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Drought Stress

Assessing Yield Gaps and Risks in Cropping Systems of Southern Brazil

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ABSTRACT

While studies often focus on increasing yields of individual crops, optimising cropping systems through adjustments in crop type, frequency and timing can also enhance annual production. Extending the soybean sowing period, motivated by the search for higher yield potential and greater cropping system efficiency, complicates the ability of maturity groups to effectively capture genotype–environment interactions in subtropical environments. This study aimed to: (i) quantify the potential and energy yield gaps of cropping systems in current Southern Brazil croplands, and (ii) analyse the energetic variability among agricultural cropping systems in the region. The main cropping systems were identified and evaluated over a 16-year period using crop simulation models, incorporating region-specific agronomic practices, climate and soil data. Metrics such as water-limited energy potential and energy gaps were used to assess performance and risk. Cropping systems with increased intensity can raise annual energy yields by up to 151 GJ ha^{-1}year^{-1} in the Paraná region and reduce energy yield gaps by 50 GJ ha^{-1}. In the Rio Grande do Sul and Santa Catarina region, the gains were 87 and 41 GJ ha^{-1}year^{-1}, respectively. More intensive systems also showed lower yield variability and enhanced production stability. These improvements support more stable and diversified income for growers in Southern Brazil. Implementing intensive cropping systems can significantly boost agricultural productivity, mitigate risks and enhance profitability through better resource use and crop sequencing.

1 | Introduction

It is projected that the global population will exceed 9 billion by 2050 (Alexandratos and Bruinsma 2012; FAO 2018). In this context, increasing food production—both in quantity and quality—is essential to meet future demand and ensure food security. Brazil plays a central role in global agricultural production and is a key contributor to global food security. The country is the world's largest producer of soybeans (42% of global production), the third largest producer of maize (14% of global production) and the 14th largest producer of wheat (FAO 2024).

Expanding agricultural frontiers, that is converting natural areas into arable land, is one possible strategy to increase food production. However, this approach often leads to significant and irreversible environmental impacts. A more sustainable alternative

Summary

- Cropping system design impacts yield and energy productivity.
- Energy yield gaps were quantified using crop simulation models.
- Intensified systems reduced yield gaps and increased stability.
- Drought-related variability was a key source of production risk.
- Findings support more resilient and profitable crop strategies.

to increase food security is to vertically increase grain production through the sustainable intensification of existing agricultural land. This can be achieved by closing the yield gap, reducing environmental impacts and improving resource efficiency (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 calculated by summing the yields of the system and the energy values of the grains (Guilpart et al. 2017). Yield potential is influenced by factors such as solar radiation intercepted by the plant canopy, temperature, atmospheric CO_2 levels and genetic traits. However, it is limited by the availability and distribution of water as well as soil and terrain characteristics that influence the water storage capacity of the soil. This potential requires optimal conditions for plant growth, including the absence of nutrient limitations and biotic stress (Evans 1993; van Ittersum and Rabbinge 1997; van Ittersum et al. 2013). CSYwi, together with the cropping system energy yield gap (CSYg) assessment, provides insights into ways to increase the annual yield per unit area by selecting cropping sequences with higher energy yields (Guilpart et al. 2017; Silva et al. 2017). This approach supports the sustainable intensification of agricultural systems.

In southern Brazil, which accounts for 27% of the country's soybean production, studies by Tagliapietra et al. (2021) and Marin et al. (2022) show a significant yield gap in soybean cultivation, primarily due to water deficits in dry periods, especially in La Niña years (Nóia Júnior et al. 2020; Nóia Júnior and Sentelhas 2019). Given the significant impact of water distribution and temperature fluctuations on yield stability, the introduction of cropping systems with temporally integrated cultivation is proving to be a promising strategy. Such systems offer growers the potential for greater yield stability (Guilpart et al. 2017; Ribas et al. 2021), improved profitability and higher crop and energy yields.

