Vol.67(spe1): e24230806, 2024
https://doi.org/10.1590/1678-4324-PSSM-2024230806
ISSN 1678-4324 Online Edition
VIII Paraná Soil Science Meeting

BABT
Brazilian Archives of Biology and Technology

Article – Agronomy/Soil Science

No-Tillage and Conservation Agriculture Adoption by Farmers in Southern Brazil

Gabriela Gomes Mantovani[1,2]
https://orcid.org/0000-0002-8382-5555

Ivan Bordin[2]
https://orcid.org/0000-0002-4904-6283

Tiago Pellini[2]
https://orcid.org/0000-0002-6667-6893

Tiago Santos Telles[2*]
https://orcid.org/0000-0001-5817-3420

[1]Instituto de Desenvolvimento Rural do Paraná - IAPAR-EMATER, Londrina, Paraná, Brasil; [2]Universidade Estadual do Paraná (UNESPAR), Apucarana, Paraná, Brasil.

Editor-in-Chief: Adriel Ferreira da Fonseca
Associate Editor: Adriel Ferreira da Fonseca

Received: 01-Aug-2023; Accepted: 31-Jan-2024

* Corresponding author: telles@idr.pr.gov.br; Tel.: +55-43-33762290 (T.S.T.).

HIGHLIGHTS

- No-tillage area in Paraná increased by 29.5% from 2006 to 2017 (2.8 to 3.7 Mha)
- Conservation agriculture went from 18.1% of farm holdings in 2006 to 31.7% in 2017
- Adoption of conservation agriculture can help to sustainable intensification of agriculture.

Abstract: in Brazil, the development of a strong technical foundation for soil and water conservation has made no-tillage (NT) the leading method for preparing land for temporary crops. Despite this, there's insufficient information regarding the extent to which farmers have adopted NT and conservation agriculture (CA) and the distribution and evolution of these practices within Paraná—a state at the forefront of NT and CA implementation. This study investigates the adoption rates of NT and CA among Paraná's farmers, focusing on temporary crops. It utilizes specialized data from the Brazilian Institute of Geography and Statistics' agricultural censuses of 2006 and 2017. Adoption rates for NT and CA were determined by comparing their proportions in both the number of farming properties and the overall land area devoted to temporary crops across various microregions. Findings indicate a rise in the adoption of NT from 68.5% to 78.9% and CA from 14.6% to 27.7% over the 2006 to 2017 period. Moreover, adoption rates varied across the 39 microregions, with the highest rates in regions dominated by temporary crops, particularly soybeans, maize, and wheat. Conversely, the lowest adoption rates were found in microregions where permanent crops and pastures prevailed, and sugarcane, cassava, and rice were the primary temporary crops.

Keywords: no-tillage system; soil conservation; soil management; land use planning; sustainability.

INTRODUCTION

In the early 1970s, soil conservation practices were adopted in Brazil to control and reverse soil erosion and degradation issues, including no-tillage – NT [1, 2]. NT emerged as an alternative to the conventional tillage, which involved plowing and harrowing and left the soil exposed and vulnerable to the erosion process [3]. NT is a technique in which sowing is carried out on the straw of the previous crop using specialized equipment that makes openings in the soil for seed deposition such that soil mobilization for planting is restricted to the area of rows or sowing holes.

In the 1970s, NT evolved into the No-Tillage System (NTS), a concept developed by the Agricultural Research Institute of Paraná (IAPAR), which proposed a new approach to crop management based on three pillars that require simultaneous attention [3, 4, 5, 6]: no soil disturbance (that is, restricted to sowing lines or holes), diversification of plants in crop rotation, and permanent soil cover (with live plants or straw residues). The NT, defined as seeding with minimal soil disturbance, is a fundamental component of the NTS. The NTS embodies a holistic agricultural strategy, encompassing a variety of cultivation practices. These include diversifying crop rotation with different plant species, utilizing green manure to enrich the soil, enhancing soil fertility, boosting crop yields, and safeguarding the soil from erosion. For these reasons, while NT is a progressive shift from traditional practices such as plowing and harrowing for soil tillage, it is not adequate to fully prevent erosion and degradation of agricultural soils under the diverse edaphoclimatic conditions found across Brazil. Therefore, adopting the more comprehensive NTS becomes crucial to ensure effective soil and water conservation [7, 8, 9]. The significance of the NTS in both Brazilian and global agriculture is such that it served as a foundational model for the Food and Agriculture Organization of the United Nations (FAO) when defining the principles of Conservation Agriculture (CA) [10, 11]. CA is now the term recognized internationally. Due to its widespread adoption and to avoid potential confusion with NT, which may not always encompass the full spectrum of practices, this article will use the term CA to refer to the system that includes the core principles of NTS.

Although NT is widely used in Brazilian agriculture, especially in the South, Southeast, and Central-West great regions, where climate conditions are more favorable for grain cultivation [4], quantitative data on the adoption of NT and CA is still needed. It is worth noting that NT is a component of CA. The CA integrates a broader spectrum of practices, including crop diversification through rotation, the application of green manure or cover crops, preservation of crop residues and straw on the field, enhancement of soil organic matter content, and support of biological processes that facilitate nutrient cycling within the soil. Studies have indicated that many farmers are not implementing CA [12, 13]. Furthermore, adopting other soil and water conservation practices, such as level planting and constructing agricultural terraces, is not widespread and tends to be leveraged by among farmers in Brazil's traditional grain production areas [8, 14]. This limited use of conservation practices can lead to increased soil erosion and degradation. Therefore, despite the advancements of NT over conventional tillage methods, it is insufficient to combat erosion and degradation of agricultural soils or to ensure soil and water conservation, given Brazil's diverse edaphoclimatic conditions [7, 8]. This highlights the importance of implementing CA.

Despite establishing a strong framework for soil and water conservation in Brazil, leading to the widespread use of NT, there is insufficient information regarding the extent of NT and CA adoption by farmers in Paraná. This is the case even in a state that has pioneered the development and use of NT and the NTS (subsequently termed CA). There may be considerable variation in implementing these conservation practices among farmers across Paraná. This study seeks to assess NT and CA adoption rates among farmers of temporary crops in the microregions of Paraná by analyzing data from the agricultural censuses of 2006 and 2017.

