FEDERAL UNIVERSITY OF RECÔNCAVO DA BAHIA
CENTER FOR AGRICULTURAL, ENVIRONMENTAL AND BIOLOGICAL SCIENCES
GRADUATE PROGRAM IN AGRICULTURAL ENGINEERING
MASTER’S DEGREE

Increasing profits and reducing climate risk through irrigation management for cassava farming in northeast Brazil.

Fábio Luís Seixas Costa

CRUZ DAS ALMAS - BA
AUGUST, 2021

Increasing profits and reducing climate risk through irrigation management for cassava farming in northeast Brazil.

FÁBIO LUÍS SEIXAS COSTA
Agroecology Technologist
Federal University of Recôncavo da Bahia

Document presented to the collegiate of the Graduate Program in Agricultural Engineering of the Federal University of the Recôncavo da Bahia, as a partial requirement for obtaining the Master's Degree in Agricultural Engineering (Irrigated Agriculture and Water Resources)

Adviser: PhD. Maurício Antônio Coelho Filho

CRUZ DAS ALMAS - BA
AUGUST, 2021

FICHA CATALOGRÁFICA

C837i Costa, Fábio Luís Seixas.

Increasing profits and reducing climate risk through irrigation management for cassava farming in northeast Brazil / Fábio Luís Seixas Costa._ Cruz das Almas, Bahia, 2021.

74f.; il.

Dissertação (Mestrado) – Universidade Federal do Recôncavo da Bahia, Centro de Ciências Agrárias, Ambientais e Biológicas, Mestrado em Engenharia Agrícola.

Orientador: Prof. Dr. Maurício Antonio Coelho Filho.

1.Mandioca – Cultivo. 2.Mandioca – Irrigação. 3.Manejo – Análise. I.Universidade Federal do Recôncavo da Bahia, Centro de Ciências Agrárias, Ambientais e Biológicas. II.Título.

CDD: 633.682

Ficha elaborada pela Biblioteca Central de Cruz das Almas - UFRB.
Responsável pela Elaboração - Antonio Marcos Sarmento das Chagas (Bibliotecário - CRB5 / 1615).
(os *dados para catalogação foram enviados pelo usuário via formulário eletrônico*).

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Examination committee of the dissertation defense of
Fábio Luís Seixas Costa

Approved August 30, 2021.

Advisor – Prof Dr. Mauricio Antonio Coelho Filho
Embrapa Cassava and Fruits

External Member - Dr. Alexandre Bryan Heinemann
Embrapa Rice and Beans

External Member - Dr. Julian Ramirez-Villegas
Consultative Group on International Agricultural Research (CGIAR)

ACKNOWLEDGMENTS

First, I would like to say thanks to my parents, the foundation of all my life, for giving me not only the education and the material base necessary to achieve this work, but also the affection and principles that guide and help me to find answers in life.

Thanks also to my partner and my daughter, two essential pieces of my life which challenge me every day to be a better person and find the real meaning of the word “love”. It’s a privilege to have you both.

During this time, me and my family had some angels that helped us a lot. I would like to say thanks to Regiane Ladeira, Jesus Delgado, Cláudia Márcia and Clóvis Matheus.

Thanks to the Graduate Program in Agricultural Engineering and all the excellent professors that work to ensure this high-level education opportunity.

To Djalma and Juliana, friends that I made during the classes. The challenge of getting prepared for exams got much easier with the company of yourselves.

Those other students that I had the opportunity to work, study or just have good conversations with: Luiz Antonio, Danívio, Erivaldo, Fábio, Francisco, Igor, Iumi, Lucio, Valbério and Rafael.

To friends from EMBRAPA, Tibério, Jair, Jorge and Mabel for the kindness and willingness to help.

To my advisor, Maurício Antonio Coelho Filho, for the trust and the challenges that made us grow a lot during this short period of time.

To the work partner that became something like a “big brother” for me, Diego Magalhães. Be sure that I will bring your patience, rigor and hard work with me through the rest of my life.

For you all, not only this work would not be possible without you, but the person and the professional that I am today.

Increasing profits and reducing climate risk through irrigation management for cassava farming in northeast Brazil.

ABSTRACT: Cassava is an important crop in almost all tropical countries. Its roots are used in several ways as food and industrial raw material. Its relevance for worldwide food security is due to its capacity to yield on marginal areas where most crops do not even grow. Also, the energy production potential is high and comparable to other major crops, which makes cassava suitable for smallholder agriculture in developing countries. However, the worldwide actual yield remains at least three folds lower compared to reported potential yield. Cassava research efforts should focus on finding important factors for low yield and management practices to increase it. As a common alternative to increase crop yield, irrigation can be used. Although the latter is not commonly applied to cassava production, promising results can be found in the literature. The present research used the MANIHOT-DSSAT cassava model to assess possible cassava response to alternative planting dates associated with irrigation. Simulations reproducing traditional rainfed cassava management – plantings at recommended dates – were used as a reference scenario. Then, a new set of simulations were done using alternative planting – plantings on non-recommended dates – and irrigation. Both sets of simulations were done for 36 years of Araripina – PE (7º 34' S, 40º 29' W), Laje – BA (13º 10' S, 39º 25' W) and Lagarto - SE (10º 55' S, 37º 39' W) climate data. The irrigation treatments consisted of 100, 80, 60, 40 and 20% of required water during the season. Yield results at different harvest times were obtained to observe the influence of harvest anticipation. The simulation results were used for the economic analysis, which was divided into two: annual and long-term. For the annual analysis, only operational costs were considered and the indicator used was the gross margin. For the long-term analysis, no cost was left out and a period of 10 years was considered. The yield value used were the 20, 30 and 40% percentile and sell prices were not kept constant. The long-term indicator was the net present value (NPV). For the traditional management scenario, higher yields were obtained for plantings at the start of the wet season with different cycle lengths. For the alternative scenario, Araripina showed the highest yield increase compared to the reference scenario, followed by Lagarto (21.3%) and Laje (8%). In general, the less stressful irrigation treatments were responsible for the highest yield values. The long-term economic analysis showed that the use of irrigation in the three regions is a viable investment in most cases. However, the benefit of the irrigation is higher only at Araripina. Then, the proposed management is not a worthwhile investment for farmers at Laje and Lagarto.

Aumentando a receita e reduzindo o risco climático através do manejo da irrigação para a cultura da mandioca no nordeste do Brasil.

RESUMO: A mandioca é uma cultura de grande importância em quase todos os países da zona tropical. Suas raízes possuem diversas finalidades como alimento e matéria-prima industrial. A relevância da mandioca para a segurança alimentar mundial se deve a capacidade desta de gerar produção em áreas marginais, onde a maioria das culturas nem sequer cresceria. Além de que, o potencial de produção de energia da cultura é alto, comparável ao de outras culturas de maior importância comercial, o que a torna bastante adequada a agricultura de pequena escala nos países em desenvolvimento. No entanto, a produtividade real de mandioca ao redor do mundo permanece, no mínimo, três vezes menor em comparação a sua produtividade potencial. Os esforços de pesquisa para a cultura devem focar em encontrar fatores importantes para a baixa produtividade, assim como práticas de manejo capazes de aumentá-la. Uma alternativa comum utilizada no aumento da produtividade na agricultura é a irrigação. Embora essa não seja comumente aplicada na produção de mandioca, resultados promissores podem ser encontrados na literatura. A presente pesquisa utilizou o modelo de mandioca MANIHOT-DSSAT para aferir a possível resposta da cultura ao plantio em datas alternativas aliado a irrigação. Simulações reproduzindo o manejo tradicional de mandioca – plantios nas datas oficialmente recomendadas – foram utilizados como cenário de referência. Em seguida, um novo conjunto de simulações foi feito utilizando plantio alternativo – plantios nas datas não recomendadas oficialmente – e irrigação. Ambos conjuntos de simulações foram feitos para 36 anos de dados climáticos de Araripina – PE (7º 34’ S, 40º 29’ O), Laje – BA (13º 10’ S, 39º 25’ O) e Lagarto - SE (10º 55’ S, 37º 39’ O). Os tratamentos de irrigação consistiram em 100, 80, 60, 40 e 20% da água requerida durante o período seco. Os resultados de produtividade em diferentes datas de colheita foram obtidos para observar a influência da antecipação da colheita. Os resultados das simulações foram submetidos à análise econômica, que foi dividida em duas partes: anual e de longo prazo. Para a análise anual apenas os custos operacionais foram considerados e o indicador utilizado foi a margem bruta. Para a análise de longo prazo todos os custos foram incluídos e um período de 10 anos foi considerado. A produtividade utilizada foi aquela obtida aos 12 meses de ciclo e os preços de venda não foram mantidos constantes. Os indicadores de longo prazo foram o valor presente líquido e o retorno do investimento. Para o cenário tradicional, os maiores valores de produtividade foram obtidos para plantios no início da estação úmida com diferentes tempos de colheita. Para o cenário alternativo, Araripina apresentou o maior aumento de produtividade comparado ao cenário de referência, seguido de Lagarto (21.3%) e Laje (8%). Em geral, quanto mais água aplicada via irrigação, maiores as produtividades. A análise econômica de longo prazo mostrou que o uso da irrigação nas três regiões é um investimento viável na maioria dos casos. No entanto, o benefício do uso da irrigação é superior somente na Araripina. Dessa forma, o manejo proposto não é um investimento interessante para os agricultores de Laje e Lagarto.

Summary

1. INTRODUCTION

Cassava is one of the most important tropical crops for food security. Its social relevance is primarily due to hardiness, which gives it drought tolerance and yield even on poor and acid soils. The harvest time is flexible; the plants can be harvested early or left on the field for months and even years serving as a reserve source of food. Furthermore, the amount of energy obtained by hectare is comparable to the most important commercial crops worldwide. These characteristics make cassava an important choice for smallholders in tropical and even subtropical latitudes.

Naturally, cassava production depends on several abiotic factors like water and nutrients availability in soil, optimal temperature and vapor pressure deficit ranges, radiation and luminosity. Traditional production regions present characteristics that fit at least the minimum crop requirements. In tropics, the crop growth is generally limited by water availability during the dry season, while in subtropical zones energy – low temperature and/or radiation – during the cold season is the limiting factor.

Although been recognized as a hardy and drought tolerant crop, climate annual variability brings instability to production and then economic uncertainty to farmers. Since the majority of cassava production in tropics is rainfed, annual rainfall amount and distribution accounts for a big part of that instability. Besides that, the inflexibility in terms of planting dates due to water availability limits commercial farms to harvest when the market supply is high.

Irrigation releases the farmers from rainfall dependency and allows agricultural planning. It makes possible more than one cycle by year for annual crops. For cassava, beyond limit water stress, irrigation could allow alternative planting and harvest dates. That management change could benefit farmers due to the more favorable market conditions at the harvest time.

The use of deficit irrigation is an alternative to avoid high water stress levels and yield instability on crops. The reduced amount of water needed comparing to no stress management is an important technique characteristic, which could make the technology adoption less hard to constrained situations such as water-limited regions and poor farmers. In that sense, drought tolerant crops could benefit greatly even from moderate irrigation levels, improving water use efficiency and economic returns.

Crop models have been widely used to access management alternatives. Simulation outputs deliver an approximation of field results, which is very useful as a supplementary source of information for later conclusions. It can also act as a first look at a problem to evaluate its relevance and better decide between investment and effort options. In that sense, the present work purpose was an economic analysis of MANIHOT-DSSAT Cassava model results for alternative planting dates and the use of irrigation to evaluate a management option for cassava production in three regions of Northeast Brazil.

2. OBJECTIVES

2.1. MAIN OBJECTIVE

To evaluate the economic advantage of alternative cassava planting associated with irrigation in three Brazilian Northeast climatic conditions using MANIHOT-DSSAT model.

2.2. SPECIFIC OBJECTIVES

1. To simulate a reference scenario based on the same management used by local farmers.
2. To simulate an alternative scenario using alternative planting dates and irrigation.
3. To analyze the gross margin and risk of both through an annual economic analysis
4. To analyze the expected benefit of the proposed management through a long-term economic analysis

3. LITERATURE REVIEW

3.1. CASSAVA

Cassava (*Manihot esculenta*, Crantz) is a crop originally from the American Tropics and cultivated in almost all tropical countries (CAMPOS; CALIGARI, 2017). Energy production by hectare is comparable to other major food crops, which makes cassava an important species in terms of food security (EL-SHARKAWY and CADAVID, 2002). According to FAO (2017), more than 290.000.000 t of cassava roots were produced worldwide in more than 25.000.000 ha. Therefore, world yield in 2017 was about 11 t ha^{-1}, a much lower value compared to cassava potential yield, which value reported in literature closes 90 t ha^{-1} of fresh root weight (PHONCHAROEN et al., 2019). That yield gap characterizes crop production worldwide and it is closely associated with majority cassava farmer's profile, who cannot afford higher production costs.

Cassava is a perennial plant that alternate growth, root carbohydrate storage and dormancy phases (ALVES, 2006). The species is cultivated primordially under rainfed conditions as an annual or biannual crop adapted to different climate. The roots are harvested from six months in optimal conditions up to twenty-four in regions with long periods of dry or cold. Furthermore, cassava is highly tolerant to abiotic stresses such as drought, low-fertility and acid soils, which allow it to yield even in marginal fields (VISSES; SENTELHAS; PEREIRA, 2018).

The minimum water requirement for cassava production is not well defined, however, the well-known resilience of plant enable the crop production in areas with low annual rainfall (less than 700 mm $year^{-1}$) and long dry seasons (four to six months). The yield impact due to low water availability within the crop cycle depends on timing, stress duration and intensity (LEBOT, 2009). Greatest susceptibility to water deficit occurs from the first to fifth month after planting, which leads to yield reduction closely to 60% (OLIVEIRA; MACÊDO; PORTO, 1982).

Some physiological mechanisms allow cassava to be recognized as drought tolerant. First, sensible stomata control as a function of soil water potential and vapor pressure deficit (above 2 kPa) ensures maintenance of high-water potential in leaves, thus water use efficiency of photosynthesis (DUQUE and SETTER, 2019; PEREIRA et al., 2018; PIPATSITEE et al., 2018). The second is the reduced leaf growth combine with leaf senescence to avoid the increase of transpiration surface in dry periods. Although the latter is a common strategy in drought-adapted plants, cassava can recover as soon as water stress ceases, which decreases the impact on yield due to dry periods (ALVES and SETTER, 2000; EL-SHARKAWY, 2012). El-Sharkawy and Cadavid (2002) found low and insignificant final yield reduction when early stress (2 to 6 months after planting) was followed by well watering until the end of the cycle (12 months). Also, there is evidence about cassava water deficit acclimation (PINHEIRO et al., 2014).

As a tropical plant, to exhibit its potential photosynthetic rate and high yield, cassava requires high solar radiation (saturation at 1800 μmol m^{-2} s^{-1}), leaf temperature (30 to 35 ºC), photoperiod (12 hours) and high relative humidity (EKANAYAKE et al., 1998). Also, the species present low tolerance to shading, which depresses growth and root storage (EL-SHARKAWY, 2004). According to El-Sharkawy (2016), cassava has C3 and C4 plant characteristics, representing an intermediate photosynthetic mechanism. The unique combination of characteristics, absent in all other crops explains the adaptation to marginal and dry planting conditions around the world.

Cassava phenology is highly dependent on the environment and management. However, there are five general development stages discussed by Alves (2006) for a free constraint planting:

1. Sprouting;
2. Leaf and root system development;
3. Canopy establishment;
4. High carbohydrate translocation;
5. Dormancy.

The first two occurs between 5 and 90 days after planting (DAP) and refers to the development and establishment of adventitious roots and buds from the stem cutting. The third concerns the greatest vegetative growth period, corresponding to the maximum growth rate of leaves and stems. That stage finishes when plants reach the maximum leaf area index (about 180 DAP), which then decreases (EL-SHARKAWY and CADAVID, 2002). The fourth stage is marked by the increment on the proportion of photoassimilates directed to storage roots, taking to high rates of dry matter accumulation until 300 DAP. From there, cassava starts a dormancy stage in which vegetative growth is minimized and translocation to the roots continues, eventually reaching the maximum dry matter accumulation. That latter stage is more evident in places with several months of low temperatures or low water availability (FAGUNDES et al., 2010).

The largest part of worldwide cassava production is rainfed. Thus, planting and harvest timing so as final yield are highly dependent on rainfall amount and distribution. The planting is performed at the beginning of the wet season and the harvest when the soil is wet enough (usually twelve months after planting). Also, since cassava demands a high amount of energy, the latter availability becomes an essential driver of growth. The combination of water and energy availability within the production cycle runs the crop development, which turns complex the evaluation of cassava response to environmental factors and its effects on the final yield (KEATING et al., 1982).

3.2. CROP MODELING

One main part of the scientific work is to set up hypotheses about how systems work. Usually, scientists make use of conceptual frameworks or/and mathematical representations to develop notions and knowledge about features from the real world. In that sense, crop models are scientific hypotheses that associate crop response – yield, growth, development – to at least one important weather, soil or management variable (FODOR et al., 2017).

Crop models integrate biophysical process knowledge from plants to predict crop performance on different production conditions. The use of crop models allows to access the uncertainty associated with several combinations of management practices and genotype choices for a specific environment (HEINEMANN; STONE; SILVA, 2010). In that sense, that kind of model helps in the decision-making process offering a tool for management planning by farmers and priorities definition by policymakers. However, research also benefits from the use of crop models. Crop response to soil, weather and management factors can be evaluated in detail, and insights about genotype specific characteristics can be obtained from crop parameters (BATTISTI et al., 2017).

There are two main types of crop models: the first is called empirical or statistical models. It explicitly represents the relationship of two or more variables and it is created directly by data. The structure of the model already exists and the parameters are fitted to adjust the specific relationship to be modeled, which is given by the data (MICHAEL et al., 2017). The second is called mechanistic or process-based models. For these, the model structure is composed of several equations, which can be physical or empirical models each representing one crop process. The whole structure is responsible to describe crop general response to environment and management factors (DOURADO-NETO et al., 2005). Unlike statistical models, process-based models contain in its structure scientific knowledge about mechanisms that control the outputs, which gives it more general applicability since it is not created directly by data (SIAD et al., 2019). Although this is true, process-based models also have parameters that must be calibrated to take into account genotype, weather and management specificities (WALLACH et al., 2019).

Process-based models are often used to make crop improvement recommendations. Heinemann et al. (2015), based on simulations of the rice crop in four Brazilian states, suggest that Brazilian upland rice breeding should focus on specific instead of a broad adaptation strategy. On the other hand, Chenu et al. (2011) warned about the existing risk of a specific adaptation strategy for Australian wheat since there is no clear dominant stress pattern on simulation results. Heinemann et al. (2017) worked with climate change and found that, although the wide adaptation strategy currently used by Brazilian upland rice breeding programs is suitable for now, it does not appear to fit well for future weather giving the increase in the frequency of droughts. They conclude that breeding should incorporate drought strategies for climate change.

For more specific environmental conditions, crop models can help to identify management alternatives to increase yield, resources use efficiency and profitability. Bergez et al. (2002) suggested a more profitable irrigation schedule for maize in France using a mechanistic crop model. The authors established a reference scenario based on real field practices and maximized the financial returns (20% increase) using a direct margin objective function. Lopez et al. (2017) present an optimization algorithm, followed by its application on a maize and soybean example, which allows model users to specify irrigation schedules for each crop growth stage, making deficit irrigation simulation studies more reliable. Economic analyses of external factor effects on farmer decision making are also present in literature. García-Vila and Fereres (2012) utilized the AquaCrop (STEDUTO et al., 2009) model to analyze farm gross margin impacts by changes in agriculture policy, market prices and water availability to irrigation in the Mediterranean. The model was used to generate water response functions, which were added to the optimization procedure so then estimate management reaction by farmers.

3.3. MANIHOT-DSSAT CASSAVA MODEL

The development of a cassava growth model faces some particularities compared to the most common annual crops with a determined cycle and phenological phases (SINGH et al., 1998). The species high drought tolerance, water use efficiency and environmental conditions responsiveness, to cite some, challenge the modelers because commonly used mathematical representations of crop processes do not fit well for cassava. Indeed, previous cassava models always had some limitations in terms of factors considered in equations or assumptions made to make the modeling possible.

Moreno-Cadena (2018) has presented in detail the most recent cassava model – MANIHOT – developed by the International Center for Tropical Agriculture (CIAT) and available in the Decision Support System for Agrotechnology Transfer (DSSAT) software (JONES et al., 2003). MANIHOT is an improvement of the previous DSSAT cassava model (MATTHEWS and HUNT, 1994), so it brings several already developed components. The author briefly reviews 12 previous cassava models, the first from 1978 and the last from 2018, and points out advances and limitations for each of them.

The main driver of growth and development in MANIHOT is the accumulation of thermal time (ºCd) as a function of temperature. The accumulation is controlled by cardinal temperatures, which defines upper and lower limits so as optimum ranges of temperature for growth. There are values of cardinal temperatures for six processes according to Moreno-Cadena (2018): General growth and germination; branching; maximum individual leaf area for the first and second branch; leaf age and growth. These values can be calibrated (changed) by the user. For each simulated day, the mean temperature is compared to cardinal temperatures resulting in a coefficient (0 – 1) meaning optimal or not optimal daily growth for each specific plant process. Then, the daily thermal time is calculated and added to the accumulated thermal time for that process. Thereby, thermal time control allows the model to mimic the crop general response to high and cool temperatures (MORENO-CADENA et al., 2019).

Development processes are controlled by the accumulated thermal time threshold. For instance, the default value at which germination occurs is 120 ºCd. First and second branching time (B01ND and B12ND) work the same way and are basic parameters used to distinguish between early and late branching genotypes. During the crop cycle, branching is divided into two parts. The first occurs from germination to first branching. The threshold to first branching is the B01ND parameter itself, in thermal time. From that, new branches appear at a constant rate – the B12ND itself – in thermal time. The number of new branches per fork is also a parameter and can be changed by the user (MORENO-CADENA, 2018).

The model basic growth unit is the node, which includes the leaf and the internode. The total number of nodes over time is a rising curve driven by the daily node formation rate (practically the same as the leaf appearance rate). As the plant age increases, that rate decreases (**Figure 1**). The LNSLP parameter is used for genotypes with a higher/lower leaf appearance rate than the reference used as the default (MORENO-CADENA, 2018).

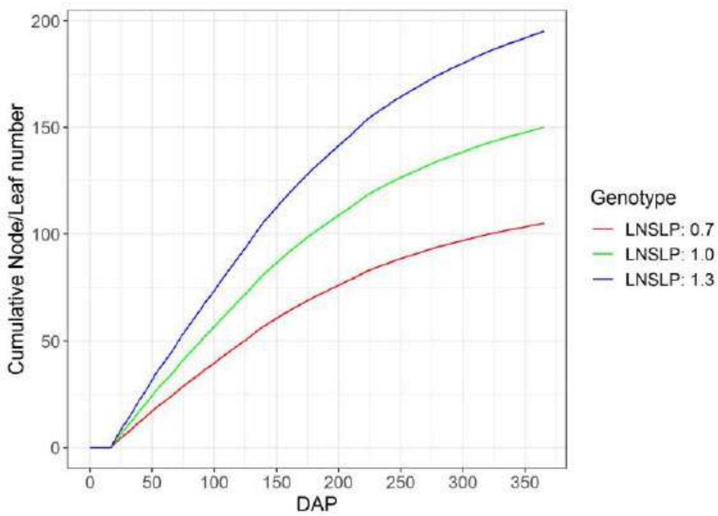

Figure 1 - Cumulative node/leaf number curves for three genotypes with different LNSLP parameter values.

The model uses a cohort concept and a symmetry assumption. One cohort is a set of nodes that appeared and develop together. When branching occurs, new branches are considered symmetric meaning that their nodes and leaves will develop identically. When a node appears, its symmetrical pairs appear too and a new cohort starts to compute (MORENO-CADENA, 2018). On one hand, the symmetry assumption eases the modeling process and reduce the computational requirement. Because one cohort includes more than one node, one calculation by cohort is enough for several nodes. On other hand, asymmetry is the general behavior in real cassava plants, regardless of the genotype. A different cohort approach was used in the previous cassava model (MATTHEWS and HUNT, 1994).

