Australian Journal of Crop Science AJCS

Aust J Crop Sci. 18(09):555-563 (2024) ISSN:1835-2707
https://doi.org/10.21475/ajcs.24.18.09.p87

Perspectives of adopting integrated weed management in Brazil

Geide A. Figueiredo Junior[1], Andréia C.S. Hirata[2], Bianca A.B. Martins[3], Patricia A. Monquero[4*]

[1]Field Research Manager at CSBP Fertilisers, Kwinana Beach WA, Australia
[2]Research Scientist and Technical Director at Sao Paulo Agency for Agribusiness Technology, Sao Paulo State Government – Brazil
[3]Global Herbicide Research - Herbicide Tolerance Trait Development at Bayer, Germany
[4]Weed Science Professor at the Federal University of São Carlos - Brazil

[*]Corresponding author: pamonque@ufscar.br, https://orcid.org/0000-0002-9123-1861

Submitted: 10/01/2024

Revised: 25/04/2024

Accepted: 28/04/2024

Abstract: Extensive agricultural production areas have made Brazil a key global producer of food and fibres, and a major consumer of herbicides. The country also excels in the field of genetically modified crops. However, challenges like limited technical support for small stakeholders and economic factors have made weed resistance problematic across various cropping systems in Brazil. Despite its growing importance, integrated weed management still faces hurdles in its full adoption. This paper discusses integrated weed management techniques within Brazil's production chains and explores management possibilities within the current technological and economic frameworks. A literature review focused on integrated weed management and its adoption in Brazilian cropping systems was conducted. It is crucial to note that the choice of integrated management techniques should be based on local conditions and challenges, technological levels, and a balance of cost, productivity, sustainability, and diversity. The paper also covers the dynamics of integrated management in response to climate change and emphasizes the significance of community involvement and education. It highlights recent and emerging technologies for managing herbicide-resistant weeds, and how this knowledge can advance integrated weed management in Brazil.

Keywords: alternative management; herbicide resistance; new technology; resistance evolution.
Abbreviations: ALS_ acetolactate synthase; ACCase_ acetyl-CoA carboxylase; RR_ roundup ready; GM_ genetically modified; IWM_ integrated weed management; ILPF_ integrated livestock-forest-cropping system.

Introduction

Weeds reduce crop yields and the quality of produce by delaying or interfering with harvests, contaminating animal feed (including poisoning), obstructing water flow, acting as plant parasites, and serving as green bridges for pests and diseases. Weeds are widespread and cause approximately US$32 billion in crop losses annually worldwide (Kubiak et al., 2022). Globally, of the two million tons of pesticides used each year, herbicides account for 47.5%, insecticides 29.5%, fungicides 17.5%, and other pesticides 5.5% (Sharma et al., 2019). In Brazil, herbicides have comprised 62% of total pesticide use from 2016 to 2020 (FAO, 2020). Indiscriminate herbicide use has led to significant challenges in crop cultivation as well as environmental and public health issues.

In Brazil, selection of herbicide-tolerant and resistant weed species started in the 1970s due to the repeated use of the same active ingredients. Over the years, this issue has escalated across various crops. Challenges with weeds resistant to commercially available herbicides, including those inhibiting Acetolactate Synthase (ALS) and Acetyl-CoA Carboxylase (ACCase) predominantly in soybeans were deemed unsustainable by farmers due to low efficacy and high control costs. The introduction of transgenic soybeans tolerant to glyphosate, known as Roundup Ready® (RR) soybeans, offered a solution. These factors explain the rapid adoption of RR technology by soybean farmers (Vargas et al., 2016).

Weed science researchers face significant challenges due to the rise in herbicide-resistant weeds. Brazil reported its first case of herbicide resistance in 1993. To date, 57 unique cases have been identified, including 19 with multi-resistance (resistance to more than one herbicide mode of action) and 38 with single-mode resistance. These cases involve 28 different weed species, both grasses and broadleaf plants, across various cropping systems. They are most common in broadacre crops such as soybeans, cereals, wheat, corn, cotton, and rice, as well as in beans, fruits, and orchards (Heap, 2024).

Glyphosate has been extensively used in agriculture for over 25 years. RR soybeans, the first transgenic glyphosate-tolerant crop, were approved in Brazil in 1998 and have been legally cultivated since 2005. This technology was rapidly adopted, with glyphosate-tolerant soybeans becoming the fastest-adopted technology in the country's agricultural history. By the 2021/2022 season, 98% of Brazil's soybean crop used this technology, making it the world's second-largest producer of genetically modified (GM) seeds, after the United States.

Additionally, 88% of corn and 78% of cotton grown in Brazil are GM (Croplife, 2023). These three crops alone contribute 44% to Brazil's Agricultural Gross Production Value (GPV) and accounted for 48% of Brazilian agribusiness exports, totalling US$ 77 billion in 2022 (MAPA, 2023).

Although glyphosate has a lower risk for resistance evolution in plants, it raises significant concerns due to its repetitive use, often at rates exceeding those recommended on the label (Christoffoleti et al., 2016). The history of GM soybean cultivation in Brazil includes illegal introduction of RR soybeans, initially in the South and later in the Midwest, prior to official approval. During this period, RR soybeans were grown without the technical monitoring and management practices needed to safeguard the technology (Adegas et al., 2017). After the introduction of RR soybeans, weed control in these crops was almost exclusively conducted using glyphosate.

The typical chemical management for glyphosate-tolerant soybeans includes a pre-plant burn down using glyphosate, often mixed with other herbicides that have pre- or post-emergent activity. After crop emergence, most growers rely solely on glyphosate, applying it two or more times during the growing season. However, this practice has accelerated selection of glyphosate-resistant weed biotypes, such as *Lolium multiflorum* (Italian ryegrass), *Conyza* spp. (fleabanes and horseweed), *Digitaria insularis* (sourgrass), *Eleusine indica* (goosegrass), and *Amaranthus hybridus* (smooth pigweed), as well as tolerant species like *Richardia brasiliensis* (white-eye), *Ipomoea* spp. (morning-glory), and *Commelina* spp. (dayflower). The emergence of glyphosate resistance has significantly complicated weed management in many soybean growing regions (Heap, 2023; Christoffoleti et al., 2016).

Glyphosate-resistant biotypes of *Lolium multiflorum* (Italian ryegrass), *Digitaria insularis* (sourgrass), and *Conyza* spp. (fleabanes and horseweed) currently infest approximately 4.2, 7.7, and 8.2 million hectares, respectively. Managing these resistant weeds, which emerge from the continuous use of herbicides with the same modes of action, represents one of the biggest challenges in crop production (Adegas et al., 2017). Herbicide tolerance has now expanded beyond glyphosate to other crops. The herbicides involved include ammonium glufosinate; 2,4-D; dicamba; imidazolinone herbicides; isoxaflutole; and sulfonylurea herbicides. Some of these genetically modified crops also incorporate insect resistance (Krenchinski et al., 2019).