MATERIAL AND METHODS

The assessment of NT and CA adoption levels in the State of Paraná, including their progression over time, was conducted using specialized datasets from the 2006 (CA 2006) and 2017 (CA 2017) agricultural censuses, which were performed by the Brazilian Institute of Geography and Statistics (IBGE). The CA 2006 dataset covered 258,052 rural properties engaged in temporary cropping on a total area of 5,414,528 hectares, whereas the CA 2017 dataset encompassed 220,132 rural holdings with temporary crops extending over 6,087,813 hectares.

The specialized data sets from the Brazilian Institute of Geography and Statistics (IBGE) were analyzed for the 39 microregions of Paraná, as depicted in Figure 1, for the reference years of the 2006 and 2017 agricultural censuses. The analysis calculated the following relative shares for each year: 1) the proportion of rural holdings with temporary crops implementing NT and CA out of the total number of rural holdings with temporary crops; and 2) the size of temporary crop areas practicing NT and CA (as reported in the agricultural census questionnaire regarding the declaration of NT use concurrent with crop rotation and continuous soil cover) out of the total area of temporary crops.

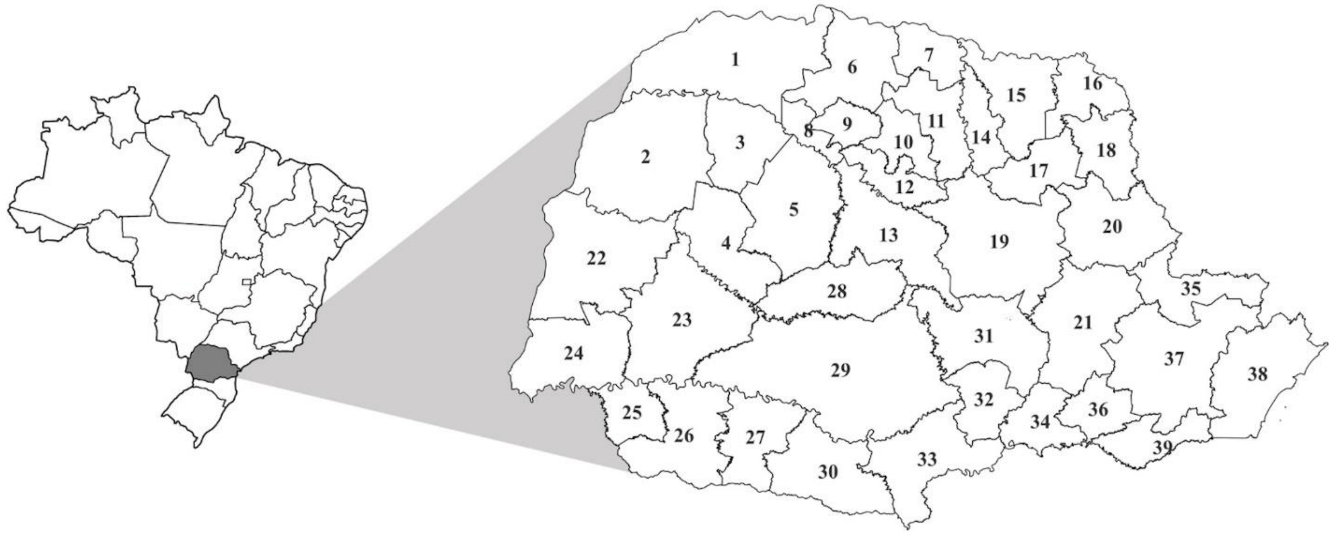

Figure 1. Microregions of the state of Paraná.

Notes: (1) Paranavaí; (2) Umuarama; (3) Cianorte; (4) Goioerê; (5) Campo Mourão; (6) Astorga; (7) Porecatu; (8) Floraí; (9) Maringá; (10) Apucarana; (11) Londrina; (12) Faxinal; (13) Ivaiporã; (14) Assaí; (15) Cornélio Procópio; (16) Jacarezinho; (17) Ibaiti; (18) Wenceslau Braz; (19) Telêmaco Borba; (20) Jaguariaíva; (21) Ponta Grossa; (22) Toledo; (23) Cascavel; (24) Foz do Iguaçu; (25) Capanema; (26) Francisco Beltrão; (27) Pato Branco; (28) Pitanga; (29) Guarapuava; (30) Palmas; (31) Prudentópolis; (32) Irati; (33) União da Vitória; (34) São Mateus do Sul; (35) Cerro Azul; (36) Lapa; (37) Curitiba; (38) Paranaguá; (39) Rio Negro.

It is worth mentioning that information on soil tillage referred only to areas of temporary crops since it is in these areas that soil tillage takes place for the planting of short-term crops, which generally required replanting after each harvest; short-term crops are defined as less than one year, except crops such as sugar cane and cassava which are also classified as temporary crops in the agricultural censuses database. For field survey purposes, IBGE defines NT as the method of planting in small furrows open in the soil covered with straw, without plowing or harrowing the land's surface, keeping the remains of previous crops in the soil. By its turn, crop rotation is defined as alternating crops of legumes, grasses, and others, with alternating fallow periods.

To create maps displaying the adoption rates of NT and CA across Paraná's microregions for the years 2006 and 2017, the calculated variables were sorted into six classes of adoption levels, as follows: (i) 0%, (ii) greater than 0% up to 20%, (iii) over 20% up to 40%, (iv) over 40% up to 60%, (v) over 60% up to 80%, and (vi) over 80% up to 100%.

The land usage and primary agricultural activities were analyzed to identify factors that could explain the differences in NT and CA adoption rates. Initially, the distribution percentage of key land use categories on farm properties was determined for each microregion. Land use was classified into five major groups: permanent crops; temporary crops, which included fields for temporary planting, flower cultivation, and fodder production if present; pasturelands, categorized into natural grasslands, well-maintained planted pastures, and poorly maintained planted pastures; woodlands and forests, encompassing areas of natural woodlands reserved for permanent conservation or as legal reserves, as well as both natural and cultivated forests; and other land uses, which covered areas used for agroforestry systems, water bodies, structures, facilities or roads, degraded lands, and lands unfit for use. Following this, for the same microregional divisions, the temporary crops were further broken down to determine the predominant types of crops within this category, with their proportions expressed as a percentage of the total harvested temporary crop area.

