Volumen 40, Nº 4. Páginas 101-111
IDESIA (Chile) Diciembre, 2022

Economic feasibility of optical sensors for variable rate nitrogen fertilization in corn

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ABSTRACT

This study aimed to determine the economic feasibility of the chlorophyll meters SPAD-502 and ClorofiLOG CFL1030 for nitrogen fertilization management in corn using deterministic and probabilistic models for small farms. To do so, representative cash flows for corn production were analyzed using three variable rate fertilization systems based on different nitrogen sufficiency indices. Thus, for each system, eight scenarios of different-sized cultivation areas and two sampling methodologies of the chlorophyll meter index (CMI) were simulated as follows: scenarios 1, 2, 3 and 4 used the CMI average obtained from 30 individual samplings in 1, 3, 5 and 7 ha areas; scenarios 5, 6, 7 and 8 used the CMI average in zones (30 individual samplings per zone), with 3, 5, 7 and 9 zones in 1, 3, 5 and 7 ha areas, respectively. The economic feasibility of the sensors was determined using different economic indicators, such as the internal rate of return (IRR) and the net present value (NPV), considering a minimum rate of attractiveness (MRA) of 6% per year with an 8-year project horizon. The risk was assessed by the Monte Carlo simulation. The results showed that regardless of the sampling approach, the SPAD-502 is economically feasible when acquired in Brazil or via importation through the USA in cultivation areas from 7 or 5 ha in size, respectively. Conversely, the ClorofiLOG CFL1030 could result in greater economic feasibility in areas from 3 ha.

Keywords: Chlorophyll meter; Site-specific N management; Risk and economic feasibility; *Zea mays* L.

RESUMEN

El objetivo de este estudio fue precisar la viabilidad económica de los medidores de clorofila SPAD-502 y ClorofiLOG CFL1030 para la gestión de la fertilización nitrogenada en maíz, utilizando modelos deterministas y probabilísticos para pequeñas explotaciones. Con este fin, se analizaron flujos de caja representativos de la producción de maíz mediante tres sistemas de fertilización de tasa variable basados en diferentes índices de suficiencia de nitrógeno. Para cada sistema se simularon ocho escenarios de áreas de cultivo de distinto tamaño y dos metodologías de muestreo del índice clorofílico (CMI). En los escenarios 1, 2, 3 y 4 se utilizó la media del CMI obtenida de 30 muestreos individuales en áreas de 1, 3, 5 y 7 ha. En los escenarios 5, 6, 7 y 8 se usó la media del CMI por zonas (30 muestreos individuales por zona), con 3, 5, 7 y 9 zonas en áreas de 1, 3, 5 y 7 ha, respectivamente. La viabilidad económica de los sensores se determinó a través de diferentes indicadores económicos, como la tasa interna de rendimiento (TIR) y el valor actual neto (VAN), considerando una tasa mínima de atracción (TMA) del 6% anual con un horizonte de proyecto de 8 años. El riesgo se evaluó mediante la simulación de Montecarlo. Los resultados evidenciaron que, independientemente del enfoque de muestreo, el SPAD-502 es económicamente viable cuando se adquiere en Brasil o mediante la importación a través de EE UU en áreas de cultivo a partir de 7 o 5 ha, respectivamente. Por el contrario, el ClorofiLOG CFL1030 podría resultar más factible económicamente en áreas a partir de 3 ha.

Palabras clave: *Medidor de clorofila, manejo de N específico del sitio, riesgo y viabilidad económica,* Zea mays *L.*

Introduction

Precision agriculture (PA) involves the development and adoption of techniques to improve agricultural systems management. In essence, PA consists of matching the application of inputs and agronomic practices to the soil and the crop demands, since these vary in space and time throughout

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Fecha de Recepción: 13 de febrero, 2022.
Fecha de Aceptación: 2 de abril, 2022.

the field (Whelan; McBratney, 2000). This may result in some effects, such as greater market competitiveness, due to optimization of input use, reduction of production costs and possibly higher productivities, allowing the producer to offer the product in the market for a more competitive price (Baio *et al*., 2017).

The advantages of adopting PA provide direct social (increase of jobs) and economic benefits (increase of income) to the Brazilian economy (Cabral; Guilhoto, 2013). However, PA's beneficial effects are more applicable to large cultivation areas, usually managed by large companies linked to agricultural production (Borghi *et al*., 2016). In contrast, for smaller areas, there is a lack of studies regarding the adoption of investment in PA technologies.

Despite its great potential, corn grain yield in Brazil (5,454 kg ha^{-1} in the 2021/2022 season) is much lower than that in the USA (11,900 kg ha^{-1}) (CONAB, 2022; USDA, 2022). This low grain yield is possibly a reflection of the occurrence of biotic and abiotic stresses and, mainly, due to poor management of base and side-dressed nitrogen fertilization and the lack of adoption of technologies by small and medium farms.

