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L'ADOPTION DE L'AGRICULTURE DE CONSERVATION AU BRÉSIL : CONSTRUCTION D'UN INDICE COMPOSITE POUR LES ÉTATS DE SANTA CATARINA ET DU PARANÁ

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TABLE DES MATIÈRES

LISTE DES FIGURES

LISTE DES TABLEAUX

RÉSUMÉ

À l'intérieur de cette recherche, nous construisons un indice d'adoption composite pour évaluer l'adoption de l'agriculture de conservation par des producteurs de soja et de maïs dans le sud du Brésil. Le niveau d'adoption des trois piliers de cette pratique, la rotation des cultures, la couverture permanente du sol, et sa perturbation minimale, est mesuré avec une série d'indicateurs notés sur une échelle de 0 à 1, et dont la pondération est établie grâce à une analyse en composantes principales. Un questionnaire d'entrevue, administré à vingt-neuf (29) producteurs de l'État de Santa Catarina et seize (16) producteurs de l'état du Paraná, a été utilisé pour récolter les données auprès des répondants, identifiés grâce à la méthode d'échantillonnage non probabiliste de type « boule de neige ». Les analyses permettent de mettre en lumière trois éléments principaux: (1) l'intensité d'adoption de certains indicateurs reliés à la rotation des cultures et à la couverture permanente du sol, et plus particulièrement ceux qui mesurent la superficie de rotation des cultures d'été et la persistance des résidus, est plus faible, alors que l'indicateur attribué à la perturbation minimale du sol a des niveaux élevés d'adoption parmi tous les agriculteurs; (2) les producteurs appartenant à la région rurale de Maringá obtiennent des notes plus faibles pour l'indice composite, ce qui suggère une configuration de marché moins favorable à la diversification des cultures dans cette région, mais aussi le rôle potentiel de la diversité géographique, susceptible de décourager l'apprentissage social et (3) l'indice composite d'adoption permet une mesure plus précise des trois composantes d'une pratique complexe comme l'AC, par rapport à une catégorisation binaire de l'adoption. Ces résultats exploratoires tendent à démontrer que l'adoption de l'agriculture de conservation dans le sud du Brésil est plus faible que ce qui est rapporté dans les statistiques officielles.

Mots-clés : adoption, agriculture de conservation, diversité géographique, indice composite, rotation des cultures, Paraná, Santa Catarina, soja, sud du Brésil

CHAPITRE I : INTRODUCTION GÉNÉRALE

Le semis direct est un système de culture sans-labour qui s'est popularisé dans les années 1970 au sud du Brésil, principalement pour lutter contre une érosion généralisée de la couche arable des sols dans les états du Paraná, de Santa Catarina et de Rio Grande do Sul (Assunção *et al.*, 2013; de Freitas et Landers, 2014; Hogarth, 2017; Kassam *et al.*, 2018). En partenariat avec les scientifiques, les producteurs agricoles ont graduellement transformé la pratique du semis directs en un système, le système de semis directs (*Sistema plantio direto,* SPD), qui est aujourd'hui reconnu comme la version brésilienne de l'agriculture de conservation (AC). Il est basé sur trois principes interdépendants : l'absence, ou la moindre perturbation du sol à travers le semis-direct, la couverture permanente morte ou vivante du sol grâce au maintien d'une biomasse végétale, et la diversification des espèces végétales via la rotation et/ou la succession des cultures (de Freitas et Landers, 2014; Kassam *et al.*, 2018). Cela prit une vingtaine d'années, à partir de son introduction au pays, pour que le modèle atteigne une adoption significative (de Freitas et Landers, 2014).

Avec des niveaux supérieurs à 50 % dans les superficies de cultures annuelles (de Freitas et Landers, 2014), tels que rapportés par la FEBRAPDP (Fédération brésilienne de semis directs sous paillis), l'adoption de l'AC au Brésil est actuellement la plus grande en Amérique du sud et la seconde au niveau mondial, après celle des États-Unis (Kassam *et al.*, 2018; Lal, 2019). La superficie attribuée à cette pratique y était estimée, pour l'année agricole 2015/2016, à environ 32 millions d'hectares (Kassam *et al.*, 2018). Le soja, principale culture du pays en superficie et au niveau de la production, serait principalement cultivé en agriculture de conservation (Cattelan et Dall'Agnol, 2018; Debiasi *et al.*, 2015). Cependant, il est possible de remettre en question l'exactitude de ces chiffres puisque, selon Landel (2015, p. 346), « Les chiffres estimant l'avancée du semis direct dans le pays sont sujets à caution, en raison du manque de données systématiques, du manque de partialité de certaines sources disponibles (études produites par des acteurs faisant la promotion de l'AC et/ou entretenant des relations de proximité avec les firmes d'agrofourniture), et aussi de la diversité des techniques prises en compte indistinctement (semis direct sous couvert ou non)».

Or, si le Brésil, premier exportateur et le deuxième producteur mondial de grains de soja, est érigé en modèle de développement économique par certains, le système de production du soja brésilien est présenté par d'autres sous l'angle de ses conséquences sociales et écologiques considérables. Le pays occupe le premier rang mondial, depuis 2008, en termes de consommation de pesticides (Laval, 2015). L'adoption de systèmes d'AC est étroitement liée à l'utilisation généralisée des herbicides, car ils remplacent le travail du sol, un outil majeur de lutte contre les mauvaises herbes (Assunção *et al.*, 2013; Cattelan et Dall'Agnol, 2018; Laurent *et al.*, 2011; Palm *et al.*, 2014). En raison de son climat tropical et des grandes surfaces cultivées, la production agricole brésilienne est confrontée à un défi majeur dans la lutte contre les ravageurs (Cattelan et Dall'Agnol, 2018). L'intensité de plusieurs problèmes phytosanitaires et de gestion des sols a augmenté : le compactage, l'infestation de mauvaises herbes difficiles à contrôler et même résistantes au glyphosate, et l'incidence de divers insectes ravageurs et maladies, parmi d'autres. Ces problèmes découlent en grande partie de la faible diversité des espèces cultivées dans les systèmes de production où le soja est présent (Debiasi *et al.*, 2015; Salvadori *et al.*, 2016).

L'adoption généralisée du modèle de l'agriculture de conservation au sud du Brésil est donc remise en question, puisque comme l'affirment Salvadori *et al.* (2016) et Denardin *et al.* (2012), la pratique du semis direct et l'agriculture de conservation sont deux concepts différents. Pour les conditions pédoclimatiques et climatiques de la région sud du Brésil, les deux principes du semis direct, qui sont la réduction ou l'élimination de la mobilisation du sol et l'entretien des résidus de culture dans le sol, sont insuffisants pour assurer la durabilité des cultures de grains annuelles. La consolidation des systèmes d'agriculture de conservation, d'autre part, repose essentiellement sur la diversification des cultures pour accroître la rentabilité, la promotion d'une couverture végétale permanente et la génération de bénéfices au niveau de la protection des plantes et du recyclage des nutriments. L'interaction entre la diversification des cultures, l'abandon du travail du sol et l'entretien d'un sol couvert en permanence assure l'amélioration progressive des caractéristiques biologiques, physiques et chimiques du sol. Les données sur l'adoption de l'agriculture de conservation au Brésil ont d'ailleurs été remises en question précédemment. Fuentes Llanillo *et al.* (2013) démontrent, par exemple, que les données de la Fédération brésilienne de semis direct sous paillis (FEBRAPDP) diffèrent de celles de l'Institut Brésilien de géographie et de statistique (IBGE). Alors que la FEBRAPDP déclarait une surface d'agriculture de conservation estimée à 25,6 millions d'hectares au Brésil en 2006, les données officielles de l'IBGE, basées sur le recensement de l'agriculture de 2006, faisaient plutôt état de 17,8 millions d'hectares de cette pratique dans les cultures annuelles.

La plupart des travaux s'étant penchés sur l'adoption de l'agriculture de conservation l'ont conceptualisée comme une distinction binaire, où l'agriculteur est classé comme adoptant ou non-adoptant à un moment spécifique (Higgins *et al.*, 2019; Knowler, 2015). Cette façon de concevoir l'adoption s'applique, pourtant, assez mal à l'AC, puisqu'il s'agit d'une technologie complexe (Farooq et Siddique, 2015; Speratti *et al.*, 2015; Wall, 2007). Par conséquent, la mise au point, par la recherche et le conseil agricole, d'un modèle « universellement applicable » est presque impossible (Speratti *et al.*, 2015; Wall, 2007). D'autre part, l'abondante littérature sur l'adoption de l'agriculture de conservation n'offre pas vraiment de perspectives sur l'adoption ou l'abandon partiels de pratiques de l'agriculture de conservation (D'Souza et Mishra, 2018).

Dans cet ordre d'idées, quelques études (ITAIPU-BINACIONAL et FEBRAPDP, 2011; Martins *et al.*, 2018; Roloff *et al.*, 2011) ont utilisé, précédemment, un indice composite pour mesurer la qualité de l'agriculture de conservation, définie comme « la capacité d'un champ sans labour particulier à maintenir ou augmenter la productivité des cultures et du bétail tout en maintenant ou en améliorant la qualité du sol, de l'eau et de l'air et les autres services environnementaux » (Roloff *et al.*, 2011, p. 1) dans des régions spécifiques du Brésil. Bien qu'elles utilisent toutes le même indice composite, le *No-Till Systems Quality Index (NTSQI)*, pour évaluer la qualité des systèmes d'agriculture de conservation plutôt que leur adoption, quelques aspects de ces recherches doivent être soulignés. D'abord, la définition de l'agriculture de conservation, des composantes à intégrer, et des seuils à partir desquels les composantes sont considérées comme ayant une bonne qualité, a été effectué dans une dynamique collaborative, à travers des ateliers intégrant de nombreuses parties prenantes et permettant aux agriculteurs locaux de donner leur opinion sur la composition de l'indice de qualité, tel que décrit par ITAIPU-BINACIONAL et FEBRAPDP (2011). De plus, l'indice permet d'évaluer la qualité des trois piliers de l'agriculture de conservation, la rotation des cultures, le maintien d'une couverture végétale permanente et la perturbation minimale du sol, à travers une série de 4 indicateurs. 4 autres indicateurs servent à évaluer la qualité des pratiques de conservation du sol à travers la fréquence des débordements et des épisodes érosifs, la compaction du sol dans la propriété en général, les sources d'engrais et le nombre d'années d'utilisation de la pratique du semis direct sur la propriété. D'autre part, l'indice composite utilisé dans ces travaux considère l'aspect multi saisonnier de la rotation des cultures, puisque l'évaluation effectuée à travers cet indice est basée sur un cycle de 3 ans de cultures. Enfin, bien que défini d'une façon subjective, le système de pondération attribue un poids important (1,5 points sur une échelle de 10) à chacun des 4 indicateurs directement reliés aux piliers de l'agriculture de conservation, attribuant ainsi un poids important (45% du poids de l'indice) aux 3 indicateurs reliés directement ou indirectement à la rotation des cultures. Ces études précédentes utilisaient donc un indice composite pour évaluer la qualité de l'agriculture de conservation chez des producteurs brésiliens, mais à notre connaissance, notre recherche est la première à mesurer le niveau d'adoption de l'agriculture de conservation des ménages agricoles par le biais d'un indice composite dont les indicateurs sont pondérés grâce à une méthode statistique, celle de l'analyse en principales composantes. Cette méthode permet, entre autres, d'accorder un poids plus important aux indicateurs pour lesquels les résultats obtenus ont une plus grande variabilité.

La chaire de recherche à laquelle je me suis joint, dirigée par le professeur Marc Lucotte, étudie la transition vers la durabilité des grandes cultures et les conséquences environnementales de l'utilisation des herbicides à base de glyphosate depuis plusieurs années. Bien que l'apparition de nouvelles molécules herbicides ait été un facteur déterminant dans l'adoption de l'agriculture de conservation à grande-échelle

(Assunção *et al.*, 2013; Hogarth, 2017), cette recherche ne vise pas à approfondir ce sujet. L'objectif principal de mon projet de recherche était plutôt de caractériser l'adoption de l'agriculture de conservation. Le terrain a été réalisé dans le sud du Brésil afin de mieux comprendre le niveau d'adoption de cette pratique chez des producteurs de grandes cultures de cette région du monde, ainsi que les raisons pour lesquelles ils adoptent ou abandonnent la pratique. Cela a abouti en la production d'un article intitulé « Adoption of Conservation Agriculture in Brazil: Construction of a composite index for the States of Paraná and Santa Catarina », co-écrit par Charles Séguin, Marc Lucotte et Rubem Silvério de Oliveira Junior. Ce dernier constitue le prochain chapitre de ce présent mémoire et sera soumis pour publication dans la revue *Ecological Economics*.