RESULTS

In 2006, 49.6% of rural holdings in Paraná implemented NT on 68.5% of the land designated for temporary crops; by 2017, this practice had expanded to 59.8% of rural holdings and 78.9% of the land area for temporary crops (refer to Table 1), signifying a notable rise in its adoption. From 2006 to 2017, the number of rural holdings with temporary crops employing NT grew by 2.8%, increasing from 128,000 to slightly over 131,000 (despite a decrease in the total number of rural holdings), and the land area using NT for temporary crops surged by 29.5%, from around 3.7 million hectares to nearly 4.8 million hectares.

Table 1. Percentage of rural properties employing no-tillage (NT) and conservation agriculture (CA) out of the total properties with temporary crops, and the proportion of land area using NT and CA compared to the overall area of temporary crops in Paraná for the years 2006 and 2017.

Variable	**2006 (%)**	**2017 (%)**	**Variation (%)**
Number of holdings with annual crops (total)	258,052	220,132	-14.7
Area with annual crops (total Mha)	5.4	6.1	12.4
No-tillage (NT)			
Share of holdings with NT (%)	49.6	59.8	20.6
Share of area with NT	68.5	78.9	15.2
Conservation agriculture (CA)			
Share of holdings with CA	18.1	31.7	44.1
Share of area with CA	14.6	27.7	82,2

Source: Based on data from the 2006 and 2017 agricultural censuses, performed by the Brazilian Institute of Geography and Statistics

In 2006, CA was implemented in 18.1% of rural holdings and on 14.6% of the area with temporary crops in Paraná; in 2017, these figures had climbed to 31.7% of rural holdings and 27.7% of the temporary crop area (refer to Table 1). The span between 2006 and 2017 witnessed a 44.1% increase in the number of rural holdings using CA for their temporary crops, growing from 67 thousand to 97 thousand, and an approximate 82% rise in the land area devoted to CA, expanding from 2.2 million hectares to around 4.1 million hectares. Despite the adoption of CA being lower compared to NT, Paraná experienced significant growth in the adoption of CA in terms of the number of rural holdings and the area under temporary crops engaging in this practice. However, the levels of adoption of NT and CA in terms of area and number of rural holdings with temporary crops are quite heterogeneous among the Paraná microregions (Figures 2 and 3).

In 2006, the microregions with the largest proportion of rural holdings employing NT for temporary crops, exceeding 80%, were Floraí (83.7%) and Pato Branco (81.2%). By 2017, this greater than 80% usage was seen in four microregions: Pato Branco (88.9%) and Floraí (87.4%) once again, with Goioerê (81.7%) and Campo Mourão (80.4%) also surpassing this threshold. Conversely, the smallest shares in both census years were recorded in the microregions of Paranaguá with 6.0% in 2006 and 11.4% in 2017, and Paranavaí with 3.6% in 2006 and 9.9% in 2017.

Upon examining the prevalence of CA among rural holdings with temporary crops, the data shows that in 2006, the microregions with the highest adoption were Pato Branco (45.2%) and Toledo (40.9%). By the year 2017, the number of microregions with more than 40% of rural holdings implementing CA increased to 27, with particular note of Pato Branco, which reached an adoption rate of 69.1%, the only microregion in the state within the 60% to 80% bracket. In contrast, the microregions with the lowest CA adoption rates in 2006 (up to 20%) included Paranaguá (0.7%), Paranavaí (0.5%), and Cerro Azul (0.3%), a trend that continued into 2017. That year, Paranavaí (1.9%) and Paranaguá (1.3%) remained the most notable among the 12 microregions with the scantiest adoption rates of CA.

