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Impacts of Weed Resistance to Glyphosate on Herbicide Commercialization in Brazil

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Abstract: Herbicides are essential tools for the phytosanitary security of agricultural areas, but their excessive use can cause problems in agricultural production systems and have negative impacts on human health and the environment. The objective of this study was to present and discuss the main causes behind the increase in herbicide commercialization in Brazil between 2010 and 2020. Data from the Brazilian pesticide database, provided by *the Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA)*, were used. In 2010 and 2020, Brazil sold 157,512 and 329,697 tons of herbicide active ingredients, respectively, representing a 128.1% increase in commercialization over 11 years. Some herbicides, such as clethodim, haloxyfop-methyl, triclopyr, glufosinate, 2,4-D, diclosulam, and flumioxazin, showed increases in sales volumes between 2010 and 2020 of 2672.8%, 896.9%, 953.5%, 290.2%, 233.8%, 561.3%, and 531.6%, respectively, percentages far exceeding the expansion of Brazil's agricultural area. The primary reason for this sharp increase in herbicide sales was the worsening cases of weeds resistant and tolerant to glyphosate, with species such as *Conyza* spp., *Amaranthus* spp., *Digitaria insularis*, and *Eleusine indica* standing out. This situation created the necessity of the use of additional herbicides to achieve effective chemical control of these weed species.

Keywords: chemical control; genetically modified crops; integrated management; pesticide market

Citation: Procópio, S.d.O.; Barizon, R.R.M.; Pazianotto, R.A.A.; Morandi, M.A.B.; Braz, G.B.P. Impacts of Weed Resistance to Glyphosate on Herbicide Commercialization in Brazil. *Agriculture* **2024**, *14*, 2315. https://doi.org/10.3390/agriculture14122315

Academic Editors: Grazyna Podolska and Anna Szafranska

Received: 4 November 2024
Revised: 4 December 2024
Accepted: 9 December 2024
Published: 17 December 2024

1. Introduction

Herbicides are a class of pesticides used to control weeds, serving as a crucial tool in integrated management [1,2], particularly in large-scale agricultural operations. Their importance lies in the fact that, without weed control, agricultural activities suffer severe damage, leading to significant yield losses that can even make crop harvests unfeasible [3,4]. On a global scale, inefficient weed control causes yield losses of approximately 32% across various crops [5]. In this context, herbicide application aims to protect crops from interference by weed communities [6,7], which tend to occur at higher densities in agricultural areas and exhibit superior adaptation to the competitive process for essential natural resources [8]. Weeds can also serve as alternative hosts for insect pests and plant disease-causing microorganisms [9,10] and exhibit allelopathic activity [11,12].

Due to their efficacy and ease of application, allowing high operational efficiency [13], herbicide use has rapidly intensified in Brazil's agricultural, forestry, and pasture areas. The widespread adoption of chemical control also results from the labor shortage in rural areas caused by the ongoing migration to urban centers, driving a preference for herbicide use over manual weed control [14]. In recent decades, glyphosate has become prominent among herbicides registered in Brazil, primarily due to its favorable agronomic characteristics, such as broad-spectrum activity [15,16], effectiveness in controlling weeds at advanced developmental stages [17], efficiency in managing perennial species that propagate vegetatively [18,19], and the absence of soil active residues [20,21]. Two transformative events in Brazilian agriculture have driven the significant increase in glyphosate use. The first was the introduction and rapid adoption of the no-tillage system in grain production areas, where pre-sowing burndown became a routine operation, initially with glyphosate as the main herbicide used for this purpose [22]. The second event was the introduction of genetically modified (GMO) cultivars, such as soybean, corn, and cotton, which were engineered to be glyphosate-resistant [23].

The lack of or insufficient rotation of herbicides with different modes of action, along with the failure to implement integrated weed management principles, led to excessive selection pressure for glyphosate on the weed community [24,25]. Over years of intensive glyphosate use, weed biotypes that are resistant to this herbicide were selected, spreading to the point that glyphosate-resistant populations are now found throughout Brazil [26,27]. Currently, there have been official reports of 20 cases of weeds with simple or multiple resistance to glyphosate [28]. Resistant biotypes identified in Brazil include the following species: *Lolium perenne*, *Conyza bonariensis*, *Conyza canadensis*, *Digitaria insularis*, *Conyza sumatrensis*, *Chloris elata*, *Amaranthus palmeri*, *Eleusine indica*, *Amaranthus hybridus*, *Euphorbia heterophylla*, *Echinochloa crus-galli*, and *Bidens subalternans* [29–32]. In addition to these species, a noteworthy challenge is the management of volunteer glyphosate-resistant corn plants, where grain losses during corn harvests have led to infestations in subsequent soybean crops, complicating chemical control [33,34].

The emergence and spread of resistant biotypes across various regions of Brazil necessitated the use of additional herbicides to complement glyphosate's action on previously controlled species [35]. Among the herbicides that began to be more intensively used as a result of the spread of resistant biotypes in Brazil's grain production areas are 2,4-D, triclopyr, diclosulam, flumioxazin, haloxyfop-methyl, clethodim, and glufosinate. Despite the increase in resistant populations, glyphosate remains the primary active ingredient used in Brazilian agriculture, with variations in formulations depending on the type of salt utilized.

Thus, the objective of this study was to present and discuss data on herbicide commercialization in Brazil, with the main hypothesis being that the increase in herbicide consumption is driven by the worsening cases of glyphosate-resistant weeds.

2. Materials and Methods

The primary data used for the analysis of pesticide commercialization and the number of formulated products per active ingredient were obtained from the *Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* (IBAMA), the agency responsible for releasing commercialization data in Brazil. According to Brazilian legislation, manufacturing and importing companies must report their annual sales volume to IBAMA, which compiles this information to produce and publish reports on pesticide sales in the country. The data collection period from IBAMA covered from 2010 to 2020. After analyzing the primary database, it was necessary to make adjustments and standardize the historical series to align it with the guidelines of the Food and Agriculture Organization of the United Nations (FAO) [36] and the Organisation for Economic Co-operation and Development (OECD) [37].

To normalize and standardize the data from the IBAMA primary database, the following data were excluded: (1) The volume of non-agricultural pesticide (NA) sales in Brazil between 2010 and 2020. (2) The sales volume of products registered exclusively as adjuvants or surfactants (2010 to 2017), which were no longer classified as pesticides in Brazil following the *Ministério da Agricultura e Pecuária* (MAPA) act nº 104 of 20 November 2017, published in the Official Gazette of 21 November 2017. From 2018 onward, these products were no longer included in IBAMA's database, and by excluding data from 2010 to 2017, the historical series was standardized. (3) The sales volume of products classified as semiochemicals and microbiologicals (2010 to 2013). Since 2014, IBAMA began reporting these biopesticides separately from chemical, biochemical, and phytochemical products in its bulletins, and (4) sales of formulated pesticide products between industries in Brazil (2010 to 2020), because counting inter-company sales could result in double counting.

Additionally, after direct consultation with FAO and OECD technicians and statisticians, who also develop and disseminate international databases related to agricultural sustainability indicators, the following standardizations were implemented: (1) For the herbicides 2,4-D, glyphosate, picloram, MCPA, aminopyralid, florpyrauxifen-benzyl, fluroxypyr, haloxyfop-methyl, imazapic, imazaquin, imazapyr, imazethapyr, triclopyr, and cyhalofop-butyl, the data were recorded in acid equivalent (a.e.). These herbicides are formulated with different derivatives to ensure formulation stability, where standardizing the data in a.e. allows normalization regardless of the derivative used in the formulation. (2) For the herbicides diquat and paraquat, the data were recorded in tons of ion equivalent. Similar to the herbicides mentioned in Item 1, these compounds are also formulated with derivatives, and data standardization ensures consistent reporting. (3) For the fungicides copper hydroxide, copper oxychloride, copper oxide, and copper sulfate, the data were recorded in tons of metallic copper equivalent to maintain consistency, and (4) for all other pesticides, the data were recorded in tons of active ingredient (a.i.).

The increase in herbicide sales in Brazil from 2010 to 2020 was compared with the growth of the Brazilian agricultural area (perennial and temporary crops) and soybean area, using data from the SIDRA system, provided by the *Instituto Brasileiro de Geografia e Estatística* (IBGE) [38]. Additionally, it was compared with the expansion of non-degraded pasture areas (pastures that effectively use agricultural inputs, such as herbicides), calculated using data from the Image Processing and Geoprocessing Laboratory of the *Universidade Federal de Goiás* (LAPIG/UFG) [39].

3. Results and Discussion

3.1. Pesticide Sales in Brazil (2010 to 2020)

The data presented in Table 1 show the evolution of pesticide sales in Brazil, divided by usage classes, from 2010 to 2020. During this period, herbicides accounted for the highest sales volume among pesticides used in Brazilian agriculture. In 2010, 157,512 tons of herbicide active ingredients were sold in Brazil, representing 53.34% of all pesticides (chemical, biochemical, and phytochemical) commercialized that year. However, by 2020, herbicide sales had reached 329,697 tons of active ingredients, marking a 128.11% increase over 11 years and accounting for 58.89% of total pesticide sales in Brazil. For comparison on a global scale, in 2019 herbicides represented approximately 52% of the total pesticide market share [40], which is slightly lower than the Brazilian percentage. Additionally, the global increase in herbicide consumption from 2010 to 2020 was 29.92% [36], significantly lower than the increase recorded in Brazil.