L'instrument de collecte de données utilisé consistait en un questionnaire d'entrevue que j'ai élaboré, et qui a été révisé et validé par deux agronomes de l'ouest de Santa Catarina et testé auprès d'un producteur de grandes cultures de cette même région. Il comportait des questions fermées et d'autres qui étaient ouvertes et semi-dirigées, permettant ainsi aux producteurs d'offrir une réponse sans choix prédéterminés. Ce questionnaire a permis de collecter des données socio-démographiques sur les participants et leurs exploitations, ainsi que sur leurs pratiques agricoles et leurs perceptions sur l'agriculture de conservation. Le premier auteur de l'étude a conduit les entrevues, compilé les données collectées auprès des producteurs agricoles, et procédé à des analyses statistiques et à l'interprétation des résultats obtenus. Les co-auteurs ont supervisé l'échantillonnage sur le terrain et les analyses statistiques et ont révisé le texte.

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partenaires ont été importants dans la sélection du terrain de recherche et de ses participants, notamment l'Entreprise SEMATTER de São Miguel do Oeste et l'Université d'État de Maringá (UEM). La région du sud du Brésil a également été choisie pour cette étude en raison des contradictions entourant l'adoption généralisée de l'AC. Alors que pour certains auteurs, le niveau d'adoption déclaré de l'agriculture de conservation dans cette région est proche de 100% (Kassam *et al.*, 2018), et que, dans les États du sud du Brésil, l'agriculture de conservation est la norme (de Freitas et Landers, 2014), d'autres auteurs affirment que c'est le semis direct, qui respecte uniquement deux piliers de l'agriculture de conservation sans intégrer la diversification des espèces végétales, qui domine la région (Salvadori *et al.*, 2016). Nous avons mené des entrevues dans quatre régions rurales du sud du Brésil, deux dans l'État de Santa Catarina et deux dans l'État du Paraná.

Le prochain chapitre de ce mémoire consiste en l'article scientifique, dans lequel on retrouve la problématique et l'objectif de recherche, les matériels et méthodes, les résultats, la discussion et la conclusion. Le dernier chapitre fait office de conclusion générale du mémoire.

CHAPITRE II: ADOPTION OF CONSERVATION AGRICULTURE IN BRAZIL: CONSTRUCTION OF A COMPOSITE INDEX FOR THE STATES OF PARANÁ AND SANTA CATARINA

Diego Callaci Trottier, Charles Séguin, Marc Lucotte, and Rubem Silvério de Oliveira Junior

Abstract

Conservation Agriculture is a crop production system characterized by minimal soil disturbance, permanent soil cover and crop rotations. The analysis attempts to assess the degree of adoption of Conservation Agriculture and its dimensions at the farm level of 45 field crop farmers (soybean and maize) in the states of Santa Catarina and Paraná, southern Brazil. We developed a composite index of Conservation agriculture using a principal component analysis based weighting scheme. Separate and pooled regression models were also applied to verify the relationship between the index and socioeconomic variables related to the farmers and their farms. The empirical results show that the intensity of adoption of some indicators related to crop rotations and permanent soil cover is lower, especially those measuring the area of the summer crop rotation and the persistence of the crop residues, while the minimal soil disturbance indicator has high levels of adoption amongst all farmers; that belonging to the Rural Region of Maringá is negatively correlated with the Adoption of Conservation Agriculture Index; and that we can better characterize the diversity of Conservation Agriculture practices with our composite index than with a binary measure of adoption. As this is an exploratory study with a convenience sample, our results are hardly generalizable, but they are consistent with previous findings suggesting that the levels of Conservation Agriculture adoption in southern Brazil are lower than those officially reported, as some farmers are not adopting fundamental pillars of the practice such as crop diversification.

Keywords: Adoption, Conservation agriculture, Southern Brazil, Composite index, Principal component analysis, Soybean, Rotations

1. Introduction

Conservation Agriculture (CA) is a crop production system characterized by three interlinked principles, namely: minimal soil disturbance, a permanent living or dead soil cover and crop rotations. Authorities worldwide reported that it was practiced on about 180 M ha (12.5% of global cropland) in 2015/2016. With levels above 50%, CA adoption is among the highest in the world in the southern parts of South America. Brazil possesses one of the largest CA areas in the world with an estimation of 32 M ha of CA in the 2015/2016 crop year (Kassam *et al.*, 2018). Brazilian soybeans are grown mainly under no-till systems (Cattelan and Dall'Agnol, 2018; Debiasi *et al.*, 2015), a term employed for Brazilian CA. A variety of names such as the no-tillage system (Fuentes-Llanillo *et al.*, 2018), direct seeding mulch-based cropping systems (DMC) (Alary *et al.*, 2016), direct planting system (Assunção *et al.*, 2013) or Zero Tillage Conservation Agriculture (ZT/CA) (de Freitas and Landers, 2014) have been used to refer to this practice. They all represent the Brazilian version of CA. To avoid confusion, we retain the term of CA for this paper.

Erected as a model of economic development by some, the soybean production system of the world's largest exporter and the second-largest producer of this commodity has several significant social and ecological consequences. Since 2008, Brazil has been ranked first in the world in terms of pesticide consumption (Laval, 2015). The adoption of CA systems is closely related to the widespread use of herbicides because they replace the use of tillage, a major tool for controlling weeds (Assunção *et al.*, 2013; Cattelan and Dall'Agnol, 2018; Laurent *et al.*, 2011; Palm *et al.*, 2014). In addition, because of its tropical climate and the large cultivated areas, the country faces a major challenge in controlling pests that affect agricultural production (Cattelan and Dall'Agnol, 2018). Several phytosanitary and soil management problems have increased in intensity, such as soil compaction, the infestation of weeds that are difficult to control and sometimes even resistant to herbicides, and havoc of various insect pests and diseases. To a large extent, these issues arise from the low diversity of species cultivated in soybean production systems (Debiasi *et al.*, 2015).

Thus, there are serious concerns about the quality of some CA systems. Despite systematically applying the no-till practice, a significant number of farmers are opting for soy mono-cropping, and/or with no living or dead plant cover between cash crops (Kassam *et al.*, 2018). In many fields, the pillars of the crop rotation and the maintenance of a constantly covered soil have been neglected. These management practices have promoted setbacks in soil conservation in recent years. As an example, in the state of Rio Grande do Sul, there is a gradual return of erosion in annual grain crops, associated with changes in the physical, chemical and biological properties of the soil, which compromises the stability of the production system (Barbieri *et al.*, 2019). These observations are in line with previous findings on the Brazilian CA situation. For example, according to Denardin *et al.* (2008), for most of the annual grain crops in the states of Rio Grande do Sul and Santa Catarina, the no-till system was not being adopted and conducted in accordance with the minimum recommendations that made it viable as a CA tool in Brazil. Bolliger *et al.* (2006) also found that many smallholder farmers only partially adopt some CA practices, rather than respecting the full principles of this cropping system.

In this paper, we measure the farm household level of adoption of Conservation Agriculture by the development of a composite index, the Adoption of Conservation Agriculture Index (ACAI), and use a principal component analysis to weight its indicators. A composite index is formed by individual indicators, on the basis of an underlying model, to measure a multi-dimensional concept that cannot be captured by a single indicator (OECD, 2008). This index contributes to understanding the patterns of the adoption of the three conservation agriculture pillars at the farm-level, in four Rural Regions of the two southern Brazil states of Paraná and Santa Catarina, where we conducted interviews with 45 soybean and maize producers. With a 3-year assessment, we were able to capture the multi-seasonal dimension of crop rotations. Using a selection of independent variables in separate and pooled linear regression models, we found a strong negative relationship between the composite index and the Maringá Rural region of belonging, suggesting a possible influence from the different soil composition of this region. Finally, we compare the composite index of adoption to the more traditional binary measure and conclude that such a continuous measure can better characterize the degree and the heterogeneity of CA adoption than a binary one. This is an exploratory study with a convenience sample; therefore, the results are not generalizable to all Brazilian producers, nor to those in the states of Paraná or Santa Catarina.

This paper is organized into seven sections. In section two, we present the basic concepts of adoption used to analyze technological change and justify the need to go beyond a binary scheme of adoption (2.1). We also explore the social practice theories and their usefulness in explaining the adoption of agricultural practices (2.2). Then, we describe previous studies that analyze agricultural practices with a composite index (2.3). In section three, we describe the study site (3.1) the data collection (3.2) and the data (3.3). In section four, we explain how our composite index was built. First (4.1), we describe the framework on which our composite indicator is based; then (4.2), we specify how our indicators were selected and (4.3) how their respective weights are defined. In section five, we schematize the results, which are discussed in section six. Research conclusions and their implications for the theory and practice on conservation agriculture adoption are presented in section seven.

2. Adoption concepts in agriculture and their complexity

2.1 The complexity of analyzing the adoption of Conservation agriculture

The study of technical change in agriculture in developing countries has often been analyzed through the lenses of the concept of adoption. On one hand, there is the individual (farm-level) adoption, while on the other, aggregate adoption (regional or national level) is usually referred to as diffusion. But there are two problems underpinning the idea that was used in much of the literature of CA adoption. The first is a conception of technology as discrete, generic and transferable packages of material and practical packages; the second is a relatively simple, largely individual, dichotomous yes/no, once-and-for-all and linear perception of technological change (Glover *et al.*, 2016). In most agricultural adoption research, the farmer is classified as an adopter or non-adopter at a single point in time (Foguesatto and Machado Dessimon, 2019; Knowler, 2015; Place and Swallow, 2000). Much of the previous work on the adoption of conservation agriculture has conceptualized it as a binary distinction (Glover *et al.*, 2016; Higgins *et al.*, 2019; Jain *et al.*, 2009; Knowler, 2015). In the case of a single technology such as a crop variety, it can be measured as the proportion of the land per unit of cropped area where it is applied: this notion is known as the intensity of adoption (Glover *et al.*, 2016; Jain *et al.*, 2009). But measuring the adoption becomes more difficult in the case of a blend of agricultural technologies, (Jain *et al.*, 2009). CA is a complex technology (Farooq and Siddique, 2015; Speratti *et al.*, 2015; Wall, 2007) that includes a set of practices such as wise soil manipulation, keeping crop residues onsite, planned and diversified crop sequences, and effective weed management (Farooq and Siddique, 2015). Therefore, the development of an appropriate "one size fits all" CA package by the research and the agricultural extension services is almost impossible (Wall, 2007). The literature on CA adoption is extensive, but it often fails to offer insights on the adoption and abandonment of partial conservation agriculture technologies or practices (D'Souza and Mishra, 2018).

CA practices are knowledge-intensive and imply a complete change in the farming system management (Speratti *et al.*, 2015), which means that the adoption process is ongoing and complex. Farmers use their tacit knowledge, practical skills and previous farming experience to define what combinations of practices or techniques are likely to be most relevant and effective in their situation, to ensure the ongoing economic and social viability of their farm. They do not simply follow a rigid, pre-formatted set of rules and procedures in the implementation of farming techniques (Higgins *et al.*, 2019). They may adopt some CA principles while maintaining a degree of flexibility in their approach. Thus, the decision exceeds any simple binary classification as a choice to adopt or not to adopt, because the farmers face a set of technology options. More realistically, the decision may involve selecting from several options or 'packages' among which not to adopt is just one of these multiple alternatives (Higgins *et al.*, 2019; Knowler, 2015).

