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Determinants of adoption of integrated systems by cattle farmers in the State of Sao Paulo, Brazil

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Abstract The level of diffusion of integrated crop-livestock systems (ICLS) and integrated livestock-forestry systems (ILFS) among cattle farmers in Brazil is still low, despite the environmental and economic benefits and governmental policy support. The present study aims at identifying the factors that determine the adoption of these systems in the State of São Paulo, Brazil. The theory of adoption and diffusion of agricultural innovations takes into consideration several economic and non-economic determinants. Data from 175 farms and multinomial logit models were used to test hypotheses on the role played by farms' scale, farms' topography, farms' type of soil, farmers' knowledge, farmers' capacity for innovation, availability of local facilities for grain trade, extension service, and credit supply. The results highlighted the important role played by farmers' human and physical resources when adopting these systems. Knowledge, scalable agricultural land and fixed capital for crop farming being the most relevant ones. Access to credit and extension service helped to overcome lack of physical capital and knowledge. Farmers with innovative capacity were the ones who showed to be more prone to adopt. Availability of local infrastructure for grain trading facilitated the adoption of ICLS. Adoption of ILFS turn out to be an alternative option in slopping land and sandy soils. Results shed light on strategies to accelerate the diffusion of those systems.

Keywords Agricultural technology adoption · Integrated systems · Cattle farming · Agricultural sustainability

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Introduction

Integrated Crop-Livestock-Forest Systems have been proposed as a more sustainable technological option for livestock production. In these systems, agricultural and livestock activities are carried out in the same area, involving intercropping, in combination or in rotation, in which complementarity and positive synergic effects are observed. Several studies have focused on the environmental and economic benefits of integrated systems over conventional monocultural systems (e.g. Balbino et al. 2011; Salton et al. 2014; Carauta et al. 2018). These diversified integrated systems would provide agronomic and ecological benefits such as improvements in soil structure, water infiltration, nutrient cycling, soil organic carbon sequestration, soil biological diversity, and controlling of weed, insects and disease populations. Economic benefits arise and have also been observed such as cost

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reduction, improvement in product quality (beef and milk), reduction of seasonality of production, reduction of market risks associated to diversification and recovering of farmland areas previously considered less suitable for agricultural production. Complementarity and positive synergic effects would result in a more efficient use of available resources.

These systems have been adopted by dairy and beef cattle farmers in Brazil as an alternative to the prevailing low yield and unsustainable cattle raising. The 2017 Agricultural Census showed Brazil had 12 million hectares of degraded pasture, with additional 47 million hectares of natural grassland (IBGE 2017). Two main types of integrated systems have been adopted by cattle farmers in Brazil: Integrated crop-livestock systems (ICLS), which integrates crops (mainly corn and soybeans) with cattle (dairy or beef); and integrated livestock-forestry systems (ILFS), which integrates forestry and cattle (dairy or beef). Crops, tree species, types of rotation, spacing and other agricultural practices vary among the adopters of both systems. In the ICLS predominant arrangement, pasture and crop were farmed in an area divided into five, four, or three tracts of land for annual rotation. No-till soybean is the most common crop cultivated in the main season. Corn, peanut, sweet potato, cassava, pumpkin and pineapple were alternatively adopted. Short-cycle crops, such as corn and other forage (mainly *Brachiaria ruziziensis*), intercropped or not, are additionally cultivated in the off-season in some cases. The adopted combination depends mostly on favorable local climate, soil, local market and farmer experience. As an example, soybean-corn-pasture rotation has been predominantly adopted in regions of clay soil and favorable climate conditions during off-season, while the soybean-pasture rotation has been adopted in regions of predominantly sandy soil and less favorable climatic conditions. It was also observed that the farming of grains (mostly soybeans), in some cases, has been conducted by means of sharecropping arrangements between a cattle farmer (who provides the land under rotation) and a crop farmer (who provides machinery and expertise).

In the case of ILFS, trees, mostly Eucalypts and Mahogany, are intercropped with pasture. Fences protect the young trees from the animals for a period of about two years, the necessary time for such plants to reach a safe height. In steep reliefs, the trees are planted following the design and spacing of the contours. In the case of flat reliefs, the spacing between the tree-lines varies from 15 to 25 m, depending on the number of lines and the target wood market (firewood and wood industry). One of the advantages of this system is the possibility of planting trees initially in small areas and afterwards opting for expanding them.

The diffusion of these systems has been supported by governmental policies in Brazil. One of them is the Low Carbon Agriculture Plan launched in 2012 with the aim of recovering 15 million hectares of degraded grassland until 2030. The ABC Plan provides resources for R&D, training of extensionists and credit for farmers in order to stimulate the adoption and accelerate the diffusion of Integrated Crop-Livestock-Forest Systems in 5 million hectares (MAPA 2012). These systems have been recommended for the recovery and/or renewal of degraded grasslands, maintenance and reconstitution of forest, adjustments to environmental legislation and as a strategy for income diversification (Gil et al. 2015; Resende et al. 2019). Additionally, it helps to comply with the commitment assumed by Brazil in the Conference of the Parties (COP-21, Paris 2015) to reduce greenhouse gas emissions.

