late planting.

The dry weight of soybean can be used as a criterion to choose between wider or narrower spacings between rows. For Board & Harville [26], if plant dry mass of late-maturing cultivars, in the stage R8, is at least 800 g m^{-2} in wide spacing, probably no benefit will be obtained by reducing row spacing. However, this value should be used carefully because it may cause lower levels of total dry mass, for example, if planting is accomplished out of the indicated time interval (early or late planting).

The removal of weeds by using reduced spacing was evaluated by Legere & Schreiber [27]. These authors found that in the middle of the soybean growing season, the contribution of pigweed (*Amaranthus retroflexus*) for total dry mass per area was 43% in soybean row spacing of 76 cm, but was only 24% for rows spaced in 25 cm. In this work, in any situation of weed infestation, grain yield was always higher in the smaller row spacing.

In some situations, however, an adequate suppression of weeds may not occur. Burnside [28] found no difference in yields between spacings of 38 and 76 cm in the presence of weeds during different periods of coexistence. Also, Nice et al. [29] found no effect on the population of sicklepod (*Senna obtusifolia*) by reducing soybean row spacing, when there was no increase in the population of the crop. Under higher populations and smaller row spacings, a reduction in population and seed production of sicklepod was observed.

Another advantage of the smaller row spacing is the possibility of using lower doses of certain herbicides due to the effect of the additional shading of weeds by crop plants. Young et al. [30] observed that the reduction in row spacing from 76 cm to 38 cm, increased weed control after herbicide application. In contrast, glyphosate presented weed control superior to 90% at row spacing of 19 cm, controlling between 75% and 90% of the weeds when crop was planted at a spacing of 76 cm.

The set of morphological and physiological traits of cultivars defines its ability to compete with weeds for environmental resources [31, 14]. However, the competitive ability of cultivars can be altered by agronomic practices [32]. Weed population and its emergence delay in relation to the crop, often define the relationships of competition between species [33].

According to Lamego et al. [13] soybean cultivars with early emergence, fast leaf area expansion, high growth rate, and higher plant height in early stages, are more capable of competing with weeds. On the other hand, weed species with fast emergence, like the ones from Genus *Brachiaria*, *Digitaria*, *Euphorbia, Bidens* and *Raphanus*, among others, are able to compete earlier for environmental resources in relation to soybean [34, 13, 14, 35]. Rizzardi et al. [36], studying competition between soybean and *Euphorbia heterophylla*, *Ipomoea ramosissima, Bidens pilosa* or *Sida rhombifolia*, reported that several management practices can minimize their interference on soybeans, like the use of more competitive cultivars, correction of soil fertility and the adequacy of the arrangement of plants.

2.2. Competition between soybean and weeds for abiotic factors

2.2.1. Competition for water

Water is the most limiting factor essential for plant growth and production [37]. The rainfall and soil moisture strongly influence the growth of weeds, affecting, therefore, competition with crops [38]. Certain morphological and physiological traits determine the ability of plants to compete for soil water. In nature, species with C_3 metabolism predominate in temperate regions, while the C_4 are prevalent in tropical and subtropical regions. The relative distribution of C_3 and C_4 species depends on the temperature during the growing season of the plants [5].

Species with carbon metabolism by the cycle C_4 are usually more efficient in the use of water (higher WUE); as a consequence, they produce more biomass per unit of water consumed.

According to Patterson and Flint [39], *Amaranthus hybridus*, with C_4 metabolism, showed higher WUE compared to soybean plants. When soybean was compared to beans and with some weed species (*Euphorbia heterophylla*, *Bidens pilosa* and *Desmodium tortuosum*), bean was the plant which used the water more efficiently from the beginning of the cycle; soybean was the plant with the highest biomass accumulation rate and greater WUE along the cycle; *Desmodium tortuosum* was the most efficient in the capture and use of water during the vegetative stage and *Bidens pilosa* after flowering [40]. In another study, soybean and the weed *Xanthium strumarium* showed similar WUEs [41].

2.2.2. Competition for light

Light is the most disputed factor in competition, highlighting the importance of plant height in defining the competitive ability of crops [5]. The high ability of plants to intercept the incident light in the canopy is a desirable feature when crop is under competition with weeds [42]. Light interception by the canopy is dependent on plant density and arrangement, branching rate, plant height, leaf area, distribution of leaves, leaf angle, angle of leaf blades and dry mass accumulation [42]. Cultivars that concentrate photosynthates in leaves, i.e., high leaf area ratio (LAR), have greater potential for ground cover [43] and consequently the greater will be their competitive ability with weeds.

The initial growth rate is directly related to light interception and use in earlier stages of the plant cycle, allowing a greater leaf area development which provides to crop a higher competitive ability [32, 44].