On the other hand, adopting new agricultural practices is a dynamic process and should include the time dimension. Nevertheless, most studies are cross-sectional and consider only a single point in time. However, considering the timing of the decision to adopt can be as important to understand as the decision itself (Knowler, 2015). Moreover, adoption estimates often do not consider the number of cropping seasons in which CA practices have been applied. However, the third CA principle, crop rotation, requires a multi-seasonal definition of adoption. Although the CA definition used in different countries usually defines crop rotation as a sequence of three crops (Andersson and D'Souza, 2014), it might not be the case for South American agricultural systems. In Brazilian CA systems, a crop succession, on one hand, consists of the arrangement of two crops in the same agricultural area for an indefinite period of time, each cultivated in a given season of the year (Debiasi *et al.*, 2015; Franchini *et al.*, 2011). On the other hand, a crop rotation is defined "as the orderly alternation of different crops, in a given time frame (cycle), in the same area and in the same season of the year" (Debiasi *et al.*, 2015; Franchini *et al.*, 2011) or "consisting of the orderly alternation of different crops in a time frame and in the same area, where a plant species is not repeated in the same place in a time frame of less than one year" (Barbieri *et al.*, 2019; EMBRAPA, 2013). In both cases, the definition requires a multi-seasonal approach to assess crop rotations from one year to another.

2.2 Other explanations for the emergence of agricultural practices: the social practices theories

In the same vein, some theories put forward alternative narratives to explain the practices implemented by the farmers. In particular, the social practice theories have analysed how social practices emerge and become "normal" practices, instead of focusing on behavior change (Roysen and Mertens, 2019), and placed "emphasis on discourses and actions which make up practices in specific sociocultural contexts"(Sahakian *et al.*, 2017, p. 509). In addition, according to these theories, "practices can only emerge, persist or change when connections between certain elements are made, sustained or broken" (Roysen and Mertens, 2019, p. 2). They consider that practices are not only the result of rational decisions of the actors but that they depend on three categories of factors: 1) the meanings of the practices in place (what does it mean, for example, to cover the soil for farmers, rather than leaving it uncovered? What are the standards that promote the maintenance or evolution of practices? Etc.); 2) the available materials (what are the instruments, infrastructures, agricultural products that determine practices and/or allow the emergence of new practices? Etc.); 3) the competences (what knowledge and skills are needed to change practices, what are the learning contexts? Etc.)(Roysen and Mertens, 2019; Sahakian *et al.*, 2017; Shove *et al.*, 2015). These three categories are interlinked to form an integrated and coordinated chain of routine and habit, and, as a consequence, the social practices change when the connections between these elements change (Roysen and Mertens, 2019). Analyzing the conservation agriculture-related practices through the lens of these theories is out of the scope of this paper, but these approaches should be highlighted as likely to provide additional or alternative explanations to the adoption of new agricultural practices.

2.3 Previous analyses of the adoption of agricultural practices with composite indexes

Previous studies have evaluated the adoption of agricultural practices through a composite index with a weighting system. Some of them derived the weighting system from principal component analysis. In particular, Mutabazi *et al.* (2015) constructed a composite index of resilience-building adaptive strategies (REBAS) of farm households, based on a set of selected indicators, to assess the adoption of resilience-building measures. With the PCA, they reveal the latent structure and internal correlations among different classes of adaptive strategies and generate scores used as weights in the construction of their index. They also apply a multiple regression model to study the relationship between the REBAS index and four types of capital (human, financial, natural and societal), revealing that faith in climate change as anthropogenic phenomena is the key human capital variable influencing the resilience-building strategies. In a similar way, Li *et al.* (2016) develop a composite index to evaluate the sustainability of farm households using a weighting scheme based on a principal component analysis. They also use multiple regression models to understand how the environmental, economic and social dimensions of their farm household sustainability (FHS) composite index are driven by seven categories of determinants, i.e. knowledge, demographics, economics, technology, settlement type, land use, and level of social participation. They conclude that the share of the area of set-aside land through the Grain for Green Program (GGP) as a proportion of the total farmland proved to be the key determinant of agricultural sustainability.

Jain *et al.* (2009) measure the adoption of improved cultivation practices by the development of a state-wise composite index, to conclude with a highly significant correlation between the latter and the state-wise agricultural productivity. However, if they also assess the determinants of the adoption index with a multiple regression model, they do not integrate a principal component analysis in their study.

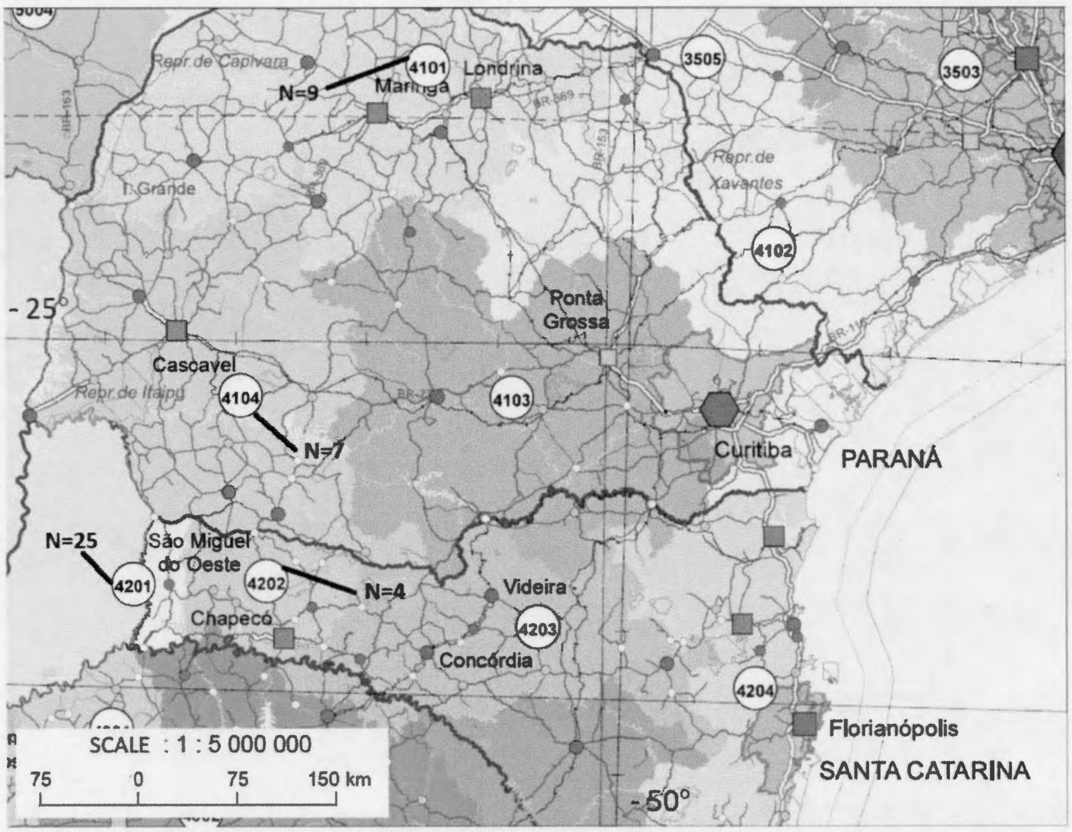
In addition, other studies (ITAIPU-BINACIONAL and FEBRAPDP, 2011; Martins *et al.*, 2018; Roloff *et al.*, 2011) have already used a composite No-Till Systems Quality Index (NTSQI) with a multi-seasonal approach of crop rotations (3 crop years) to assess the quality of Brazilian CA, defined as " the capacity of a given no-till field to maintain or increase crop and livestock productivity while maintaining or enhancing soil, water and air quality and other environmental services" (Roloff *et al.*, 2011, p. 1). The study conducted by ITAIPU-BINACIONAL and FEBRAPDP (2011) assessed the quality of CA of 25 producers with the composite index, and the results presented a good amplitude, ranging from 4.8 to 9.7 on a scale of 0 to 10, which led the authors to conclude that the index was able to clearly differentiate between the No-Till practices of the farmers. The indicator with the highest frequency of critical cases (52%), Terrace adequacy (TA) was related to the proper terrace management. The other indicators that appeared to be critical, in 32% of the cases, were related to the diversity of crops in the rotation scheme (Rotation diversity – RD) and the persistence of the crop residues (Residue persistence – RP), both related to the assessment of the crop rotation pillar of CA. The results from Roloff *et al.* (2011) were, similarly, from a sample of 24 farmers, and the values obtained for the composite index ranged from just below 6 to near 9, on the same scale. The two most critical indicators were TA (54% of the sample) and RP (29% of the sample), which led the authors to conclude "that actions aimed at improving NTS quality for those farmers must focus on terrace adequacy and on increasing the number of grass cover crops in the rotation, by using winter cover crops such as black oats" (Roloff *et al.*, 2011, p. 2). In the study of Martins *et al.* (2018), the ex-ante phase-field study had a similar sample size, with 19 producers from 12 different watersheds in 5 states of Brazil: São Paulo, Mato Grosso do Sul, Goiás, Paraná, and Rio Grande do Sul. The results from their study also show critical values for the average scores of the RD (0,67 out of 1,00) and the RP (0,50 out of 1,00) indicators obtained by the farmers from the Rolândia and Cambé regions in Paraná. These previous studies used a composite index to assess the quality of conservation agriculture, but to the best of our knowledge, our research is the first to measure the farm household level of adoption of conservation agriculture with a composite index by using indicators weighted through a principal component analysis.

3. Material and Methods

3.1 Description of Study Sites

The Southern Brazil region was chosen for this study because of the widely reported adoption of CA and the controversy surrounding it. The declared adoption level of CA farming in this region is close to 100% (Kassam *et al.*, 2018). In the southern states of Brazil, the practice of no-till conservation agriculture is presented as the norm (de Freitas and Landers, 2014) but some authors have doubts about these figures (Bolliger *et al.*, 2006; Denardin *et al.*, 2008; Fuentes Llanillo *et al.*, 2013; Landel, 2015). We conducted 45 baseline field interviews in four Rural Regions, two in the State of Santa Catarina and two in the state of Paraná. The geographical delimitation of the Rural Regions is based on the regional geographic differences as well as municipal contiguity, but also on the economic flows of the main agricultural products (IBGE, 2015a). In Figure 1, it is possible to see the geographical location of the regions from which respondents come, as well as the number of respondents from each region. 25 interviews were conducted in the Rural Region of São Miguel do Oeste (4201) and four (4) in Chapecó (4202), in the west of Santa Catarina state. In the state of Paraná, 9 interviews took place in the north-central region of Maringá (4101), while the other 7 were in the southwestern region of Cascavel (4104).

Figure 1. The number of interviews in each Rural Region in Paraná and Santa Catarina



Cascavel (4104): 7 interviews; Chapecó (4202): 4 interviews; Maringá (4101): 9 interviews; São Miguel do Oeste (4201): 25 interviews.

Source: IBGE (2015b)

3.2 Data collection

The target population for this study was soybean and corn growers. 45 interviews were conducted during the period between September and December 2017.[1] A nonprobability snowball sampling method was used to identify respondents because information about them was not easily accessible and the area was difficult to reach. This technique involves the use of a known contact who identifies other persons to be considered as study participants (Kaweesa *et al.*, 2018). The starting point was the cover crops specialized enterprise, SEMATTER, established in the city of São Miguel do Oeste, Santa Catarina, identified with the help of a CA specialist from Quebec, Canada. An agronomist of SEMATTER, in turn, identified soybeans and corn farmers. Respondents were asked to refer other potential study participants, and other agronomists referred by SEMATTER also helped the researchers to reach the first 36 farmers, both from Santa Catarina and Paraná states. Subsequently, a Weed Science professor at the State University of Maringá (UEM) helped to reach 9 additional soybean and corn growers.

The administration of an interview questionnaire was the method used to collect data from farmers. The questionnaire, containing close-ended, multiple-choice and open-ended questions, was organized under different sections, to collect information on the socio-economical characteristics of the property administrator, the agricultural practices, and the vision of conservation agriculture. The interviews were conducted in the presence of the agronomists or the Weed Science professor, who helped to ensure that the questions had been well understood by the interviewees and duly been responded. Data was initially entered in Excel sheets before analysis using Stata software version 15.

[1] All the farmers voluntarily agreed to speak with us and signed a consent form approved by the UQAM Research Ethics Committee (CERPE).