The main policies supporting Integrated Crop-Livestock-Forest Systems in Brazil have been focused on cattle farmers, instead of crop farmers. On the one hand, the adoption by cattle farmers could improve the environmental and economic sustainability in areas of degraded pasture, which present low yields and low level of fixed capital investment. On the other hand, crop farmers would be more averse to adopting because they have already profited from monocultural crop systems. In short, policymakers assumed that the adoption by cattle farmers would provide more marginal benefits than the adoption by crop farmers.

Despite the environmental and economic benefits and the governmental policy support, the level of diffusion of those systems among cattle farmers is still low. This fact lead us to raise our main research question. *If the adoption of these systems offers so many advantages, why did some cattle farmers decide to adopt and others not?* The theory of the adoption of innovation and empirical studies on the adoption of integrated systems underpinned our hypotheses. Economic and non-economic determinants of farmers' decision to adopt or not adopt an innovation, such as socioeconomic profile of farmers, farms characteristics and the institutional environment, have been investigated. We were particularly interested in testing hypotheses on the role played by farm size, topography, type of soil, facilities for trade, provision of extension service, access to credit and knowledge and the innovative capacity displayed by the farmers. The analysis of these factors would be helpful for policy designing and farmers' decision-making process. Our empirical investigation relies on a sample of farmers in the State of São Paulo, Brazil.

A sample of 66 ICLS adopters, 24 ILFS adopters and 85 non-adopters provided the data for our study. In 2017, there were 8,3 million head of cattle in 106,514 farms of São Paulo, 5% share of the Brazilian total herd (IBGE, 2017). Conventional non-integrated systems are mostly adopted on these farms. The hypotheses on adoption determinants were tested by means of a multinomial logit model. "Theoretical framework and hypotheses" section presents the theoretical framework and hypotheses on factors that explain adoption. "Material and methods" section presents the sampling method and the statistical model used to test the hypotheses. The results and discussion are presented in "Results and discussion" section. Final remarks and policy implications are presented in "Conclusion" section.

Theoretical framework and hypotheses

The literature on adoption of innovation provides the analytical framework to answer our research question. Early studies pointed out the lack of information as the main reason for delaying adoption. Once the first adoption has occurred and as time passes, the number of adopters increases and, consequently, information on the use of the new technology is continuously accumulated. As the risk associated with adoption decreases during this process, the number of firms desiring to adopt is enlarged. However, as the proportion of adopters increases, the number of potential adopters falls. The diffusion of information is the main drive of this process, which is known as the epidemic model because of its resemblance with the spread of an infectious disease.

The main criticism of epidemic models is that they do not take into account what unique characteristics of a firm can affect the decision-making process. In David's (1975) seminal study on innovation diffusion, the individual firms' adoption decision was at the center of the analysis. He explained why, for the mechanical reaper, so many years elapsed between McCormick's patent in 1834 and the widespread adoption of the reaper in the 1950s. Given the indivisibility of the machine and the absence of cooperative arrangements, only large farms, with economy of scale, had initially adopt. Davies (1979) re-established David's model using the Probit Analysis, which, at that time, was being used in the study of the diffusion of durable goods. In his model, the decision to adopt is taken when some variables, such as farm size, reach a certain level. In other words, there is a "threshold" level to cross. Therefore, adoption would be explained by microeconomic characteristics.

The Probit models assume that different firms can provide different evaluations of the same innovation (Geroski 2000). They serve to explain why some adopt early and others adopt late—or do not adopt at all (Karshenas and Stoneman 1993). Hypotheses on the effect of observable factors on the adoption decision process can be tested in Probit Models, including the role of information, which is the driver of the epidemic models. Empirical results of these models are useful for the designing of policies trying to accelerate the diffusion of particular technologies. These models have been used to test hypotheses on the effect of characteristics of firms and sectors on the adoption of manufacturing technologies, such as Galliano and Roux (2008) and Galliano and Orozco (2011). Feder et al. (1985) provided a review on models of adoption behavior and empirical studies on adoption of agricultural innovations in developing countries. Their review comes up with an evaluation of factors affecting farmer's adoption decision. Most of these factors were tested using Probit Models.

There are many studies testing factors explaining farmers' adoption decision in many regions. Some examples are: Souza Filho et al. (1999) on factors influencing the adoption of sustainable agricultural technologies in the State of Espírito Santo, Brazil; Deressa et al. (2009) on adaptation methods to climate change in Ethiopia; Carrer et al. (2013) on the determinants of feedlot adoption by beef cattle farmers in the state of São Paulo, Brazil; Vinholis et al. (2017) on beef cattle traceability in São Paulo State, Brazil; Ward et al. (2016) on conservation agriculture in Malawi; Rathod et al. (2017) on artificial insemination in India dairy sector; Hu et al. (2019) on the effect of farm size on the diffusion of agricultural technology in

China; and Mellon-Bedi et al. (2020) on improved maze varieties and cropping systems strategies in Ghana. The Probit Model has been used to test hypotheses on the adoption of integrated systems: Bussoni et al. (2015) in Uruguay, Dhakal et al. (2015) in Nepal, Gil et al. (2016) in Brazil, Mfitumukiza et al. (2017) in Uganda, Asante et al. (2018) in Ghana, Mekuria and Mekonnen (2018) in Ethiopia, Ayantunde et al. (2020) in the Sahelian zone of Burkina Faso and Jara-Rojas et al. (2020) in Colombia.