Two reasons can be given to justify the use of higher quantities of herbicides compared to other pesticide categories. The first reason is that fungicides and insecticides are typically applied during the crop cycle (from sowing to harvest), whereas herbicides are used before, during, and after the crop cycle [41]. Their use is common before crop establishment (pre-sowing burndown) and after harvest (burndown of spontaneous vegetation during the fallow period). The second reason is the limited availability of bioherbicides in the Brazilian market, unlike bioinsecticides and biofungicides, which are already well-established in Brazilian agriculture. This has led to the exclusive use of chemical molecules for weed control in agricultural areas. Bioherbicides can be formulated with microorganisms or phytotoxins derived from microorganisms, insects, or plant extracts that act as natural agents for weed control [42].

Table 1. Sales data and representative percentage of each pesticide class (2010 to 2020). Grouping standard proposed by OECD [37].

Year	Total	Insecticides [1]	Fungicides [2]	Herbicides	Others [3]
	Tons of Active Ingredient [4]				
2010	295,287	72,856	63,365	157,512	1554
2011	314,862	77,950	61,298	173,171	2443
2012	383,999	75,146	55,117	251,094	2642
2013	407,792	96,135	53,541	256,004	2112
2014	420,467	104,172	61,028	252,765	2502
2015	445,684	95,636	74,354	272,852	2842
2016	451,276	86,627	85,605	276,147	2897
2017	453,111	86,174	90,882	273,502	2553
2018	490,495	83,711	110,698	293,053	3033
2019	564,635	98,562	132,357	329,697	4019
2020	610,098	101,783	144,241	359,308	4766
	Percentage (%) of total sales in the year				
2010	100.00	24.67	21.46	53.34	0.53
2011	100.00	24.75	19.47	55.00	0.78
2012	100.00	19.57	14.35	65.39	0.69
2013	100.00	23.57	13.13	62.78	0.52
2014	100.00	24.78	14.50	60.12	0.60
2015	100.00	21.46	16.68	61.22	0.64
2016	100.00	19.20	18.97	61.19	0.64
2017	100.00	19.02	20.06	60.36	0.56
2018	100.00	17.07	22.57	59.74	0.62
2019	100.00	17.46	23.44	58.39	0.71
2020	100.00	16.68	23.64	58.89	0.79

[1] Includes insecticides, acaricides, molluscicides, and nematicides. [2] Includes fungicides, bactericides, and pesticides used in seed treatment. [3] Includes fumigants, growth regulators, and seed protectants. [4] For the herbicides 2,4-D, glyphosate, picloram, MCPA, aminopyralid, florpyrauxifen-benzyl, fluroxypyr, haloxyfop-methyl, imazapic, imazaquin, imazapyr, imazethapyr, triclopyr, and cyhalofop-butyl, data are reported in tons of acid equivalent. For the herbicides diquat and paraquat, data are reported in tons of ion equivalent. For fungicides such as copper hydroxide, copper oxychloride, copper oxide, and copper sulfate, data are reported in tons of metallic copper equivalent. All other pesticides are reported in tons of active ingredients.

Regarding pesticide sales data, the introduction of *Bt* technology in soybean, corn, and cotton cultivars, combined with the increased use of bioinsecticides (both microbiological and macrobiological), likely contributed to the reduced share of chemical insecticides in the Brazilian pesticide market [43,44]. On the other hand, the growing share of fungicides in Brazil can be attributed mainly to the following factors: (1) weakening of some breeding programs focused on disease resistance/tolerance, resulting in the release of cultivars susceptible to various diseases and requiring more chemical control intervention; and (2) increased pathogen resistance to fungicides, leading to a significant rise in the use of multi-site fungicides in preventive applications, particularly in crops like soybeans [45,46]. It is worth noting that the recommended dose per area for multi-site fungicides is significantly higher than for more recently introduced site-specific fungicides.

Several factors explain the increased use of herbicides during the studied period (2010 to 2020) in Brazil: (1) expansion of no-till farming areas [47,48], where herbicide applications for pre-sowing burndown are common, with higher doses often used due to the more advanced growth stages of weeds. Brazilian farmers have become more aware of soil conservation [49], leading to the replacement of mechanical weed control practices, such as plowing, harrowing, and scarifying, which expose the soil to erosion; (2) growth in second-crop corn areas [50], where farmers use herbicides for pre-harvest soybean desiccation to advance corn sowing, in addition to increased herbicide use in corn crops themselves; (3) reduction in rural labor availability, which hinders the use of manual weed control methods [51]. Data from the World Bank Group [52] show that the rural population in Brazil decreased by 31.58% between the years 2000 and 2020;

(4) lack of bioherbicides or microbiological herbicides on the Brazilian market, unlike the growing availability of bioinsecticides and biofungicides; and (5) greater availability of products formulated from the same herbicide active ingredient, increasing competition among manufacturers/importers, which may have driven prices down for some herbicides. Examples of this price reduction can be found in the database of the *Companhia Nacional de Abastecimento* (CONAB) [53]: The herbicide clethodim (same formulated product and same active ingredient concentration) was sold for USD 51.41 per liter in 2010 and was marketed for USD 8.45 per liter in 2020 (based on data from Paraná State, Brazil). The herbicide haloxyfop (same formulated product and same active ingredient concentration) was sold for USD 32.82 per liter in 2010 and was marketed for USD 9.92 per liter in 2020 (based on data from São Paulo State, Brazil). (6) Increased areas infested with herbicide-resistant weed biotypes, particularly for glyphosate [54–56].

Herbicide-resistant weeds are the most significant factor behind the increased herbicide sales and are the central theme of the present material. It is important to note that the rise in herbicide sales does not necessarily indicate abusive behavior by farmers. Unlike other pesticides, there is often resistance among agricultural experts to increasing herbicide doses, as this could increase the risk of crop injuries, prolong residual herbicide activity, and cause carryover problems for subsequent crops. Additionally, higher herbicide doses raise production costs.

In addition to evaluating the commercialization of herbicides, it is relevant to investigate whether the environmental hazard potential profile of these products changed during the analyzed period. In Brazil, IBAMA is the institution responsible for assessing pesticides based on the environmental risks associated with their use, categorizing them into four classes: Class I: Highly hazardous to the environment; Class II: Very hazardous to the environment; Class III: Hazardous to the environment; and Class IV: Slightly hazardous to the environment To determine these classifications, IBAMA evaluates various factors, such as bioaccumulation, toxicity to non-target organisms, biodegradation, and soil mobility. In 2010, 0.001% of the herbicides sold in Brazil were classified as Class I, while 18.90% belonged to Class II and 81.10% to Class III. These proportions changed minimally by 2020, with 0.02% of the herbicides classified as Class I, 20.63% as Class II, and 79.35% as Class III. Notably, during this time frame, no herbicides classified as Class IV were sold in Brazil.

Regarding the human toxicity potential of herbicides sold in Brazil, it is important to highlight that between 2010 and 2020, no herbicides classified by the World Health Organization [57] as Ia (extremely hazardous) or Ib (highly hazardous) were marketed. An integrative analysis of the consolidated database showed that not all herbicide active ingredients experienced increased sales in Brazil from 2010 to 2020. Therefore, this study presents and discusses the sales results for herbicides that saw the highest sales growth during this period and are recommended for use in grain production areas.

3.2. Evolution of Herbicide Sales in Brazil (from 2010 to 2020)

The evolution of 2,4-D herbicide sales (tons of acid equivalent) is represented in Figure 1A, where a nearly linear increase from 2010 to 2020 can be observed. The herbicide 2,4-D is a synthetic auxin, characterized by causing various metabolic disturbances in sensitive plants, such as abnormal growth, death of root tissues, epinasty, and obstruction of phloem [58]. In Brazil, the herbicide 2,4-D is primarily marketed in the form of amine salt and is indicated for the control of broadleaf weeds [59]. In Brazil, 15,323 tons of this herbicide's active ingredient were sold in 2010, while in 2020, this number rose to 51,149 tons, representing an increase of 233.8%. The observed increase in usage exceeds the increase recorded during this 11-year period concerning the area of agriculture designated for harvesting (annual and perennial crops) (24.3%), the soybean area (59.4%), and the area of pastures without degradation (16.0%), which can be classified as the most demanding agricultural activities for 2,4-D in the country (Figure 1B).