Brazil has recently enacted Law nº. 1459/2022, known as the new Agrochemicals Law, which introduces significant changes to the regulations surrounding the approval, use, and marketing of pesticide products. Effective on December 28, 2023, the law includes the following key provisions: 1) reduction in the timeline for analysing pesticide registration requests from 36 months to 24 months, expediting the approval process for new technical products; 2) a ban on pesticides only in cases deemed to pose an unacceptable risk, marking a high risk to human health and the environment. This change refines the rules and clarifies prohibitions related to the concept of "danger;" and 3) adjustment of fines for violations, which previously were US$4,132 (based on an exchange rate of R$4.84/US$1 as of December 28, 2023). Under the new law, they range from US$413 to US$413,223, depending on the severity of the infraction. Fines may be doubled for repeat offenses (Agência Senado, 2023).

Challenges and benefits of implementing Integrated Weed Management in Brazil

The increasing evidence of biodiversity loss in agricultural landscapes, including reduction or disappearance of many weed species (Fried et al., 2009), highlights the urgent need for alternative strategies to maintain stable and sustainable agricultural production. A deeper understanding of ecosystem services related to global biodiversity in agroecosystems and their impact on agricultural production is critical. This knowledge is essential for forecasting the future availability of ecosystem services and developing sustainable management strategies (Dainese et al., 2019).

In intensive agricultural systems, the reliance solely on herbicides for weed management often overlooks other viable control methods. Integrated Weed Management (IWM) utilizes a variety of techniques to achieve sustainable weed control, offering environmental, technical, and economic benefits. While herbicides are a component of IWM, they are not the sole focus. IWM encourages the use of several non-chemical weed control options, tailored to specific factors such as the type of crop, weed species and infestation level, climate conditions, growth stages of weed and crop, the critical period of weed-crop competition, available resources, and yield objectives.

In this context, IWM is seen as a pivotal tool for enhancing sustainability in cropping systems. It promotes a shift from *simplistic* to *diversified* weed control strategies, integrating various approaches to tackle the challenge effectively.

From April to June 2018, a survey was conducted among growers and consultants to assess their perceptions and challenges regarding cropping systems and weed management in Brazil. The survey included 343 participants, primarily growing soybeans (73%) and corn (66%), representing 21 of the 27 Brazilian states. Most respondents were agronomists (69%), with the remainder being university and industry representatives (22%), growers (21%), and consultants (9%). According to the Brazilian Institute of Geography and Statistics (IBGE) in 2020, these stakeholders manage a total of 5.7 million hectares, which is part of the 78 million hectares of Brazilian territory used for crops and planted forests.

The survey also revealed that in addition to using herbicides, 45% of the participants employ mechanical weed control methods, and 75% use cultural methods such as no-tillage and crop rotation. Furthermore, 61% of the respondents incorporate cover crops to suppress weeds and enhance the physical-chemical properties of the soil (Oliveira et al., 2020).

Despite the rise in herbicide resistance cases, agricultural producers perceive herbicides as easier, faster, and more cost-effective tools for weed management. Generally, it is simpler to manage weeds with herbicides than with non-chemical methods. Consequently, many farmers are uncertain about the return on investment regarding time and money when it comes to non-chemical weed control strategies.

In Brazil, where approximately 90% of the population is urban, there is less reliance on labour, further encouraging the intensive use of pesticides. The latest agrarian census in Brazil, conducted in 2017, reported 15 million people working in agriculture, with almost 2 million aged over 65, and only 6% having university-level education. This lack of knowledge and adherence to traditional methods can restrict the options available for pest management (Pereira et al., 2022).

Despite the importance of the IWM theme and growing interest in this approach, its adoption in cropping systems is not as widespread as the theory suggests. One significant factor influencing this scenario is the access to technical assistance.

As of the most recent data, only 20% of Brazilian agricultural establishments receive any form of technical guidance. Technical guidance and public rural extension have shown a reduction between the 2006 and 2017 agricultural censuses. However, other sources of technical guidance, such as self-guidance at large-scale farms and through cooperatives, have seen considerable growth. Agricultural consulting firms, often focusing on larger properties and agricultural enterprises, represent another growing source of guidance, though they tend to serve very specific segments of the farming community. Currently, 178 million hectares, or 50.8% of the total area of agricultural establishments, receive some form of guidance.

The absence of technical assistance has several impacts on agricultural activities, e.g., production and weed control. However, there is a significant regional disparity in access to agricultural technical guidance across Brazil. In the South region, 48.6% of establishments receive guidance, compared to 28.6% in the Southeast and 23.6% in the Midwest. The North and Northeast regions are the least assisted, with only 10.4% and 8.2% of establishments receiving assistance, respectively (Pereira et al., 2022)

It is crucial to note that a significant portion of the technical assistance provided to Brazilian agricultural establishments is conducted by agrochemical companies, which offer guidance tailored specifically to their products (Castro et al., 2022). The fact that 80% of rural establishments do not receive any form of technical guidance has various repercussions on agricultural activities, affecting production levels, income, and especially pest management. For subsistence or family-based agriculture, management challenges often stem from the diversity of production systems and strategies, which are determined by different objectives. This diversity can cause the potential impact of these small-scale farmers to become fragmented across local groups, reducing their collective efficacy in the agricultural sector (Rocha Jr et al., 2020).

Corcioli et al. (2022) argue that Brazil's current agricultural policies indirectly finance foreign corporations using public funds, without substantially benefiting domestic agribusiness. Recently, studies have highlighted that a considerable portion of agricultural policy funds are allocated to a few transnational corporations that dominate the agricultural supply market in Brazil, especially in the seeds and agrochemicals sectors. This also includes investment resources directed towards purchasing agricultural machinery, a sector predominantly controlled by multinationals.

The agrochemical sector is categorized into patented products and generic products that become authorized after the patent exclusivity period ends. Patents are predominantly held by foreign multinational groups. Although generic products are largely controlled by multinational corporations, some nationally owned companies maintain significant involvement. Nonetheless, domestically owned companies account for less than 6% of the agrochemicals marketed in Brazil (Aenda, 2023).

The cost of implementing more sustainable systems often plays a crucial role in the limited adoption of integrative techniques for IWM in cropping systems. Economic factors significantly influence the adoption rates of practices such as crop rotation and the use of species to form mulch. Consequently, the integration of diverse strategies for weed control is not widely practiced by growers. Many are inclined to employ no-till practices, but their fields frequently remain fallow during the winter months, missing opportunities for further sustainable practices (Gazzieiro et al., 2009).

Given this scenario, public policies or programs that promote more sustainable production systems are essential. Practices such as no-till agriculture referred to as the 'Straw Direct Planting System'combined with proper crop rotation and the strategic use of herbicides, can significantly enhance the management of resistant weeds.

