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Exploring the complexity of smallholders' intense use of glyphosate in maize crops from South Mexico: Remarks for an ongoing agroecological transition

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Recently, Mexico has launched policies of agroecological transition that seek to foster healthier agri-food systems. One of these policies is the reduction and eventual elimination of glyphosate by 2024. Despite being the most used herbicide in Mexico and the world, little information exists about what factors determine a greater or reduced use of glyphosate in different socio-ecological contexts. This study aimed to explore different agricultural management, biophysical and social variables and their effects on glyphosate use in maize crops by smallholders (<8 ha). A questionnaire and semi-structured interviews were performed with 142 farmer families in four regions of the state of Chiapas to document the use of herbicides and glyphosate. By using regression trees, we identified those variables that determine a greater or lesser use of glyphosate for each region and jointly. The average volume of glyphosate for the four regions during an agricultural cycle was 2.7 l/ha^{-1}. Sets of variables were associated with syndromes of greater use of glyphosate and herbicides in general, such as small plots (<0.67 ha), indigenous population, younger farmers, fewer family members, rainfed conditions, and plots without mechanization. These results can help the design of contextualized and flexible policies of transition, consistent with the socio-ecological heterogeneity of Mexico.

KEYWORDS

glyphosate, milpa, paraquat, Chiapas, annual crops, agroecological transition, 2,4-D Amina

Introduction

Efforts directed toward having more resilient and sustainable agri-food systems are currently considered a worldwide priority (Food Agriculture Organization, 2018; Wezel et al., 2020). Mexico has launched a series of policies to move in this direction and foster healthier agri-food systems. Among these policies, the gradual reduction and the prohibition of the herbicide called glyphosate have been raised. In response to the available evidence regarding the effects to human health and ecosystems, in 2015 the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC) reclassified glyphosate as a "probable carcinogen for humans" (International Agency for Research on Cancer, 2017). In December of 2020 in Mexico, a presidential decree was issued that prohibits the use of this agrochemical starting in 2024 and the supposed staggered elimination of the same starting from 2021. The decree likewise prohibits the planting of transgenic maize and urges the creation of scientific research that helps transition toward "sustainable and culturally adequate alternatives" (DOF, 2020). Mexico is not the first country to implement measures like these and recognize the toxicity of this herbicide, in addition to establishing the need to put into practice alternatives for its use (PAN, 2018; Malkanthi et al., 2019; Beckie et al., 2020; CONACYT, 2020; MacLaren et al., 2020; Ramírez Muñoz, 2021).

On a worldwide scale, the use of glyphosate has increased by 1,500% since 1996 (Clapp, 2021). Mainly, this increase was because of the commercialization and the sowing of genetically modified crops tolerant to glyphosate, as well as the release of its commercial patent in 2000 (CONACYT, 2020). Currently, approximately 56% of the global use of glyphosate in agriculture is destined for transgenic crops (Benbrook, 2016). Nevertheless, it has also been found that glyphosate has managed to penetrate peasant and small-scale agriculture (Mariaca-Méndez et al., 2007; Bernardino et al., 2016; Mascorro-de Loera et al., 2019). In the case of Mexico, even though transgenic crops on the commercial scale are banned, the use of glyphosate has been widely adopted. At the national level ∼60% of the open-air farmers use chemical herbicides in their production (INEGI, 2019). Glyphosate is the pesticide with the highest import volumes at the national level; however, there is no information on how it is distributed and used in the country (Instituto Nacional de Ecología y Cambio Climático et al., 2020). It has been identified that glyphosate is used for diverse crops, underscoring its application to maize with 35% of the total national use (Alcántara-de la Cruz et al., 2021).

Maize is the most important crop in terms of human consumption and for the volume of production in Mexico (Sweeney et al., 2013). Smallholders contribute around 50% of the national production of such a crop (Puyana, 2012; González-Ortega et al., 2017), in addition to supporting self-sufficiency to millions of peasant families and for diversifying their livelihood options (Bellon et al., 2018). Mexico it's the center of origin and domestication of maize, dating from 6,000 to 10,000 years ago (Perales and Golicher, 2014). Traditionally, maize cropping by smallholders was associated with the system called "milpa," which involved little use of external inputs, the use of native seeds or landraces, polyculture, and little or no mechanization (Toledo et al., 2003; Bellon et al., 2018). During the last decades, this type of production has experienced drastic changes. Much of the labor has been mechanized, and the use of agrochemicals has been generalized (Vigouroux et al., 2011). In particular, the use of manual means of weed control has been substituted by herbicide application (Vázquez et al., 2004; Parsons et al., 2009; McClung de Tapia et al., 2014).

Even though different agroecological alternatives exist for weed management (Liebman et al., 2004; PAN, 2018; CONACYT, 2020; MacLaren et al., 2020; Ramírez Muñoz, 2021), various factors have encouraged the increasingly greater use of chemically synthesized herbicides and glyphosate (Desquilbet et al., 2019; Anaya-Zamora et al., 2020; Clapp, 2021). In Mexico, historically, the countryside policies have promoted the adoption of technology packages associated with the use of improved maize varieties and agrochemicals (Bellon and Hellin, 2011). These agrochemicals are frequently imposed as part of agricultural subsidies to farmers. The role of national and international agribusiness in this strong adoption has been key, partnering with different government agencies. On the other hand, the North American Free Trade Agreement (NAFTA) since 1994, also promoted a massive migration of peasants to urban centers or the United States by creating a collapse in maize prices (García-Barrios et al., 2009; Puyana, 2012). Those who continued their production—above all market-driven—resorted to the application of chemically synthesized herbicides with backpack sprayers that implied a decrease in human labor and an investment in time. Currently, the scarce availability of a workforce in the countryside affects practices like manual weeding (Keleman et al., 2009). Herbicide adoption is also influenced by biophysical conditions of the plots, such as hillside agriculture where mechanized labors are limited and soil conditions that favor weed growth (Beckie et al., 2020).