The review of theoretical and empirical studies allowed us to identify three groups of factors that may affect the adoption of ILCS and ILFS by farmers in our sample: farm characteristics (such as farm size, availability of machinery, farmland slope, soil texture), farmers' characteristics (such as experience in agriculture and innovative capacity) and regional characteristics (such as access to rural extension service, access to rural credit and availability of dry and storage facilities).

The effect of farm size has been tested in many empirical studies. This variable has been used to test not only the effect of economies of scale but also farmers' willingness to take the risks associated with new technologies (Geroski 2000). Feder et al. (1985) argued that economies of scale are relevant for the adoption of capital-intensive technologies. For example, crop production in ICLS can require investment in machinery and availability of large plots of land, as shown by Takeshima et al. (2018) and Wang et al. (2020). In such case, it is possible to raise the hypotheses on the effect of availability of land and machinery idle capacity. The joint production of crop and cattle would reduce idle capacity, resulting in a more efficient use of the available resources. Economies of scope can also arise from the adoption of such systems. In line with this approach, Asante et al. (2018) found a positive effect of the availability of tillage equipment on ICLS adoption in Ghana. Moreover, Mekuria and Mekonne (2018) found a positive effect of farm size on ICLS adoption in Ethiopia. Therefore, we can raise our first empirical hypothesis:

Hypothesis 1a The greater the availability of agricultural land combined with fixed capital in machinery, the greater the probability of adopting ICLS.

Conversely, ILFS is characterized by less complex farming operations, which require less fixed capital. Adoption of IFLS is less sensitive to the effect of economies of scale and could be associated to small farms. However, most small farmers could not afford the test of an innovation (Hu et al. 2019). They would not willing to take risks, as found by Bussoni et al. (2015) in the evaluation of the adoption of ILFS in Uruguay. Therefore, the following hypothesis can be raised:

Hypothesis 1b No significant effect of the availability of large land tracts and fixed capital in the probability of adoption of ILFS is expected.

The topography of the farm can be critical to the decision of adopting certain agricultural systems. Grain production is generally done on terrains of up to 6% of slope, even though sometimes a steeper one is used (Thomas et al. 2007). On this flat or low sloping land, the traffic of tractors and other machinery is much easily done, reducing production costs. It can be assumed that level land and low sloping land is important for implementing ICLS. The following hypothesis can be raised:

Hypothesis 2a The probability of adopting ICLS would be higher on farms which predominantly present level or low sloping land.

Conversely, mechanical operations are difficult in steeply sloping land. In this case, cattle grazing with trees along contour lines, which reduces soil erosion (Ribeiro et al. 2007), could be an alternative option. Therefore:

Hypothesis 2b The probability of adopting ILFS would be higher on farms that present steeply sloping land.

The soil physical texture can be heterogeneously distributed both among farms and even on a single farm. In the regions where sandy soil is predominant, the raising of cattle is predominant too, while crop monoculture is less favorable. The sandy soils do not allow water retention, making it more difficult to cultivate short-cycle crops in the off-season such as corn. The adoption of ICLS in sandy soils is beneficial because it reduces the risks associated with crop farming. In such case, the rotation between crops and forages with deep root system, which is usual in ICLS, contributes to improve the structure of this soil type, enabling the cultivation of crops. Additionally, crop cultivation in ICLS turns to be a good option for pasture reform since it may lead to weed control, pest decrease, reduction of fertilizer applications and income diversification. In fact, Gil et al. (2015) observed a positive link between ICLS adoption and sandy soils in the state of Mato Grosso, Brazil. Such significant improvement is not clearly observed on farms in which clay soil is predominant. In this case, high yield monocultural systems can prevail. Similarly, Mekuria and Mekonne (2018) found that single crops are cultivated on fertile soils, while ICLS are found on poor soils in Ethiopia. Therefore:

Hypothesis 3a We expect that the predominance of sandy soil positively affects the probability of adopting ICLS.

Similarly, the adoption of ILFS as a substitute for traditional cattle grazing systems in sandy soils is clearly beneficial. The trees bring more thermal comfort for cattle, a better carbon cycle balance, reduction of soil erosion and income diversification. Therefore:

Hypothesis 3b We expect that the predominance of sandy soil positively affects the probability of adopting ILFS.

Farmers' capabilities can also play an important role in the adoption of ICLS and ILFS. Schultz (1975) provided a seminal study on the effect of human factors on the adoption of agricultural technologies. The author argued that the farmers' ability to perceive, interpret, and respond to new events is an advantage in the context of technological change. This ability increases as experience increases (Feder et al. 1985). It is expected that experience in crop farming has a positive effect on the probability of adopting ICLS. Crop farming in these systems increases risks, as well as organizational complexity. The production of crops, such as corn and soybeans, requires managerial expertise, which is helpful capability when farmers need to make quick decisions in short cycle crop farming. This type of crop farming, with narrow "windows" for farming operations, requires good planning and production organization, which implies specific knowledge, sometimes tacit knowledge, obtained mainly by years of experience. Thus, it is reasonable to expect that farmers with accumulated experience in such farming activities feel more confident to adopt ICLS. Gil et al. (2015) identified high technological capacity among adopters of ICLS in Mato Grosso, Brazil. In the case of ILFS, wood farming is less complex and less susceptible to climate-induced disruption. However, some knowledge of crop farming is desirable for the cultivation of trees, especially in its initial stages. Dhakal et al. (2015) found that household's experience in agroforestry significantly affects adoption of agroforestry-based farming systems in Nepal. Therefore:

Hypothesis 4a The higher the farmer's experience with crop farming, the higher the probability of adopting ICLS.