Despite the growing interest in sustainable intensification, there is still limited understanding of how different cropping systems perform in terms of energy efficiency, yield stability and return on investment across the diverse agroclimatic conditions of Southern Brazil. Most existing studies focus on individual crops rather than integrated systems, and few consider long-term simulations that incorporate climatic variability and site-specific management (Tagliapietra et al. 2021; Winck et al. 2023). As a result, decision-making for cropping system design remains constrained by insufficient quantitative data on production risks and energy trade-offs. This study addresses this gap by providing a comprehensive assessment of energy yield potential and risk across multiple cropping systems, offering insights to support more informed, efficient and resilient agricultural strategies in the region.

In this study, agricultural simulation models were employed to characterise the current cropping systems in the subtropical region of southern Brazil. Grower's management practices, including sowing dates, crop varieties, plant density and other agronomic practices, were analysed in conjunction with climate and soil data to estimate CSYw and CSYg for soybean, wheat and maize. This analysis followed the approach proposed by Guilpart et al. (2017) and adhered to the protocols of the Global Yield Gap Atlas project (Grassini et al. 2015; van Bussel et al. 2015, http://www.yieldgap.org/methods). The objectives of this study were twofold: (i) to quantify the potential energy yield and energy yield gap of cropping systems on existing croplands in southern Brazil and (ii) to analyse the energy yield variability of current agricultural cropping systems in the region.

2 | Material and Methods

2.1 | Characterisation of the Locations and the Cropping System

The study was conducted in southern Brazil, encompassing the states of Paraná, Santa Catarina and Rio Grande do Sul (Figure 1). This region accounts for 31.4% of Brazil's soy production, 90% of wheat production and 19.8% of maize production (CONAB 2024a). According to the Köppen climate classification, the region's climate is classified as humid subtropical (Cfa), characterized by the absence of a pronounced dry season (Wrege et al. 2016). The study area was further divided into climate zones (CZ) using the methodology proposed by van Wart et al. (2013) and implemented by Tagliapietra et al. (2021). This classification takes into account three agroclimatic variables that are crucial for soybean cultivation: (i) the total number of annual degree days, (ii) the annual drought index and (iii) temperature seasonality. This approach allows for more accurate estimates of yield potential, actual yield and consequently the yield gap.

Cropping systems (CS) and actual yields (Ya) (Figure 1) were determined separately for each buffer zone (BZ) and overlaid with the harvested areas of each crop to determine the CS and the corresponding average 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 CS, the percentage of each FC within each CS was taken into account. This was done using a weighted average that takes into account the area of each FC within each CS.

The study area was divided into two groups: the PR region, outlined in red (Figure 1), where three cropping systems predominate: CS1 (soybean–maize), CS2 (soybean) and CS3 (soybean–wheat). The second group, the RSC region marked in blue (Figure 1), comprised the systems CS2 (soybeans), CS3 (soybeans–wheat) and CS4 (maize).