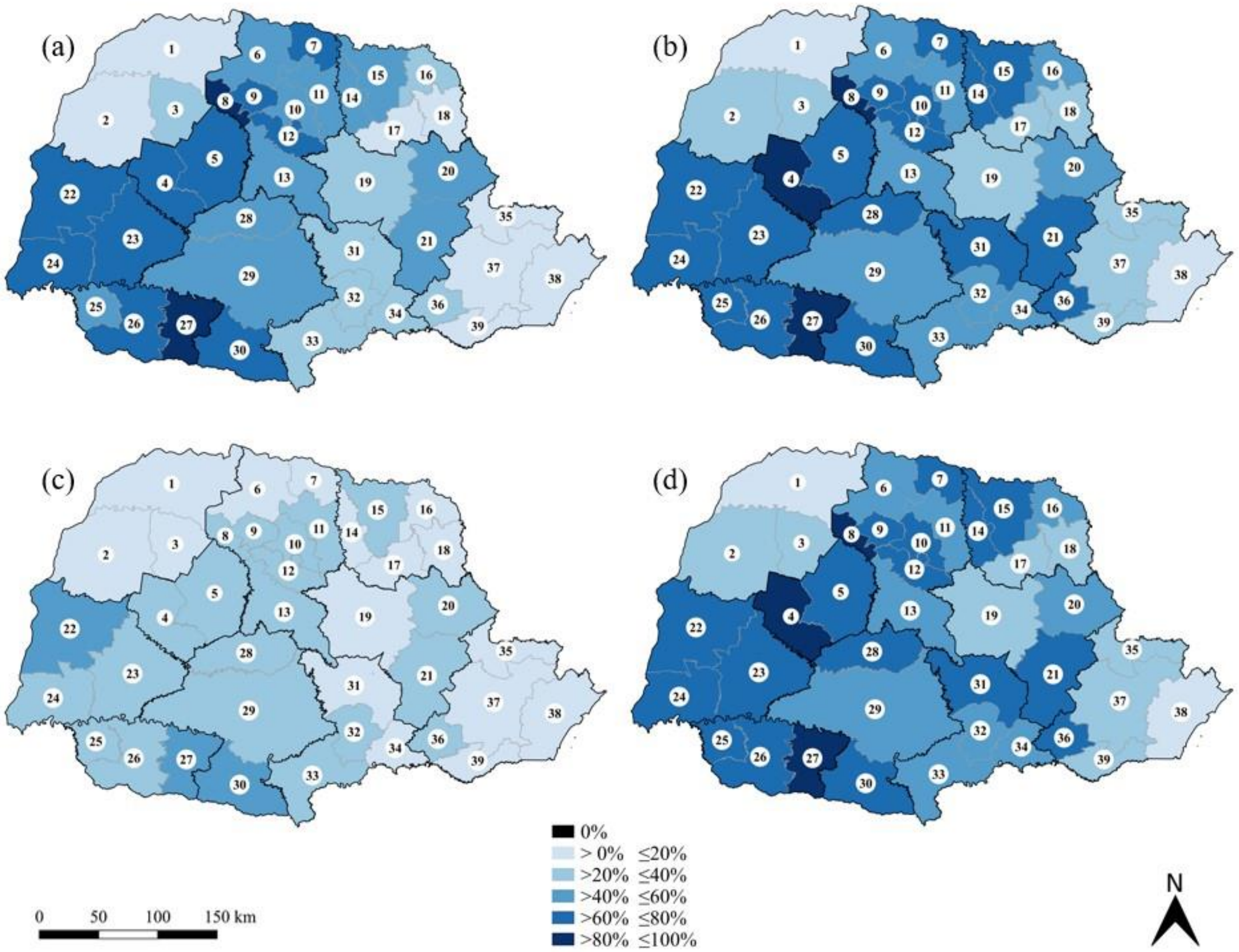

Figure 2. Share of rural holdings with no-tillage (a) in 2006 and (b) in 2017, and with conservation agriculture (c) in 2006 and (d) in 2017, by microregion of Paraná.
Source: Based on data from the 2006 and 2017 agricultural censuses, performed by the Brazilian Institute of Geography and Statistics.

Regarding the extent of NT and CA usage based on the proportion of temporary crop areas, a trend somewhat less pronounced than that observed with the number of rural holdings was noted. In 2006, Toledo (91.8%), Maringá (90.9%), Cascavel (89.5%), Pato Branco (88.7%), and Floraí (88.2%) were prominent among the nine microregions with the largest areas – surpassing 80% – utilizing NT. By 2017, NT had broadened its reach in temporary crop areas, with 23 microregions reporting over 80% of their areas under NT, particularly Pato Branco (97.4%), Ponta Grossa (95.6%), Toledo (95.1%), Cascavel (93.3%), and Campo Mourão (92.9%). On the opposite end, in 2006, Paranavaí (9.6%), Cerro Azul (6.9%), and Paranaguá (3.2%) recorded the smallest percentages - below 20% - of NT adoption, a status that persisted into 2017 for Paranaguá (15.3%) and Paranavaí (12.5%) alone.

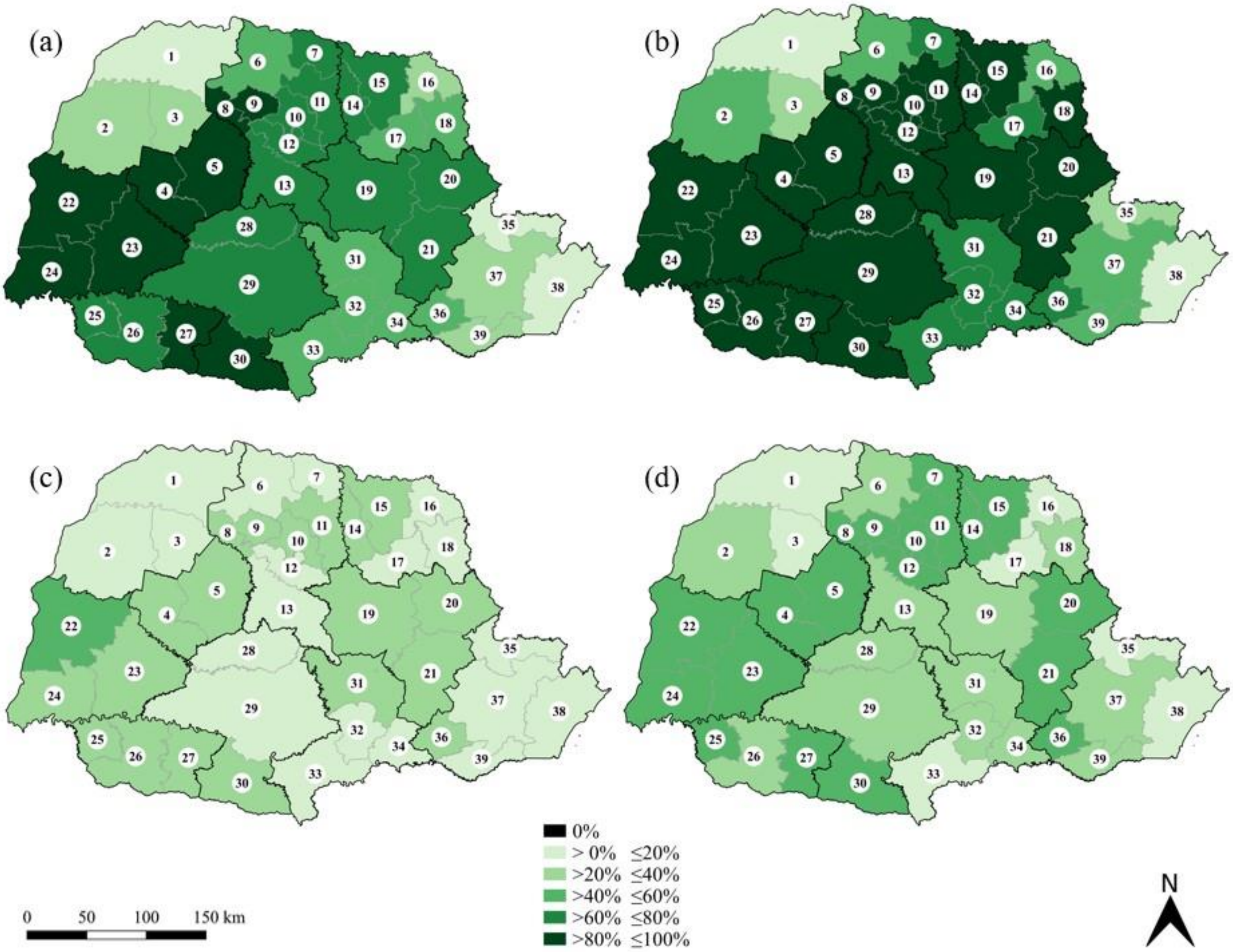

Figure 3. Share of area under no-tillage (a) in 2006 and (b) in 2017, and with conservation agriculture (c) in 2006 and (d) in 2017, by microregions of Paraná.