Hypothesis 4b The higher the farmer's experience with crop farming, the higher the probability of adopting ILFS.

Innovativeness is another human factor and refers to the capacity of farmers to innovate. This innovative capacity is the ability of introducing changes or new ideas to the way something is done (Bergevoet 2005). The literature shows that the propensity of individuals for assuming risks and innovating is one of the main determinants of the diffusion of new technologies. In a study with a sample of German farmers, Mante and Gerowitt (2007) verified that farmers' openness towards new or unusual production methods has been proved as significant for the adoption of low-input practices on arable land. Folmer et al. (2010) claimed that an innovative person has a higher likelihood to perceive and pursue business opportunities and found this attribute to be one of the main determinants of entrepreneurship among farmers in Bengal. Therefore:

Hypothesis 5a Cattle farmers with high innovative capacity (innovativeness) tend to show a higher probability of adopting ICLS.

Hypothesis 5b Cattle farmers with high innovative capacity (innovativeness) tend to show a higher probability of adopting ILFS.

The local availability of support services, such as rural extension and storage, can affect the decision of adopting agricultural systems. Gil et al. (2016) suggested that the supply chain infrastructure plays a relevant role in the decision of adopting integrated systems in Brazil. They pointed out that these systems occur more frequently in the same regions of grain and cattle processing facilities and research organization. The local availability of grain storage facilities might be critical to the ICLS economic viability (Bowman et al. 2013; Garrett et al. 2013; Vanwey et al. 2013). In the case of an absence of grain support services, the adoption of ILFS becomes the viable alternative. Therefore:

Hypothesis 6a We expect that the availability of grain support services positively affect the probability of adopting ICLS.

Hypothesis 6b We expect that the availability of grain support services negatively affect the probability of adopting ILFS.

It has been shown that the rural extension services play an important role in the adoption of both crop–livestock farming systems (Gil et al. 2016; Mekuria and Mekonnen 2018; Ayantunde et al. 2020) and agroforestry-based farming systems (Dhakal et al. 2015; Mfitumukiza et al. 2017). Latawiec et al. (2017) found that a shortfall in access to technical extension services is a significant problem in the adoption of improved pasture management techniques (e.g., ICLS and ILFS) by farmers of the state of Mato Grosso, Brazil. Mfitumukiza et al. (2017) pointed out that limited extension services in Uganda constrains adoption and, consequently, the benefits provided by agroforestry, such as more food, more fodder, erosion control and soil fertility enrichment. Having experts nearby increases the potential of information diffusion about the systems and increases farmers' confidence to adopt them (Ward et al. 2016; Carrer et al. 2017). In addition, rural extension services can help farmers to take more efficient choices (Feder et al. 1985). Blackstock et al. (2010) argue that, given the complexity of modern agriculture, extension services should not only transfer knowledge, but also facilitate interaction and learning in order to obtain customized solutions. These tasks of the rural extension services are useful when farmers have to decide whether or not to adopt ICLS and IFLS. These systems can accommodate various arrangements of crop, livestock and forestry. The choice of the best combination for a given farm can be made with the help of the extension service staff, who are knowledgeable about the socio-economic and biophysical conditions of the region. Therefore:

Hypothesis 7a We expect that availability of local extension service has a positive effect on the probability of adopting ICLS.

Hypothesis 7b We expect that availability of local extension service has a positive effect on the probability of adopting ILFS.

Access to financial resources—"own money" or credit—is another frequently investigated determinant of adoption. This factor has positively affected the adoption of both ICLS (Asante et al. 2018; Carauta et al. 2018; Carrer et al. 2020) and ILFS (Mfitumukiza et al. 2017; Jara-Rojas et al. 2020). Feder et al. (1985) argues that access to credit is particularly important for the adoption of technologies that requires large initial investment, mainly investment in indivisible assets. The Brazilian ABC Program is an important source of credit, in which subsidized interest rates and special payment terms are offered. The main objective is to speed up the diffusion of sustainable technologies and practices (e.g. ICLS and ILFS) by reducing farmer's budget constraints. Carauta et al. (2018) performed a bioeconomic microsimulation to evaluate the effect of such credit program on the adoption of integrated systems in the state of Mato Grosso, Brazil. The authors found evidences that access to ABC credit can speed up the diffusion. Carrer et al. (2020) estimated a simultaneous equations system to analyze the impact of the access to credit on the adoption of ICLS by farmers in the state of São Paulo, Brazil. The authors found that the probability of adoption among farmers who had access to rural credit was 37.5 percentage points higher than the probability for adopting by those who did not benefit from it. Based on these findings, we raise the hypotheses:

Hypothesis 8a Access to ABC Credit Program increases the probability of adoption of ICLS.

Hypothesis 8b Access to ABC Credit Program increases the probability of adoption of ILFS.

Material and methods

The data used in this study was obtained from a survey conducted among farmers between June 2016 and April 2017. A total of 175 in-person interviews in 30 municipalities of the State of São Paulo provided information about the characteristics of the farms, production systems and farmers. A structured questionnaire was used for the interviews.