Nitrogen (N) is the nutrient most required by plants, and it directly influences the corn grain yield. It acts directly on the plant's biochemical processes as a constituent of proteins, enzymes, coenzymes, nucleic acids, and chlorophyll (Santos *et al*., 2010). Despite its importance in plant growth, the excessive use of N makes production costlier and negatively affects the environment. Thus, an imbalance between N supply and plant nutritional demand results in economic losses and low N use efficiency (NUE) (Ali *et al*., 2017).

The optimization of N use has recently become one of the main targets of study regarding PA in Brazil. In this sense, the management of N fertilization at a variable rate using optical sensors has provided cost reduction in the production process, as well as greater sustainability by increasing NUE (Shaver *et al*., 2017). This is due to the possibility of synchronizing the N applications with the period of greatest demand of the plant.

Several studies have reported that the major advantages of optical sensors and technologies for site-specific N management are the fertilizer economy and the decrease in environmental impact, rather than the increase in crop productivity (Biermacher *et al*., 2009; Martins *et al*., 2020). On the other hand, there is a lack of studies about the economic feasibility and the uncertainty associated with the use of such sensors since their acquisition cost is relatively high when compared to conventional agricultural costs.

Previous studies have evaluated the environmental and economic benefits of site-specific fertilizer application (Pampolino *et al*., 2007), the profitability of an optical sensor for N application at a variable rate (Biermacher *et al*., 2009), and the economic feasibility of autonomous field machinery in grain crop production (Shockley *et al*., 2019). However, none of these studies considered the uncertainty regarding investment in PA-related technologies for small farms. Additionally, these technologies have not been considered together with the temporal aspects of the final product price variability, inputs, and crop productivity. Therefore, this study aimed to determine the economic feasibility of the chlorophyll meters SPAD-502 and ClorofiLOG CFL1030 for nitrogen fertilization management in corn using deterministic and probabilistic models for small farms.

Materials and Methods

Data source

The data used in this study were obtained from a field experiment with the corn hybrid DKB310 PRO2, conducted in Januária, Northern Minas Gerais state, Brazil (15º 28' 55" S; 44º 22' 41" W; 474 m above sea level) from February to June 2018 as described in Martins *et al.* (2020). In the field, the technical feasibility of the variable-rate nitrogen fertilization based on the SPAD-502 chlorophyll meter readings was evaluated in relation to the conventional fertilization (pre-fixed doses).

The variable rate application was performed based on different thresholds of the nitrogen sufficiency index (NSI), which considers the ratio of the CMI between the variable-rate and reference treatments (Francis; Piekielek, 1999). The total N dose to be applied was 112 kg ha^{-1} in the form of urea (44% of N), which corresponded to the economic optimum nitrogen rate (EONR). A description of the methodology used to define the EONR is presented by (Martins *et al*., 2020). Thus, for treatment 1 (reference plot), 50% of the dose was manually applied in each experimental plot at the four fully expanded leaves stage (V4) and

50% at the V8 stage. In contrast, the variable-rate treatments were organized as follows: Treatment 2 had a fixed NSI of 95%, monitored in the V8, V10, and V14 stages, respectively; Treatments 3 and 4 had a variable NSI of 98, 95 and 93%, monitored in the same stages of T2.

Initially, the variable rate treatments received 44.8 kg ha^{-1} of N (T2 and T3) and 33.6 kg ha^{-1} of N (T4) in the V4 stage. Further applications were based on the NSI value in the V8, V10 and V14 stages. Thus, when the NSI value was below the proposed threshold, treatments T2 and T3 received 22.4 kg ha^{-1} of N at each monitored stage (V8, V10, and V14). For treatment T4, N was applied when needed at the rate of 33.6, 28.0 and 16.8 kg ha^{-1} in the V8, V10, and V14 stages, respectively (Table 1).

Additionally, at the moment of the CMI readings in the V8, V10, and V14 stages, data were also obtained with the ClorofiLOG CFL 1030 chlorophyll meter (Falker Agricultural Automation, Inc., Brazil). The readings from both chlorophyll meters were taken on 30 leaves from random plants in each experimental plot. These data were obtained for comparison purposes in decision making regarding fertilization and subsequent economic feasibility analysis, in which any of the chlorophyll meters were used. However, it is noteworthy that the decision-making process for fertilization purposes during the field experiment was performed only based on the SPAD-502 readings. Moreover, although the field experiment was carried out using five treatments, in the economic analysis only the variable-rate treatments (T2, T3, and T4) were used since the idea behind the study was to present scenarios of adoption and non-adoption for both optical sensors.

Lastly, at 120 days after plant emergence, the corn ears were manually harvested in the experimental area. Then, all corn ears were mechanically milled, and the grain yield (kg ha^{-1}) was determined and adjusted to 13% moisture. The average grain yield obtained was 7,035, 6,762, and 6,722 kg ha^{-1} for treatments T2, T3, and T4, respectively. For treatments T2, T3, and T4, on average 193.45, 203.64, and 200.45 kg ha^{-1} of urea was applied (44% of N), respectively.