Ecologically-based agriculture and organic food production are becoming more prominent globally. Boutagayout et al. (2023) highlight that agroecological weed management adopts ecological principles to enhance system resilience, biodiversity, and productivity. This approach avoids reliance on synthetic herbicides, opting instead for cultural, mechanical, physical, or biological methods. Agroecological systems help mitigate the environmental downsides of conventional herbicide-based systems by maintaining a balance between weeds and crop components, thus preventing herbicide resistance, and minimizing impacts on non-target organisms.

In Brazil, support for agroecology is structured through the National Policy for Agroecology and Organic Production and the National Plan for Agroecology and Organic Production, collectively known as "*Brasil Agroecológico*," as explained by Baiardi and Pedroso (2020). These initiatives are implemented via public notices that detail how to access research resources, set up vegetable gardens, organize high school courses, offer technical assistance, and promote events. The Brazilian National Council for Scientific and Technological Development (CNPq) is a key promoter of scientific research in agroecology, supporting relevant events and fostering research in this field. Moreover, in recent years, Brazilian federal universities have introduced undergraduate courses in agroecology.

The theoretical principles of agroecology align well with the realities of family-organized agricultural systems, which typically feature diversified production structures and a desirable level of complexity. These systems easily integrate agroecological practices, enhancing their efficiency without compromising the oversight and management of the production process.

Importance of community engagement and education

It is critical that farmers prioritize integrated weed management, especially given the increasing issue of weed resistance in Brazil. Managing weeds on an individual basis proves ineffective, as the dynamics of these plants involve the entire environment and production chain. This includes choosing seeds free from weed propagules, addressing inadequate control, and tackling the proliferation of hard-to-control species, all of which collectively impact agricultural areas.

Technical assistance is vital for raising awareness and training communities based on their local circumstances. According to Vidal et al. (2006), the process to identify resistance and implement control measures is often delayed. Typically, seeds or plants suspected of resistance are sent to research facilities capable of performing diagnostic tests for herbicide resistance. Efforts are then made to persuade farmers to adopt alternative weed management methods, such as crop and herbicide rotation. Early detection of resistance, through continuous crop monitoring, allows for the quarantine of affected areas and facilitates the eradication of the resistant biotype.

Deffontaines et al. (2020) point out that the complexity of practices promoted by extension services can hinder their adoption. The simple practices that farmers currently employ are part of a slow change process that involves gradual knowledge acquisition. A redesign of cropping systems might occur through a gradual increase in practice complexity or through specific systemic changes at the cropping system level. Sharing knowledge and resources non-competitively can

Table 1. Integrated Herbicide-Resistant Weed Management Practices: Current and Future Technologies in the United States. Adapted from a poster presented in the 10th International IPM Symposium – Implementing IPM across Borders and Disciplines (https://ipmsymposium.org/2022/posters.html), it shows predominant IWM technologies in the United States.

<table>
<tr><th>Current IWM</th><th>Future IWM</th></tr>
<tr><td>1. Plant crops in a weed-free field</td><td rowspan="2">1. Sensor-based and image-analysis:
- Unmanned Aerial Vehicles (UAV) / Drones can be used for early season weed mapping and site-specific weed management;
- Remote Sensing can detect weed patches and map plant densities;
- Robotics can be used as automatic weeders such as inter- and intra-row weeders in vegetable and specialty crops; and
- Precision Sprayer can detect and differentiate crops from weeds and precisely spray weed patches.</td></tr>
<tr><td>2. Regular field scouting</td></tr>
<tr><td>3. Using herbicides with multiple modes of action (MOAs) to effectively manage troublesome weeds</td><td>2. Heat-based technologies:
- Flame weeding consists of an exposure to intense heat. It can be hand-held / tractor-mounted in organic agriculture. It is cheaper than hand weeding, but may pose risk of crop injury; and
- Electrocution is weed control via electric shock using high-electric power (20kV). It has been tested in row crops (soybean); however, it has high costs and may be hazardous to operators.</td></tr>
<tr><td>4. Application of labelled herbicide rates at recommended weed growth stages</td><td rowspan="2">3. Weed seed destruction (both conceptualized and developed in Australia):
- Harrington Seed Destructor (HSD): it destroys weed seeds during harvest, is highly effective (>95% control), widely used in Australia and being adopted in the U.S.; however, it has a high power-requirement (54kW); and
- Narrow Window Burning: it is the burning of all residues within narrow windows using harvester-mounted chute; windows (50-70cm) are burned later. It is a relatively inexpensive method but poses fire risks and air quality issues.</td></tr>
<tr><td>5. Use of cultural practices as crop competitiveness to supress weeds</td></tr>
<tr><td>6. Use of biological and mechanical practices whenever possible</td><td>4. Crop improvement technologies:
- Gene Stacking RNA: it consists of using herbicide-resistant crops. It is the most widely adopted tool. It uses transgene technology, mutation breeding, and many herbicide MOAs;
- Interference (RNAi): gene silencing using small RNA molecules and short interfering RNA (siRNA); and
- Genome Editing: use of CRISPR/Cas9, a precise editing, allowing stacking; however, there are public concerns and regulatory burden.</td></tr>
</table>

accelerate changes among farmers, promoting the redesign of cropping systems. Moreover, the structure and function of relational networks can restrict changes in practices on a watershed scale.

Traditional and emerging techniques for Integrated Weed Management in Brazil

Chemical weed control remains the predominant method in Brazil and globally. For any shift away from this reliance, new weed control technologies must prove highly effective, reliable, and economically viable for routine use within cropping systems.

Among control techniques, 90% of soybean growers acknowledge the importance of using herbicides with different mechanisms of action or combining them to manage herbicide-resistant biotypes (Ulguim et al., 2017). Furthermore, in approximately 80% of RR soybean areas, three or more herbicide applications per year are common, with about half of these areas also practicing crop rotation (Vargas et al., 2013). However, incorrect herbicide usage can lead to several issues including: (1) damage to non-target vegetation or organisms affecting biodiversity, (2) crop damage due to phytotoxicity, (3) residues in soil and water reducing their quality, (4) health and safety concerns for humans, and (5) a rise in herbicide-resistant weed biotypes (Abouziena et al., 2016).

Alternative tactics such as solarization, cover crops, mulching, natural herbicides, and the use of water vapor have been successfully adopted in many countries. Additionally, innovative techniques such as the use of Fresnel lenses, electrocution control (gaining popularity in Brazil), biological control, and lasers show potential in IWM. Simple practices, such as selecting more competitive crop varieties and controlling the seed bank, also significantly impact weed presence in agricultural areas (Abouziena et al., 2016; Mitchell et al., 2018).

Biological control is another technique that can make weed management more efficient and sustainable. Although it is a promising tool, its full potential remains largely untapped due to limited financial support. The socio-economic benefits of effectively controlling specific resistant and difficult-to-manage weed biotypes could be substantial.