The sampling method could not be based on a random selection due to two reasons: (1) satisfactory number of observations from a random selection would be difficult to obtain because the number of adopters was expected to be small; and (2) a list of adopters, from which a sample could be drawn, was not available. Therefore, we followed two steps to obtain the sample. The first one being the identification of adopters. For this, we phoned the experts at the governmental extension service offices in order to obtain a list of actual adopters in their respective areas of influence. We learned that most adopters were found in the central and western regions of the state. These two regions comprised 80% of the total cattle herd of the state (IBGE 2017). In order to reduce logistic costs of in-person interviews, it was decided that the sample should be limited to these two regions.

As a second step, we asked experts to provide lists of non-adopters located in the vicinity of each selected adopter's farm. They had to be farmers who applied conventional non-integrated systems to raise cattle on native or cultivated grass which may or may not be associated with supplementary feed. Crop farming and/or tree cultivation activities could be held on these farms, but not carried out on the cattle raising land and should not involve intercropping either in combination or in rotation, as is the case on the adopters' farms. Non-adopters were randomly selected from such lists.

This sampling method decreased not only the survey logistic costs, but also the scope for discriminating adopters from non-adopters in terms of local environmental characteristics. Three groups of cattle farmers were obtained from this sample: 66 ICLS adopters; 24 ILFS adopters and 85 non-adopters (base scenario).

A multinomial logistic regression model was used to test hypotheses on factors which can explain farmers' decisions regarding the adoption of ICLS and ILFS (Eq. 1). This kind of model has been widely used to analyze farmers' adoption decisions (Alam 2015; Burton et al. 1999; Deressa et al. 2009; Rathod et al. 2017). The dependent variable is based on three possible choices, where the choice parameter j is 0 if the farmer did not adopt both ICLS and ILFS (non-adoption), 1 if the farmer adopted ICLS and 2 if the farmer adopted ILFS.

$$\log\left(\frac{\Pr Y = j|\boldsymbol{X}}{\Pr Y = 0|\boldsymbol{X}}\right) = X\boldsymbol{\beta} + \varepsilon \tag{1}$$

The probability of adopting integrated systems (j = 1 for ICLS and j = 2 for ILFS) relative to non-adoption (j = 0, base scenario) is a function of explanatory variables (X) and random errors (ε). β is a vector of coefficients, which shows the impact of changes in the explanatory variables (X) on the probability of integrated systems adoption relative to the base scenario. The parameters of Eq. 1 are estimated by maximum-likelihood.

Impacts of the explanatory variables are measured by their marginal effects, according to Eq. 2. The effect of small changes (usually interpreted as unitary changes) in a specific X_i variable on the likelihood of adoption of ICLS relative to non-adoption of ICLS, and on the likelihood of adoption of ILFS relative to non-adoption of ILFS, calculated at mean values of the explanatory variables, is given by:

$$\frac{\Delta Pr_j}{\Delta X_i} = \frac{\partial Pr_j}{\partial X_i} = \beta_i \frac{1}{1 + e^{-x_i\beta}} \times \frac{e^{-x_i\beta}}{1 + e^{x_i\beta}} \tag{2}$$

The model specification must avoid high correlations between explanatory variables because they cause multicollinearity. The specification must also avoid endogeneity, which creates bias in the coefficient estimates and reduces the ability to provide inferences (Greene 2000). An augmented Durbin-Wu-Hausman test was used to test endogeneity. The assumption of Independence of Irrelevant Alternatives (IIA) must be satisfied in the multinomial logit model (Hausman and McFadden 1984). The Hausman and McFadden (HM) test was used in this case.

Results and discussion

Table 1 presents the mean and standard deviation of the share of farming activities in each group of farmers. Three observations can be drawn from it. Firstly, cattle raising is relevant in the three groups, as shown by the high share of the pasture area. Secondly, the percentage share of corn/soybean was the highest in the group of ICLS adopters, while tree cultivation was the highest in the group of ILFS adopters. These results indicate that the sample is well specified and these systems promote diversification. Thirdly, corn/soybean, forestry and other farming activities are found in the group of non-adopters. In fact, 18 non-adopters declared 30% or more of their farmland was

Table 1 Farmland use, share of farming activities, mean and standard deviation

	Non-adopters (n = 85) (%)	ICLS adopters (n = 85) (%)	ILFS adopters (n = 85) (%)
Pasture	82.9	64.2	74.4
SD	20.9	26.5	19.0
Soybean/Corn	8.4	27.5	3.5
SD	12.8	25.4	5.3
Forestry	2.7	0.5	13.0
SD	4.7	0.8	10.2
Other*	5.9	7.8	9.0
SD	8.8	11.7	13.8

*Sugarcane, peanut, cassava, fruit, vegetables and hay

occupied with activities other than pasture for cattle raising, which indicates that the sample of non-adopters does not comprise only specialized cattle farmers. Nevertheless, 36 non-adopters stated that 100% of their farmland was occupied with pasture for cattle raising.

These figures corroborate the assumption that many conventional cattle raising activities are held by specialized farmers. They also allow for a better understanding of the adoption decision. When specialized cattle farmers decide to adopt ICLS they take two simultaneous decisions. The decision of adopting ICLS and the decision of introducing grains. When specialized cattle farmers decide to adopt ILFS they also take two simultaneous decisions. The decision of adopting ILFS and the decision of introducing forestry. However, in the case of non-specialized farmers, the single and crucial decision is the adoption of the new production system. Our model deals with this issue by testing farmers' experience in crop farming as an adoption determinant.