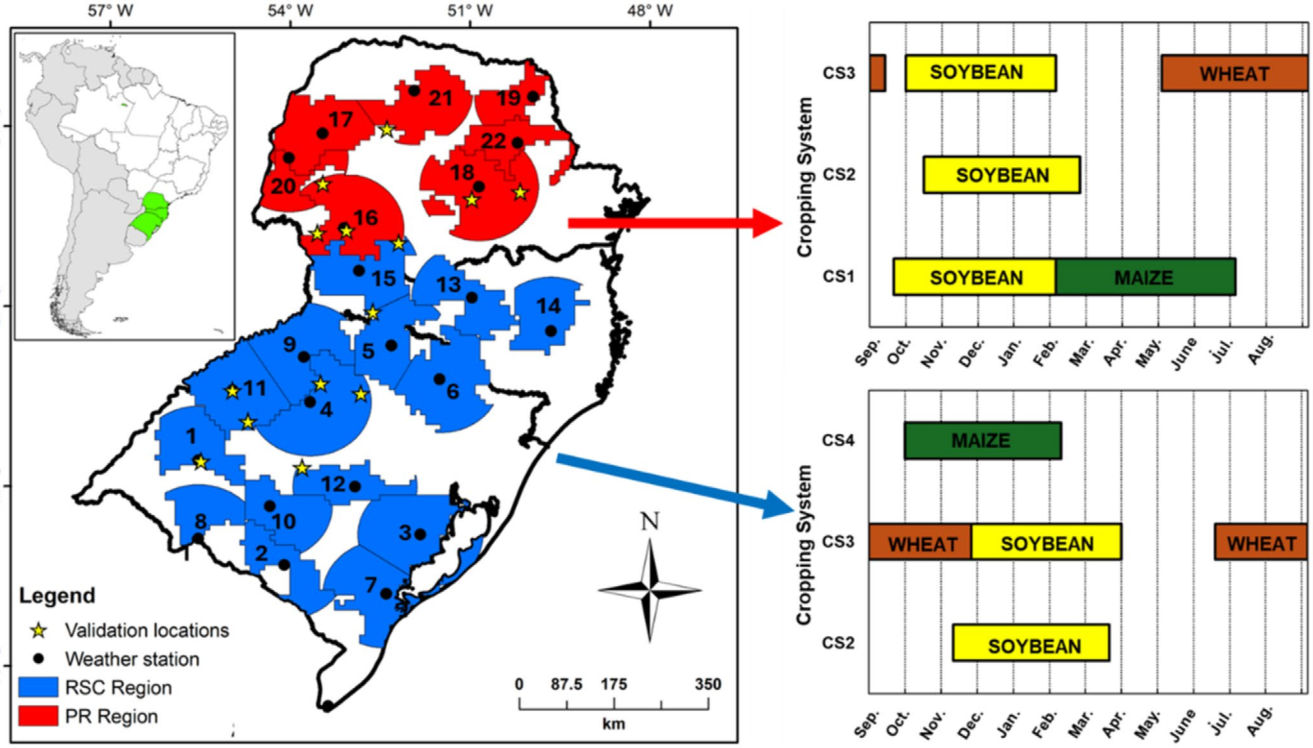

FIGURE 1 | Map of South America and Brazil (inset), highlighting the three states in southern Brazil with the buffer zones for cropping systems. The red buffer zones indicate the PR region (state of Paraná), while the blue buffer zones represent the RSC region (states of Rio Grande do Sul and Santa Catarina). The yellow stars indicate the locations of the experiments used to evaluate the models.

2.2 | Meteorological and Soil Data

Grassini et al. (2015) emphasise that a robust and reliable estimate of the water-limited yield potential (Yw) requires meteorological data over a period of at least 15 years. To satisfy this requirement, observed meteorological data from the Brazilian National Institute of Meteorology (INMET) were used. Based on the defined climate zones (CZ), buffer zones (BZ) with a diameter of 100 km were created (Figure 1). BZs with more than 5% of the harvested area were selected for the crops studied. This resulted in 22 functional BZs (1–22), which together represent 73% of the cultivated area for soybeans, 75% for wheat and 64% for maize (Figure 1).

The selection of soils within each BZ was based on the following criteria: (i) soil covering more than 20% of the BZ area, and (ii) inclusion of additional soils until at least 50% of the BZ area was represented (Edreira et al. 2017). The soil data were obtained from the Radambrasil project (Cooper et al. 2005), as described in Table 1.

2.3 | Simulation of Yield Potential and Water-Limited Yield Potential of Cropping Systems

Yield potential (Yp) and water-limited yield potential (Yw) were estimated using the DSSAT (v4.8.2) platform models: CSM-CROPGRO-Soybean for soybeans (Boote et al. 1998), CERES-Maize for maize (Jones and Kiniry 1986) and CERES-Wheat for wheat (Ritchie and Otter 1985). The yield potential of a cropping system was determined by summing the yield potential of all crops within the system. Accordingly, the following metrics were applied: CSYwi, which represents the water-limited energy potential of the cropping system, and CSYai, which represents the actual energy yield of the cropping system.

To facilitate comparisons between cropping systems with different species (cereals and oilseeds), the energy per unit land and time was used according to the methodology of Guilpart et al. (2017). The energy yield (GJ ha^{-1}) was calculated by multiplying the crop yield by the energy content, using the following values: 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).

Simulations were conducted for 16 growing seasons (from 2007/2008 to 2021/2022) to ensure accuracy and reliability (Grassini et al. 2015). Varieties/hybrids, plant densities, row spacing and predecessor crops that best represent each BZ were used (Figure 1, Tables 1 and 2). Details of the traits and variables used to simulate yield potential and water-limited potential in different BZs are provided in Tables 1 and 2.