3.3 Summary statistics

The statistics on the respondent farmers and their farms are listed in Table 1. As this is an exploratory study, we should be cautious in generalizing the results. Moreover, the latter are difficult to extrapolate to the general population because of the differences observed between the sample and the study population, which will be described in the following text. As far as farm attributes are concerned, we observe that the average percentage of cultivated land being leased to another owner is 24% and that more than half (51%) of the producers raise livestock for profit (representing at least 5% of their income). There is also a large variation in labor availability, as the average of 3,48 employees per farm is lower than the standard deviation of 3,52.

Table 2 presents a set of selected characteristics, for which the Brazilian national and state-level data was available. When comparing the characteristics of the field crop producers of the sample group and their farms to the data from the 2017 agricultural census from the Brazilian Institute of Geography and Statistics (IBGE, 2017a), we observe differences in the age distribution (Table 2). The producers interviewed, men only, are on average 48 years old, which is a little bit older, but very close to the national average age (46,5 years old) of rural producers (ABMRA, 2017). However, the proportion of producers under 30 years of age is 11%, while the producers in this category represent only 4% in both states, and 5% at the national level. The proportion test shows that the percentages differences between the sample group and the IBGE data for this age category are statistically significant (0.05 significance level). The same test shows no statistically significant difference for the 30 to less than 60 years old age category. Lastly, there is a statistically significant difference (0.05 level) between the 60 years old and over category of Santa Catarina, Paraná, and Brazil, where they represent more than a third of the producers' population (34%), and the sample group where they are 20%.

Table 1. Socio-economic variables of the sample group

Variables (definition)	**Freq.**	**Percent.**	**Mean**	**Std. dev.**
Age of farmers (years)	45		48.06	11.80
Less than 30 years	5	11.11		
30-60 years	31	68.89		
60 years or more	9	20.00		
Education Level	45			
Primary or less	20	44.44		
Secondary or technical	17	37.78		
Higher education	8	17.78		
Farm size (hectares)	45		208.80	226.12
Below 50 ha	11	24.44		
50-200 ha	22	48.89		
200 ha or more	12	26.67		
Land ownership (% owned land per total land managed (vs. leased))	45		76.45	27.85
Labor availability (Number of Employees including family labor)	45		3.48	3.52
Livestock farming (5% of income or more)	45		.49	.51
1 = yes	22	49.89		
0 = no	23	51.11		
Farm inheritance	45			
1 = yes	32	71.11	.71	.45
0 = no	13	28.89		
Rural Region (IBGE classification)	45			
Maringá (4101)	9	20.00		
Cascavel (4104)	7	15.56		
São Miguel do Oeste (4201)	25	55.56		
Chapecó (4202)	4	8.89		

Source: Field survey (2017) and IBGE (2015a)

Table 2. Comparison between selected variables of the sample group and state and national level data (N=45)

Variable	Sample group (N=45)	Paraná (N=305,115)	Santa Catarina (N=497,823)	Brazil (N=5.072,152)
Age				
Less than 30 years old	11%*(pt)	4%	4%	5%
30 to 60 years old	69%	62%	63%	60%
60 years old and over	20%*(pt)	34%	34%	34%
Education Level				
Primary or less	44%**(pt)	71%	76%	79%
Secondary or technical	38%**(pt)	21%	17%	15%
Higher education	18%**(pt)	8%	6%	6%
Farm Size				
Below 50 ha	24%**(pt)	85%	89%	81%
50-less than 200 ha	40%**(pt)	10%	9%	12%
200 ha or more	36%**(pt)	4%	2%	5%
Mean Farm Size (ha)	**208.8**(tt)**	**48.2**	**35.2**	**69**

*, ** = 0.05 and 0.01 significance levels, respectively, for the one-sample test of proportion (pt) and the one-sample t-test (tt)

Sources: Field survey (2017) and IBGE (2017)

The average education level of producers interviewed in this study is also higher than that of producers in the states of Santa Catarina and Paraná, and Brazil. While the distribution shows that most producers have a Primary level or less (70% for both states and 79% at the national level), the proportion of this category is 44% for the sample group. 56% of the sample group has at least a secondary level of education, while it is less than 30% for Brazil, Paraná, and Santa Catarina. All these proportions differences are statistically significant at a 0.01 significance level. It should also be noted that in our sample, the younger farmers had a higher level of education. The 5 producers who were 30 year old or younger all had, at least, a secondary or technical level of education. Among the 31 sample farmers that were in the 30 to 60 years old category, most of them (14) had a secondary or technical level of education, while almost the same number (12) were below and only 5 of them had a higher education degree. And eight of the nine farmers above 60 years of age had only reached a primary level of education or below, whereas only one of them had a secondary or technical level of education.

There are also significant differences (at 0.01 level) in farm size. The farms below 50 ha represent 24% of the sample group, while in the two Brazilian states and in the whole country, they constitute over 80% of the farms. The farms between 50 and 200 ha and larger than 200 ha are overrepresented in the study, as they count for 76% of the sample group, while these combined categories are less than 18% at all the other geographic scales. The results of the one-sample t-test, used to test the null hypothesis that the population mean is equal to the ones retrieved from IBGE data, also show a statistically significant difference between the mean farm size of the sample group (209 ha) and the state-level and national values.

4. Building an Adoption of conservation agriculture index

4.1 The framework of the composite indicator

We focus on the adoption of conservation agriculture at the farm household scale to develop an *ex-post* assessment of the CA adoption of farms. In order to identify the indicators capturing the essence of conservation agriculture at the farm level, we applied a framework inspired by the No-Till Systems Quality Index (NTSQI) by ITAIPU-BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011). Based on this framework, we chose to build a composite "Adoption of Conservation Agriculture Index" (ACAI), as a composite indicator "should ideally measure multidimensional concepts which cannot be captured by a single indicator" (OECD, 2008, p. 13) like Conservation agriculture, a complex technology (Farooq and Siddique, 2015; Speratti *et al.*, 2015; Wall, 2007). Some of the benefits of the composite indicators include: that they can summarise complex, multi-dimensional realities with a view to supporting decision-makers; that they are easier to interpret than a battery of many separate indicators; that the reduce the visible size of a set of indicators without dropping the underlying information; and that they enable users to compare complex dimensions effectively. It should be noted, however, that there may also be disadvantages associated with the use of composite indicators, such as the fact that they can send misleading policy messages if they are poorly constructed or misinterpreted; that they may be misused if the construction process is not transparent or if it lacks sound statistical or conceptual principles; that the selection of indicators and weights could be the subject of political dispute; and that they may disguise serious failings in some dimensions and increase the difficulty of identifying proper remedial action, if the construction process is not transparent, among other disadvantages (OECD, 2008).

4.2 Selection of Conservation Agriculture indicators

Here the three pillars of CA, namely minimal soil disturbance, a permanent living or dead soil cover and crop rotations, as defined by many authors (Kassam *et al.*, 2018; Kaweesa *et al.*, 2018; Knowler and Bradshaw, 2007; Lemken *et al.*, 2017; Palm *et al.*, 2014; Pannell *et al.*, 2014; Speratti *et al.*, 2015) are represented by a set of six key indicators presented below, to reflect these pillars directly or indirectly in a similar manner to ITAIPU-BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011). They are selected based on their specificity and relevance in the study area and the availability of data, and the objective of this approach was also to represent these pillars of CA adoption with a minimum number of indicators. A fourth component used by ITAIPU-BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011) to evaluate an off-site outcome, was previously addressed by the evaluation of terrace adequacy (TA), assessed by the run-off over-topping frequency, and conservation evaluation (CE), based on the absence of signs of erosive run-off. As our goal was to assess the adoption and not the quality of the Brazilian no-till systems, we kept the indicators used to reflect the three CA pillars and did not integrate the run-off component indicators, nor the indicators previously used to assess plant nutrition (BN) or the time of adoption of no-till (AT), as it was done elsewhere (ITAIPU-BINACIONAL and FEBRAPDP, 2011; Roloff *et al.*, 2011).

The crop rotation pillar is evaluated through the rotation intensity (RI) and rotation diversity (RD) indicators that were kept from the assessments of ITAIPU-BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011). An indicator that was not included in previous studies, the summer crop rotation area (SCRA3), was also used to measure this CA pillar. Soil cover permanence is assessed by the crop residue persistence (RP), and soil cover intensity (SCI). In the original NTSQI used by ITAIPU-BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011), the RP indicator was related to the crop rotations pillar, but the choice to use it to assess the permanent soil cover dimension was based on the fact that this indicator also measures the soil cover permanence through the number of grass cover crops used in the rotation. For the SCI indicator, it is a modified version of the rotation intensity (RI) indicator used in the study of Martins *et al.* (2018), also based on the NTSQI index, where they replaced the original RI indicator by this one, which evaluates the number of months covered by living plants in the 3 years reference period; thus, for our study, it was used as an indicator of the permanent soil cover dimension of CA. The minimal soil disturbance is assessed by tillage intensity (TI), which calculates, in percentage, the average area not tilled in the past 3 years, instead of the previous indicator used by ITAIPU-BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011), tillage frequency (TF), which calculated the proportion, in years, between the number of years without tillage compared to the time considered ideal for stabilizing the system. All indicators are determined for a 3-year period, arguably easily remembered by farmers (ITAIPU-BINACIONAL and FEBRAPDP, 2011; Roloff *et al.*, 2011).

The value of each indicator (I_i) based on a benchmark is calculated as described in Equations (1):

$$I_i = \frac{E_i}{B} \tag{1}$$

where E_i is a present or future value of a field parameter for farm i and B is a regional benchmark value suggested by experimental results or expert opinion, as is the case with critical values, in the NTQSI framework (ITAIPU-BINACIONAL and FEBRAPDP, 2011; Roloff *et al.*, 2011). We used the benchmarks and critical values previously defined in the original NTQSI for the indicators we kept in our study (Table 3), as the original research was also conducted with farmers from southern Brazil Rural regions. Through our field observations with the 45 producers interviewed, it was defined that these values could be applied to our study, because of the similarity between farm household agricultural systems concerned by both studies. However, the authors of the original framework used, as explained in Roloff *et al.* (2011, p. 2) a "subjective weighting factor used to emphasize some indicators over others, again set through expert knowledge". In our study, we carried out a principal component analysis to "derive an objective weighting scheme for aggregating indicators" as it was done previously by Mutabazi *et al.* (2015, p. 1260), where the technique is used to construct a single composite indicator of resilience-building adaptive strategies of farm households.

Table 3 Evaluation parameters over a period (*E_i*), benchmark values (*B*) and critical indicator values.

Indicator	E_i	*B*	Critical value
Rotation pillar			
Summer crop rotation area (SCRA3)	Percentage of the area of the summer crop rotated past 3 years: [0,1]		
Rotation intensity (RI)	Number of crops (NC) past 3 years to the CA benchmark (NC/9): [0,1]	9	0.56
Rotation diversity (RD)	Number of crop species (CS) past 3 years to the CA benchmark (CS/4): [0,1]	4	0.50
Permanent soil cover pillar			
Residue persistence (RP)	Number of grass cover crops (GCC) past 3 years to the CA benchmark (GCC/6): [0,1]	6	0.50
Soil cover intensity (SCI)	Number of months (NM) with living cover (except fallow land and spontaneous plants) past 3 years to the CA benchmark (NM/36): [0,1]	36	0.75
Minimal soil disturbance pillar			
Tillage intensity (TI)	Percentage of the area not tilled (mean over the past 3 years) (MNTA): [0,1]		

Source: Authors calculations using field survey data

4.3 Weighting scheme of the Adoption of Conservation Agriculture Index indicators

The composite index, ACAI, was constructed using the six indicators and a weighting scheme derived from a principal component analysis (PCA). PCA is a statistical procedure that allows extracting from a set of variables the few orthogonal linear combinations of the variables that capture most successfully the common information. (Filmer and Pritchett, 2001). With this method, a primary dataset consisting of mutually correlated random variables can be represented by a set of independent hypothetical variables, called principal components, and the new set of data typically contains fewer variables than the original data. Those principal components contain almost the same information as the full set of primary variables (Gniazdowski, 2017). The PCA was performed on the data collected from the interview questionnaires with the 45 rural producers. The appropriateness of the PCA was tested with STATA/MP 15.1, by performing a Kaiser-Meyer-Olkin test and Bartlett's sphericity test, and by applying a varimax rotation, as previously done by Bidogeza *et al.* (2009) and Li *et al.* (2016).