The multinomial logistic regression approach was used to test the hypotheses presented in "Theoretical framework and hypotheses" section. The dependent variable (ADOPTION) and nine explanatory variables are described in Table 2. Their mean and standard deviation are in Table 3.

High correlations between TRACTOR and AREA (0.64) and between LTRACTOR and LAREA (0.62) were found. The effect of these variables was then estimated separately in two multinomial models to avoid multicollinearity (Table 4). The estimates of LAREA are in Model 1, while the estimates of LTRACTOR are in Models 2. The estimates show the effect of changes in explanatory variables on the probability of adopting either ICLS or ILFS relative to non-adoption.

The potential endogeneity between ADOPTION and STORAGE was tested. For this, a two-stage model was additionally estimated, taking "the production value of grains of the municipalities where farms are located" as the instrumental variable. Model 1 and Model 2 were then compared with the two-stage model. The Durbin-Wu-Hausman test rejected the null hypothesis that STORAGE is endogenous at 5% level.

Hausman and McFadden (HM) test indicated that the assumption of Independence of Irrelevant Alternatives (IIA) was not violated. The Likelihood Ratio Test rejected the joint hypothesis that the coefficients of explanatory variables are all zero. Model 1 predicted correctly 85% the observations, while Model 2 predicted 86%.

The effect of agricultural land and fixed capital availability on adoption was estimated by the variables LAREA and LTRACTOR, which allowed for testing Hypotheses 1a and 1b. The high correlation between LAREA and LTRACTOR corroborates the assumption that on large farms, mainly those devoted to crops, investment in fixed capital is high. The signs of the parameters estimated for both LAREA and LTRATOR were positive and significant at 1% and 5% levels, respectively, confirming Hypothesis 1a. The greater the availability of agricultural land in combination with fixed capital, the greater the probability of adopting ICLS. These results corroborate the findings of Asante et al. (2018) and Mekuria and Mekonnen (2018). Economies of scale and scope can be obtained, resulting in more efficient use of the resources. However, in the case of ILFS, the marginal effects of LAREA and LTRACTOR were negative and

Table 2 Description of variables

Variables	Description
	Dependent variable
Adoption	0 for non-adoption (base scenario); 1 for adoption of ICLS; and 2 for adoption of ILFS
	Explanatory variables
Ltractor Hypotheses 1a and 1b	Log of number of tractors (TRACTOR) used in the farm
Larea Hypotheses 1a and 1b	Log of farm size (own and rented agricultural land of the farm, AREA, in hectares)
Slope Hypotheses 2a and 2b	0 for predominantly level land or sloping land (approximately 0% to 8%); and 1 for predominantly steeply sloping land (greater than 8%)
Soil Hypotheses 3a and 3b	0 for sandy soil texture; 1 for medium sand; and 2 for clay
Experience Hypotheses 4a and 4b	0 if farmer does not have experience in crop farming; 1 if farmer has experience in crop farming
Innovative Hypotheses 5a and 5b	Indicator of farmer's innovative capacity assuming values from 0 to 1; 0 for the lowest capacity and 1 for the highest
Storage Hypotheses 6a and 6b	1 if grain drying and storage services are available in the region; and 0 otherwise
Extension Hypotheses 7a and 7b	1 if local extension service personnel have experience in integrated systems; 0 otherwise
Credit Hypotheses 8a and 8b	1 for access to credit provided by the ABC Program in 2013/14, 2014/15 or 2015/16 seasons; 0 otherwise

Table 3 Explanatory variables, mean and standard deviation

	Non-adopters (n = 85)		ICLS adopters (n = 66)		ILFS adopters (n = 24)	
	Mean	SD	Mean	SD	Mean	SD
Tractor	2.15	2.15	3.29	2.62	1.46	0.78
Area	274.5	289.7	477.2	404.7	166.9	144.9
Slope	0.412	0.821	0.106	0.310	0.542	0.509
Soil	1.635	0.704	1.636	0.757	1.250	0.442
Experience	0.718	0.452	0.864	0.346	0.916	0.282
Innovative	0.739	0.163	0.790	0.141	0.706	0.139
Storage	0.675	0.471	0.848	0.361	0.333	0.482
Extension	0.435	0.499	0.697	0.463	0.375	0.494
Credit	0.047	0.213	0.242	0.432	0.292	0.464

statistically significant at 5% and 10% levels. Such result does not corroborate Hypothesis 1b. The negative sign of the parameters points out the fact that the probability of adopting of ILFS on small farms is greater than on large farms. A possible explanation could be that farmers with less land available would have more incentives to adopt ILFS because of its lower technological and managerial complexity. As seen in Feder et al. (1985), economies of scale are not relevant for low capital-intensive agricultural technologies. Operations such as tree planting are sporadic and can be outsourced, so the farmer does not undertake a high fixed cost. Moreover, the tree planting and spacing in ILFS is flexible. It can be