2.4 | Evaluation of Crop Simulation Models

The genetic coefficients for soybean, wheat and maize were derived from Mercau et al. (2007), Mercau and Otegui (2014) and Monzon et al. (2007, 2012). The models were evaluated

TABLE 1 | Characterisation of the variables used to simulate the yield potential and water-limited yield potential for the buffer zones in the RSC region (Rio Grande do Sul and Santa Catarina) in southern Brazil.

Buffer[a] (location-state)	Cropping system (%)	Sowing date	Cultivar/hybrid maturation	Plant density (pl/m^2)	Soil type (%)
1. Alegrete—RS	Soybean (74%)	20 Nov.	MG 6.5	30	Ultisol (11%)
	Soybean—Wheat (23%)	30 Nov.–15 Jun.	MG 6.5—Early	30–400	Entisol (34%)
	Maize (3%)	20 Nov.	Super early	6	Alfisols (38%)
	Soybean (96%)	20 Nov.	MG 6.5	30	Ultisol (33%)
2. Bagé—RS	Soybean–Wheat (2%)	30 Nov.–15 Jun.	MG 6.5—Early	30–400	Alfisols (25%)
	Maize (2%)	10 Oct.	Super early	6	
	Soybean (86%)	20 Nov.	MG 6.5	30	Ultisol (59%)
3. Camaquã—RS	Soybean–Wheat (4%)	30 Nov.–15 Jun.	MG 6.5—Early	30–400	Alfisols (24%)
	Maize (10%)	10 Oct.	Super early	6	
	Soybean (87%)	25 Oct.	MG 5.5	30	Ultisol (21%)
4. Cruz Alta—RS	Soybean–Wheat (10%)	05 Nov.–10 Jun.	MG 5.5—Early	30–350	Oxisol (67%)
	Maize (3%)	20 Sep.	Super early	6	
	Soybean (72%)	30 Oct.	MG 5.5	30	Inceptisol (19%)
5. Erechim—RS	Soybean–Wheat (15%)	10 Nov.–20 Jun.	MG 5.5—Early	30–350	Oxisol (69%)
	Maize (13%)	20 Sep.	Super early	6	
	Soybean (72%)	30 Oct.	MG 5.5	30	Nitisol (21%)
6. Lagoa Vermelha—RS	Soybean–Wheat (11%)	10 Nov.–20 Jun.	MG 5.5—Early	30–350	Oxisol (65%)
	Maize (17%)	20 Sep.	Super early	6	
	Soybean (91%)	20 Nov.	MG 6.5	30	Ultisol (29%)
7. Pelotas—RS	Soybean–Wheat (2%)	30 Nov.–15 Jun.	MG 6.5—Early	30–400	Alfisols (46%)
	Maize (7%)	10 Oct.	Super early	6	
	Soybean (91%)	20 Nov.	MG 6.5	30	Ultisol (21%)
8. Santana do Livramento—RS	Soybean–Wheat (4%)	30 Nov.–15 Jun.	MG 6.5—Early	30–400	Alfisols (70%)
	Maize (5%)	10 Oct.	Super early	6	
	Soybean (56%)	25 Oct.	MG 5.5	30	Inceptisol (18%)
9. Santo Augusto—RS	Soybean–Wheat (33%)	05 Nov.–10 Jun.	MG 5.5—Early	30–350	Oxisol (76%)
	Maize (11%)	20 Sep.	Super early	6	
	Soybean (92%)	20 Nov.	MG 6.5	30	Ultisol (21%)
10. São Gabriel—RS	Soybean–Wheat (6%)	30 Nov.–15 Jun.	MG 6.5—Early	30–350	Entisol (26%)
	Maize (2%)	10 Oct.	Super early	6	Alfisols (44%)
	Soybean (66%)	25 Oct.	MG 5.5	30	Nitisol (16%)
11. São Luiz Gonzaga—RS	Soybean–Wheat (28%)	05 Nov.–10 Jun.	MG 5.5—Early	30–350	Oxisol (66%)
	Maize (6%)	20 Sep.	Super early	6	
	Soybean (94%)	25 Oct.	MG 6.0	30	Ultisol (26%)