To reverse this dependence on the use of glyphosate and of chemically synthesized herbicides in general, it is necessary to understand how this complex ensemble of agricultural management, social, and biophysical conditions act favoring or diminish their use. In this sense, the objectives of this study are: (i) to make an agronomic characterization of the use of glyphosate and other herbicides in maize crop systems by smallholders; and (ii) to identify sets of variables (management, social, and biophysical) that explain the variability in the volume application of glyphosate specifically. We develop our research in the state of Chiapas in southern Mexico, which possesses a great ethnolinguistic, ecological, and biophysical diversity, as well as native maize varieties (Brush and Perales, 2007). Although various factors can affect high or low glyphosate and herbicides use by farmers (Colbach et al., 2020), it is possible to identify groups of characteristics or syndromes that can result in greater use of glyphosate and/or herbicides in general. These syndromes can help us to understand the needs of different groups of farmers for a transition to not using glyphosate. Although we focus on glyphosate because its ban is approaching in the coming years, we explore the use of other herbicides, since it has been documented the use of various herbicides in the region (Bernardino et al., 2016; Mascorro-de Loera et al., 2019). This research strives to contribute information to create agroecological alternatives for the use of glyphosate within the context of a country with great socio-ecological heterogeneity like Mexico.

Materials and methods

Study site

Our research employed a case study design with aggregated units (Yin, 2003), the units represent four municipalities of different socioeconomic regions within the state of Chiapas (Figure 1). The state of Chiapas is among the five largest maize producers in Mexico, mostly by smallholders' production in rainfed areas (Eakin et al., 2015). In Chiapas, for more than 60 years, the use of agrochemicals (fertilizers, herbicides, and insecticides) has been promoted through different programs and government supports (Bellon, 1991; Eakin et al., 2014). Chiapas poses high levels of poverty, around 75% of its population is considered in a condition of poverty (CONEVAL, 2020). The selected regions have a high ecological and cultural value, with the presence of different indigenous groups, many of whom plant maize as part of their livelihoods. Some of the common characteristics among regions is that all farmers plant maize for the double purpose of self-consumption and selling the surpluses to the market. The use of improved varieties started in the 1960s, accompanied by the introduction of fertilizers, herbicides and pesticides (Bellon, 1991; Arellano-Monterrosas et al., 2002), yet many farmers still plant *criollo*[1] seeds. Most of the regions have tropical weather, except for the Altos region that has temperate weather. Next, each of the regions are described, and some important characteristics are indicated in Table 1. Photographs of the representative maize plots in the four regions appear in Figure 2.

The Valleys region's main economic activity is agriculture where seasonal crops are grown. Within the region, we worked in the municipality of Ocozocoautla in valley areas (VO). Within this municipality, five locations were selected, two of them (Aguacero and Lázaro Cárdenas) with a mostly Tzotzil indigenous population. In the remaining three locations, the population is considered *mestizo*[2] (Ignacio Zaragoza, Galeana and San José). The altitude of the sampled plots ranges from 680 to 960 m. Most of the land is rainfed with some exceptions of irrigated land. The soil is mainly rocky limestone, creating rugged slopes not appropriate for mechanized agriculture. Planting in polyculture is common, where maize, bean and squash are the most common crops; cattle raising is also practiced.

The Frailesca region is characterized by the presence of annual crops, coffee plantations, along with cattle raising (Cortina-Villar et al., 2012). Within the Frailesca region, the study was developed in the municipality of Villaflores (SV), specifically in mountainous areas part of the La Sepultura Biosphere Reserve (LSBR). Data from three localities was obtained: California, Tres Picos and Tierra y Libertad. The three localities have a predominantly *mestizo* population (Cortina-Villar et al., 2012). The altitude of the sampled plots ranges from 865 to 1,243 m. The plots were situated behind the forest limit of the LSBR, which possess a high slope not suitable for mechanized agriculture. Mostly seasonal agriculture is practiced, with some exceptions to irrigation agriculture. Planting in polyculture is common, where maize, bean and squash are the most common crops. After the harvest, the stubble is used for livestock.

In the Altos region, agriculture and temporary or permanent migration are the predominant activities, with maize, bean, squash and coffee as the main crops (Maldonado-López et al., 2017). Within the Altos region, the study was developed in the municipality of Amatenango del Valle (AV) in the locality of the same name, with indigenous Tzeltal families. The use of native maize varieties or *criollo* varieties has been maintained by the population in AV. Nevertheless, there is a high dependence on agrochemicals such as herbicides and fertilizers (Bernardino et al., 2016). The studied plots have an average altitude of 1,808 m located in stepped plateaus with shallow and rocky soil, which are inadequate for mechanized agriculture. The agriculture of AV is mainly rainfed with few irrigated plots supplied from nearby springs. The farming activities (sowing, weeding, agrochemical application and harvesting) are mostly supported by social relationships among relatives and close friends. Due to population growth, the size of plots of land for each family unit has decreased and its use is intensive and continuous year after year without rest.

The agricultural activities in the Selva region are mainly maize cultivation, cattle ranching and more recently oil palm plantation (Zermeño-Hernández et al., 2016), these activities are strongly influenced by the people's place of origin (Wies et al., 2022). The maize crop systems studied belong to

1 *Criollo* maize or seeds refer to different types of seeds that farmers can plant, manage, and select without having to purchase them. These include landraces or native seeds passed from generation to generation, and *acriollados* or creolized seeds which represent mixtures of modern improved varieties and landraces (Bellon et al., 2006).

2 *Mestizo* refers to people with mixed ethnic race that do not self-defined as belonging to an indigenous ethnic group.