The daily growth and weight increment for each node are based on node age and plant age. The node age acts as a rising at a decreasing rate curve: as the node becomes “older” it will grow less and accumulate less weight. The plant age, however, acts as a curve parameter penalizing the node growth as a whole, meaning that first nodes will have not only a high growth rate but also the greater accumulated weight among all nodes in the plant. To consider genotype specificity about node weight, the parameter NODWT was defined as the average weight of the first 20 nodes when thermal time reaches 3400 ºCd. According to Moreno-Cadena et al. (2019), NODWT is one of the most sensible genotype parameters in MANIHOT (**Figure 02**) due to its close relation with assimilates partition, which is explained further.

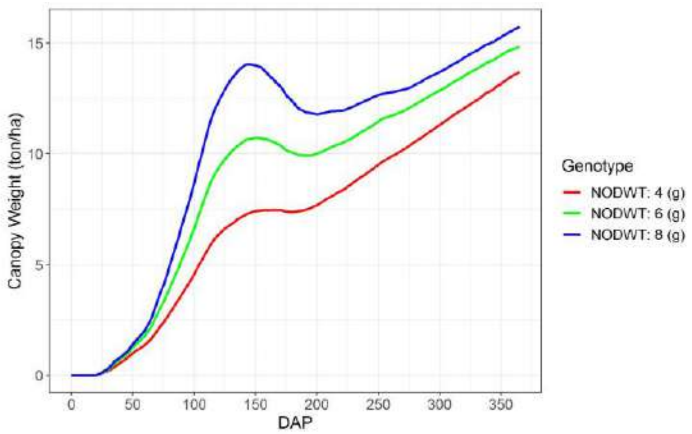

Figure 2 – Canopy Weight for three genotypes with different NODWT parameter values.

The leaves are an important model component. Its number, size and duration determine the amount of available energy for growth, development and root storage. Therefore, MANIHOT presents one parameter for each specific leaf characteristic. Potential leaf area is the maximum size one leaf can reaches from appearance to senescence without stress penalties. The potential leaf area depends on plant age at the time of leaf appearance. Moreno-Cadena (2018) defined the parameter maximum leaf area (LAXS) and used experimental results to set 900 ºCd as the crop cycle point of maximum potential leaf area. That is, the leaves that appeared at that time will eventually reach the largest size among all the others. Therefore, high values of LAXS characterize genotypes with large leaves (**Figure 3**). The parameter LAXS is also among the most sensible and it influences important model outputs as leaf area index, aboveground biomass and yield (MORENO-CADENA et al., 2019).

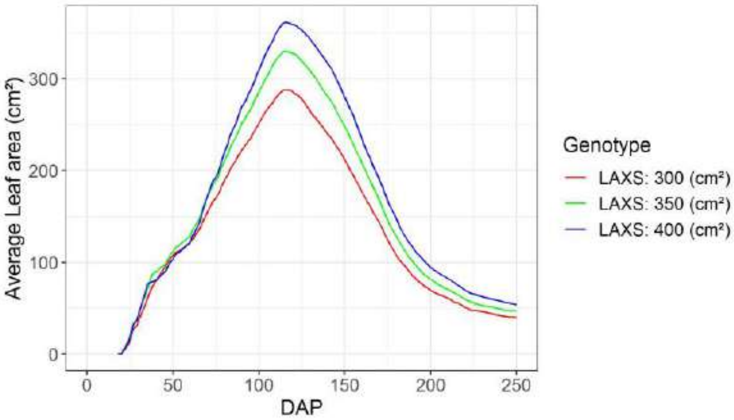

Figure 3 – Average leaf area (cm^2) for three genotypes with different LAXS parameter values.

The leaf life cycle is called duration and includes three phases: expansion, active and senescence. Thermal time thresholds control the passage from one phase to another (**Figure 4**). Thus, as the average temperature increases, the leaf duration decreases.

Leaf size (cm^2) and leaf weight (g) start to increase daily once the cohort appears and stop when the leaf active phase begins. The daily leaf growth (cm^2/day) depends on potential leaf size and daily average temperature. The calculation begins with the daily assimilate partition resulting in the daily leaf weight increment (g/day). The latter is multiplied by the parameter LPEFR (leaf-petiole ratio) to separate what goes to the petiole from what goes to the leaf. The leaf part (g) is then multiplied by the parameter SLAS, which stands for specific leaf area (cm^2 g^{-1}) resulting in the daily leaf growth (cm^2/day). Moreno-Cadena et al. (2019) show that LPEFR and SLAS are among the less sensible parameters suggesting even to replace the first by a constant.

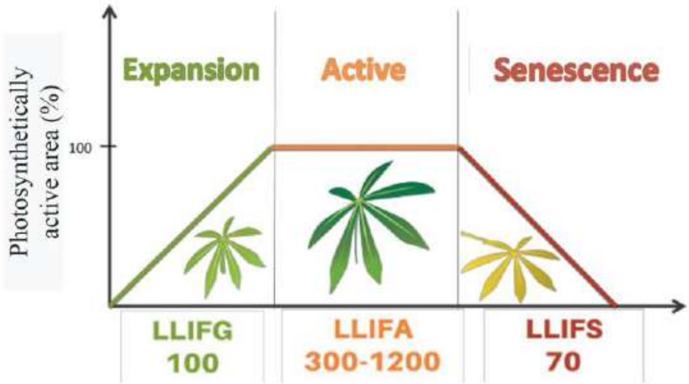

Figure 4 – Scheme of leaf life phases versus the photosynthetically active area. Codes indicate the parameter responsible for each phase duration. Numbers indicate the default values used for these parameters (thermal time thresholds – Cdº). **Source**: Adapted from Moreno-Cadena (2018).

During the leaf expansion phase, the assimilates production starts but the amount produced is not enough for leaf growth. External energy is necessary for that phase, meaning that assimilated energy from older leaves will be translocated to new leaves. When the leaf reaches the active phase, the photoassimilates production occurs without additional energy requirement and the leaf starts to feed other plant organs. The duration of the active phase is defined by the parameter LLIFA, which allows users to account for different leaf retention behavior between genotypes. According to Moreno-Cadena et al. (2019), leaf area index (LAI) was the only output variable that showed high sensibility to LLIFA and it occurred only in a warm environment.

The previous description omitted the effect of water deficit on germination, node and leaf growth, leaf appearance and branching. Usually, a stress factor is used to penalize plant processes if it is necessary. An important stress factor is the water deficit, which here is calculated based on soil the water availability. While most crop models use a default approach, the ratio between real and potential evapotranspiration as the water deficit index, the maintenance of leaf water potential and sensible stomata control influence the cassava transpiration, what makes default index not a good choice for cassava modeling. Instead, two soil water content thresholds are used, an upper and a lower limit. When the actual water content is above the upper limit, it means no stress and the process is computed without penalty. When the actual water content is between the upper and lower limits, it means stress and the process is computed with a penalty. When the actual water content is below the lower, it means maximum stress and the process stops (MORENO-CADENA, 2018).

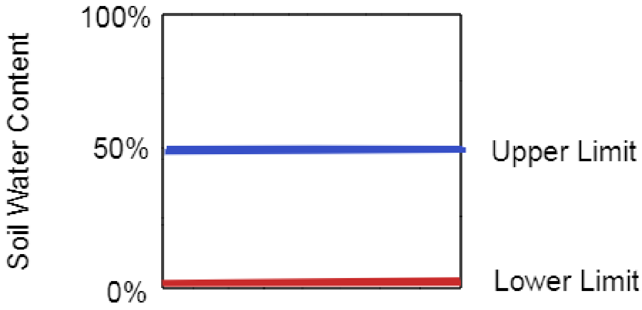

Figure 5 – Water stress factor scheme. Two thresholds (upper and lower) based on ratio of soil water content from wilting point (0%) to field capacity (100%). The values 0.5 and 0.0 are used for the photosynthesis process.

The model works daily. For each day, processes are computed based on plant age and daily environmental conditions. Potential daily growth is estimated adding stem and leaf potential growth plus 10% for fiber roots (MORENO-CADENA et al., 2019). The result is used as the daily total assimilates demand. Daily actual growth, on the other hand, depends first on daily assimilation production. This is calculated by solar radiation intercepted times the parameter PARUE (radiation use efficiency; g $_{\text{[dry matter]}}$ MJ^{-1}). Assimilates are primarily used to feed the growth of plant organs (stems, leaves and fiber roots) and meet the daily demand. The remaining value is used to increase storage roots (**Figure 6**). Alongside LAXS and NODWT, PARUE is one of the most sensible parameters in MANIHOT (MORENO-CADENA et al., 2019).

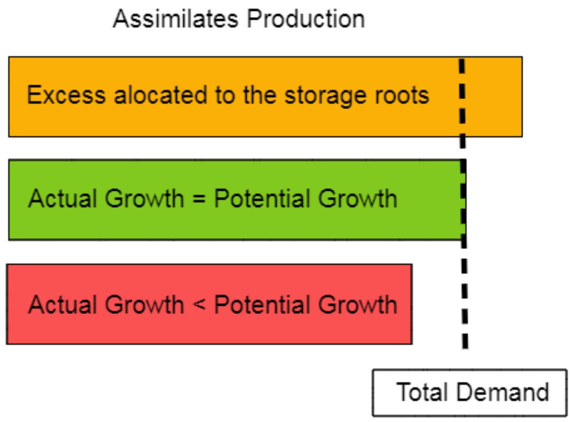

Figure 6 – Assimilates partition scheme

4. MATERIALS AND METHODS

4.1. REGIONS STUDIED

Three regions of the Northeast Brazil were chosen to be part of the analysis. The choice was made based on importance in terms of cassava production. **Table 1** show the six counties with the highest cassava root production at 2017, 2018 and 2019 (IBGE, 2021).

County	***Region***	***2017***	***2018***	***2019***	***Total***
			------------------ *ton* -----------------		
Araripina (PE)	Region 1	24,060	68,000	98,000	190,060
Salitre (CE)	Region 1	55,120	69,395	63,803	188,318
Lagarto (SE)	Region 2	103,680	36,000	30,600	170,280
Laje (BA)	Region 3	50,352	54,200	52,800	157,352
Araripe (CE)	Region 1	40,200	50,373	59,660	150,233
Teotônio Vilela (AL)	Region 2	50,000	45,000	45,332	140,332

Table 1 – The six Northeast counties with the highest cassava root production.
Source: IBGE (2021)

Since places within each region have very similar climatic condition, one place was chosen for each region to represent it. Araripina was chosen for region 1, Lagarto was chosen for region 2 and Laje was chosen for region 3.

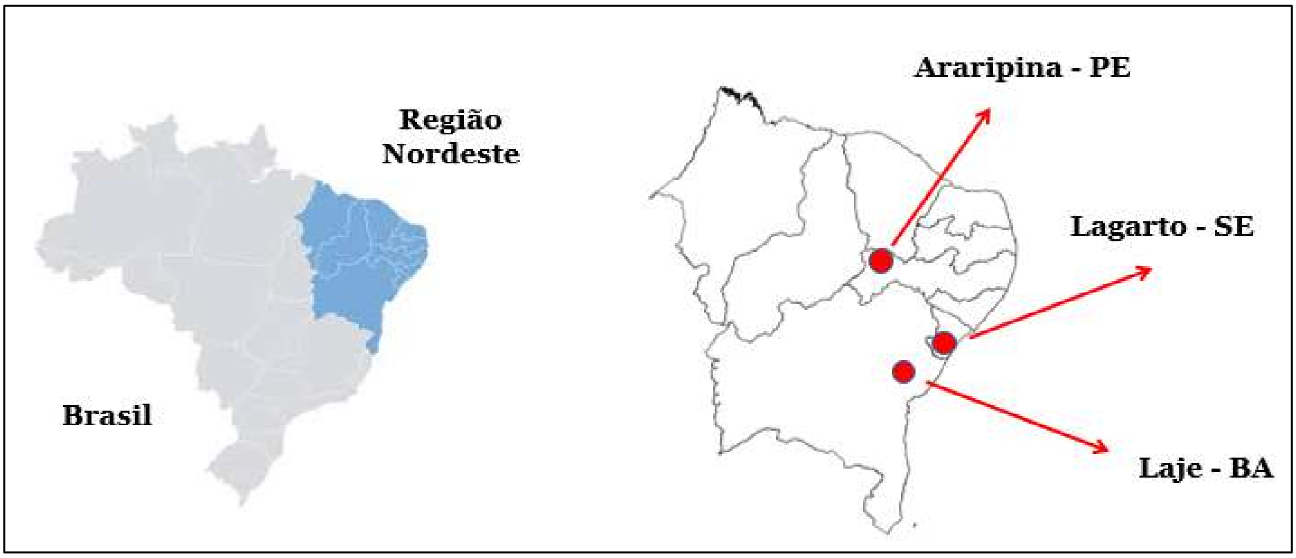

Figure 7 – Northeast sites chosen as representatives of each climate type

4.2. ENVIRONMENT CHARACTERIZATION

Araripina is located at geographical coordinates 7º 34’ South and 40º 29’ West at an altitude of 639 m. The climate classification is BSh according to Köppen, with an annual average rainfall of 640 mm ranging from 403 to 877 mm. The wet season extends from December to May and the dry season from June to November. The average annual temperature is 24.9 °C and the average annual air relative humidity is 61% (XAVIER et al., 2016).

Laje is located at geographical coordinates 13º 10’ South and 39º 25’ West at an altitude of 190 m. The annual average rainfall is 1314 mm ranging from 1109 to 1519 mm. The wet season extends from February to August and the dry season from September to January. The average annual temperature is 25.2 °C and the average annual air relative humidity is 76% (XAVIER et al., 2016).

Lagarto is located at geographical coordinates 10º 55’ South and 37º 39’ West at an altitude of 183 m. The annual average rainfall is 1218 mm ranging from 927 to 1509 mm. The wet season extends from March to September and the dry season from October to February. The average annual temperature is 25.9 °C and the average annual air relative humidity is 75% (XAVIER et al., 2016).

Figure 8, 9 and **10** present the annual distribution of the main meteorological variables in Araripina, Laje and Lagarto, respectively. The same variables are also show at **Table 1, 2** and **3.**

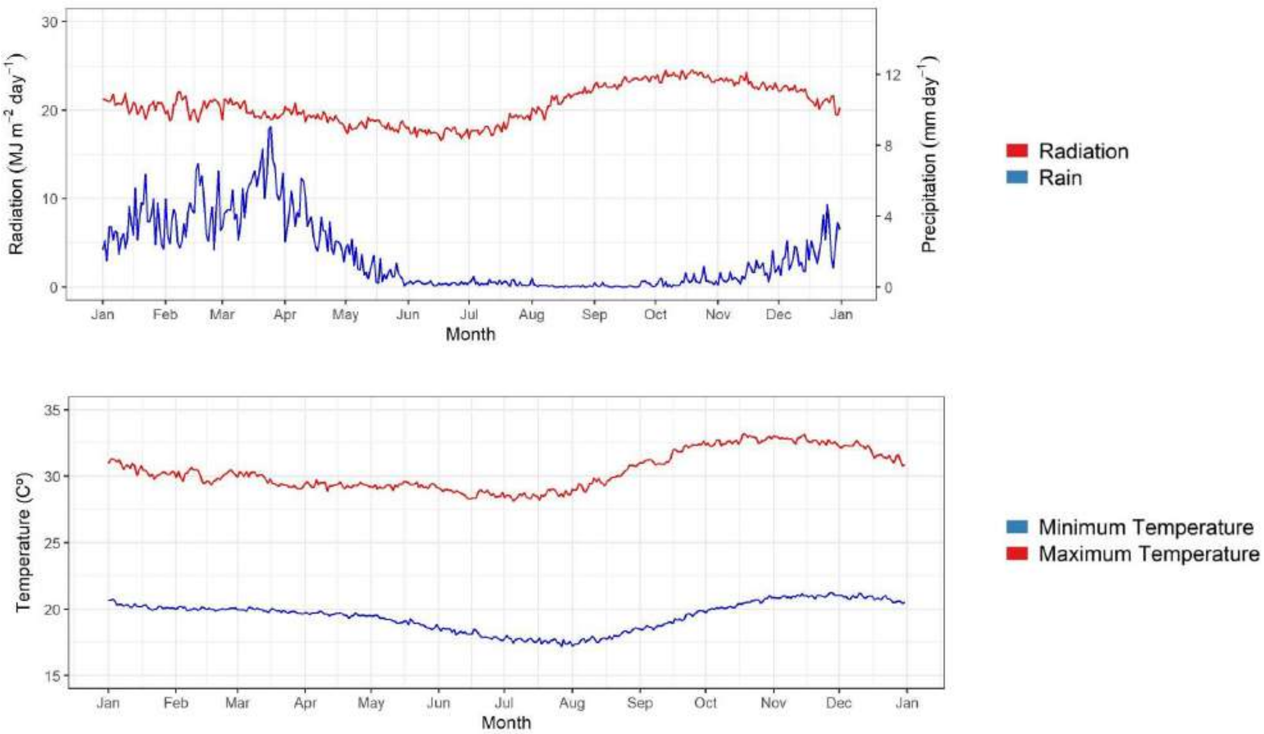

Figure 8 – Daily values of the main meteorological variables in Araripina - PE averaged over 36 years. **A)** Precipitation and Radiation; **B)** Minimum and Maximum Temperature.

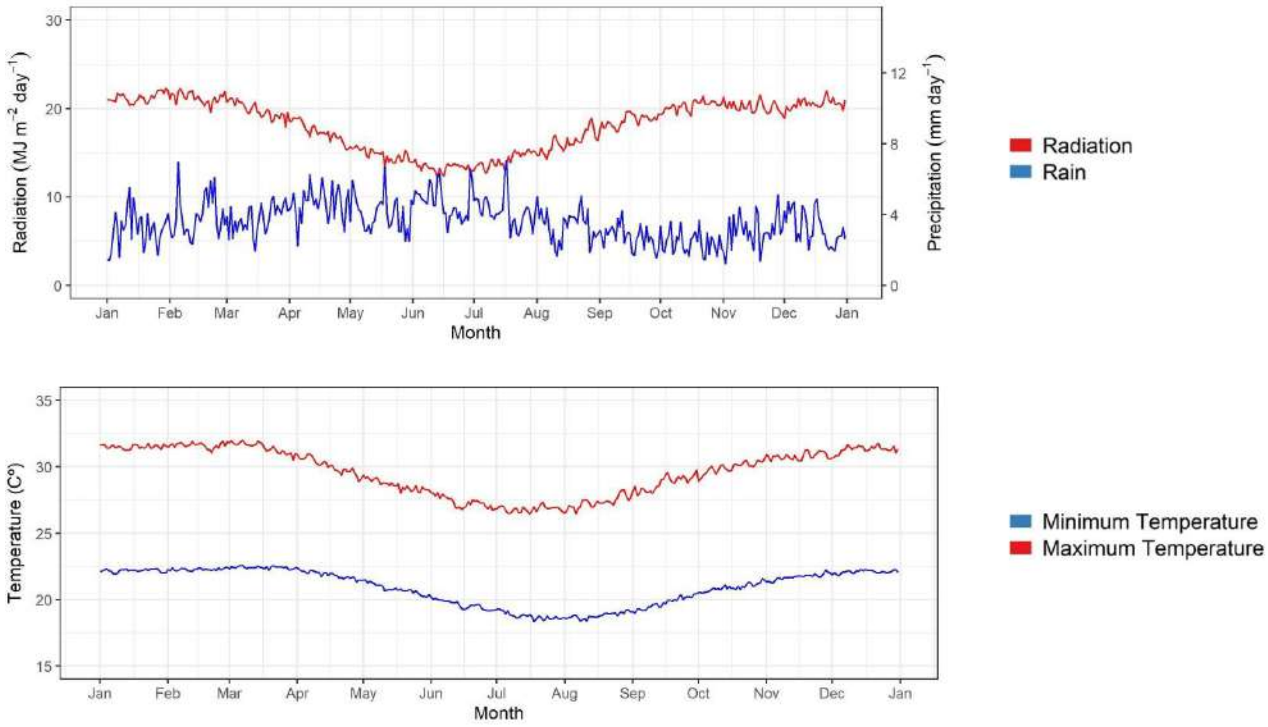

Figure 9 – Daily values of the main meteorological variables in Laje **-** BA averaged over 36 years. **A)** Precipitation and Radiation; **B)** Minimum and Maximum Temperature**.**

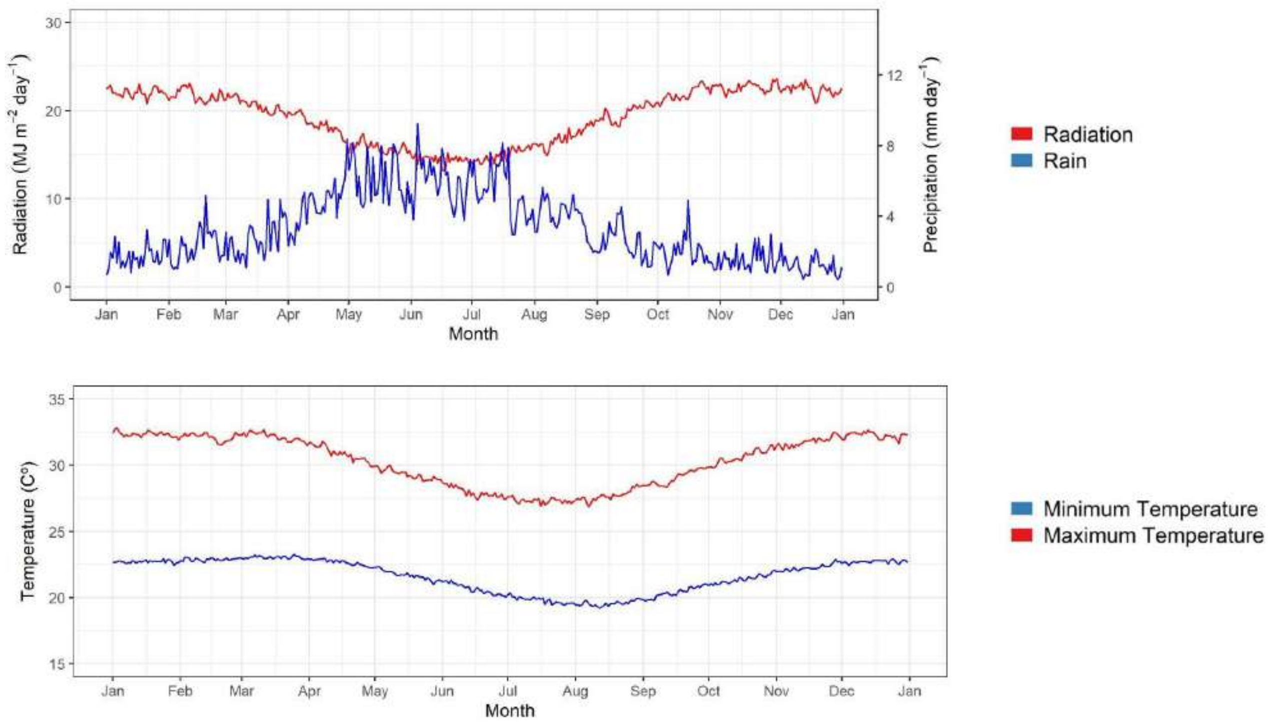

Figure 10 – Daily values of the main meteorological variables in Lagarto - SE averaged over 36 years. **A)** Precipitation and Radiation; **B)** Minimum and Maximum Temperature**.**

Month	***Rain*** *(mm)*	***Radiation*** *(MJ m^{-2})*	***Max. Temperature*** *(Cº)*	***Min. Temperature*** *(Cº)*
January	105	638	30.5	20.2
February	115	575	30	20
March	171	617	29.7	19.9
April	101	580	29.4	19.6
May	31	565	29.3	19
June	6	524	28.7	18.1
July	7	568	28.6	17.6
August	2	655	29.8	17.9
September	2	694	31.6	19.1
October	9	740	32.7	20.4
November	23	691	32.7	21
December	64	667	31.8	20.8

Table 1 – Total monthly rain, radiation, maximum and minimum temperature in Araripina - PE averaged over 36 years. **Data source**: Xavier et al. (2016)**.**

Month	***Rain*** *(mm)*	***Radiation*** *(MJ m^{-2})*	***Max. Temperature*** *(Cº)*	***Min. Temperature*** *(Cº)*
January	98	659	31.5	22.2
February	112	599	31.6	22.3
March	116	615	31.4	22.4
April	139	521	30.1	21.9
May	124	459	28.6	20.8
June	142	399	27.3	19.6
July	128	441	26.8	18.7
August	105	503	27.3	18.8
September	82	559	28.8	19.8
October	75	630	30	20.9
November	92	605	30.8	21.7
December	100	637	31.3	22.1

Table 2 – Total monthly rain, radiation, maximum and minimum temperature in Lage - BA averaged over 36 years. **Data source**: Xavier et al. (2016)**.**

Month	***Rain*** *(mm)*	***Radiation*** *(MJ m^{-2})*	***Max. Temperature*** *(Cº)*	***Min. Temperature*** *(Cº)*
January	53	684	32.4	22.7
February	67	613	32.1	22.9
March	82	639	32.2	23
April	140	553	30.9	22.7
May	188	490	29.3	21.7
June	184	432	28	20.6
July	166	464	27.3	19.8
August	120	527	27.7	19.6
September	75	593	29.1	20.4
October	59	683	30.7	21.4
November	48	678	31.8	22.3
December	35	693	32.3	22.7

Table 3 – Total monthly rain, radiation, maximum and minimum temperature in Lagarto - SE averaged over 36 years. **Data source**: Xavier et al. (2016)**.**

4.3. DATA AND SIMULATIONS

Climate data from January 1980 to December 2016 came from gridded database. This database is been used by several authors to allows crop simulation where meteorological data is not available or is not complete. Literature shows that simulation results do not appear to be significantly different when measured data is used (BATTISTI, 2019).

