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MODELOS AGRÍCOLAS PARA AUMENTAR A EFICIÊNCIA PRODUTIVA NOS SISTEMAS DE PRODUÇÃO DE GRÃOS EM AMBIENTES SUBTROPICAIS

Santa Maria, RS
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Tese apresentada ao curso de Doutorado em Agronomia, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do título de Doutor em Agronomia

Orientador: Prof. Dr. Nereu Augusto Streck

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Eduardo Lago Tagliapietra

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Aos meus pais Ivanete e Lauro Tagliapietra, pela educação, incentivo, compressão e possibilitarem a realização dos meus sonhos.

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“Se o dinheiro for a sua esperança de independência, você jamais a terá. A única segurança verdadeira consiste numa reserva de sabedoria, de experiência e de competência.”

(Henry Ford)

RESUMO

MODELOS AGRÍCOLAS PARA AUMENTAR A EFICIÊNCIA PRODUTIVA NOS SISTEMAS DE PRODUÇÃO DE GRÃOS EM AMBIENTES SUBTROPICAIS

Autor: Eduardo Lago Tagliapietra
Orientador: PhD. Nereu Augusto Streck

Estudos sobre lacunas de produtividade em culturas individuais para identificar a possibilidade de aumentar a produtividade são frequentes na literatura. No entanto, a produtividade anual também pode ser aumentada pela alteração do tipo, número e arranjo temporal dos ciclos de cultivo individuais dentro da sequência de cultivo. A ampliação da época de semeadura da cultura da soja, motivada pela busca dos maiores potenciais de produtividade e eficiências no sistema de produção, resulta na dificuldade de o sistema de classificação de grupos de maturidade relativa capturar a interação genótipo x ambiente de forma satisfatória para ambientes subtropicais. Os objetivos deste estudo foram: (i) quantificar o potencial e a lacuna energética por unidade de área e tempo dos principais sistemas de produção do Sul do Brasil e (ii) desenvolver um sistema de indicação de cultivares de soja com base no ciclo agronômico ótimo de cada GMR para o Sul do Brasil, visando aumentar a eficiência produtiva da cultura. Os principais sistemas de produção do Sul do Brasil foram identificados e estimados quanto ao potencial energético limitado pela água e as lacunas energéticas, os quais foram calculadas usando modelos agrícolas ao longo de um período de 16 anos. As estimativas levaram em consideração as práticas de manejo representativas de cada região. O ajuste na estimativa de grupos de maturação seguiu a metodologia descrita por Alliprandini et al. (2009), e o ciclo agronômico ótimo para GMRs distintos e épocas de semeadura foi estimado usando a função limite proposta por French e Schultz (1984). A adoção de sistemas de produção aumenta a produtividade energética das terras cultivadas no Sul do Brasil, reduzindo os riscos de produção e servindo como uma forma de diversificação de renda para os produtores. A utilização de sistemas mais intensivos pode resultar em 151 e 87 GJ ha^{-1} ano^{-1} (CSYgAi) a mais de produção anual de energia na região PR e RSC respectivamente, enquanto a diminuição da lacuna de energética na cultura individual 50 e 41 GJ ha^{-1} ano^{-1}. Conhecer a duração do ciclo de desenvolvimento da cultura em diferentes épocas de semeadura, aliada ao ciclo agronômico ótimo, possibilitou otimizar o posicionamento das cultivares, aumentando a produtividade da cultura. Um incremento médio de 8% na produtividade pode ser alcançado com a utilização do software Best Cultivar como ferramenta para o melhor posicionamento das cultivares em épocas de semeadura, maximizando assim a interação genótipo x ambiente.

Palavras-chave: Ciclo agronômico ótimo. modelos de cultivos. lacuna energética. sistemas de produção. potencial de produtividade.

ABSTRACT

AGRICULTURAL MODELS TO INCREASE PRODUCTION EFFICIENCY IN GRAIN CROPPING SYSTEMS IN SUBTROPICAL ENVIRONMENTS

Author: Eduardo Lago Tagliapietra
Advisor: PhD. Nereu Augusto Streck

Studies on yield gaps in individual crops to identify the possibility of increasing yield are frequent in the literature. However, annual yield can also be increased by altering the type, number, and temporal arrangement of individual cropping cycles within the cropping sequence. The expansion of the soybean sowing period, motivated by the search for greater yield potential and efficiencies in the production system, results in the difficulty for the classification system of relative maturity groups to capture the genotype x environment interaction satisfactorily for environments subtropics. The objectives of this study were: (I) quantify the potential and energy gap per unit area and time of the main production systems in South of Brazil and (II) develop a system for indicating soybean cultivars based on the optimal agronomic cycle of each GMR for the South of Brazil, aiming to increase the productive efficiency of the crop. The main production systems in the South of Brazil were identified and estimated for water-limited energy potential and energy gaps, which were calculated using agricultural models over 16 years. The estimates considered the management practices representative of each region. The adjustment in the estimation of maturation groups followed the methodology described by Alliprandini et al. (2009), and the optimal agronomic cycle for different GMRs and sowing times was estimated using the limit function proposed by French and Schultz (1984). Adopting production systems increases the energy yield of cultivated land in the South of Brazil, reducing production risks and serving as a form of income diversification for farmers. The use of more intensive systems can result in 151 and 87 GJ ha^{-1} $year^{-1}$ (CSYgAi) more annual energy production in the PR and RSC regions, respectively, while reducing the energy gap in individual crops in 50 and 41 GJ ha^{-1} $year^{-1}$. Knowing the duration of the crop development cycle at different sowing times, combined with the optimal agronomic cycle, made it possible to optimize the positioning of cultivars, increasing crop yield. An average increase of 8% in yield can be achieved using the Best Cultivar software to better position cultivars at sowing times, thus maximizing the genotype x environment interaction.

Keywords: Optimal agronomic cycle. crop models. energy gap. production systems. yield potential.

LISTA DE ILUSTRAÇÕES

symbol the average. (CS1 – soybeans - maize; CS2 – soybeans - soybeans; CS3 – soybeans - wheat; CS4 - maize).

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SUMÁRIO

1. INTRODUÇÃO

As crescentes taxas de desenvolvimento econômico nos países mais populosos do mundo, o grande aumento na demanda por energia, grãos e produtos animais e a relativa estagnação no aumento das produtividades das principais culturas agrícolas pressionam ainda mais a necessidade de atingirmos maiores produtividades independentemente da cultura (CASSMAN et al, 2003; ROYAL SOCIETY DE LONDRES, 2009; CONAB, 2017).

Entre as iniciativas em escala global, que tem como objetivo aumentar a produção de alimentos de forma vertical, sustentável e com o mínimo de impacto ambiental se destaca o projeto Global Yield Gap Atlas (GYGA) (www.yieldgap.org), um esforço internacional para identificar os fatores limitantes da produtividade e concentrar ações para reduzir a lacuna de produtividade das principais culturas agrícolas ao redor do Planeta. O Brasil, como um dos maiores produtores mundiais de alimentos, tem a obrigação de qualificar pessoas e desenvolver ciência e tecnologia para participar da solução e das oportunidades mundiais no tema da seguridade alimentar.

Esse tipo de estudo é de extrema importância para conhecer a trajetória futura dos preços dos alimentos e da segurança alimentar, pois o objetivo de muitos pesquisadores e formuladores de políticas públicas é melhorar a produtividade das culturas agrícolas a uma taxa suficiente para manter baixos os preços dos alimentos e evitar a expansão significativa de terras agrícolas (LOBELL; CASSMAN; FIELD, 2009). Identificado as lacunas de produtividade e os fatores biofísicos e de manejos que causam essa lacuna, passa a ser de extrema importância ferramentas que auxiliam a tomada de decisão do produtor, de maneira que seja mais assertivo em práticas de manejos que vem causado lacuna de produtividade.

Estudos de lacuna de produtividade (LP) de culturas individuais para identificar a possibilidade de aumentar a produtividade nas escalas local e regional são muito frequentes na literatura (por exemplo, MERLOS et al., 2015; Tagliapietra et al., 2021; WINCK et al., 2023 e EDREIRA et al., 2018), porém, a produtividade anual também pode ser aumentada alterando o tipo, número e arranjo temporal dos ciclos de cultivo individuais dentro da sequência de cultivo (EVANS, 1993, GUILPART et al., 2017 e SILVA et al., 2017). A expansão da análise LP de culturas individuais para o nível do sistema de cultivo pode ajudar a identificar oportunidades para aumentar a produtividade anual, não apenas diminuindo as lacunas de rendimento de culturas individuais, mas também por meio de rearranjos táticos no padrão de sequência de culturas (AGUS et al., 2019).

Diante disso o presente trabalho vem a suprir uma lacuna sobre retorno energético por unidade de área e tempo em uma região aonde o potencial de produtividade, a diversificação de culturas e o impacto na produção mundial é muito expressivo. Além disso, esse trabalho desenvolve uma metodologia para estimativa da duração do ciclo de desenvolvimento da cultura da soja quando submetidas a diferentes épocas de semeadura, aliado a identificação do ciclo agronômico ótimo proporciona identificar qual a melhor duração de ciclo para melhor aproveitamento das condições ambientais (radiação e temperatura) nos períodos de maior exigência para cultura. Baseados nessas informações os consultores técnicos e os agricultores poderão tomar decisões de posicionamento de cultivares em função da época de semeadura de maneira mais assertiva, assim atuando na principal causa que limita produtividade em ambientes subtropicais brasileiro, definido por Tagliapietra et al., (2021), que é a época de semeadura.

É necessário que pesquisadores, extensionistas, consultores e produtores atuem conjuntamente de modo a identificar razões que possam colaborar para expressar a produtividade das culturas em todo o seu potencial, o que constitui a motivação para este estudo. Neste sentido, o objetivo deste estudo foi (i) quantificar o potencial e a lacuna energética por unidade de área e tempo, dos principais sistemas de produção do Sul do Brasil e (ii) desenvolver um sistema de indicação de cultivares de soja com base no ciclo agronômico ótimo de cada GMR para o Sul do Brasil, para o aumentar a eficiência produtiva da cultura.

2. DESENVOLVIMENTO

2.1 ARTIGO 1 - BEST CULTIVAR: AN UPDATE OF MATURATY GROUP CLASSIFICATION FOR REACHING SOYBEAN YIELD POTENTIAL - *(será submetido a Computers and Electronics in Agriculture)*

Eduardo Lago Tagliapietra[1,2]; José Eduardo Minussi Winck[1]; Nereu Augusto Streck[2]; Michel Rocha da Silva[1]; Alexandre Ferigolo Alves[2]; Darlan Scapini Balest[2]; Cristian Savegnago[2]; Marcos Dalla Nora[2]; Romulo Pulcinelli Benedetti[1]; Leonardo Silva Paula[3]; Victória Brittes Inklman[4]; Alencar Junior Zanon[2]

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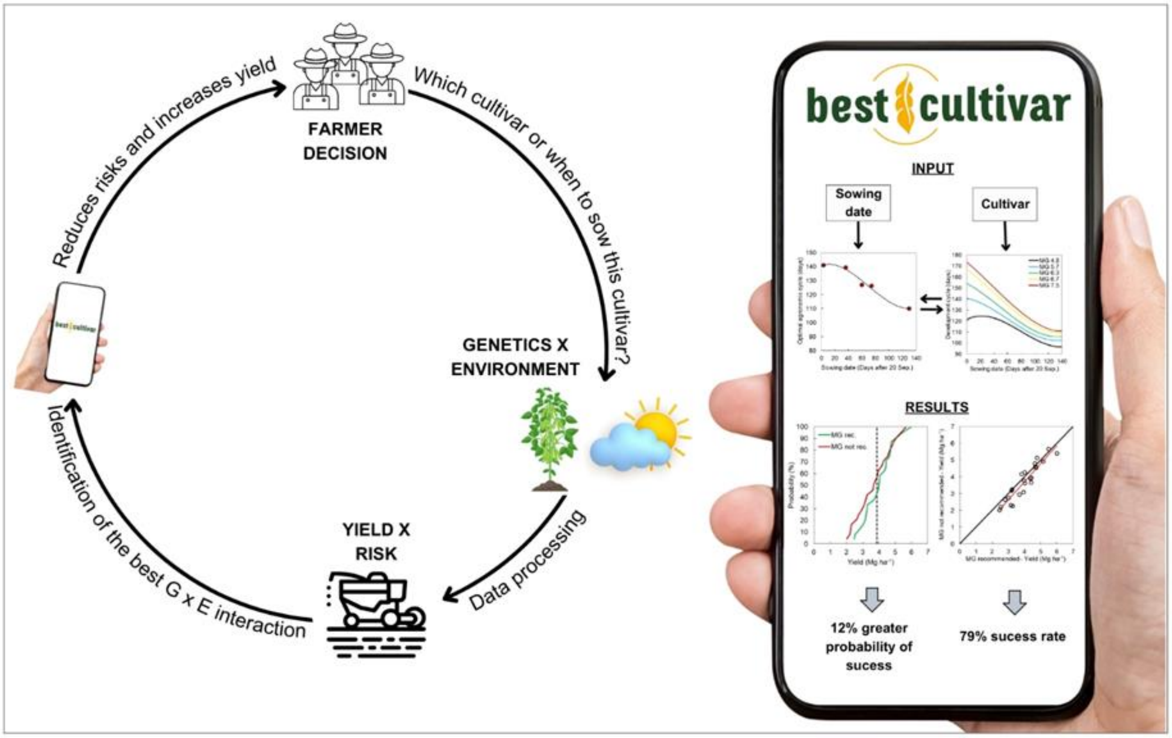
GRAPHICAL ABSTRACT



ABSTRACT

The expansion of the sowing season, motivated by the search for greater yield potential and higher efficiency of the production system, results in the classification system of relative maturity groups cannot satisfactorily capture the interaction between genotype and environment in a subtropical environment. Knowledge of the duration of the crop development cycle at the time of sowing, combined with the optimal agronomic cycle, makes it possible to optimize the positioning of cultivars and increase crop yield. The objectives of this study were (i) to propose advances in the maturity group classification system considering the sowing date to achieve yield potential and (ii) to develop a system for indicating soybean cultivars based on the optimal agronomic cycle for southern Brazil. A database containing 72 field experiments in eleven agricultural years (from 2010-2011 to 2022-2023), covering 44 municipalities in southern Brazil, was used to estimate the development cycle and the optimal agronomic cycle depending on the sowing date. To better represent the development cycle of soybeans as a function of sowing date, the maturity group classification system was further developed, using adapted 3rd order polynomial equations. The optimal agronomic cycle ranged from 141 to 111 days. An average yield increase of 0.43 Mg ha^{-1} can be achieved by using the Best Cultivar software, which serves as a tool for the best positioning of cultivars at the sowing times and thus maximizes the interaction between genotype and environment.

Keywords: Digital agriculture, Optimal agronomic cycle, *Glycine max* (L.) Merr., Crop models, Sowing date.