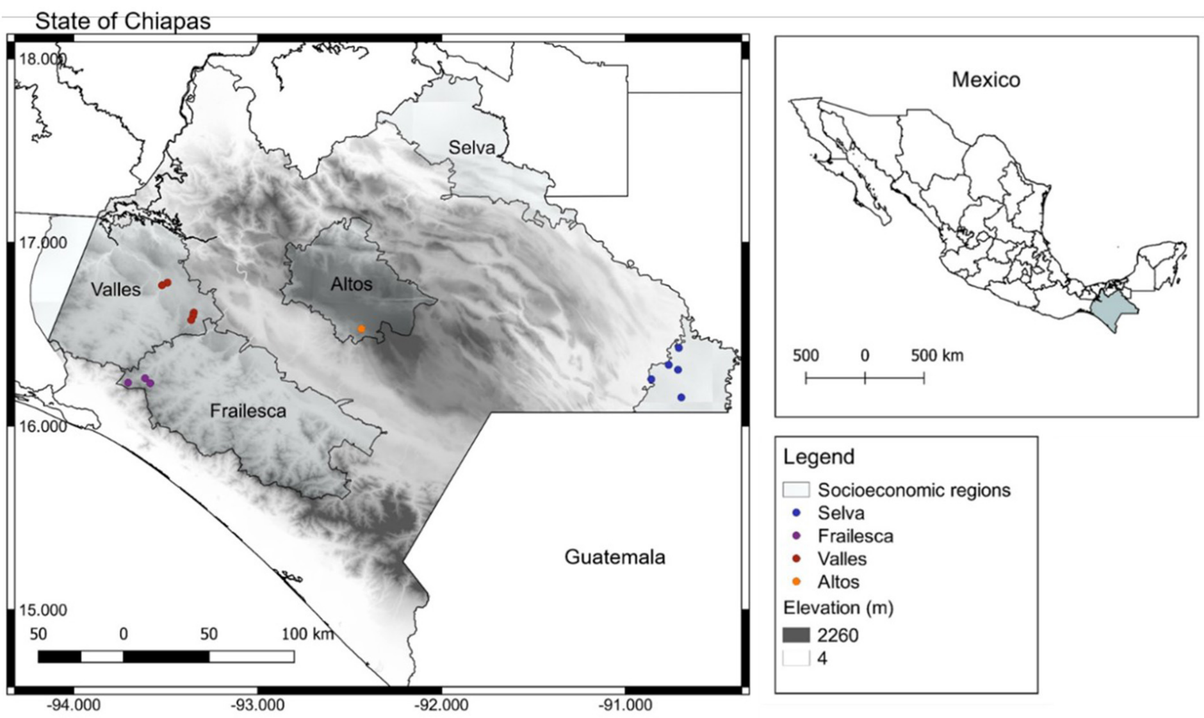

FIGURE 1
Map of the location of the state of Chiapas and the four socioeconomic regions studied.

TABLE 1 General characteristics of the regions and localities within the study site.

Municipality and study region	Socio-economic region	Localities	Altitudinal range	Households/ plots	Ethnic origin
Ocozocoautla—Valles de Ocozocoautla (VO)	Valles	Galeana, Ignacio Zaragoza, San José, Aguacero (A), Lázaro Cárdenas (LC) (5)	680–960 m	41	Indigenous Tzotzil (A and LC) and *mestizo*
Villaflores—Sierra de Villaflores (SV)	Frailesca	Tierra y Libertad, Tres Picos, California (3)	865–1,193 m	37	Mainly *mestizo*
Amatenango del Valle (AV)	Altos	Amatenango del Valle (1)	1,850–2,100 m	32	Indigenous Tzeltal
Marqués de Comillas (MC)	Selva	Quiringuicharo, Zamora Pico de Oro, La Victoria, San José, Reforma Agraria (5)	96–219 m	32	Mainly *mestizo*

the municipality of Marqués de Comillas (MC). Marqués de Comillas adjoins the Montes Azules Biosphere Reserve. The studied locations were: Reforma Agraria, La Victoria, Quiringuicharo, Zamora Pico de Oro, and Barrio San José. The most frequent soils are alluvial plains and low sandstone hills (Wies et al., 2022), some of these are adequate for the mechanized agriculture. The maize crop systems are small scale (1–5 ha) with both hybrid and *criollo* varieties and the use of chemical inputs, such as fertilizers, herbicides, and insecticides are widespread.

Methodological approach and data collection

The data collection in each region originally comes from other studies, mainly the realization of postgraduate theses. For all the locations, permission from the ejidal authorities was sought to undertake the different studies. The methods included conducting semi-structured interviews and questionnaires with the farmers. All the plots of maize crops were visited in the cases of SV, VO, and MC to record coordinates, altitude, slope,

FIGURE 2
Fields and maize crops in four regions. **(A)** The VO region, plot in rocky soil; **(B)** the SV region, plot after the maize harvest; **(C)** the AV region, plot with a variety of *criollo* maize and herbicide application by the family; **(D)** The MC region, plot with mechanization in the maize harvest. Credits: **(A)** Sofia Monroy; **(B)** Riccardo Pavesi; **(C)** Daniel Mascorro; and **(D)** Carolina Berget.

and associated crops. In the case of AV, periodic visits to 10 plots were performed during the agricultural cycle conducting participant observation. The data was collected in different years for each region: VO in 2019, SV and MC in 2018, and 2016 for AV; during the spring-summer cycle. The interviews were performed directly by the authors to the farmers and heads of families with free, previous, and informed consent. The selection of participants was random and subsequently voluntary at all sites, with the prerequisite that they had a maize crop for the agricultural cycle studied.

The information collected in all the sites documented the general use of inputs in maize crops, including sociodemographic and agricultural management data from the farmers and their families. Afterwards, a database was constructed with 78 variables and qualitative information required for the analysis and interpretation of herbicide and glyphosate use. Plot level data were standardized to one hectare for comparisons. The volumes of the different herbicides also standardized to express liters of formulated ingredients in their commercial form. The names of the herbicides and the active ingredients were validated by the farmer or later with regional information about agrochemicals' use (Bernardino, 2013).

Data analysis

For the agronomic characterization of the glyphosate use we employed descriptive statistics for variables, such as herbicide volume (glyphosate, 2,4-D, and paraquat), the moment of application, wages, and seed type, among others. In order to delineate the different glyphosate use profiles and to identify the variables that establish differences between these profiles, regression trees analyses were carried out, for each region independently and jointly. The regression tree method allows the binary and recursive partition of a response variable (in our case glyphosate volume) under the control of a set of both categorical and quantitative explanatory variables (Borcard et al., 2011). The result is a tree with "leaves" or terminal nodes that are comprised of a subset of observations that minimize the variation within each group and maximize it among groups (Borcard et al., 2011).

To construct the regression trees, firstly, those variables that could generate an effect in the use of herbicides and glyphosate were selected. In total 21 variables were analyzed: 20 explanatory variables in response to the volume of glyphosate variable. The first regression tree included all four regions with 142 observations given by each plot and farmer. Afterwards, each of the regions was analyzed separately, constructing an independent regression tree to identify variables that could be masked in the analysis at the macroregional level.