(Continues)

TABLE 1 | (Continued)

Buffer[a] (location-state)	Cropping system (%)	Sowing date	Cultivar/hybrid maturation	Plant density (pl/m^2)	Soil type (%)
12. Cachoeira do Sul—RS	Soybean–Wheat (3%)	05 Nov.–10 Jun.	MG 6.0—Early	30–350	Alfisols (63%)
	Maize (3%)	20 Sep.	Super early	6	
	Soybean (67%)	20 Nov.	MG 5.5	30	Inceptisol (33%)
13. Caçador—SC	Soybean–Wheat (5%)	30 Nov.–30 Jun.	MG 6.0—Early	30–400	Oxisol (16%)
	Maize (28%)	20 Sep.	Super early	6	Nitisol (47%)
	Soybean (51%)	20 Nov.	MG 5.5	30	Inceptisol (81%)
14. Ituporanga—SC	Soybean–Wheat (5%)	30 Nov.–30 Jun.	MG 6.0—Early	30–400	Ultisol (19%)
	Maize (44%)	20 Sep.	Super early	6	
	Soybean (73%)	20 Nov.	MG 5.5	30	Entisol (28%)
15. Novo Horizonte—SC	Soybean–Wheat (13%)	30 Nov.–30 Jun.	MG 6.0—Early	30–400	Oxisol (53%)
	Maize (13%)	20 Sep.	Super early	6	

Abbreviation: MG, maturity group.
[a]The number refers to the buffers represented in Figure 1.

using independent data from experiments conducted over different sowing dates, development cycles, years and locations in southern Brazil (Figure 2). The observed data for soybean cultivation came from the following locations: 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, data were collected from 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, data were taken from 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) for the validation of the crop models with independent data was 4.9, 6.1 and 4.1 days for phenology and 0.61, 0.98 and 2.96 Mg ha^{-1} for soybean, wheat and maize yield, respectively, indicating satisfactory model performance (Merlos et al. 2015; Tagliapietra et al. 2021; Marin et al. 2022).

2.5 | Return on Investment

Return on investment (ROI) is used to assess the investment efficiency of crops and to compare different cropping systems. While ROI quantifies financial performance, production risk is also a crucial factor, although it is often challenging to measure. For this study, ROI was calculated using data from CONAB for the period from 2013 to 2021 (CONAB 2024b) for the PR and RSC regions. The ROI was calculated as follows (Equation 1):

$$ROI=(GI-OC)/OC \quad (1)$$

where GI represents gross income and OC represents operating costs.

Gross income (GI) 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 both the actual yield scenario (Ya) and the water-limited yield scenario (Yw) for each buffer zone (BZ). The operating costs (OC) include the sum of the fixed and variable production costs for the crops.

3 | Results

3.1 | Water-Limited Yield Potential, Actual Yield and Yield Gap in Cropping Systems

The cropping system with the highest water-limited yield potential (CSYw) was CS1 (soybean–maize) with a range between 228 and 307 GJ ha^{-1}year^{-1} (Figure 3A). This system is predominant in the state of Paraná (PR region). The second highest CSYw was observed in CS3 (soybean–wheat), which is widespread throughout the study area, with values between 162 and 229 GJ ha^{-1}year^{-1} (Figure 3C). The remaining systems, CS4 and CS2, had CSYw values of 120–244 GJ ha^{-1}year^{-1} and 71–155 GJ ha^{-1}year^{-1}, respectively (Figure 3B,D).