Abbreviations: Genotype (G), environment (E), relative maturity groups (MG), optimal agronomic cycle (OAC), sowing (SOW), physiological maturation (R8), sowing date (SD), square error (RMSE), mean absolute error (EMA) and root mean square error percentage (RMSE%)

2.1.1 Introduction

Soybeans are grown on 127.8 million hectares worldwide, with the largest area under cultivation in the subtropical and tropical regions of South America (Brazil, Argentina, and Paraguay), which accounted for 50.5% of the global soybean production area in the last five years (USDA, 2024). In the last 20 years, soybean yields in Brazil have increased by 33% (IBGE, 2024). This increase in yield is partly due to the introduction of early maturing soybean cultivars with indeterminate growth.

A better understanding of the interaction between genotype (G) and environment (E) in soybean was obtained by modifying the classification of early, middle, and late development cycles (EMBRAPA, 1997) for maturity groups (ALLIPRANDINI et al., 2009). This classification was adapted to Brazil and uses relative maturity groups (MG) (POEHLMAN, 1987), ranging from 000 to 10 and considering the response of the cultivars to the photoperiod (latitude) (ALLIPRANDINI et al., 2009). However, the Brazilian classification in MG is based on the duration of the crop cycle in the first half of November, which may not accurately reflect the duration of the crop cycle in the off-season sowing periods.

The increasing extension of sowing into September, for example, is due to the search for greater yield potential (ZANON et al., 2016; TAGLIAPIETRA et al., 2021) and in January/February to the expansion of the cultivated area through double cropping (FOLLMAN et al., 2019). In this context, in southern Brazil, Argentina and Paraguay, there is an increase in the duration of the crop development cycle for early sowings (September and October) and a shortening of the cycle for late sowings (January and February) (ZANON et al., 2015). In this new scenario, the MG classification system developed for temperate regions, where the sowing window is practically 30 days (POEHLMAN, 1987), cannot satisfactorily capture the interaction between genotype (G) and environment (E) for the environment subtropical with a large window at sowing (about five months). In this context, recent studies indicate that the two most important factors driving the yield difference in soybean in subtropical environments are sowing date and cultivar (ARAMBURU MERLOS et al., 2015; DI MAURO et al., 2018; TAGLIAPIETRA et al., 2021; RIZZO et al., 2022).

It is therefore necessary to adapt the MG classification system considering the new sowing periods. The definition of the duration of the cycle for each sowing date is important to adapt the agricultural models and plan the coincidence of the period in which the critical phases of the defining yield components occur with the period of the highest photothermal coefficient, with the aim of increasing soybean production without increasing the use of inputs, but rather maximizing the G x E interaction (KANTOLIC et al., 2008; ZANON et al., 2016). In this context, we define the concept of optimal agronomic cycle (OAC) for soybean, i.e. the sowing date that provides the best use of the biophysical environment for each relative maturity group.

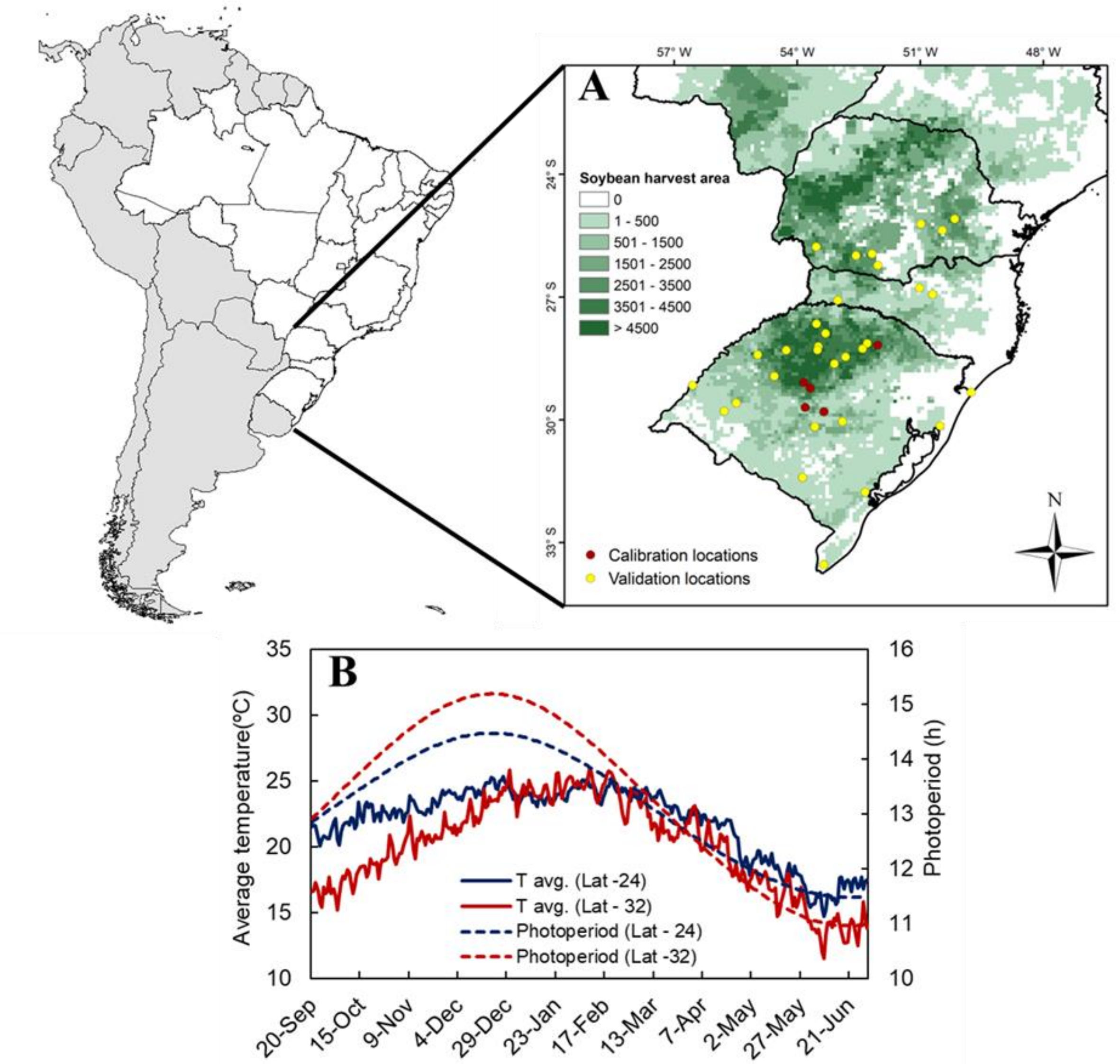
By defining the duration of the cycle at each sowing date and the AOC, we propose a model for determining soybean cultivars for southern Brazil (Best Cultivar), thus integrating the cycle between R&D&I (Research, Development, and Innovation) in this new era of digital agriculture. To this end, the objective of this study was to (i) propose an evolution of the maturity group classification system that considers the sowing date to reach the yield potential of each MG and (ii) develop a system to indicate soybean cultivars based on the optimal agronomic cycle of each MG for southern Brazil.

2.1.2 Material and methods

2.1.2.1 Characterization of the experimental sites and cultivars

The area analyzed in this study corresponds to soybean growing areas in a subtropical environment in Brazil. 72 field experiments were conducted in eleven agricultural years (from 2010-2011 to 2022-2023) in research institutes and commercial cultivars covering 44 municipalities in southern Brazil (Figure 1A; Supplementary Table 1). The climate of the region is humid subtropical (Cfa) with no defined dry season, based on the Koeppen climate system (WREGE et al., 2011). The soil types vary depending on the experimental site, from deep (> 2 m) to shallow (<1 m), with a broad range of textural class. The photoperiod varies in the study area from 14.5 to 11.5 hours at a latitude of -24º and from 15.2 to 11 hours at a latitude of -32º (Figure 1B), with average temperatures varying from 25.3 to 14.7 ºC and from 25.9 to 11.5 ºC, respectively, covering the different soil and climatic conditions of the subtropical environments.

Figure 1: (A) Geographical location of the southern region of Brazil, with the red and yellow circles representing the experimental sites used in the study. The experiments were conducted during 11 agricultural seasons (2010 to 2021). (B) Variation of photoperiod and average daily air temperature over 11 years (2010 to 2021), dashed lines represent the photoperiod and solid lines the average temperature. The blue color represents latitude -24º and the red color represents latitude -32º.



The water regime of the experiments was irrigated and rainfed, with a wide sowing window ranging from September 22 to February 19 and a MG range between 4.8 and 8.3 (Supplementary Table 1). The sowing dates, cultivars and their interactions were considered as an environment (n = 294) representing commercial growing conditions.

2.1.2.2 Experimental design and agronomic determinations

The experimental design consisted of randomized blocks with four repetitions. The distance between the rows was 0.45 m and the planting density varied between 26 and 30 plants/m². Soybean seeds were inoculated and supplied with nutrients to achieve the yield potential (GYGA, 2021; www.yieldgap.org) based on soil analysis. Crop protection measures against weeds, diseases and pests were applied to keep the crop free from biotic stress.

The phenology of the crop was monitored three days per week according to the phenological scale of Fehr and Caviness (1977). To determine the grain yield (13% moisture), an area of 4 m² was harvested in each plot. For more details on how the experiments were conducted, see Richter et al, (2014), Zanon et al (2015a, 2015b), Zanon et al (2016a, 2016b), Cera et al (2017), Bexaira et al (2021) and Tagliapietra et al (2018, 2021).

2.1.2.3 Model for estimating the entire development cycle at sowing date

The previously described dataset was used to develop the model to estimate the duration of the entire development cycle (SOW – R8) when sowing took place outside the first fortnight of November. The data were divided into five groups according to the MG of the cultivars: Group I (MG 4.8 - 5.4); Group II (MG 5.5 - 5.9); Group III (MG 6.0 - 6.4); Group IV (MG 6.5 - 6.9) and Group V (MG 7.0 – 8.3). Following the methodology described by Alliprandini et al. (2009) for estimating MG, a relationship between the total development cycle (SOW – R8) and sowing time was established and the equations that showed the best statistical fit were selected using Table Curve 2.0 software. and biological significance to form the model.

After selecting the equations, the median of the MG used to create the equations was calculated to determine which MG best represented the equation within the group of cultivars (I to V). Once the MG representing the equations of the five groups was identified, interpolation between the equations was performed, resulting in the model that estimates the full developmental cycle per group of relative maturity.

The model was validated using an independent data set collected in two boundary agricultural seasons (2019-2020 and 2020-2021). The root mean square error (RMSE), mean absolute error (EMA) and root mean square error percentage (RMSE%) were used to analyze the performance of the model for estimating the duration of the soybean development cycle in a subtropical environment.

2.1.2.4 Boundary function for estimating the optimal agronomic cycle for soybeans

The function method proposed by French and Schultz (1984) was used to quantify the optimal agronomic development cycle to achieve the yield potential of soybeans at seeding times. The data set was divided into five groups according to sowing time: Group I (September 20 - September 30); Group II (October 01 - November 04); Group III (November 05 – November 30); Group IV (December 01 – December 31); and Group V (January 01 – February 28). The boundary function consists of relating the variable under study (development cycle) to the reference variable (yield) and creating a potential equation relating the variables under study to the upper part of the yields (5% of the highest yields). The choice of equations is based on the best statistical fit and biological significance, using yield stabilization as a criterion for choosing the optimal development cycle, i.e. when the increase in yield is less than 0.5% with variation in the variables studied.

The selected equations were used to calculate the median of the sowing dates (limit functions) used to generate the equations to determine which sowing date best represents the equation within the sowing range of the groups (I to V). After identifying the sowing date and the respective optimal agronomic development cycle (OAC) represented by the equations of the five groups, the variables were related to each other and a new equation was created using Table Curve 2.0 software, from which the model estimating the optimal agronomic cycle as a function of sowing date was created.

2.1.2.5 Best Cultivar Software

A software called "Best Cultivar" was developed to combine the methodology for estimating the entire development cycle with the optimal agronomic cycle to obtain an indication of the best sowing date for each cultivar or the best cultivar for the sowing date. The Python programming language was used to develop the software, with the support of the Pandas, Sqlalchemy and Googleapiclient libraries to process the data obtained. The Ionic framework was used to implement the hybrid version for Android/iOS mobile devices.

Validation of the methodology and software was performed using a set of independent data collected over three agricultural seasons (2020-2021 to 2022-2023) as listed in Supplementary Table 1 and shown in Figure 1A. The experimental dataset was divided into recommended and non-recommended cultivars by the software and subjected to correlation and probability analyses to evaluate the performance of the optimal agronomic cycle methodology in conjunction with the "Best Cultivar" software.

2.1.3 Results and discussion

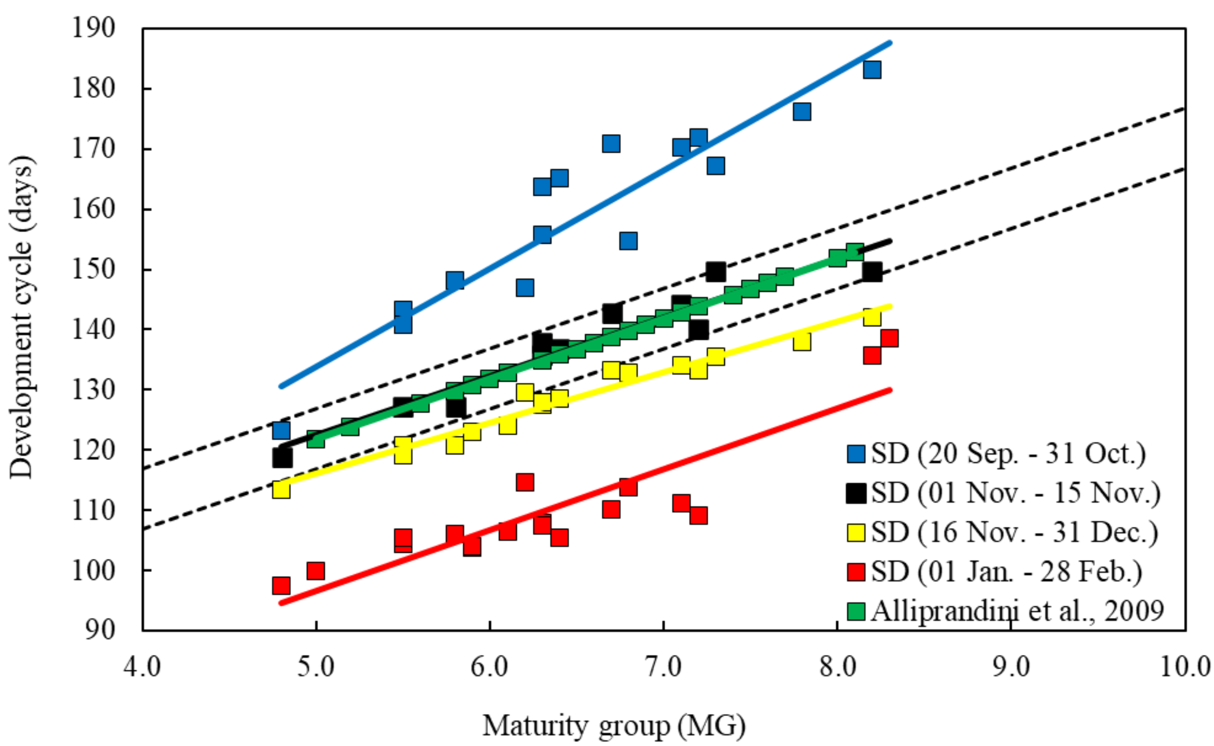
2.1.3.1 Relation of the relative maturity group at different sowing date

Based on experiments conducted in the main soybean growing areas of the southern region of Brazil (Figure 1), considering a wide range of MGs (4.8 to 8.3) and sowing dates (September 20 to February 28), a variation of 97 to 183 days of the total development cycle was found. If cultivars with different MGs are sown at the same sowing date (Figure 2), it is to be expected that the higher the MG, the longer the duration of the entire development cycle of the variety (ZANON et al., 2015).