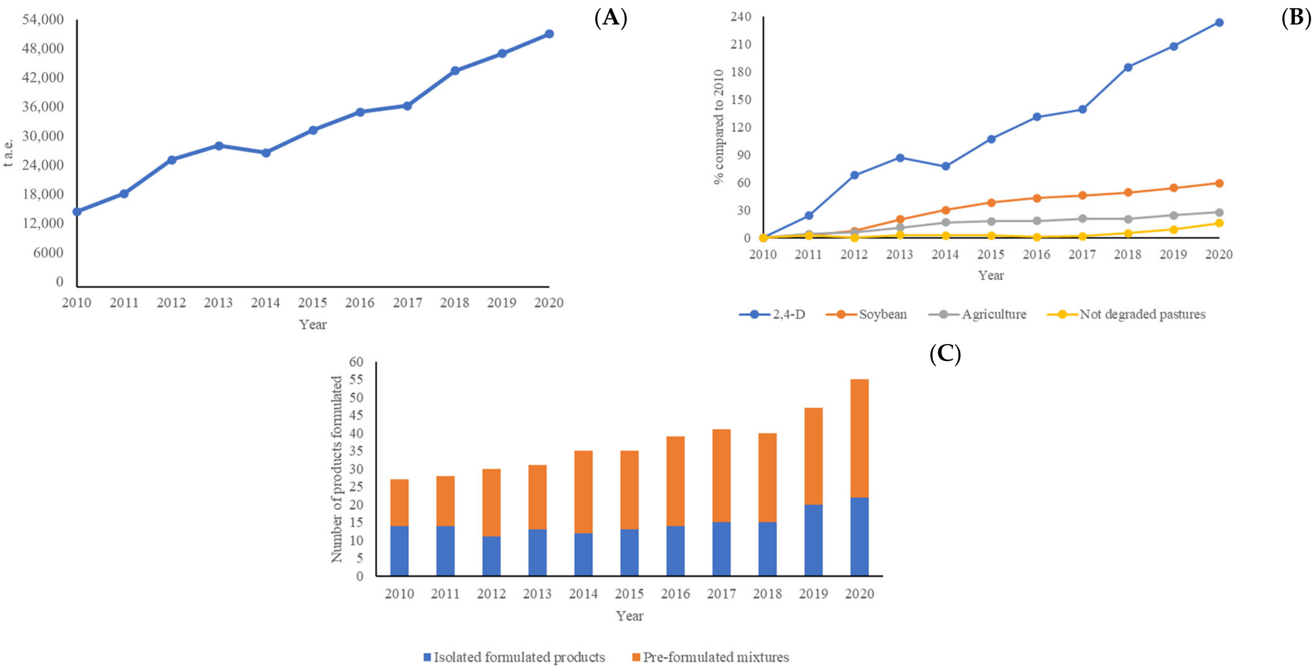

Figure 1. Sales of 2,4-D (tons of a.e.) from 2010 to 2020 (**A**). Evolution of herbicide sales in relation to the year 2010, compared to the evolution of soybean area (IBGE), the area of agriculture designated for harvesting (annual and perennial) (IBGE), and the area cultivated with pastures without degradation (LAPIG/UFG) (**B**). Number of formulated products based on 2,4-D sold in Brazil (**C**) (period from 2010 to 2020).

The main reason for the increased use of 2,4-D during this period is the worsening cases of glyphosate-resistant weed biotypes, specifically the increasing infestation of biotypes from different *Conyza* spp. species and areas infested with resistant *Amaranthus* spp. biotypes [27,60]. As a result, glyphosate, which previously provided effective control of these weed species, began requiring complementary herbicides during pre-sowing burndown to help manage resistant biotypes, driving the sales of 2,4-D in Brazil. It is important to note that the Enlist™ technology, which enables the selective use of 2,4-D, glyphosate, and glufosinate in crops like soybean and corn [61], was not available in the Brazilian market during the evaluated period (2010 to 2020) and, therefore, cannot be considered one of the factors responsible for the observed increase in use.

Other factors may have also contributed to this rise in 2,4-D consumption in Brazil, including: (1) increased use of herbicides in pastures between 2010 and 2020 [62]; (2) expansion of no-till farming in Brazil, as the main agricultural use of this herbicide is linked to pre-sowing burndown, especially before soybean crops; (3) increased availability of 2,4-D products in the Brazilian market. In 2010, 27 formulated products containing the active ingredient 2,4-D were sold, 14 containing only 2,4-D (as a single active ingredient) and 13 pre-formulated mixtures with other active ingredients. By 2020, the number of formulated products containing 2,4-D had increased to 55 (22 single active ingredient products and 33 pre-formulated mixtures), representing a 103.7% increase in product availability (Figure 1C); (4) expansion of agricultural areas infested with glyphosate-tolerant weeds, such as *Commelina benghalensis*, *Spermacoce latifolia*, *Ipomoea* spp., and *Tridax procumbens* [63,64]; and (5) shorter plantback intervals for soybean sowing compared to other auxin herbicides.

Another auxin herbicide, triclopyr, also experienced an increase in sales between 2010 and 2020 (Figure 2A). In 2010, 228 tons of triclopyr (acid equivalent) were sold, while in 2020, this volume increased to 2405 tons, representing a 953.5% increase in sales. This rise far exceeds the increase in soybean area (59.4%) and the area of pastures without degradation (16.0%), two agricultural activities where triclopyr is potentially used (Figure 2B). The main causes for the increase in triclopyr sales from 2010 to 2020 are as follows: (1) worsening cases of glyphosate-resistant weed biotypes, particularly the increased infestation of *Conyza* spp. biotypes, including those resistant to 2,4-D (rapid necrosis) [65], where triclopyr became a tool for management [66], and (2) expansion of areas infested with species from the genera *Spermacoce*, *Borreria*, and *Mitracarpus*, with triclopyr becoming one of the go-to herbicides for controlling these species during the off-season. Other less impactful factors may have also contributed to the rise in triclopyr sales, such as (1) increased availability of triclopyr-based products in the Brazilian market, especially products formulated with triclopyr as the sole active ingredient (a 400% increase in the availability of single-active ingredient formulations from 2010 to 2020) (Figure 2C), and (2) lower antagonism when mixed with ACCase-inhibiting herbicides compared to 2,4-D [67].

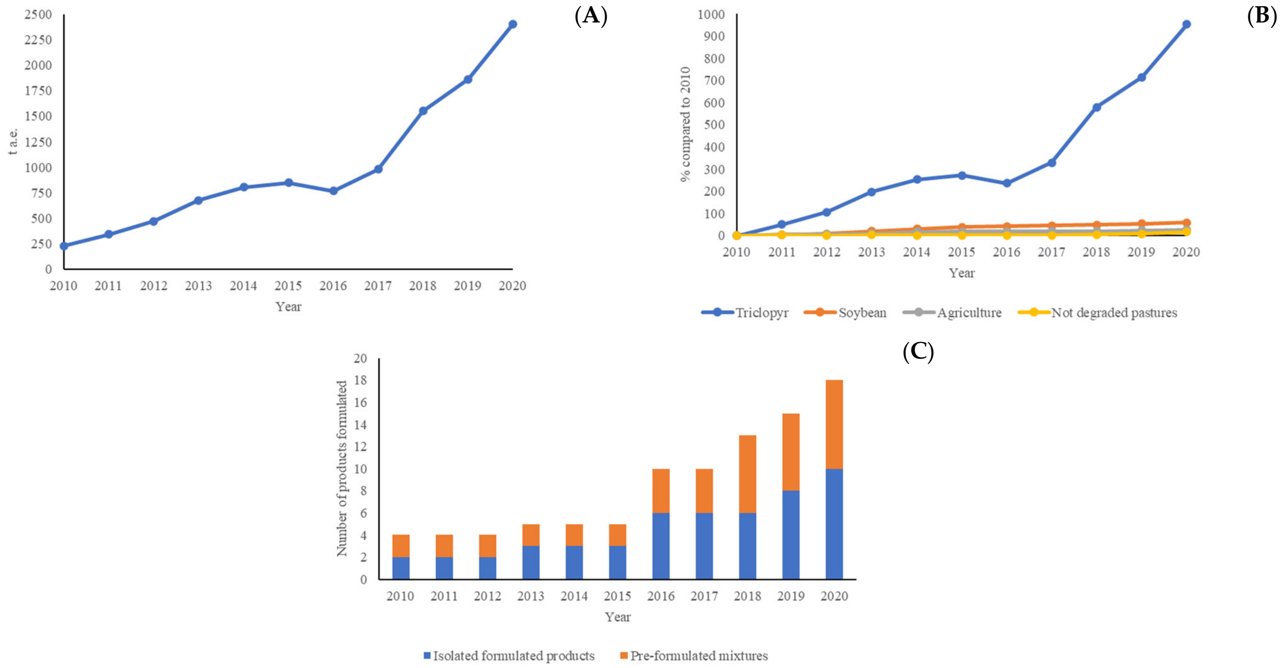

Figure 2. Sales of triclopyr (tons of a.e.) from 2010 to 2020 (**A**). Evolution of the commercialization of herbicide in relation to the year 2010, compared to the evolution of the soybean area (IBGE), the area of agriculture intended for harvest (temporary and permanent) (IBGE), and the area cultivated with pastures showing no degradation (LAPIG/UFG) (**B**). Number of formulated products based on triclopyr marketed in Brazil (**C**) (period from 2010 to 2020).

Haloxyfop-methyl and clethodim are herbicides used for post-emergence control of grasses, being selective for broadleaf crops such as soybean [68]. Both herbicides inhibit the enzyme acetyl-CoA carboxylase (ACCase), blocking lipid synthesis and, consequently, the formation of cell walls [69]. These two graminicides had increases in sales in Brazil between 2010 and 2020 (Figure 3A). In 2010, 111.3 tons of haloxyfop-methyl and 244.5 tons of clethodim (active ingredient/acid equivalent) were sold. By 2020, these amounts rose to 1109.8 tons of haloxyfop-methyl and 6779.6 tons of clethodim, representing an 896.9% increase in haloxyfop-methyl consumption and a 2672.8% increase for clethodim (Figure 3B). These increases far exceed the growth in agricultural area (24.3%) and soybean-planted area (59.4%) during the same period.