The rate of biomass accumulation in shoots becomes a key factor for competitive success [40]. Earlier emergence of weeds in soybean, in relation to crop emergence, increased grain yield losses of soybean [13]. Evaluating the efficiency of capture and utilization of light by soybean and bean against the weeds *Bidens pilosa*, *Euphorbia heterophylla* and *Desmodium tortuosum*, Santos et al. [45] observed the highest accumulation rate of dry mass and the largest leaf area index for soybean, indicating its greater ability to capture light and shade the competing plants. Bean, especially after flowering, was more effective in draining its photosynthates for leaf formation.

2.2.3. Competition for nutrients

Nitrogen (N), phosphorus (P) and potassium (K), are of great importance for understanding yield losses by crops [46]. According to Anguinoni et al. [47] the capacity for absorption of nutrients in plants depends on the magnitude and the morphology of the root system and its efficiency in absorption of these elements. Crops with fast root growth maximizes the use of water and nutrients [48] so an accelerated growth of the root system constitutes a desirable feature for better nutrient use [49].

Under field conditions, in a study of competition for nutrients between soybean or bean with the weeds *Euphorbia heterophylla*, *Bidens pilosa* and *Desmodium tortuosum*, Bidens pilosa was the plant species with higher leaf area increasing following N applications and soybean accumulated the highest biomass in its root system, which tended to decrease with the addition of N. *B. pilosa* and *E. heterophylla* increased its biomass as N was increased [46]. The total content of N in soybean leaves decreased as the dose of N was increased; however, for all weed species, N content in leaves increased according to the doses of N. The higher efficiency of roots in N uptake was found for bean plants. *B. pilosa* and *E. heterophylla* were the most efficient species in N use. The supply of N favored more the weed species not belonging to the legume family than soybean and bean; therefore, an inadequate management of N in these crops may exacerbate the problem of weed interference [46].

For the same species evaluated in the previous experiment, soybean was the species that showed the largest increase of P in root biomass as the dose of this nutrient was increased. *Desmodium tortuosum*, soybean and *B. pilosa* showed greater response to the addition of increasing doses of P in relation to dry matter accumulation [50]. The efficiency of P uptake by *D. tortuosum*, soybean and common bean decreased as the dose was increased. *E. heterophylla* and bean, performed worst on the efficient use of available P in soil.

3. Critical period of weed interference

The critical period of weed control (CPWC) has been defined by Silva et al. [51] as a window in the crop growth cycle during which weeds must be controlled to prevent quantitative and qualitative yield losses. In essence, the CPWC represents the time interval between two separately measured crop-weed competition components: (1) the critical timing of weed removal (CTWR) or the maximum amount of time early-season weed competition can be tolerated by the crop before it suffers irrevocable yield reduction, and (2) the critical weed-free period (CWFP) or the minimum weed-free period required from the moment of planting, to prevent unacceptable yield reductions [52]. The former component is estimated to determine the beginning of the CPWC, whereas the latter determines its end. Results from both components are combined to determine the CPWC. Theoretically, weed control before and after the CPWC may not contribute to the conservation of the crop yield potential.

The beginning and end of the CPWC determined using the functional approach will depend on the level of acceptable yield loss (AYL) used to predict its beginning and end. Many studies report 5% as the maximum AYL. But it can be adjusted depending on the cost of weed control and the anticipated financial gain [52].

Silva et al. [53], evaluated the CTWR in soybean, cv. BRS-244 RR in low, medium and high weed density and observed that the CTWR was 17 days after emergence (DAE) in low infestation area and 11 DAE in medium and high infestation area, considering 5% of tolerance of crop yield decrease. According to the authors, weed interference during the full crop cycle reduced soybean grain yield in 73%, 82% and 92%, for low, medium and high weed density, respectively. Meschede et al. [54], evaluated the CPWC of *Euphorbia heterophylla* in soybean crop, cv BRS 133, under low seeding rate, and observed that the presence of weeds caused daily yield loss of 5.15 kg ha^{-1}, whereas their absence provided a daily yield gain of 7.27 kg ha^{-1}. According to the authors, weed-crop coexistence for up to 17 DAE did not cause any negative effect on crop yield, and the maximum length of time in which weeds had to be controlled to prevent crop yield losses was 44 DAE; the CPWC was, therefore, from 17 to 44 DAE. Carvalho and Velini [55], observed that weeds germinated 20 days after the emergence of soybean, cv. IAC-11, did not affect crop yield.

Different results of CPWC showed that the degree of weed interference on crops depends on the infesting plant community (species, density and population), on the crop (cultivar, spacing and density) and environment (soil, climate and management). Thus, it is necessary a greater number of studies to create a data base and in the future create models to predict the adequate moment of weed control for each situation.

4. Weed control methods in soybeans

According to Hart [56], the population of weeds may be divided into three components: the active seed, the inactive/dormant seeds and plants.