The duration of a variety's development cycle varies by region, i.e. soybeans exhibit different development rates depending on the photoperiod to which they are exposed during the growing season (SETYONO et al., 2007). As a result, the method proposed by Alliprandini et al. (2009), which was adapted for altitude and latitude, performed excellently in the first two weeks of November, but could not reproduce the new sowing windows in a subtropical environment (Figure 2).

Figure 2 shows that when sowing is brought forward (20 September – 31 October) compared to the first weeks of November, a period estimated by Alliprandini et al. (2009) for the cycle length of MG, the duration of the development cycle increases, especially for MG above 6.0. However, when the sowing date is shifted (January-February), the duration of the crop cycle is shortened regardless of the MG used.

Figure 2: Relationship between the entire development cycle and the relative maturity group (MG) at the sowing times. The blue squares represent sowing in the period from September 20 to October 31, the black squares represent sowing in the period from November 1 to 15 (period used by ALLIPRANDINI et al, 2009, for the estimation of MG in Brazil), the yellow squares for sowing from November 16 to December 31, the red squares for sowing from January 1 to February 28 and the green squares for the data of Alliprandini et al., (2009), corrected for altitude and latitude. The dashed lines show the cycle variation of + or – 5 days in the methodology of Alliprandini et al. (2009).



2.1.3.2 Estimation of the entire development cycle during the sowing period

In order to improve the prediction of the duration of the development cycle of a cultivar subjected to different sowing times and MG, a 3rd degree polynomial equation with statistical fit and biological significance was established, with an r^2 between 0.83 and 0.96 and a p-significant value ($p < 0.001$), indicating that the estimation of the total duration of the development cycle as a function of sowing time is adequate for all groups of relative soybean maturity for the southern region of Brazil (Table 1). From these relationships, a cultivar with MG 5.0 sown in October has the same cycle length in days as a cultivar with MG 6.0 sown in the first two weeks of November and MG 7.0 sown in early December. This head start helps the grower to plan and manage the plot, plan the sowing and harvesting of areas, increasing the efficiency of machine use, plan the sowing and reduce climatic risks (water deficit and surplus) and harvest losses.

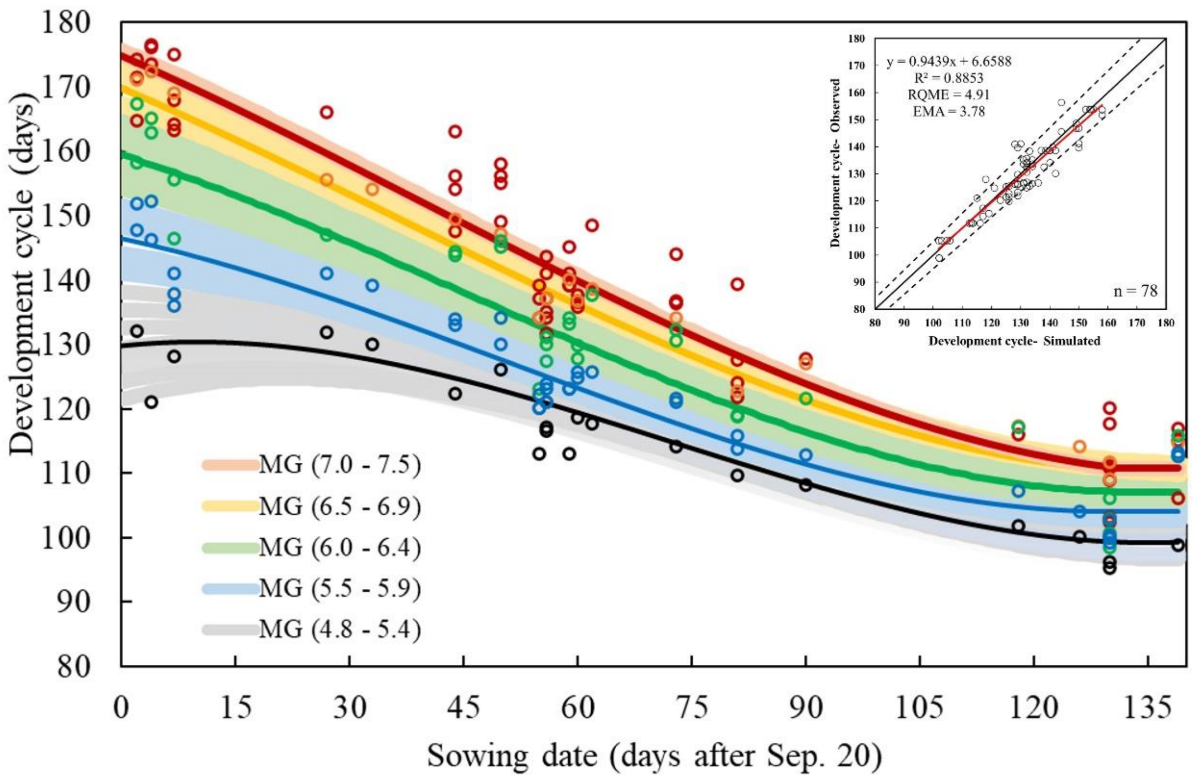
Table 1: Adjusted equations to estimate the development cycle of different MGs depending on the sowing date. With X equal to the sowing days after September 20. MG: Relative maturity group; Equations: Polynomial equations generated; R^2: Coefficient of determination

MG	Equations	R^2	p-value
4.8	$Y = 0.00003567X^3 - 0.008529X^2 + 0.3179X + 121.4498$	0.83	< 0.01
5.7	$Y = 0.00002319X^3 - 0.003550X^2 - 0.2569X + 146.4111$	0.91	< 0.01
6.3	$Y = 0.00002281X^3 - 0.003055X^2 - 0.4061X + 162.0694$	0.90	< 0.01
6.7	$Y = 0.00001723X^3 - 0.001691X^2 - 0.5406X + 172.4305$	0.97	< 0.01
7.5	$Y = 0.00002045X^3 - 0.002657X^2 - 0.4969X + 175.5963$	0.89	< 0.01

The duration of the development cycle changes during sowing and is different for different MGs. When sowing in September, the cycle difference between the MGs is greater (54 days), which decreases with the delay in sowing (14.8 days in January) (Figure 3). The reason for the greater differences in the length of the development cycle between the MGs in September lies in the different flowering induction rates. For example, MGs smaller than 5.5 have an optimal photoperiod of more than 12 hours, while MGs larger than 6.0 have a lower induction rate because their optimal photoperiod is shorter than or close to 12 hours (SETIYONO et al., 2007). However, when sown in January and

February, all MGs have a maximum development rate (ZANON et al., 2018) and the cultivars have a maximum flowering induction due to the decreasing photoperiod.

Figure 3: Total development cycle (days) by relative maturity group (MG) as a function of sowing date, for the southern region of Brazil. The overlay shows a comparison between the simulated total development cycle and the observed one for soybean cultivation. The solid black line represents y = x, and the dashed black lines represent y = x ± 5%. The solid red line represents the fitted linear regression, RMSE = root mean square error and MEA = mean absolute error.



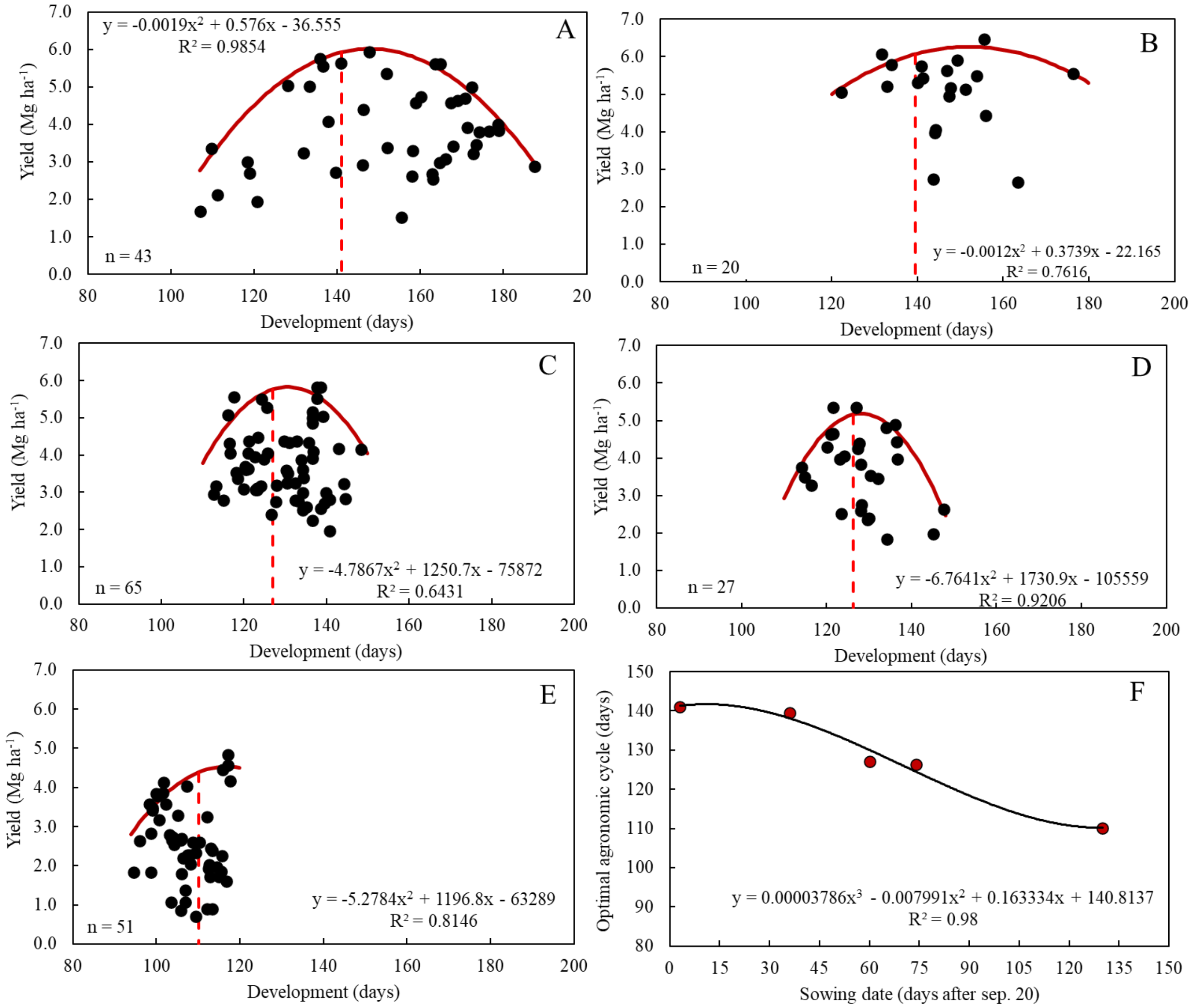
Visual analysis of the scatter data around the 1:1 line shows excellent predictive ability over a wide range of cycle lengths (Figure 3). The RMSE values were 4.91, with the equations for each MG and a wide seeding time. The MEA and R^2 statistics confirm the high predictive power of the equations.

2.1.3.3 Optimal agronomic cycle for soybeans depending on sowing date

The OAC ranged from 141 to 111 days (Figure 4) for sowing from Sept. 20 to Feb. 28. In groups I (Sept. 20 - Sept. 30) and II (Oct. 1 - Nov. 4) (Figure 4A; 4B), the period with the highest yield potential for soybeans in subtropical environments (ZANON et al., 2016 , TAGLIAPIETRA et al., 2021), the OAC was 141 and 140 days, respectively. This indicates that cultivars of MG 4.8 to 5.9 have the best adaptation of cycle length for this sowing date and yield potential, as the critical period of plant development coincides with the maximum availability of environmental resources (solar radiation, temperature) (SANTACHIARA et al., 2017; SUHRE et al., 2014). Cycles longer than those mentioned above lead to a reduction in yield potential due to factors such as lodging, shading in the lower part of the plant and consequent death of leaves and pods.

Groups III (05 – Nov. – 30 Nov.), IV (01 Dec. – 30 Dec.) and V (01 Jan. – 28 Feb.) had OACs of 127, 126 and 110 days respectively. In this case, MGs between 6.0 and 6.9 are given for the sowing times of groups III and IV and between 6.5 and 7.5 for group V. Delaying the sowing time shortens the overall cycle and reduces the photothermal coefficient, which reduces the yield potential (ZANON et al., 2016; TAGLIAPIETRA et al., 2021). In studies on the adaptability and positioning of cultivars for latitude 24 to 30º S in Brazil, it was found that cultivars with MG 5.3 to 5.9 perform better for high yields (ZDZIARSKI et al., 2018; BALEST et al., 2022). Thus, by suggesting improvements in the most suitable MG recommendations for each sowing season, yield losses can be reduced.

Figure 4: Soybean yield (Mg ha-1) as a function of the entire development cycle (days) for different sowing times: (A) Group I (Sept. 20 - Sept. 30); (B) Group II (Oct. 1 - Nov. 4); (C) Group III (Nov. 5 – Nov. 30). Nov. - Nov. 30); (D) Group IV (Dec. 1 – Dec. 30); (E) Group V (Jan. 1 – Feb. 28) and (F) the optimal agronomic cycle (days) depending on the sowing time for the southern region of Brazil. The solid red line represents the threshold function and the red dotted line the optimal agronomic cycle.



After understanding the optimal agronomic cycle as a function of the different sowing dates (Figure 4), a general equation was derived that relates the optimal agronomic cycle (OAC) to the corresponding sowing date (Figure 4F). This equation makes it possible to determine the OAC for the entire soybean sowing window in the southern region of Brazil.