To obtain composite scores, Equations (4) and (5) are assigned as follows:

$$PC_{ki} = \sum_{l} a_k^l \quad (4)$$

$$\mathrm{ACAI}_i = \sum_{k} v_k(PC_{ik}) \quad (5)$$

where PC_{ki} is the kth principal component for the ith farmer, a_k^l is the loading of the kth component for the lth indicator (see Table 5 for the component loadings for each indicator). ACAI_i is the composite score of adoption of the ith farmer, v_k is the percentage of variance accounted by the kth principal component. Each of the principal components is a linear combination of the original X values for the p variables. For example, the first principal component for the ith farmer (PC_{1i}) is given as:

PC_{1i} = 0.63(SCRA3) + -0.09(RI) + 0.58(RD) + 0.49(RP) + 0.(SCI) + -0.02(TI)

Also, to facilitate the interpretation of ACAI_i for the econometric analysis, it was standardized at a 0 to 100 scale as follows in Eq. (6):

$$ACAI_i^s = \frac{H_i - H_{\min}}{H_{\max} - H_{\min}} \tag{6}$$

Where $ACAI_i^s$ is the adjusted index of the ith farmer for i = 1,..., I. H_i is the unadjusted index value for the ith farmer in the sample group, $H_{\min}$ is the minimum value of the unadjusted index in the sample group, and $H_{\max}$ is the maximum value of the unadjusted index in the sample group.

5. Results

5.1 Conservation agriculture practices of the sample group (before PCA)

In table 4, the results of the six indicators representing the three pillars of Conservation Agriculture are presented. Overall, we can see that the average score for each indicator is relatively elevated, as most of the sample farmers are above the critical value, with the exception of the summer crop rotation area (SCRA), which has a lower mean score, with no defined threshold (critical value). On the opposite, the tillage intensity indicator (TI), which also does not have a defined critical value, has a high mean score. However, it is important to be careful with these numbers, as they can be influenced by extreme values.

Table 4. Conservation agriculture practices of the sample group.

Indicator : Ei /Benchmark	Mean Score (Mean E_i Value)	Mean Score Std. deviation	Critical value (CV)	Farmers Above CV (%)	Farmers = or under CV (%)
Rotation pillar					
Summer crop rotation area (SCRA3): ASC(3)	0.55 (0.24)	0.43			
Rotation intensity (RI) : NC/9	0.75 (6.71)	0.13	0.56 (NC=5)	45 (100%)	0 (0%)
Rotation diversity (RD) : CS/4	0.86 (3.98)	0.19	0.50 (CS=2)	38 (84%)	7 (16%)
Permanent soil cover pillar					
Residue persistence (RP) : GCC/6	0.78 (4.71)	0.24	0.50 (GCC=3)	29 (65%)	16 (35%)
Soil cover intensity (SCI): NM/36	0.88 (31.78)	0.09	0.75 (NM=27)	44 (98%)	1 (2%)
Minimal soil disturbance pillar					
Tillage Intensity (TI): ΣANT/3	0.92 (0.92)	0.12			

Source: Authors calculations using field survey data

In the first CA pillar, rotation, the summer crop rotation area (SCRA) indicator has the lowest average score among all indicators. In this case, extreme values have an influence on the mean score, as the standard deviation is really large (0.43). This implies that some farmers changed their summer crop from one year to another, or that the area where they planted their summer crop had a different crop at least once in the 3 years period of reference (2014-2016), while others had the same summer crops, from one year to another, in the same area. In the sample, only 15 (33%) individuals had a rotation in all (100%) of their summer crop area, while the remaining 30 (67%) did not. On the opposite, for the rotation intensity (RI) indicator, the standard deviation was small (0.13). The higher mean score of 0.75 implies that the sample farmers had an average of 6.71 different crops in their cultivated area in the reference period. Consequently, they were all above the critical value of 0.56 previously defined by ITAIPU-BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011). Finally, as far as the rotation diversity (RD) is concerned, the mean score is also high and the standard deviation relatively small (0.19), but there is a lower proportion of farmers (84%) with scores above the critical value defined for this indicator. Thus, 7 farmers (16%) were at the critical value of 0.50, as they only had 2 different species in their cropping system for the 3 years reference period. It is also important to remember that, even if the number of producers who obtained a critical value for the RD and RI indicators is small, the SRCA indicator reveals that the practices measured through these indicators are not necessarily uniform over the entire area, since the area that benefits from a rotation in the summer is variable.

The permanent soil cover pillar of CA was assessed by two indicators: residue persistence (RP) and soil cover intensity (SCI). The average score for residue persistence is relatively high (0.78), as the interviewees had an average of 4.71 grass cover crops in 3 years, but the standard deviation of the average score is also high (0.24). This reveals a mixture of low and high scores, as 29 (65%) of the croppers were above the critical value and the other sixteen (35%) were below, as they had only 3 grass cover crops (or less) for the reference period. On the other hand, the average SCI score was high (0.88) with a small standard deviation (0.09), meaning that on average, farmers had their soil covered by living plants (other than fallow land and spontaneous plants) for almost 32 (31,78) months over the 36-month period evaluated.

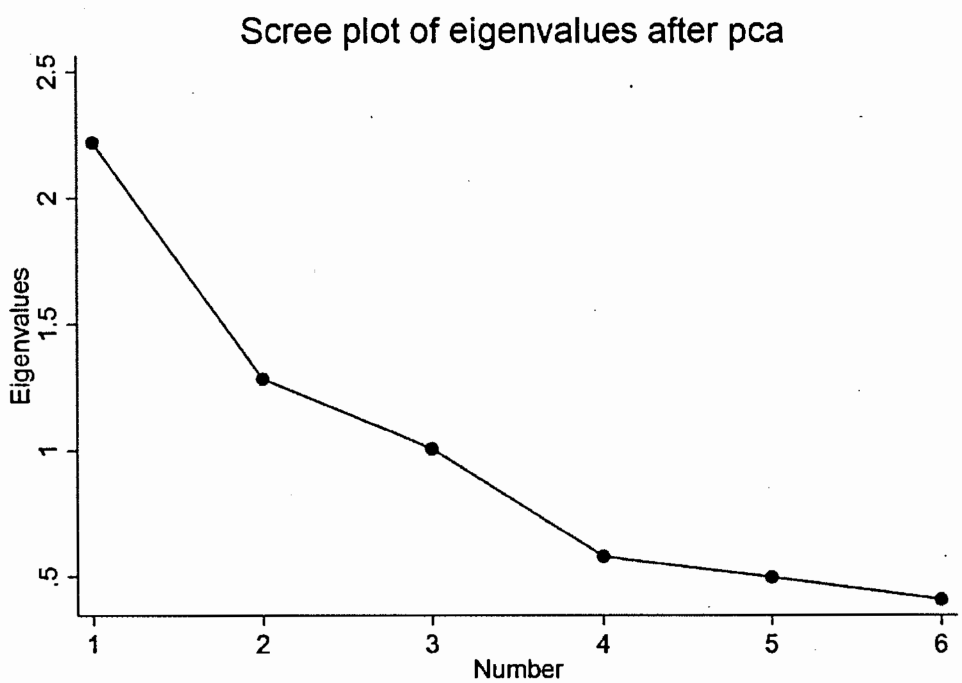
Finally, for the minimal soil disturbance pillar, the average score for tillage intensity (TI) is the highest (0.92) amongst all the CA indicators. It reveals that the level of adoption of the minimal or no-till practice, through the minimal soil disturbance, is the highest among all indicators in the entire sample, as the standard deviation (0.12) is also quite small. Although this indicator has no critical value, since it is a modified version of the original indicator used to measure the minimal soil perturbation, it is important to note that, among the producers surveyed, 15 (33%) had not tilled any part of their entire property during the reference period.

5.2 Appropriateness of a principal component analysis

The whole data set for the 45 participants was used for statistical analysis after reviewing the data to detect missing values, potential errors, outliers, and correlations. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett sphericity test were conducted on the dataset to confirm if a principal component analysis was appropriate. The KMO compares the value of the partial correlation coefficients in relation to the total correlation coefficients (Antony and Visweswara Rao, 2007), and PCA may be inappropriate if the variables are largely independent or correlate strongly (Bidogeza *et al.*, 2009). After applying the KMO to our dataset, the six indicators of Conservation Agriculture previously described were included in the principal component analysis (PCA). The acceptability threshold of the KMO is a score above 0.50, while the maximum value is 1 (Bidogeza *et al.*, 2009; Kaiser, 1974). Recent articles usually used 0.50 as a threshold for the KMO score to validate the appropriateness of PCA (Bidogeza *et al.*, 2009; Li *et al.*, 2016; Mutabazi *et al.*, 2015). The result of the overall KMO was 0.6471. Bartlett's sphericity test is used to examine the independence of the data, and its results show it was highly significant (Chi-square: 44.425; Degrees of freedom:15; Significance: $P < 0.001$).

The aim was to generate aggregating weights for the composite score, although the PCA results also provide insights into correlations among the three CA dimensions. Only the components with an eigenvalue greater than 1 were retained, in accordance with the Kaiser's criterion (see Figure 2). The idea of this criterion is that the amount of variation explained by a factor is represented by the eigenvalues; an eigenvalue of 1 represents a substantial amount of variation (Field, 2009, p. 640). Furthermore, according to Field (2009), even if Kaiser's criterion tends to overestimate the number of factors to retain, there is some evidence that it is accurate when there are less than 30 variables, which is the case in our research.

Figure 2. Scree plot of the eigenvalues after the principal component analysis



5.3 Components of the Adoption of Conservation Agriculture Index

The six indicators of Conservation Agriculture (see Table 5) were used in the PCA. The varimax method was applied to the components. This method consists of an orthogonal rotation that tries to load a smaller number of highly-correlated variables onto each factor, with the result of an easier interpretation (Bidogeza *et al.*, 2009). The loading is the correlation between a component and an indicator, revealing the contribution of the indicators to the variation accounted for by this component (Li *et al.*, 2016)

The three principal components obtained from the PCA explained 75.2% of the variance in the data. The first principal component (PC1), which explains 37% of the variance, is correlated with two variables (summer crop rotation area and rotation diversity) of the rotation pillar of CA, but also with one of the variables representing the permanent soil cover pillar, the Residue persistence (RP) indicator. Hence, PC1 indicates that the area of rotation of the summer crop (SCRA3) and the number of species in the 3 years rotation (RD) indicators are correlated with the number of grass cover crops in the 3 years rotation (RP) indicator. Consequently, PC1 represents mainly the rotation pillar of CA, but also, to a lesser extent, the permanent soil cover pillar.

The second component (PC2), explaining 21.4% of the variance, is strongly correlated with an indicator of the rotation pillar of CA, and another one of the permanent soil cover pillar. While the first correlation (0.6810) is a little bit stronger, it is almost the same as the other (0.6777). Thus, PC2 depicts a correlation between the number of crops in the last 3 years (RI) and the number of months with living soil cover in the past 3 years (SCI), and as a result, PC2 represents both the rotation and the permanent soil cover pillars.

The third component (PC3), explaining 16.7% of the variance, is highly correlated with the indicator of the minimal soil disturbance pillar of CA, i.e. the tillage intensity. Thus, PC3 still represents the third pillar of CA after our principal components analysis.