The exploration of essential oils as bioherbicides has also shown potential. Studies suggest that certain bioactive species can be sources of effective compounds for bioherbicide formulations. Notably, essential oils from the Brazilian pepper tree (*Schinus terebinthifolius*) and rue (*Ruta graveolens*) have shown promising results (Maldaner et al., 2021).

Researchers at the Federal University of Santa Maria in Brazil have recently made significant progress in the field of sustainable agriculture by partnering with a biotechnology company to register the country's first bioherbicide. This innovation stems from a study on the effects of products derived from the secondary metabolism of a fungus, *Phoma dimorpha*, on controlling several problematic weed species including *Echinochloa* sp., *Amaranthus cruentus*, *Senna obtusifolia*, and *Bidens pilosa* (Chaves Neto et al., 2021).

In Brazil, the adoption of cover crops and the no-tillage system have seen significant growth in agricultural practices. By 2020, the area dedicated to grain production using the no-tillage system reached 36 million hectares. When combined with the integrated system and the addition of sugarcane cultivation, which accounts for 8.4 million hectares, the total area using these sustainable practices amounted to approximately 44.4 million hectares. The Brazilian Federation of Direct Planting System (FEBRAPDP) has set an ambitious target to increase this to cover 75% of the planted area by 2030, utilizing sustainable systems (IBGE, 2017). According to the latest Agricultural Census, 19% of rural establishments in Brazil, which translates to around 553,000 properties, have adopted the no-tillage system, which involves using straw as a cover on the soil surface.

In Brazil, the use of cover crops stands out, particularly in the Cerrado region, using species such as *Urochloa* sp. (liverseed grass and Alexander grass), *Canavalia brasiliensis* (Brazilian jack bean), *Crotalaria juncea* (sunn hemp), *Pennisetum glaucum* (pearl millet), *Mucuna aterrima* (velvet bean), *Raphanus sativus* (radish), *Cajanus cajan* (pigeon pea), *Sorghum bicolor* (shattercane), and *Triticum aestivum* (bread wheat) (Carvalho et al., 2018). Meanwhile, in southern Brazil, important cover crops are *Avena strigosa* (black oat), *Lolium multiflorum* (Italian ryegrass), *Secale cereale* (feral rye), *Lupinus albus* (white lupin), *Vicia sativa* (common vetch), and *Raphanus sativus* (radish) (Ziech et al., 2015). The selection of cover crop species is influenced by the main cultivated crop, the timing of sowing, and region (Carvalho et al., 2018; Ziech et al., 2015).

The use of cover crops significantly influences soil vegetation cover, reducing weed infestation and altering the composition of the weed population. This can be particularly beneficial in managing difficult-to-control weed species, such as herbicide-resistant biotypes (Gomes Jr. et al., 2008; Borges et al., 2014). The effectiveness of cover crops in weed management stems from their rapid growth and highly competitive potential, which inhibit the proliferation of the soil seed bank. Additionally, the substantial biomass produced by cover crops, when managed chemically or mechanically, creates a stubble layer on the soil surface that further aids in weed control. Cover crops thus serve multiple roles in IWM, functioning as physical (stubble), cultural (rotation), and sometimes chemical (through allelopathic effects) methods of weed suppression.

The integration of agriculture and livestock is a crucial component of production systems in Brazil, especially given the extensive areas dedicated to livestock. This integrated system includes practices such as no-tillage planting in stubble, crop-grass intercropping, and crop and herbicide rotation, which all contribute positively to weed management. This integration typically occurs on livestock farms by introducing grain crops like rice, soy, corn, and sorghum into pastures to rejuvenate pasture production. Farms that specialize in grain crops also benefit from using forage grasses to enhance soil coverage in a no-tillage system. Additionally, in the off-season, forage is used to feed cattle, and some farms systematically rotate between pasture and crops to intensify land use and capitalize on the synergism between these activities. These practices often involve partnerships between farmers and ranchers to maximize efficiency and benefits (Vilela et al., 2011).

In 2005, the area dedicated to ILPF systems in Brazil was approximately 1.87 million hectares. By 2018, this figure had increased to 15 million hectares, representing an eightfold increase over thirteen years (Telles et al., 2021). It is important to highlight that in Brazil, intermediary institutions like agricultural cooperatives, associations of rural producers, and rural extension services play a significant role in the adoption, adaptation, and dissemination of these integration systems. These institutions are pivotal in facilitating the flow of information, providing technical guidance, aiding in commercialization, and enabling access to financing and risk management mechanisms, all of which are essential for the success of the ILPF model (Vinholis et al., 2022).

Mulching is also a widely used physical weed control tool in Brazil, especially in horticultural areas. Various materials are utilized for mulching, including plastic film, straw, and agro-industrial residues such as sugarcane bagasse, peanut shells, and coffee by-products.

The use of synthetic materials like polyethylene (PE) mulch is particularly popular among vegetable producers due to its numerous benefits. These include enhanced weed control, improved water use efficiency, increased yields and product quality, and accelerated plant development resulting from raised soil temperatures. This is especially beneficial in crops like garlic and vineyards (Haque et al., 2033; Hegazi et al., 2020). However, in tropical climates with hot summers, such as those in Brazil, the use of dark-coloured plastics can adversely affect germination and crop development (Hirata et al., 2015; Saleh et al., 2001), in such cases, lighter-coloured plastics like yellow or white are recommended alternatives.

An additional challenge is that some perennial weeds, such as *Cyperus* spp. (smallflower umbrella sedge, rice flatsedge), can penetrate plastic mulches and continue to grow. Moreover, the disposal of plastic waste becomes problematic as it must be completely removed from the fields. The presence of plastic waste not only impacts the environment but also interferes with crop rotation practices, as residual plastic in the field can lead to soil contamination (Saleh et al., 2000).

In Brazil, the issue of resistant weeds is less prominent in vegetable crops, particularly leafy varieties. This is partly due to their cultivation on smaller plots, which facilitates the use of intensive techniques such as plastic mulching, frequent rotation of various vegetables throughout the year, and a reliance on mechanical control owing to the limited number of herbicides approved for use in these crops. Consequently, there is greater diversification in vegetable cultivation compared to broadacre crops. Additionally, certain vegetables such as tomatoes, potatoes, and sweet potatoes are often grown on leased pasture lands to address phytosanitary concerns.

As for alternative weed control methods in Brazil, the use of electrical discharge is becoming an increasingly considered option, especially in areas with annual or perennial organic crops. This technique involves attaching an applicator with electrodes to a tractor, which then delivers an electric shock of 5,000 volts to the weeds. This electrical discharge disrupts the sap conduction in the plants, leading to their death within a week. Developed over the last three decades through collaborations between private companies and research institutions, this technology has yielded various solutions in both the design of applicators and electro-electronic technology (Brighenti et al., 2018). Despite ongoing small-scale experiments, there are currently no reports of this method being used on a commercial scale for weed control in Brazil, using either conventional electric current or microwaves (Silva et al., 2018).