In terms of actual yield (CSYa), the highest values were also recorded for CS1, ranging from 133 to 163 GJ ha^{-1}year^{-1} (Figure 3E). This was followed by CS3 with yields between 67 and 135 GJ ha^{-1}year^{-1} (Figure 3G), CS4 with yields of 34–124 GJ ha^{-1}year^{-1} (Figure 3H) and CS2 with yields between 40 and 85 GJ ha^{-1}year^{-1} (Figure 3F). Despite the highest CSYa, CS1 also had a significant management gap with values between 68 and 169 GJ ha^{-1}year^{-1} (Figure 3I). The yield gaps for the other systems were as follows: 69–150 GJ ha^{-1}year^{-1} for CS4 (Figure 3L),

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

Buffer[a] (location-state)	Cropping system (%)	Sowing date	Cultivar/hybrid maturation	Plant density (pl/m^2)	Soil type (%)
16. Dois Vizinhos—PR	Soybean (37%)	01 Oct.	MG 5.5	30	Oxisol (38%)
	Soybean–Maize (25%)	01 Oct.–15 Feb.	MG 5.5—Super early	30–6	Entisol (32%)
	Soybean–Wheat (31%)	15 Oct.–01 May	MG 5.5—Early	30–350	Nitisol (16%)
17. Brasilândia—PR	Soybean (17%)	01 Oct.	MG 6.5	30	Oxisol (23%)
	Soybean–Maize (79%)	15 Sep.–10 Feb.	MG 6.0—Super early	30–6	Ultisol (40%)
	Soybean–Wheat (4%)	15 Sep.–01 May	MG 6.0—Early	30–350	Nitisol (27%)
18. Ivaí—PR	Soybean (66%)	20 Oct.	MG 6.5	30	Oxisol (55%)
	Soybean–Maize (5%)	01 Oct.–15 Feb.	MG 5.5—Super early	30–6	Inceptisol (27%)
	Soybean–Wheat (17%)	10 Oct.–15 Apr.	MG 6.0—Early	30–350	
19. Joaquim Távora—PR	Soybean (23%)	25 Oct.	MG 7.0	30	Ultisol (22%)
	Soybean–Maize (25%)	01 Oct.–15 Feb.	MG 6.5—Super early	30–6	Entisol (26%)
	Soybean–Wheat (45%)	10 Oct.–15 Apr	MG 6.0—Early	30–350	Nitisol (42%)
20. Mar. Can. Rondon—PR	Soybean (5%)	01 Oct.	MG 6.5	30	Oxisol (14%)
	Soybean–Maize (78%)	15 Sep.–10 Feb.	MG 6.0—Super early	30–6	Nitisol (73%)
	Soybean–Wheat (16%)	15 Sep.–15 Apr	MG 6.0—Early	30–350	
21. Maringá—PR	Soybean (18%)	20 Oct.	MG 6.5	30	Oxisol (30%)
	Soybean–Maize (60%)	01 Oct.–15 Feb.	MG 6.0—Super early	30–6	Nitisol (51%)
	Soybean–Wheat (21%)	10 Oct.–01 May	MG 6.0—Early	30–350	
22. Ventânia—PR	Soybean (54%)	25 Oct.	MG 7.0	30	Oxisol (39%)
	Soybean–Maize (8%)	15 Sep.–15 Feb.	MG 6.5—Super early	30–6	Ultisol (29%)
	Soybean–Wheat (25%)	10 Oct.–15 Apr	MG 6.0—Early	30–350	Inceptisol (21%)

Abbreviation: MG, maturity group.
[a]The number refers to the buffers represented in Figure 1.

61–110 GJ ha^{-1}year^{-1} for CS3 (Figure 3K) and 17 to 73 GJ ha^{-1}year^{-1} for CS2 (Figure 3J).

3.2 | Stability of Cropping Systems

In the PR region (Figure 4A), the CS2 system exhibited the highest coefficient of variation (CV) across the BZs, with values ranging from 22% to 56%. However, when an additional crop was introduced into the system, as seen in CS1 and CS3, a decrease in CV was observed (CS1: 16%–44%, CS3: 13%–30%) compared to CS2, which comprises only a single crop. A statistically significant relationship was found between the CV and the increase in the energy value (linear equation) for CS2 and CS3. Furthermore, the Tukey test, with a 5% probability, identified CS3 as the system with the greatest stability in terms of CV.

Similarly, in the RSC region, single-crop systems exhibited the highest CVs. CS2 and CS4 showed CVs ranging from 17% to 65% and 18% to 67%, respectively. Conversely, CS3 demonstrated a CV variation of 7%–27%, which, according to the Tukey test, was statistically significant, making it the most stable system in terms of CV in this region. Notably, all cropping systems in this region exhibited a significant response in CV reduction with increasing CSYw.