Table 5. PCA components used for Adoption of Conservation Agriculture Index (ACAI) index construction and their loadings

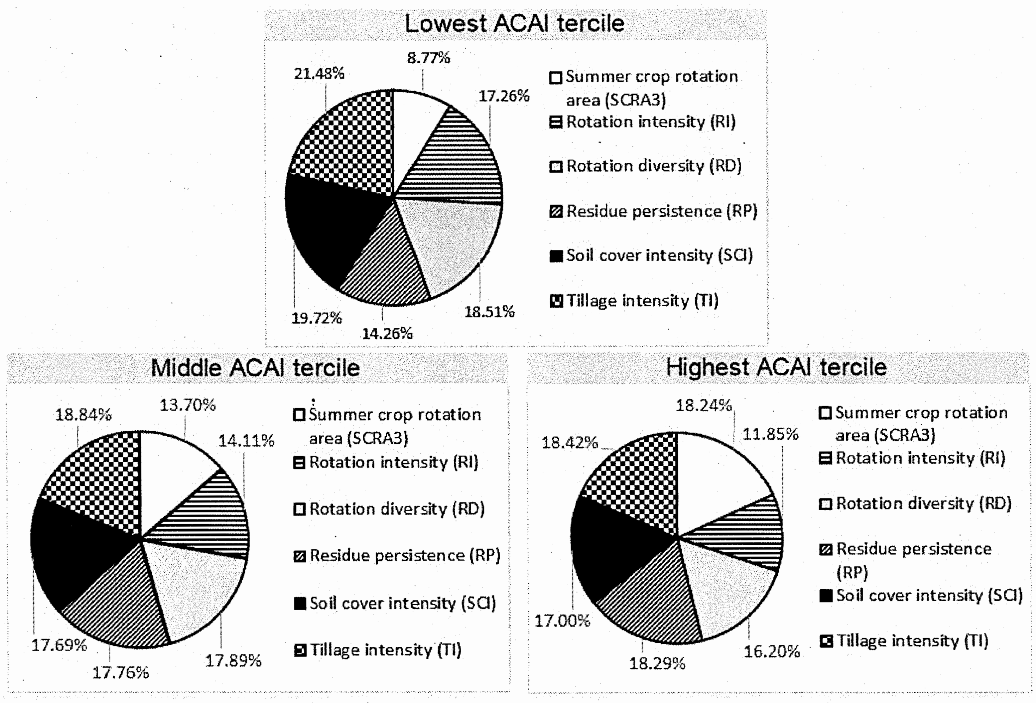
	Descriptive		Principal component (Bold figures highlight the highest component loading)		
Indicator	Mean	Std. Deviation	1	2	3
Rotation pillar					
Summer crop rotation area (SCRA3)	0.55	0.43	**0.6259**	-0.1667	-0.0978
Rotation intensity (RI)	0.75	0.13	-0.0932	**0.6810**	-0.3088
Rotation diversity (RD)	0.87	0.19	**0.5898**	0.0294	0.0960
Permanent soil cover pillar					
Residue persistence (RP)	0.74	0.24	**0.4976**	0.2197	-0.0491
Soil cover intensity (SCI)	0.88	0.09	0.0606	**0.6777**	0.3024
Minimal soil disturbance pillar					
Tillage Intensity (TI)	.92	0.12	-0.0203	-0.0033	**0.8899**

Source: Authors calculations using field survey data

5.4 Contribution to the ACAI scores by indicator

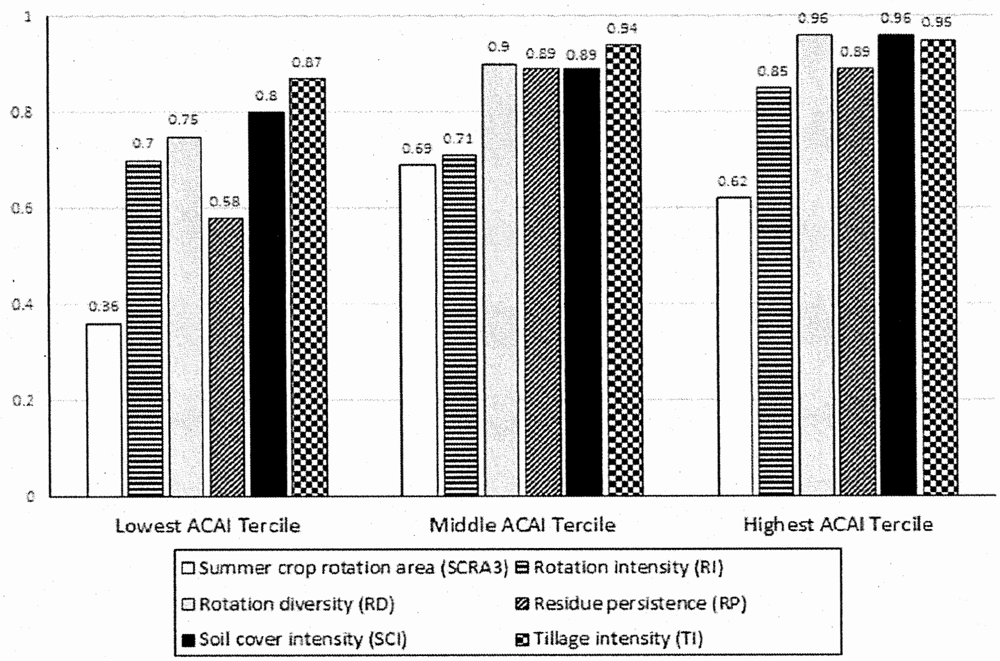
Figure 3 shows the indicators' contribution to the ACAI of the lowest, middle and the highest terciles of the sample group for the reference period (2014-2016). The variables correlated with the first principal component (PC1), representing mainly the rotation pillar (SCRA and RD indicators) but also the permanent soil cover pillar (RP indicator), account for the largest proportion of the the ACAI for the three equal groups: they contribute to 41.54% of the lowest ACAI tercile, 49.35% of the middle tercile's index, and 47.14% for the highest tercile. Figure 3 also shows that the SCRA and the RP indicators contribute less to the ACAI in the lowest tercile (respectively 8.77% and 14.26% of the ACAI) when compared to the middle (13.7% and 17.76%) and highest (11.85% and 17%) tercile. The contribution of the variables related to the second principal component (PC2), almost equally correlated with the pillars of crop rotation (RI) and permanent soil cover (SCI), decreases in the upper terciles. For the lowest ACAI tercile, they count for 36.98% of the ACAI score. For the middle ACAI tercile, it is for less than a third of the score (31.80%). Regarding the upper tercile, the total contribution of the RI and SCI indicators is 28.85%. Finally, the third principal component, which continues to be represented by the tillage intensity indicator (TI) related to the minimal soil disturbance dimension of Conservation agriculture, represents a similar proportion of ACAI in the three terciles: 21.48% for the lowest, 18.84% for the middle and 18.42 for the highest ACAI tercile. Consequently, for all terciles, the third principal component, as expected, represents the smallest proportion of the ACAI. However, when taken individually, the indicator that is correlated to this principal component, SCRA, is the one that represents the largest proportion of ACAI among all indicators, for all three terciles. It accounts for 21.48% of the ACAI in the first tercile; 18.84% of the middle tercile; and 18.42% of the highest tercile.

Figure 3. Contribution to the ACAI scores by indicator



In figure 4, the comparison of the mean scores of ACAI indicators renders some of these differences even more obvious. In the case of the summer crop rotation area (SCRA3), the mean score of the lowest tercile (0.36) is equal to the half, or less, than those of the middle (0.69) and highest (0.62) terciles. Thus, the summer crop rotation is lower for the farmers with a globally lower adoption of CA. The lowest ACAI tercile has lower mean scores for the variables related to the first principal component: for SCRA, as mentioned above; the mean rotation diversity (RD) score is 0.15 points above the mean RD for the middle tercile, and 0.21 points above the highest tercile. And the mean RP score (0.58) is 0.31 points above the average score of the other two terciles, who both get 0.89 as the mean score for this indicator. The same applies to the residue persistence (RP) indicator. Both the middle and highest terciles have a 0.89 mean score for this indicator, 0.31 points higher than the first tercile on a 0-1 scale. On the opposite, all the terciles have relatively high mean scores for the tillage intensity (TI) and the soil cover intensity indicators (SCI). The mean scores for these two indicators range from 0.80 to 0.95.

Figure 4. Mean score of indicators by ACAI tercile



5.5 Application of the separate and pooled regression models

Relationships between the ACAI score and the selected CA socio-economic variables related to the farmers and their farms were assessed by least-squares regressions, because of the small sample group size. The results of the regressions are listed in Table 6. To ensure the absence of multicollinearity the VIF test statistics and bivariate correlation were assessed (mean VIF = 2.63, max VIF = 4.82, Corr: all $r < 0.42$).

Table 6. Separate regressions vs Pooled regression with ACAI and selected variables

Variables	Separate regressions		Pooled regression (N =45, R2=0.4373)	
	Coeff. (β)	Std. Err.	Coeff. (β)	Std. Err.
Age of farmers				
(N = 45, R2 = 0.002)				
30-60 years	2.905	11.174	-10.790	11.610
60 years and over	3.673	12.933	-3.830	14.636
Reference category	Less than 30 years			
Education Level				
(N = 45, R2 = 0.005)				
Secondary or technical	1.903	7.639	1.036	7.566
Higher education	-2.465	9.687	7.624	12.592
Reference category	Primary or less			
Farm size				
N = 45, R2 = 0.040				
50-200 ha	-5.475	8.703	-4.552	9.464
200 ha or more	4.843	8.907	-11.980	12.586
Reference category	Below 50 ha			
Rural Region				
(N = 45, R2 = 0.277)				
Maringá	-36.583***	12.005	-43.144***	13.542
Cascavel	-1.707	12.522	-2.428	14.098
São Miguel do Oeste	-15.79	10.759	-21.407	13.350
Reference category	Chapecó			
Land ownership	-13.497	12.246	-24.409*	13.879
N = 45, R2 = 0.2765				
Labor availability	1.127	.967	1.688	1.096
N = 45, R2 = 0.0306				
Livestock farming	-.516	6.840	-7.344	7.414
N = 45, R2 = 0.0001				
Farm inheritance	-13.463*	7.260	-9.815	7.528
N = 45, R2 = 0.0741				

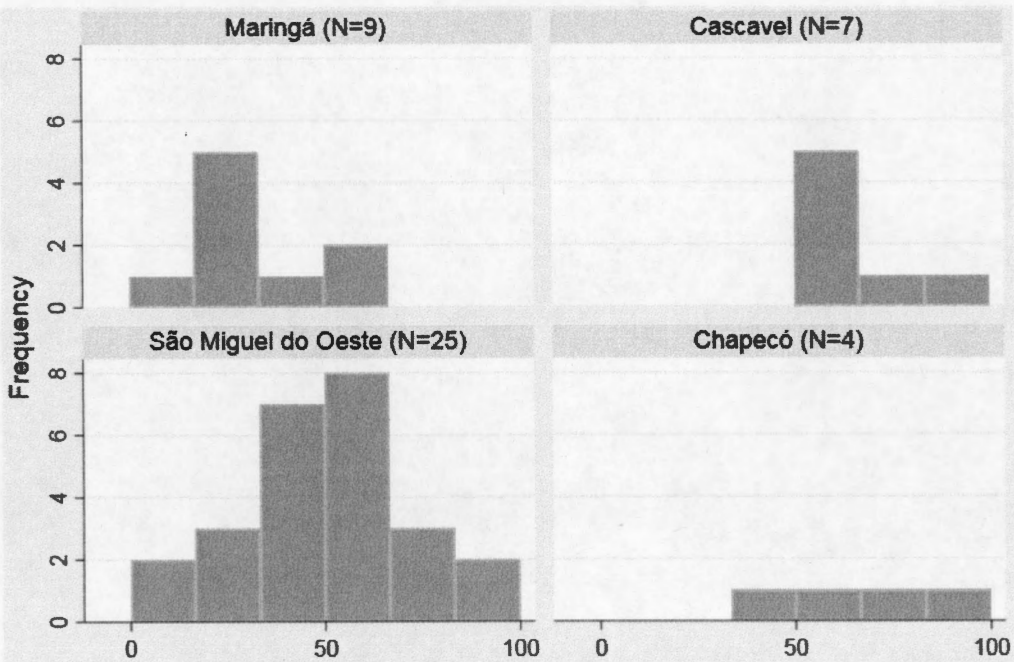
*, **, *** = 0.1, 0.05 and 0.01 significance levels, respectively

We observe in Table 6 that the ACAI does not significantly correlate with the independent variables of age (dummy), education (dummy), farm size (dummy), labor availability, land tenure and livestock farming (dummy). However, in the separate regressions model, the farm inheritance variable (i.e. if the farm was inherited from the family) shows a negative coefficient (-13.5) at a 0.1 significance level. In the pooled regression model, the land ownership variable, which represents the percentage of owned land per total land managed (versus leased), has a negative relationship (-24.4) with the ACAI, also at a 0.1 significance level. Lastly, the Maringá Rural Region dummy has a negative relationship (0.01 significance level) with the ACAI in the separate (-36.5) and pooled (-43.1) regression models. Thus, living in this Rural Region predicted a significantly lower ACAI score of 36.5 points in the separate regressions model and 43.1 points in the pooled regression model. These results also show that there are regional differences in the ACAI scores.