The use of lasers and robotics for weed control in Brazil is still in the early stages, with relatively few studies conducted. However, there are several promising and innovative approaches being explored for weed management in agriculture. Techniques such as the application of infrared radiation, lasers (Mathiassen et al., 2006), microwave radiation (Brodie et al., 2007), ultrasonic control systems, and real-time robotic weed control systems (Pérez-Ruiz et al., 2012) are potential methods for field conditions. Electromagnetic radiation at a wavelength of 10.6 µm (laser) can be used to control weed species like *Amaranthus viridis* (slender amaranth), *Bidens pilosa* (hairy beggarticks), *Cenchrus echinatus* (southern sandbur), *Digitaria horizontalis* (sourgrass), *Eleusine indica* (goosegrass), *Panicum maximum* (Guinea grass), and *Urochloa decumbens* (signal grass). Control can be achieved when these weeds are at the stages of one to three leaves, or pairs of leaves, fully expanded (Pavan et al., 2022).

In Brazil, the adoption of robotic technology in agriculture has been relatively slow and uneven, as observed globally. Several factors contribute to this limited uptake, including a low-skilled workforce, few computers on farms, high importation fees for cutting-edge equipment, inadequate technical support, low market values for agricultural products, predominantly small-scale production (most of the 5 million rural establishments are family farms occupying smaller areas), and comparatively low land prices (Lowenberg-DeBoer et al., 2006; Hackenhaar et al., 2015).

However, when automation technology is integrated with weed detection and a control device, it creates a potentially more effective tool for managing agricultural challenges (Westwood et al., 2018). In terms of mechanical control, traditional methods like hand weeding or hoeing are safe and very effective against annual and biennial weeds. Despite this, about 84% of Brazil's population lives in urban areas, which makes rural labour scarce and expensive, even though it often lacks specialization (IBGE, 2017).

In specific agricultural practices in Brazil, such as in citrus orchards, mechanical weed control is prevalent. Citrus growers frequently use *Urochloa* species as a cover crop, which is then mowed with an ecological mower. This mower redistributes the *Urochloa* biomass from the inter-row spaces to the planting lines as in-situ mulch (Martinelli et al., 2022). This technique, known as "ecological mowing," enhances weed control and may increase fruit yields. This method might also exert an allelopathic effect from cover crops like signal grass (*Urochloa decumbens*) and ruzi grass (*U. ruziziensis*) on weeds (Martinelli et al., 2017). In cases like sourgrass (*Digitaria insularis*), mowing has been found to control weeds as effectively or even better than chemical-only systems, offering an alternative to herbicide use (Raimondi et al., 2020).

The use of flame for weed control, though not the most sustainable method, has shown effectiveness in specific scenarios such as controlling emerged aquatic weeds. Studies have demonstrated that flaming can significantly reduce the biomass of aquatic plants like *Eichhornia crassipes* (water hyacinth), *Brachiaria subquadripara* (armgrass millet), and *Pistia stratiotes* (water lettuce) (Marchi et al., 2005). However, the lack of commercial interest in producing specialized equipment often leads to the use of makeshift flamethrowers. These homemade devices not only increase the risk of accidents for operators but also risk damaging commercial crops due to imprecision and high fuel costs (Costa et al., 2018).

Growers should consider several key points for effective weed management: (1) understanding the soil seed bank as a reservoir of weed seeds, which can persist for long periods; (2) start each planting season with a field free from weeds; 3) prevention is always be the best recommended treatment; and 4) the risk of not controlling weed seed production for periods of up to one year. Successful and sustainable weed management relies on integrating various control techniques, both chemical and non-chemical, instead of depending solely on one method.

Climate change resilience

The impact of climate change on integrated weed management in Brazil is crucial, given the country's varied soil and climate conditions. Rising carbon dioxide (CO_2) levels, along with changes in global temperature and precipitation, pose significant challenges for weed management and crop production. Environmental factors such as CO_2, light, temperature, relative humidity, and soil moisture each uniquely influence how herbicides are absorbed, translocated, and activated within plants. Additionally, the way these factors interact can lead to unpredictable outcomes on the effectiveness of herbicides (Varanasi et al., 2016).

Higher temperatures from climate change can increase weed competitiveness and alter crop-weed dynamics. The responsiveness of plant species to rising temperatures depends on their genetic traits and their ability to access water and nutrients (Tungate et al., 2007). MacDonald et al. (2009) emphasize the need to understand the environmental conditions that favour abundance and competitiveness of specific weed species, as well as their potential damage to crops (i.e., their damage niche) to develop proactive management strategies.

Additionally, research is needed to identify adaptive strategies that support crop production under changing climatic conditions, assessing their effectiveness, time requirements, and economic and ecological costs (Ramesh et al., 2017). Innovative weed management strategies, such as new herbicides, herbicide-resistant crops, and new bioagents, are essential to build resilience and reduce vulnerability to climate change, but concerns about their economic, environmental, and health impacts persist (Anwar et al., 2021). For instance, increased CO_2 could enhance root biomass, making weeds, such as Canada thistle (*Cirsium arvense*) and other perennial weeds that reproduce asexually from below-ground organs, more difficult to control (Zisca et al., 2004). More frequent disking/harrowing to manage these weeds could exacerbate the problem (Anwar et al., 2021).

A study in Northeast Brazil found that farmers aware of climate change impacts are more likely to adopt adaptive measures. However, while there is general awareness of climate change, many farmers lack the knowledge to effectively address it (Carlos et al., 2019). There is also a critical need for better access to technical assistance to help producers adopt adaptation and mitigation strategies. Therefore, public policies should aim to enhance such access since 70% of the producers considered in this study do not have it (Carlos et al., 2019).

In response to these needs, the sectoral plan for mitigation and adaptation to climate change was established in 2010, aimed at developing a Low Carbon Emission Economy in Agriculture, known as the ABC Plan (Telles et al., 2021). This plan encourages actions to mitigate greenhouse gas emissions and promotes the adoption of Sustainable Production Systems, including no-till agriculture and the Crop, Livestock, and Forest Integration (ILPF: Integração Lavoura Pecuária e Floresta, in Portuguese) system. A key feature of the ABC Plan is a credit program linked to rural credit with subsidized interest rates to facilitate these practices (MAPA, 2012).

However, an evaluation of the program indicates that its effectiveness varies across the national territory, influenced by diverse factors such as risk profiles, climate regimes, levels of technical knowledge, and economic development. These factors significantly affect the practical implementation of the program (Gianetti et al., 2021).

New technologies, what is next?

Recent developments and recommendations in IWM, particularly from countries like the United States and Australia, emphasize advanced strategies for managing herbicide-resistant weeds in agricultural fields. Table 1 shows the predominant IWM technologies in the United States, wherein guidelines advise planting in weed-free fields to ensure a weed-free start. This approach is crucial especially when dealing with competitive weeds like Palmer amaranth (*Amaranthus palmeri*) in soybeans. Research by Sanctis et al. (2021) demonstrated that reducing weed competition early in the growing season allows pre-emergence herbicides to safeguard crop yields and postpone the need for post-emergence applications.