Among the main reasons for the sharp increase in the consumption of haloxyfop-methyl and clethodim herbicides are: (1) a significant rise in grain-growing areas infested with glyphosate-resistant biotypes of *Digitaria insularis* [26]. This situation created the need for supplementary control of this species, both in pre-sowing burndown operations and in post-emergence soybean management, substantially increasing the demand for these herbicides. More recently, another grass species resistant to glyphosate that could contribute to the increased use of haloxyfop-methyl and clethodim is *Eleusine indica*. However, this trend has not been observed with the same intensity, as multiple-resistant biotypes (EPSPS and ACCase) of this species have spread, limiting the effectiveness of these herbicides [70]; and (2) the increasing challenge posed by volunteer glyphosate-resistant corn plants. With the growing adoption of glyphosate-resistant corn hybrids in Brazil, controlling volunteer corn plants, resulting from mechanical harvesting failures, has become more problematic. This created the need to introduce new herbicides for controlling these plants before soybean sowing or even in established soybean fields. Among the effective herbicides for this purpose are ACCase inhibitors, such as haloxyfop-methyl and clethodim [71].

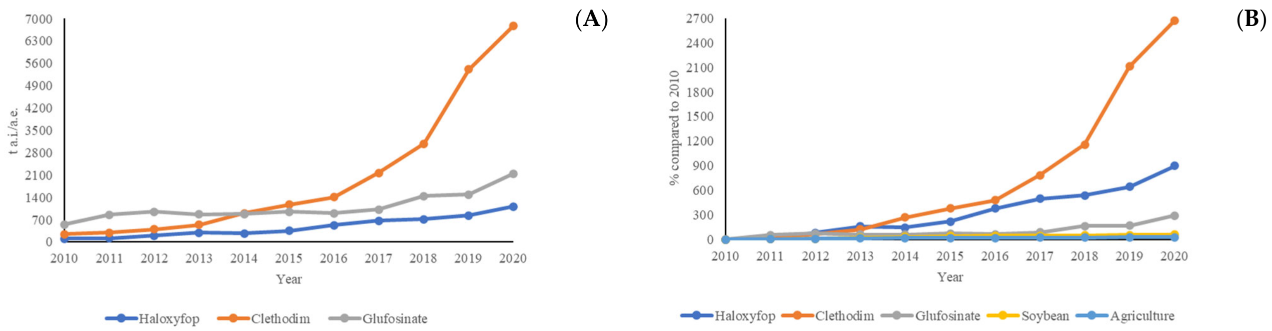

Figure 3. Sales of haloxyfop-methyl, clethodim, and glufosinate (tons of a.i./a.e.) (**A**). Evolution of the commercialization of herbicides in relation to the year 2010, compared to the evolution of the soybean area (IBGE) and the area of agriculture intended for harvest (temporary and permanent) (IBGE) (**B**). Sales data for haloxyfop-methyl are presented in effective ingredients.

The increased availability of haloxyfop-methyl and especially clethodim products may have also contributed to the rise in herbicide sales. In 2010, only one formulated product containing the isolated active ingredient haloxyfop-methyl was available in the Brazilian market. By 2020, this number had grown to nine products, including seven with haloxyfop-methyl as a single active ingredient and two pre-formulated mixtures (Figure 4A), representing an 800% increase in haloxyfop-methyl-based product availability over 11 years. For clethodim, the increase in formulated products during the same period was 600%, rising from two products in 2010 (one isolated and one pre-formulated mixture) to 14 products in 2020 (11 isolated and three pre-formulated mixtures) (Figure 4B).

The higher increase in clethodim consumption compared to haloxyfop-methyl may be related to the lower cost per hectare of clethodim application. It is important to note that the rise in glyphosate-resistant *Digitaria insularis* biotypes and volunteer corn plants (Roundup Ready™—RR™) was a key driver encouraging pesticide manufacturers and importers to register and market generic products based on haloxyfop-methyl and clethodim in Brazil, as these resistance cases created substantial demand for this group of herbicides. In summary, the increased availability of formulated products can be seen as a response to the worsening weed resistance to glyphosate in Brazil.

Three key factors can be identified as predominant drivers of the increase in the commercialization of the herbicide glufosinate in Brazil (Figures 3 and 4C): (1) increase in areas infested with glyphosate-resistant weeds, such as *Conyza* spp., *Digitaria insularis*, *Eleusine indica*, and *Amaranthus* spp. [72]. This is the most important factor driving the rise in glufosinate sales in Brazil; (2) introduction of transgenic soybean, corn, and cotton cultivars resistant to post-emergence applications of glufosinate in the Brazilian market; and (3) growth in the availability of glufosinate-based formulated products, especially after 2017 (one formulated product in 2010; nine in 2020). This increase is largely due to the sharp rise in glyphosate-resistant weeds in Brazil's grain crops, which has spurred companies' interest in marketing this active ingredient. It is also important to note that the ban on paraquat use in Brazil had a significant impact on glufosinate sales. Glufosinate shares some similar agronomic characteristics with paraquat, such as a broad spectrum of control, contact action, and the absence of residual soil activity [73]. However, the impact of this ban became more evident only in the later years of the analyzed period.

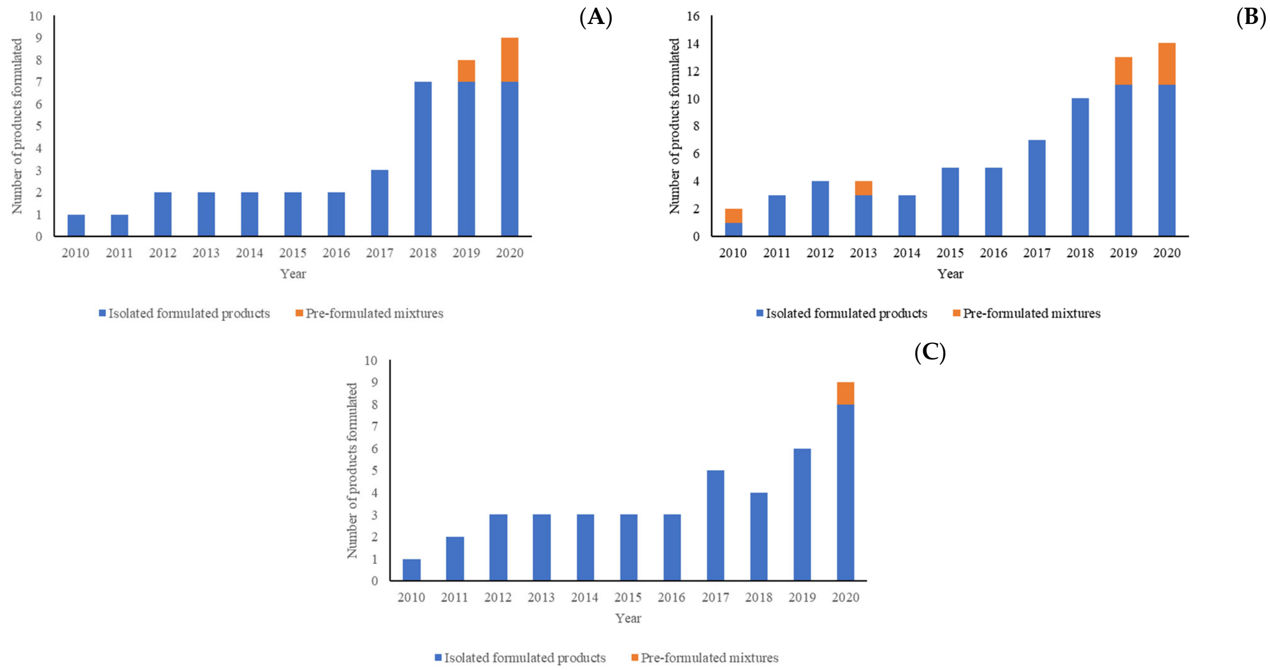

Figure 4. Number of formulated products based on haloxyfop-methyl (**A**), clethodim (**B**), and glufosinate (**C**) marketed in Brazil, subdivided by products containing only the active ingredient (isolated) or pre-formulated mixtures containing the respective herbicides (period from 2010 to 2020).

In the context of glyphosate-resistant weeds, the use of herbicides with residual soil activity has re-emerged in recent years in grain production areas. Looking ahead, there are expectations for the increased adoption of these herbicides in agricultural production systems, as they can control weed populations in the pre-emergence stage of crops [74]. Figures 5 and 6 show the sales data (tons of active ingredient and percentage growth) and the number of formulated products for the herbicides diclosulam and flumioxazin, which experienced sales growth between 2010 and 2020. Although flumioxazin had higher sales volumes, comparing the application rates per hectare for the crops registered for diclosulam suggests that diclosulam usage also increased substantially and is comparable to flumioxazin (Figure 5A). Moreover, considering only the percentage increase in sales relative to the first year of analysis (2010), both diclosulam and flumioxazin saw growth, with increases exceeding 520.0% (Figure 5B).