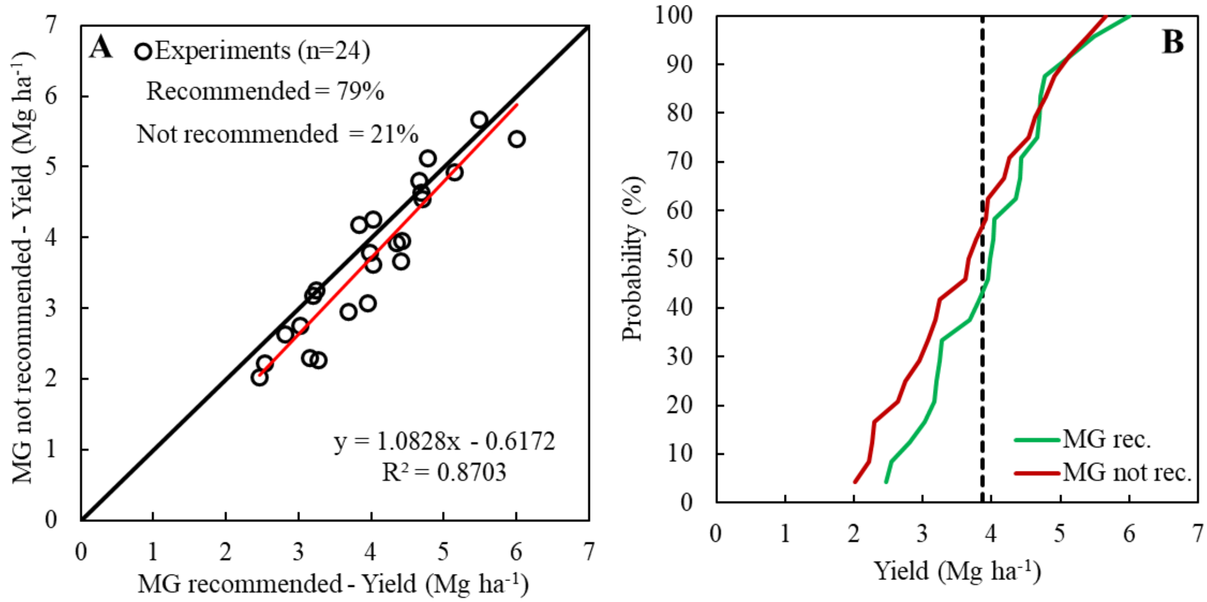
2.1.3.4 "Best Cultivar" Software

The interaction between cycle duration (Figure 3) and OAC (Figure 4F) made it possible to determine the entire development cycle that the cultivar must have so that the most critical phases (during pod development and grain filling) coincide with the higher photothermal coefficient (KANTOLIC et al., 2008; ZANON et al., 2016). This interaction led to the development of the Best Cultivar software, which positions the cultivar at its best sowing time. This enables better utilization of the production environment and ensures the positioning of the best cultivar (MG) to achieve the yield potential per sowing season.

The "Best Cultivar" was evaluated based on three agricultural harvests (2020-2021 to 2022-2023) with a total of 24 experiments in the southern region of Brazil. The evaluation (Figure 5A) found that 79% of the evaluated experiments showed favorable yield values for the cultivars recommended by the "Best Cultivar", with an average of 0.43 Mg ha^{-1} more than the non-recommended cultivars.

A cumulative yield probability function was performed for the cultivars recommended and not recommended by "Best Cultivar" (Figure 5B). The probabilities of achieving a higher or lower yield than 3.8 Mg ha^{-1} (average of the experiments) are indicated by a vertical line (dashed black). The probability analysis shows that the probability of achieving a yield of 3.8 Mg ha^{-1} or more is 58% for the recommended cultivars, while the probability is 46% for the non-recommended varieties.

Figure 5: Evaluation of the Best Cultivar Sotfware. The comparison between recommended and non-recommended cultivars is shown in panel A, where the solid black line represents y = x and the solid red line represents the fitted linear regression. In panel B, a probability analysis for the yield 3.85 Mg ha^{-1} (average of the analyzed database), dashed black line, depending on the recommendation of the Best Cultivar software.



Based on this study, technical advisors and farmers will be able to make more informed decisions about the positioning of cultivars according to sowing date. The total cycle estimation developed in this study makes it possible to know the actual duration of the total development cycle when cultivars are sown at any date of the sowing window in a subtropical environment, so that the variations in the duration of the total development cycle of a cultivar at different sowing times can be captured. The optimal agronomic cycle makes it possible to determine the best cycle length to take better advantage of environmental conditions (radiation and temperature) during the periods of greatest demand for the crop, which is essential for reducing the production gap in soybean cultivation.

2.1.4 Conclusions

Advances in maturity group classification using adjusted 3rd degree polynomial equations have been fundamental to understanding the developmental cycle of soybeans in relation to sowing date. The optimal agronomic cycle ranged from 141 to 111 days, demonstrating the importance of understanding the interaction between genetics and environment. The Best Cultivar software showed a significant probability of success where an increase in production efficiency was suggested in 79% of cases. In addition, a 12% probability of greater success was identified.

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Table supplementary 1: Characterization of soybean experiments conducted in eleven agricultural years (2010-2023) in a subtropical environment in southern Brazil.

Location	Growing season	Sowing window	Cultivars	MG range	Water supply[a]	Soil type
Água Santa - RS	13-14 and 14-15	08 Nov. - 03 Dec.	14	4.8 - 8.2	Rainfed	Oxisols
Águas de Chapecó - SC	21-22	8 Nov.	13	5.0 - 6.7	Rainfed	Utisols
Alegrete - RS	20-21	28 Oct - 08 Dec	24	5.4 - 6.7	Irrigated and rainfed	Utisols
Barra do Ribeiro - RS	21-22	4 Dec.	27	5.4 - 6.5	Rainfed	Alfisols
Caçador - SC	21-22 to 22-23	23 Nov. - 09 Dec.	28	5.1 - 6.6	Rainfed	Oxisols
Cachoeira do Sul - RS	19-20	17 Nov.	3	5.9 - 6.5	Rainfed	Alfisols
Camaquã - RS	20-21	20 Nov.	17	5.4 - 6.7	Rainfed	Alfisols
Candelária - RS	20-21 to 21-22	29 Oct - 09 Nov	42	5.0 - 6.8	Rainfed	Utisols
Capão do Cipó - RS	18-19	15 Oct.	2	6.4 - 6.5	Rainfed	Oxisols
Capiravi do Sul - RS	20-21 and 22-23	19 Nov - 08 Dec	68	5.1 - 6.7	Rainfed	Alfisols
Condor - RS	19-20	19 Nov.	3	5.9 - 6.5	Rainfed	Oxisols
Coronel Domingues Soares - PR	19-20	18 Oct.	2	5.5 - 5.9	Rainfed	Oxisols
Coronel Vivida - PR	19-20	29 Sep.	3	5.5 - 5.9	Rainfed	Oxisols
Coxilha - RS	20-21	28 Oct. - 08 Dec.	5	5.0 - 6.5	Rainfed	Oxisols
Dois Irmãos das Missões - RS	22-23	25 Nov.	51	5.0 - 6.5	Irrigated and rainfed	Oxisols
Hulha Negra - RS	21-22	13 Nov.	18	5.2 - 6.5	Rainfed	Molisols
Ibirubá - RS	20-21 and 22-23	06 Nov. - 07 Dec.	29	5.1 - 6.4	Rainfed	Oxisols
Itaqui - RS	20-21	15 Nov.	14	5.0 - 6.8	Rainfed	Alfisols
Jacutinga - RS	22-23	17 Nov.	27	5.1 - 6.1	Rainfed	Oxisols
Júlio de Castilhos - RS	13-14 and 20-21	17 Nov. - 18 Nov.	21	4.8 - 8.2	Rainfed	Utisols
Lébon Regis - SC	21-22	24 Nov.	10	5.2 - 6.6	Rainfed	Oxisols
Mangueirinha PR	18-19	10 Nov.	1	5.7	Rainfed	Oxisols
Manoel Viana - RS	18-19 and 20-21	27/Oct. - 06/Nov.	12	5.0 - 6.7	Irrigated and rainfed	Utisols
Não Me Toque - RS	19-20	23 Oct.	1	5.7	Rainfed	Oxisols
Nova Palma - RS	20-21	17 Nov.	7	5.0 - 6.5	Rainfed	Utisols
Palmeira das Missões - RS	21-22	21 Nov.	20	5.3 - 6.4	Rainfed	Oxisols
Panambi - RS	18-19	15 Oct.	1	5.7	Rainfed	Oxisols

Passo Fundo - RS	21-22 to 22-23	26 Oct. a 10 Nov.	33	5.0 - 6.5	Rainfed	Oxisols
Pelotas - RS	12-13	9 Nov.	11	4.8 - 8.2	Rainfed	Alfisols
Ponta Grossa - PR	18-19	22 Sep.	1	5.7	Rainfed	Oxisols
Prudentópolis - PR	19-20	18 Nov.	3	5.5 - 5.9	Rainfed	Oxisols
Realeza - PR	18-19	6 Oct.	1	5.7	Rainfed	Oxisols
Restinga Sêca - RS	13-14 and 14-15	13 Nov. - 14 Nov.	6	4.8 - 8.2	Rainfed	Utisols
Santa Maria - RS	10-11 to 20-21	05 Aug. - 19 Feb.	50	3.9 - 8.3	Irrigated and rainfed	Utisols
Santa Vitória do Palmar - RS	21-22	30 Oct.	26	5.2 - 7.1	Irrigated	Alfisols
Santo Ângelo - RS	19-20	10 Oct. - 11 Nov.	5	5.0 - 6.5	Rainfed	Oxisols
São Carlos - SC	22-23	18 Nov.	24	5.1 - 6.5	Rainfed	Oxisols
São Luiz Gonzaga - RS	18-19 and 19-20	14 Oct. - 24 Oct.	3	5.9 - 6.5	Rainfed	Oxisols
São Sepé - RS	19-20	16 Nov.	3	5.9 - 6.5	Rainfed	Utisols
Tapejara - RS	22-23	24 Nov.	26	5.1 - 6.1	Rainfed	Oxisols
Teixeira Soares - PR	19-20	9 Nov.	3	5.5 - 5.9	Rainfed	Oxisols
Torres - RS	20-21 to 22-23	03 Nov. - 13 Nov.	43	5.0 - 6.7	Rainfed	Histosols
Trindade do Sul - RS	22-23	25 Nov.	26	5.1 - 6.1	Irrigated	Oxisols
Tupanciretã - RS	21-22 to 22-23	21 Oct. - 27 Nov.	68	5.0 - 7.4	Irrigated	Oxisols

[a]Irrigated: water supply 70% of field capacity, and rainfed: no water supply.

2.2 ARTIGO 2 - ASSESSING CROPPING SYSTEM YIELD GAP AND RISK IN SOUTHERN BRAZIL - *(submetido a Field Crops Research)*

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ABSTRACT

Studies on yield gaps in individual crops to increase yield are often found in the literature. However, the annual yield of a cropping system can also be increased by changing the type, number, and timing of each cropping cycle. The extension of the sowing period of soybean, motivated by the search for greater yield potential and cropping system efficiency, makes it difficult for groups of relative maturity to satisfactorily capture genotype-environment interactions in subtropical environments.). The objectives in this study were: (i) to quantify the potential and energy gap of cropping systems in the current croplands in Southern Brazil, and (ii) to analyze the energetic variability of the agricultural cropping systems that exist in the Region. The main cropping systems in Southern Brazil were identified and estimated in terms of their water-limited energy potential and energy gaps, which were calculated using crop simulation models over a 16-year period. The estimates took into account the agricultural practices representative of each region. The introduction of cropping systems increases the energy yield of cultivated land, reduces production risks and serves as a way of income diversification for producers. The adoption of more intensive systems can lead to 151 and 87 GJ ha-1 year-1 (CSYgAi) higher annual production in the PR and RSC regions, respectively, while the reduction in the energy gap for the individual crop was 50 and 41 GJ ha-1 year-1, respectively.

Keywords: Crop model, Energy gap, Cropping systems, Return on investment, Production stability.

2.2.1 Introduction

It is estimated that the world population will exceed 9 billion people in 2050 (ALEXANDRATOS & BRUINSMA, 2012; FAO, 2018), and in this scenario it is necessary to increase food production, both quantitatively and qualitatively, to meet future food needs and ensure food security. Brazil is one of the protagonists in agricultural production and therefore an important player in food security, as it is the world largest producer of soybeans (42% of global soybeans), the third largest producer of maize (14% of global maize production) and 14th in wheat production (FAO, 2024).

The expansion of agricultural frontiers, i.e. the conversion of natural environments into agricultural land, is an alternative to increasing food production, but this approach may lead to major and irreversible impacts on the environment. An alternative to increasing food security is to increase cereal production vertically through sustainable intensification of current croplands by reducing the yield gap and environmental impacts and increasing the efficiency of resource use (DEVKOTA et al., 2015; GUILPART et al., 2017; SILVA et al., 2022).

The estimation of the water-limited energy yield potential in cropping systems (CSYwi) is determined by the sum of the yield of the systems and the energy value of the grains (GUILPART et al., 2017). Yield potential is determined by solar radiation intercepted by the canopy, temperature, atmospheric CO_2 and genetic traits, while it is limited by the amount and distribution of water and by soil and terrain characteristics that influence the water-holding capacity of the soil for the plant, but the plant grows without nutrient limitations and free from biotic stress (EVANS, 1993; VAN ITTERSUM; RABBINGE, 1997; VAN ITTERSUM et al., 2013). CSYwi, along with the determination of the energy yield gap of the cropping system (CSYg), facilitates the identification of opportunities to increase annual yield per unit area by selecting cropping sequences with higher energy yield (GUILPART et al., 2017; SILVA et al., 2017), aiming for the sustainable intensification of the systems.

In the Southern region of Brazil, where 27 % of Brazilian soybean is produced, studies such as Tagliapietra et al. (2021) and Marin et al., (2022) indicate that soybean cultivation has a large yield gap caused by the water deficit during dry spells, which is intensified during La Niña years (Nóia Júnior et al., 2019; Nóia Júnior & Sentelhas et al., 2019). Given the significant influence of water distribution and temperature fluctuations, which increase the instability of single-crop production, the adoption of cropping systems with temporally integrated cultivation arises as a promising strategy for producers seeking yield stability (GUILPART et al., 2017; RIBAS et al., 2020) and profitability combined with high crop yields and energy yields.

In this study, agricultural simulation models were used to characterize the current cropping systems in the subtropics of Southern Brazil, i.e. the management practices adopted by producers such as sowing date, varieties, sowing density and other practices were studied together with climate and soil data to evaluate the CSYw and CSYg comprising soybean, wheat and maize crops in southern Brazil, following the approach proposed by Guilpart et al, 2017, and the protocols of the Global Yield Project Gap Atlas (Grassini et al., 2015; Van Bussel et al., 2015, http://www.yieldgap.org/methods). The objectives in this study were: (i) to quantify the potential and energy gap of cropping systems in the current croplands in Southern Brazil, and (ii) to analyze the energetic variability of the agricultural cropping systems that exist in the Region.