Afterwards, some of the important variables in the regression tree of all the regions were selected to explore relationships with the volume of glyphosate and generate sets of predictors performing different tests. ANOVAs were used to see differences in categorical variables like water regime (rainfed, irrigated, river influence) for example. *T*-tests were employed for binary variables like if crop rotation is practiced or not, for example. Linear regressions were used to explore relationships between continuous variables and the volume of glyphosate, like the volume of other herbicides, for example. To assess the significance and the effect of the explanatory variables in the variation of the glyphosate volume (or R^2-values), linear models were adjusted. All the analyses were performed following basic routines in R statistical program version 3.6.1 and Rstudio version 1.2.5019 (R Core Team, 2019).

Results

Agronomic characterization of herbicides and glyphosate use in maize crops

Farmers managing the studied maize crop systems reported that the use of glyphosate is mostly given in the pre-emergence states (Figure 3); in some cases, it was applied post-emergence between the rows. In the case of AV, it was used almost exclusively post-emergent to the crops but in early vegetative stages. It is common that farmers combine glyphosate with the herbicide 2,4-D in the same application. Seven commercial names were registered for glyphosate from the surveys; nevertheless, one brand predominates in 60% of the cases. In 2019, the average cost of this commercial brand of glyphosate in the studied regions was 110 Mexican pesos per liter (around 5.5 USDs), farmers reported. This price was very similar to the other two most used herbicides: 2,4-D and paraquat.

With respect to other weed management strategies, 54% of the farmers resort to manual weeding using tools like the machete and hoe. The use of manual weeding is concentrated in the AV and SV regions, although this is usually not sufficient to control the weeds during a complete agricultural cycle and

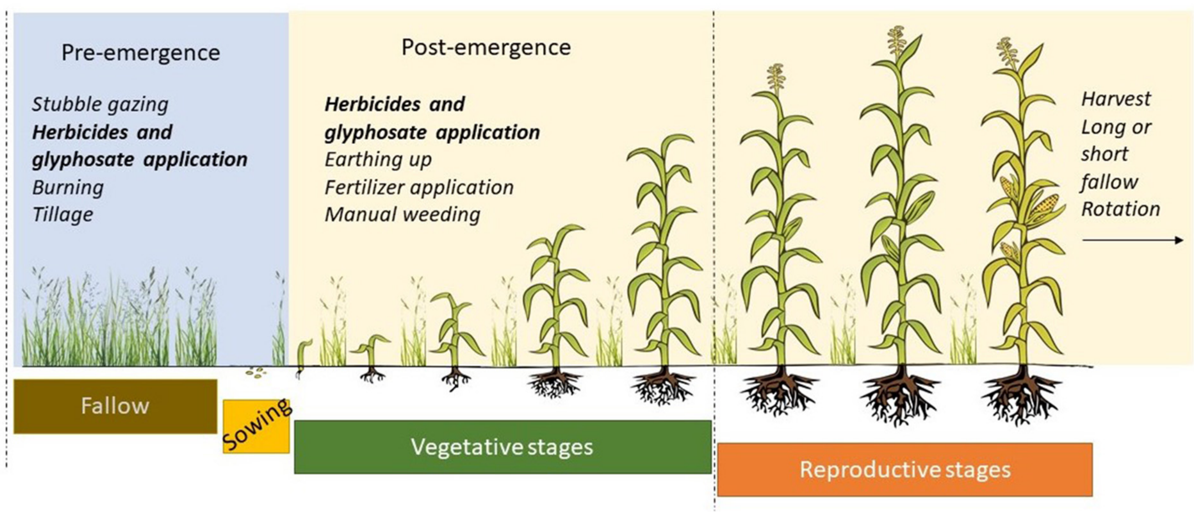

FIGURE 3
Main management practices in each stage of the maize productive cycle and moments of herbicide and glyphosate application. Not all the practices are performed in all the plots.

TABLE 2 Average volumes of the different herbicides per hectare in an agricultural cycle for each region.

	VO	SV	AV	MC	Total by herbicide
Gylphosate (l/ha^{-1})***	3.2 (1.8)^a	2.8 (2.3)^a	3.6 (2.0)^a	0.8 (1.5)^b	2.7 (2.2)
2,4-D (l/ha^{-1})***	3.2 (1.4)^a	3.8 (3.6)^a	2.4 (1.8)^a	0.1 (0.4)^b	2.5 (2.5)
Paraquat (l/ha^{-1})***	3.4 (1.8)^a	4.3 (3.2)^a	4.4 (2.7)^a	0.7 (0.9)^b	3.3 (2.7)
Total by region (l/ha^{-1})***	9.4 (3.9)^a	11.3 (6.4)^a	10.3 (4.8)^a	1.6 (1.6)^b	8.4 (5.9)

Total volumes by region can be higher than the sum of three herbicides because other lesser used herbicides exist. ***Significantly different values with $p < 0.001$. The letters indicate those groups that differ among themselves.

most of the farmers also apply herbicides. From a total of 93 plots, data were obtained about daily wages dedicated to weed control (both manual and with herbicides). Among them, the average of daily wages dedicated to this task is 5 per hectare per agricultural cycle. Nevertheless, this quantity varies greatly and can reach 24 wages. These daily wages are performed by family members or relatives, otherwise they are paid, the cost of a daily wage is between 100 and 150 Mexican pesos. Other common practices before and after the sowing of maize in the studied plots are shown in Figure 3.

The main herbicides used were paraquat, followed by glyphosate, and then by 2,4-D (Table 2). In 86 of the studied plots (60.6%), these three herbicides were applied during the studied agricultural cycle. In 22 of them, only two herbicides were used (15.5%) and in 24 only one herbicide (16.9%). Of the total sample, only 10 farmers (7%) did not use any herbicide. The region that uses the largest total volume of herbicides is SV. The herbicide applications per agricultural cycle can vary between 1 and 4 applications. Other herbicides used less frequently are saflufenacil, ametryn, lodosulfuron, and topramezone. The use of herbicides and glyphosate did not differ significantly among the plots cultivated with *criollo* maize from those planted with hybrid maize. The only region that shows significant differences in the use of the three herbicides is MC, with much smaller volumes that the other three regions (Table 2).