The genotype information used was obtained from the calibration of MANIHOT model made at *Embrapa Mandioca e Fruticultura*, Cruz das Almas, Bahia (research work not yet published). Relevant genotype parameters are shown in **Table 4**. The soil information was obtained from DSSAT default data. The chosen soil has a sandy loam texture with 150 cm of depth (**Table 5**).

The simulations were done using the MANIHOT cassava model. For all simulations conducted in this work, crop response to soil nutrients was considered ideal (the DSSAT modules responsible to calculate it were turned off) and there were no pests or diseases.

The planting density was set to 1.39 plant m^{-2}, corresponding to the spacing used on field experiments (0.8 m x 0.9 m).

Since the goal was to evaluate the viability of alternative management, two sets of simulations were done. The first aimed to establish the rainfed reference scenario. For this, planting dates follow the Agricultural Climate Risk Zoning[1] (*Zoneamento Agrícola de Risco Climático* - ZARC). The ZARC define best planting dates for each crop x county combination at Brazilian territory. For cassava, the criteria used to define that is the probability of have enough soil water available during the most sensible crop phase (from 1 to 150 DAP). The **Table 6** show ZARC recommendations for each place. Three planting dates for each recommended month were used (every ten days). No irrigation was applied for this scenario. Harvest dates were chosen to obtain crop cycles duration from eight to twelve months (from 240 to 360 DAP) for Lagarto and Laje, and from fourteen to eighteen (from 420 to 540 DAP) for Araripina.

For the second set of simulations (alternative scenario), planting dates outside the recommendation were used. Again, three planting dates by month and crop cycles lasting from eight to twelve months (240 to 360 DAP). For the irrigation, water was applied during all the season using a soil-based irrigation management, which followed the general parameters:

- Management depth: 0.6 m
- Irrigation threshold: 60% of soil water content or depletion of 40% (ALLEN et al., 1998)
- Irrigation efficiency: 80%
- Sprinkler system

[1] http://indicadores.agricultura.gov.br/zarc/index.htm

PARAMETER	FILE	UNIT	VALUE
B01ND	.CUL	ºCd	550
B12ND	.CUL	ºCd	550
BR1FX	.CUL	#	2.00
BR2FX	.CUL	#	2.00
BR3FX	.CUL	#	2.00
BR4FX	.CUL	#	2.00
LAXS	.CUL	cm^2	450
SLAS	.CUL	$cm^2\ g^{-1}$	200
LLIFA	.CUL	ºCd	1100
LPEFR	.CUL	-	0.25
LNSLP	.CUL	-	0.80
NODWT	.CUL	g	9.00
NODLT	.CUL	cm	2.00
PARUE	.ECO	$g\ MJ^{-1}$	2.45
TBLSZ	.ECO	Cº	13.00
PGERM	.ECO	ºCd	120
PHTV	.SPE	KPa	0.80

Table 4 – Genotype parameter values for BRS-Formosa. Thermal time from planting to first branching (B01ND); mean thermal time between branching levels after the first branching (B12ND); the number of branches for each branching point (BR#FX); maximum individual leaf area (LAXS); specific leaf area (SLAS); active leaf area duration after full expansion (LLIFA); leaf-petiole weight fraction (LPEFR); leaf appearance slope as a proportion of the leaf appearance reference curve (LNSLP); node weight (NODWT); internode length (NODLT); PAR conversion factor (PARUE); base temperature for leaf development (TBLSZ); germination duration (PGERM); vapor pressure deficit sensitivity threshold (PHTV). **Source:** *Embrapa Mandioca e Fruticultura* MANIHOT calibration.

Depth (cm)	Permanent Wilting (m^3 m^{-3})	Field Capacity (m^3 m^{-3})	Saturation Point (m^3 m^{-3})	Bulk Density (g cm^{-3})
	Sandy Loam – Clay 10%, Silt 30%, Sand 60%			
5	0.052	0.176	0.359	1.61
15	0.052	0.176	0.359	1.61
30	0.052	0.176	0.359	1.61
45	0.073	0.192	0.360	1.61
60	0.073	0.192	0.360	1.61
90	0.128	0.232	0.361	1.61
120	0.143	0.243	0.359	1.62
150	0.138	0.243	0.360	1.62

Table 5 – Soil hydraulic properties.
Source: DSSAT files.

Place	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lagarto												
Laje												
Araripina												

Table 6 – Planting dates recommended by ZARC for each place.
Source: Agricultural Climate Risk Zoning

Water treatments consisted of 100, 80, 60, 40 and 20% of the water required. To set irrigation treatments, a first simulation with automatic irrigation was done using the above parameters. This DSSAT option mimics irrigation management and restores the soil water content when it reaches the level defined by the user (here, depletion of 40%). For each planting date x year combination, the automatic irrigation schedule applied was extracted from simulation outputs. These schedules consisted of a sequence of value pairs: the DAP (days after planting at which the irrigation event occurred) and the corresponding water depth applied. The schedule with original water depth values was used as the 100% treatment. For the remaining treatments, the same schedule was applied but water depth values were reduced to 80, 60, 40 and 20% (JIANG et al., 2012).

For the reference scenario, it was conducted 30 (planting dates) x 35 (years) x 1 (soil), for a total of 1,050 model runs. For the alternative scenario, it was conducted 78 (planting dates) x 35 (years) x 5 (irrigation treatments) x 1 (soil), for a total of 13,650 model runs.

For both reference and alternative scenarios yield outputs were obtained and converted from dry matter (*kg* ha^{-1}) to fresh matter (*ton* ha^{-1}) considering that water represents 66% of the latter (factor of 0.33). Beyond that, total water applied (cumulative irrigation, *mm*) was also obtained for the alternative scenario and used for the economic analysis.

4.4. ECONOMIC ANALYSIS

Simulation outcomes were used as inputs for the economic analysis. The unit area used was one hectare. Variable costs are dependent on total water applied, while fixed costs are constant by hectare. Rainfed treatment did not include irrigation costs.

The set of costs presented by Alves et al. (2003) was updated using the IGP-DI (FGV) index[2]. The values were corrected from Jan 2003 to May 2020 (correction factor of 2.8541). The basic costs by hectare (irrigation independent) are shown in **Table 7**.

Irrigation costs were subdivided into:

1. Investment
2. Variable (dependent of total water applied)
3. Fixed (independent of total water applied)

To establish investment cost, an average value between eight Brazilian research works was used (**Table 8**). This reference values came from central pivot, drip and conventional sprinkler systems. Original values were updated using the IGP-DI (FGV) index according to the research year.

Variable costs consisted of workforce, pumping and water. The following micro-sprinkler project parameters were used: 3 *cv* hydraulic pump, sprinkler application rate of 54

[2] The citizen calculador (*calculadora do cidadão)* from Brazilian Central Bank. Available at: https://www3.bcb.gov.br/CALCIDADAO/publico/exibirFormCorrecaoValores.do?method=exibirFormCorrecaoValores. Accessed in June 2020.

L hour^{-1}, area covered by one sprinkler 7 m^2, energy consumption tax of 0.3173 *R$ kWh*$^{-1}$. From this information, pumping and workforce costs by water applied were defined as 0.1 and 0.8 *R$ mm*$^{-1}$, respectively (for a workforce cost of 50 *R$ day*$^{-1}$). The water cost was defined as 70% of pumping cost.

Fixed costs consisted of depreciation and maintenance. Depreciation was calculated based on investment cost using a residual value of 10% and a depreciation time of 10 years, which result in a value of 838 *R$ ha*$^{-1}$ *year*$^{-1}$. For maintenance, it was used the highest percentage value present by Vieira et al., (2010) – 8% of total investment cost – and the result was 744 *R$ ha*$^{-1}$ *year*$^{-1}$.

The sales prices (*R$ ton*$^{-1}$) were obtained from the National Supply Company (*Companhia Nacional de Abastecimento* – CONAB)[3]. Monthly prices from six years (January 2014 – June 2020) were updated using the IGP-DI (FGV) index. **Table 9** shows a summary of the monthly values.

Two types of economic analyses were done: Annual and Long Term. The first aims to assess if the financial operational balance would be positive. For that, only operational costs were considered and irrigation investment cost was left out. The sale price used was the mean value from Table 7 according to the corresponding harvest month. For each model run, it was obtained the revenue and variable costs based on DSSAT outputs. The revenue (*R$ ha*$^{-1}$) was calculated multiplying the yield (*ton ha*$^{-1}$) by the sale price (*R$ ton*$^{-1}$). Variable costs (*R$ ha*$^{-1}$) were calculated multiplying the total water applied (*mm*) by the workforce, pumping and water costs (*R$ mm*$^{-1}$). The gross margin (*R$ ha*$^{-1}$) was obtained by subtracting fixed and variable costs from revenue.

To compare reference and alternative scenarios, gross margin baselines values were obtained by the highest result for each place. The baseline represents the best result a farmer can obtain without irrigation and planting at recommended dates.

The Long-Term analysis aims to assess if the investment in irrigation would be a good choice for local farmers. This analysis was done only for the alternative scenario. For that, all costs were considered as well as investment in irrigation. Unlike the annual analysis, 20, 30 and 40% percentile yield values were used. For a single planting date, sale price was not kept constant. Twenty values between 200 and 500 *R$ ton*$^{-1}$ (values range from Table 7) were used to observe the influence of sale price variability on long term results.

[3] http://sisdep.conab.gov.br/precosiagroweb/. Accessed in July 2020

For each planting date x irrigation treatment combination, the yield value was multiplied by all the 20 sale prices to obtain 20 revenue values (*R$ ha^{-1}*). This leads to 20 (sale prices) x 78 (planting dates) x (5) irrigation treatments x (3) percentiles, 23,400 results used in the Long-Term analysis.

Variable costs were calculated using the average cumulative water applied (*mm*) for each planting date x irrigation treatment combination. A period of 10 years and the long-term financial indicator Net Present Value (NPV) were used to evaluate the results.

The Net Present Value (NPV, *R$ ha^{-1}*) is the benefit (the difference between revenue and cost) adjusted to the discount rate[4]. A positive value indicates that the proposed management strategy would be a profitable investment. The NPV at the tenth year was calculated as presented by Arco-verde and Amaro (2020):

$$NPV = \sum_{j=1}^{10} \frac{R_j - C_j}{(1+i)^j} - I$$

Where:

R = Revenue on period j

C = Costs on period j

j = period (year)

i = project discount rate

I = initial investment

[4] A value of 5% was used. Northeast Constitutional Fund (*Fundo Constitucional do Nordeste – FNE)* and the newest National Monetary Council rule (*Conselho Monetário Nacional – CMN*). Available at: https://www.editoraroncarati.com.br/v2/Diario-Oficial/Diario-Oficial/RESOLUCAO-CMN-N%C2%BA-4-832-DE-25-06-2020.html . Accessed in August 18, 2020.

Specification	Unit	Quantity	Unit Price (Alves et al., 2003)	Unit Price (updated)	Total value (Updated)
			------------------------ R$	------------------------	
			Inputs		
Stems	*m³*	6	8	22.83	137
Urea	*kg*	67	0.6	1.71	115
Simple superphosphate	*kg*	333	0.5	1.43	475
Potassium chloride	*kg*	67	0.6	1.71	115
Ant killer	*kg*	3	2.5	7.14	21.5
Herbicide	*kg*	1	73	90	90
Insecticide	*kg*	1	40	49	49
			Soil Preparation		
Plowing	*hour / tractor*	*3*	*20*	*57*	*171*
Harrowing	*hour / tractor*	*1.5*	*20*	*57*	*86*
Groove	*hour / tractor*	*2*	*20*	*57*	*114*
			Fertilization		
Fertilizers application	*day / worker*	*4*	*8*	*50**	*200*
			Planting		
Stems transport	*day / worker*	*2*	*8*	*50**	*100*
Stems selection and preparation	*day / worker*	*3*	*8*	*50**	*150*
Planting	*day / worker*	*3*	*8*	*50**	*150*
			Management		
Weeding (04)	*day / worker*	*48*	*8*	*50**	*2400*
Pesticides application	*day / worker*	*11*	*8*	*50**	*550*
			Harvest		
Harvest	*day / worker*	*25*	*8*	*50**	*1250*
			Total		
Operational Costs				*100 %*	*6173*
Taxes				*20 %*	*1234*
Total Cost by hectare				*120 %*	*7407*

Table 7 – Detailed Costs by hectare for cassava at Cruz das Almas, Ba. Updated values were obtained multiplying the original value (Alves et al., 2003) by the correction factor (2.8541). Values marked by an asterisk were changed to a value closer to reality.

Publication	Total area (ha)	Crop	State	Total investment	Investment by hectare	Investment by hectare (updated)
Justino et al., (2019)	70	Common Beans	*Goiás*	*R$ 350,000.00*	*R$ 5,000.00*	*R$ 5,600.00*
Souza (2014)	75	Coffee	*Minas Gerais*	*R$ 257,000.00*	*R$ 3,430.00*	*R$ 9,226.70*
Ferri (2017)	20	Soy	*Rio Grande do Sul*	*R$ 219,000.00*	*R$ 10,950.00*	*R$ 13,030.50*
Barbosa (2015)	1	Tomato	*Bahia*	*R$ 6,200.00*	*R$ 6,200.00*	*R$ 8,804.00*
Oliveira et al., (2010) and Silva (2007)	22	Coffee	*Minas Gerais*	*R$ 101,200.00*	*R$ 4,600.00*	*R$ 8,970.00*
Souza (2004)	75	Coffee	*Minas Gerais*	*R$ 284,937.00*	*R$ 3,799.00*	*R$ 10,219.31*
Oliveira et al., (2016)	1	Broccoli	*Mato Grosso do Sul*	*R$ 8,884.00*	*R$ 8,884.00*	*R$ 11,371.52*
Castro Júnior et al., (2015)	10	Cowpea	*Maranhão*	*R$ 51,000.00*	*R$ 5,100.00*	*R$ 7,242.00*
Average						**R$ 9,308.00**

Table 8 – Works used to establish irrigation investment costs.

Month	Minimum	Mean	Maximum
	----------- R$ ton^{-1} -----------		
January	*233*	*473*	*847*
February	*319*	*496*	*681*
March	*282*	*417*	*598*
April	*269*	*438*	*607*
May	*263*	*413*	*652*
June	*250*	*425*	*930*
July	*254*	*416*	*621*
August	*254*	*396*	*583*
September	*250*	*369*	*562*
October	*226*	*398*	*579*
November	*271*	*431*	*704*
December	*326*	*439*	*676*

Table 9 – Cassava monthly sale prices summary.
Source: CONAB (2020).

5. RESULTS

5.1. YIELD RESULTS

Figure 11 and **Figure 12** shows yield results for the rainfed simulations according to region, planting date and cycle length. The region influence yield results greatly. The average yield was 18, 34 and 39 *ton* ha^{-1} for Araripina, Lagarto and Laje, respectively.

Cycle length influence yield differently. For Araripina average yields rose from 12 *ton* ha^{-1} on 14 months to 21 *ton* ha^{-1} on 18 months, an increase of 75%. For Lagarto, average yields were reduced from 34 *ton* ha^{-1} on 8 months to 33 *ton* ha^{-1} on 12 months, a small decrease of 2.9%. For Lage, however, average yields rose from 35 *ton* ha^{-1} on 8 months to 42 *ton* ha^{-1} on 12 months, an increase of 20%.

Planting dates also influence yield. Averaged over cycle length and months, the yield at Araripina was reduced from 19 *ton* ha^{-1} on January to 16.6 *ton* ha^{-1} on February, a decrease of 15.7%. For Lagarto, values of 41, 37, 31 and 25 *ton* ha^{-1} were obtained for March, April, May and June, respectively. For Laje, values of 42, 40, 39, 36.6 and 36 *ton* ha^{-1} were obtained for February, March, April, May and June, respectively.

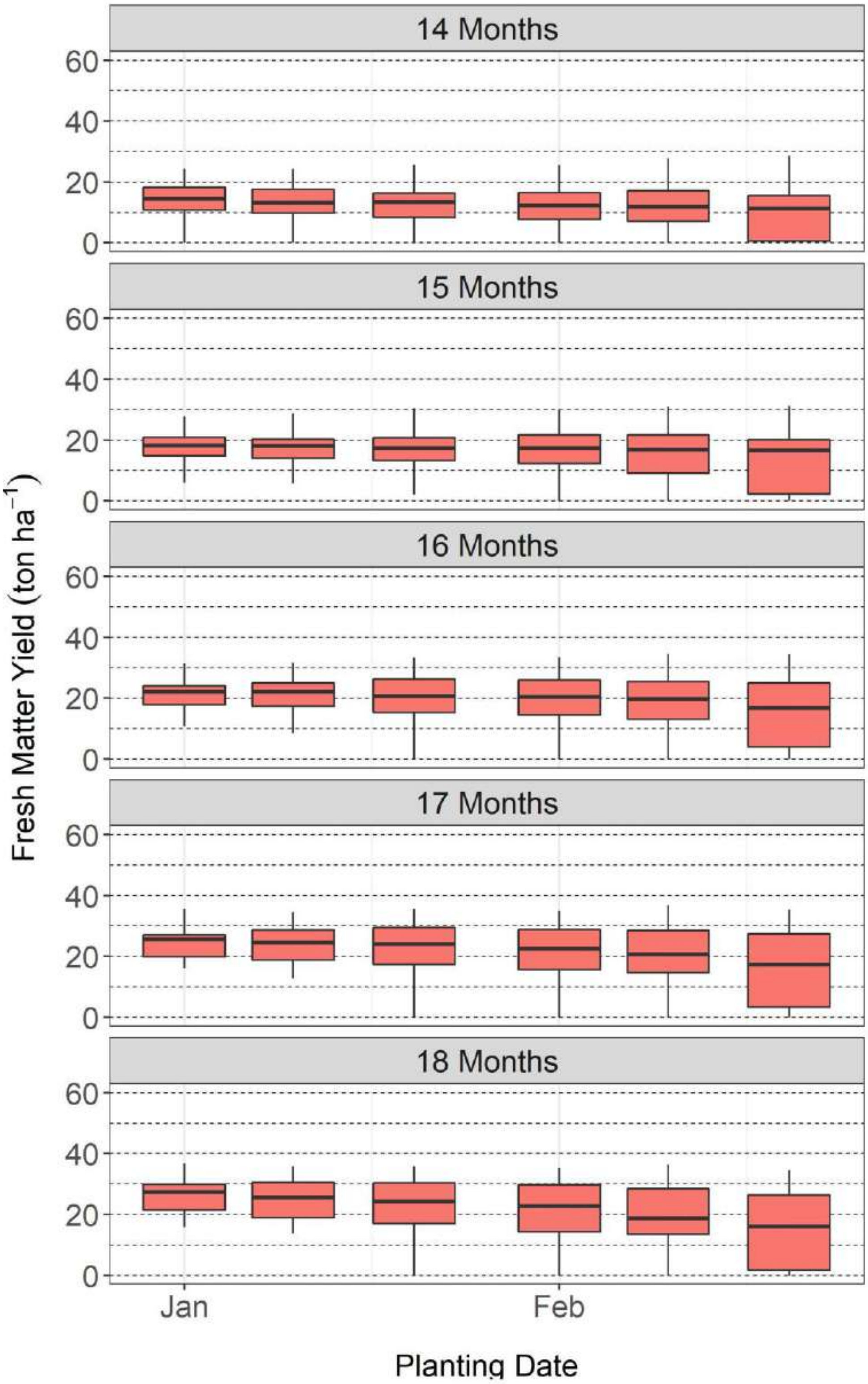

Figure 11 – Yield results for rainfed simulations to Araripina, planting date and cycle length. Each box is the result of 35 simulated years.

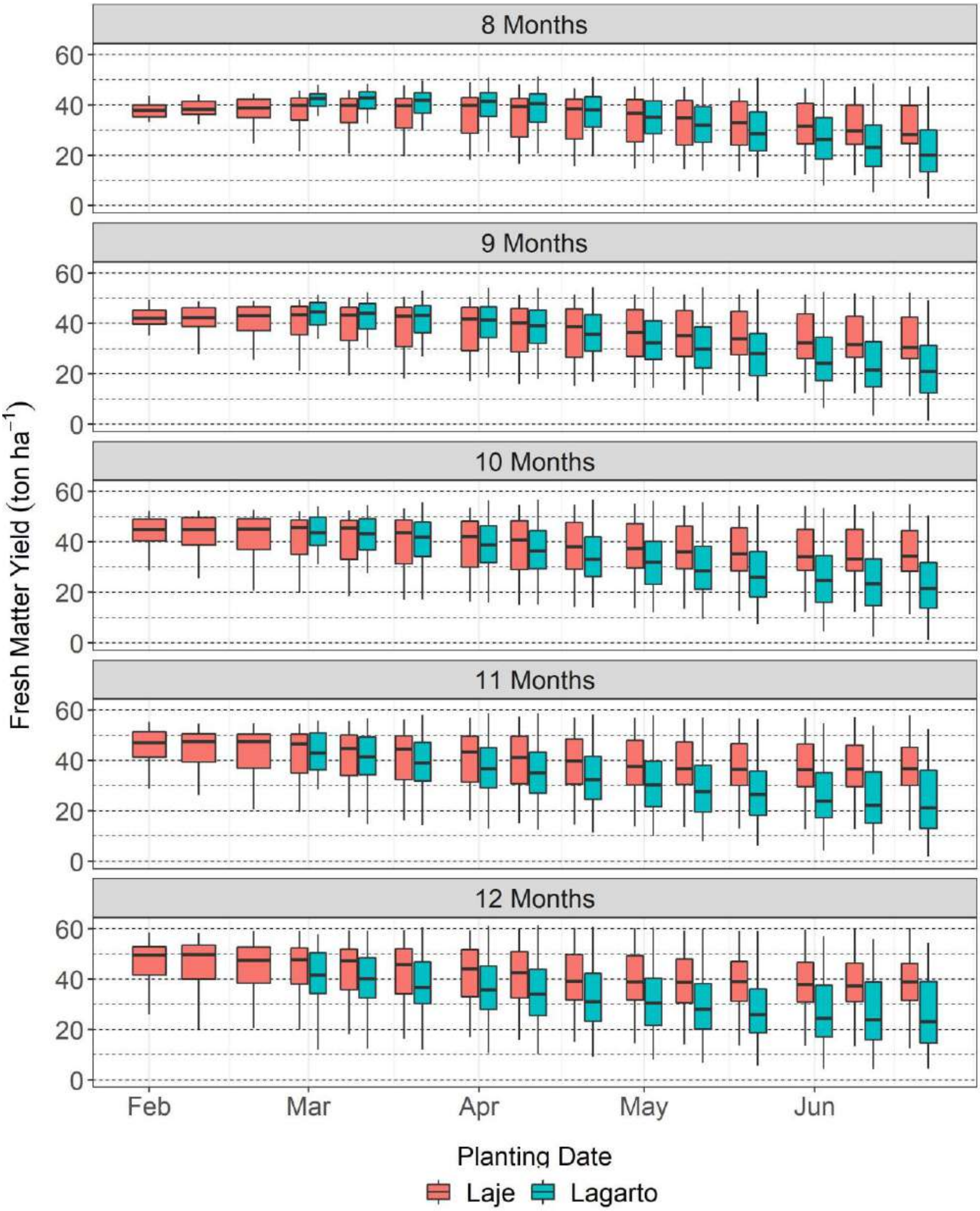

Figure 12 – Yield results for rainfed simulations to Lage and Lagarto, planting date and cycle length. Each box is the result of 35 simulated years.