2.2.2 Material and methods

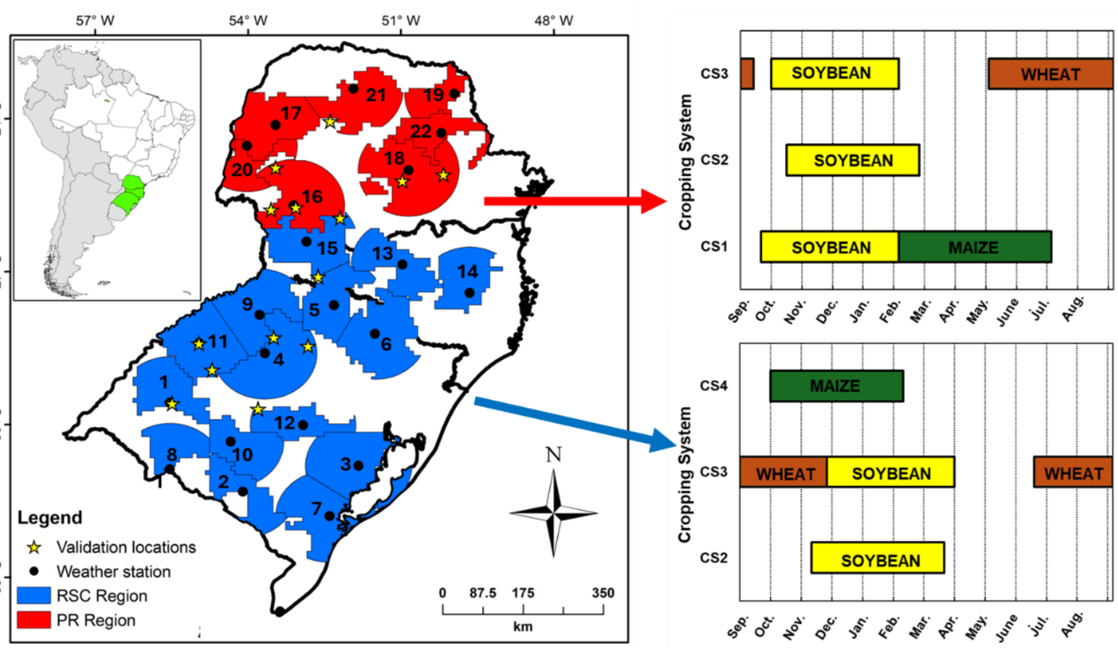
2.2.2.1 Characterization of the locations and the cultivation system

The study region was the South of Brazil that comprises the States of Paraná, Santa Catarina, and Rio Grande do Sul (Figure 6), where 31.4% of the land in Brazil is cultivated with soybean, 90% with wheat and 19.8% with maize (CONAB, 2024). The climate of the region is humid subtropical (Cfa) with no defined dry season, based on the Köppen climate system (WREGE et al., 2011). The region was divided into climate zones (CZ) according to the methodology proposed by Van Wart et al., (2013) and used by Tagliapietra et al., (2021). This classification takes into account three agroclimatic variables that determine soybean cultivation, namely: (i) the total annual number of degree days, (ii) the annual drought index and (iii) temperature seasonality. This allows a more accurate estimation of the yield potential, the determination of the current yield and consequently the yield gap.

The cropping systems (CS) and the actual yield (Ya) (Figure 1) were identified individually for each buffer zone (BZ) and overlaid with the harvested areas of each crop to identify the CS, as well as with the average yield for the Ya. The data on harvested areas and average yields were obtained from the Brazilian Institute of Geography and Statistics (IBGE) using the average of 5 years (2018-2022). When calculating the yield potential, water-limited potential, actual yield, and yield gap for each cropping system (CS), the percentage of each FC in each CS was taken into account. This process was carried out using a weighted average, considering the corresponding area of each FC.

The region studied was divided into 2 groups: the PR region, buffered in red (Figure 6), a region where 3 cropping systems were predominante, CS1: soybean – maize, CS2: soybean and CS3: soybean – wheat. The second group, the RSC region, consists of blue buffers (Figure 1) containing the systems CS2: soybean, CS3: soybean – wheat and CS4: maize.

Figure 1: Map of South America and Brazil (inset), and map of the three States in Southern Brazil showing the buffer zones with the cropping systems. The red buffer zones represent the PR region (state of Paraná); the blue color represents the RSC region (states of Rio Grande do Sul and Santa Catarina). The yellow stars represent the experiments used to evaluate the models.



2.2.2.2 Meteorological and soil data

According to Grassini et al., (2015), for a robust and reliable estimate, it is necessary to estimate the water-limited yield potential (Yw) for at least 15 years. To fulfil this criterion, the meteorological stations from the Brazilian National Institute of Meteorology (INMET) network were used during this period, and to create buffer zones (BZs) (GRASSINI et al., 2015) in an area of 100 km diameter delimited by climate zones (CZ) (Figure 1). BZs with more than 5% of the harvested area of the studied crops were selected. In this way, 22 FCs (1 to 22) were selected, covering a total of 73% of the cultivated area for soybeans, 75% for wheat and 64% for maize (Figure 1).

Soils were selected according to the proportion in each FC based on the following criteria: (i) soils covering more than 20% of the FC area, and (ii) selection of soils until a minimum representation of 50% of the FC was reached (EDREIRA et al., 2017). The soil data from the Radambrasil project (COOPER et al., 2005) described in Tables 1 and 2 were used.

Table 1: Characterization of the variables used to simulate the yield potential and water-limited yield potential for the buffer zones in the RSC (Rio Grande do Sul and Santa Catarina) region of Southern Brazil.

Buffer (Location-State)	Cropping system (%)	Sowing date	Cultivar/hybrid maturation	Plant Density (pl/m²)	Soil type (%)
1 - Alegrete - RS	Soybean (74%)	20 nov.	GMR 6.5	30	Ultisol (11%)
	Soybean - Wheat (23%)	30 nov. - 15 jun.	GMR 6.5 - Early	30 - 400	Entisol (34%)
	Maize (3%)	20 nov.	Super early	6	Alfisols (38%)
2 - Bagé - RS	Soybean (96%)	20 nov.	GMR 6.5	30	Ultisol (33%)
	Soybean - Wheat (2%)	30 nov. - 15 jun.	GMR 6.5 - Early	30 - 400	Alfisols (25%)
	Maize (2%)	10 oct.	Super early	6	
3 - Camaquã - RS	Soybean (86%)	20 nov.	GMR 6.5	30	Ultisol (59%)
	Soybean - Wheat (4%)	30 nov. - 15 jun.	GMR 6.5 - Early	30 - 400	Alfisols (24%)
	Maize (10%)	10 oct.	Super early	6	
4 - Cruz Alta - RS	Soybean (87%)	25 oct.	GMR 5.5	30	Ultisol (21%)
	Soybean - Wheat (10%)	05 nov. - 10 jun.	GMR 5.5 - Early	30 - 350	Oxisol (67%)
	Maize (3%)	20 sep.	Super early	6	
5 - Erechim - RS	Soybean (72%)	30 oct.	GMR 5.5	30	Inceptisol (19%)
	Soybean - Wheat (15%)	10 nov. - 20 jun.	GMR 5.5 - Early	30 - 350	Oxisol (69%)
	Maize (13%)	20 sep.	Super early	6	
6 - Lagoa Vermelha - RS	Soybean (72%)	30 oct.	GMR 5.5	30	Nitisol (21%)
	Soybean - Wheat (11%)	10 nov. - 20 jun.	GMR 5.5 - Early	30 - 350	Oxisol (65%)
	Maize (17%)	20 sep.	Super early	6	
7 - Pelotas - RS	Soybean (91%)	20 nov.	GMR 6.5	30	Ultisol (29%)
	Soybean - Wheat (2%)	30 nov. - 15 jun.	GMR 6.5 - Early	30 - 400	Alfisols (46%)
	Maize (7%)	10 oct.	Super early	6	
8 - Santana do Livramento - RS	Soybean (91%)	20 nov.	GMR 6.5	30	Ultisol (21%)
	Soybean - Wheat (4%)	30 nov. - 15 jun.	GMR 6.5 - Early	30 - 400	Alfisols (70%)
	Maize (5%)	10 oct.	Super early	6	
9 - Santo Augusto - RS	Soybean (56%)	25 oct.	GMR 5.5	30	Inceptisol (18%)
	Soybean - Wheat (33%)	05 nov. - 10 jun.	GMR 5.5 - Early	30 - 350	Oxisol (76%)

	Maize (11%)	20 sep.	Super early	6	
10 - São Gabriel - RS	Soybean (92%) Soybean - Wheat (6%) Maize (2%)	20 nov. 30 nov. - 15 jun. 10 oct.	GMR 6.5 GMR 6.5 - Early Super early	30 30 - 350 6	Ultisol (21%) Entisol (26%) Alfisols (44%)
11 - São Luiz Gonzaga - RS	Soybean (66%) Soybean - Wheat (28%) Maize (6%)	25 oct. 05 nov. - 10 jun. 20 sep.	GMR 5.5 GMR 5.5 - Early Super early	30 30 - 350 6	Nitisol (16%) Oxisol (66%)
12 - Cachoeira do Sul - RS	Soybean (94%) Soybean - Wheat (3%) Maize (3%)	25 oct. 05 nov. - 10 jun. 20 sep.	GMR 6.0 GMR 6.0 - Early Super early	30 30 - 350 6	Ultisol (26%) Alfisols (63%)
13 - Caçador - SC	Soybean (67%) Soybean - Wheat (5%) Maize (28%)	20 nov. 30 nov. - 30 jun. 20 sep.	GMR 5.5 GMR 6.0 - Early Super early	30 30 - 400 6	Inceptisol (33%) Oxisol (16%) Nitisol (47%)
14 - Ituporanga - SC	Soybean (51%) Soybean - Wheat (5%) Maize (44%)	20 nov. 30 nov. - 30 jun. 20 sep.	GMR 5.5 GMR 6.0 - Early Super early	30 30 - 400 6	Inceptisol (81%) Ultisol (19%)
15 - Novo Horizonte - SC	Soybean (73%) Soybean - Wheat (13%) Maize (13%)	20 nov. 30 nov. - 30 jun. 20 sep.	GMR 5.5 GMR 6.0 - Early Super early	30 30 - 400 6	Entisol (28%) Oxisol (53%)

Table 2: Characterization of the variables used to simulate the yield potential and water-limited yield potential for the buffer zones in the PR (Paraná) region of Southern Brazil.

Buffer (Location-State)	Cropping system (%)	Sowing date	Cultivar/hybrid maturation	Plant Density (pl/m²)	Soil type (%)
16 - Dois Vizinhos - PR	Soybean (37%)	01 oct.	GMR 5.5	30	Oxisol (38%)
	Soybean - Maize (25%)	01 oct. - 15 feb.	GMR 5.5 - Super early	30 - 6	Entisol (32%)
	Soybean - Wheat (31%)	15 oct. - 01 may	GMR 5.5 - Early	30 - 350	Nitisol (16%)
17 - Brasilândia - PR	Soybean (17%)	01 oct.	GMR 6.5	30	Oxisol (23%)
	Soybean - Maize (79%)	15 sep. - 10 feb.	GMR 6.0 - Super early	30 - 6	Ultisol (40%)
	Soybean - Wheat (4%)	15 sep. - 01 may	GMR 6.0 - Early	30 - 350	Nitisol (27%)
18 - Ivaí - PR	Soybean (66%)	20 oct.	GMR 6.5	30	Oxisol (55%)
	Soybean - Maize (5%)	01 oct. - 15 feb.	GMR 5.5 - Super early	30 - 6	Inceptisol (27%)
	Soybean - Wheat (17%)	10 oct. - 15 abr.	GMR 6.0 - Early	30 - 350	
19 - Joaquim Távora - PR	Soybean (23%)	25 oct.	GMR 7.0	30	Ultisol (22%)
	Soybean - Maize (25%)	01 oct. - 15 feb.	GMR 6.5 - Super early	30 - 6	Entisol (26%)
	Soybean - Wheat (45%)	10 oct. - 15 abr.	GMR 6.0 - Early	30 - 350	Nitisol (42%)
20 – Mar. Can. Rondon - PR	Soybean (5%)	01 oct.	GMR 6.5	30	Oxisol (14%)
	Soybean - Maize (78%)	15 sep. - 10 feb.	GMR 6.0 - Super early	30 - 6	Nitisol (73%)
	Soybean - Wheat (16%)	15 sep. - 15 abr.	GMR 6.0 - Early	30 - 350	
21 - Maringá - PR	Soybean (18%)	20 oct.	GMR 6.5	30	Oxisol (30%)
	Soybean - Maize (60%)	01 oct. - 15 feb.	GMR 6.0 - Super early	30 - 6	Nitisol (51%)
	Soybean - Wheat (21%)	10 oct. - 01 may	GMR 6.0 - Early	30 - 350	
22 - Ventânia - PR	Soybean (54%)	25 oct.	GMR 7.0	30	Oxisol (39%)
	Soybean - Maize (8%)	15 sep. - 15 feb.	GMR 6.5 - Super early	30 - 6	Ultisol (29%)
	Soybean - Wheat (25%)	10 oct. - 15 abr.	GMR 6.0 - Early	30 - 350	Inceptisol (21%)

2.2.2.3 Simulation of the yield potential and the water-limiting yield potential of cropping systems

Yield potential (Yp) and water-limited yield potential (Yw) were estimated using the DSSAT platform models CSM-CROPGRO-Soybean (BOOTE et al., 1998), CERES-Maize (JONES and KINIRY , 1986) and CERES-Wheat (RITCHIE and OTTER, 1985) for the soybean, maize and wheat crops, respectively. For the estimation of yield potential of a crop, the yield potential of a particular cropping system was determined from the sum of the yield potentials of all crops comprising the cropping system. Therefore, the following are presented: CSYwi for the water-limited energy potential of the cropping system and CSYai for the actual energy yield of the cropping system.

To compare cropping systems with different species (cereals and oilseeds), it is necessary to express them in energy per unit area and time, hence the approach by Guilpart et al., (2017) was used. The energy yield (GJ ha^{-1}) was calculated by the product of Crop yield and energy content, for which the following values were used: 1480 kJ per 100 g of maize at 15.5% moisture, 2280 kJ per 100 g of soybeans at 13% moisture and 1471 kJ per 100 g of wheat at 14% moisture (USDA - National Nutrient Database).

The simulations were carried out for 16 growing seasons (from 2007/2008 to 2021/2022) to ensure an accurate and reliable estimate (Grassini et al., 2015). The varieties/hybrids, plant densities, row spacing and predecessor crops that best represent each FC were used (Figure 1, Table 1 and 2). Details of the traits and variables used to simulate yield potential and water-limited potential in the different FCs are described in Tables 1 and 2.

2.2.2.4 Estimating the energy and yield gap of cropping systems

The yield gap estimates of the systems were determined by the differences between yield potential of the most energetic system (CS*), yield potential of the system (CSYpi), and current system yield (CSYai).

$$CSYgAi = CS^* - CSYpi \quad (1)$$

$$CSYgMi = CSYpi - CSYai \quad (2)$$

where CSYgAi is defined as the yield gap resulting from the spatial and/or temporal arrangement of the crops. CS* is the yield potential of the most energetic system, CSYpi is the yield potential of the system, CSYgMi is defined as the gap due to the management of the individual crops within the current cropping system, CSYai is the current yield of the cropping system.