Source: Based on data from the 2006 and 2017 agricultural censuses, performed by the Brazilian Institute of Geography and Statistics.

The adoption of CA, indicated by its coverage in terms of temporary crop area (as depicted in Figure 3c and 3d), remains considerably lower compared to NT. In 2006, only the Toledo microregion achieved more than a 40% share of its temporary crop area using CA (Figure 3c). However, by 2017, the number of microregions with CA levels between 40% and 60% rose to eleven, signaling adoption growth. Notably, the microregions of Toledo (53.1%), Pato Branco (51.4%), Foz do Iguaçu (48.7%), Londrina (46.5%), and Goioerê (44.9%) led the way (Figure 3c). These areas with higher CA adoption rates are typically characterized by basaltic soils, a dominance of temporary crops in land use, and primarily cultivating soybeans, corn, and wheat (Figure 4). Conversely, the lowest CA adoption rates in temporary crop areas were recorded in Paranavaí (1.0% in 2006 and 2.3% in 2017), Cerro Azul (0.3% in 2006 and 0.8% in 2017), and Paranaguá (0.1% in both 2006 and 2017) (Figures 3c and 3d). These particular microregions, known for sandy soils (Paranavaí and parts of Paranaguá) or morphological transitions with steep slopes (Cerro Azul), tend to have land use dominated by permanent crops and livestock, with sugar cane, cassava, and rice as the chief temporary crops (Figures 4 and Table 2).

The review of land use distribution across rural holdings, categorized by primary usage types from 2006 to 2017 (as shown in Table 2), reveals an expansion in the acreage of temporary crops and woods and forests across all microregions in Paraná. There were exceptions, however: Jaguariaíva did not experience an increase in temporary crops, and Jacarezinho and Pitanga saw no growth in woods and forests. This expansion occurred concurrently with a decline in the proportions of land devoted to permanent crops and pasture areas.

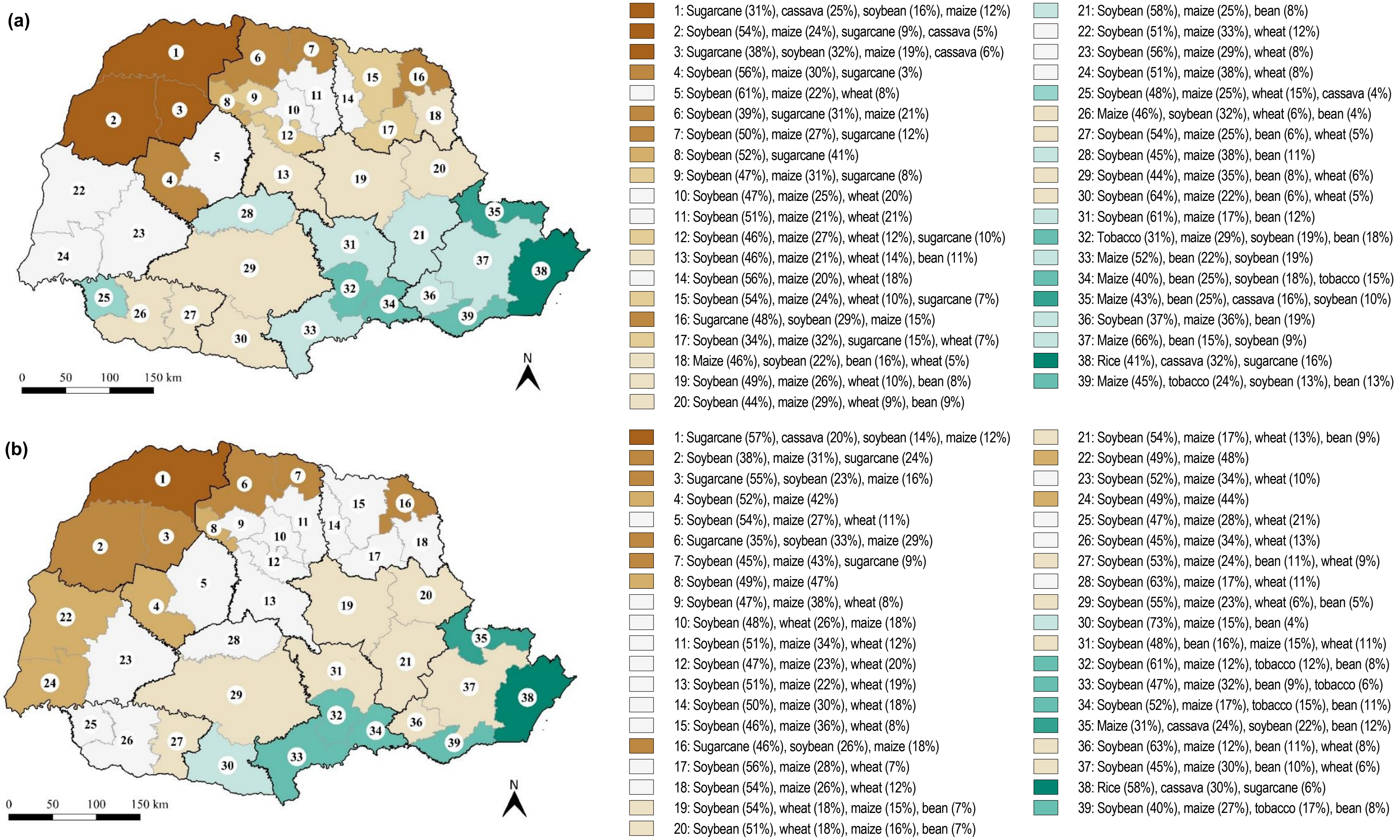

Figure 4. Share of products of temporary crops in terms of the total area of temporary crops harvested in 2006 and 2017, by microregions of Paraná.
Source: Based on data from the 2006 and 2017 agricultural censuses, performed by the Brazilian Institute of Geography and Statistics.