The active seed (ready to germinate) can come from three sources: production by plants, seeds from outside the system and seeds that were dormant and that, for some reason, have become active. The dormant seed can also come from three sources: active seeds, plants and outside the system.

Weed management involves activities directed at the weeds (direct management) and, or, the system formed by soil and crop (indirect management). The direct management refers to the direct elimination of weeds using herbicides, manual or mechanical action and biological action. In soil management (indirect management) the relationship active and inactive seed can be worked. In this case, germination of the weeds should be increased before controlling them, using techniques such as the sequential application of desiccants.

According to Silva et al. [7], weed control possibilities include preventive, cultural, mechanical, biological and chemical methods. However, to maintain the sustainability of agricultural systems, it is important to integrate these control measures by observing the characteristics of soil, climate and socioeconomic aspects of the producer. The achievement of an environmentally and economically compatible integration requires deep knowledge of the available strategies, promoting balance with the management measures of soil and water, as well as the control of pests and diseases. To adopt any measure of control, the medium in which the weeds are should be treated as an ecosystem that can respond to any changes imposed, thus, not limited to the application of herbicides or using any other method alone. Furthermore, efforts will encourage the improvement of the quality of life, both of the farmer directly involved, as the whole population which will benefit from the supply chain.

4.1. Preventive control

It is harder to control weeds once they establish themselves, so preventing foreign weeds from entering a new area is usually easier and costs less than controlling after they have spread.

According to Silva et al. [57], the preventive control of weeds is the use of practices aimed at preventing the introduction, establishment and, or, spread of certain problematic species in areas not yet infested by them. These areas can be a country, a state, a municipality or a piece of land inside the farm.

In federal and state levels, there are laws regulating the entry of seeds into the country or state and its internal commercialization. Under these laws are the tolerable limits of seeds of each weed species and also the list of prohibited seeds per crop or crop group.

Locally, it is the responsibility of individual farmers or cooperatives, to prevent the entry and spread of one or more weed species that may become serious problems for the region. In summary, *the human element is the key to preventive control*. The efficient occupation of the agroecosystem space by the crop reduces the availability of appropriate factors for growth and development of weeds, and can be considered an integration between preventive and cultural method.

Choosing the right cultivars is actually the first step in successfully establishing a crop. In the soybean case, there is a large number of cultivars adapted to different regions of the world.

Some of the measures that can prevent the introduction of the species are: use of high purity seeds, clean thoroughly machines, harrows and harvesters; carefully inspect seedlings acquired with soil and also all the organic matter (manure and compost) from other areas; clean irrigation canals; quarantine of introduced animals, etc. [5].

Chauhan et al. [58] affirm that most crops have their seeds contaminated with weeds, especially when weed seeds resemble the size and shape of crop seeds. Contamination usually happens during the time of crop harvesting when weeds that have life cycles similar to those of crops set seeds. When even a small amount of weed seeds is present, it may be enough for a serious infestation in the next season. The idea should be to minimize the weed infestation area and decrease the dissemination of weed seeds from one area to another or from one crop to another. Control of weed species is achieved by reducing plants and propagules to the point at which their presence does not seriously interfere with an area of economic use. The planning of post-infested weed control programs should be done in such a way that the build-up of weed seeds is reduced drastically within a short period. Proper care should be taken to restrict the weed seed bank size in the area by using integrated methods of weed control. In undisturbed or no-till systems, seeds of weeds and volunteer crops are deposited in the topsoil [59, 60, 61]. Therefore, an appropriate strategy is needed to avoid high weed infestations and to prevent unacceptable competition with the emerging crop [60].

4.2. Cultural control

The competitive ability of weeds largely depends on the time of emergence in relation to the soybean, in such a way that, if the crop germinates faster, and also occurs a delay on the emergence of weeds, competition will be reduced [5].

According to Silva et al [57], cultural control is the use of common practices for the proper management of water and soil as crop rotation, variation of crop row spacing, living mulches, cover crops etc. Amending the soil, neutralizing the aluminum content and increasing the pH, favors the crop and not certain weed species adapted to acid soils conditions and high contents of Al. Fertilization applied at the planting furrow is a common practice, and also favors soybean, so the fertilizer do not stand so close to the weeds in the inter-rows. These practices help to reduce the seed bank of weeds. It consists, therefore, in using their own ecological traits, both from crops and weeds, in order to benefit the establishment and development of crops.

One of the main practices is crop rotation. Its benefits depend on the selection of crops and their sequence in the system. Continuous cultivation of a single crop or crops having similar management practices allows certain weed species to become dominant in the system and, over time, these weed species become hard to control [58]. According to Kelley et al. [62], soybean production is improved by using crop rotation as a management practice. Numerous studies have shown decreased yield when soybean was grown continuously in monoculture than when rotated with another crop [63, 64, 65]. In the short-term, benefit of crop rotation was increased soybean yield, which would likely increase soybean profitability. In the long-term, rotations with high residue-producing crops, such as wheat and grain sorghum, significantly increase total soil C and N concentrations over time, which may further improve soil productivity [62].