In 2013, Australia saw its agricultural sector come together to form 'WeedSmart,' which introduced 'The Big 6' framework a combination of chemical, mechanical, and cultural tactics designed to assist growers in controlling crop weeds. This approach focuses on using combined tactics rather than only one. For instance, a study in Western Australia documented a decline in ryegrass (*L. rigidum*) seed density to virtually zero after 11 consecutive years of implementing harvest weed seed control (HWSC), crop competition (narrow row spacing), and herbicide applications. These methods are cost-effective and have a high adoption potential among growers (Borger et al., 2016).

'The Big 6' includes critical strategies such as never reducing herbicide dosage, ensuring spraying efficiency through the right nozzles, adjuvants, and water rates; using clean crop seeds to avoid planting resistant weed seeds; maintaining clean field borders to prevent resistance development; and testing weed seeds for resistance by sending samples to university labs. Since IWM is a dynamic subject, WeedSmart has reworked 'the Big 6' in consultation with its industry and research partners. It embraces new research on weed control and focuses specially on spray efficacy.

Globally, the focus is increasingly on precision weed control, particularly weed detection, utilizing technology such as cameras, sensors, and artificial intelligence (and its algorithms) (Cameron et al., 2014). These technologies enable more targeted herbicide application, reducing overall usage, enhancing control efficiency, and minimizing weed seed dispersion. Technologies like spot spraying, known as 'green-on-brown' (GoB) and 'green-on-green' (GoG), allow for specific application where weeds are detected against a background of soil or within crops, respectively. Examples of GoB include WEEDit, WeedSeeker, and SwarmFarm Robotics, with some utilizing machine learning to enhance detection accuracy in complex situations like grass weeds in cereal crops (Allmendinger et al., 2022; Olsen et al., 2020; McCarthy et al., 2010). Machine learning has been applied for challenging detections as grass weeds in cereal crops. Recently, autonomous weed control technologies have also been scaled up, such as those by SwarmFarm Robotics (Olsen et al., 2020).

For Brazil, the adoption of these cutting-edge technologies in managing resistant weeds would benefit greatly from government support. This could include fostering collaborations between Brazilian researchers and international experts, providing tax incentives for modern agricultural equipment, and encouraging joint research initiatives. The more Brazil integrates and diversifies these new IWM techniques within its cropping systems, the less significant the issue with resistant weeds is likely to become.

References

Abouziena H F, Haggag WM (2016) Weed control in clean agriculture: a review1. Planta Daninha. 34 (3): 377-392.

Adegas FS, Vargas L, Gazziero DL, Karam D, Silva AF and Agostinetto D (2017) Impacto econômico da resistência de plantas daninhas a herbicidas no Brasil. [Online]. Embrapa. Available: https://ainfo.cnptia.embrapa.br/digital/bitstream/item/162704/1/CT132-OL.pdf [03 June 2023].

Allmendinger A, Spaeth M, Saile M, Peteinatos GG, Gerhards R (2022) Precision chemical weed management strategies: a review and a design of a new CNN-based modular spot sprayer. Agron. 12 (7): 1620-1627.

Aenda (2020). Associação Brasileira dos Defensivos Genéricos *(AENDA)*. Available online at: https://www.aenda.org.br/ (accessed December 20, 2020).

Agencia Senado (2023) Senado aprova projeto que facilita registro de agrotóxicos. https://www12.senado.leg.br/noticias/materias/2023/11/28/senado-aprova-projeto-que-facilita-registro-de-agrotoxicos

Anwar MP, Islam AKMM, Yeasmin S, Rashid MdH, Juraimi AS, Ahmed S, Shrestha A (2021) Weeds and their responses to management efforts in a changing climate. Agronomy. 11(10): 1921. https://doi.org/10.3390/agronomy1110192.

Baiardi A, Pedroso MTM (2020) Demystifying agroecology in Brazil. Ciência Rural. 50 (11): e20191019. https://doi.org/101590/0103-8478cr20191019.

Borges WLB, Freitas RS, Mateus GP, Sá ME, Alves MC (2014) Supressão de plantas daninhas utilizando plantas de cobertura do solo. Planta daninha. 32 (4): 755-763.

Borger CPD, Riethmuller G, D'Antuono M (2016) Eleven years of integrated weed management: long-term impacts of row spacing and harvest weed seed destruction on *Lolium rigidum* control. Weed Res. 56 (2): 359-366.

Boutagayout A, Bouiamrine EH, Agnieszka S, Oihabi KL, Romero P, Rhioui W, Nassiri L, Belmalha S (2023) Agroecological practices for sustainable weed management in Mediterranean farming landscapes. Environment, Development and Sustainability. 1-55. https://doi.org/10.1007/s10668-023-04286-7 1

Brighenti AM, Oliveira MF, Coutinho Filho AS (2018) Controle de plantas daninhas por roçada articulada e eletrocussão. In: Controle de Plantas Daninhas: Métodos Físico, Mecânico, Cultural, Biológico e Alelopatia. Oliveira MF, Brighenti AM (eds), Embrapa, Brasília, p.11-33.

Brodie G, Hamilton S, Woodworth J (2007) An assessment of microwave soil pasteurization for killing seeds and weeds. Plant Prot Q. 22:143-149.

Cameron J, Storrie A (2014) Summer fallow weed management: a reference manual for grain growers and advisers in the Southern and Western grains regions of Australia. [Online] GRDC (2014). Available: https://grdc.com.au/__data/assets/pdf_file/0028/98632/summer-fallow-weed-management-manual.pdf.pdf [15 January 2022].

Castro CN, Pereira CN (2022) Agricultura Familiar, Assistência Técnica e Extensão Rural e Política Nacional de Ater. [Online]. IPEA (2017). Available: https://repositorio.ipea.gov.br/bitstream/11058/8114/1/td_2343.PDF [15 January 2022].

Carlos SM, Cunha DA, Pires MV (2019) Conhecimento sobre mudanças climáticas implica em adaptação? Análise de agricultores do Nordeste brasileiro. Rev. Econ. Sociol. Rural. 57(3): 455-471.

Carvalho AM, Oliveira AD, Coser TR, Martins AD, Marchão RL, Pulronik K, Sá MAC (2018) Plantas de cobertura do solo recomendadas para a entressafra de milho em sistema plantio direto no Cerrado. Comunicado Técnico 181, Embrapa, Planaltina.

Christoffoleti PJ, Nicolai M, Lopez-Ovejero RF, Borgato EA, Netto AG and Melo MSC (2016) Resistência de plantas daninhas a herbicidas: termos e definições importantes. In: Aspectos de Resistência de Plantas Daninhas a Herbicidas. Esalq, Piracicaba, pp. 11-32.