Figure 13 shows yield for Araripina alternative scenario. Averaged over all planting dates and irrigation treatments, yields of 22, 24.2, 26, 27.4 and 28.5 *ton ha*$^{-1}$ were obtained for 8, 9, 10, 11 and 12 months, respectively. The second was water treatment. The yields results were 39.2, 34.8, 28.7, 23.7, 20 and 5.6 *ton ha*$^{-1}$ for the treatments 100, 80, 60, 40, 20 and rainfed, respectively. Planting dates also influence yield. Averaged over all cycle lengths and irrigation treatments, values of 16.4, 16.2, 18.4, 21.6, 24.6, 28.1, 30.6, 33.3, 34.9 and 32.1 *ton ha*$^{-1}$ for March, April, May, June, July, August, September, October, November and December, respectively.

The influence of cycle length on yield was dependent on planting date. The average yield at 12 months harvest was +23%, +65%, +103%, +105%, +76%, +45%, +20%, +6%, -3% and -8% different than the 8 months harvest for March, April, May, June, July, August, September, October, November and December, respectively. This difference was also influenced by irrigation treatments. The average yield at 12 months harvest was 28.7%, 28.3%, 30.8%, 33.8%, 38.1% and 1.8% higher than the 8 months harvest for the treatments 100, 80, 60, 40, 20 and rainfed, respectively.

For Araripina, as expected, much higher yield results were obtained in the alternative scenario compared to the reference one. The higher average yield result from reference was 25 ton ha^{-1} (at January 01, harvest at 18 months), while the same from alternative scenario were 47.9 (at November 20, harvest at 12 months), 44.2 (at November 01, harvest at 11 months), 39.8 (at October 20, harvest at 10 months), 36.4 (at October 20, harvest at 9 months), 33.8 (at October 20, harvest at 9 months) and 22.9 *ton ha*$^{-1}$ (at November 20, harvest at 8 months) for 100, 80, 60, 40, 20 and rainfed water treatments, respectively. This means that irrigation was able to increase average yields by 91, 76, 59, 45 and 35% for 100, 80, 60, 40 and 20 water treatments, respectively.

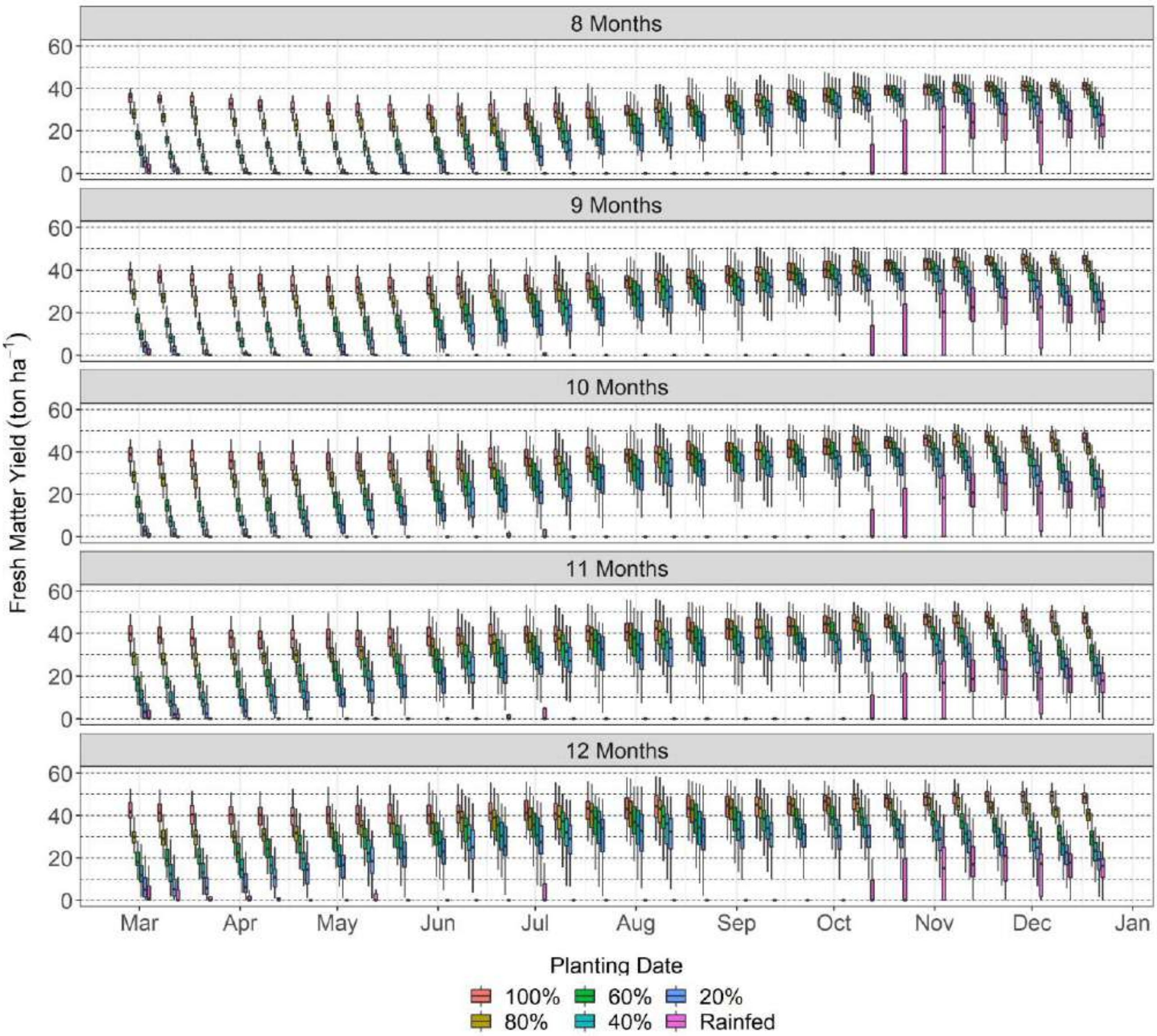

Figure 13 – Yield results for Araripina alternative scenario according to irrigation treatment, planting date and cycle length. Each box is the result of 35 simulated years.

Figure 14 shows the yield for the Laje alternative scenario. The first factor that influenced the yield was the harvest time. Averaged over all planting dates and irrigation treatments, yields of 35.7, 38.8, 41.3, 43.5 and 45.8 *ton ha*$^{-1}$ were obtained for 8, 9, 10, 11 and 12 months, respectively. The second was irrigation treatment. The yield results were 44.4, 43.9, 42.6, 40.9, 39.4 and 35.1 *ton ha*$^{-1}$ for the treatments 100, 80, 60, 40, 20 and rainfed, respectively. Planting dates also influence yield. Averaged over all cycle lengths and irrigation treatments, values of 40.9, 40.4, 40.1, 40.1, 41.1, 42.1 and 42.6 *ton ha*$^{-1}$ for July, August, September, October, November, December and January, respectively.

The influence of cycle length on yield was dependent on planting date. The average yield at the 12 months harvest was 20.4%, 21.6%, 23.9%, 28.6%, 34.3%, 36.1% and 34.4% higher than the 8 months harvest for July, August, September, October, November, December and January, respectively. This difference was also influenced by irrigation treatments. The average yield at the 12 months harvest was 24%, 24.1%, 25.8%, 28.6%, 31.6% and 39.4% higher than the 8 months harvest for the treatments 100, 80, 60, 40, 20 and rainfed, respectively.

For Lage, the average yields did not present an important increase compared to the reference scenario. The higher average yield result from reference was 46 ton ha^{-1} (at February 01, harvest at 12 months), while the same for the alternative scenario were 49.7 (at January 10, harvest at 12 months), 49.6 (at December 20, harvest at 12 months), 49.2 (at December 20, harvest at 12 months), 48.7 (at January 01, harvest at 12 months), 48.2 (at January 01, harvest at 12 months) and 45.5 ton ha^{-1} (at January 10, harvest at 12 months) for 100, 80, 60, 40, 20 and rainfed water treatments, respectively. This means that irrigation was able to increase average yields by 8, 7.8, 6.9, 5.8 and 4.7% for 100, 80, 60, 40 and 20 water treatments, respectively.

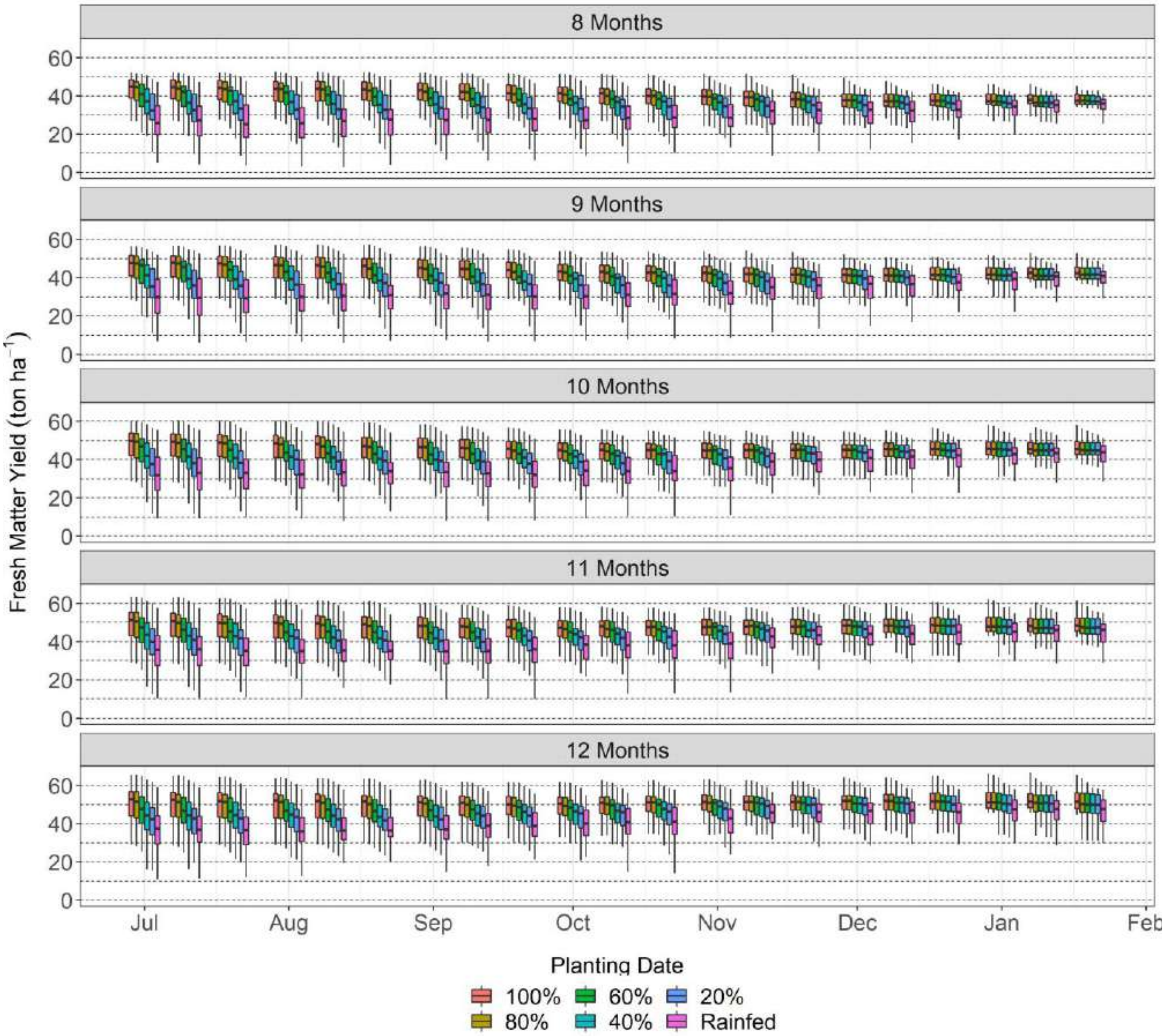

Figure 14 – Yield results for Laje alternative scenario according to irrigation treatment, planting date and cycle length. Each box is the result of 35 simulated years.

Figure 15 shows the yield for the Lagarto alternative scenario. Averaged over all planting dates and irrigation treatments, yields of 30.1, 33.3, 36.1, 38.6 and 41 *ton ha*$^{-1}$ were obtained for 8, 9, 10, 11 and 12 months, respectively. For irrigation treatments, yields results were 43.9, 41, 37.8, 34.8, 32.4 and 25 *ton ha*$^{-1}$ for the treatments 100, 80, 60, 40, 20 and rainfed, respectively. Planting dates also influence yield. Averaged over all cycle lengths and irrigation treatments, values of 32.6, 30.9, 30.7, 32.2, 35.2, 39, 42.2 and 43.6 *ton ha*$^{-1}$ for July, August, September, October, November, December, January and February, respectively.

The influence of cycle length on yield was dependent on planting date. The average yield at the 12 months harvest was 20.7%, 34.9%, 45.6%, 50.3%, 50.6%, 44.4%, 33.2% and 19.7% higher than the 8 months harvest for July, August, September, October, November, December, January and February, respectively. This difference was also influenced by irrigation treatments. The average yield at the 12 months harvest was 25.7%, 27.8%, 33.8%, 40%, 45.8% and 57.9% higher than the 8 months harvest for the treatments 100, 80, 60, 40, 20 and rainfed, respectively.

For Lagarto, the yields increased compared to the reference scenario. In general, rainfed yields were already high, which limits the importance of irrigation for this region. The higher average yield result from reference was 43 ton ha^{-1} (at March 01, harvest at 9 months), while the same for the alternative scenario were 52.2 (at February 20, harvest at 12 months), 50.5 (at January 01, harvest at 12 months), 49.2 (at January 01, harvest at 12 months), 47.7 (at January 01, harvest at 12 months), 46.6 (at January 20, harvest at 12 months) and 41.3 ton ha^{-1} (at February 20, harvest at 11 months) for 100, 80, 60, 40, 20 and rainfed water treatments, respectively. This means that irrigation was able to increase average yields by 21, 17, 14, 10 and 8% for 100, 80, 60, 40 and 20 water treatments, respectively.

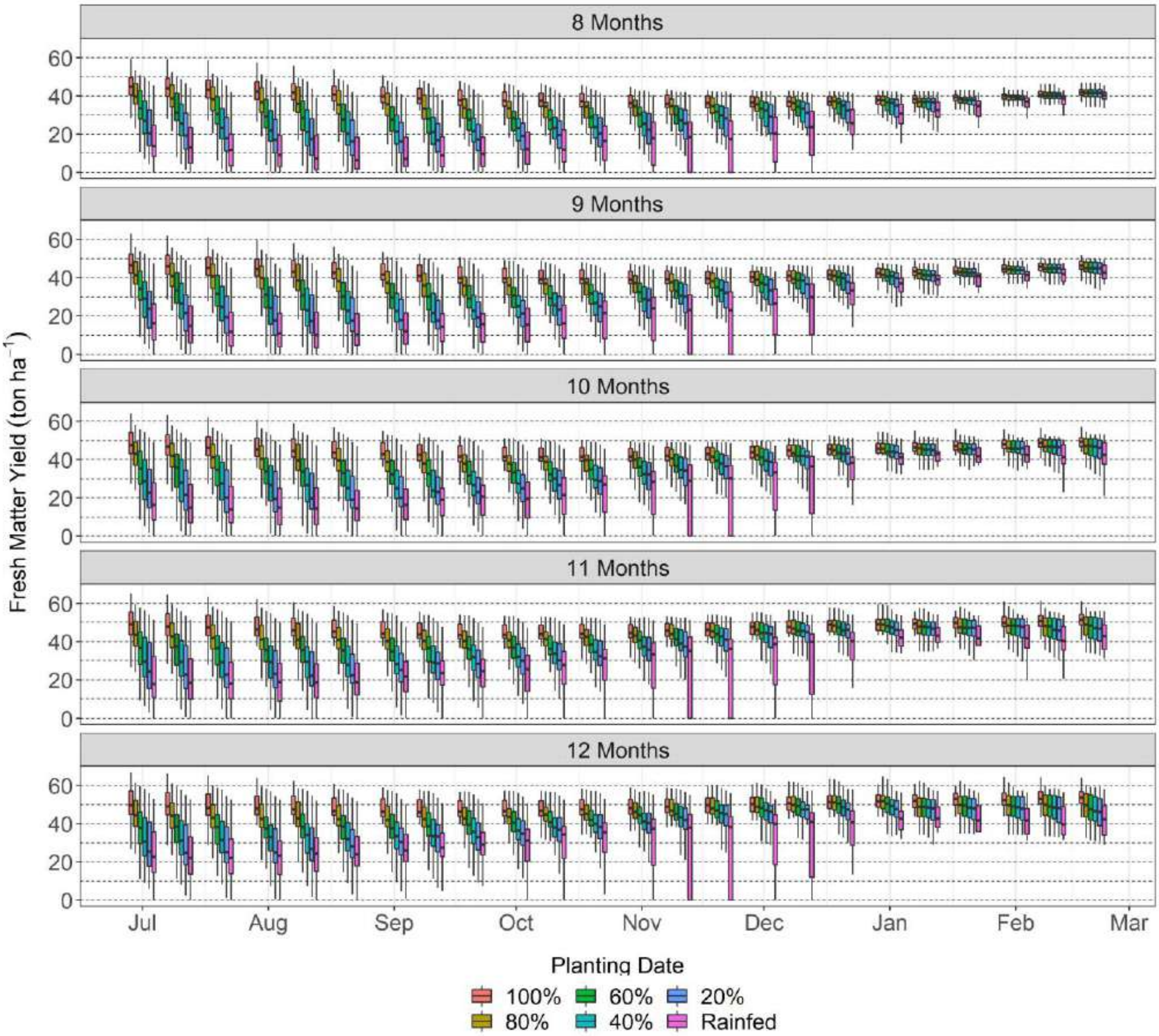

Figure 15 – Yield results for Lagarto alternative scenario according to irrigation treatment, planting date and cycle length. Each box is the result of 35 simulated years.

5.2. ANNUAL ECONOMIC ANALYSIS

Figure 16 and **Figure 17** show the gross margins values according to region, planting date and cycle length for the reference scenario. As well as yield, region influence these results greatly. The average gross margin was -317, 7,537 and 9,770 *R$* ha^{-1} for Araripina, Lagarto and Laje, respectively.

The results were influenced by the harvest time. Averaged over all planting dates, the gross margin at Araripina was -2,038, -770, 135, 548 and 537 *R$* ha^{-1} for 14, 15, 16, 17 and 18 months, respectively. For Lagarto, values of 7,835, 8,190, 7,920, 7,180 and 6,540 *R$* ha^{-1} were obtained for 8, 9, 10, 11 and 12 months, respectively. For Laje, values of 7,840, 9,410, 10,270, 10,660 and 10,660 *R$* ha^{-1} were obtained for 8, 9, 10, 11 and 12 months, respectively.

According to planting date, the average gross margin was 317 and -952 *R$* ha^{-1} for January and February, respectively. For Lagarto, values of 11,200, 9,290, 6290 and 3,336 *R$* ha^{-1} were obtained for March, April, May and June, respectively. For Laje, values of 11,046, 10,950, 10,077, 8,910 and 7,840 *R$* ha^{-1} were obtained for February, March, April, May and June, respectively.

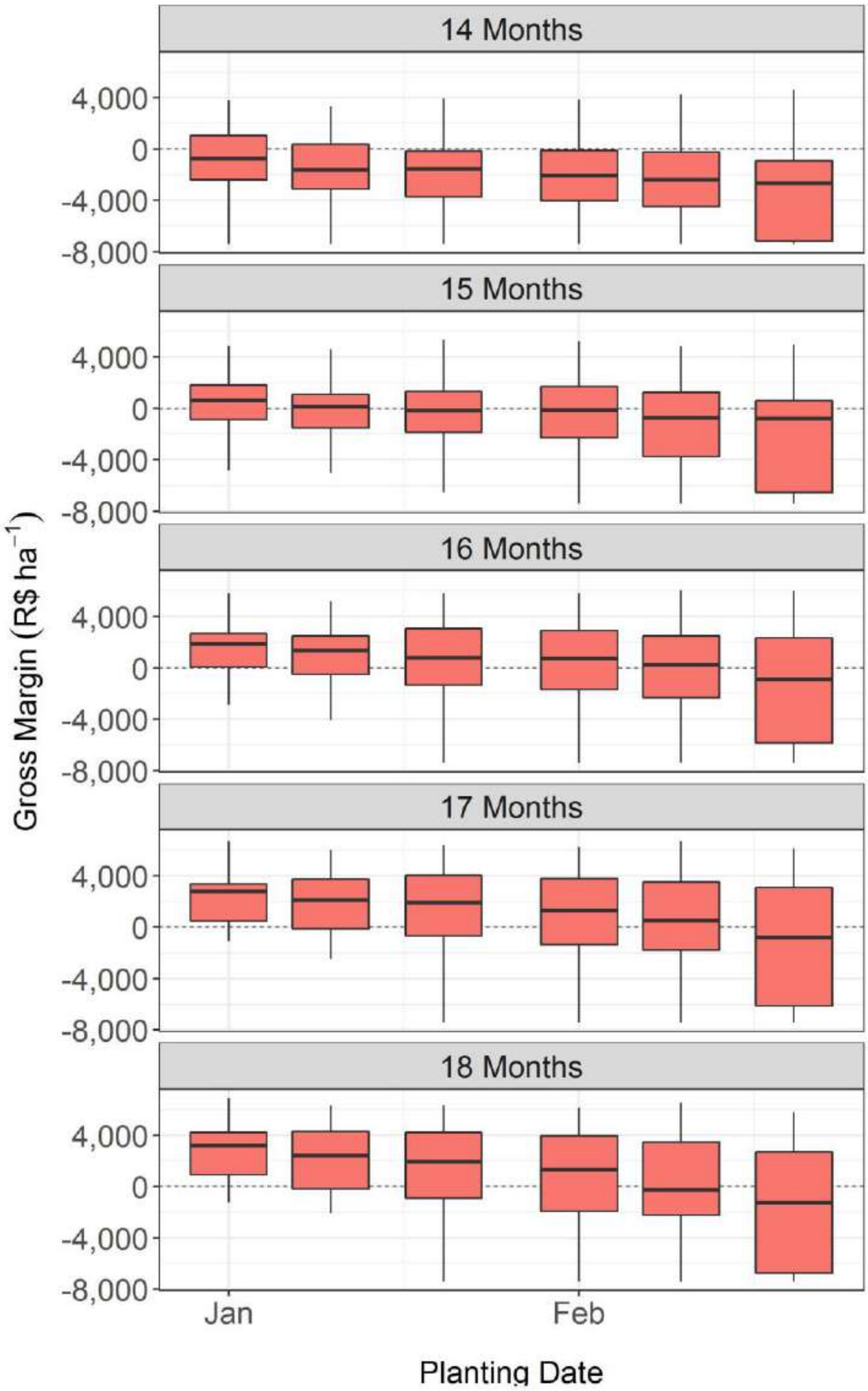

Figure 16 – Gross Margin results for Araripina rainfed scenario according to planting date and cycle length. Each box is the result of 35 simulated years.