Variation of the spacing or plant density in the row is another practice that can contribute to the reduction of weed interference on the crop, depending on the architecture of the cultivated plants and weed species. The reduction of spacing between rows often provides competitive advantage for most crops over shading sensitive weeds. In this case, by reducing the spacing between rows, provided it does not exceed the minimum limit, there is increased light interception by the canopy of cultivated plants. This effect is dependent on factors like the type of species to be cultivated, morphophysiological traits of genotypes, weed species present in the area and season and weather conditions at the time of its emergence, as well as environmental conditions [66, 67, 68].

The main goal of using cover crops for weed control is replacing an unmanageable weed population with a manageable cover crop. This is accomplished by selecting the phenology of the cover crop to preempt the niche occupied by weed populations [69]. They have been used to manage weeds in soybean [70, 71, 72, 73]. According to Silva et al. [57], green covers are crops that usually are very competitive with weeds. Lupine, vetch, ryegrass, turnips, oats and rye are used in southern Brazil. In the subtropics, velvetbean, crotalarias, pigeon pea, jack-bean and lab-lab can be used. Its main effect is to reduce the seed bank and also improve soil physical-chemical conditions. However, these plants may also have inhibitory effects over others and can reduce infestations of some weed species after desiccation or incorporated in soil, and must be carefully chosen in each case. The presence of the mulch creates conditions for the installation of a dense and diverse microbiote in the soil, especially in the surface layer, with a high amount of microorganisms responsible for the elimination of dormant seeds by deterioration and loss of viability.

Both the composition and the population density of a weed community are influenced by the level of mulching in the production system [74]. The mulch has physical (interference on germination and seedling survival rate), chemical (allelopathic effect) and biological (installation of a dense and diverse microbiocenose in the topsoil) effects on weeds [75,76].

Thus, of the numerous known advantages of no-tillage - a practice that keeps the soil covered by crop residues - stands out the improvement in weed control. Trezzi & Vidal [77] found that the presence of residues of sorghum shoot (4 t ha^{-1}) was sufficient to reduce 91, 96 and 59% the population of *Sida rhombifolia, Brachiaria plantaginea* and *Bidens pilosa*, respectively.

According to Silva et al. [57], in no-tillage, using systemic herbicides as desiccants, together with not revolving the soil, whether to produce corn for grain or silage, excellent results were found in the management of purple nutsedge (*Cyperus rotundus*). In two years in this system, it is possible to reduce population levels of nutsedge in favor of no-tillage, compared to conventional tillage, for both corn and beans, to the order of 90 to 95%, being that in three years, the reduction on the bank of tubers in the soil can reach more than 90%. The greatest benefits of no-tillage system in the integrated management of purple nutsedge (*Cyperus rotundus*) are obtained due to the integration of chemical control provided by the use of the systemic herbicide for desiccation of the vegetation at pre-sowing, to the cultural control exercised by the lack of soil disturbance and consequent lack of fragmentation of the vegetative structures of the nutsedge, and to the adoption of highly competitive crops, mainly by light, such as corn and beans. Thus, the population levels of purple nutsedge can be reduced, especially during the crop development period that is sensitive to weed interference, or approximately 45 days after emergence, as not to cause reductions in infested crop yields. Furthermore, the ability of sprouting of the nutsedge tubers collected in the soil under integrated management is diminished over time, remaining dormant [78].

4.3. Mechanical control

According to Silva et al. [57], weed plucking, or weeding, is the oldest method of weed control. It is still used to control weeds in home gardens and in the removal of weeds between crop rows, when the main method of control is the use of a hoe.

The manual weeding made with a hoe is very effective and still widely used in our agriculture, especially in mountainous regions, where there is subsistence agriculture, and for many families, this is the only source of work. However, in a more intensive agriculture in larger areas, the high cost of manpower and the difficulty of finding workers when necessary and in the desired quantity, make this method only complementary to others, and should be done when the weeds are still young and the soil is not too humid. It can assume great importance in seed production fields, being a good alternative for using isolated or as a complement for other control methods [79].

According to Silva et al. [57], mechanized cultivation, made by cultivators pulled by animals or tractors, is widely accepted in Brazilian agriculture, being one of the main methods of weed control on properties with smaller areas planted. The main limitations of this method are the difficulty of controlling weeds in the crop rows, low efficiency when performed in wet conditions (wet soil), and it is also inefficient to control weeds that reproduce by vegetative parts. However, all the annual species, when young (2-4 pairs of leaves), are easily controlled in conditions of heat and dry soil. Cultivation breaks the intimate relationship between root and soil, suspending the absorption of water, and exposes the roots to unfavorable environmental conditions. Depending on the relative size of weeds and crops, the displacement of the soil on the row, using special hoe cultivators, can cause the burial of seedlings and thereby promote weed control even in the rows of the crop.