Table 2. Share of major groups of land use in rural holdings in the microregions of Paraná state in 2006 and 2017.

Microregion	**2006**					**2017**				
	Permanent crops	**Temporary crops**	**Pastures**	**Woods or forests**	**Other**	**Permanent crops**	**Temporary crops**	**Pastures**	**Woods or forests**	**Other**
Paranavaí	11,71	20,22	56,77	7,58	3,72	1,72	33,53	53,45	8,49	2,81
Umuarama	6,29	21,18	61,14	8,92	2,46	1,17	31,89	52,86	11,09	2,99
Cianorte	8,67	44,82	34,81	9,02	2,69	1,09	52,69	30,62	13,32	2,28
Goioerê	1,85	58,94	25,84	11,31	2,06	0,07	62,93	22,30	13,12	1,58
Campo Mourão	9,01	50,73	22,35	14,66	3,24	0,27	60,51	17,76	19,39	2,07
Astorga	21,36	33,75	32,34	6,35	6,21	2,03	56,96	25,07	12,47	3,47
Porecatu	6,37	64,40	16,35	8,43	4,44	0,65	68,95	10,81	14,02	5,57
Floraí	3,60	82,10	5,35	6,98	1,98	1,16	84,49	4,18	8,27	1,90
Maringá	7,37	55,91	23,01	9,32	4,38	2,31	66,07	15,93	10,34	5,36
Apucarana	17,60	39,07	24,70	13,26	5,38	4,45	54,54	18,73	17,61	4,67
Londrina	20,74	43,00	19,52	10,73	6,00	2,47	62,34	12,64	19,07	3,48
Faxinal	14,06	33,91	36,47	11,86	3,70	0,84	48,22	31,91	16,26	2,76
Ivaiporã	6,83	27,48	45,56	16,69	3,45	1,28	34,96	41,03	19,56	3,17
Assaí	11,63	41,12	29,77	12,18	5,30	3,28	48,91	25,50	18,58	3,74
Cornélio Procópio	14,59	44,67	26,15	9,60	4,99	2,23	58,12	22,03	13,54	4,07
Jacarezinho	9,85	29,66	46,05	10,56	3,88	1,60	31,09	52,32	9,74	5,25
Ibaiti	6,88	12,35	59,17	18,57	3,03	3,55	15,22	52,51	25,12	3,60
Wenceslau Braz	6,53	16,01	61,44	13,14	2,89	4,44	23,77	50,77	17,49	3,54
Telêmaco Borba	3,05	17,77	20,92	46,71	11,54	1,41	23,71	24,02	46,80	4,05
Jaguariaíva	1,63	26,37	23,17	41,61	7,22	0,46	25,32	12,98	57,27	3,97
Ponta Grossa	2,15	48,06	15,76	26,53	7,50	0,38	48,64	12,32	31,40	7,27
Toledo	2,49	65,72	15,94	12,06	3,79	0,30	68,87	13,42	13,45	3,96
Cascavel	1,61	41,20	34,77	19,28	3,15	0,51	43,86	30,86	21,80	2,97
Foz do Iguaçu	2,35	56,95	24,32	12,36	4,02	0,32	59,56	20,84	15,53	3,75
Capanema	1,54	45,58	28,82	18,96	5,11	0,59	47,58	28,23	19,47	4,13
Francisco Beltrão	2,92	37,76	33,30	19,59	6,44	0,64	40,53	30,60	22,81	5,42
Pato Branco	1,51	51,27	24,20	17,90	5,12	0,37	54,82	21,44	18,97	4,41
Pitanga	2,29	28,58	44,67	20,12	4,34	1,05	29,40	44,23	19,74	5,58
Guarapuava	2,08	30,57	28,69	31,89	6,76	1,40	31,34	28,38	32,60	6,28
Palmas	4,25	31,06	22,84	34,33	7,52	0,33	33,14	20,93	38,91	6,69
Prudentópolis	3,60	42,89	13,06	32,07	8,38	1,82	50,21	13,97	27,53	6,47
Irati	1,97	46,06	8,49	32,23	11,26	1,58	46,37	7,09	35,09	9,87
União da Vitória	5,87	15,30	12,30	56,47	10,07	3,90	14,02	10,69	61,01	10,37
São Mateus do Sul	5,78	38,34	7,89	37,60	10,39	5,29	43,15	5,61	34,82	11,13
Cerro Azul	6,43	20,46	27,77	40,48	4,86	2,74	4,09	22,22	63,18	7,78
Lapa	2,01	42,54	13,74	32,46	9,25	1,09	51,03	13,12	29,67	5,09
Curitiba	3,05	23,19	20,18	38,02	15,56	0,86	21,75	16,24	51,02	10,13
Paranaguá	15,59	5,81	9,54	55,12	13,95	15,14	5,18	11,81	61,57	6,31
Rio Negro	2,12	29,73	9,64	47,63	10,88	0,38	34,59	8,65	48,20	8,18

Source: Based on data from the 2006 and 2017 agricultural censuses, performed by the Brazilian Institute of Geography and Statistics.

During the period in question, the proportion of temporary crops decreased across all microregions. Conversely, Jacarezinho, Wenceslau Braz, and Prudentópolis did not see a decrease in the proportional contribution of pastures to the total land area of rural holdings (as indicated in Table 2). This suggests that with the rise in conservative agricultural practices such as NT and CA, which are associated with the management of temporary crops, there was a parallel increase in the adoption of these methods in line with the growing proportion of temporary crop areas in Paraná's agriculture. This trend also underscores the heightened significance of measures focused on soil and water use and conservation in the region, particularly in the context of temporary crops taking over land from permanent crops and pastures.

In sandy soil regions like the Paranavaí microregion, the combination of the highest temperatures leads to increased evapotranspiration and reduced winter precipitation, resulting in a more precarious soil water balance. Consequently, it becomes significantly challenging to establish and preserve adequate vegetation cover all year round. This scarcity of continuous ground coverage presents a significant barrier to implementing CA practices effectively.