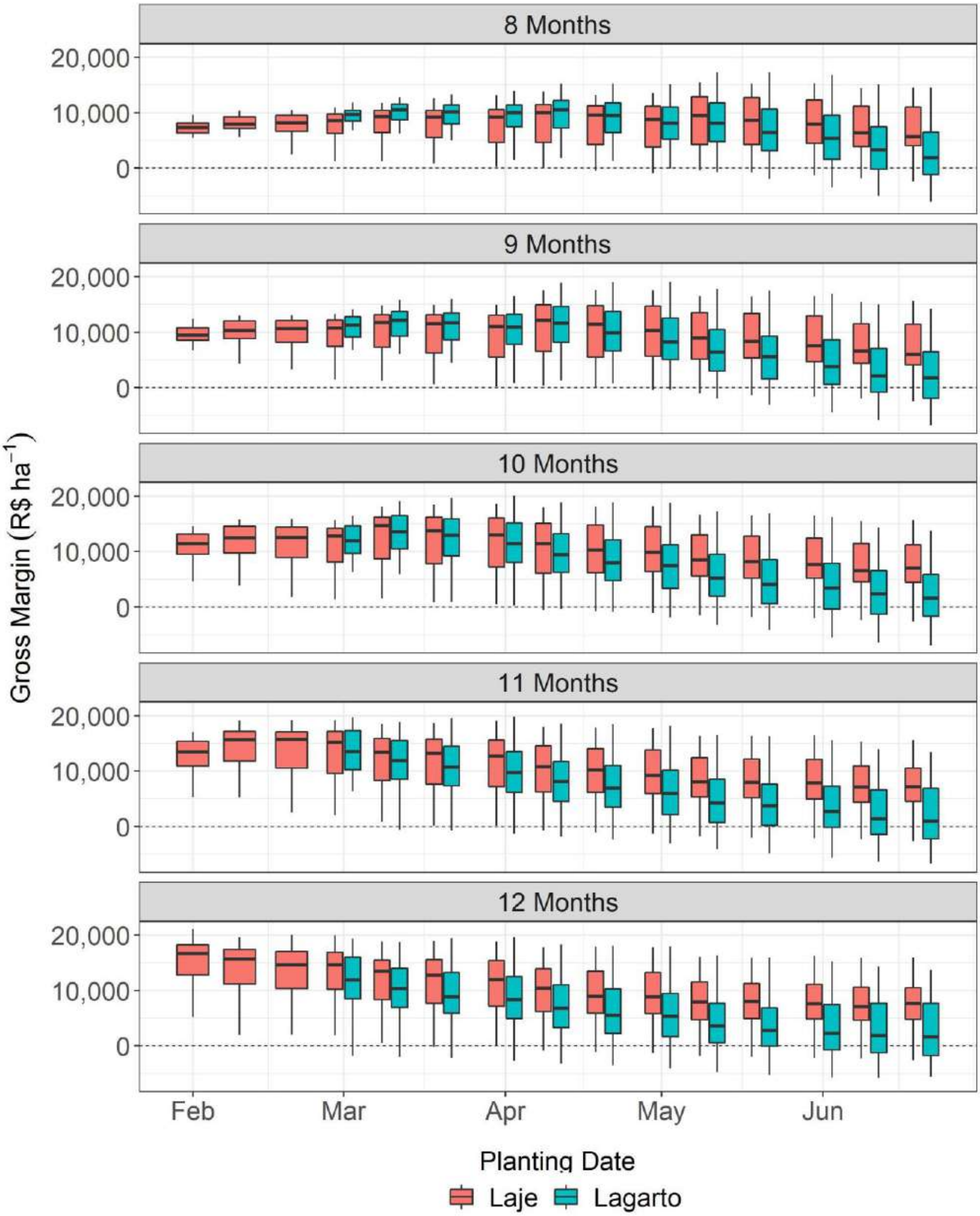

Figure 17 – Gross margin results for Lage and Lagarto rainfed scenario according to planting date and cycle length. Each box is the result of 35 simulated years.

Figure 18 shows the gross margin for Araripina according to irrigation treatment, planting date and cycle length. Averaged over all planting dates and irrigation treatments, gross margin values of 181, 1,032, 1,688, 2,186 and 2,624 *R$ ha*$^{-1}$ were obtained for 8, 9, 10, 11 and 12 months, respectively. Irrigation treatments also influenced gross margins directly. Average gross margin results were 6,904, 5,060, 2,508, 464, -1,056 and -5,155 *R$ ha*$^{-1}$ for the treatments 100, 80, 60, 40, 20 and rainfed, respectively. Planting dates also influence the annual economic results. Averaged over all cycle lengths and irrigation treatments, values of -1,627, -1,682, -878, 184, 1,165, 2,275, 3,059, 4,087, 4,826 and 4,015 *R$ ha*$^{-1}$ were obtained for March, April, May, June, July, August, September, October, November and December, respectively.

The influence of cycle length on gross margin was dependent on planting date. The average gross margin at the 12 months harvest was 83.5%, 103.5%, 141%, 195%, 330%, 563%, 77%, 24%, 9.3% and 9.5% higher than the 8 months harvest for March, April, May, June, July, August, September, October, November and December, respectively. This difference was also influenced by irrigation treatments. The average gross margin at the 12 months harvest was 70%, 91%, 280%, 276%, 102% and 3.6% higher than the 8 months harvest for the treatments 100, 80, 60, 40, 20 and rainfed, respectively.

For Araripina, much higher average gross margin results were obtained in the alternative scenario compared to the reference one. The higher average gross margin result from reference was 2,176 R$ ha^{-1} (at January 01, harvest at 18 months), while the same for the alternative scenario were 11,670 (at December 10, harvest at 12 months), 9,018 (at November 10, harvest at 12 months), 6,190 (at October 10, harvest at 11 months), 4,900 (at October 20, harvest at 9 months), 4,079 (at November 01, harvest at 8 months) and 1,397 R$ ha^{-1} (at November 20, harvest at 8 months) for 100, 80, 60, 40, 20 and rainfed water treatments, respectively. This means that irrigation was able to increase average gross margins by 436, 314, 184, 125 and 87% for 100, 80, 60, 40 and 20 water treatments, respectively.

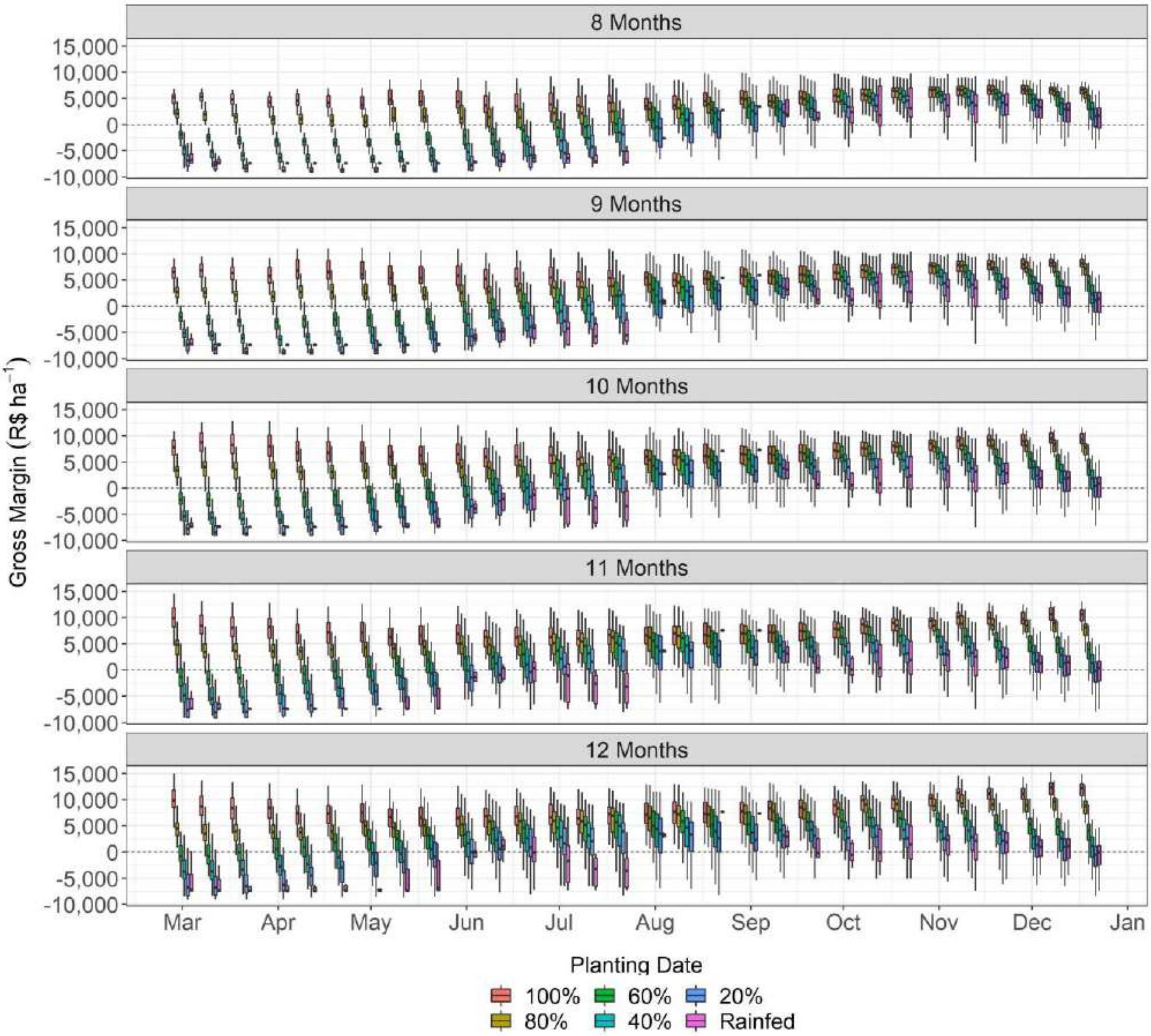

Figure 18 – Gross margin for Araripina alternative scenario according to irrigation treatment, planting date and cycle length. Each box is the result of 35 simulated years.

Figure 19 shows the economic risk for Araripina based on planting date, cycle length and water treatment. For the 100% water treatment, all planting dates and harvest times resulted in a low risk (below 20%). The same is true for the 80%, except for a harvest time of 8 months where some planting dates before August present medium risk (20% < risk < 40%). The 60, 40 and 20% water treatments show a similar behavior in terms of economic risk. For planting dates in September, October, November and December, low to medium risks were obtained for all harvest times. However, from March to August, higher (40% <

risk < 60%) to very high (above 60%) were obtained. During this period, the risk was inversely proportional to the harvest time. The rainfed was the water treatment with the higher economic risk. The lower values (high and medium risk) were obtained in November and December. Before that, the risk is too high to justify the management choice.

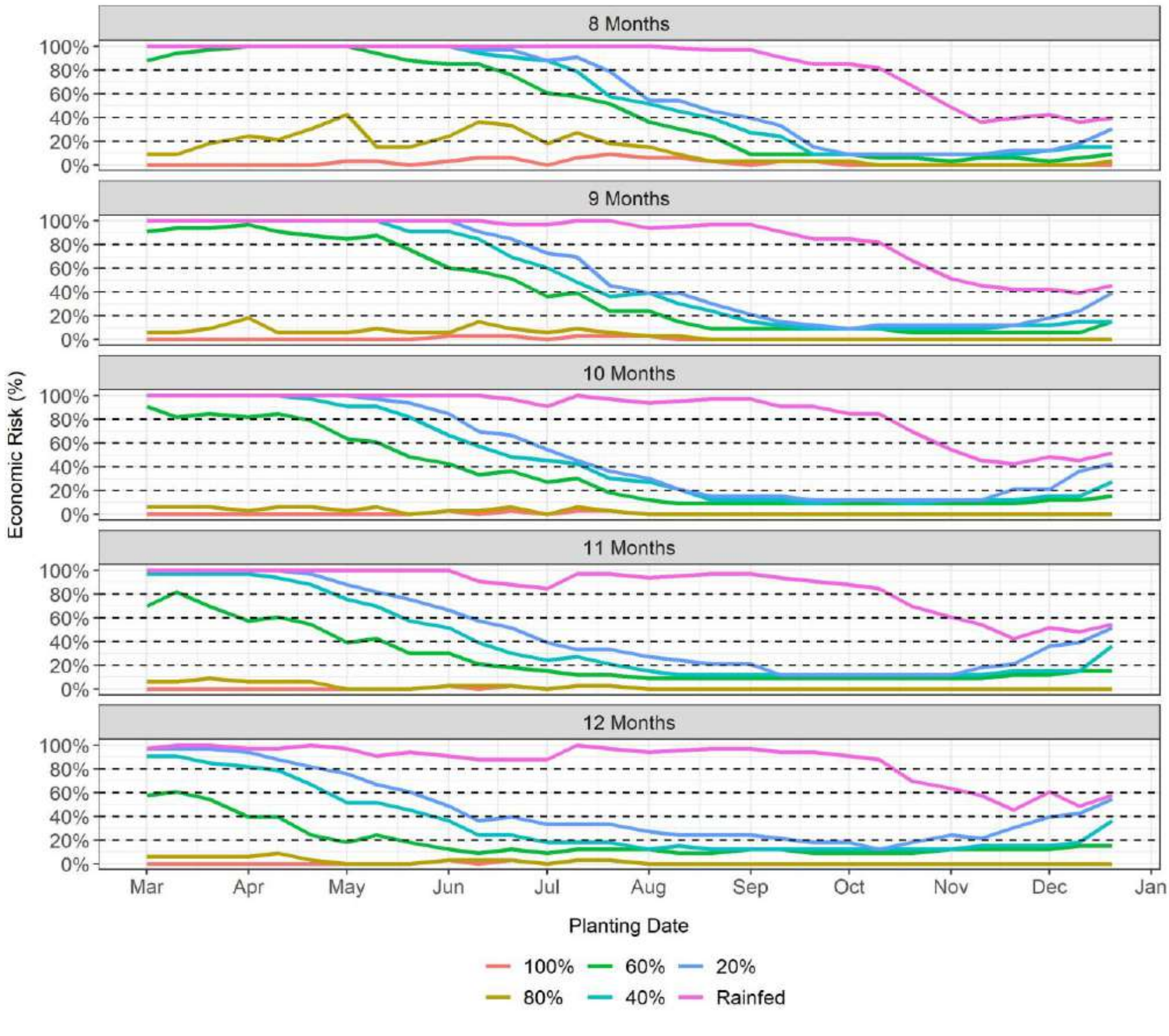

Figure 19 – Economic Risk for Araripina alternative scenario according to irrigation treatment, planting date and cycle length.

Figure 20 show the gross margin for Lagarto according to irrigation treatment, planting date and cycle length.

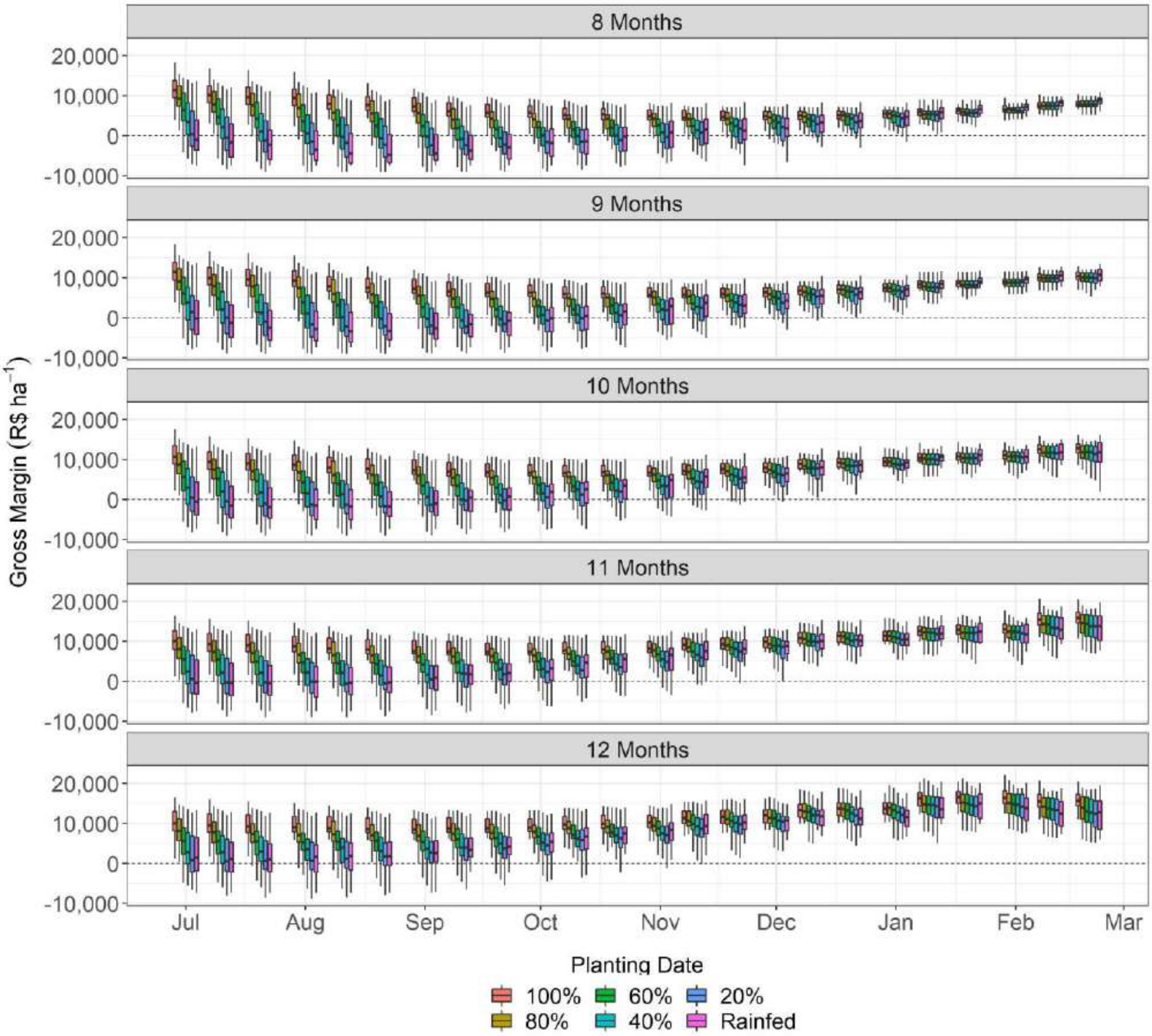

Figure 20 – Gross margin for Lagarto alternative scenario according to irrigation treatment, planting date and cycle length. Each box is the result of 35 simulated years.

Harvest time influenced gross margin results. Averaged over all planting dates and irrigation treatments, gross margin values of 3,346, 4,495, 5,700, 7,066 and 8,458 *R$ ha*$^{-1}$ were obtained for 8, 9, 10, 11 and 12 months, respectively. Irrigation treatments also influenced gross margins directly. Gross margin results were 8,720, 7,582, 6,342, 5,177, 4,272 and 2,859 *R$ ha*$^{-1}$ for the treatments 100, 80, 60, 40, 20 and rainfed, respectively. The annual economic results were also influenced by the planting month. Averaged over all cycle lengths and irrigation treatments, values of 4,511, 3,393, 3,111, 3,695, 5,085, 7,045, 9,160 and 10,515 *R$ ha*$^{-1}$ were obtained for July, August, September, October, November, December, January and February, respectively.

The influence of cycle length on gross margin was dependent on planting date. The average gross margin at the 12 months harvest was 9.8%, 97%, 298%, 404%, 333%, 238%, 169% and 88% higher than the 8 months harvest for July, August, September, October, November, December, January and February, respectively. This difference was also influenced by irrigation treatments. The average gross margin at the 12 months harvest was 71%, 87%, 130%, 211%, 370% and 1958% higher than the 8 months harvest for the treatments 100, 80, 60, 40, 20 and rainfed, respectively.

For Lagarto, slightly higher average gross margin results were obtained in the alternative scenario compared to the reference one. The higher average gross margin result from reference was 13,322 R$ ha^{-1} (at March 01, harvest at 11 months), while the same for the alternative scenario were 16,046 (at February 01, harvest at 12 months), 14,608 (at January 20, harvest at 12 months), 14,364 (at January 20, harvest at 12 months), 14,052 (at January 20, harvest at 12 months), 13,768 (at January 20, harvest at 12 months) and 12,703 R$ ha^{-1} (at February 20, harvest at 11 months) for 100, 80, 60, 40, 20 and rainfed water treatments, respectively. This means that irrigation was able to increase average gross margins by 20, 9.6, 7.8, 5,4 and 3.3% for 100, 80, 60, 40 and 20 water treatments, respectively.

Figure 21 shows the economic risk for Lagarto based on planting date, cycle length and water treatment. From December to February, all water treatments present economic risks ranging from low (below 20%) to medium (20% < risk < 40%). The 100% and 80% water treatments present a low risk for all planting dates and harvest times. The 60% water treatment showed some dates (August to November) with medium risk before the harvest time of 12 months. The 40% water treatment showed high risk for harvest before 11 months and planting dates between August and November. The 20% water treatment showed a very high risk for harvest times of 8 and 9 months and planting in August and September.

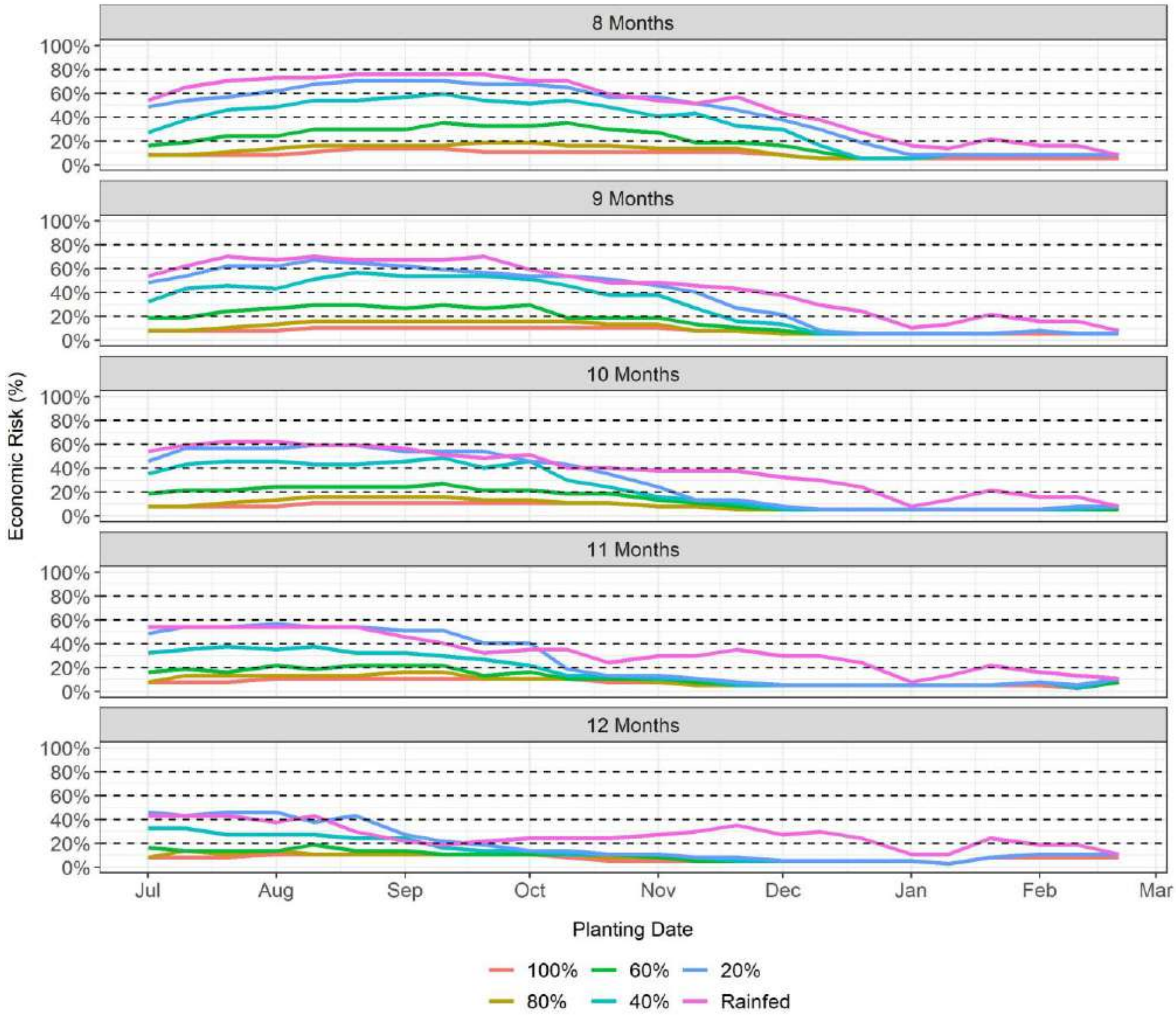

Figure 21 – Economic Risk for Lagarto alternative scenario according to irrigation treatment, planting date and cycle length.