Table 4 Estimates and marginal effects of the multinomial logit models

Variables	Model 1				Model 2			
	ICLS adoption		ILFS adoption		ICLS adoption		ILFS adoption	
	β	Marginal	β	Marginal	β	Marginal	β	Marginal
Intercept	− 8.329***	–	1.675	–	− 3.369***	–	0.194	–
Ltractor	–	–	–	–	0.614**	0.163**	− 0.787^{+}	− 0.077*
Larea	0.778***	0.180***	− 0.236	− 0.043**	–	–	–	–
Slope	− 1.060**	− 0.228***	0.087	0.039	− 1.078**	− 0.247**	0.054	0.035
Soil	− 0.434^{+}	− 0.068	− 0.924*	− 0.063^{+}	− 0.440*	− 0.075	− 0.867*	− 0.053^{+}
Experience	1.127**	0.208*	1.386*	0.080	0.655	0.099	1.726**	0.111*
Innovative	2.856**	0.691**	− 1.870	− 0.241*	1.979*	0.496*	− 1.553	− 0.175
Storage	1.360***	0.337***	− 1.164**	− 0.138***	1.220**	0.309***	− 1.059*	− 0.115***
Extension	0.729*	0.164**	− 0.050	− 0.026	0.752**	0.175**	− 0.145	− 0.033
Credit	1.856***	0.354***	1.912***	0.102*	1.870***	0.365***	2.122***	0.106*
Log–Likelihood function			− 127.278		–		130.261	
Chi squared (16 d.f.)			96.287				86.322	
p value			0.000				0.000	
R2 McFadden			0.2776				0.2488	

*significant at 10%; **significant at 5%; ***significant at 1%; $^{+}$significant at 15%

done on small plots and staggered over time. At the same time, the farming operations are less dependable on narrow weather windows.

The variable SLOPE allowed for testing the effect of topography in the decision of adopting (Hypotheses 2a and 2b). The estimated marginal effects were negative for ICLS adoption at 1% significance level. The probability of adoption is lower on predominantly steeply sloping land than on predominantly level land or sloping land. Mechanized crop production can become technically and/or economically unviable on steeply sloping land. The opposite is the case on predominantly level land, a determinant condition for the rotation systems of ICLS. Such results are in accordance with Hypothesis 2a. The coefficients and marginal effects of the variable SLOPE on the adoption of ILFS, in turn, were not statistically significant; then, Hypothesis 2b was not confirmed.

The parameters estimated for SOIL showed negative effect on the probability of adoption of both ICLS and ILFS at 10% significance level in model 2, corroborating both Hypotheses 3a and 3b. This result confirms that on farms in which clay soil is predominant, mostly fertile soils, the additional benefits of both ICLS and ILFS were not sufficiently robust to make adoption an attractive option. The opposite occurs on farms in which the soil is predominantly sandy. In this case, the adoption of ICLS and ILFS greatly improves soil structure, yields and economic returns. The marginal benefits perceived by the farmers are larger making adoption a sound choice. This result corroborates the findings of Gil et al. (2016) and Mekuria and Mekonnen (2018).

EXPERIENCE presents a positive effect on the probability of adopting ICLS at 5% significance level in Model 1. The estimated marginal effect shows that previous experience in crop cultivation increases by 20.8% the probability of ICLS adoption, which confirms Hypothesis 4a. Farmers who had experience in crop farming can better deal with the technical and organizational complexities of ICLS and are more prone to accept it. We can assume that the level of risk they perceive was lower than that of inexperienced farmers. They are more confident that ICLS might ultimately be beneficial. Such finding is in accordance with others studies on agricultural innovation adoption (Dhakal et al. 2015; Gil et al. 2015; Ward et al. 2016). Crop farming experience was also relevant to explain the adoption of ILFS as can be shown by the positive and statistically significant (at 5% level in Model 2) estimated parameters. Such result corroborates Hypothesis 4b. Even though ILFS management is less complex than ICLS, crop farming experience would reduce perceived operational risks, mainly during the initial years of the trees.

The variable INNOVATIVE is an indicator of a farmer's innovative capacity, which was calculated as a summation of values attributed by farmers for three statements: (a) "I like trying out new technologies in my rural property"; (b) "I take on challenges more often than other farmers"; (c) "I find it easy to come up with solutions in order to deal with unexpected challenges in farming". These statements are an adaptation of the work of Bergevoet (2005). Farmers were asked to specify their level of agreement or disagreement with each statement, according to a Likert-type scale: strongly disagree (value 1), disagree (value 2), neither agree nor disagree (value 3), agree (value 4) and strongly agree (value 5). The indicator value for each farmer is the sum of the corresponding values for each given answer, normalized to be between 0 and 1.

The effect of INNOVATIVE was positive and significant for explaining ICLS adoption, which corroborates Hypothesis 5a. Adoption of innovations is generally associated with the capacity of assuming challenges facing uncertainties. This is the case of cattle farmers who move from traditional methods of cattle raising to ICLS. For them, adoption of ICLS increases the complexity of management. The positive parameter of INNOVATIVE means that some farmers are prone to face them even though they lack previous experience. Nevertheless, the parameter of INNOVATIVE was not statistically significant to explain ILFS adoption. Thus, Hypothesis 5b was rejected.

The parameters estimated for STORAGE presented high levels of significance. They revealed positive effect on ICLS adoption of and negative effect on ILFS adoption, corroborating Hypotheses 6a and 6b. The local availability of grain drying and storage services increases the probability of ICLS adoption. The commercialization of grains is more feasible in these places, generating incentives for ICLS adoption. This result corroborates Gil et al. (2016). The lack of such facilities is not a barrier to ILFS adoption, which becomes a viable option in this context.