Figure 4 illustrates the proportion of yields from temporary crops within the total harvested area of such crops by microregion. Soybeans have emerged as the predominant crop across the majority of microregions, with their share in the total harvested area of the state rising from 42.6% in 2006 to 47.9% in 2017. In microregions where NT and CA practices are most prevalent, the temporary crop mix primarily consists of soybeans, maize, wheat, and sometimes beans. These crops are central to the rotational farming systems practiced in Paraná's agriculture. The harvested area percentages for these specific crops have remained relatively unchanged between 2006 and 2017 in areas with the highest NT and CA adoption levels.

In the two microregions with the lowest adoption of NT and CA, there was an increase in the share of sugarcane (Paranavaí) and rice (Paranaguá, typically in an irrigated system) in the total area harvested, with the percentage of cassava decreasing while still remaining among the main products. Sugarcane, rice (when considering the irrigated systems), and cassava are three temporary crops that face technological constraints in the adoption of NT and CA techniques.

DISCUSSION

The initial premises of the study that there is significant heterogeneity in how farmers carry out soil and water conservation and that the level of adoption of NT and CA in temporary crops by farmers varies according to the microregions of the state of Paraná, were confirmed. NT was adopted on 68.5% of the temporary crop area in Paraná in 2006, increasing to 78.9% in 2017; CA was less prevalent, adopted on 14.6% of the temporary crop area in 2006 and rising to 27.7% in 2017. These trends show a significant uptake of NT yet a restrained use of CA, not reaching the desired level for sustainable agriculture standards. The growth in CA from 2006 to 2017, while notable, remains limited due to several factors: (i) the often-delayed economic return from CA, with rural producers typically favoring systems that provide immediate profits [15]; (ii) a tendency to favor simpler production systems that focus on crop succession rather than rotation [16, 17]; (iii) farmers being confined to growing the predominant grain of their region due to logistics, infrastructure, and market considerations, deterring them from diversifying crops [18, 19]; and (iv) the dominance of crops like cassava or sugarcane in some regions, as opposed to grain [20, 21] (Table 2).

CA expansion in Paraná depends on integrating crop rotation, yet farmers frequently rely on technology packages from agricultural cooperatives, agreeing to settle payments with grain yields. Paraná's agribusiness model, heavily involving cooperatives, presents a multifaceted input supply network. Furthermore, the state's grain market focuses on two primary crops: soy for export and corn for livestock feed. Consequently, the decision of what to cultivate isn't solely in the hands of the farmers; they are entwined with their regions' dominant grain production systems, explaining the scant use of diverse crop rotation. Two interrelated hurdles to adopting CA emerge in this setting: the lack of crop rotation and farmers' reliance on region-specific technology packages.

Understanding the reluctance of farmers to implement optimal soil and water conservation methods has long been a subject of study, considering both technological and socioeconomic factors influencing their decisions. Despite over a century of research, a robust theoretical framework, and established best practice recommendations available to farmers [2], the uptake remains uneven. IAPAR has advocated for CA, known as SPD, since 1977 [3]. The myopic economic perspective of these agents is sometimes cited as a contributing factor, yet it doesn't fully account for the hesitancy in adopting superior agricultural practices. Additionally, farmers typically favor less complex operations [16]. This preference explains the swift adoption of NT and the prevalence of crop succession over rotation due to its operational simplicity.

Although the vast majority of medium and large-scale farmers in South American countries, including Brazil, who use tractor-based farming systems have switched from conventional tillage to NT, small-scale rural holdings that use exclusively animal traction or manual labor have not widely adopted CA, even with massive efforts to disseminate the necessary technology through development aid projects and actions by local governments [22]. The constraints observed in regions characterized by smaller rural holdings may stem from limited mechanization and are often compounded by the soil's prevalent degradation and nutrient scarcity. These factors hinder cultivation by intensifying competition from the diverse array of spontaneous species in the soil's seed bank [23].

In areas like southern Brazil where NT is the main method of soil tillage, this shift has occurred in conjunction with the growth of soybean cultivation areas, a crop of significant economic value for the country [4]. Typically, these agricultural systems involve rotating soybeans during the spring/summer with either maize or wheat in the fall/winter. Market demands and supportive government policies have led many farmers to adopt a single-crop system of soybeans during the summer. Occasionally, they do this without any protective vegetation cover in the intervals, which can still lead to soil erosion and degradation despite the use of NT. Such practices do not align with the principles of CA. Efforts to tackle this issue in Brazil and Uruguay have included legal mandates for the use of cover crops specifically with soybeans, and subsidy programs for CA [17].

This research reveals that microregions predominantly growing sugarcane, cassava, and rice exhibit reduced adoption rates of no-tillage compared to findings in other regions. In southern Brazil, sugarcane, beans, and tobacco cultivation contribute substantially to the persistence of traditional soil tillage practices, as conventional tillage. These crops present technical barriers to modifying soil management techniques and are often grown in landscapes that hinder the deployment of farm machinery and equipment [4, 20].

Soil conservation techniques are limited in sugarcane cultivation, which predominantly uses conventional tillage [21]. Many of these constraints are due to the crop's intrinsic characteristics; as a semi-perennial with an average cycle of five years, it primarily relies on conventional tillage involving plowing and repeated harrowing, alongside the use of heavy machinery for harvest and infield transportation [24]. The adoption of NT in lowland regions typically used for growing irrigated rice remains at an early stage (below 5%), primarily due to the hydromorphic condition of the soils and the need to manage the crop's particularly resistant leftover biomass, which necessitates soil turning periodically [25]. This also applies for cassava, where NT is rarely adopted by producers and the harvest operation of this tuber requires soil revolving [26].

The research recommendations go in the direction of CA, combining productivity, profitability, and sustainability; however, few producers fully implement the CA technologies. In Brazil, agriculture is one of the pillars of the economy, but soil and water conservation is still a bottleneck for this sector, as we are failing to use a more economically and environmentally efficient technology.

The economic return of CA is may appear to be short-lived but increase over the years. The benefits associated with soil conservation practices, including enhanced soil quality and reduced expenditures on pesticides, makes the crop rotation system increasing the crop yield averages [15, 27], and rising agricultural land prices [28]. Thus, it is identified that crop planning and management are fundamental factors for the adoption of CA technology.