Regarding the economic analysis, except for the sensors, all prices of inputs used were collected from the study region. The price per kg of corn (US\$ kg^{-1}) was based on the average local price from the last five years (2014, 2015, 2016, 2017, and 2018 up to September), which is established by the Central of Supply of Minas Gerais (Ceasa - Minas). It should be mentioned that only five years were used due to the lack of data from previous years.

The labor expenses were calculated considering the Brazilian minimum wage for 2018 and the hours spent performing all field operations during cultivation. Moreover, the exchange rate from the Brazilian currency (Real (R$)) to the US dollar was obtained using the average value for the period from 01/2014 to 09/2018 (1 US dollar = R$ 3.17). Finally, the minimum rate of attractiveness (MRA) used was 6% per year, which refers to the interest rate paid by savings accounts in Brazil.

Economic feasibility analysis

Since the focus of this study was to compare the adoption and non-adoption of the SPAD-502 chlorophyll meter an economic feasibility analysis

Table 1. Initial and variable-rate applications of N in the field experiment with the corn hybrid DKB310 PRO2 in Januária, Minas Gerais state, Brazil.

Treatment	Initial dose of N (kg ha^{-1})	**Variable-rate N (kg ha^{-1})**					
		V8	NSI (%)	V10	NSI (%)	V14	NSI (%)
T0	–	–	–	–	–	–	–
T1	56.00	56.00	–	–	–	–	–
T2 (S1)	44.80	22.40	95.00	22.40	95.00	22.40	95.00
T3 (S2)	44.80	22.40	98.00	22.40	95.00	22.40	93.00
T4 (S3)	33.60	33.60	98.00	28.00	95.00	16.80	93.00

For the variable-rate treatments (T2, T3, and T4), from the V8 vegetative stage, all applications of N were performed when the NSI value was below the proposed threshold; V8, V10 and V10, represent the vegetative stages of 8, 10, and 14 fully expanded leaves; NSI, Nitrogen sufficiency index. S1, S2, and S3 are the variable-rate fertilization systems used in the economic analysis.

to purchase this sensor was developed. To do so, two conditions of acquisition were considered: a) acquisition in Brazil by paying the local price of the device and b) acquisition via importation from the United States. Thus, the study evaluated the additional investment, expenses, revenues and cost savings that occurred due to the optical sensor use and procedures related to conventional fertilization.

Therefore, cash flows (CF) were created using the following outputs:

a) the investment in the first year with the equipment purchase (sensor);
b) operational expenses (fertilizers, seeds, herbicides, pesticides, and hourly labor) in the stages of soil preparation, planting and side-dressing fertilizations;
c) Chlorophyll meter index sampling (variable-rate treatments);
d) herbicide and pesticide applications; and
e) crop harvesting.

Conversely, the cash flow inputs were composed of corn sales.

The time horizon of the project was defined based on the assumption of a rapid rate of obsolescence and deterioration of the electronic equipment (Biermacher *et al.*, 2009). However, due to the absence of software or hardware updates for the chlorophyll meter, a period of 8 years instead of 5 years, which was recommended by the authors mentioned above, was considered as the project horizon, *i.e.*, the time over which the sensor will depreciate.

Thus, to evaluate the economic feasibility of the project, scenarios based on cultivation areas were created with two approaches of the CMI sampling in the field: global sampling (a single sampling composed of 30 readings of the chlorophyll meter throughout the field), and sampling in zones (subareas), in which 30 readings of the sensor per zone were performed along the field. The size of all scenarios was chosen based on the suitability of manually performing all field operations, and also by the fact that these field's sizes are common in the study region. Thus, the scenarios were established as follows:

a) global sampling of the CMI average that was obtained in 30 plants randomly chosen in the experimental field and extrapolated to 1, 3, 5, and 7 ha, which corresponded to scenarios 1, 2, 3 and 4;
b) sampling of the CMI divided into equally sized field zones (subareas), in which 30 plants per zone were sampled. Then, we used 3, 5, 7, and 9 zones for scenarios 5, 6, 7, and 8, respectively. The area simulated for scenarios from 5 to 8 was the same as that for the scenarios from 1 to 4.

The time spent (labor hours) during the CMI samplings was obtained in the field at the V8, V10, and V14 corn vegetative stages. For that, it was considered the hourly labor costs of one worker walking in the field to carry out the CMI measurements according to the sampling approach. Then, the results were adjusted for each area-scenario according to the sampling approach. Moreover, the constitution of each cash flow value was similar to that for 1 hectare. However, inputs and outputs were adjusted to their respective areas.