Management, biophysical, and social determinants in glyphosate use

The results from the regression tree differentiates 5 groups of farmers (terminal nodes) with a range of glyphosate use from 1.1 to 4.2 l/ha^{-1}, and an average of 2.7 l/ha^{-1} (Figure 4). The group with lower volumes of glyphosate use is determined by farmers using also lower volumes of the 2,4-D herbicide ($<$ 0.85 l/ha^{-1}). Other variables that are also associated with this group include plot altitudes lower than 449 m, water regime determined by river floodplain influence, and use of lower volumes of the paraquat herbicide ($<$ 0.5 l/ha^{-1}). This first group on average uses 1.1 l/ha^{-1} of glyphosate and is comprised of 40 farmers. The following group in terms of lower glyphosate use is characterized by having opposite values from the previous group. In addition to plots larger than 0.67 ha, in altitudes higher than 814 m, they use manual weeding methods and plant in polyculture to a lesser extent ($<$ 2 associated crops). The group who uses the greatest quantity of glyphosate (4.2 l/ha^{-1}) is compose by farmers who likewise use greater volumes of 2,4-D ($>$0.85 l/ha^{-1}) and paraquat ($>$ 0.5 l/ha^{-1}). Furthermore, they plant in rainfed conditions, irrigation, or with residual moisture in plots above 449 m with $<$0.67 ha of extension. This group is comprised by 20 farmers. Other characteristics that determine greater use in glyphosate are the non-use of manual weeding, plots without fallow periods, intercropping maize, and the indigenous origin of the farmer.

In Table 3, the ranking of important variables associated with an increase or decrease in glyphosate use is shown. Variables positively associated with greater volumes of glyphosate in general are greater volumes of the 2,4-D and paraquat herbicides; the plots' higher altitude; the rainfed, irrigation, and residual moisture water regimes; and the belonging to an indigenous ethnic group. Some of the variables that generate a negative effect with the volume of applied glyphosate are as follows: crops with river floodplain influence, larger plots, plot rest or longer fallow periods, no intercropping, performing manual weeding practices, and larger family units. These and other variables are explored in more depth in the Supplementary material.

Identification of groups with greater glyphosate use in different regions

The summarized results from the regression trees that were constructed for the different regions are shown in Table 4. For region VO, the group with the highest glyphosate use is comprised of farmers younger than 43 years old (4.6 l/ha^{-1}), who form a group by themselves (terminal node). Conversely, the older farmers over 43 years old, who also use *criollo* or native maize seeds, are the group who use glyphosate the least (1.8 l/ha^{-1}). In an average range, there are the 43-year-old or older farmers, who use hybrid seeds, and use fewer than 3.5

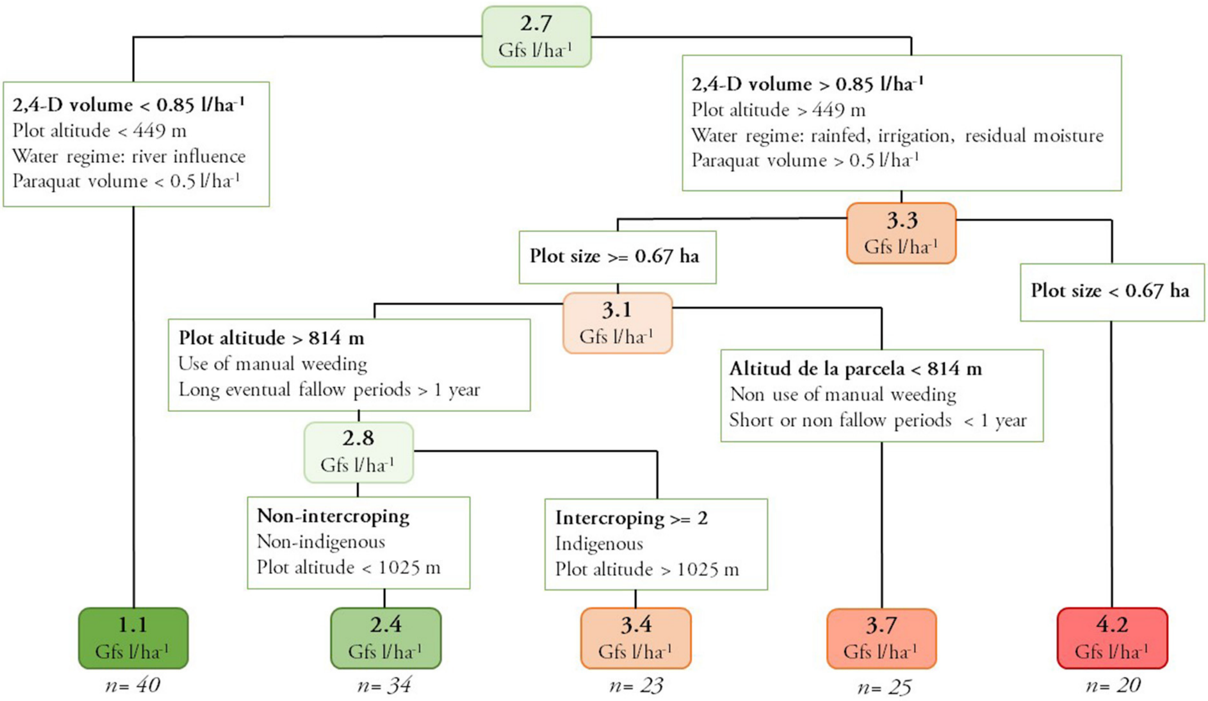

FIGURE 4
Regression tree of the joint regions and their 5 terminal nodes or groups. Relative error = 0.71, or fraction of the variance not explained by the regression tree (1–R^2). Inside the white boxes, the main variables that define the separation from the groups are shown in bold, and with standard letters the substitute variables, which have a behavior similar to the main variables, although they do not separate the groups. The colored boxes indicate the average values of the response variable (volume of glyphosate in liters/ha^{-1}) and if these are low (green) or high (orange) values.

TABLE 3 The most important variables in the construction of the regression tree and its effect on the increase or decrease in glyphosate use.