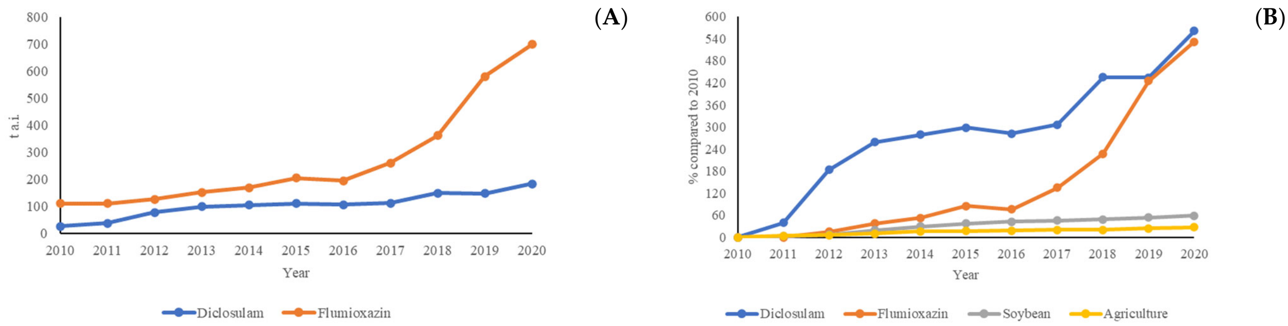

Figure 5. Sales of diclosulam and flumioxazin (tons of a.i.) (**A**). Evolution of herbicide sales compared to the year 2010, alongside the evolution of soybean area (IBGE) and the area of agriculture designated for harvest (temporary and permanent) (IBGE) (**B**).

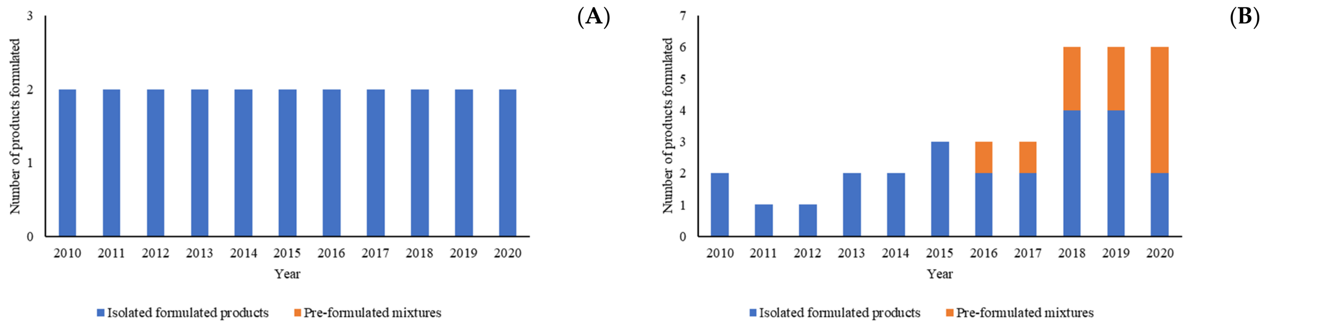

Figure 6. Number of formulated products based on diclosulam (**A**) and flumioxazin (**B**) marketed in Brazil, subdivided by products containing only the active ingredient (isolated) or pre-formulated mixtures containing the respective herbicides (period from 2010 to 2020).

Several factors can explain the increase in the commercialization of diclosulam and flumioxazin in the Brazilian market, among which the following stand out: (1) increased adoption of herbicides used in soybean pre-emergence applications, as certain products containing these active ingredients rank among the most widely used for this purpose [75]; (2) greater occurrence of glyphosate-resistant weeds, including *Conyza* spp. and the *Amaranthus* spp. complex (*A. hybridus* and *A. palmeri*), which diclosulam and flumioxazin effectively control in pre-emergence [60]; and (3) increased use of herbicides with residual soil activity, such as diclosulam and flumioxazin, in pre-sowing burndown applications for soybean crops.

Regarding the evolution of formulated products containing diclosulam and flumioxazin in the Brazilian agrochemical market, distinct behaviors can be observed depending on the active ingredient (Figure 6). For diclosulam, only two formulated products containing this active ingredient, one registered for sugarcane and another for soybean, were marketed during the period analyzed in this study (Figure 6A). Given the herbicide's high efficacy in controlling the main weeds infesting the crops for which diclosulam is registered [76], future prospects suggest a potential increase in the number of formulated products based on this active ingredient.

For flumioxazin, the number of formulated products marketed in Brazil increased, particularly from 2015 onward (Figure 6B). This reflects one of the unique characteristics of flumioxazin's weed control action: unlike other herbicides, flumioxazin exhibits residual soil activity (pre-emergence control), offering the added benefit of effective weed control in early post-emergence stages through contact action [77,78]. This is especially true when flumioxazin is used in combination with other herbicides. Additionally, due to its lower acquisition cost compared to other pre-emergent herbicides, along with these agronomic advantages, the number of formulated products containing flumioxazin has increased in recent years.

Despite the issues of weed resistance and tolerance discussed throughout this manuscript, data presented in Table 2 show that the commercialization of glyphosate in Brazil increased from 101,385 tons of active ingredient in 2010 to 209,345 tons in 2020, representing a 106.5% increase over the period. Furthermore, in 2010, glyphosate sales accounted for 64.37% of total herbicide sales in Brazil, whereas in 2020 this percentage dropped to 58.26%, indicating that other herbicides experienced higher growth rates in sales compared to glyphosate. This shift may reflect the widespread occurrence of glyphosate-resistant biotypes in agricultural areas across the country. Notably, glyphosate accounted for 34.33% of all pesticide sales in Brazil in 2010, a scenario that remained virtually unchanged in 2020 (34.31%). Several factors may explain the increased use of glyphosate in Brazil, including: (1) expansion of no-till farming; (2) greater adoption of GMO cultivars resistant to glyphosate, such as soybean, corn, and cotton; (3) increased use of cover crops (e.g., *Brachiaria* and *Panicum*), either in monoculture or intercropped systems, where glyphosate is the main tool for pre-sowing burndown [79]; (4) additive or synergistic effect when mixed with other herbicides with different modes of action, enhancing weed control [80]; and

(5) increased availability of glyphosate-based products. In 2010, 36 glyphosate-formulated products were sold in Brazil, including 35 single-ingredient products and only one pre-mix. By 2020, this number rose to 47 products, a 30.6% increase, with 45 single-ingredient products and two pre-mixes (Table 2).

Table 2. Information on glyphosate commercialization in Brazil in 2010 and 2020.

Information	Year	
	2010	**2020**
Glyphosate commercialization (tons of active ingredients)	101,385	209,345
% of total herbicide commercialization	64.37	58.26
% of total pesticide commercialization	34.33	34.31
Number of Formulated products	36	47
Number of isolated formulated products	35	45
Number of pre-formulated mixtures with other active ingredients	1	2
Salt formulation	% of total glyphosate sales	
Isopropylamine	51.59	12.55
Ammonium	21.49	27.06
Potassium	26.92	35.88
Dimethylammonium	0.00	0.75
Diammonium	0.00	9.26
[Isopropylamine + potassium]	0.00	14.50

The type of salt formed from glyphosate also changed between 2010 and 2020. Chemically, glyphosate is formulated as ammonium, diammonium, dimethylammonium, potassium, or isopropylamine salts [81]. In 2010, isopropylamine salt accounted for 51.59% of glyphosate sales in Brazil. However, by 2020, its share dropped to 12.55%, with potassium salt becoming the most sold, representing 35.88% of total glyphosate sales (Table 2). Changes in the type of glyphosate salt used in commercial products can affect the speed of weed control [22] and influence environmental factors after application, such as absorption speed and the impact of rainfall following application (rainfastness).

The data indicate disproportionate growth in the sale of herbicides used to manage glyphosate-resistant weeds, including both pre- and post-emergence products. This suggests that the resistance of weeds to glyphosate is a primary factor driving increased herbicide consumption. As a result, the quantitative data clearly highlight the negative impacts of glyphosate resistance, leading to agronomic and economic losses and significantly increasing the need for additional herbicides.

Despite the spread of resistant biotypes, glyphosate has not been widely replaced by other herbicides. Instead, it is often supplemented with additional molecules [82], as discussed in this study, contributing to the rising consumption of herbicides in Brazil. This increase in herbicide use is primarily due to a greater number of active ingredients applied per season, not higher doses. It is important to note that herbicide selectivity for crops is based on dose limits [83], since exceeding these limits can cause significant yield losses. Before resistance became widespread, glyphosate isolated was considered sufficient to control weeds across many agricultural areas [84]. Today, however, most soybean fields require two, three, or more active ingredients to complement glyphosate's action, both before sowing (burndown) and during the crop cycle (pre- and post-emergence).