After the cash flow's development, the economic feasibility of using both chlorophyll meters in corn was determined only for the variable rate treatments. This decision was taken due to the focus of the study that was sought to define area-scenarios of adoption and non-adoption of the chlorophyll meter, instead of comparing the economic feasibility between the conventional and variable rate fertilization systems. Thus, the NSI thresholds were defined here as fertilization systems 1 (S1), 2 (S2), and 3 (S3), which referred to treatments 2, 3, and 4, respectively (Table 1). Then, the following indexes were obtained according to the equations proposed by Rezende and Oliveira (2013):

a) Net present value (NPV). The decision criterion consists of accepting the investment if the NPV > 0, rejecting the investment when NPV < 0, and in conditions of equality, the investment is considered as economically indifferent (Rezende; Oliveira, 2013).
b) Discounted benefit-cost ratio (B/C): The criterion consists of dividing the sum of the benefits' present value (inflows) by the sum of the discounted costs (outflows). Thus, if the B/C > 1, the project is worthwhile if B/C < 1, the project is not economically feasible, and when in the condition of equality, the project is considered economically indifferent (Rezende; Oliveira, 2013).

c) Internal rate of return (IRR). The IRR is the discount rate that makes the NPV equal to zero. Therefore, an investment project will be worthwhile if the IRR > MRA (6% per year), if the IRR < MRA is not feasible, and when IRR = MRA the investment is economically indifferent (Rezende; Oliveira, 2013).
d) Payback time: To estimate the risk of the project based on the time demanded for the return of the investment, the payback time was used. Thus, the period to recover the investment was determined. The payback time shows the liquidity of the project, that is, the faster the initial investment is paid, the lower the payback time and, consequently, the greater the liquidity of the project (Rezende; Oliveira, 2013).

Lastly, a comparative analysis was carried out to determine the economic feasibility of the investment in the chlorophyll meter ClorofiLOG CFL1030 for all proposed scenarios. This comparison between the sensors was justified by the absence of differences in the decision making for fertilization purposes after using the SPAD-502 and the ClorofiLOG CFL1030 during the leaf sampling in the V8, V10, and V14 stages.

Moreover, the absence of differences in the decision making based on different sensor readings corroborates the results obtained by other authors (Schlichting *et al.*, 2015), who reported no differences between the SPAD-502 and the ClorofiLOG CFL1030 in the direct determination of the chlorophyll content in relation to foliar nitrogen in wheat plants. Lastly, regardless of the sensor's brand, both chlorophyll meters proved to be worthwhile tools for identifying the spatial variability and crop nitrogen requirements throughout the field, as reported in other studies (Altarugio *et al.*, 2019; Edalat *et al.*, 2019).

Economic feasibility analysis under risky conditions

To evaluate the risk involved in each investment proposal for the acquisition of these sensors, the Monte Carlo simulation technique was used through the Microsoft Excel software (Redmond, WA, USA) and the add-in @Risk, version 7.5. For that, the following input variables were considered: corn price (US\$ kg^{-1}); working hours (US\$ h^{-1}); the quantity of urea used (kg ha^{-1}); and the corn grain yield (kg ha^{-1}). The other variables (fertilizers except for urea, seeds and agricultural pesticides and herbicides), whose quantities were fixed independently of the fertilization system, had their prices fixed in the simulation. In this case, the quantity was adjusted according to the area of each scenario.

The corn price source was the corn price series from January 2014 to September 2018, which was acquired from the Ceasa - Minas. The hourly labor wage was based on the data series of the minimum wage for the same period acquired from the Institute of Applied Economic Research (IPEA). Then, both data series were converted into US dollars (US\$) using the average value of each month in the data series as the exchange rate. Lastly, the corn price and labor cost data were represented by a histogram distribution type in the @risk.

The other variables were represented by a triangular distribution, which is used as a strategy for incorporating risk into variables that usually present the absence of historical data series. This distribution has as input parameters: the minimum, the modal (most likely) or average value of the variable under study, and the maximum value. As mentioned before, the use of the triangular distribution represents an alternative when sufficient historical data for a particular variable is not available (Baitelle *et al.*, 2018).

The triangular distribution was used to incorporate risk in the variables "grain yield" and "quantity of urea used" for the 15 experimental plots of the three fertilization systems. For grain yield, the following values were used: 4,328, 6,840 and 8,386 kg ha^{-1}, which corresponded to the minimum, average and maximum values, respectively. For the amount of urea used, the values were 114.55, 203.64 and 254.55 kg ha^{-1}, corresponding to the minimum, modal and maximum values, respectively.

In addition, when adjusting the simulation model, Pearson's correlation between grain yield and the total quantity of urea used ($r = 0.5490$) was inserted to avoid incoherent results (*i.e.,* high productivity situations with higher/lesser amounts of urea used). Finally, the simulation was performed using the hypercubic square sampling method, and 50,000 iterations were required to meet the sampling convergence requirements of the @risk.