Costa NV, Rodrigues-Costa ACP, Coelho EMP, Ferreira SD, Barbosa JA (2018) Métodos de controle de plantas daninhas em sistemas orgânicos: breve revisão. Rev Bras Herbic. 17(1): 25-44.

Croplifebrasil (2020) O Cultivo de Plantas Transgênicas no Brasil. [Online]. Available: https://croplifebrasil.org/noticias/plantas-transgenicas-no-brasil/ [25 September 2023]

Corcioli G, Medina SG, Arrais CA (2022) Missing the target: Brazi´s agricultural policy indirectly subsidizes foreign investments to the detriment of smalhoder farmers and local agribusiness. Front. Sustain. Food Syst., Sec. Land, Livelihoods and Food Security. 5: 1-10. https://doi.org/10.3389/fsufs.2021.796845

Dainese M, Martin EA, Aizen MA, Albrecht M, Bartomeus I, Bommarco R, Carvalheiro LG, Chaplin-Kramer R, Gagic V, Steffan-Dewenter I (2019) A global synthesis reveals biodiversity-mediated benefits for crop production. Sci. Adv. 5 (10): eaax0121.

Deffontaines L, Mottes C, Della Rossa P, Lesueur-Jannoyer M, Cattan P, Le Bail M (2020) How farmers learn to change their weed management practices: Simple changes lead to system redesign in the French West Indies. Agricultural Systems. 179: 102769.

Dempster F, Llewellyn R, Azeem M, Busi R, Yes, No, maybe – getting value from herbicide resistance testing (2022) [Online]. GRDC (2022). Available: https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/03/yes,-no,-maybe-getting-value-from-herbicide-resistance-testing [15 March 2022].

FAO, Pesticides Use, Pesticides Trade and Pesticides Indicators – Global, Regional and Country Trends, 1990–2020. FAOSTAT Analytical Briefs, 46. Rome. https://doi.org/10.4060/cc0918en (2022).

Fried G, Petiti S, Dessaint F, Reboud X (2009) Arable weed decline in Northern France: Crop edges as refugia for weed conservation? Biological Conserv. 142 (2): p 238-243.

Gianetti GW, Ferreira Filho JBS (2021) O Plano e Programa ABC: uma análise da alocação dos recursos. Rev. Econ. Sociol. Rural. 59(1): e216524.

Gomes Jr. FG, Christoffoleti PJ (2008) Biologia e manejo de plantas daninhas em áreas de plantio direto. Planta Daninha. 26 (4): 789-798.

Haque MS, Islam MR, Karim MA, Khan MAH (2003) Effects of natural and synthetic mulches on garlic (Allium sativum L.). Asian J. Plant Sci. 2 (1): 83-89.

Hackenhaar NM, Hackenhaar C, Abreu YV (2015) Robótica na agricultura, Interações. 16 (1): 119-129.

Heap I (2024) The International Herbicide-Resistant Weed Database. Available: www.weedscience.org [29 March 2024].

Hegazi A (2020) Plastic mulching for weed control and water economy in vineyards. Acta Hortic. 536:245-250.

Hirata ACS, Hirata EK, Barrionuevo RM, Monquero PA (2015) Manejo de milheto para plantio direto de alface no verão com ou sem levantamento de canteiros. Hortic. Bras. 33: 398-403.

IBGE (2017). Censo Agropecuário 2017: Resultados Definitivos. [Online]. Available: https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2017/resultados-definitivos. [15 January 2022].

Kubiak A, Agnieszka WM, Niewiadomska A and Pilarska AA (2022) The Problem of weed infestation of agricultural plantations vs. the assumptions of the european biodiversity strategy. Agronomy. 12 (1808).

Krenchinski FH, Cesco VJS, Castro EB, Carbonari CA and Velini ED (2019) Ammonium glufosinate associated with post-emergence herbicides in corn with the CP4-EPSPS and Pat Genes, Planta Daninha. 37: e019184453.

Lowenberg-DeBoer J, Griffin TW (2006) Potential For Precision Agriculture Adoption In Brazil. [Online]. Purdue University. Available: https://ag.purdue.edu/ssmc/frames/SSMC_newsletter6_06.pdf [15 January 2022].

McDonald A, Riha S, DiTommaso A, DeGaetano A (2009) Climate change and the geography of weed damage: Analysis of U.S. maize systems suggests the potential for significant range transformations. Agriculture, Ecosystems & Environment. 130(3/4):131-140.

Maldaner J, Steffen GPK, Steffen RB, Morais RM, Saldanha CW, Missio EL, Moro TS, Silva RF (2021) Óleos essenciais: potencial bioherbicida para o controle do capim annoni. [Online]. SEAPDR/DDPA. Available: ttps://www.agricultura.rs.gov.br/upload/arquivos/202107/01182034-n-5-2021-oleos-essenciais-potencial-bioherbicida-para-o-controle-do-capim-annoni.pdf.

MAPA (2023) Exportações do Agronegócio Fecham 2022 com US$ 159 Bilhões em Vendas. [Online]. Available: https://www.gov.br/agricultura/pt-br/assuntos/noticias/exportacoes-do-agronegocio-fecham-2022-com-us-159-bilhoes-em-vendas/DezembroBalanaComercialdoAgronegcioResumidaversosite1.xlsx [06 August 2023].

MAPA (Ministério da Agricultura, Pecuária e Abastecimento) (2023) Plano setorial de mitigação e adaptação às mudanças climáticas para consolidação da economia de baixa emissão de carbono na agricultura. MAPA (2012). Available: https://www.gov.br/agricultura/pt-br/assuntos/sustentabilidade/agricultura-de-baixa-emissao-de-carbono/publicacoes/download.pdf.

Marchi SR, Velini ED, Negrisoli E, Corrêa MR (2005) Utilização de chama para controle de plantas daninhas emersas em ambiente aquático. Planta Daninha. 23(2): 311-319. DOI: 10.1590/S0100-83582005000200019.

McCarthy C, Rees S, Baillie C (2010) Machine vision-based weed spot spraying: a review and where next for sugarcane? In Proceedings of the 32nd Annual Conference of the Australian Society of Sugar Cane Technologists, Mackay, p.424-432.

Mathiassen SK, Bak T, Christensen S, Kudsk P (2006) The effect of laser treatment as a weed control method. Biosyst Eng. 95 (4): 497-505.

Martinelli R, Rufino-Jr. LR, Desiderio DR, La Cruz RA, Monquero PA, Azevedo FA (2022). The impacts of ecological mowing combined with conventional mechanical or herbicide management on weeds in Orange. Weed Res. 62(6):431-445.

Martinelli R, Monquero PA, Fontanetti A, Conceição PM, Azevedo FA (2017) Ecological mowing: an option for sustainable weed management in young citrus orchards. Weed Technol. 31(2): 260-268.