When considering individual crops, water (Ygw) and management (Ygm) gaps were defined as follows:

$$Ygw = Yp - Yw \quad (3)$$

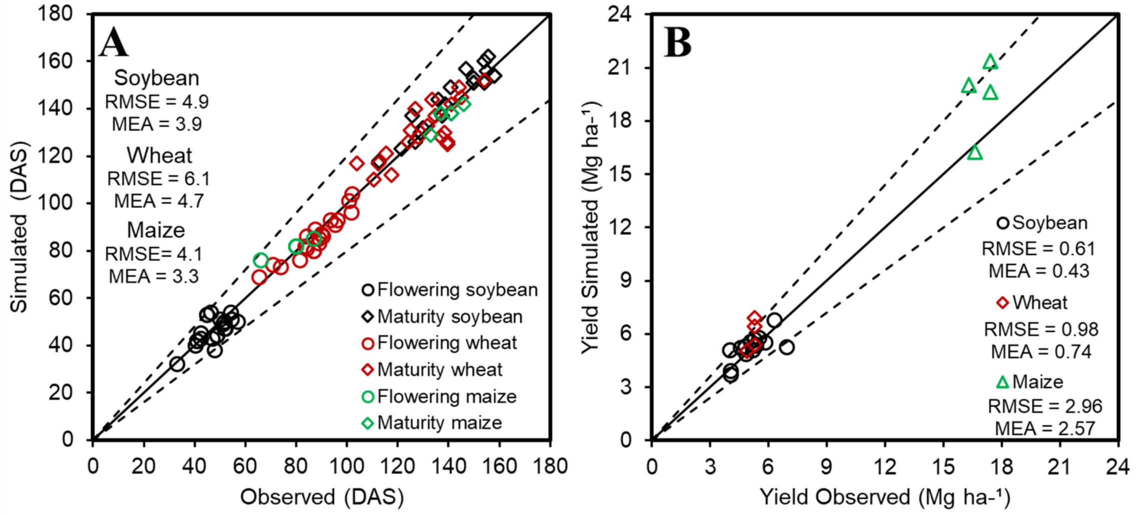
$$Ygm = Yw - Ya \quad (4)$$

where Yp is the yield potential of the crop and Yw is the water-limited yield potential of the crop. Yw is the water-limited yield potential of the crop and Ya is the actual yield of the crop.

2.2.2.5 Evaluation of crop simulation models

The genetic coefficients for soybean, wheat, and maize were derived from Mercau et al., (2007, 2014) and Monzon et al., (2007, 2012). The model was evaluated with independent data from experiments conducted with variation in sowing date, developmental cycle, different years, and locations in Southern Brazil (Figure 2). The data observed for soybean cultivation were from Santa Maria (-29.69; -53.80), Manoel Viana (-29.58; -55.49), Não-Me-Toque (-28.48; -52.82), Panambi (-28.29; - 53.49), São Luiz Gonzaga (-28.41; -54.96), Capão do Cipó (-28.92; -54.70), Prudentópolis (-25.22; -50.97), Mangueirinha (-25.94; -52.19), Ponta Grossa (-25.09; -50.16), and Realeza (-25.78; -53.54). For wheat cultivation Santa Maria (-29.69; -53.80), Ponta Grossa (-25.09; -50.16), Cascavel (-24.96; -53.80), Campo Mourão (-24.04; -52.38), and Dois Vizinhos (-25.73; -53.06). For maize cultivation in Santa Maria (-29.69; -53.80), Júlio de Castilhos (-29.23; -53.68), and Chapeco (-27.09; -52.61). The root mean square error (RMSE) found in the validation of the crop models with independent data was 4.9, 6.1 and 4.1 days, and for yield 0.61, 0.98 and 2.96 Mg ha^{-1} for soybean, wheat and maize, respectively, indicating a satisfactory performance of the crop models (MERLOS et al., 2015; TAGLIAPIETRA et al., 2021; MARIN et al., 2022).

Figure 2: Comparison between observed and simulated phenology in Days after Sowing - DAS (A) and grain yield data (B). The solid lines represent y = x and the dotted lines represent y = x ± 20%. RMSE = root mean square error (with units of days and Mg ha^{-1}), and MEA = mean absolute error (with units of days and Mg ha^{-1}).



2.2.2.6 Return on investment

The return on investment (ROI) has been used to measure the investment efficiency of crops and compare them with other cropping systems. In this way, the production risk is quantified in the financial part, but is often one of the highest difficulties for farmers and advisors to quantify but has huge implications for farm management. To calculate the ROI, data from CONAB was used for the period from 2013 to 2021 (CONAB, 2023) for the regions studied (PR and RSC region).The ROI was calculated as the follow:

$$ROI = (GI - OC) / OC \quad (5)$$

where GI the gross income and OC the operating costs.

The gross income was calculated by multiplying the crop yield by the selling price for each year (from 2013/2014 to 2021/2022) to obtain the GI for the Ya scenario and for the Yw of each FC. The operational costs are the sum of the fixed and variable production costs of the crops.

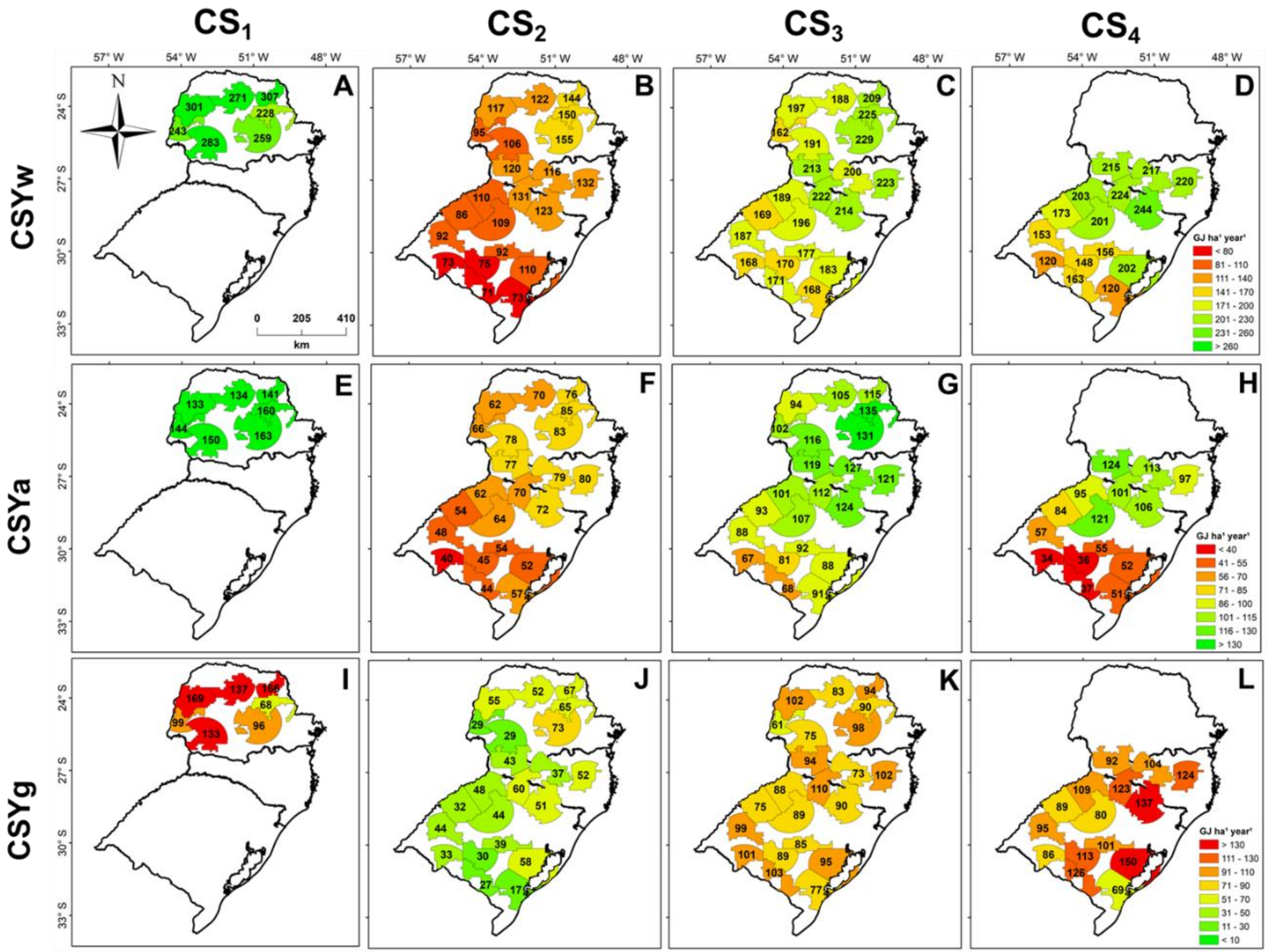
2.2.3 RESULTS

2.2.3.1 Water-limited yield potential, actual yield and yield gap in cropping systems

The cropping system with the highest CSYw was CS1 (soybean – maize) with a variation of 228 to 307 GJ ha^{-1} $year^{-1}$ (Figure 3A), a system predominant in the state of Paraná (PR region). The second system that had the highest CSYw values and was common throughout the study region was CS3 (soybean – wheat), with values between 162 and 229 GJ ha^{-1} $year^{-1}$ (Figure 3C). The other systems (CS4 and CS2) had CSYw values between 120 and 244 GJ ha^{-1} $year^{-1}$ and 71 and 155 GJ ha^{-1} $year^{-1}$, respectively (Figure 3B and D).

The highest CSYa was recorded in CS1 (133 to 163 GJ ha^{-1} $year^{-1}$) (Figure 3E), followed by CS3 (67 to 135 GJ ha^{-1} $year^{-1}$) (Figure 3G), CS4 (34 to 124 GJ ha^{-1} $year^{-1}$) (Figure 3H) and CS2 (40 to 85 GJ ha^{-1} $year^{-1}$) (Figure 3F). However, CS1, even with the highest CSYa, is a system with a large management gap to be explored (68 to 169 GJ ha^{-1} $year^{-1}$) (Figure 3I). The other systems have gaps of 69 to 150 GJ ha^{-1} $year^{-1}$ (CS4) (Figure 3L), 61 to 110 GJ ha^{-1} $year^{-1}$ (CS3) (Figure 3K) and 17 to 73 GJ ha^{-1} $year^{-1}$ (CS2) respectively (Figure 3J).

Figure 3: Energy potential limited by water (CSYw), actual energy yield (CSYa) and energy gaps (CSYg), both expressed in energy (GJ ha^{-1} $year^{-1}$) for the regions with cropping systems in southern Brazil: CS1 (soybean – maize), CS2 (soybean), CS3 (soybean – wheat), and CS4 (maize).

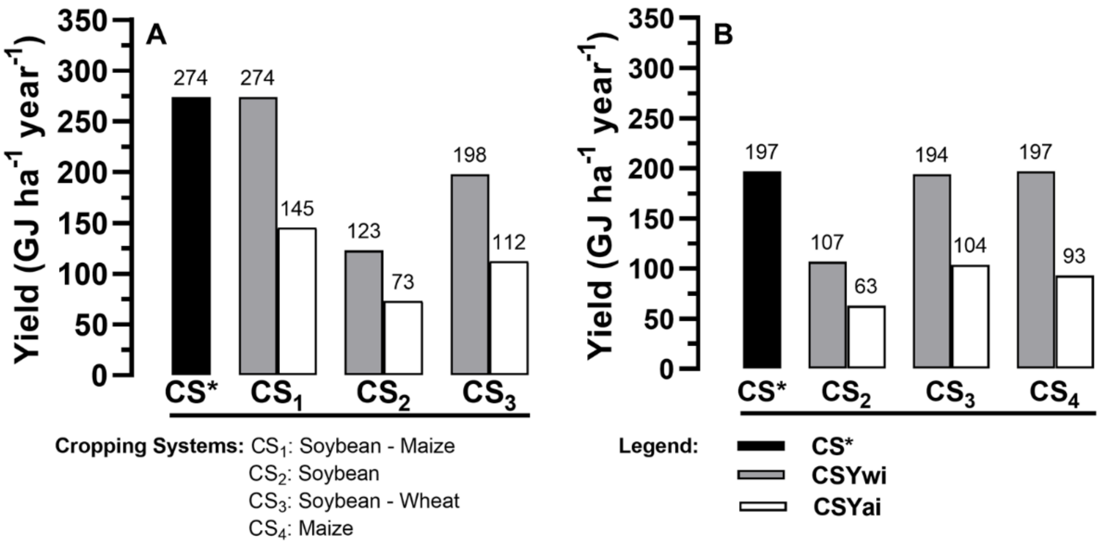


2.2.3.2 Cropping systems in Southern Brazil

In the PR region (Figure 4A) the most energetic system (CS*) was the cropping system that integrates the cultivation of soybeans and maize according to the second harvest (CS1). This system has an average CSYwi of 274 GJ ha^{-1} $year^{-1}$ and a CSYai of 145 GJ ha^{-1} $year^{-1}$, and therefore this system has no CSYgAi as it is the most energetic system in the studied region, but it has a CSYgMi of 129 GJ ha^{-1} $year^{-1}$ (47%). For CS2, a CSYwi of 123 GJ ha^{-1} $year^{-1}$ and a CSYai of 73 GJ ha^{-1} $year^{-1}$ were estimated, i.e. a CSYgAi of 55.1% and CSYgMi of 40.6%. For CS3, CSYwi and CSYai were 198 and 73 GJ ha^{-1} $year^{-1}$ respectively. In this scenario, CSYgAi reached 27.7%, while CSYgMi was 43.4%.

Figure 4B shows the CS* for the RSC region where the system with the highest energy value was CS4 (maize). The CSYw of CS4 was 197 GJ ha^{-1} $year^{-1}$, a value very similar to that of CS3 (194 GJ ha^{-1} $year^{-1}$). The main difference between these two systems is the CSYgMi, which is 52.8% (CS4) and 46.4% (CS3), respectively. CS2, on the other hand, has a CSYwi of 107 GJ ha^{-1} $year^{-1}$ and a CSYai of 63 GJ ha^{-1} $year^{-1}$, both values are lower compared to the PR region. The CSYgAi of this system was 45.7%, which is a significant reduction compared to the PR region, while the CSYgMi remained similar at 41.1%.

Figure 4: Energy potential of the most energetic cropping system (black bars), energy potential of the current cropping systems (grey bars) and current energy yield of the cropping systems (white bars) in Southern Brazil, where A stands for the region of the state of Paraná (CS PR) and B for the region of the states of Santa Catarina and Rio Grande do Sul (CS RSC). CS* = energy potential of the most energetic cropping system, CSYwi: energy potential of the current cropping system, CSYai: actual energy yield of the cropping system.

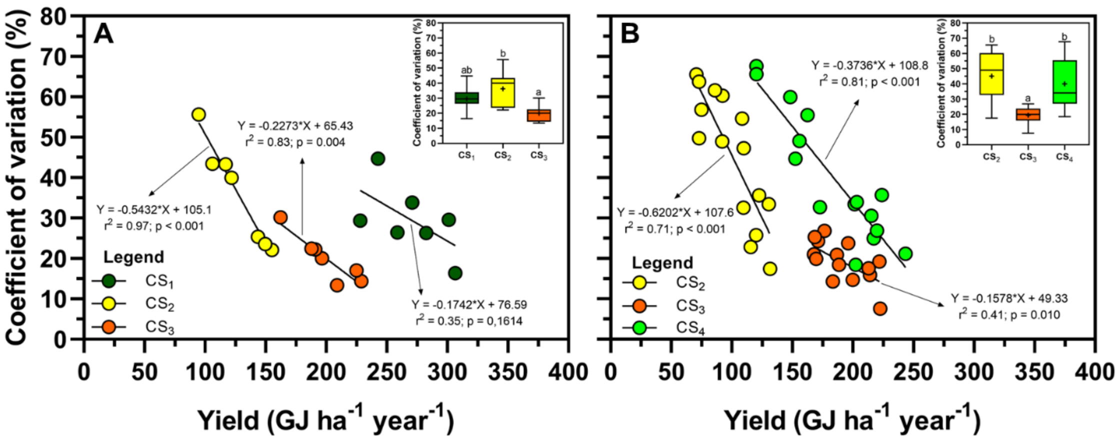


2.2.3.3 Stability of cropping systems

In the PR region (Figure 5A), it was observed that the CS2 system had the highest coefficient of variation (CV) along the FCs, ranging from 22% to 56%. When another crop was added to the system, as in the case of CS1 and CS3, a decrease in CV was observed in both systems (CS1 = 16% to 44% and CS3 = 13% to 30%) compared to CS2, which has only one crop in the system. In the CS2 and CS3 systems, the relationship between the CV and the increase in the energy value (linear equation) of the system was statistically significant. In addition, the Tukey test revealed differences between the systems with a probability of 5, highlighting CS2 as the system with the greatest stability in terms of CV.