The output variable used for analysis of the feasibility of the investment was the NPV. The IRR was not used since, in the simulation process, many results for this indicator showed errors. These errors occurred when the input variables result in negative values during the whole period of the investment (8 years). In this situation, it is not possible to obtain a value for the IRR (Mendonça *et al*., 2009).

Results and Discussion

Economic feasibility analysis

The results of the economic feasibility indicators for the S1, S2, and S3 fertilization systems (variable-rate treatments T2, T3 and T4) showed that in an 8-year project horizon using the 6% per year MRA, the initial investment option for the scenario of the SPAD-502 being acquired in Brazil (price: US$ 6,527.72) resulted in economic feasibility only for scenario 4 (global sampling in 7 ha) of the S1 system. In this scenario, the NPV would be US$ 1,465.84 with an IRR of 11.41%, which would return US$ 0.22 per dollar invested with a payback time of 6.23 years. In contrast, the acquisition of the SPAD-502 via importation from the United States (price: US$ 4,853.35) resulted in economic feasibility for scenarios 3 (global sampling in 5 ha, S1 system), 4 (global sampling in 7 ha, S1, and S2 systems) and 8 (sampling in 9 zones in 7 ha, S1 system). Moreover, for these scenarios, the NPV and IRR would range from US$ 856.34 to US$ 3,140.21 and from 7.29 to 20.59% with a maximum payback time of 7.52 years (Scenario 4, S2 system).

Scenarios with smaller areas did not present economic feasibility due to the high investment required for both options of acquisition of the SPAD-502 and labor costs in field operations carried out during crop cycle. In addition, in the S2 and S3 systems, the lack of economic feasibility in most scenarios is also justified by the lower corn yield (6,726.6 and 6,722.4 kg ha^{-1}) compared to the S1 system (7,035.6 kg ha^{-1}) and the higher amount of urea used. Moreover, scenarios with sampling in zones whose purpose would be to increase the NUE through a more accurate sampling did not present positive profitability (IRR > MRA), also due to the higher expenses with the chlorophyll meter samplings.

On the other hand, the comparative feasibility analysis using the Falker ClorofiLOG CFL1030 meter, whose acquisition value is US$ 1,892.72, resulted in economic feasibility for scenarios in all fertilization systems (S1, S2, and S3). All three fertilization systems resulted in positive profitability in scenarios with area from 3 ha and with global sampling, *i.e.,* a composite sample composed of 30 readings of the CMI throughout the field. Regarding the sampling in zones, with exception to the S1 system, the other systems were economically feasible only for scenarios above 5 ha area. Thus, only scenarios 7 (sampling in 7 zones in 5 ha) and 8 (sampling in 9 zones in 7 ha) presented an NPV > 0, IRR > MRA, and payback times of less than eight years (Table 2).

In general, the deterministic analysis showed that for the ClorofiLOG CFL1030 and the SPAD-502 acquired under both investment options, the minimum cultivation area should be from 3 and 7 ha. Moreover, for scenario 4 (global sampling in 7 ha, S1

Table 2. Economic feasibility indexes of the ClorofiLOG CFL1030 chlorophyll meter for nitrogen fertilization management using variable-rate systems in corn.

Scenarios		Economic feasibility indexes			
		NPV (US$)	B/C	IRR (%)	Payback (years)
S1	1	–750.80	0.603	–5.28	> 8*
	2	1533.07	1.810	23.90	3.96
	3	3816.95	3.017	46.26	2.27
	4	6100.82	4.223	66.88	1.59
	5	–802.52	0.576	–6.19	> 8
	6	1006.81	1.532	18.19	4.79
	7	2698.90	2.426	35.66	2.87
	8	4061.78	3.146	48.52	2.17
S2	1	–1163.69	0.385	–13.39	> 8
	2	294.42	1.156	9.80	6.69
	3	1752.53	1.926	26.19	3.70
	4	3210.64	2.696	40.57	2.56
	5	–1215.41	0.358	–14.59	> 8
	6	–231.84	0.878	2.81	> 8
	7	634.48	1.335	13.92	5.62
	8	1171.60	1.619	20.01	4.50
S3	1	–1209.39	0.361	–14.45	> 8
	2	157.32	1.083	8.06	7.24
	3	1524.03	1.805	23.80	3.97
	4	2890.74	2.527	37.52	2.74
	5	–1261.11	0.334	–15.70	> 8
	6	–368.94	0.805	0.82	> 8
	7	405.98	1.214	11.18	6.29
	8	851.70	1.450	16.44	5.10

NPV: Net present value; B/C: Discounted benefit-cost ratio; IRR: Internal rate of return; Scenarios 1, 2, 3, and 4: global sampling of the chlorophyll meter index average for 1, 3, 5, and 7 ha; Scenarios 5, 6, 7, and 8: Sampling divided into zones (subareas), using 3, 5, 7 and 9 zones for 1, 3, 5 and 7 ha respectively. Systems S1, S2, and S3 refer to the variable rate treatments T2, T3, and T4, respectively. *Scenarios where the investment would not be recovered over the 8-year project horizon.

system), which showed the highest profitability and liquidity, the investment would result in an IRR and payback time of 11.41, 20.59, and 66.88% and 6.23, 4.41, and 1.59 years, respectively, for investment in the SPAD-502 (acquired in Brazil and via importation) and the ClorofiLOG CFL1030. In addition, the minimum gain (B/C) should be highlighted since an investment in these sensors would return 0.22, 0.64 and US$ 3.22 per dollar invested.