Explanatory variable	VI*	Variable state	Effect in glyphosate
Herbicide 2,4-D volume (l/ha^{-1})	30	Continuous	+
Plot altitude (m)	20	Continuous	+
Water regime	12	Rainfed, irrigated, soil moisture	+
		River floodplain	-
Plot size (ha)	10	Continuous	-
Plot rest or longer fallow periods	10	Yes	-
		No	+
Herbicide paraquat volume (l/ha^{-1})	9	Continuous	+
Associated crops (intercropping)	4	Discrete	+
Belong to an indigenous ethnic group	3	Yes	+
		No	-
Practice manual weeding	1	Yes	-
		No	+
Size of the family unit	1	Discrete	-

*VI refers to the variable importance for the construction of the regression tree, the total sum the 100% importance. The colors of the explanatory variables indicate if they are management (purple), biophysical (green) or social variables (brown) (inspired in Colbach et al., 2020).

l/ha^{-1} of 2,4-D herbicide. On average, this group uses 2.7 l/ha^{-1} of glyphosate. Finally, farmers with the same characteristics as the previous group but who use quantities >3.5 l/ha^{-1} of 2,4-D herbicide, form a group that uses on average 4.1 l/ha^{-1} of glyphosate. This group is the second that uses higher volumes of glyphosate.

In the SV region, the group who use the most glyphosate is formed by farmers with plots under 0.9 ha and who also have

TABLE 4 Summary of the regression trees of each region: number of terminal nodes, the main explanatory variables, average values of the response variable (l/ha^{-1} of glyphosate), and the percentage of the regional sample within each terminal node.

Terminal node		Explanatory variables*		Glyphosate l/ha^{-1}	% of *N*
		Split variable	Terminal node variable		
VO	1	–	Age < 43 years	4.6	32
RE = *0.58*	2	Age ≥ 43 years	Criollo seed	1.8	32
	3	Age ≥ 43 years; Hybrid seed	2,4-D < 3.5 l/ha^{-1}	2.7	22
	4	Age ≥ 43 years; Hybrid seed	2,4-D > 3.5 l/ha^{-1}	4.1	15
SV	1	Plot size < 0.9 ha	Family members < 5	5.2	27
RE = *0.56*	2	Plot size < 0.9 ha	Family members ≥ 5	2.2	14
	3	Plot size ≥ 0.9 ha	Yield > 2.5 ton/ha^{-1}	2.4	27
	4	Plot size ≥ 0.9 ha	Yield < 2.5 ton/ha^{-1}	1.4	32
AV	1	–	Family members < 5	4.5	41
RE = *0.72*	2	Family members ≥ 5	Paraquat > 4.6 l/ha^{-1}	4.2	22
	3	Family members ≥ 5	Paraquat < 4.6 l/ha^{-1}	2.2	38
MC	1	Paraquat < 0.23 l/ha^{-1}	Rainfed	2.4	16
RE = *0.75*	2	Paraquat < 0.23 l/ha^{-1}	River floodplain	0.8	38
	3	Paraquat ≥ 0.23 l/ha^{-1}	Age < 51 años	0.7	16
	4	Paraquat ≥ 0.23 l/ha^{-1}	Age ≥ 51 años	0.1	31

RE, Relative error or variance fraction not explained by the tree. *The explanatory variables are read consecutively for each region. For example, in the VO region in node 4 refers to: 43-years-old farmers or older, using hybrid seeds, and applying more than 3.5 l/ha^{-1} of 2,4-D herbicide.

family units with fewer than five members. The average volume that this group uses is 5.2 l/ha^{-1} of glyphosate. Farmers with the same sized plots but with more than five family members, use on average up to tree liters less of glyphosate per hectare than the previous group. Another group is comprised by farmers with larger plots (>0.9 ha) and with yields >2.5 tons per hectare. This group on average use 2.4 l/ha^{-1} of glyphosate. Finally, the group with the lowest glyphosate use is comprised by farmers with 0.9 ha plots or larger and with yields <2.5 ton/ha^{-1}, with an average use of 1.4 l/ha^{-1} of glyphosate.

For the AV region, the group that uses more glyphosate shares one of the same characteristics with the group that most uses glyphosate in the SV region i.e., families composed of fewer than five members. On average, this group use 4.5 l/ha^{-1} of glyphosate. This group represents little more than one third of the sample in the region. The following group is formed by farmers with families of five members or more and using on average volumes of paraquat higher than 4.6 l/ha^{-1}. This group on average uses 4.2 l/ha^{-1} of glyphosate. The last group, who uses less glyphosate in the region (2.2 l/ha^{-1}), differs from the previous one by using <4.6 l/ha^{-1} of paraquat, which shows the reciprocal relationship that exists between these two herbicides.

Farmers in the MC region use the least glyphosate and herbicides of the four regions. Within this region, the group using more glyphosate (2.4 l/ha^{-1}), on the other hand, uses less paraquat (<0.23 l/ha^{-1}). This group also sows under rainfed conditions. The second group also uses volumes of paraquat <0.23 l/ha^{-1} but sow in river floodplain condition, using only 0.8 l/ha^{-1} of glyphosate. For their part, the farmers that use 0.23 l/ha^{-1} or more of paraquat and are younger than 51 years, use on average 0.7 l/ha-1 of glyphosate. Finally, the group that uses glyphosate the least is characterized by using paraquat in the same quantities as the previous group, but the farmers are 51 years or older. This group uses volumes of only 0.1 l/ha^{-1} on average. In this region the herbicide paraquat has an antagonistic relationship with glyphosate contrary to the AV region (Supplementary Figure 4).

Discussion

The different profiles of glyphosate use show that certain biophysical, social, and management characteristics are determining a greater or lesser use in the studied areas. No single factor or characteristic (biophysical, social, or management) is determining by itself a greater use of glyphosate, but instead a complex series of factors determine glyphosate use together. These characteristics result in what we call "syndromes of greater or lesser use." The syndrome of greater use is associated with small production units (<0.67 ha), an indigenous origin population, younger farmers, small family units, land in rainfed conditions, and without the possibility of mechanization. This syndrome also entails positive associations with the other two most used herbicides in the regions: 2,4-D and paraquat. That is to say, this syndrome is for synthetic herbicides use in general. For its part, the syndrome of lesser use is associated with larger production units (>0.67 ha), in river floodplain terrains, larger family units, older farmers, longer fallow periods, crop rotations, use of manual weeding, and mechanized plots. We discuss some of the implications, opportunities, and policy considerations for the glyphosate phase-out and agroecological transition for these different types of smallholders.