The questions listed here for future research and studying are related to: the impact of sustained incentives on the adoption of CA by farmers; financial support for the research and development of conservation technologies adapted to sugarcane, cassava and rice crops; determine whether or not temporary crops in regions with less adoption of NT and AC are being cultivated in areas of agronomic suitability according to land use class; and, lastly, verify whether the lowest adoption of NT and CA in Paraná is correlated to farm scale or type of producer categories.

Funding: This research was funded by the National Council for Scientific and Technological Development (CNPq), and Fundação Araucária.

Conflicts of Interest: The authors declare no conflict of interest.

REFERENCES

1. Derpsch R. [No-tillage: A revolution in agriculture]. Plantio direto: revolução na agricultura. A Granja. 1972; 299:26-7.
2. Telles TS, Dechen SCF, Guimarães MF. Institutional landmarks in Brazilian research on soil erosion: a historical overview. Rev Bras Cienc Solo. 2013;37(6):1431-40.
3. Muzilli, O. [Effects of no-tillage, compared to conventional tillage, on the fertility of arable layer of the soil]. Rev Bras Cienc Solo. 1983;7(1):95-102.
4. Fuentes-Llanillo R, Telles TS, Junior DS, Melo TR, Friedrich T, Kassam A. Expansion of no-tillage practice in conservation agriculture in Brazil. Soil Tillage Res. 2021;208:104877.

5. Telles TS, Righetto AJ, Costa GV, Volsi B, Oliveira JF. Conservation agriculture practices adopted in southern Brazil. Int J Agric Sustain. 2019;17(5):338-46.
6. Possamai EJ, Conceição PC, Amadori C, Bartz MLC, Ralisch R, Vicensi M, et al. Adoption of the no-tillage system in Paraná State: A (re)view. Rev Bras Cienc Solo. 2022;46:e0210104.
7. Silva RL, De Maria IC. [Erosion in no-tillage system: influence of ramp length and seeding direction]. Rev Bras Eng Agr Amb. 2011;15(6):554-61.
8. Minella JPG, Merten GH, Barros CAP, Ramon R, Schlesner AL, Clarke RT, et al. Long-term sediment yield from a small catchment in southern Brazil affected by land use and soil management changes. Hydrol Process. 2018;32(2):200-11.
9. Deuschle D, Minella JPG, Hörbe TAN, Londero AL, Schneider FJA. Erosion and hydrological response in no-tillage subjected to crop rotation intensification in southern Brazil. Geoderma. 2019;340:157-63.
10. Kassam A, Friedrich T, Shaxson F, Pretty J. The spread of conservation agriculture: Justification, sustainability, and uptake. Int J Agric Sustain. 2009;7(4):292-320.
11. Kassam A, Friedrich T, Derpsch R. Global spread of conservation agriculture. Int J Environ Stud. 2018;76(1):29-51.
12. Telles TS, Lourenço MAP, Oliveira JF, Costa GV, Barbosa GMC. Soil conservation practices in a watershed in Southern Brazil. An Acad Bras Cienc. 2019;91(3):e20180578.
13. Melo TR, Asai GA, Higashi GE, Londero AL, Barbosa GMC, Telles TS. Perception and level of soil and water conservation practices adoption by farmers in a watershed. Cienc Agron. 2023;54:e20218307.
14. Didoné EJ, Minella JPG, Merten GH. Quantifying soil erosion and sediment yield in a catchment in southern Brazil and implications for land conservation. J Soils Sediments. 2015;15(11):2334-46.
15. Volsi B, Higashi GE, Bordin I, Telles TS. The diversification of species in crop rotation increases the profitability of grain production systems. Sci Rep. 2022;12:19849.
16. Telles TS, Melo TR, Righetto AJ, Didoné EJ, Barbosa GMC. Soil management practices adopted by farmers and how they perceive conservation agriculture. Rev Bras Cienc Solo. 2022;46:e0210151.
17. Friedrich T, Derpsch R, Kassam A. Overview of the global spread of conservation agriculture. Field Actions Sci Rep. 2012;6(Special issue):1941.
18. Emran MS, Shilpi F. The extent of the market and stages of agricultural specialization. Can J Economics. 2012;45(3):1125-53.
19. Feliciano D. A review on the contribution of crop diversification to Sustainable Development Goal 1 “No poverty” in different world regions. Sustain Dev. 2019;27(4):795-808.
20. Fuentes-Llanillo R, Telles TS, Soares Júnior D, Pellini T. Tillage systems on annual crops in Brazil: figures from the 2006 Agricultural Census. Semin Cienc Agrar. 2013;34(6):3691-8.
21. Arcoverde SNS, Souza CMA, Nagahama HJ, Mauad M, Armando EJ, Cortez JW. Growth and sugarcane cultivars productivity under notillage and reduced tillage system. Rev Ceres. 2019a, 66(3):168-77.
22. Derpsch R, Lange D, Birbaumer G, Moriya K. Why do medium- and large-scale farmers succeed practicing CA and small-scale farmers often do not? Experiences from Paraguay. Int J Agric Sustain. 2016;14(3):269-81.
23. Petersen P, Tardin JM, Marochi F. Participatory development of no-tillage systems without herbicides for family farming: The experience of the Center-South Region of Paraná. Environ Dev Sustain. 1999;1:235-52.
24. Arcoverde SNS, Souza CMA, Cortez JW, Maciak PAG, Suárez, AHT. Soil physical attributes and production components of sugarcane cultivars in conservationist tillage systems. Eng Agric. 2019, 39(2): 216-24.
25. Sousa RO, Carlos FS, Silva LS, Scivittaro WB, Ribeiro PL, Lima CLR. No-tillage for flooded rice in Brazilian subtropical paddy fields: history, challenges, advances and perspectives. Rev Bras Cienc Solo. 2021,45:e0210102.
26. Gobbi KF, Takahashi M, Azevedo MCB, Fidalski J, Lugão SMB. Cassava yield in conventional and no-tillage cultivation in integrated crop-livestock systems. Pesqui Agropecu Bras. 2022;57:e02677.
27. Davis AS, Hill JD, Chase CA, Johanns AM, Liebman M. Increasing cropping system diversity balances productivity, profitability and environmental health. PLoS ONE. 2012;7(10): e47149.
28. Telles TS, Maia AG, Reydon BP. How soil conservation influences agricultural land prices. Agron J. 2022;114(5):3013-26.