Figure 22 show the gross margin for Laje according to irrigation treatment, planting date and cycle length.

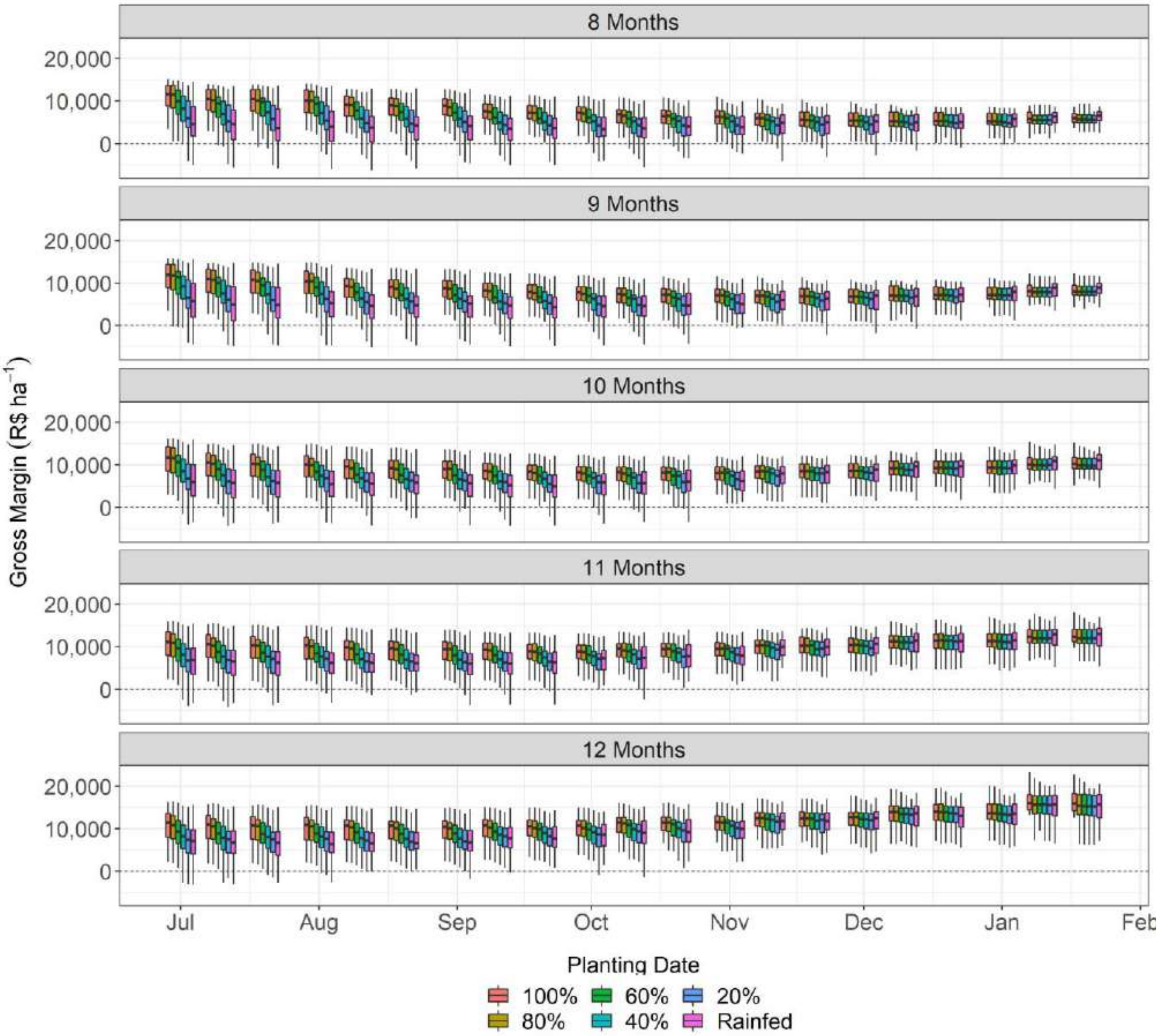

Figure 22 – Gross margin for Laje alternative scenario according to irrigation treatment, planting date and cycle length. Each box is the result of 35 simulated years.

Harvest time influenced the gross margin results. Averaged over all planting dates and irrigation treatments, gross margin values of 5,715, 6,668, 7,593, 8,645 and 10,116 *R$ ha*$^{-1}$ were obtained for 8, 9, 10, 11 and 12 months, respectively. Irrigation treatments also influenced gross margins directly. Gross margin results were 8,784, 8,601, 8,094, 7,449, 6,865 and 6,719 *R$ ha*$^{-1}$ for the treatments 100, 80, 60, 40, 20 and rainfed, respectively. The annual economic results were also influenced by the planting month. Averaged over all cycle lengths and irrigation treatments, values of 7,997, 7,276, 6,836, 6,839, 7,455, 8,394 and 9,343 *R$ ha*$^{-1}$ were obtained for July, August, September, October, November, December and January, respectively.

The influence of cycle length on gross margin was dependent on planting date. The average gross margin at the 12 months harvest was 6%, 21%, 48%, 84%, 125%, 149% and 163% higher than the 8 months harvest for July, August, September, October, November, December, January and February, respectively. This difference was also influenced by irrigation treatments. The average gross margin at the 12 months harvest was 58%, 59%, 67%, 81%, 99% and 117% higher than the 8 months harvest for the treatments 100, 80, 60, 40, 20 and rainfed, respectively.

For Laje, average gross margin results from the alternative scenario did not differ from the reference one. The higher average gross margin result from reference was 15,110 R$ ha^{-1} (at February 01, harvest at 12 months), while the same for the alternative scenario were 15,179 (at January 10, harvest at 12 months), 14,548 (at January 20, harvest at 12 months), 14,509 (at January 10, harvest at 12 months), 14,452 (at January 10, harvest at 12 months), 14,428 (at January 10, harvest at 12 months) and 14,726 R$ ha^{-1} (at January 10, harvest at 12 months) for 100, 80, 60, 40, 20 and rainfed water treatments, respectively. This means that irrigated results differ from reference by +0.4, -3.7, -3.9, -4.3 and -4.5% for 100, 80, 60, 40 and 20 water treatments, respectively.

Figure 23 shows the economic risk for Laje based on planting date, cycle length and water treatment. At a harvest time of 8 months, the rainfed and 20% water treatments present some planting dates with medium risk (20% < risk < 40%). From 9 to 12 months, it is safe to say that any planting date offer low economic risk (below 20%) at Laje.

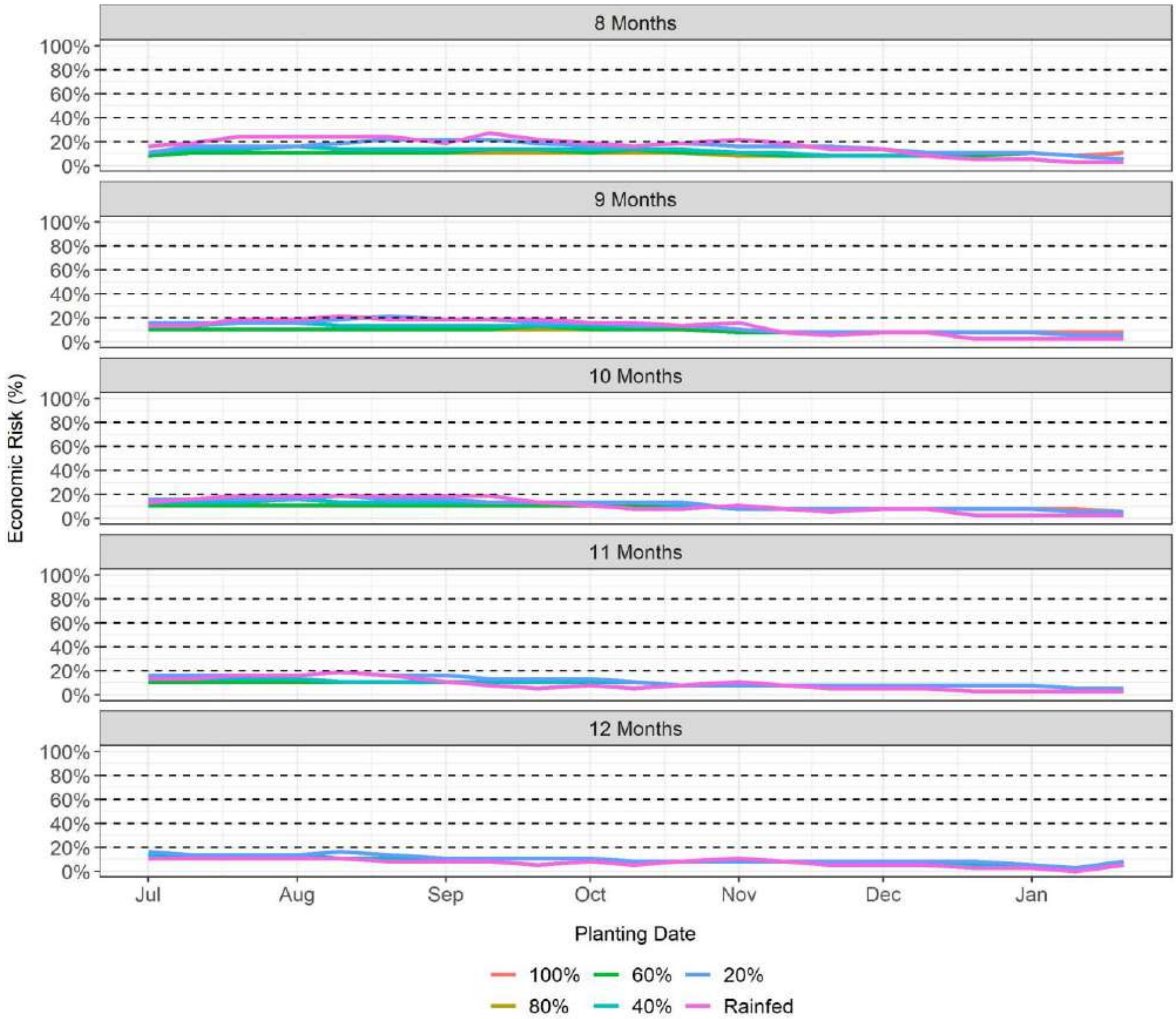

Figure 23 – Economic Risk for Laje alternative scenario according to irrigation treatment, planting date and cycle length.

Place	*20%*	*30%*	*40%*	*Average*
		R$ ha^{-1}		
Araripina	451	1,043	2,067	2,176
Lagarto	9,466	10,792	11,689	13,322
Laje	12,321	13,680	15,594	15,110

Table 10 – Baselines of gross margin results from reference scenario.

5.3. LONG TERM ECONOMIC ANALYSIS

Figures 24, 25 and **26** show the Araripina NPV using yield value at 20, 30 and 40% percentiles, respectively, based on planting date, water treatment and sale prices. According to planting months and respectively for the three percentiles, positive NPV values represent 13.3, 15.6 and 16.9% for March, 8.8, 11.7 and 12.8% for April, 8, 10.6 and 11.7% for May, 9, 11.1 and 14.4% for June, 13.3, 15.8 and 21.7% for July, 20.8, 28.9 and 36.7% for August, 41.4, 47.2 and 51.4% for September, 53.9, 58.1 and 60.8% for October, 54.2, 61.1 and 68.1% for November and 45.3, 51.9 and 61.7% December. According to water treatments and respectively for the three percentiles, positive NPV values represent 60.2, 64.2 and 67% for the 100%, 40.5, 46.5 and 52% for the 80%, 27, 31.2 and 35.5% for the 60%, 20, 24 and 28.8% for the 40%, 13.7, 18.3 and 22.7% for the 20% and 0, 3 and 7.6% for the rainfed treatment.

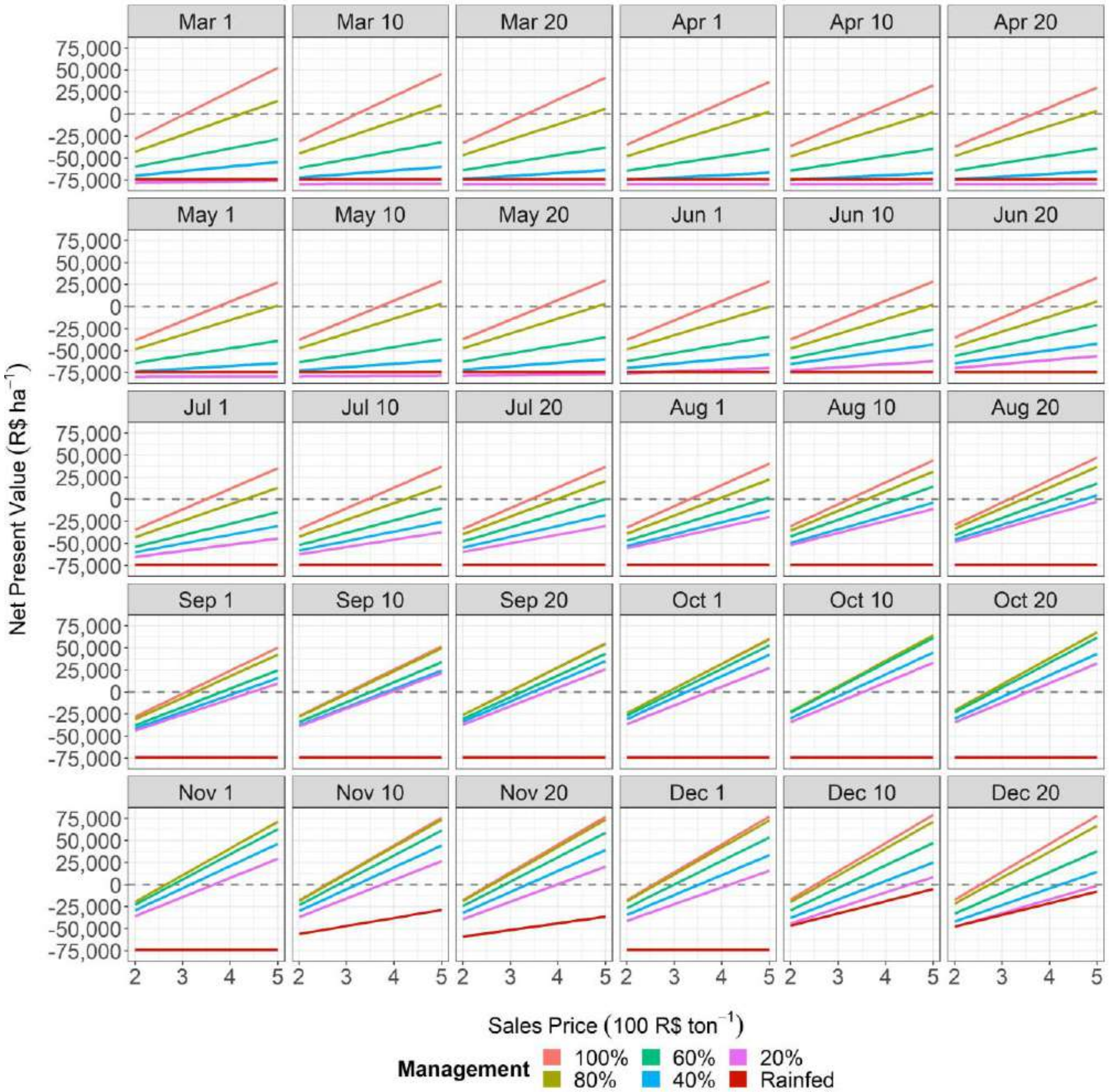

Figure 24 – Net present value at 10 years using the yield at 20% percentile for Araripina by planting date, irrigation treatment and sales price.

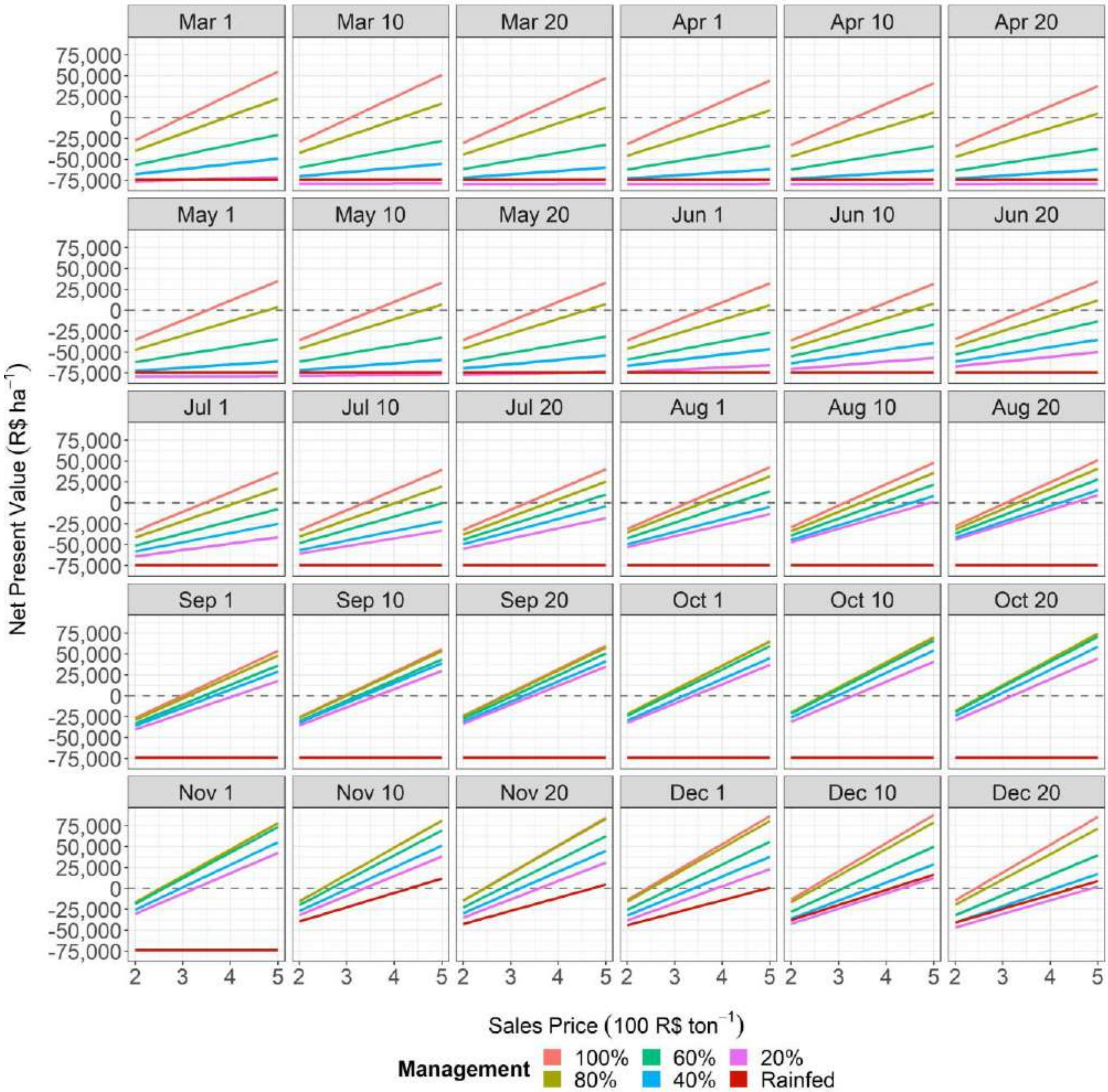

Figure 25 – Net present value at 10 years using the yield at 30% percentile for Araripina by planting date, irrigation treatment and sales price.

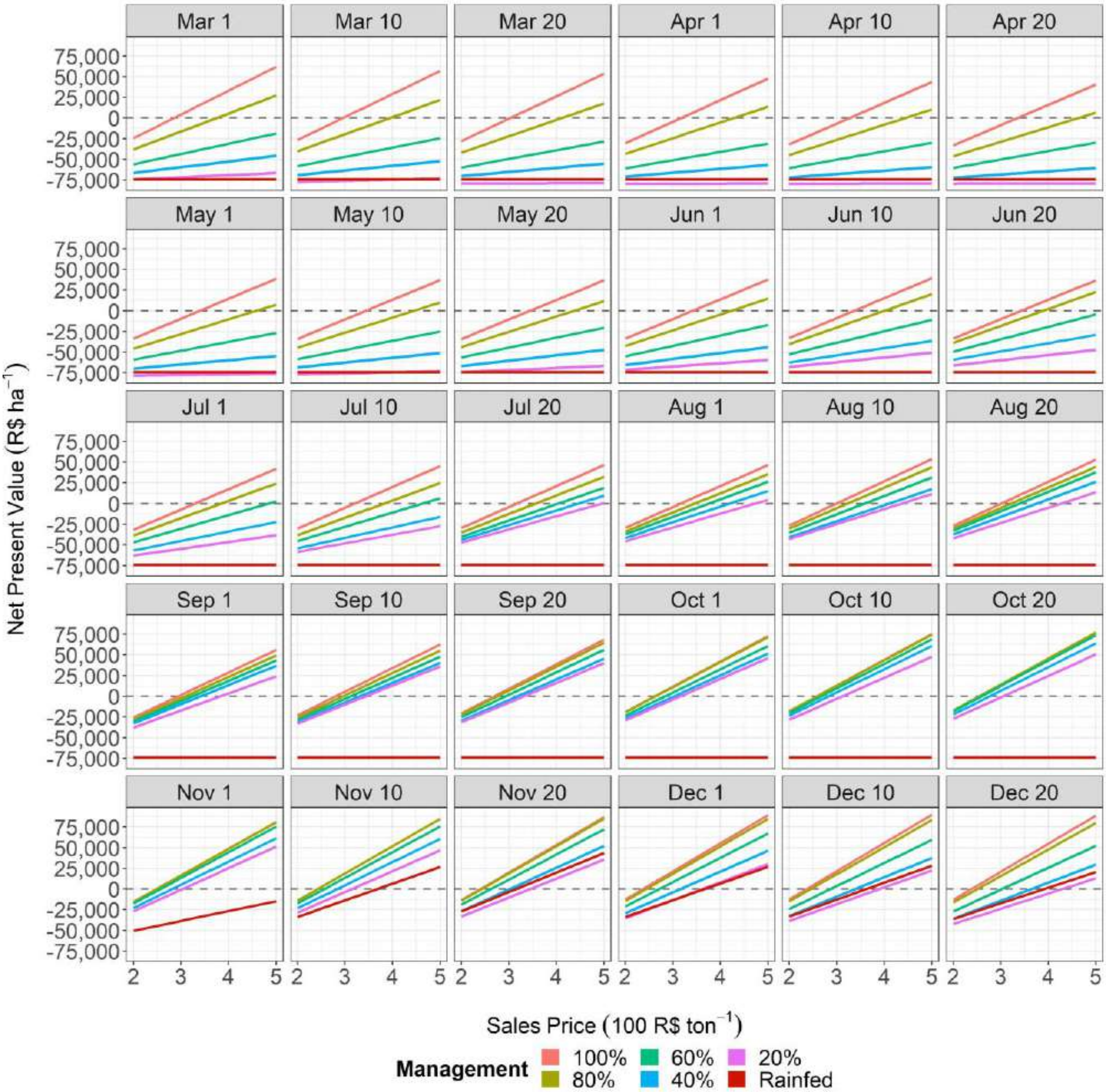

Figure 26 – Net present value at 10 years using the yield at 40% percentile for Araripina by planting date, irrigation treatment and sales price.