5.6 Regional differences in ACAI scores

Figure 5 shows the differences in ACAI by Rural Regions. In the Rural Region of São Miguel do Oeste, the ACAI scores are almost normally distributed, but the number of farmers with a score over 50 is a little bit higher than those below. The Rural Region of Chapecó, where the smallest number of interviews were conducted, also shows a diversity of scores amongst the 4 participants, but 3 of them have an ACAI score above 50. As previously shown by the results of the pooled regression model, the field crop producers of the two Rural Regions in the state of Paraná have a very different distribution of their relative ACAI scores, even with a similar number of participants. In Cascavel, all have scores above 50, while in the Maringá region, most of the producers have ACAI scores below 40. It is also important to note that, since the scores have been standardized, they should be interpreted in relation to the highest and lowest scores in the sample. And once again, these differences in the adoption of conservation agriculture practices, through the composite index, cannot be generalized to the entire population of these Rural regions, since this is a small convenience sample.

Figure 5. ACAI by Rural Region



6. Discussion

6.1 Relationships between principal components

The correlation between the three indicators of the first principal component (PC1), summer crop rotation area (SCRA3), rotation diversity (RD) and residue persistence (RP) is not surprising, because in the original NTSQI, designed by ITAIPU-

BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011), the residue persistence was an indicator of the crop rotation dimension. However, we decided to put the residue persistence indicator in the permanent soil cover pillar, since it measures the degree of persistence or durability of the mulch on the soil surface (ITAIPU-BINACIONAL and FEBRAPDP, 2011). After applying the principal components analysis, the correlation between SCRA3 and RP becomes clearer. One possible explanation is that farmers usually divide their summer crop rotation area between soybean and corn. A typical summer crop rotation model would be 75% of the area cultivated with soybean, and 25% of corn (Debiasi *et al.*, 2015). Almost all the farmers (42 out of 45) cultivated corn, but not all of them were doing so in the summer season. Some of them did a soybean/corn succession, having the corn as the second crop. Corn is a grass and it has a great potential of producing phytomass in the aerial and underground parts (Debiasi *et al.*, 2015; ITAIPU-BINACIONAL and FEBRAPDP, 2011). Thus, the area covered with corn instead of soybean has a greater potential to cover the soil with mulch residues after the summer crop, and as a consequence, a potential positive impact on the residue persistence (RP) score.

In the case of the second principal component (PC2), the correlation between the rotation intensity (RI) and the soil cover intensity (SCI) was expected, because the rotation intensity indicator was used in the initial versions of the NTSQI by ITAIPU-BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011), and replaced, in subsequent versions of the same index (Martins *et al.*, 2018), by another rotation intensity indicator, defined as the number of months with living soil cover in the past 3 years, which is also integrated in our index as the soil cover intensity (SCI) indicator. The lowest ACAI tercile also has the lowest mean rotation intensity (RI) score (0.70), indicating that they did not have a permanent soil living cover. This indicator, defined to assess the degree of living cover over a defined period, is a count of how many months the soil had a living cover, except for fallow land or spontaneous plants. The presence of a living cover means greater surface protection and the production of new straw to replace the previous one that decomposes over time. The continuous presence of living roots preserves macropores and creates new ones, while also promoting an environment favorable to nutrients recycling, maintenance of the rhizosphere biodiversity and balance between more and less oxidizable fractions of organic matter. The benchmark initially defined for the western region of Paraná is the cultivation of a commercial culture or a cover crop in all three seasons: summer, the second crop (safrinha) and winter (ITAIPU-BINACIONAL and FEBRAPDP, 2011). We kept the benchmark of 9 possible crops in 3 years, since our field observations demonstrated that it was feasible in all Rural Regions of the present study; there was always at least one producer who had cultivated 9 crops in 3 years, except in the Maringá Rural Region, where the farmer with the best score cultivated 7 crops in 3 years.

The other aspect revealed by Figures 3 and 4 is that the CA pillar of minimal soil disturbance has similar levels of adoption amongst all the terciles of ACAI. Figure 3 shows that the share of the tillage intensity is similar in the 3 groups, while in Figure 4, the mean score of this indicator is very high for all the terciles. This implies that, in all three groups, the minimal soil disturbance pillar of CA, measured through the tillage intensity (TI) indicator and represented by the third principal component of our composite index, has a higher level of adoption than the indicators correlated with the first and second principal components, both related to the crop rotation and permanent soil cover pillars. This is consistent with previous findings that in recent years, there are failures in the implementation of the CA system, and that some of its basic principles like the crop rotations and the maintenance of a permanently covered soil have not been used (Barbieri *et al.*, 2019). This situation has been previously reported, both for the states of Santa Catarina (Denardin *et al.*, 2008) and Paraná (Bolliger *et al.*, 2006).

6.2 Separate and pooled regressions between the socio-economic variables and the ACAI

The relationship between some of the selected socio-economic variables (age, education, farm size, land tenure, livestock farming, and labor availability) and CA adoption was assessed in previous studies. All these variables have been difficult to link to the adoption of conservation agriculture because they revealed both significant, insignificant and negative correlations in different studies. This led to the conclusion that there are few if any universal variables explaining the CA adoption (Knowler, 2015; Knowler and Bradshaw, 2007).

The land ownership and the farm inheritance variables show a correlation with the ACAI at a 0.1 significance level, but the relationship does not stand in the two models. The suggested negative relationship between land ownership and ACAI is in contradiction with previous findings that farmers are more likely to adopt sustainable agricultural practices on their own land (Foguesatto and Machado Dessimon, 2019), but as proposed by Place and Swallow (2000), a farm-level analysis could mask many important relationships between fields or parcels with different tenure rights. Moreover, these authors underscore the importance of understanding what was already present on the farm at the time of inheritance since the observed technology might have been inherited. We cannot say with any confidence that there is a significant negative relationship between these variables and the ACAI, because of the small sample size and the large standard errors, but the relative stability of the coefficient and their significance in at least one model suggests the need for further research on the impacts of the proportion of owned land (vs. leased) and the inheritance of the farm on the adoption of conservation agriculture. A study of these variables at the parcel or field level might lead to different conclusions on their role in CA adoption.

In the case of the Rural Region variables, the coefficients have to be interpreted in relation to Chapecó because it is the omitted dummy in the model. The Rural Regions of São Miguel do Oeste and Cascavél are not statistically different from this region in terms of ACAI, while Maringá predicts a significantly lower degree of adoption in both regression models. We expected that the Rural Region may have an influence on the ACAI since the practices of the interviewed farmers seemed to change from one region to another, and, especially in Maringá, where 7 farmers out of 9 did no summer crop rotation at all, by repeating the same crop over on same area year after year, over the 3-years reference period. The less diversified systems in the region of Maringá support the conclusion by Fuentes-Llanillo *et al.* (2018) that specialized no-till grain production systems in the north of Paraná are economically profitable even if they are based on crop successions, and that they are usually more profitable than the diversified ones.

Another possible interpretation is that the differences between the Rural Regions might be related to the different soil composition. Assunção et al. (2013) found, in previous research in the state of São Paulo, that soil heterogeneity decreased CA adoption. The similarity between the soil composition of the São Miguel do Oeste, Chapecó and Cascavel Rural Regions, and their differences with the soils of the Maringá region, based on the Brazilian system of soil classification (dos Santos et al., 2018) seem to confirm this assertion. The first three Rural Regions have a similar composition, with a blend of high activity clay haplic cambisols, brown latosols, and litolic neosols, while the soils of the Maringá region are divided between red latosols and red nitosols. But once again, caution should be exercised in interpreting these differences between Rural Regions, as this is a small convenience sample.

6.3 Summary and implications

Some differences with the original index from ITAIPU-BINACIONAL and FEBRAPDP (2011) and Roloff *et al.* (2011) should be highlighted. Through the construction and use of our composite index, ACAI, we integrated a new indicator to the crop rotation pillar, the summer crop rotation area (SCRA), used an indicator previously related to this pillar, residue persistence (RP) to asses the permanent soil cover dimension, and modified the previous tillage intensity (TI) indicator to assess the minimal soil disturbance. The new weighting scheme, meant to find the linear combination of the variables with maximum variance (Filmer and Pritchett, 2001), was fundamental in the application of our composite index and the results obtained. In contrast to previous studies, where it was defined through expert knowledge, we applied a principal component analysis to weight each indicator. In the first principal component, explaining 37% of the variance, the summer crop rotation area (SCRA) had the highest loading (0.6259), which means that this indicator had a heavier weight in the composite index. And with the lowest scores among all indicators, the summer crop rotation area, as a new indicator with a high standard deviation, had a significant impact on the results of the composite index and supports the previous conclusions of the lack of crop diversification. Thus, in this paper, we address the fact, as previously stated by Jain *et al.* (2009, p. 110) "that most adoption studies view the adoption decision in dichotomous terms, but there is a need for the adoption study covering the intensity of use" through the integration of an indicator that allows to measure the area dedicated to the rotation of the summer crop.

The heterogeneity of practices between the regions, and within the sample, also seem to confirm that a binary measure of adoption is inadequate to capture the complexity of the application of conservation agriculture principles. In our study, 44 out of 45 respondents said that they were adopters of the practice when asked if they adopted (or not) conservation agriculture. However, the application of the composite index to the sample reveals a diversity of practices between grain croppers, and also between regions, and as illustrated by Figure 5, it includes producers that have a very low level of crop diversification in their systems. It does not necessarily mean, however, that they would be considered as non-adopters of CA in a binary scheme of adoption, as it would depend on the thresholds defined for the different indicators or for the index in general.

The CA pillar of rotation is not always defined in the same way, nor is the threshold at which the practice of crop rotation is considered to be adopted by a farmer, but we have based ourselves on the local research and development definition of this practice. As demonstrated in this study, this practice cannot be analyzed in an appropriate way by a binary adoption scheme, or without considerating the multi-seasonal definition of crop rotations. To move to binary measures, we would have to determine thresholds at each of the continuous measures, even the ones with no critical values, to decide how to represent the information disaggregated by several adoption percentages, and that would again mask the richness of the information, by putting it into several categories rather than in a single measure. But the index developed could also suggest a revision of the criteria for binary classification. If people really want to use such a classification, perhaps they should at least change the criteria to make it more reflective of reality. Sometimes a binary classification is useful, but if it is too biased, it can be misleading. Thus, the threshold at which a set of agricultural practices is defined as Conservation Agriculture may need to be redefined, especially in the Brazilian context.

7. Conclusion

This study intended to assess the conservation agriculture adoption of farm households in four Rural regions in the states of Paraná and Santa Catarina, southern Brazil. In order to operationalize the concept of farm household adoption of CA, a composite index was built to evaluate the adoption of its three fundamental dimensions, rotation, permanent soil cover, and minimal soil disturbance. To reveal the latent structure and internal correlations among indicators, and mainly to generate a weighting scheme for the composite index, a principal component analysis was applied. Using an indicator-based adoption index, we obtain a continuous measure that can better characterize the degree of adoption and the heterogeneity of a complex practice such CA in the southern states of Paraná and Santa Catarina, when compared to a binary measure of adoption. With our composite index, we were able to capture different degrees of crop rotations or successions, permanent soil cover and minimal soil disturbance practices. As this was an exploratory study, with a nonprobability sampling method and a small sample size, it is important to be careful in generalizing our results. However, the composition of our sample leads us to affirm that, even for a group where it is assumed that it may be easier for them to adopt a better quality of soil conservation practices i.e. large landowners with better formal education than the average, the crop diversification remains insufficient. Our results support the previous conclusions regarding the lack of crop diversification in the CA systems of southern Brazil through the use, among other things, of an innovative indicator that evaluates the intensity of crop rotation adoption by measuring the area on which the practice is applied in the summer, in a multi-seasonal adoption assessment, over a period of 3 years. Thus, the area under good-quality CA in this region could be significantly lower than the area under no-till cropping systems (Kassam et al., 2018), and the distinction between these two systems must be clearly established.