Based on that, the adoption of the ClorofiLOG CFL1030 would result in a project with higher profitability and liquidity when compared to the acquisition of the SPAD-502. Thus, the minimum area of cultivation for decision making in favor of the investment would be 3 ha, if the ClorofiLOG CFL1030 was adopted. Conversely, when using the SPAD-502 acquired in Brazil or via importation, the minimum area would be 5 and 7 ha, respectively.

The deterministic analysis was performed only based on the investment value and in situations of adopting or not one of these sensors. However, it is well known that during cultivation, there may be variations in the amount of urea used, crop yield, and especially in the sales price of corn (US$ kg^{-1}). In this case, it is necessary to emphasize the need for good planning by the decision-maker with great attention to the market price, since, as a commodity, corn has a very volatile pricing policy characterized as cyclical or seasonal, which alternates between periods of increases or reductions in prices.

Finally, the deterministic analysis represents the first step to determine the risk associated with the investment, since it considers the influence of each variable independently when, in fact, they should be analyzed together (Carvalho *et al.*, 2014). This results in uncertainties regarding the future behavior of the variables used in the feasibility analysis.

Economic feasibility analysis under risky conditions

To overcome the main limitations of the deterministic model, a risk analysis was performed using the Monte Carlo simulation (probabilistic model). This method analyzes the risk associated with the cash flow input variables combined. In this case, the Monte Carlo simulation allows the visualization of multiple scenarios and their probabilities using random numbers, which aggregates relevant information to the decision-making process under risky situations (Rego *et al.*, 2017).

The cumulative probability distribution of the NPV obtained by the Monte Carlo simulation using the chlorophyll meters sampling scenarios with an MRA of 6% per year and the SPAD-502 being acquired in Brazil is shown in Figure 1. The interpretation is given by reading the probability (Y-axis) of the occurrence of the NPV value. For example, the probability of NPV < 0 in scenarios 1 and 5 (Figure 1A) is 99.40%. These scenarios are presented in pairs since they have the same cultivation area and differ only in the chlorophyll meter index sampling approach. Thus, the risk analysis corroborates the deterministic analysis since it showed that the investment in scenarios 1 and 5 are not worthwhile. These scenarios presented a high risk of failure since the average NPV values were -US$ 5,222.97 and -US$ 5,269.31, respectively, for scenarios 1 and 5.

Regarding the remaining scenarios, the simulation showed that in the most profitable conditions (Figure 1D, scenarios 4 and 8), the probability of the NPV > 0 would be 54.30% and 49.00%, respectively, for scenarios 4 and 8 (7 ha). In addition, the results also showed that the average NPV in scenarios 4 and 8 would be US$ 2,599.33 and US$ 743.80. This result demonstrates that, as in the deterministic analysis, the investment in scenario 4 is economically feasible. In contrast, for scenario 8, unlike the deterministic analysis, the SPAD-502 can be recommended for 7-ha areas with sampling in zones.

Similarly, the simulation for the SPAD-502 obtained via importation showed that scenarios with less than 3 ha, regardless of the sampling type, would present at a maximum 40.59% probability of the NPV > 0 (Scenario 2, global sampling in 5 ha). In contrast, scenarios with 5 and 7 ha, which were economically feasible in the deterministic analysis, the probability of the NPV > 0 would be 53.80 and 49.50% for scenarios 3 and 7 (Figure 2C), and 59.60 and 53.70%, respectively, for scenarios 4 and 8 (Figure 2D). Thus, the SPAD-502 acquisition would be favorable for scenarios from 5 ha, regardless of the sampling approach.

In contrast, the investment in the ClorofiLOG CFL1030 shows that, except for scenarios 1 and 5, which presented 35.46% and 34.73% probability of the NPV > 0 (Figure 3A), the other scenarios would present at least 57.72% probability of the NPV > 0 (Scenario 6, sampling in 5 zones in 3 ha). Thus, even with a relatively high risk, this result shows the