The parameters estimated for the variable EXTENSION show positive effect on the probability of ICLS adoption at 10% significance level, corroborating Hypothesis 7a and the findings of Gil et al. (2016) and Mekuria and Mekonnen (2018) and Ayantunde et al. (2020). An extension service capable of transferring knowledge in integrated systems is important for promoting ICLS, because these systems are technologically complex. The estimated marginal effect of EXTENSION indicates that the presence of local extension service with such expertise increases the likelihood of ICLS adoption in 17%. However, the variable EXTENSION does not explain ILFS adoption, as is shown by the statistically non-significant parameter. Thus, Hypothesis 7b is not confirmed. In fact, our data showed that 63% of ILFS adopters had neighbors as their main source of information.

The results for the variable CREDIT show the important role played by ABC Credit Program in the adoption of both ICLS and ILFS. The parameters for this variable were positive and statistically significant at 1% level, corroborating Hypotheses 8a and 8b. This finding is in line with Carauta et al. (2018)'s evaluation on the effectiveness of the ABC Credit Program in the adoption of integrated systems and with other empirical studies on the role of credit in the diffusion of integrated systems (Mfitumukiza et al. 2017; Asante et al. 2018; Carrer et al. 2020; Jara-Rojas et al. 2020).

Conclusion

Data obtained from a sample of 175 cattle farmers in the state of São Paulo, Brazil, allowed us to provide evidence of why the level of ICLS and ILFS diffusion is still low, even though there has been environmental and economic benefits and government policy incentives. Multinomial logit model estimations were used to test hypotheses on factors that determine adoption. Economies of scale and scope, farm topography and soil, farmer's knowledge and capacity for innovation, grain storage services, extension service, and credit can play an important role in the adoption decision. This approach allowed us to highlight the role played by the heterogeneity of resources and capabilities in the adoption of these systems.

The decision to adopt ICLS was found to be strongly dependent on farmer's availability of physical and human resources, mainly scalable agricultural land e fixed capital for the production of crops, and knowledge on crop farming. It was found that cattle farmers who had also previously adopted crop systems and were endowed with large amount of land and fixed assets for crop production (machinery and equipment) had higher probability of adopting ICLS than specialized cattle farmers. Cattle farmers with such experience and physical capital endowment are able to obtain economies of scope adopting ICLS. They perceive less risk and face lower initial investment when deciding on ICLS adoption, because more information on crop farming, land and fixed assets are available from the start. However, cattle farmers with such experience and physical capital endowment are less commonly found. Specialized cattle farmers who lack these capabilities and physical resources are the norm. Therefore, a major barrier to diffusion should be overcome.

Credit provided by the ABC Program was an important determinant for deciding on ICLS and ILFS. It should be taken into account that cattle farmers, instead of crop farmers, are the main targets of this program. Adoption of ICLS by specialized cattle farmers would require physical resources that most of them do not possess. Therefore, access to credit helps to overcome this barrier. The majority of specialized cattle farmers lack knowledge on crop farming as well. Having easy access to credit would not be a very helpful policy for overcoming such obstacle. Easy access to qualified extension service would be the preferable policy. In our models, we found that subsidized credit supply and governmental extension service proved to be helpful in promoting diffusion. However, many cattle farmers still did not choose to adopt. Lack of innovative capacity, which indicates unwillingness to take risks, inhibits adoption.

Large availability of agricultural land played an important role because economies of scale can be obtained with adoption. The availability of land with certain characteristics is also important. Soil characteristics such as texture and slope do affect the decision to adopt those systems. Availability of suitable land for the mechanized farming, mostly level soil, increases the probability of ICLS adoption. However, in the case of clay soils, the probability of adopting ICLS is smaller because crop monoculture presents economic advantages. We found evidence that ICLS and ILFS are attractive options for farms with predominantly sandy soils, as the perceived marginal benefits are higher than in the case of clay soils. The adoption of ILFS on sandy soil land was a proper alternative for soil conservation, erosion reduction and income diversification, mainly on sloping areas.

The estimated econometric model also revealed that adoption of ICLS is positively associated with the existence of local infrastructure for grain trading. Unavailability of local grain buyers, storage and transportation facilities is strong barrier to adoption as well. In these regions, adoption of ILFS can be a better option.

Such results shed light on some potential strategies that could help accelerate the diffusion of those systems. For instance, by establishing partnerships between cattle farmers and crop farmers, the resistance for adopting the systems could be weakened. It was observed that, in few cases, ICLS adoption was made possible using a strategy of sharecropping between a cattle farmer and a crop farmer by means of crop-pasture rotation. The crop farmer makes use of his previous experience and his machinery, while the cattle farmer provides his partner with the land and gets the technical benefits associated with crop-pasture rotation. ICLS diffusion could be increased with the establishment of favorable organizational arrangements, which could be promoted by farmers' organizations and extension services.

It is clear now that many adopters of such systems recognized their advantages for farming in sandy soils. Therefore, policies aimed at the diffusion of such systems would have a greater impact in regions with restrictions on monoculture. However, lack of infrastructure for the trading of crops and qualified extension services can inhibit this opportunity, even though support policies are in place. Therefore, the development of infrastructure and services for grain trading should be considered.

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