Like the PR region, the RSC region also showed the highest CV in single-crop systems. CS2 and CS4 showed CVs between 17% and 65% and 18% and 67%, respectively. CS3, on the other hand, showed a variation of 7% to 27%, which is a statistical difference according to the Tukey test and is the system with the greatest stability in terms of CV in this region. It is important to emphasize that all cropping systems in this region showed a significant response to cv reduction with increasing CSYw.

Figure 5: Water-limited energy potential (CSYw) of cropping systems and the interannual coefficient of variation for the different buffer zones within each system in Southern Brazil. (A) for the region of the state of Paraná (CS PR) and (B) for the region of Santa Catarina and Rio Grande do Sul (CS RSC). In the inset of the figure, the difference in the coefficient of variation between the systems in each region is represented by Blox Plot, followed by the mean test (Tukey test) at 5% significance. In Blox Plot, the boxes delimit the 25th and 75th percentiles, the whiskers represent the maximum and minimum values, the horizontal line the median, and the + symbol the mean. CS1 (soybean – maize), CS2 (soybean), CS3 (soybean – wheat) and CS4 (maize).



The graph in Figure 6A shows the values of Yp, Yw, Ygw and Ygm for the different crops within each cropping system. In CS1, the soybean crop had the lowest values for Yp (6.3 Mg ha^{-1}) and Yw (4.4 Mg ha^{-1}) compared to the CS3 (Yp = 6.7 Mg ha^{-1} and Yw = 5.2 Mg ha^{-1}) and CS2 (Yp = 6.9 Mg ha^{-1} and Yw = 5.6 Mg ha^{-1}) systems.

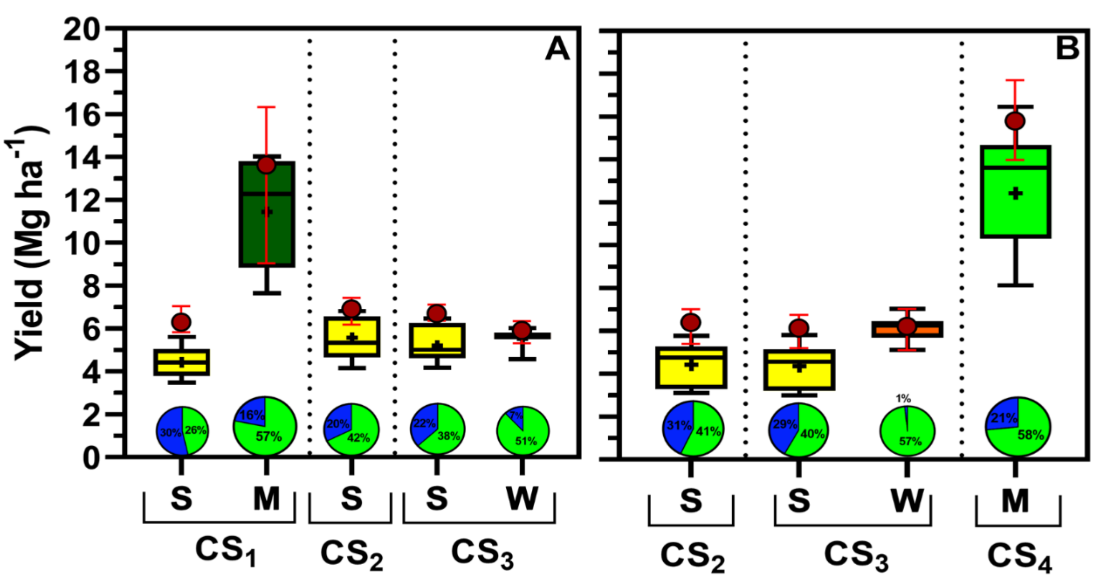
When analyzing the second maize harvest, a significant deviation in Yp (13.6 Mg ha^{-1}) and Yw (11.4 Mg ha^{-1}) was observed in CS1, mainly due to climatic risks, especially low temperatures during the critical periods of the grain filling phase. Maize is the crop with the largest yield gap in these regions (Ygw = 16% and Ygm = 57%). The wheat crop in the CS3 system illustrates the proximity of the values of Yp (5.9 Mg ha^{-1}) and Yw (5.5 Mg ha^{-1}), resulting in a low Ygw (7%) but a high Ygm (57%).

In the RSC region, the values of Yp (6.4 and 6.2 Mg ha^{-1}) and Yw (4.4 and 4.3 Mg ha^{-1}) are uniform for soybean cropping in the CS2 and CS3 systems, as shown in Figure 11B. This uniformity results in similar Ygw (31% and 29%) and Ygm (41% and 40%)

values between them. In CS3, the wheat crop stands out, which, similar to the PR region, has a small Ygw (1%) and a large Ygm (57%).

Maize as the main crop in the season, represented by the CS4 system, has high Yp (15.8 Mg ha^{-1}) and Yw (12.4 Mg ha^{-1}) values. However, considerable instability between sites and years can be observed, as indicated by the dispersion and standard deviation of the data. It is important to emphasize that maize in this region, as in the PR region, has the highest Yg values (Ygw = 21% and Ygm = 58%).

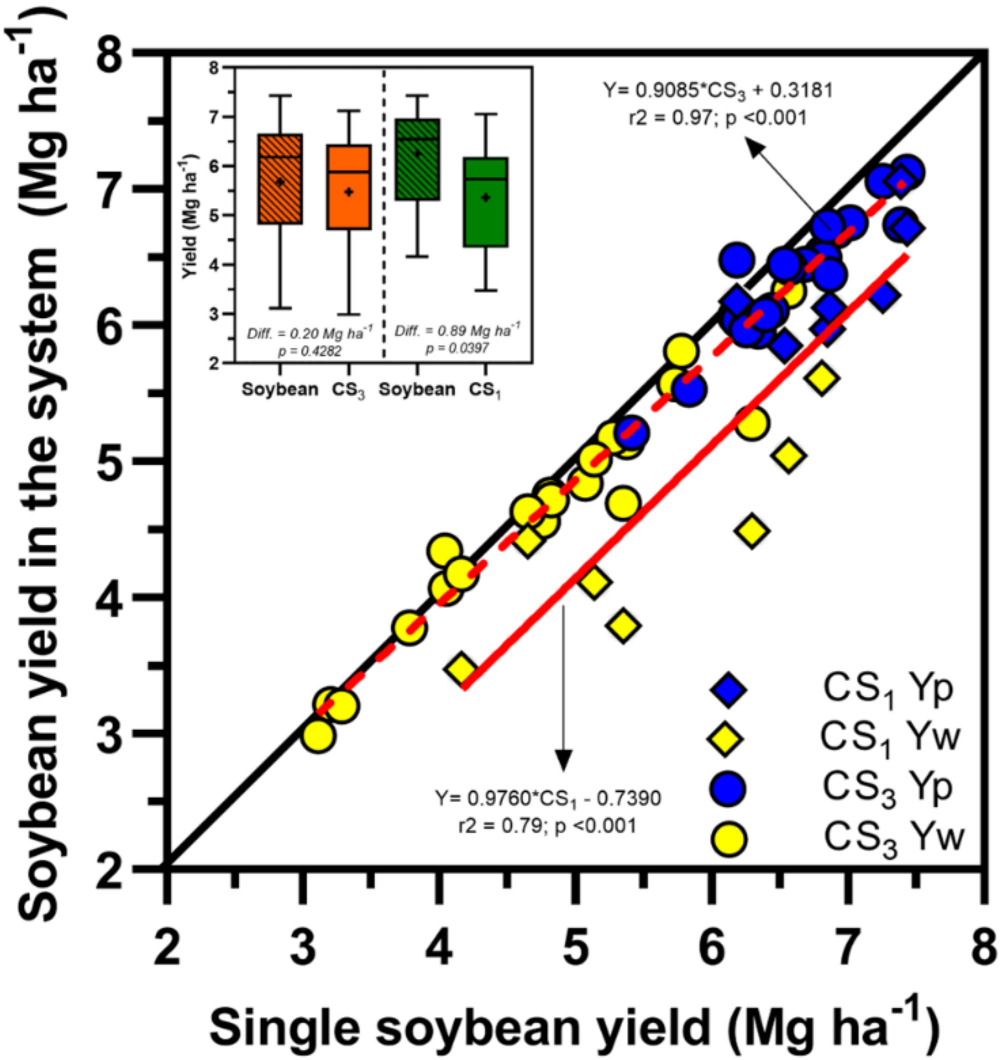
Figure 6: Yield potential (Yw) limited by water for crops within the individual cropping systems in Southern Brazil, shown as a Blox plot (colours yellow/green/orange). The boxes delimit the 25th and 75th percentiles, the whiskers represent the maximum and minimum values, the horizontal line the median, and the + symbol the mean value. The red circles show the yield potential (Yp), while the red error bars refer to your Yp standard deviation. In the pizza-type circles at the bottom of each panel, the water gap (Ygw = Yp-Yw) is shown in blue, and the management gap (Ygm = Yw – Ya) is shown in green, both as a percentage for each crop within each system. (A) for the region of the state of Paraná (CS PR) and (B) for the region of the states of Santa Catarina and Rio Grande do Sul (CS RSC). CS1 (soybean – maize), CS2 (soybean), CS3 (soybean – wheat) and CS4 (maize).



2.2.3.4 Soybean system (CS2) x soybean – wheat (CS3) and soybean – maize (CS1) systems

When comparing the CS2 and CS3 systems (Figure 7), we found a significant relationship between them that is favorable to CS2, as we can see from the red dashed line. However, when data are analyzed by a mean test (Tukey at 5% significance, in the inset of Figure 7), no statistical difference was found, with the difference between CS2 and CS3 being 0.2 Mg ha^{-1}. When comparing CS2 with CS1, there is not only a significant correlation between them, but also a statistical difference of 0.89 Mg ha^{-1} in favor of CS2.

Figure 7: Yield of soybeans (CS2) compared to cropping systems with maize (CS1) or wheat (CS3). The circles represent the comparison with the soybean (CS2) versus soybean-wheat (CS3) system and the squares represent soybean (CS2) versus soybean–maize (CS1). The blue color represents the yield potential (Yp) and the yellow color represents the yield potential limited by water (Yw). The solid black diagonal line shows y = x. Adjusted linear regression parameters (red solid and dashed line) and the coefficient of determination (R2) are also shown. The box on the left shows the yield difference between soybean crops in different cropping systems, with the boxes delimiting the 25th and 75th percentiles, the whiskers representing the maximum and minimum values, the horizontal line the median, and the + symbol the average.

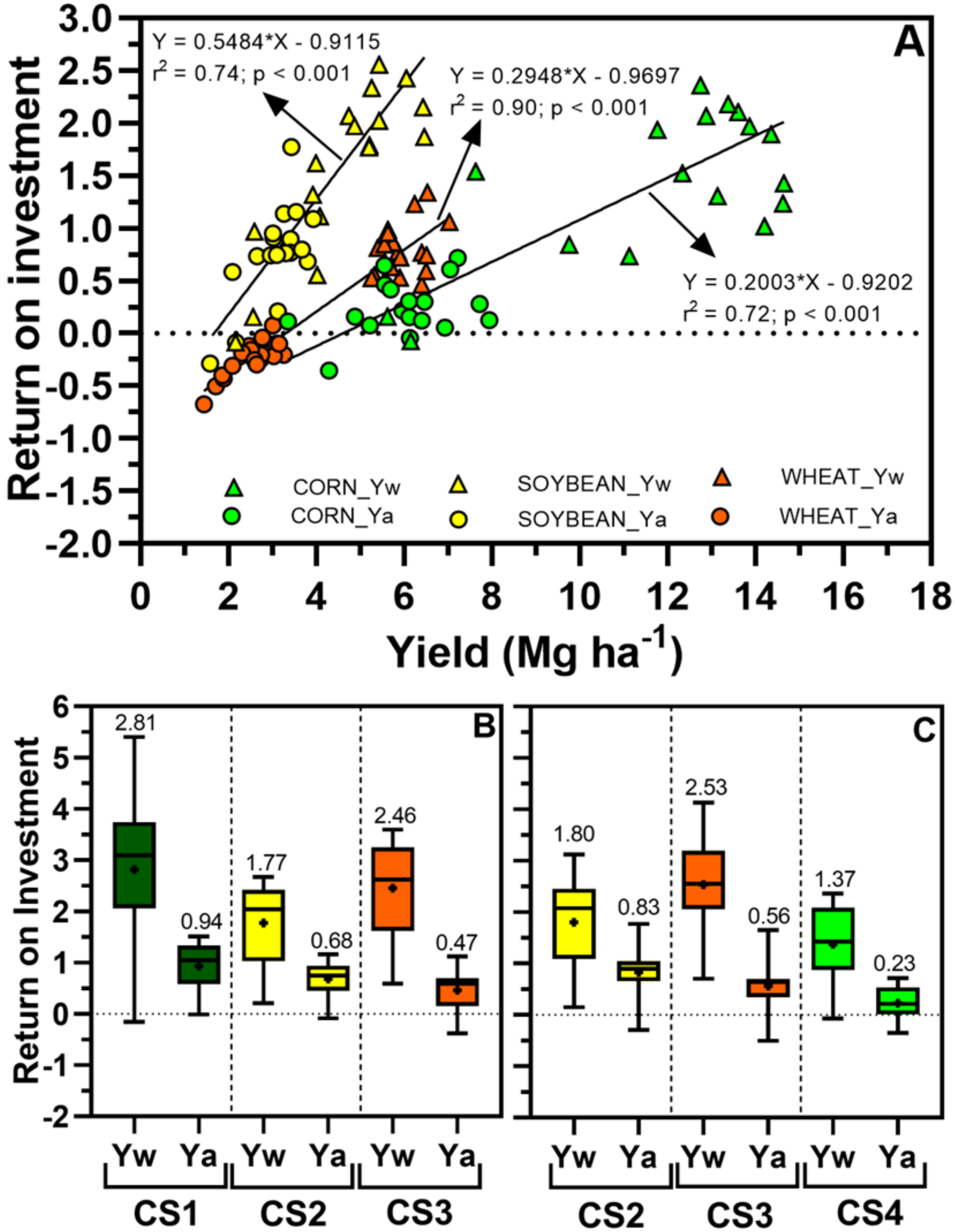


3.5 Return on investment in cropping systems

When analyzing the ROI (Figure 8), we found that soybean cultivation has the highest ROI when looking at the current average yield, with an average ROI of 0.75 and a variation between years of -0.28 and 2.55, followed by maize with an average ROI of 0.24 (variation between years: -0.35 to 2.3) and finally wheat with an average ROI of -0.24 (variation between years: -0.67 to 0.08) (Figure 8A). However, when analyzing ROI in terms of water-limited yield potential, the average ROI was 1.18, 1.52, and 0.80 for soybeans, maize, and wheat, respectively (Figure 8A).