4.4. Biological control

Biological control is the use of natural enemies (fungi, bacteria, viruses, insects, birds, fish, etc.) capable of reducing weed populations, reducing their ability to compete. This is maintained by the population balance between the natural enemy and the host plant. It should also be considered as biological control the allelopathic inhibition of weeds [6].

According to Charudattan & Dinoor [80], bioherbicide is defined as a plant pathogen used as a weed-control agent through inundative and repeated applications of its inoculum. In the United States and many other countries, the prescriptive use of plant pathogens as weed control agents is regarded as a "pesticidal use" and therefore these pathogens must be registered or approved as biopesticides by appropriate governmental agencies. Currently, one fungus species is registered as bioherbicide in the United States for use in soybeans. Collego®, based on *Colletotrichum gloeosporioides* f.sp. *aeschynomene*, is used to control *Aeschynomene virginica* (northern jointvetch), a leguminous weed, in soybean and rice crops in Arkansas, Mississippi, and Louisiana [80].

Charudattan & Dinoor [80] also state that, among the limitations of biocontrol of weeds by plant pathogens, the most important are the limited commercial interest in this approach to weed control due to the fact that markets for biocontrol agents are typically small, fragmented, highly specialized, and consequently the financial returns from biocontrol agents are too small to be of interest to big industries; and the complexities in production and assurance of efficacy and shelf-life of inoculum can further stifle bioherbicide development. For instance, the inability to mass-produce inoculum needed for large-scale use is a serious limitation that has led to the abandonment of several promising agents. The authors conclude that plant pathogens hold enormous potential as weed biocontrol agents. In addition to the use of plant pathogens as biocontrol agents, it is likely that pathogen-derived genes, gene products, and genetic mechanisms (e.g., hypersensitive plant cell death and herbicidal biochemicals) will be exploited in the near future to provide novel weed management systems. On the other hand, the present over-reliance on chemical herbicides and the tendency to base weed-management decisions purely on economic considerations, at expense of the exclusion of ecological and societal benefits, is a serious limitation that could stifle biological control.

4.5. Chemical control

There are several advantages in using herbicides: pre-emergence control, eliminating the weeds precociously; hits targets that the hoe or cultivator does not reach, like the weeds in the crop row; reduces or eliminates the risk of damage to the roots and to young plants; do not alter soil structure and, therefore, reduces risk of erosion; controls more efficiently the perennial weeds; reduces the need for labor; increases the speed and efficiency of the control operation per unit area, reducing the cost per treated area; controls the weeds for a longer period, when the use of a cultivator is impossible in view of the crop growth; and can be used in rainy periods, when the mechanical control is not efficient and when labor is required for other activities. However, it has the disadvantage of requiring skilled labor, because, if done improperly, can poison the crop, the environment and, especially, the applicator himself. Although herbicides are very effective in controlling weeds, they may promote the development of resistant biotypes, a fact that would further exacerbate the problem within an area [81].

According to Oliveira Jr. et al. [82], the most common strategies used in the management of both cover crops and weed vegetation in areas of no-tillage are reduced to three: desiccation immediately before sowing, between seven and ten days before sowing or anticipated drying.

These authors undertook a study aimed to evaluate the interaction between tillage systems and weed control in post emergence in soybean with these three strategies. They concluded that, although desiccation in different management systems have been effective, the anticipation of desiccation in anticipated management favored the emergence and initial soybean development, providing greater productivity gains, given the infestation conditions. The management system also affected the flow of weed emergence after soybean emergence, with fewer reinfestations in the anticipated management system, due to the control of initial flows given by the second application of this management system. Management applied at planting and ten days before planting, hindered the development of soybean, resulting in lower productivity, while anticipated management provided the highest yield.

Procópio et al. [83] carried out a study in which they compared the effects of tillage systems on the control of the weeds *Digitaria insularis*, *Synedrellopsis grisebachii* and *Leptochloa filiformis* before soybean planted in no-till. The authors found satisfactory control and prevention of regrowth of *D. insularis* and *L. filiformis* when glyphosate was applied five days prior to soybean planting or when the sequential application of glyphosate and paraquat + diuron was done. Sequential applications of the mixture paraquat + diuron were not effective in controlling or preventing the regrowth of *D. insularis* and *L. filiformis* and the weed *S. grisebachii* proved to be tolerant to glyphosate. The use of a non-residual herbicide such as glyphosate fails by not controlling weeds emerged after application, and eventually produce seeds that can easily replenish the seed bank [84]. Adding a residual herbicide to glyphosate can be a consistent management to control the weeds as they germinate and promotes long-term activity which controls plants which emerge later [85].