Water Treatment	20% *(R$/ton)*	30% *(R$/ton)*	40% *(R$/ton)*
		400 R$ < Sell price < 500 R$	
100%	79,256	88,031	89,856
80%	73,851	83,377	84,983
60%	63,033	73,387	75,688
40%	46,388	58,619	64,003
20%	33,282	44,472	51,344
Rainfed	-4,918	16,377	43,542
		300 R$ < Sell price < 400 R$	
100%	43,875	50,710	52,132
80%	39,829	47,225	48,475
60%	31,482	39,547	41,332
40%	18,587	28,122	32,316
20%	8,454	17,169	22,518
Rainfed	-20,211	-3,623	17,537
		200 R$ < Sell price < 300 R$	
100%	13,548	18,721	19,797
80%	10,666	16,236	17,183
60%	4,438	10,542	11,884
40%	-5,242	1,981	5,155
20%	-12,827	-6,234	-2,190
Rainfed	-33,319	-20,766	-4,753

Table 11 – Higher net present value results for Araripina by sell price range, water treatment and percentile.

Figures 27, 28 and **29** show the Lagarto NPV using yield value at 20, 30 and 40% percentile, respectively, based on planting date, water treatment and sale prices. According to planting months and respectively for the three percentiles, positive NPV values represent 28.1, 34.4 and 38.9% for July, 22.8, 29.4 and 33.6% for August, 21.1, 27.8 and 32.2% for

September, 23.9, 29.2 and 34.4% for October, 33.9, 40.3 and 50% for November, 50.8, 61.9 and 71.7% for December, 78.6, 83.1 and 84.7% for January and 86.9, 88.1 and 91.7% for February. According to water treatments and respectively for the three percentiles, positive NPV values represent 75.6, 79.8 and 81.2% for the 100%, 64.8, 70 and 74.2% for the 80%, 41.5, 53.3 and 61.7% for the 60%, 29.6, 33.3 and 40.6% for the 40%, 25.8, 29.2 and 33.3% for the 20% and 22.3, 30 and 36.9% for the rainfed treatment.

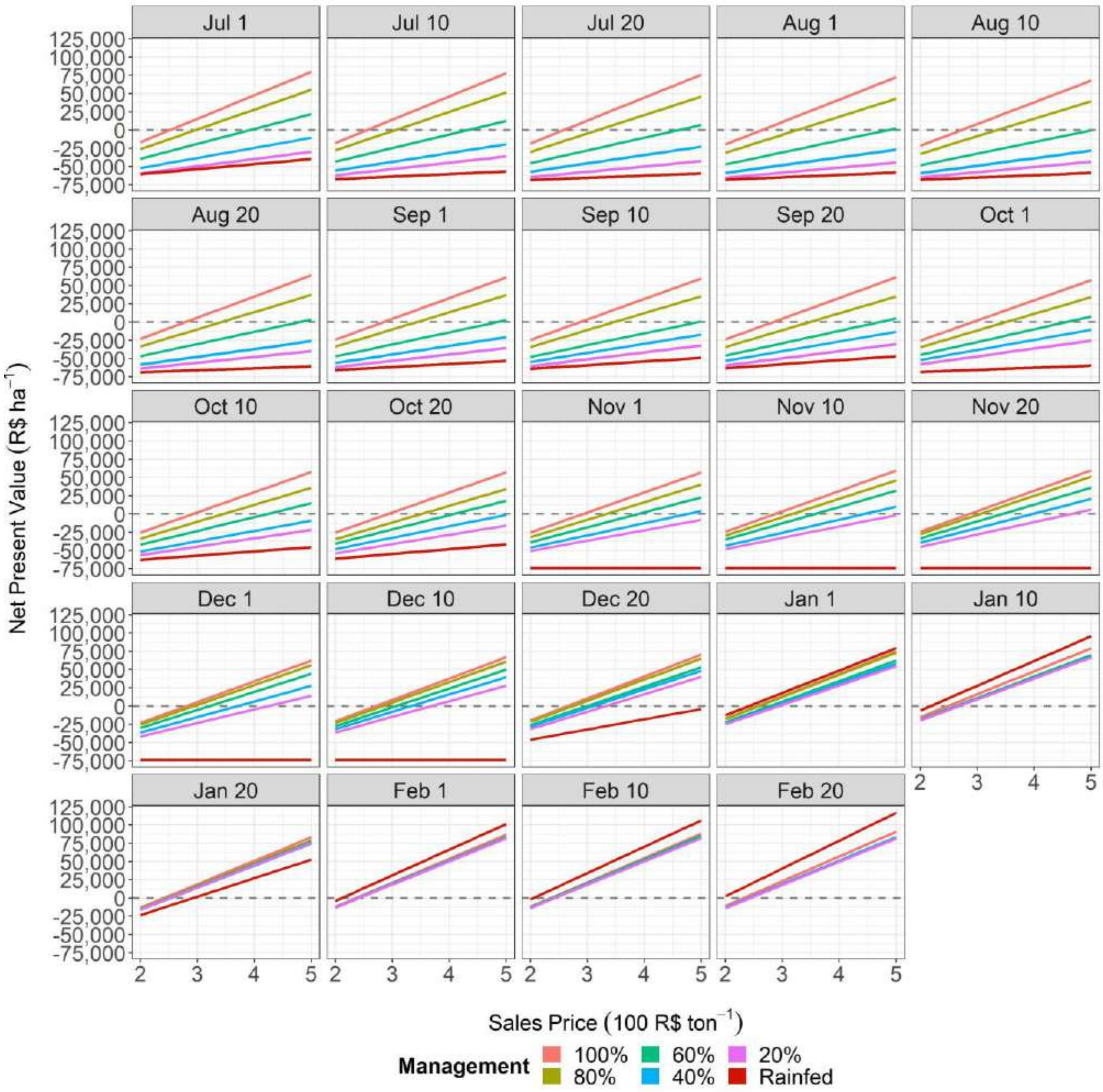

Figure 27 – Net present value at 10 years using the yield at 20% percentile for Lagarto by planting date, irrigation treatment and sales price.

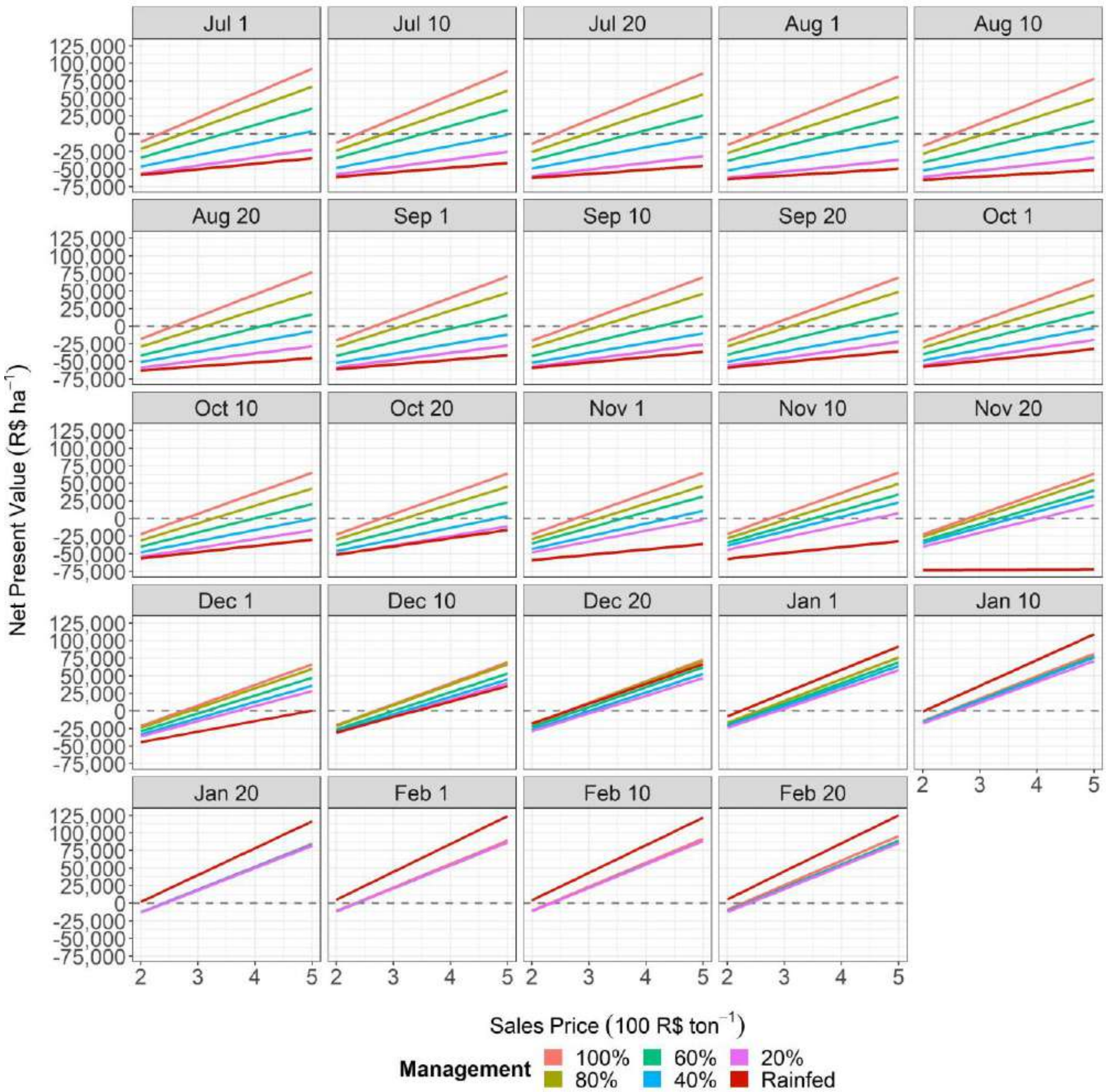

Figure 28 – Net present value at 10 years using the yield at 30% percentile for Lagarto by planting date, irrigation treatment and sales price.

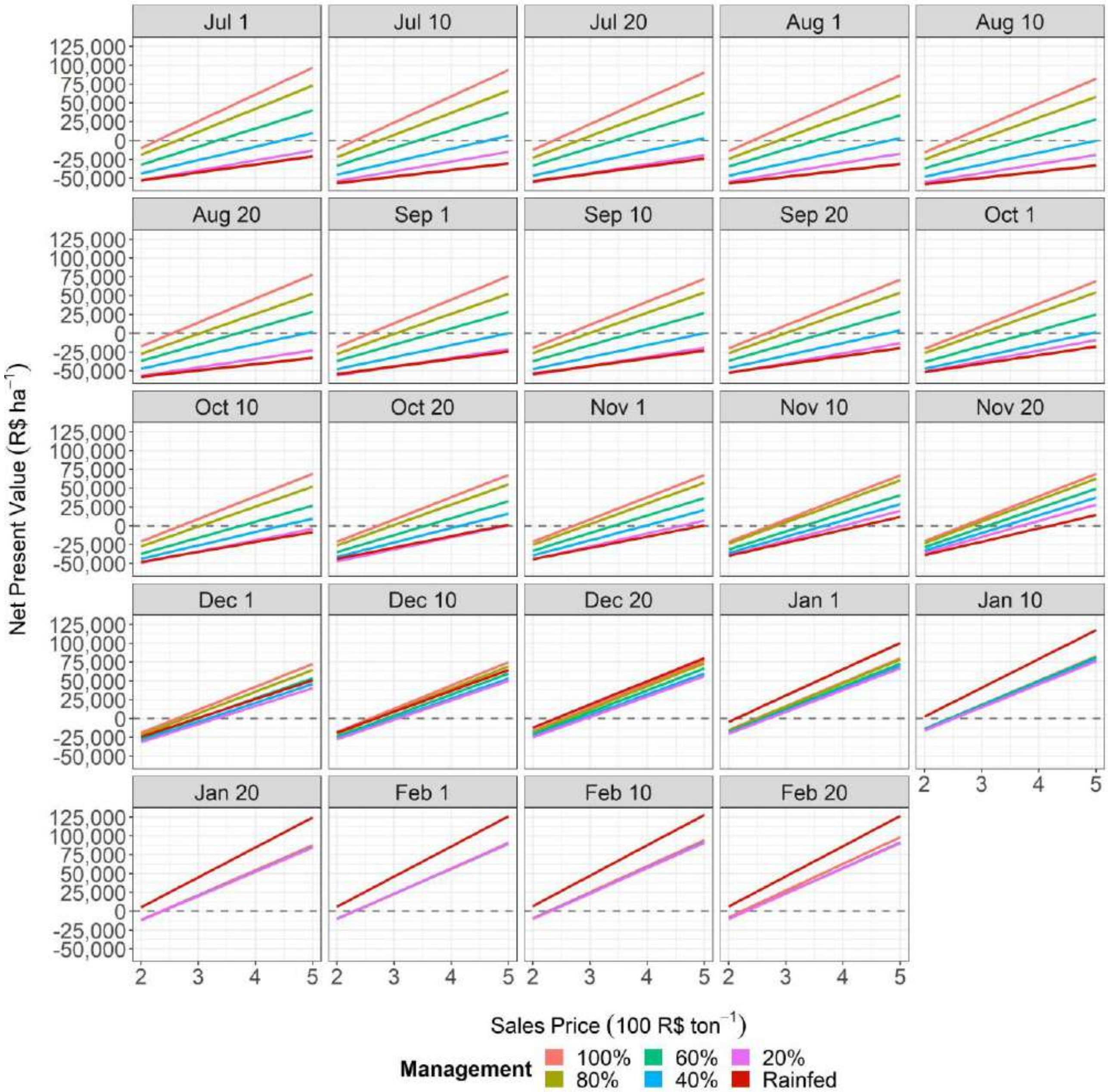

Figure 29 – Net present value at 10 years using the yield at 40% percentile for Lagarto by planting date, irrigation treatment and sales price.

Water Treatment	20% *(R$/ton)*	30% *(R$/ton)*	40% *(R$/ton)*
		400 R$ < Sell price < 500 R$	
100%	90,944	95,558	98,469
80%	85,472	88,993	91,930
60%	85,078	88,785	91,927
40%	83,461	88,654	91,623
20%	82,139	88,567	91,223
Rainfed	116,809	125,188	128,158
		300 R$ < Sell price < 400 R$	
100%	53,435	57,029	59,296
80%	49,350	52,086	54,381
60%	49,067	51,954	54,402
40%	47,827	51,876	54,189
20%	46,911	51,831	53,900
Rainfed	74,608	81,135	83,448
		200 R$ < Sell price < 300 R$	
100%	21,284	24,004	25,720
80%	18,389	20,451	22,196
60%	18,200	20,385	22,238
40%	17,327	20,351	22,102
20%	16,918	20,343	21,909
Rainfed	38,436	43,375	45,126

Table 12 – Higher net present value results for Lagarto by sell price range, water treatment and percentile.

Figures 30, 31 and **32** show the Laje NPV using yield value at 20, 30 and 40% percentile, respectively, based on planting date, water treatment and sale prices. According to planting months and respectively for the three percentiles, positive NPV values represent 62.2, 72.2 and 77.2% for July, 64.4, 72.2 and 76.9% for August, 63.9, 71.4 and 75.6% for September, 63.9, 69.2 and 75.3% for October, 64.2, 72.8 and 78.3% for November, 72.8, 79.4 and 83.6% for December and 80.8, 84.7 and 87.2% for January. According to water treatments and respectively for the three percentiles, positive NPV values represent 66.5, 71 and 74% for the 100%, 65.2, 69.8 and 73.8% for the 80%, 61.7, 66.7 and 69.6% for the 60%, 55.4, 62.1 and 65.2% for the 40%, 49, 56.2 and 61.5% for the 20% and 56.5, 65.6 and 71.7% for the rainfed treatment.

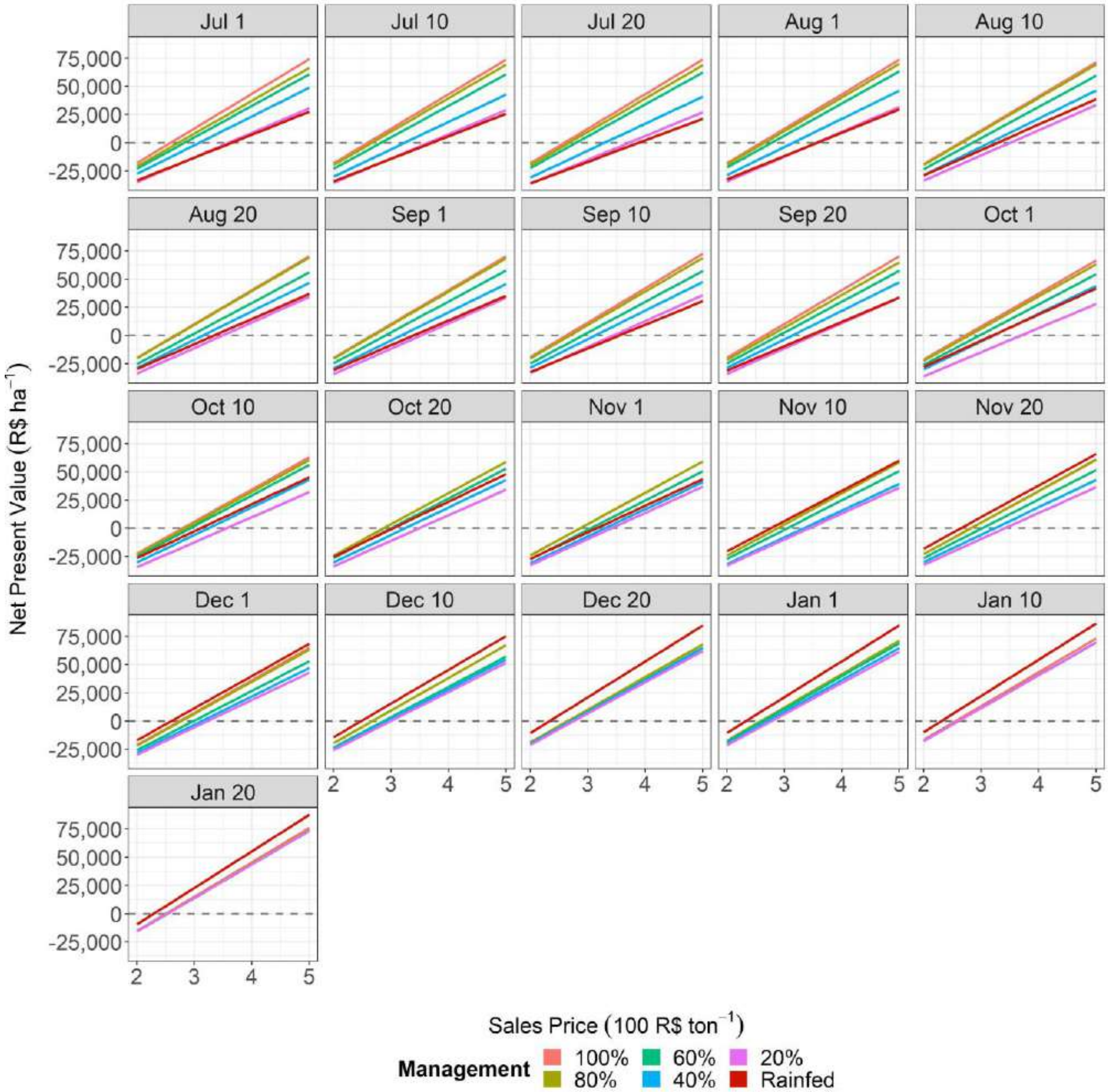

Figure 30 – Net present value at 10 years using the yield at 20% percentile for Laje by planting date, irrigation treatment and sales price.

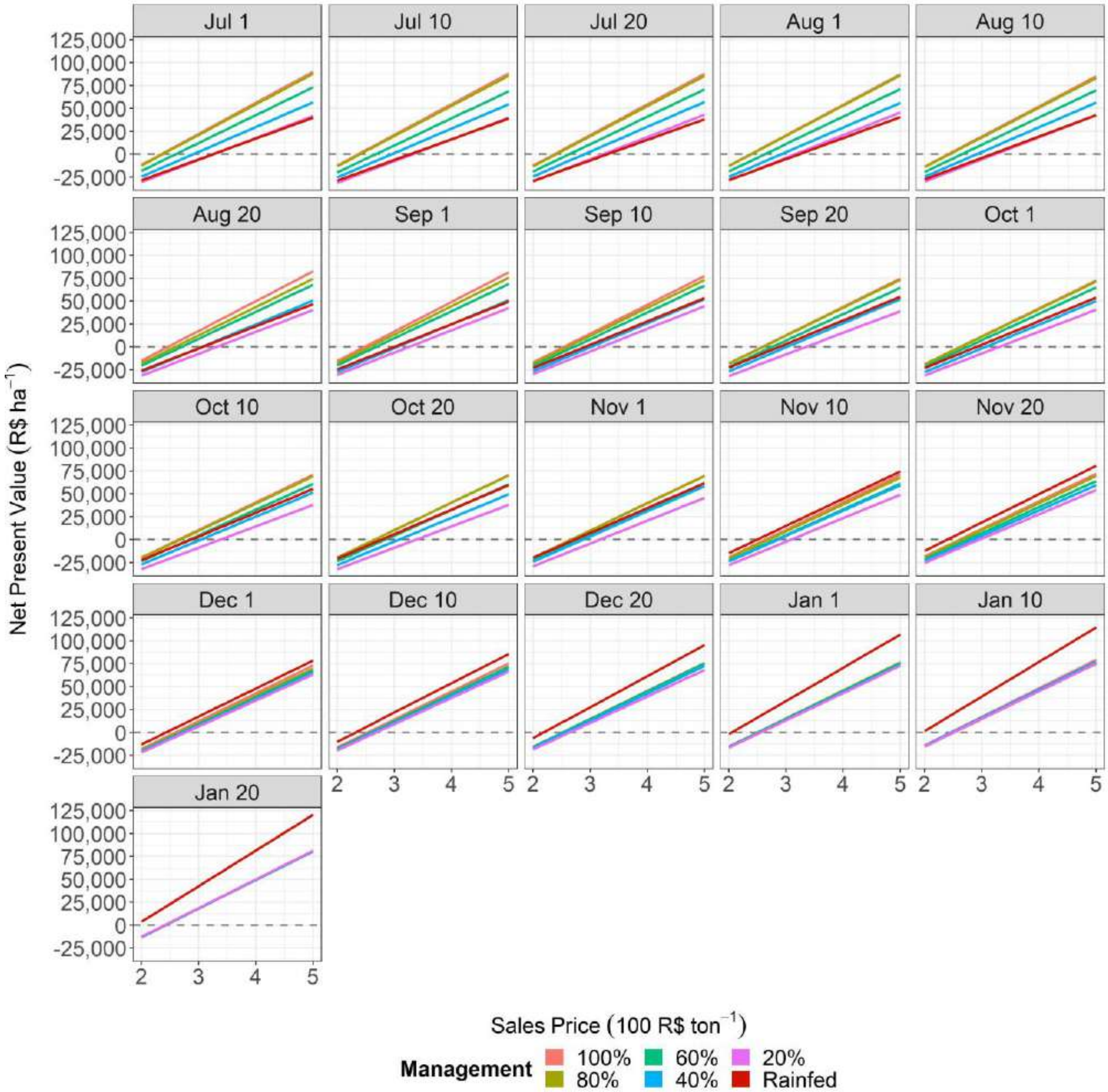

Figure 31 – Net present value at 10 years using the yield at 30% percentile for Laje by planting date, irrigation treatment and sales price.