The use and abuse of glyphosate, 2,4-D and paraquat

Our results show that farmers who apply higher volumes of glyphosate, also apply more 2,4-D and paraquat, and in three of the four studied regions the volumes used are statistically the same. Regarding glyphosate use, the volumes used are found within the range reported by industrial agriculture (Arellano-Aguilar and Rendón von Osten, 2016; CONACYT, 2020). Nevertheless, the variability within the sample (0–10 l/ha^{-1}) shows farmers that currently have a high dependence on herbicide and others that manage to crop without using it. For those who use glyphosate and 2,4-D dissolved in the same solution to control a wide spectrum of weeds (i.e., monocots, broadleaf, annuals, and perennials), during the pre-emergence crop stage, a possible antagonism could be producing the opposite effect on the weed control (Li et al., 2020). Another important aspect for discussion is the possible development of resistance to these three herbicides by the regional weed communities, which could trigger increasingly greater use of these herbicides. Such a phenomenon has been recorded in different parts of the world, where over the last years, the resistance of many weeds to glyphosate has increased, gradually reducing its effectiveness (Beckie, 2011; MacLaren et al., 2020).

Faced with the suppression of glyphosate, it is possible that the farmers who already know this triad of herbicides could just increase the use of 2,4-D, paraquat, or other synthetic herbicides. This scenario is possible if they do not know about viable agroecological alternatives and it is dangerous since paraquat, for example, is considered an even higher toxic herbicide in relation to glyphosate (Bernardino et al., 2016). This scenario of input substitution was documented in Sri Lanka, in conjunction with rising herbicide costs during the glyphosate ban (Malkanthi et al., 2019). For this reason, we consider important a policy that monitors the prices of inputs in this transition stage and rapidly mobilizes the agroecological alternatives across the country.

Social and land tenure characteristics in glyphosate use

The social and land tenure characteristics that are associated with the syndrome of higher glyphosate use are the following: (a) the size of the production unit—smaller areas, higher volumes of glyphosate; (b) ethnic origin—the indigenous population tends to use greater volumes; (c) the size of the family—in some regions the smaller families use higher volumes, and d) the farmers' age—younger farmers tend to use higher volumes. These results agree with those found by Bernardino et al. (2016) in a study where the factors that explain pesticide use for different crops, including maize, in three municipalities in the Highlands of Chiapas were characterized. Like our results, these authors found that in smaller plots a more intensive use of the land is made, using large quantities of pesticides. In addition, one explanation of the high pesticide use and the ethnic origin relates to their functional illiteracy of the Spanish language because their native language is Tzotzil or Tzeltal, creating difficulty to follow the herbicides labels' recommendations, and the model of the Green Revolution in which they learned to manage crops since an early age (Bernardino et al., 2016).

Our results show that the younger smallholders generally use larger volumes of glyphosate, mainly in the VO and MC regions. Many farmers of productive ages migrate to other cities as a temporary strategy for obtaining complementary income, without abandoning farming activities (Pacheco-Ladrón de Guevara, 1999). In the VO and AV regions, the seasonal-type migration and working outside the countryside considerably affect the time available for practices like manual weeding, creating an excessive use of agrochemicals (Keleman et al., 2009). In the state of Chiapas, a large proportion of the maize farmers depend on other income sources outside the countryside (Eakin et al., 2015). We believe that using large amounts of glyphosate for weed control is a strategy resorted to by some of the younger farmers for longer periods of absence from the field. On the other hand, older age is usually associated with having traditional and ecological knowledge, affecting management decisions and the use of inputs in maize cultivation (Bellon and Hellin, 2011). Our interpretation is that some older farmers can bare certain knowledge for weed management that is unrelated to the use of synthetic herbicides and glyphosate, leading to less use.

The size of the family nucleus, and therefore the members' participation in the farming activities that sustain the farmer economy (Maldonado-López et al., 2017), influences the quantity of applied herbicides in the maize crop, which is evident in the cases of AV and SV. This result responds to the need for workforce for crop maintenance and, if there is no workforce, large quantities of herbicide are usually applied to save time and effort (Chikoye et al., 2004). Another problem related to the composition of the family unit and the use of herbicides refers to child labor in fieldwork. This problem has been documented in the SV region (Pavesi, 2018), either to teach them how to farm or to reduce the need for paid day workers. This implies that these minors are exposed to a great quantity of agrochemicals, like glyphosate, at a very early age, increasing the possibility of intoxication and other health problems caused by high occupational exposure (CONACYT, 2020).

Management practices and plot characteristics in the use of glyphosate

Our results show that less glyphosate use is positively associated with management practices such as crop rotation and longer fallow periods (Supplementary Figures 9, 10). Crop rotation, including cover crops, has been commonly associated with a lower incidence of weeds and a reduction in synthetic herbicide use with important environmental benefits (Hunt et al., 2017; Rosenzweig et al., 2018; Adeux et al., 2019). Regarding fallowing and its association with lower glyphosate use, we believe that this result is related to the maintenance of more diverse weed communities in crop plots, which generate less competition (Storkey and Neve, 2018) in contrast to homogenous weed communities dominated by few but very aggressive weeds.

In the high-altitude zones (i.e., AV, VO, and SV) greater use of glyphosate and herbicides, in general, are found. These regions are associated with no possibility of mechanization and steep slopes. Conversely, in the MC region, with altitudes lower than 500 m, where mechanization is possible, fewer quantities of glyphosate are used. In areas of steeper slopes conditions are prone to runoff and erosion, which provoke the reduction of glyphosate and other herbicides' effect (Borggaard and Gimsing, 2008; Todorovic et al., 2014; Richards et al., 2018). In addition, these conditions create difficulties for performing manual weeding (Pavesi, 2018). Particularly, in the SV region, where the soils possess a predominantly sandy texture, glyphosate absorption might be low and leaching high (Borggaard and Gimsing, 2008; Todorovic et al., 2014).