According to Arregui et al. [86], there are several soil-applied broadleaf herbicides that effectively control weeds like *Ipomoea* spp., *Commelina* spp. and *Sida spinosa*. Chlorimuron and sulfentrazone reduce *Ipomoea* spp. density [87]; *S. spinosa* density decreased with imazaquin, metribuzin and sulfentrazone applications [87] and with cloransulam and diclosulam [88].

The same authors [86] affirm that soil-applied herbicides as metribuzin and imazaquin may be beneficial reducing early season competition of weeds, particularly those inherently more tolerant to glyphosate such as *Parietaria debilis* or *Commelina erecta*, which survive pre-planting glyphosate applications. Likewise, when dry conditions are observed during vegetative soybean growth, glyphosate applications could be less effective for weed control and the resulting competition could reduce soybean yields.

Hager et al. [89], in a study to examine the influence of herbicide application timing and dose on efficacy of six soil-applied herbicides for common waterhemp (*Amaranthus rudis*) control in soybean, found that sulfentrazone controlled this weed better and reduced its density more than other herbicides.

Nosworthy [90], evaluating broadleaved weed control and economics of conventional and glyphosate-containing herbicide programmes in glyphosate-resistant soybean planted in wide rows, found that pre-emergence herbicides followed by glyphosate, controlled *Ipomoea lacunosa* L. eight weeks after emergence (WAE). *I. hederacea* var. *integriuscula* Gray control with pre-emergence herbicides followed by glyphosate was 100% with similar control from chlorimuron plus sulfentrazone followed by lactofen, whereas control following the single glyphosate application was 84%. *Amaranthus palmeri* S. Wats. control nine WAE was 100% following single or sequential glyphosate applications, while control ranged from 76% to 96% with pre-emergence herbicides followed by lactofen. However, early season weed interference when a single application of glyphosate was delayed until four WAE reduced soybean yields an average of 389 kg ha^{-1} compared to pre-emergence herbicides followed by glyphosate.

5. Principles of integrated weed management

The concept of Integrated Weed Management (IWM), a component of Integrated Pest Management, has been proposed (i) to decrease the density of weeds emerging in crops, (ii) to reduce their relative competitive ability (in order both to preserve crop yields and to limit the replenishment of weed seed bank), and (iii) to control emerged weeds using non chemical techniques, with the overall aim of reducing the need for herbicide application at the cropping system level [91]. IWM advocates the use of all available weed control options such as: plant breeding, fertilization, crop rotation, tillage practices, planting pattern, cover crops and mechanical, biological and chemical controls. To define the correct weed management strategies, it is necessary to know the ability of the weed species, in relation to the crop, to compete for water, light and nutrients, which are factors responsible for decreasing crop yield [6].

Usually, it is not taken into consideration that a good program of weed management should allow for maximum production in the shortest time, the maximum sustainable production and minimal environmental and economic risk. Wilson et al. [92] in a study to compare the Ohio farmer model to a weed scientist decision model about management of weeds, concluded that farmers understand but do not practice IWM. The failure to adopt may be attributed to gaps in their understanding of the human role in weed dispersal, their focus on the risks associated with weeds without recognition of their ecological benefits, and the tendency to overlook risks associated with management.

Therefore, to accomplish the IWM, it is required knowledge in botany, plant physiology, molecular biology, climatology and application technology, among others.

The strategies for the integrated weed management in different weed species can be divided as short or long-term. Measures such as weeding or direct employment of herbicides (chemical control) can be considered as short-term, accounting for only temporary control, requiring new applications to each crop season. In the case of long-term measures, the use of cultural practices and control by other biological agents, has permanent character and take into account more pronounced changes in different agronomic practices. From this, results the integrated management, which should integrate prevention and other control methods that promote short (mechanical and chemical methods) and medium and long-term (cultural and biological methods) control.

According to Chauhan et al. [58], any single method of weed control cannot provide season-long and effective weed control. Therefore, a combination of different weed management strategies should be evaluated for widening the weed control spectrum and efficacy for sustainable crop production. The use of clean crop seeds and seeders and field sanitation (irrigation canals and bunds free from weeds) should be integrated for effective weed management. Combining good agronomic practices, timeliness of operations, fertilizer and water management, and retaining crop residues on the soil surface improve the weed control efficiency of applied herbicides and competitiveness against weeds. In Canada, for example, integrating superior cultivars with a high seeding rate and the earliest time of weed removal led to a 40% yield increase compared with the combination of a weaker cultivar, the lowest seeding rate, and the latest time of weed removal [93].

According to Bernards et al. [94], the development of an IWM program is based on a few general rules that can be used at any farm:

a. use agronomic practices that limit the introduction and spread of weeds, preventing weed problems before they started;

b. help the crop compete with weeds; and

c. use practices that keep weeds off balance and do not allow weeds to adapt.