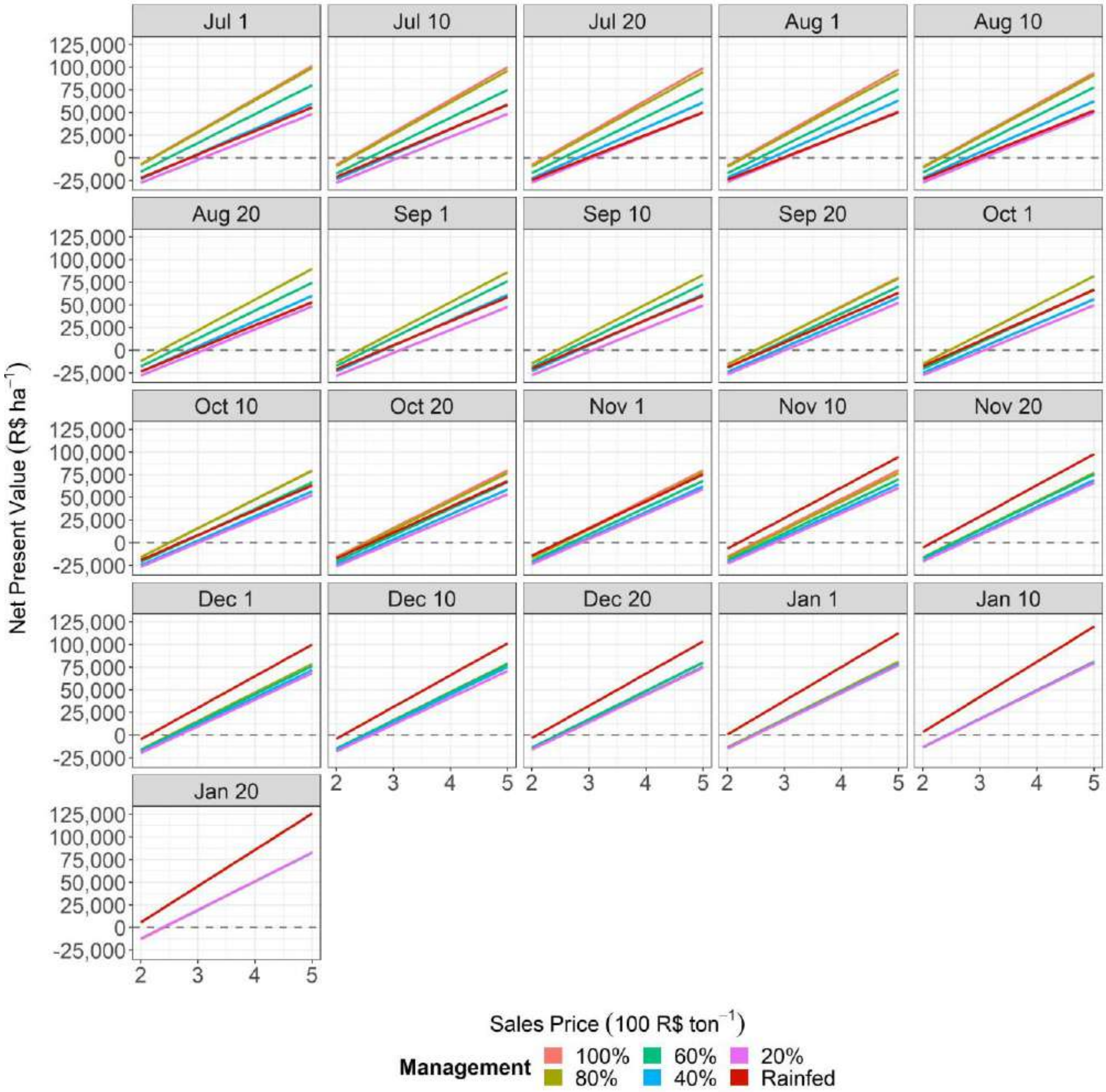

Figure 32 – Net present value at 10 years using the yield at 40% percentile for Laje by planting date, irrigation treatment and sales price.

Water Treatment	**20%** *(R$/ton)*	**30%** *(R$/ton)*	**40%** *(R$/ton)*
		400 R$ < Sell price < 500 R$	
100%	76,112	90,101	101,337
80%	74,479	87,948	99,379
60%	73,531	80,551	82,841
40%	73,703	81,259	82,709
20%	73,710	81,387	82,931
Rainfed	87,809	120,635	125,991
		300 R$ < Sell price < 400 R$	
100%	42,489	52,668	61,421
80%	41,368	51,041	59,944
60%	40,644	46,112	47,896
40%	40,792	46,678	47,808
20%	40,811	46,791	47,994
Rainfed	52,019	77,588	81,760
		200 R$ < Sell price < 300 R$	
100%	13,670	20,583	27,207
80%	12,988	19,406	26,144
60%	12,455	16,593	17,943
40%	12,583	17,037	17,892
20%	12,613	17,138	18,049
Rainfed	21,341	40,691	43,848

Table 13 – Higher net present value results for Laje by sell price range, water treatment and percentile.

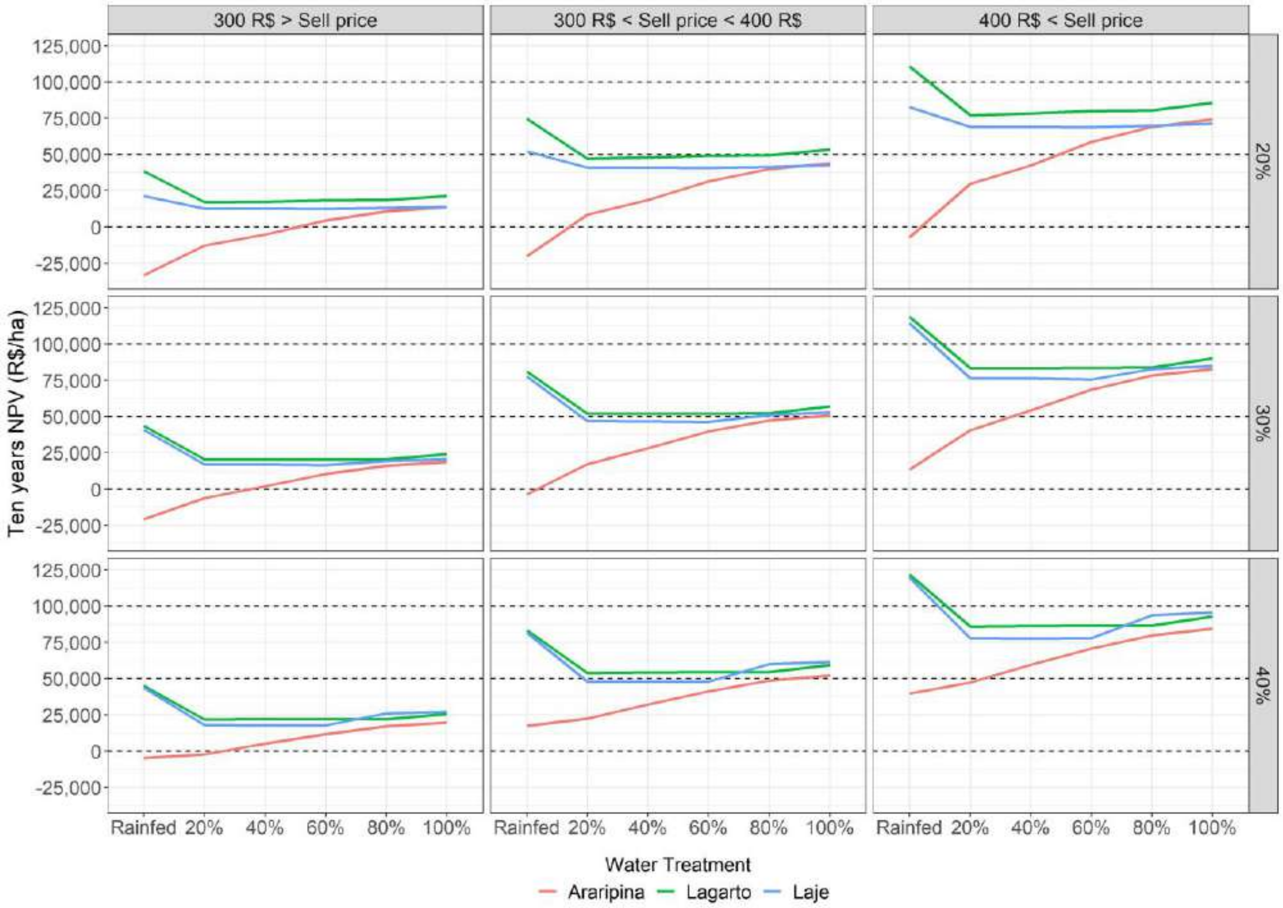

Figure 33 – Higher NPV results by region, sell price range, water treatment and percentile.

6. DISCUSSION

6.1. REFERENCE SCENARIO YIELD RESULTS

The decrease in average yield as the wet season advances is a general result for the rainfed simulations. This states that the best cassava planting dates are at the beginning of the wet season due to water availability in the first months after planting, which is the most sensible crop stage.

The yields for Lagarto and Laje were much higher than those for Araripina. The crucial factor for these results was the soil water availability which is much lower in Araripina. After two or three months of planting, the dry period begins and it affects the growth, development and productivity.

While the dry season is well defined at Araripina, the same is not true for Lagarto and Laje. This can be seen from yield results. For both places, even with a decreasing average as the wet season advances, the higher yield variability points to a higher variability of water condition between different years. This means that, there are years at which precipitation occurs even during the dry season, allowing a better condition for plants, then higher yields.

The influence of cycle length was not always positive. If soil water availability decreases over the time, roots lose weight and productivity reduces. This phenomenon is especially important at Araripina, where yields decrease from 8 to 12 months (data not show) and a longer crop cycle is necessary to achieve feasible results.

6.2. ALTERNATIVE SCENARIO YIELD RESULTS

At Araripina, similar lower yields as obtained for the reference scenario were observed for high water stress treatments and plantings at March, April and May. Also, for these months, there was a higher difference in yield results between irrigation treatments. This difference was not so high for plantings in October and November, mainly for 8 and 9 months of crop cycle. For these last, irrigation treatments seem to make a small difference and that could indicate an opportunity to deficit irrigation management.

In order to explain the results presented above, one planting date from March and another from October were chosen to represent both phenomena. The simulation from March shows a high yield difference between irrigation treatments, while the October one shows a small difference. **Figure 34, 35** and **36** show daily yield outputs for a very rainy season (1984, rain > 1,000 mm), medium rainy season (1990, rain > 400 mm) and a little rainy season (2012, rain < 350 mm), respectively.

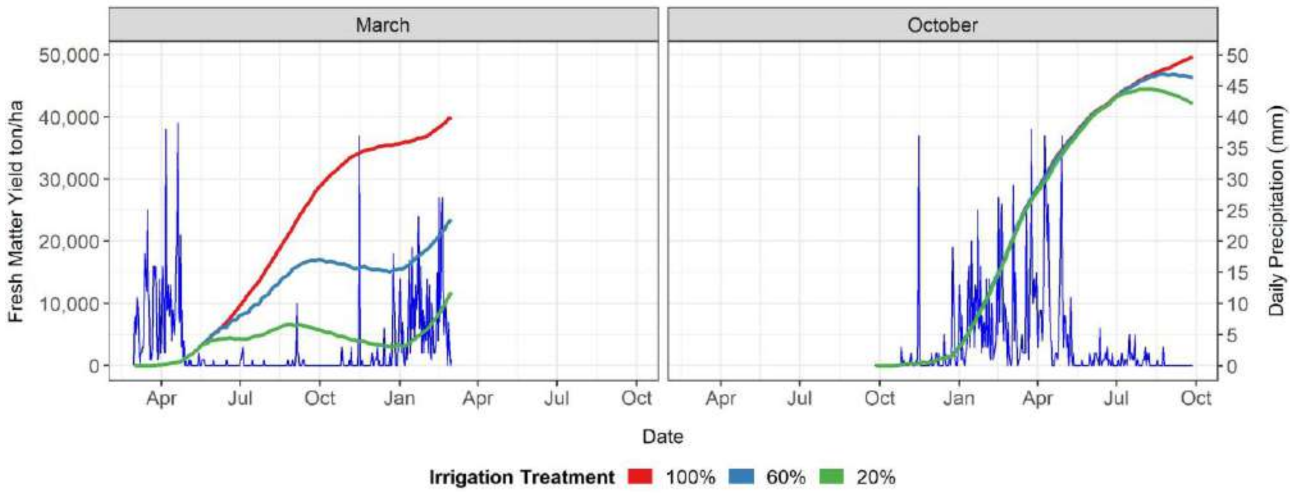

Figure 34 – Daily yield output for Araripina, simulation at year 1984, for two planting dates and three irrigation treatments.

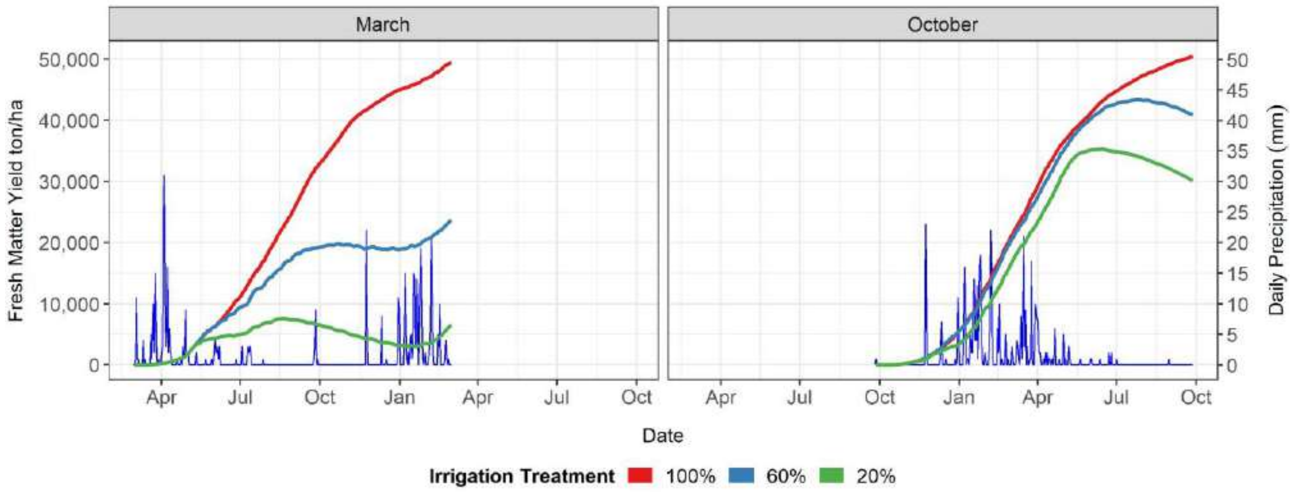

Figure 35 - Daily yield output for Araripina, simulation at year 1990, for two planting dates and three irrigation treatments.

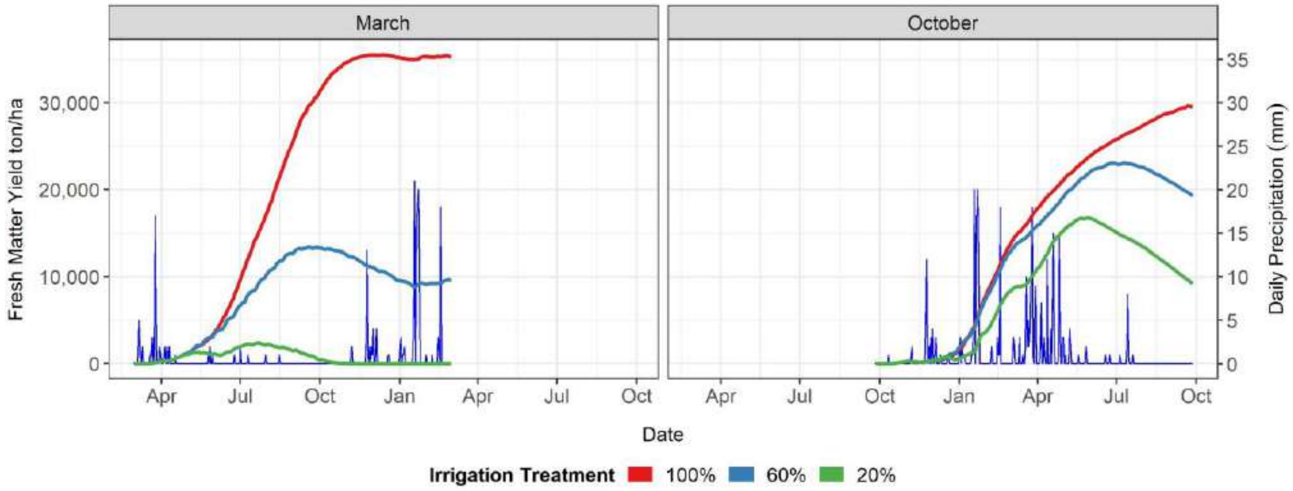

Figure 36 - Daily yield output for Araripina, simulation at year 2012, for two planting dates and three irrigation treatments.

Daily results show that the difference between irrigation treatments happens early at March plantings and later at October plantings. Even in a dry year such as 2012, for October plantings, yields from different treatments follow very close until May (seven months after planting). The same pattern is true for the other two examples (1984 and 1990).

In Lagarto, the same phenomenon happened as in Araripina. Plantings from July to October show a high difference between irrigation treatments. From November on, this difference decreased and the final yield did not respond as before to the higher amount of water applied. The explanation here is the same as for Araripina: The proximity to the wet season made yields from different treatments follow very closely for a significant period. When the dry season begins, then the different amounts of water applied by each irrigation treatment start to affect plants.

6.3. ANNUAL ECONOMIC ANALYSIS

For the reference scenario, the annual economic analysis agrees to yield results pointing to the beginning of the wet season as the best planting time for cassava in the three regions evaluated. For Lagarto and Araripina plantings at the end of the wet season are not only less economically interesting, but also risky since negative gross margins were obtained. These results indicate that, for this regions, late plantings must be avoided and even disfavored. For Lage, the same is not true since the risk of late plantings is small.

The early harvest, even with lower gross margins, is a safe option for Lage and Lagarto, but risky for Araripina. The data shows that, 14 and 15 months harvest must be avoided for this region due to the high percentage of negative gross margin results.

For the alternative scenario, irrigation treatments influenced the annual economic returns. In general, the more water applied, the higher the profit. Although the low water stress treatments are related to higher variable costs, the high yields achieved by them were able to compensate with high gross margins. It indicates that regions could benefit from irrigation accordingly to water availability.

The choice of planting date, irrigation treatment and cycle length, however, exclude some combinations at which average gross margins were negative. These not recommended management choices are frequent (22%), rare (3.5%) and nonexistent (0%) for Araripina, Lagarto and Laje, respectively.

Some combinations of planting dates and harvest times do not justify the application of more water by irrigation. For Lagarto, until 11 months harvest, plantings at January and February present very close average gross margins. On the other hand, the high-water stress treatments sometimes present a higher variation and then uncertainty. The same happens with Laje at December and January. These results can indicate an opportunity to save water and also achieve high economic returns.

LONG-TERM ECONOMIC ANALYSIS

The long-term analysis first conclusion is about long-term viability of the use of irrigation on cassava in the studied regions. According to it, farmers can expect to have profit by choosing a safe combination of planting date and irrigation treatment for each of the three regions.

The second conclusion is about the advantage of apply irrigation instead of rainfed management. Using ten years as the basis of comparison, the evaluated management would be a worthwhile investment if the final economic benefit is higher than the rainfed management one.

For Araripina, the baseline results of the reference scenario were 451, 1,043 and 2,067 R\$ ha^{-1} for 20, 30 and 40% percentiles, respectively (Table 10). Considering these results and same economic external conditions, it means that, planting at best planting dates by ten years, the farmer final economic benefit would be between 4,510 and 20,670 *R\$* ha^{-1}.

Data shows that irrigation management at Araripina would improve long term benefit. For sell prices higher than 300 *R\$* ton^{-1}, which is very frequent, any irrigation treatment used will improve the long-term benefit range. Using the 20% treatment, the benefit would be between 8,454 and 22,518 *R\$* ton^{-1} (87 and 8.9% higher than reference) for prices lower than 400 *R\$* ton^{-1} or between 33,282 and 51,344 *R\$* ton^{-1} (637 and 148% higher than reference) for prices higher than 400 *R\$* ton^{-1}. By the other hand, using the 100% treatment, the benefit would be between 43,875 and 52,132 *R\$* ton^{-1} (872 and 152% higher than reference) for prices lower than 400 *R\$* ton^{-1} or between 79,256 and 89,856 *R\$* ton^{-1} (1,657 and 334% higher than reference) for prices higher than 400 *R\$* ton^{-1}.

For sell prices lower than 300 *R\$* ton^{-1}, only irrigation treatments 80 and 100% have the advantage of increase the minimum value of the range, decreasing the uncertainty compared to reference. The 100% irrigation treatment will return a benefit between 13,548 and 19,797 *R\$* ton^{-1} (+200% and -4.3% different than reference) and the 80% irrigation treatment will return a benefit between 10,666 and 17,183 *R\$* ton^{-1} (+136% and -16.8% different than reference).

For Lagarto, the higher annual economic results of the reference scenario were 9,466, 10,792 and 11,689 R\$ ha^{-1} for 20, 30 and 40% percentiles, respectively. Considering these results and same economic external conditions, it means that, planting at best planting dates by ten years, the farmer final economic benefit would be between 94,660 and 116,890 *R\$* ha^{-1}.

Data shows that irrigation management at Lagarto will not improve long term benefit in any combination of factors. The values at Rainfed water treatment at the higher sell price range (400 R\$ < Sell price < 500 R\$) can be attributed to how the economic result was calculated for the reference and the alternative scenario. Since rainfed higher yields from both are compatible and costs are the same, the sell price is the factor responsible for the difference. For the reference scenario, monthly sell prices (Table 09) were used, while the alternative scenario used fixed prices.

For Laje, the higher annual economic results of the reference scenario were 12,321, 13,680 and 15,594 R$ ha^{-1} for 20, 30 and 40% percentiles, respectively. Considering these results and same economic external conditions, it means that, planting at best planting dates by ten years, the farmer final economic benefit would be between 123,210 and 155,940 R$ ha^{-1}. Economic analysis shows that irrigation management at Laje will not improve long term benefit in any combination of factors.

These results clearly indicate that, even being a profitable option in the three studied regions, the use of irrigation in cassava production is worthwhile investment only at Araripina. In Lagarto and Laje, the long-term benefit of rainfed production is higher than irrigated one. The reason is that, the amount of annual rainfall in these two regions is almost enough to cassava, making irrigation a minor factor in increasing yields.

CRITICAL DISCUSSION ABOUT SIMULATION CHOICES

Several choices were made in order to make the research possible. Since model results heavily depend on these choices, it’s important to discuss the implication of each regarding conclusions and future improvements.

For the sake of simplification, the same soil (sandy loam) was used for the whole research. The soil characteristics mainly imply on 1) the amount of water from rain that the soil can store, which directly affects the soil water availability and 2) how deep is the root system (soil depth). It means that a more clay soil would store more water from rain, which would favor the rainfed simulations, increasing yields and the economic benefit for this scenario. More robust research could use 1) soil types most frequent at Araripina-PE, Lagarto-SE and Lage-BA, 2) soils with different textures to analyze the influence of soil storage on climate risk.

Regarding the genotype used, the parametrization was done with data obtained from field experiments conducted at Embrapa Cassava and Fruits, Cruz das Almas, Bahia, from 2018 to 2020. These field experiments used the BRS-Formosa, a well-known and widely adopted cassava genotype at Bahia, therefore representative for the sites evaluated.

The climate types used for the study were chosen based on the major producers of the Brazilian Northeast region. A different criterion could be used to evaluate the crop viability with and without irrigation in a variety of climate conditions.

7. CONCLUSIONS

1. Cassava yields were in general sensible to cycles length, planting dates and water treatments.
2. The higher yields for the reference scenario were obtained for those plantings made at the beginning of the wet season with 18, 9 and 12 months of cycle length for Araripina, Lagarto and Laje respectively.
3. In general, the higher yields for the alternative scenario were obtained using the less stressful water treatments.
4. At the alternative scenario, planting dates at the end of the dry season suffer less influence of irrigation treatments.
5. The higher annual economic benefits for the reference scenario agreed with yields and were obtained at the beginning of the wet season with 18, 11 and 12 months of cycle length for Araripina, Lagarto and Laje, respectively.
6. The higher annual economic benefits for the alternative scenario were obtained at the end of the dry season, using the less stressful water treatments and 12 months of crop cycle length.
7. The long-term economic analysis showed that the use of irrigation in the three regions is a viable investment in most cases.
8. However, the long-term economic analysis showed that the use of irrigation is an advantage only at Araripina.
9. The proposed management is not a worthwhile investment for farmers at Laje and Lagarto.

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