Another finding of this study shows that the condition of humidity (i.e., rainfed, irrigated, residual moisture, and river floodplain influence) affects glyphosate use, being the rainfed condition that leads to greater use. This mainly contrasts with the river floodplain influence in the MC region. Seasonal floods could control the weeds, at least in the pre-planting stage, decreasing the necessity for applying glyphosate at this moment (Carey et al., 2015). Nevertheless, the behavior of weeds in river floodplain or irrigation systems has been poorly explored in contrast to rainfed systems in maize crops. In rainfed systems, weed growth aligns with the crop's emergence, causing the smallholders to resort to greater use of glyphosate, above all in pre-emergent stages to reduce the competition in the emergent stage. Understanding the different stages in the life cycle of weeds and their ecological pressures—for example, seed predation, hydric stress, pathogens, or herbivory—(MacLaren et al., 2020), can help the design of agroecological alternatives for weed control, especially for rainfed maize systems.

Our results also show that in plots where intercropping is established (mainly maize, bean, and squash) an unexpectedly greater amount of glyphosate is used. In the studied regions, usually, the planting of beans and squash is delayed with respect to maize, resulting in a larger number of herbicides applications in the pre-and post-emergence stages (Pavesi, 2018). In addition, this practice is often linked to the use of other herbicides like 2,4-D that have a different action than glyphosate. This condition can lead to a greater application of glyphosate in plots with intercropping. Nevertheless, for generating stronger statements, studies directed toward understanding this phenomenon should be performed because this could be a "mirage" effect of other characteristics associated with the region such as plot size and ethnic origin. What can be demonstrated is that, even in a traditional system like milpa, closely associated with self-consumption, farmers use large quantities of glyphosate and herbicides.

On the other hand, in the studied regions (except AV, which had no yield data), farmers who did not use glyphosate for the studied agricultural cycle had variable yields, which were not statistically different from those who did use it (Supplementary Figures 7, 8). These results support Colbach et al. (2020) proposal, who suggest that reducing herbicide use rarely results in yield losses, especially if the farmers compensate with other management practices. In addition, it has been seen that the intensity of herbicide use has no direct relation to crop yield (Wies et al., 2022). Usually, this intensity depends on other management practices and their frequency, such as tillage and the mechanical control of weeds (Colbach and Cordeau, 2018). In our sample, the cases that did not use glyphosate and had considerable yields could represent alternatives put into practice, which are important to study in greater detail.

Regional socio-ecological heterogeneity and its relationship to glyphosate use

Given regional heterogeneity, particular characteristics affect glyphosate use in each region. This interregional and intraregional heterogeneity has been indicated as a determinant in maize production and management practices at the national level, in addition to being a challenge for policy interventions (Keleman et al., 2009; Eakin et al., 2015). For example, the family size and the use of large quantities of glyphosate in the AV region show us the interrelation of temporary migration, the productive age of the farmer, and the performance of other economic activities. These characteristics can be irrelevant in sites that can hire day workers, but in those with economic or workforce constraints, it can be a crucial determinant.

Another example is the combination of hybrid and *criollo* seeds in the VO region, which fulfill different needs in the farmers' livelihood. Usually, *criollo* maize production is destined for self-supply with less investment and inputs, including glyphosate; while hybrid maize is market-driven using more investment and inputs (Bellon and Hellin, 2011). Therefore, incentivizing the planting of *criollo* maize in some regions can help decrease glyphosate use, above all if *criollo* maize prices are competitive (Keleman et al., 2013). While other differences in management practices can be found between *criollo* and hybrid maize—like herbicide application timing (Bellon, 1991)—these were not explored here and represent a knowledge gap.

Another result that is worth discussing is how three of the four studied regions do not differ statistically in the volumes of glyphosate, 2,4-D, and paraquat used (Table 3). Unlike this tendency, in the MC region, various conditions, such as the possibility of mechanization, plots with river floodplain influence, crop rotations, and experimentation with greater planting densities (Wies et al., 2022), significantly reduce glyphosate use. It has been shown that increasing the planting density of maize by more than twice the recommended density can reduce weed biomass by up to 99% (Mhlanga et al., 2016). All these characteristics make farmers in this region less dependent on glyphosate and, in turn, less susceptible to its elimination. It would then be more compelling to look for alternatives to the use of glyphosate in regions that do not have these characteristics.

Conclusions

This study identifies a series of social, biophysical, and management variables that lead to syndromes from high or low glyphosate use by smallholder farmers in different regions of Chiapas. Greater use of glyphosate is usually accompanied by greater use of other herbicides, such as 2,4-D and paraquat. Small production units (<0.67 ha), high altitudes in mountainous areas, indigenous population, and rainfed conditions are characteristics associated with greater glyphosate use. In three of the four studied regions, the volumes of glyphosate used are very similar to the range reported for industrial agriculture. In exploring glyphosate use by region, other significant variables emerge at the local level, such as the smallholder's age, size of the nuclear family, or type of seed sown (*criollo* or hybrid). This study shows how the smallholder production sector—vital in providing maize on a national scale—is strategic for transitioning to the disuse of glyphosate.

Since this study worked with few farmers in a particular region, it has shortcomings in generalizing to the maize farming sector, other studies in different regions and socio-ecological conditions should be conducted to create a nuanced transition policy. Although, in Chiapas, as in many other Mexican states, for various decades the use of agrochemicals, including glyphosate, has been promoted and incentivized through diverse governmental programs partnering with national and international agribusiness companies. This is why, we consider it crucial to strengthen the autonomy of smallholders and their livelihoods with less dependence on external inputs and, above all, inputs that endanger human health and ecosystems. These recommendations support the idea that a change of the current production model is necessary, focusing on having more sustainable agricultural systems and not a substitution of one input for another. Many agroecological alternatives for weed management already exist, and it will be very important to mobilize them in the transition process.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AM-S and MA contributed to conception and design of the study. LG-B gave conceptual insights for developing sections. AM-S, GW, RP, and DM-dL wrote sections of the manuscript and organized the dataset. AM-S and GW performed statistical analysis. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.908779/full#supplementary-material

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