Combining agronomic practices based on these rules will allow the farmer to design an IWM program for his reality. There is not a single recipe for all conditions and years. The plan will need to be changed and adjusted to a particular farming operation and season. The goal is to manage, not eradicate weeds.

6. Herbicide resistant weeds in transgenic soybeans

Soybean is a crop characterized by the high consumption of herbicides. Chemical control is the most usual, given the characteristics of practicability, efficiency and speed on its execution.

Most of the farmers in Brazil and the world adopt the chemical method for weed control. This is because this technology is very efficient, has attractive cost compared to alternative methods, is easy to use and is professionally developed. However, most producers have only an immediatist and economical vision of weed control and this could lead to environmental problems in the medium and long-term. Although it is public domain that repeated applications of herbicides with the same mechanism of action on a genetically diverse population of weeds may cause strong selection pressure and evolution of resistance [95], it has been a common practice in many parts of the world. As a consequence, the population of herbicide-resistant weeds has expanded rapidly in several regions, making it a hard solution problem in many areas with intensive agriculture. Evidence suggests that the appearance of resistance to a herbicide, in a plant population, is due to the selection of pre-existent resistant biotypes, because of the selection pressure exerted by repeated applications of the same active ingredient, finding conditions for propagation and prevalence [96].

In 2005, transgenic soybean was officially released for planting in Brazil. From this moment on, several products and product combinations have been replaced by a single active ingredient, the glyphosate. Glyphosate is a systemic herbicide used for postemergence control of grasses and broadleaved weeds [97]. In transgenic soybean, it is used in single or sequential applications, at doses and times that will vary according to each scenario.

Currently, the technology of glyphosate-resistant soybean, readily accepted and adopted by the producers caused the use of this herbicide to expand, with average of three applications of glyphosate per cycle of soybean, at desiccation and two after crop emergence. Furthermore, the glyphosate is the primary herbicide for several crops such as fruits, coffee, eucalyptus and desiccation for no-tillage [96].

The technology of glyphosate-resistant soybean allows to reduce or eliminate the need to apply other herbicides for the management of different weed species, which contributes to increased selection pressure and emergence of resistant biotypes. Moreover, some aspects of population dynamics of weeds and the possibility of selecting glyphosate-tolerant species must be considered. The type of management and herbicides used in an area cause changes in the type and proportion of species which compose the local population. This is explained by the fact that herbicides do not control evenly the species in the area; so, some end up being benefited and multiply. In these situations, a low occurrence of plants in the area can become a serious problem for the producer. Thus, the repeated and continuous use of the same herbicide or herbicides with the same mechanism of action, makes the selection of species inevitable [98].

Conyza canadensis is an example of problematic weed in soybeans, in which were detected cases of resistance of biotypes from this species to glyphosate in various parts of the world in transgenic soybeans fields. Experiments conducted by Vargas et al. [99], Moreira et al. [100] and Lamego & Vidal [101] demonstrated that application of 360 g a.e. ha^{-1} of glyphosate is enough, under greenhouse studies, to distinguish between resistant or susceptible biotypes of Conyza bonariensis and C. canadensis.

The resistance factors (GR_{50}) ranged between 7 and 11 for *C. canadensis* [100] and between 10 and 15 [100] and 2.4 [101] for *C. bonariensis*. It is noteworthy that determining the resistance level of suspect populations supports the decisions on strategies to control these biotypes.

Up to date, 23 cases of glyphosate resistant weeds were found in weed species worldwide, described in Table 1.