Given this scenario, it is essential to implement integrated weed management strategies, including preventive control (e.g., cleaning machinery and acquiring certified, weed-free seeds), and cultural control (e.g., crop rotation, no-till farming with surface mulch, narrower row spacing, selecting fast-growing cultivars, and using high-vigor seeds). Additionally, whenever possible, herbicide rotation with different modes of action should be practiced, along with the use of sprayers equipped with weed-detecting sensors for post-emergence applications. Research investments aimed at identifying biological control agents to develop bioherbicides, as well as improving physical weed control methods (e.g., robotics, laser beams, electromagnetic waves, or boiling water with sealing foam), are also strategic and sustainable approaches. These combined efforts are crucial to preventing a future collapse in chemical weed control effectiveness and avoiding unsustainable herbicide loads in agricultural environments.

4. Conclusions

The commercialization of herbicides in Brazil saw an increase between 2010 and 2020. Some herbicides, such as clethodim, haloxyfop-methyl, triclopyr, glufosinate, 2,4-D, diclosulam, and flumioxazin, experienced increases in sales of 2672.8%, 896.9%, 953.5%, 290.2%, 233.8%, 561.3%, and 531.6%, respectively, far exceeding the growth rate of Brazil's agricultural area. Several factors may have contributed to this substantial rise in herbicide consumption; however, the primary cause was the worsening cases of glyphosate-resistant weed biotypes in Brazilian agricultural areas, particularly among species such as *Conyza* spp., *Amaranthus* spp., *Digitaria insularis*, and *Eleusine indica*. This situation created the need to supplement glyphosate with other herbicides to achieve effective chemical control of these species.

The data highlight that weed resistance to glyphosate has driven a substantial increase in the commercialization of herbicides with different profiles for both pre- and post-emergence applications, resulting in agronomic and economic impacts. This scenario led to the need for glyphosate to be supplemented with other molecules rather than replaced, contributing to an increase in the number of active ingredients used per season. This situation underscores the importance of integrated practices, such as rotating herbicide modes of action and implementing preventive and cultural controls, to ensure the effectiveness of chemical control and reduce dependency on herbicides. Investments in bioherbicides, nanotechnology related to herbicide formulation, and physical methods such as robotics and laser emissions are becoming essential to tackle future challenges and offer innovative and sustainable alternatives in weed management.

Author Contributions: Conceptualization, S.d.O.P. and R.R.M.B.; methodology, S.d.O.P., R.R.M.B. and R.A.A.P.; software, R.R.M.B. and R.A.A.P.; validation, S.d.O.P., R.R.M.B., R.A.A.P. and M.A.B.M.; formal analysis, S.d.O.P., R.R.M.B. and R.A.A.P.; investigation, S.d.O.P., R.R.M.B. and R.A.A.P.; resources, S.d.O.P. and R.R.M.B.; data curation, S.d.O.P. and R.A.A.P.; writing—original draft preparation, S.d.O.P., R.R.M.B. and G.B.P.B.; writing—review and editing, S.d.O.P., R.R.M.B., R.A.A.P. and G.B.P.B.; visualization, S.d.O.P., R.R.M.B., R.A.A.P. and G.B.P.B.; supervision, S.d.O.P., R.R.M.B., R.A.A.P. and M.A.B.M.; project administration, R.R.M.B.; funding acquisition, R.R.M.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received funding from the *Ministério da Agricultura e Pecuária* (MAPA) through a resource administered by the *Empresa Brasileira de Pesquisa Agropecuária* (EMBRAPA) (Project number: 10.22.10.018.00.00), and the APC was funded by MAPA.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are available from the corresponding author.

Acknowledgments: Special thanks to EMBRAPA *Meio Ambiente* analyst Renan Milagres Lage Novaes for his valuable contributions in reviewing the present material.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

References

1. Abouziena, H.F.; Haggag, W.M. Weed control in clean agriculture: A review. *Planta Daninha* **2016**, *34*, 377–392. [CrossRef]
2. Parven, A.; Meftaul, I.M.; Venkateswarlu, K.; Megharaj, M. Herbicides in modern sustainable agriculture: Environmental fate, ecological implications, and human health concerns. *Int. J. Environ. Sci. Technol.* **2024**. [CrossRef]
3. Wang, A.; Zhang, W.; Wei, X. A review on weed detection using ground-based machine vision and image processing techniques. *Comput. Electron. Agric.* **2019**, *158*, 226–240. [CrossRef]
4. Pinto, P.H.G.; Lima, S.F.; Andrade, M.G.O.; Contardi, L.M.; Ávila, J.; Reis, B.O.; Bernardo, V.F.; Vendrusculo, E.P. Weeds in soybean cultivation with different predecessor cover crops. *Rev. Agric. Neotrop.* **2021**, *8*, e5890. [CrossRef]

5. Zhang, H.; Cao, D.; Zhou, W.; Currie, K. Laser and optical radiation weed control: A critical review. *Precis. Agric.* **2024**, *25*, 2033–2057. [CrossRef]
6. Alptekin, H.; Ozkan, A.; Gurbuz, R.; Kulak, M. Management of weeds in maize by sequential or individual applications of pre- and post-emergence herbicides. *Agriculture* **2023**, *13*, 421. [CrossRef]
7. Nath, C.P.; Singh, R.G.; Choudhary, V.K.; Datta, D.; Nandan, R.; Singh, S.S. Challenges and alternatives of herbicide-based weed management. *Agronomy* **2024**, *14*, 126. [CrossRef]
8. Samim, M.; Haqmal, M.; Afghan, A.; Khaleeq, K.; Ahmadi, A. Response of soybean to nitrogen levels and weed management on growth, yield and economic efficiency. *J. Res. Appl. Sci. Biotechnol.* **2023**, *2*, 139–145. [CrossRef]
9. Kumar, S.; Rana, S.S. Weed management strategies in soybean (*Glycine max*)—A review. *Indian J. Agric. Sci.* **2022**, *92*, 438–444. [CrossRef]
10. Gorayeb, E.S.; Nascimento, S.C.; Santos, A.N.M.R.; Batalhon, L.; Albuquerque, M.R.M.; Oliveira, V.G.F.; Souza, V.B.; Bogo, A.; Silva, F.N. Survey of viruses and vectors in tomato plants, alternative hosts, and weeds in the state of Santa Catarina, Brazil. *Plant Pathol.* **2024**, *73*, 444–454. [CrossRef]
11. Scavo, A.; Mauromicale, G. Integrated weed management in herbaceous field crops. *Agronomy* **2020**, *10*, 466. [CrossRef]
12. Choudhary, C.S.; Behera, B.; Raza, M.B.; Mrunalini, K.; Bhoi, T.K.; Lal, M.K.; Nongmaithem, D.; Pradhan, S.; Song, B.; Das, T.K. Mechanisms of allelopathic interactions for sustainable weed management. *Rhizosphere* **2023**, *25*, 100667. [CrossRef]
13. Thompson, M.; Chauhan, B.S.; Thierfelder, C.; Esser, A. Weed control in conservation agriculture in southern Africa. *Sustainability* **2021**, *13*, 5950. [CrossRef]
14. Gianessi, L.P. The increasing importance of herbicides in worldwide crop production. *Pest Manag. Sci.* **2013**, *69*, 1099–1105. [CrossRef]
15. Kanatas, P.; Travlos, I.; Papastylianou, P.; Gazoulis, I.; Kakabouki, I.; Tsekoura, A. Yield, quality and weed control in soybean crop as affected by several cultural and weed management practices. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2020**, *48*, 329–341. [CrossRef]
16. Rivas-Garcia, T.; Espinosa-Calderón, A.; Hernández-Vázquez, B.; Schwentesius-Rindermann, R. Overview of environmental and health effects related to glyphosate usage. *Sustainability* **2022**, *14*, 6868. [CrossRef]
17. Procópio, S.O.; Pires, F.R.; Menezes, C.C.E.; Barroso, A.L.L.; Moraes, R.V.; Silva, M.V.V.; Queiroz, R.G.; Carmo, M.L. Effects of burndown herbicides in weed control in soybean crop. *Planta Daninha* **2006**, *24*, 193–197. [CrossRef]
18. Toni, L.R.M.; Santana, H.; Zai, D.A.M. Adsorption of glyphosate on soils and minerals. *Quim. Nova* **2006**, *29*, 829–833. [CrossRef]
19. Ringselle, B.; Bakken, A.K.; Höglind, M.; Jørgensen, M.; Tørresen, K.S. Effects of integrated grassland renewal strategies on annual and perennial weeds in the sowing year and subsequent production years. *Eur. J. Agron.* **2023**, *146*, 126799. [CrossRef]
20. Dalcin, L.S.; Terra, T.G.R.; Leal, T.C.A.B.; Terra, M.A.; Chaves, C.C. Efeito residual de herbicidas em dessecação de pré-plantio na cultura do sorgo granífero. *J. Biotechnol. Biodivers.* **2019**, *7*, 363–373. [CrossRef]
21. Beckie, H.J.; Flower, K.C.; Ashworth, M.B. Farming without glyphosate? *Plants* **2020**, *9*, 96. [CrossRef] [PubMed]
22. Pereira, B.C.S.; Braz, G.B.P.; Souza, M.F.; Reginaldo, L.T.R.T.; Ferreira, C.J.B. Performance of glyphosate-based products applied alone and in combination with herbicides in burndown. *Rev. Caatinga* **2023**, *36*, 765–774. [CrossRef]
23. Braz, G.B.P.; Freire, E.S.; Pereira, B.C.S.; Farnese, F.S.; Souza, M.F.; Loram-Lourenço, L.; Sousa, L.F. Agronomic performance of RR® soybean submitted to glyphosate application associated with a product based on *Bacillus subtilis*. *Agronomy* **2022**, *12*, 2940. [CrossRef]
24. Arsenijevic, N.; Dewerff, R.; Conley, S.; Ruark, M.; Werle, R. Influence of integrated agronomic and weed management practices on soybean canopy development and yield. *Weed Technol.* **2022**, *36*, 73–78. [CrossRef]
25. Amaral, G.S.; Alcántara-De la Cruz, R.; Martinelli, R.; Rufino Junior, L.R.; Carvalho, L.B.; Azevedo, F.A.; Silva, M.F.G.F. Occurrence of multiple glyphosate-resistant weeds in Brazilian citrus orchards. *AgriEngineering* **2023**, *5*, 1068–1078. [CrossRef]
26. Ovejero, R.F.L.; Takano, H.K.; Nicolai, M.; Ferreira, A.; Melo, M.S.C.; Cavenaghi, A.L.; Christoffoleti, P.J.; Oliveira, R.S., Jr. Frequency and dispersal of glyphosate-resistant sourgrass (*Digitaria insularis*) populations across Brazilian agricultural production areas. *Weed Sci.* **2017**, *65*, 285–294. [CrossRef]
27. Mendes, R.R.; Takano, H.K.; Gonçalves Netto, A.; Picoli Junior, G.J.; Cavenaghi, A.L.; Silva, V.F.V.; Nicolai, M.; Christoffoleti, P.J.; Oliveira, R.S., Jr.; Melo, M.S.C.; et al. Monitoring glyphosate- and chlorimuron-resistant *Conyza* spp. populations in Brazil. *An. Acad. Bras. Ciênc.* **2021**, *93*, e20190425. [CrossRef]
28. Heap, I. Herbicide Resistant Weeds in Brazil. 2024. Available online: https://www.weedscience.com/Summary/Country.aspx?CountryID=5 (accessed on 5 August 2024).
29. Moreira, M.S.; Nicolai, M.; Carvalho, S.J.P.; Christoffoleti, P.J. Glyphosate-resistance in *Conyza canadensis* and *C. Bonariensis*. *Planta Daninha* **2008**, *25*, 157–164. [CrossRef]
30. Araújo, L.S.; Correia, N.M.; Tornisielo, V.L.; Labate, M.T.V.; Tsai, S.M.; Carbonari, C.A.; Victória Filho, R. Goosegrass (*Eleusine indica*) resistant to multiple herbicide modes of action in Brazil. *Weed Sci.* **2023**, *71*, 189–197. [CrossRef]
31. Correia, N.M. Chemical and cultural management strategies for glyphosate-resistant sourgrass in central Brazil. *Pesqui. Agropecu. Bras.* **2023**, *58*, e02900. [CrossRef]
32. Sulzbach, E.; Turra, G.M.; Cutti, L.; Kroth, L.V.E.; Tranel, P.J.; Merotto Júnior, A.; Markus, C. Smooth pigweed (*Amaranthus hybridus*) and unresolved *Amaranthus* spp. from Brazil resistant to glyphosate exhibit the EPSPS TAP-IVS substitution. *Weed Sci.* **2024**, *72*, 48–58. [CrossRef]