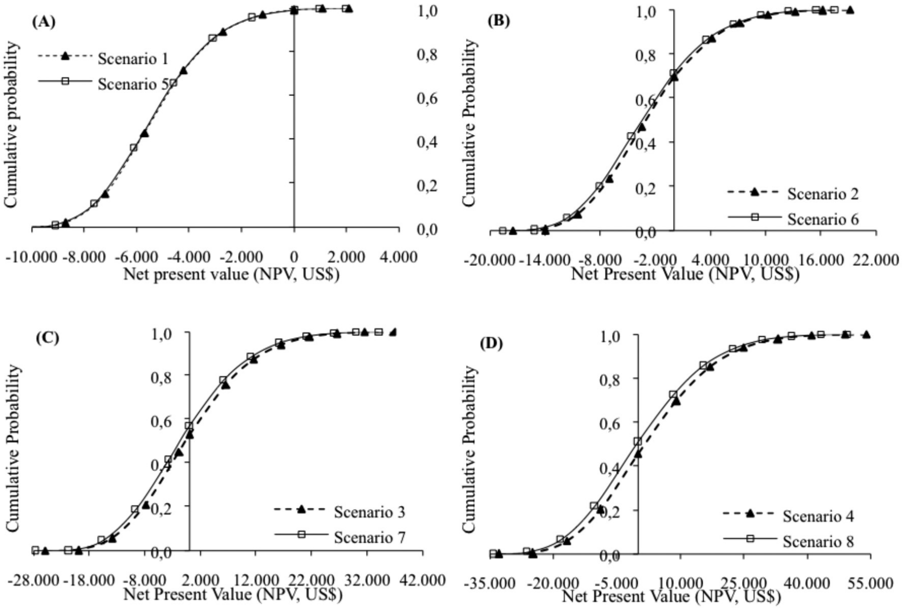

Figure 1. Cumulative probability distribution of the net present value (NPV) obtained by the Monte Carlo simulation of the chlorophyll meter index sampling scenarios using the SPAD-502 acquired in Brazil. Scenarios 1, 2, 3, and 4: global sampling of the chlorophyll meter index average for 1, 3, 5, and 7 ha; Scenarios 5, 6, 7, and 8: Sampling divided into zones (subareas), using 3, 5, 7, and 9 zones for 1, 3, 5, and 7 ha, respectively. (a) Scenarios 1 and 5; (b) Scenarios 2 and 6; (c) Scenarios 3 and 7; (d) Scenarios 4 and 8.

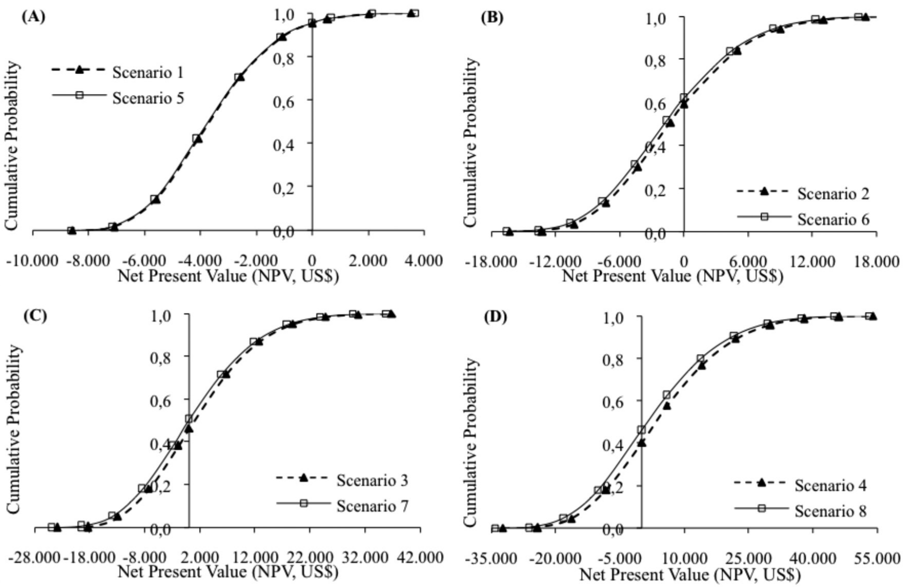

Figure 2. Cumulative probability distribution of the net present value (NPV) obtained by the Monte Carlo simulation of the chlorophyll meter index sampling scenarios using the SPAD-502 acquired via importation in the USA. Scenarios 1, 2, 3, and 4: global sampling of the chlorophyll meter index average for 1, 3, 5, and 7 ha; Scenarios 5, 6, 7, and 8: Sampling divided into zones (subareas), using 3, 5, 7, and 9 zones for 1, 3, 5, and 7 ha, respectively. (a) Scenarios 1 and 5; (b) Scenarios 2 and 6; (c) Scenarios 3 and 7; (d) Scenarios 4 and 8.