Weed species	Occurrence/observation	Type of resistance
1. Amaranthus palmeri	USA/2005*	Multiple resistance to ALS and EPSPs inhibitors
2. Amaranthus tuberculatus	USA/2005	Multiple resistance, triple (ALS, Protox and EPSPs inhibitors) and double (ALS and EPSPs inhibitors)
3. Ambrosia artemisiifolia	USA/2004	Multiple resistance to ALS and EPSPs inhibitors
4. Ambrosia trifida	USA/2004	Multiple resistance to ALS and EPSPs inhibitors
5. Bromus diandrus	Australia/2011	
6. Chloris truncata	Australia/2010	
7. Conyza bonariensis	South Africa, Spain, Brazil, Israel, Colombia, USA/2003, Australia, Greece, Portugal	Multiple resistance to Photosystem I and EPSPs inhibitors
8. Conyza canadensis	USA/2000, Brazil, China, Spain, Czech Republic, Poland and Italy	Multiple resistance to ALS and EPSPs inhibitors and to Photosystem I and EPSPs inhibitors
9. Conyza sumatrensis	Spain and Brazil/2009	
10. Cynodon hirsutus	Argentina/2008	
11. Digitaria insularis	Paraguay and Brazil/2005	
12. Echinochloa colona	Australia/2007, USA and Argentina	
13. Eleusine indica	Malaysia/1997, Colombia and USA	Multiple resistance to ALS and EPSPs inhibitors
14. Kochia scoparia	USA/2007 and Canada	Multiple resistance to ALS and EPSPs inhibitors
15. Leptochloa virgata	Mexico/2010	
16. Lolium multiflorum	Chile/2001, Brazil, USA, Spain and Argentina	Multiple resistance to ALS and EPSPs inhibitors, ACCase and EPSPs inhibitors, triple resistance to ALS, ACCase and EPSPs inhibitors
17. Lolium perenne	Argentina/2008	
18. Lolium rigidum	Australia/1996, USA, South Africa, Spain, Israel and Italy	Multiple Resistance, double (Photosystem II and EPSPs inhibitors), triple (ACCase, Photosystem I and EPSPs inhibitors), quadruple (ALS , ACCase, EPSPs and dinitroanilines inhibitors)
19. Parthenium hysterophorus	Colombia/2004	
20. Plantago lanceolata	South Africa/2003	
21. Poa annua	USA/2010	
22. Sorghum halepense	Argentina/2005 and USA	
23. Urochloa panicoides	Australia/2008	

* Observation year of the first resistance case. Source: Weed Science [103]

Table 1. Glyphosate (EPSPs inhibitor) resistant weed species, countries of occurrence and type of resistance.

6.1. Management of herbicide resistant weeds in soybean

The rational management of herbicides with different mechanisms of action is a very important practice. Furthermore, the use of herbicides with little soil residual activity and optimization of doses and number of applications reduces the selection pressure, decreasing the risks of selection of plant resistance to herbicides. Another very efficient technique for the management of weeds consists in using mixtures of herbicides with different mechanisms of action. In this case, the prevention of resistance is based on the fact that the active ingredients efficiently control both biotypes of the same species, i.e., the biotype resistant to a herbicide is controlled by another active ingredient of the mixture [98]. It is noteworthy that the herbicide mixture of different mechanisms of action as a means of management and prevention of resistance is more efficient when the reproductive system of the weed is self pollination, since the genetic recombination of different alleles which confer resistance is less likely to occur in relation to allogamous plants.

Due to the numerous cases of herbicide-resistant weed biotypes in Brazil, several studies were performed looking for alternatives to control these plants, finding that the use of herbicides with different mechanisms of action is a viable alternative for managing resistance [103]. Table 02 shows alternative herbicides suitable for soybean according to the resistant species in the area.

Weed	Alternative herbicides
Lolium multiflorum/ post-emergence	Fluazifop-p, Haloxyfop-r, Clethodim, Sethoxydim
Lolim multiflorum/ desiccation	Paraquat and Ammonium-Glufosinate
Conyza bonariensis and *Conyza canadensis*/ post-emergence	Clorimuron-ethyl
Conyza bonariensis and *Conyza canadensis* / desiccation	Paraquat + Diuron, Ammonium-Glufosinate, Clorimuron-ethyl and 2,4-D

Table 2. Alternative herbicides to control glyphosate resistant weeds in soybean crop used in Brazil.

Weed resistance is an evolving phenomenon in world and, in certain cases, may restrain the use of some herbicides. Therefore, weed resistance to herbicides should be managed through the use of alternative strategies associated to the application of herbicides. Crop rotation is a good strategy to break the life cycle of weed, preventing its dominance in the area. When the same cultural techniques are applied, year after year, in the same soil, the interference of these weeds is greatly increased. When the main goal is the weed control, the choice of the rotating crop should fall on plants with very contrasting growth habits and cultural characteristics [98]. Thus, when using crops with different physiological needs, a change occurs in weed species from one crop to another and, if it becomes necessary to use herbicides, there is a greater chance they will have different mechanisms of action. The rotation is an effective method both in preventing the appearance of resistant biotypes as in managing installed resistance.

Only with a rational management and using several control methods will the resistance be mitigated and the likelihood of the emergence of new cases minimized [98].

7. Final comments

The challenge of agriculture sustainability requires solving the trade-off between producing satisfying levels of agricultural products, both in terms of quantity and quality, and reducing the environmental impacts and preserving non renewable resources. Weed management is a key issue, because herbicides are the most sprayed pesticides around the world and they are some of the mostly found contaminating substances in the surface and below-ground waters. Therefore, it is necessary to adopt correct strategies for weed management, but for that it is necessary to know the ability of weed species, present in a given area, in relation to the crop, to compete for water, light and nutrients, factors responsible for decreasing crop yield. Simple measures like choosing the correct cultivar, adopting correct tillage practices, using cover crops and crop rotation are responsible for decreasing the use of herbicides and, consequently, contribute for environmental sustainability.

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