33. Marca, V.; Procópio, S.O.; Silva, A.G.; Volf, M. Chemical control of glyphosate-resistant volunteer maize. *Rev. Bras. Herbic.* **2015**, *14*, 103–110. [CrossRef]
34. Buchling, C.; Braz, G.B.P.; Procópio, S.O.; Ferreira, C.J.B.; Silva, A.G.; Coradin, J. Pre-emergence control and interference of voluntary maize plants on a soybean crop in Brazilian *Cerrado*. *Acta Sci. Agron.* **2022**, *44*, e54544. [CrossRef]
35. Pereira, B.C.S.; Ferreira, C.J.B.; Braz, G.B.P.; Souza, M.F.; Tavares, R.L.M.; Rosa, M.; Carmo, E.L.; Vian, G.H.; Silva, A.P.S.; Machado, F.G. Can soil compaction alter morphophysiological responses and soybean yield under application of selective herbicides? *Appl. Environ. Soil Sci.* **2023**, *2023*, 5518677. [CrossRef]
36. FAOSTAT. Pesticide Use. 2024. Available online: https://www.fao.org/faostat/en/#data/RP (accessed on 22 September 2024).
37. OECD. *OECD Compendium of Agri-Environmental Indicators*; OECD Publishing: Paris, France, 2013. Available online: https://www.oecd-ilibrary.org/agriculture-and-food/oecd-compendium-of-agri-environmental-indicators_9789264186217-en (accessed on 26 February 2024).
38. IBGE (Instituto Brasileiro de Geografia e Estatística). Sistema IBGE de Recuperação Automática—SIDRA. 2024. Available online: https://sidra.ibge.gov.br/home/pms/brasil (accessed on 18 April 2024).
39. LAPIG/UFG (Image Processing and Geoprocessing Laboratory of Universidade Federal de Goiás). Atlas das Pastagens Brasileiras. 2024. Available online: https://lapig.iesa.ufg.br/p/38972-atlas-das-pastagens (accessed on 14 April 2024).
40. Qu, R.Y.; He, B.; Yang, J.F.; Lin, H.Y.; Yang, W.C.; Wu, Q.Y.; Li, Q.X.; Yang, G.F. Where are the new herbicides? *Pest Manag. Sci.* **2021**, *77*, 2620–2625. [CrossRef] [PubMed]
41. Chauhan, B.S.; Singh, R.G.; Mahajan, G. Ecology and management of weeds under conservation agriculture: A review. *Crop Prot.* **2012**, *38*, 57–65. [CrossRef]
42. Hasan, M.; Ahmad-Hamdani, M.S.; Rosli, A.M.; Hamdan, H. Bioherbicides: An eco-friendly tool for sustainable weed management. *Plants* **2021**, *10*, 1212. [CrossRef]
43. Horikoshi, R.J.; Dourado, P.M.; Berger, G.U.; Fernandes, D.S.; Omoto, C.; Willse, A.; Martinelli, S.; Head, G.P.; Corrêa, A.S. Large-scale assessment of lepidopteran soybean pests and efficacy of Cry1Ac soybean in Brazil. *Sci. Rep.* **2021**, *11*, 15956. [CrossRef]
44. Bortoloti, G.; Sampaio, R.M. Demandas tecnológicas: Os bioinsumos para controle biológico no Brasil. *Cad. Ciênc. Tecnol.* **2022**, *39*, e26927. [CrossRef]
45. Zambolim, L.; Juliatti, F.C.; Guerra, W. How to cope with the vulnerability of site specific fungicides on the control of Asian soybean rust. *Int. J. Res. Agron.* **2021**, *4*, 14–25. [CrossRef]
46. Machado, F.J.; Barro, J.P.; Godoy, C.V.; Dias, A.R.; Forcelini, C.A.; Utiamada, C.M.; Andrade Júnior, E.R.; Juliatti, F.C.; Grigolli, J.F.J.; Campos, H.D.; et al. Is tank mixing site-specific premixes and multi-site fungicides effective and economic for managing soybean rust? A meta-analysis. *Crop Prot.* **2022**, *151*, 105839. [CrossRef]
47. Fuentes-Llanillo, R.; Telles, T.S.; Soares Junior, D.; Melo, T.R.; Friedrich, T.; Kassam, A. Expansion of no-tillage practice in conservation agriculture in Brazil. *Soil Tillage Res.* **2021**, *208*, 104877. [CrossRef]
48. Possamai, E.J.; Conceição, P.C.; Amadori, C.; Bartz, M.L.C.; Ralisch, R.; Vicensi, M.; Marx, E.F. Adoption of the no-tillage system in Paraná State: A review. *Rev. Bras. Cienc. Solo* **2022**, *46*, e0210104. [CrossRef]
49. Tavares Filho, J.; Rinschede, M. Vision of the farmers, professional and students of the agronomic area in respect of soil and water conservation in Londrina, PR. *Semin. Cienc. Agrar.* **2009**, *30*, 1195–1202. [CrossRef]
50. Ulrich, A.; Sousa, T.L.M.; Guimarães, A.G.; Thompson, W.; Lobo Junior, A.R.; Evaristo, A.B. Performance of second-crop maize hybrids in different population densities. *Rev. Agrogeoambiental* **2023**, *15*, e20231740. [CrossRef]
51. Santiago, A.D.; Procópio, S.O.; Braz, G.B.P.; Ferreira, C.J.B. The use of pre-emergence herbicides in cassava decreases the need of manual weeding. *Rev. Ceres* **2020**, *67*, 223–230. [CrossRef]
52. World Bank Group. Urban Population (% of Total Population)—Brazil. 2024. Available online: https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?locations=BR (accessed on 4 December 2024).
53. CONAB. Companhia Nacional de Abastecimento. Insumos Agropecuários. 2024. Available online: https://consultaweb.conab.gov.br/consultas/consultaInsumo.do?method=acaoCarregarConsulta (accessed on 4 December 2024).
54. Krzyzaniak, F.; Albrecht, L.P.; Albrecht, A.J.P. *Digitaria insularis*: Cross-resistance between ACCase inhibitors and multiple resistance to glyphosate. *Aust. J. Crop Sci.* **2023**, *17*, 556–562. [CrossRef]
55. Guidugli, T.B.; Bacha, A.L.; Martins, H.L.; Novello, B.D.; Alves, P.L.C.A. Glyphosate-resistant *Digitaria insularis* effect on eucalyptus initial growth. *New For.* **2024**, *55*, 1209–1229. [CrossRef]
56. Kalsing, A.; Velini, E.D.; Merotto, A.; Carbonari, C.A. The Population genomics of *Conyza* spp. in soybean macroregions suggest the spread of herbicide resistance through intraspecific and interspecific gene flow. *Sci. Rep.* **2024**, *14*, 19536. [CrossRef]
57. World Health Organization. *The WHO Recommended Classification of Pesticides by Hazard and Guidelines to Classification 2019*; World Health Organization: Geneva, Switzerland, 2020.
58. Marcinkowska, K.; Praczyk, T.; Gawlak, M.; Niemczak, M.; Pernak, J. Efficacy of herbicidal ionic liquids and choline salt based on 2,4-D. *Crop Prot.* **2017**, *98*, 85–93. [CrossRef]
59. Carini, A.J.; Galon, L.; Rossetto, E.R.O.; Silva, F.A.C.; Tonin, R.J.; Perin, G.F. Seletividade de sais de 2,4-D aplicados em diferentes estádios fenológicos de cultivares de trigo. *Rev. Bras. Ciênc. Agrár.* **2024**, *19*, e3749. [CrossRef]
60. Braz, G.B.P.; Takano, H.K. Chemical control of multiple herbicide-resistant *Amaranthus*: A review. *Adv. Weed Sci.* **2022**, *40*, e0202200062. [CrossRef]