Mitchell C, Hawes C, Iannetta P, Birch ANE, Begg G, Karley AJ (2018) An agroecological approach for weed, pest and disease management in Rubus plantations. In: Raspberry Breeding, Challenges and Advances. Graham J and Brennan (eds), p.63-81.

Oliveira MC, Lencina A, Ulguim AR and Werle R (2020) Assessment of crop and weed management strategies prior to introduction of auxin-resistant crops in Brazil. Weed Technol. 35 (3): 155-165.

Olsen A (2020) Improving the Accuracy of Weed Species Detection for Robotic Weed Control in Complex Real-time Environments, PhD Thesis, James Cook University (2020).

Pavan GB (2022) Uso de Laser de CO2 no Controle de Plantas Daninhas, Thesis Doutorado, Universidade Estadual Paulista (2022). Available: https://repositorio.unesp.br/handle/11449/236736 [15 January 2022].

Pereira CN, Castro CN (2002) Assistência Técnica na Agricultura Brasileira: uma Análise Sobre a Origem da Orientação Técnica por Meio do Censo Agropecuário de 2017. [Online]. IPEA (2021). Available: https://repositorio.ipea.gov.br/bitstream/11058/10893/1/td_2704.pdf.

Pérez-Ruiz M, Slaughter DC, Gliever CJ, Upadhyaya SK (2012) Automatic GPS-based intra-row weed knife control system for transplanted row crops. Comput Electron Agric. 80: 41-49. DOI: 10.1016/j.compag.2011.10.006.

Raimondi RT, Constantin J, Mendes RR, Oliveira Jr RS, Rios FA (2020). Glyphosate-resistant sourgrass management programs associating mowing and herbicides. Planta Daninha.38: e02021592.

Ramesh K, Matloob A, Aslam F, Florentine SK, Chauhan BS (2017) Weeds in a changing climate: vulnerabilities, consequences, and implications for future weed management. Front. Plant Sci.12(8): 1-12. <https://doi.org/10.3389/fpls.2017.00095>

Rocha Junior AB, Silva RO, Peterle Neto W and Rodrigues CT (2020) Efeito da utilização de assistência técnica sobre a renda de produtores familiares do Brasil no ano de 2014. Rev. Econ. Sociol. Rural. 58 (2): e194371.

Sanctis JHS, Barnes ER, Knezevic SZ, Kumar V, Jhala AJ (2021) Residual herbicides affect critical time of Palmer amaranth removal in soybean. Agron J 113:1920–1933. DOI: 10.1002/agj2.20615.

Saleh MM, El-Shabasi MSS (2001) Effect of clear and black plastic mulch and clear polyethylene low tunnels on yield and fruit quality of strawberry plants. J Agric Sci Mansoura Univ 26:3899-3906.

Sharma A, Kumar V, Shahzad B, Tanveer M, Sidhu GPS, Handa N, Kohli SK, Yadav P, Bali AS, Parihar RD, Dar OI, Singh K, Jasrotia S, Bakshi P, Ramakrishnan M, Kumar S, Bhardwaj R, Thukral AK (2019) Worldwide pesticide usage and its impacts on ecosystem. Applied Sciences. 1 (11446).

Silva AF, Concenço G, Aspiazú I, Galon L, Ferreira E (2018) Métodos de controle de planta daninhas. In: Controle de Plantas Daninhas: Métodos Físico, Mecânico, Cultural, Biológico e Alelopatia. Oliveira MF, Brighenti AM (eds), Embrapa, Brasília, pp.11-33.

Swarmfarm: Robotic agriculture. [Online]. Swarmfarm (2019). Available: https://www.swarmfarm.com/ [26 September 2023].

Telles TS, Vieira Filho JER, Righetto AJ, Ribeiro MR (2021) Desenvolvimento da Agricultura de Baixo Carbono no Brasil. [Online]. IPEA (2021). Available: https://www.ipea.gov.br/portal/images/stories/PDFs/TDs/td_2638.pdf [15 January 2023].

Tungate KD, Israel DW, Watson DM, Rufty TW (2007) Potential changes in weed competitiveness in an agroecological system with elevated temperatures. Environmental and Experimental Botany. 60(1):42-49.

Ulguim AR, Agostinetto D, Vargas L, Silva JDG, Silva BM and Westendorff NR (2017) Agronomic factors involved in low-level wild poinsettia resistance to glyphosate. Rev Bras Cienc. Agrar. 12:51-9.

Varanasi A, Prasad PVV, Jugulam M (2016) Impact of climate change factors on weeds and herbicide efficacy. Advances in Agronomy. 35: 107-146.

Vargas L, Adegas F, Gazziero D, Karam D, Agostinetto D, Silva W T (2016) Resistência de plantas daninhas a herbicidas no Brasil: histórico, distribuição, impacto econômico, manejo e prevenção. In: A Era Glyphosate: Agricultura, Meio Ambiente e Homem (Meschede DK and Gazziero DLP) Embrapa, Londrina, pp. 219-239.

Vargas L, Nohatto MA, Agostinetto D, Bianchi MA, Paula JM, Polidoro E, Toledo RE (2013) Práticas de manejo e a resistência de *Euphorbia heterophylla* aos inibidores da ALS e tolerância ao glyphosate no Rio Grande do Sul. Planta Daninha. 31 (2): 427-435.

Vidal RA, Lamego FP, Trezzi MM (2006) Diagnóstico da resistência aos herbicidas em plantas daninhas. Planta Daninha. 24(3): 597-604.

Vilela L, Martha Jr GB, Macedo MCM, Marchão RL, Guimarães Jr R, Pulrolnik K, Maciel GA (2011) Sistemas de integração lavoura-pecuária na região do Cerrado. Pesq. Agropec. Bras. 46 (10): 1127-1138.

Vinholis MMB, Carrer MJ, Souza Filho HM, Bernardo R (2022) Sistemas de integração lavoura-pecuária-floresta no Estado de São Paulo: estudo multicasos com adotantes pioneiros. Rev. Econ. Sociol. Rural. 60(1): e234057.

Westwood JH, Charudattan R, Duke SO, Fennimore SA, Marrone P, Slaughter DC, Swanton C Zollingeral R (2018) Weed management in 2050: perspectives on the future of weed science. Weed Sci. 66 (2): 275-285.

Ziech MF, Olivo CJ, Ziech ARD, Paris W, Agnolin CA and Meinerz GR, (2015) Nutritive value of pastures of Cynodon mixed with forage peanut in southwestern Paraná State. Acta Sci. 37 (3): 243-249. DOI: 10.4025/actascianimsci.v37i3.26872.

Zisca LH, Faulkner S, Lydon J (2004) Changes in biomass and root:shoot ratio of field-grown Canada thistle (Cirsium arvense), a noxious, invasive weed, with elevated CO2: implications for control with glyphosate. Weed Science. 52:584–588.