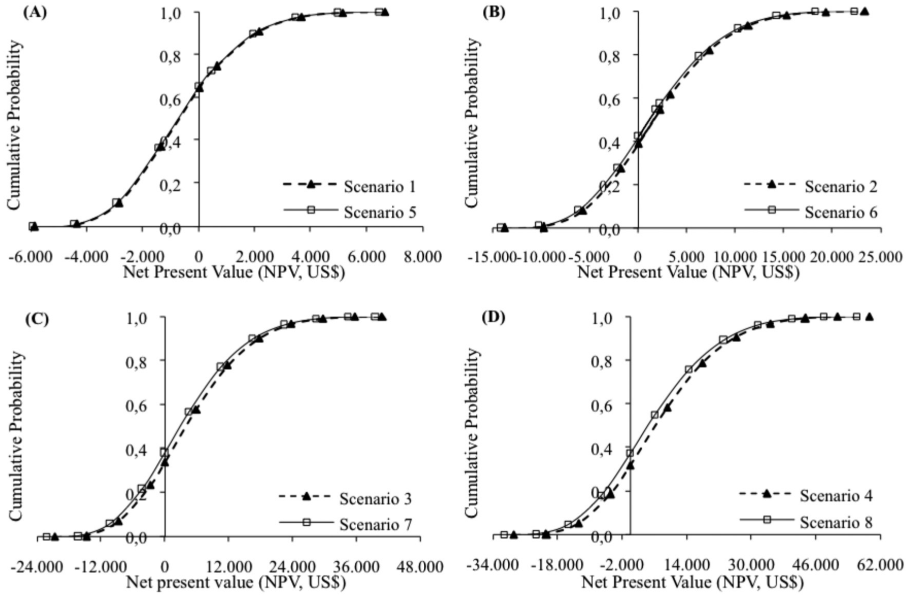

Figure 3. Cumulative probability distribution of the net present value (NPV) obtained by the Monte Carlo simulation of the chlorophyll meter index sampling scenarios using the ClorofiLOG CFL1030. Scenarios 1, 2, 3, and 4: global sampling of the chlorophyll meter index average for 1, 3, 5, and 7 ha; Scenarios 5, 6, 7, and 8: Sampling divided into zones (subareas), using 3, 5, 7, and 9 zones for 1, 3, 5, and 7 ha, respectively. (a) Scenarios 1 and 5; (b) Scenarios 2 and 6; (c) Scenarios 3 and 7; (d) Scenarios 4 and 8.

possibility of investing in areas from 3 ha (Scenarios 2 and 6), regardless of the fertilization system (S1, S2, and S3). This result differs from that observed in the deterministic analysis in which, except for the S1 system, the ClorofiLOG CFL1030 would only be economically feasible in areas from 3 ha in size with global sampling.

In relation to scenarios from 5 ha (Figure 3C and 3D), the probability of NPV > 0 was 66.07% and 61.79%, and 68.00% and 62.60%, respectively, for scenarios 3 and 7 (5 ha), and 4 and 8 (7 ha). In these scenarios, the average NPV ranged from US$ 3,625.96 to US$ 7,240.98. In addition, it can be seen that the probability of investment failure between scenarios of 5 and 7 ha is close. This is due to the low balance (US$) of the discounted cash flow in these scenarios since the high value of the investment, and the expenses with labor ended up deducting the revenues obtained from the corn sales.

The influence of the sampling approach (global or zone sampling) on NPV values was also analyzed. All scenarios with sensor sampling in zones presented lower NPV values, which was expected since the SPAD-502 and ClorofiLOG CFL1030 are sensors that require foliar contact for sampling. Therefore, there is a higher labor expense for foliar sampling. Thus, for those scenarios that presented an NPV > 0, the difference in values of this index due to the sampling type is small, for example, scenarios 3 and 7 (ClorofiLOG CFL1030), where the average NPV was US$ 4,640.73 and US$ 3,625.96, respectively. In contrast, for scenarios 4 and 8, there was a higher difference in NPV values, which were US$ 7,240.98 and US$ 5,400.57, respectively.

It can be seen that the increase in the NPV value difference between global or zone-based sampling is directly proportional to the cultivation area size and the number of sampling zones. Based on that, it should be noted that there is a limitation of using chlorophyll meters for larger areas and with manual work. Thus, for cultivation areas larger than 7 ha, it would be appropriate to use crop canopy reflectance sensors, whose sampling principle is based on vegetation biomass scanning. Furthermore, the use of agricultural mechanization would be ideal since this type of sensor can be attached to both tractors and other agricultural implements. This would certainly reduce labor expenses in field operations and sampling time during the corn crop cycle.

Conclusion

The study showed that the investment in the SPAD-502 chlorophyll meter, regardless of the sampling approach, would be economically feasible in cultivation areas from 7 ha when acquired in Brazil and from 5 ha when obtained via importation. In contrast, the ClorofiLOG CFL1030, if adopted, would result in greater economic feasibility in cultivation areas from 3 ha regardless of the foliar sampling type. Lastly, these sensors can be recommended for small areas (up to 7 ha), especially in Brazil, whose level of adoption of precision agriculture technologies in small farms is very low or nonexistent.

Acknowledgments

This study was partially financed by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Finance Code 001.

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