61. Oliveira, T.S.; Martins, H.L.; Carrega, W.C.; Barroso, A.A.M.; Alves, P.L.C.A. Selectivity of 2,4-D choline salt, glyphosate, glufosinate, and their mixtures for Enlist E3™ soybeans. *Afr. J. Agric. Res.* **2024**, *20*, 693–701. [CrossRef]
62. Merotto Júnior, A.; Gazziero, D.L.P.; Oliveira, M.C.; Scursoni, J.; Garcia, M.A.; Figueroa, R.; Turra, G.M. Herbicide use history and perspective in South America. *Adv. Weed Sci.* **2022**, *40*, e020220050. [CrossRef]
63. Kalsing, A.; Rossi, C.V.S.; Lucio, F.R.; Minozzi, G.B.; Gonçalves, F.P.; Valeriano, R. Efficacy of control of glyphosate-tolerant species of the *Rubiaceae* family through double-knockdown applications. *Planta Daninha* **2020**, *38*, e020190700. [CrossRef]
64. Perissato, M.M.; Albrecht, A.J.P.; Albrecht, L.P.; Rosa, W.B.; Perissato, S.M.; Larini, W.F. Efficacy of herbicides applied to *Commelina benghalensis* in the west of the state of Paraná. *Rev. Agric. Neotrop.* **2023**, *10*, e7243. [CrossRef]
65. Queiroz, A.R.S.; Delatorre, C.A.; Lucio, F.R.; Rossi, C.V.S.; Zobiole, L.H.S.; Merotto Júnior, A. Rapid necrosis: A novel plant resistance mechanism to 2,4-D. *Weed Sci.* **2020**, *68*, 6–18. [CrossRef]
66. Cantu, R.M.; Albrecht, L.P.; Albrecht, A.J.P.; Silva, A.F.M.; Danilussi, M.T.Y.; Lorenzetti, J.B. Herbicide alternative for *Conyza sumatrensis* control in pre-planting in no-till soybeans. *Adv. Weed Sci.* **2021**, *39*, e2021000025. [CrossRef]
67. Pedrollo, N.T.; Peripolli, M.; Cassol, J.C.; Dornelles, S.H.B. Clethodim and triclopir in association in glyphosate resistant voluntary corn control. *Vivências* **2022**, *18*, 263–274. [CrossRef]
68. Lee, S.; Payne, C.; Rees, S.; Ahrens, H.; Arve, L.; Asmus, E.; Bojack, G.; Arsequell, E.L.B.; Gatzweiler, E.; Helmke, H.; et al. Investigation of Acetyl-CoA Carboxylase-inhibiting herbicides that exhibit soybean crop selectivity. *Pest Manag. Sci.* **2024**. [CrossRef]
69. Barroso, A.L.L.; Dan, H.A.; Procópio, S.O.; Toledo, R.E.B.; Sandaniel, C.R.; Braz, G.B.P.; Cruvinel, K.L. Efficacy of ACCase-inhibiting herbicides in controlling grass weeds in soybean crops. *Planta Daninha* **2010**, *28*, 149–157. [CrossRef]
70. Correia, N.M.; Araújo, L.S.; Bueno Júnior, R.A. First report of multiple resistance of goosegrass to herbicides in Brazil. *Adv. Weed Sci.* **2022**, *40*, e020220007. [CrossRef] [PubMed]
71. Braz, L.B.P.; Braz, G.B.P.; Procópio, S.O.; Silva, A.G.; Braz, A.J.B.P.; Ferreira, C.J.B. Chemical control in different glyphosate resistant maize hybrids. *Rev. Bras. Milho Sorgo* **2018**, *17*, 535–547. [CrossRef]
72. Adegas, F.S.; Correia, N.M.; Silva, A.F.; Concênço, G.; Gazziero, D.L.P.; Dalazen, G. Glyphosate-resistant (GR) soybean and corn in Brazil: Past, present, and future. *Adv. Weed Sci.* **2022**, *40*, e0202200102. [CrossRef]
73. Takano, H.K.; Dayan, F.D. Glufosinate-ammonium: A review of the current state of knowledge. *Pest Manag. Sci.* **2020**, *76*, 3911–3925. [CrossRef]
74. Schelter, M.L.; Prates, A.A.; Fruet, D.L.; Souza, M.P.; Guerra, N.; Oliveira Neto, A.M. Response of soybean cultivars with different maturation times to pre-emergence herbicides. *Semin. Cienc. Agrar.* **2023**, *44*, 841–858. [CrossRef]
75. Coradin, J.; Braz, G.B.P.; Machado, F.G.; Silva, A.G.; Sousa, J.V.A. Herbicidas aplicados em pré-emergência para o controle de milho voluntário e capim-amargoso. *Rev. Cientif. Rural.* **2019**, *21*, 28–38. [CrossRef]
76. Braz, G.B.P.; Oliveira Júnior, R.S.; Zobiole, L.H.S.; Rubin, R.S.; Voglewede, C.; Constantin, J.; Takano, H.K. Sumatran Fleabane (*Conyza sumatrensis*) control in no-tillage soybean with diclosulam plus halauxifen-methyl. *Weed Technol.* **2017**, *31*, 184–192. [CrossRef]
77. Stephenson, D.O.; Spivey, T.A.; Deliberto, M.A.; Blouin, D.C.; Woolam, B.C.; Buck, T.B. Effects of low-dose flumioxazin and metribuzin postemergence applications on soybean. *Weed Technol.* **2019**, *33*, 87–94. [CrossRef]
78. Ferrier, J.; Soltani, N.; Hooker, D.C.; Robinson, D.E.; Sikkema, P.H. Biologically effective dose of flumioxazin and pyroxasulfone for control of multiple herbicide–resistant waterhemp (*Amaranthus tuberculatus*) in soybean. *Weed Sci.* **2022**, *70*, 243–248. [CrossRef]
79. Santos, F.L.S.; Silva, W.T.; Calil, F.N.; Cunha, P.P.; Costa, R.B.; Ximenes, P.A. Desiccation of forage plants from *Urochloa* genus using glyphosate herbicide. *Rev. Agric. Neotrop.* **2022**, *9*, e6772. [CrossRef]
80. Lima, D.B.C.; Silva, A.G.; Procópio, S.O.; Barroso, A.A.L.; Dan, H.A.; Costa, E.C.; Braz, A.J.B.P. Herbicides selection for controlling soybean volunteer plants resistant to glyphosate. *Rev. Bras. Herbic.* **2011**, *10*, 1–12. [CrossRef]
81. Benbrook, C.M. Trends in glyphosate herbicide use in the United States and globally. *Environ. Sci. Eur.* **2016**, *28*, 3. [CrossRef] [PubMed]
82. Riley, E.B.; Bradley, K.W. Influence of application timing and glyphosate tank-mix combinations on the survival of glyphosate-resistant giant ragweed (*Ambrosia trifida*) in soybean. *Weed Technol.* **2014**, *28*, 1–9. [CrossRef]
83. Kudsk, P.; Streibig, J.C. Herbicides—A two-edged sword. *Weed Res.* **2003**, *43*, 90–102. [CrossRef]
84. Okada, M.; Hanson, B.D.; Hembree, K.J.; Peng, Y.; Shrestha, A.; Stewart, C.N.; Wright, S.D.; Jasieniuk, M. Evolution and spread of glyphosate resistance in *Conyza bonariensis* in California and a comparison with closely related *Conyza canadensis*. *Weed Res.* **2015**, *55*, 173–184. [CrossRef]