When analyzing ROI by cropping system (Figure 8 B and C), CS1 was found to have the highest yield for both Ya (ROI = 0.94) and Yw (ROI = 2.81) for the regions studied in the PR region. For the RSC region, the ROI was 0.83, 0.56 and 0.23 for the CS2, CS3 and CS4 systems, respectively, with respect to Ya and 1.80, 2.53 and 1.37 23 (CS2, CS3 and CS4, respectively) when analyzing Yw.

Figure 8: Return on investment (ROI) compared to current yield (circles) and water-limited potential (triangles) for different years (2013 – 2021) for soybeans (yellow), maize (green) and wheat (orange) in Southern Brazil (A). The Blox plot shows (B) the return on investment for each cropping system for the region of the state of Paraná (CS PR) and (B) for the region of Santa Catarina and Rio Grande do Sul (CS RSC). In the Blox plot, the boxes delimit the 25th and 75th percentiles, the whiskers represent the maximum and minimum values, the horizontal line the median, and the + symbol the average. (CS1 – soybeans - maize; CS2 – soybeans - soybeans; CS3 – soybeans - wheat; CS4 - maize).


A
Y = 0.5484*X - 0.9115
r2 = 0.74; p < 0.001
Y = 0.2948*X - 0.9697
r2 = 0.90; p < 0.001
Y = 0.2003*X - 0.9202
r2 = 0.72; p < 0.001
CORN_Yw
CORN_Ya
SOYBEAN_Yw
SOYBEAN_Ya
WHEAT_Yw
WHEAT_Ya
Return on investment
Yield (Mg ha-1)
B
C
Return on Investment
2.81
0.94
1.77
0.68
2.46
0.47
1.80
0.83
2.53
0.56
1.37
0.23
Yw Ya Yw Ya Yw Ya
CS1 CS2 CS3
Yw Ya Yw Ya Yw Ya
CS2 CS3 CS4

2.2.4 Discussion

In this study, we have determined the potential for energy production in different cropping systems in southern Brazil. To our knowledge, this is the first attempt to quantify the production risk of the systems and the respective crops within each system to enable greater production stability for farmers in Brazil, a leading country in producing soybean, maize and wheat. And in doing that we identified opportunities for improvements in the energy production of crops in the subtropics of Southern Brazil.

The use of two annual crops increases energy production in Southern Brazil, with CS1 (PR region) having the highest energy production (Figure 1). This system has a CSYw of 208 to 307 GJ ha^{-1} $year^{-1}$ (Figure 3A), a system that predominates in the western region of the PR, which corresponds to 43% of the production area. In this part of the PR, temperatures are higher, allowing the sowing of soybeans and subsequent cultivation of maize with less risk of low temperatures during the grain filling phase.

The CS3 system stands out across the entire region. The system that integrates the cultivation of soybeans and wheat has a CSYw of 149 to 209 GJ ha^{-1} $year^{-1}$ (Figure 3C). This system, together with CS1, is the system that has higher energy production, and producers in the PR region should focus on adopting the CS1 system, while producers in the RSC region should focus on adopting the CS3 system. However, the integration of more than one cropping system on the same area can be interesting for farmers as it combines high energy yields with management practices that help with crop management, thus reducing the yield gap (TAGLIAPIETRA et al., 2021, WINCK et al., 2023).

Double cropping systems (CS1 and CS3) can also help to reduce the fixed costs of production (CALVIÑO & MONZON, 2009) while having positive effects on the environment, such as reducing the risk of runoff (CAVIGLIA, 2005) and introducing crop rotation practices that improve the physical properties of the soil.

We are not only looking for systems that provide high energy value over time, thus intensifying the cropping system, but also for systems that offer greater production stability to farmers. With this in mind, the coefficient of variation of the systems was analyzed. It was found that single-crop systems have a CV and, consequently, greater production instability.

The CS2 and CS4 systems (Figure 5) clearly show a greater range in CV. In the PR region, we can observe a variation of 22 to 55% in CS2, which is statistically different from systems CS1 and CS3, thus showing greater interannual and local instability compared to the other systems consisting of two crops for the purpose of cereal production. In the RSC region, we have a higher CV for systems CS2 and CS4, 17 to 65% and 18 to 67%, respectively, which are not statistically different from each other, but unlike system CS2, these results can be explained by frequent water deficit spells. The uneven distribution of precipitation and the influence of the ENSO phenomenon in the region (NÓIA JÚNIOR & SENTELHAS et al., 2019) have a direct impact on the Yw of crops, as reported by Tagliapietra et al., (2021) and Winck et al., (2023), who indicated a water limitation of up to 50% of the Yp for the subtropics of Brazil. Battisti & Sentelhas (2019) found that the Southern region of Brazil has the lowest soybean yields and the highest coefficient of variation, although there is no defined dry season in this region, but the influence of ENSO promotes droughts.

By analyzing Yp, Yw and Yg of the crops within each cropping system (Figure 6), we were able to determine the instability and risk of yield penalties of each crop for the cropping system. The soybean crop has similar Yp and Yw values between systems in the same region, but they differ between the PR and RSC regions, with Yw being higher in the PR region (average Yw of 5.1 Mg ha^{-1}) than in the RSC region, which has an average Yw of 4.3 Mg ha^{-1}). Marin et al., (2022) also reported similar results and find a higher usable yield (5.2 Mg ha^{-1}) for the tropic Atlantic forest biome region of Brazil. This higher Yw is directly related to the accumulation of rain among regions during the development cycle. In the PR region the average precipitation was 847 mm and 106 mm higher in the 16-year average (2017-2021) than in the RSC region (741 mm).

Wheat shows a very similar response in the PR and RSC regions. In contrast to soybeans, where the largest gap is Ygw, in this crop the main gap is caused by management, which is 51% (PR region) and 57% (RSC region) of Yw. These values are higher than those reported by Merlos et al., (2015) in Argentina, who determined a Ygm of 41% of a Yw of 6.5 Mg ha^{-1}, and similar to those reported by Edreira et al., (2018) for the United States (Ygm = 52%). This significant management gap in Southern Brazil is related to the lower grain quality in some years, resulting from a very rainy Spring (time of wheat grain filling and harvest), which leads to a reduction in weight per hectolitre of wheat and, together with the instability of the grain selling price, leads farmers to reduce investments in crop management, especially in fertilization (which is one of the main production costs).

Maize was the one that showed the most instability, both in the PR region, in which maize is grown as a second crop, and in the RSC region. This is because, when grown as a single crop, maize crop is exposed to climatic variability often related to the ENSO phenomena, while soybeans, when grown in succession, are exposed to the risk of low temperatures during the grain filling phase. In addition to high variability, maize has the largest gaps in management and water availability (Figure 6). In China, farmers have reached maize yield about 50% of yield potential (Meng et al., 2013), close to the global average (Licker et al., 2010). On the other hand, in the United States, where 43% of maize acreage is irrigated, farmers have been achieving a yield equivalent to 80% of yield potential (GRASSINI et al., 2011). The large yield gap in maize in Southern Brazil could be related to the greater risk of crop failure due to water deficits, which leads producers to invest less to mitigate the risks of financial losses, in addition to investing in agricultural insurance.

Analyzing the soybean yield compared to the different systems it comprises, it was observed that in systems that do not significantly change the sowing date for periods of lower Yp, the soybean yield in the cropping system does not differ from that of the individual soybeans. This is the case with the CS3 system (Figure 7), where the soybean harvest suffers a delay in the sowing date but remains in the high yield range (TAGLIAPIETRA et al, 2021; ZANON et al., 2016). If a cropping system (CS1) forces a change in sowing date to lower Yp times, in addition to changing the maturity group to shorter cycles (which have a lower potential at this sowing date), this will result in a reduction in the yield of the soybean (Figure 7), so the introduction of these systems must be done more cautiously to ensure that the result of using two crops is economically efficient for the producer. Therefore, the introduction of another crop should be considered as an option to intensify production and generate more income for producers.

Soybean cultivation had the highest return on investment at 0.75 (Figure 8A), which justifies the fact that it is the staple crop of cereal cropping systems in Southern Brazil.

This higher return is related to its higher sales value, which at 315 dollars per ton (2013/2014-2021/2022) is twice that of wheat and maize (160 and 150 dollars respectively) (CONAB, 2023). It is also the crop that has the smallest yield gap, averaging 38% (Figure 7), compared to wheat and maize, whose Ygm in the Southern region of Brazil averages 54% and 57%, respectively.

The ROI is one of the main indicators that leads the producer to choose a cropping system. In the PR region (Figure 8B), the system with the highest ROI was the CS1 system with an average ROI of 0.94, which occupies 43% of the region's acreage. The system with the lowest ROI is CS3 (ROI = 0.47). This lower value is the result of the generally low Ya of the wheat crop combined with a lower commercial price, which justifies a greater number of years with negative ROI (Figure 8A). This shows the importance of reducing Ygm to increase Ya and thus ROI (MARIN et al., 2022). This system is very promising. We showed that when analyzed in terms of Yw (Figure 8 B and C), the system has high ROI values, namely 2.46 and 2.53 for the PR and RSC regions, respectively, with the system having the highest ROI for the RSC region. In addition, CS3 had a low coefficient of variation (Figure 5). This ensures greater yield stability for the producer and high energy production for the system (CSYw 162 to 229 GJ ha^{-1} $year^{-1}$) (Figure 3K).

In the RSC region, the system with the highest ROI (Figure 8C) is currently CS2 (ROI = 0.83), followed by CS3 (ROI = 0.56) and the system with the lowest ROI is CS4 (ROI = 0.23). This system, consisting only of maize cultivation, is characterized by its potential energy value (Figure 4), but a high production risk with a high CV (Figure 5), mainly due to the large water gap in this system (Figure 6). Therefore, this system is an interesting alternative for areas with supplemental irrigation and in “El Nino” years, where rainfall amount and distribution tends to be greater and more uniform (NOIA JUNIOR et al., 2020).

The introduction of cropping systems increases the energy yield of cultivated areas in Southern Brazil while reducing production risks and serving as a way of income diversification for producers. However, these cropping systems also have the highest energy yield gaps, demonstrating the need to investigate best management practices for these cropping systems. The use of more intensive systems can lead to 151 and 87 GJ ha^{-1} $year^{-1}$ (CSYgAi) higher annual energy production in the PR and RSC regions, respectively, while reducing the energy gap for individual crops by 50 and 41 GJ ha^{-1} $year^{-1}$, respectively.

This study showed which are the most important cropping systems from different points of view in Southern Brazil. In addition to the energy yield, it is also possible to determine which systems have the highest ROI and the lowest risk. In terms of ROI, the systems with the highest returns for farmers are the systems where farmers produce the most, namely CS1 with 43% (PR region) and CS2 with 76% (RSC region), which is due to the fact that farmers currently mainly focus on profitability. If the vision is the production risk, we have a great variation among years, we can highlight CS1 in the PR region, especially in “El Nino” years (NOIA JUNIOR & SENTELHAS, 2019; NOIA JUNIOR et al, 2020), where the highest accumulated rainfall favors crops (soybean – maize), and CS3 (PR and RSC region) in years favorable to wheat production, when there is less rainfall in Spring, allowing a higher quality of wheat grain.

By determining the energy potential for each cropping system, technical advisors and farmers can make decisions about the positioning of the cropping system on their land, taking into account the basic characteristics for sustainable, economic production with lower production risk. A better understanding of the cropping systems in the different study regions provides clues to increase the assertiveness of farmers so that energy production can be increased, risks reduced, and profitability increased. However, future studies pointing to more alternative cropping systems or the incorporation of other crops into existing systems, with the quantification of their potential and risks, as well as a better understanding of cropping systems in relation to the ENSO phenomenon in the Southern Brazil region are essential for producers.

2.2.5 Conclusions

In the present study, we analyzed energy efficiency, stability, and production risk in various production systems. In the PR region, the most energetic system was CS1 (Soybean – corn), while in the RSC region, it was the CS4 (Corn) and CS3 (Soybean – Wheat) systems.

In the South of Brazil, systems that incorporate multiple crops have a lower coefficient of variation and, consequently, greater interannual yield stability. The highest economic return was in the CS1 (Soybean – corn) system in the PR region, and the CS2 (Soybean) system based on current yield. However, by reducing the wheat crop management gap, the CS3 system becomes a viable alternative in terms of economic return, production stability, and energy efficiency.

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3. CONSIDERAÇÕES FINAIS

Identificamos oportunidades de melhorias na produção nos diferentes sistemas no Sul do Brasil. Essas informações podem servir de subsídios a produtores e técnicos para identificar sistemas de produção com maior retorno sobre investimento e maior estabilidade. Este é um dos poucos estudos em que resultados com abordagem de sistema de produção buscando identificar potencial e lacunas energética, além de trazer ferramentas para auxiliar o produtor na tomada de decisão em uma das práticas de manejo que mais causa lacuna de produtividade, que são a época de semeadura e a escolha da cultivar (TAGLIAPIETRA et al., 2021).

A implementação de sistemas de produção contribui para o aumento da eficiência energética nas áreas cultivadas do sul do Brasil, diminuindo simultaneamente os riscos associados à produção e proporcionando uma valiosa diversificação de receitas para os agricultores. No entanto, é importante destacar que esses sistemas também evidenciam lacunas consideráveis na produtividade energética, indicando a necessidade de uma análise mais aprofundada das melhores práticas de manejo a serem aplicadas a esses sistemas de produção.

A capacidade de melhor representar a duração do ciclo de desenvolvimento de uma cultivar de soja em função a época de semeadura foi um avanço importante para o sistema de classificação de grupos de maturidade. Com as equações geradas nesse estudo possibilita saber a real duração do ciclo de desenvolvimento dos diferentes GMRs cultivados no Sul do Brasil e em toda a janela de semeadura da cultura da soja. Esse ajuste, aliados a identificação do ciclo agronômico ótimo da soja, o qual identifica qual o melhor ciclo que a cultura necessita apresentar para expressar sua máxima eficiência nas diferentes épocas de semeadura, tornou-se uma ferramenta para o melhor posicionamento das cultivares em épocas de semeadura, assim maximizando a interação genótipo x ambiente.

Em resumo, o desenvolvimento desse trabalho buscou alternativas com a utilização de modelos de simulação agrícolas, de identificar fatores de produção, a nível de sistema e cultura individual, que possam auxiliar o produtor a produzir o alimento de uma maneira mais eficiente, com maior estabilidade, lucratividade e sustentabilidade, buscando assim aumentar a produção de energia e aumentar a segurança alimentar do país e do mundo.

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