The Brazilian R&D for CA and soybean agriculture has often emphasized the importance of crop rotations, not only as a good agricultural practice but as a fundamental pillar of the soybean CA systems. As stated by authors like Salvadori *et al.* (2016) and Denardin *et al.* (2012), no-till practice and conservation agriculture are two different concepts. For the soil and climatic conditions of the southern region of Brazil, the two principles of no-till, the reduction or elimination of soil movement and the maintenance of crop residues in the soil are insufficient to promote the sustainability of annual grain crops. The consolidation of conservation agriculture systems, on the other hand, is essentially based on the diversification of crops to increase profitability, the promotion of a permanent soil cover, and generating plant protection benefits and nutrients cycling. The interaction between crop diversification, the absence of tillage and the maintenance of a permanently covered ground ensures the gradual improvement of the biological, physical and chemical characteristics of the soil.

The lack of crop diversification in CA systems observed in previous research and in our study also raises several questions on the official data on CA adoption in Brazil. How are these statistics compiled and analyzed? Are they based on a binary measure of adoption of CA, where the practice of no-tillage is the exclusive criteria for defining if a farmer is a CA adopter? Even if the crop rotation pillar is not adopted, will farmers be considered as adopters? Previous research by Fuentes Llanillo *et al.* (2013) revealed that the data on CA adoption reported by the FEBRAPDP, estimated by using secondary data supplied by the Agricultural Research and Rural Extension Service of Santa Catarina state (EPAGRI) and the Institute of Technical Assistance and Rural Extension of Paraná state (EMATER-PR), amongst others, showed significant differences with the data provided by the Brazilian Institute of Geography and Statistics (IBGE), with the publication of the 2006 Agricultural Census results. Their study, based on special tabulations presented by the 2006 Agricultural Census, indicates that Conservation Agriculture was used on approximately 17.8 million hectares (Mha) of annual crops, while previous estimations reported that the surface area of CA in Brazil was 25.6 Mha in 2006. The estimations of Denardin *et al.* (2012) for the 2009/2010 cropping season are even lower, as they explain that while the area with soybean/corn crops in the summer season is 37,6 million hectares, close to 27,6 Mha are of this area is not cultivated with any crop (commercial or not) in the winter. The principle of species diversification through crop successions is not applied. Thus, their estimation of the area under CA is only 10.4 Mha.

The last agricultural census in Brazil took place in 2017. The only question on crop rotations in the 2017 agricultural census questionnaire (section 06) of the IBGE (2017a) is whether this practice was performed (or not) on the farm, giving no insights on the intensity of the rotation. The other potential problem of the census is the reference period, October 1st, 2016 to September 30, 2017. This one year period of reference implies that only crop successions can be measured. The rotation of the crop grown during the summer, or even during the winter, from one year to another cannot be assessed. There is a question, in section 11, about the area of direct planting into crop residues (*plantio direto na palha*), a concept for which the definition in the Census Taker instructions manual (IBGE, 2017b) does not include crop rotations. Previous research by Denardin *et al.* (2012) clearly described the difference between the direct planting into crop residues (*plantio direto na palha*) and the direct planting into crop residues system (*sistema plantio direto na palha*), which represents CA. Thus, the panoply of terms used for Brazilian CA and no-till practices can lead to confusion, and as a result, the CA agriculture in Brazil may have been overestimated. Consequently, the IBGE may benefit from the inclusion of some of the variables we used in our index to assess the degree of CA adoption, such as the proportion of the summer crop area where a rotation is done from one year to another, to have a more accurate measure of CA adoption in Brazil.

CHAPITRE III : CONCLUSION GÉNÉRALE

CONCLUSION GÉNÉRALE

La présente recherche a permis d'analyser l'adoption des trois pilliers de l'agriculture de conservation, soit la rotation des cultures, la couverture végétale permanente et le travail minimal du sol de 45 producteurs de soja et de maïs de Santa Catarina et du Paraná. L'objectif était de construire et appliquer un indice composite d'adoption permettant de mieux capturer la diversité des pratiques d'AC dans cette région, par rapport à l'utilisation d'une mesure binaire de l'adoption. Basé sur l'indice composite développé par ITAIPU-BINACIONAL and FEBRAPDP (2011) et Roloff *et al.* (2011), il permet de tenir compte du caractère multi saisonnier de la rotation des cultures, puisque l'évaluation de tous les indicateurs de l'indice se fait sur une période de 3 ans. Dans le contexte brésilien, la pratique de la rotation des cultures ne peut pas être mesurée sur une période inférieure à une année agricole complète, en considérant la définition de la rotation des cultures d'acteurs locaux comme l'Entreprise Brésilienne de Recherche Agricole (EMBRAPA, 2013). Or, si notre indice composite se base sur des travaux précedemment effectuées par ITAIPU-BINACIONAL and FEBRAPDP (2011), Martins *et al.* (2018) et Roloff *et al.* (2011), quelques différences méritent d'être soulignées. D'abord, nous l'utilisons pour mesurer le niveau d'adoption de l'agriculture de conservation, et non sa qualité, comme c'était le cas dans les études précedemment mentionnées; en ce sens, nous gardons de l'indice original uniquement les indicateurs directement reliés aux trois piliers de l'agriculture de conservation. De plus, le système de pondération n'est pas déterminé par une opinion subjective, mais dérivé d'une analyse en composantes principales, qui accorde un poids plus élevé aux indicateurs dont les données présentent une plus forte variance. Enfin, l'intégration, d'une part, d'un indicateur qui permet de mesurer la superficie attribuée à la rotation de la culture d'été (SCRA), et d'autre part, la modification de l'indicateur relié à la perturbation minimale du sol (TI), permettent de mesurer l'intensité de l'adoption de ces pratiques de l'agriculture de conservation de façon plus précise qu'une mesure binaire.

Il se dégage des résultats que, parmi les trois composantes principales obtenues, les deux premières sont corrélées, à la fois, à des indicateurs attribués à la rotation des cultures et au maintien d'une couverture végétale permanente sur le sol, alors que la troisième continue à représenter exclusivement le pilier de la perturbation minimale du sol. Les indicateurs dont le poids est plus élevé dans l'indice composite sont donc corrélés avec la première composante principale. Plus particulièrement, il s'agit de la superficie de rotation de la culture d'été (SCRA), de la diversité de la rotation (RD) et de la persistance des résidus (PR), qui obtiennent des plus faibles notes moyennes, un plus grand écart-type et, qui ont, conséquemment, la plus grande variabilité dans l'échantillon. Ce qui implique que certains producteurs ne pratiquaient la rotation des cultures que dans une faible proportion de leur culture principale d'été, avaient une faible diversité d'espèces dans leur système agricole, ou un sol dont la couverture permanente par des plantes mortes ou vivantes n'était pas assurée en raison d'un nombre insuffisant de graminées dans système de rotation. La plupart des agricultueurs ayant de telles pratiques venaient de la région rurale de Maringá. Toutefois, le semis direct sans labour était adopté à un haut niveau par presque tous les individus de l'échantillon, puisqu'ils obtenaient, de façon générale, des résultats très élévés à l'indicateur qui mesurait l'absence de la pratique du labour (TI) au cours des 3 dernières années. Cela tend à confirmer les constatations émanant d'études précédentes, selon lesquelles dans certaines parties du sud du Brésil, il y a eu, au cours des dernières années, des failles dans la mise en œuvre de certains principes de l'Agriculture de conservation, tels que la rotation des cultures et le maintien d'une couverture du sol permanente (Barbieri *et al.*, 2019; Bolliger *et al.*, 2006; Denardin *et al.*, 2008). Ainsi, les superficies cultivées en agriculture de conservation dans cette région pourraient être significativement inférieures à celles cultivées en uniquement en semis direct (Kassam et al., 2018), et la distinction entre ces deux systèmes doit être clairement établie. Cependant, comme il s'agissait d'une étude exploratoire, avec une méthode d'échantillonnage non probabiliste et un échantillon de petite taille, les résultats ne sont pas généralisables à l'ensemble de la population de Santa Catarina ou du Paraná, ni à celle du Brésil.

D'autre part, l'abandon, ou la non-adoption de la diversification des cultures par les producteurs de cette région doit être remise en contexte. Les agriculteurs doivent s'adapter à un environnement macroéconomique qui n'est pas nécessairement favorable à la diversification des cultures. Ainsi, à l'instar de Fuentes-Llanillo *et al.* (2018), qui décrivent une situation dans laquelle les systèmes de production de céréales spécialisés sans labour dans le nord du Paraná sont, de façon générale, plus rentables que ceux qui sont diversifiés, quelques témoignages recueillis sur le terrain ont permis de mieux comprendre cette réalité. Certains producteurs ont ainsi révélé que les bas prix du maïs les ont forcés à diminuer la superficie de cette culture, ou à l'abandonner complètement, et à compter presque exclusivement sur le soja en été ; en hiver, la même situation s'appliquait à la culture du blé, avec de faibles niveaux de rentabilité ; et qu'il n'y avait que peu, ou pas de débouchés commerciaux pour vendre leurs cultures de couverture d'hiver, alors que l'implantation de ces cultures avait un coût qui était parfois élevé.

Enfin, il est utile de rappeller que l'agriculture de conservation, efficace pour lutter contre l'érosion des sols, n'est pas toujours une panacée au niveau environnemental. La plupart des systèmes d'agriculture de conservation dépendent de l'utilisation d'herbicides, notamment pour la gestion des adventices (au lieu du labour) et la destruction de couverts végétaux avant le semis de la culture, qui peut être faite avec des herbicides dits « dessicants ». Les données disponibles confirment la dépendance et l'augmentation de la consommation d'herbicides avec l'adoption des pratiques sans labour, principalement les herbicides à base de glyphosate (Landel, 2015). Au Brésil, les cultures tolérantes aux herbicides sont semées sur d'immenses superficies et jouent un rôle économique majeur ; en conséquence, l'impact des mauvaises herbes résistantes au glyphosate est significatif (Bonny, 2016). Cette dynamique était évidente lors de nos entretiens avec les producteurs agricoles du sud du Brésil, puisque la totalité d'entre eux utilisaient des semences de soja et/ou de maïs génétiquement modifiées, et qu'ils déclaraient presque tous avoir des problèmes avec des mauvaises herbes résistantes au glyphosate.

Au niveau mondial, il y a présentement 38 espèces d'adventices qui ont développé une résistance au glyphosate. Parmi elles, environ la moitié ont évolué dans des systèmes de culture résistantes au glyphosate, alors que l'autre moitié s'est développée dans des vergers, des plantations, des céréales, des jachères, ainsi que dans des zones non-cultivées. Le Brésil est actuellement le quatrième pays en importance au niveau de la diversité des espèces résistantes au glyphosate, avec 8 espèces répertoriées. Les cas les plus sérieux sont ceux de la famille *Conyza* spp. (*C. canadensis, C. bonariensis* et *C. sumatrensis*), *Digitaria insularis*, *Eleusine indica* et, plus récemment, *Amaranthus palmeri* (Heap and Duke, 2018). L'expansion de ces plantes résistantes, notamment l'amaranthe de Palmer (*A. palmeri)*, menace l'agriculture de conservation, puisque dans certains cas le labour est la seule option efficace (Bonny, 2016). Or, bien que le labour était perçu comme l'une des options disponibles pour lutter contre les mauvaises herbes résistantes au glyphosate, les agriculteurs passés en entrevue cherchaient généralement à l'éviter. Une grande partie d'entre disait plutôt avoir augmenté les doses ou le nombre d'applications d'herbicides à base de glyphosate au cours des dernières années, ou utiliser des mélanges comprenant d'autres herbicides pour affronter cette résistance au glyphosate. Cette dynamique n'est pas sans rappeler les modèles techniques et socioéconomiques hérités de la révolution verte (Petersen *et al.*, 2013), « un type particulier de changement technique dans l'agriculture du tiers-monde découlant de l'amélioration du matériel génétique, de l'utilisation intensive d'engrais et de l'irrigation contrôlée. » (Scott, 2014, p. 293). Ces modèles ont soumis les producteurs ruraux familiaux à une dépendance technologique, avec des coûts de production et des niveaux d'endettement à la hausse, ainsi qu'à la dégradation environnementale des agroécosystèmes et l'empoisonnement des humains avec les pesticides (Petersen *et al.*, 2013). Ces constatations portent à croire que le défi de faire des grandes cultures d'une manière environnementalement durable dans le sud du Brésil pourrait s'avérer plus difficile à relever que prévu.

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