The graph in Figure 5A shows the values of Yp, Yw, Ygw and Ygm for 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 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 analysing the second maize harvest, a significant decrease in Yp (13.6 Mg ha^{-1}) and Yw (11.4 Mg ha^{-1}) was observed in CS1, primarily due to climatic risks, especially low temperatures during the critical grain filling phase. Maize showed the largest yield gap in these regions, with Ygw = 16% and Ygm = 57%. The wheat crop in CS3 showed a close alignment between Yp (5.9 Mg ha^{-1}) and Yw (5.5 Mg ha^{-1}), resulting in a low Ygw (7%) but a high Ygm (57%).

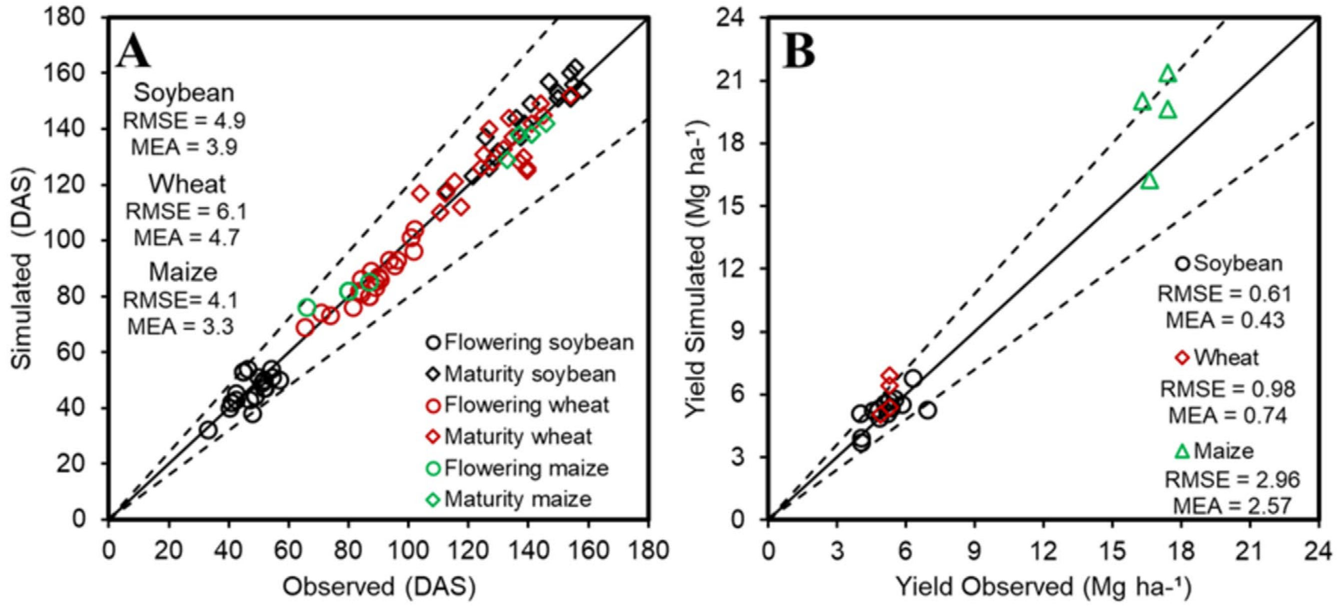

FIGURE 2 | Comparison between observed and simulated data for phenology (days after sowing—DAS) (A) and grain yield (B). The solid lines represent $y=x$ and the dotted lines represent $y=x\pm 20\%$. The root mean square error (RMSE) and the mean absolute error (MEA) are given in units of days and Mg ha^{-1}.

In the RSC region, Yp (6.4 and 6.2 Mg ha^{-1}) and Yw (4.4 and 4.3 Mg ha^{-1}) values were consistent for soybean cropping in CS2 and CS3, as shown in Figure 5B. This consistency resulted in comparable Ygw (31% and 29%) and Ygm (41% and 40%) values in the two cropping systems. In CS3, wheat cropping mirrored the PR region, with a low Ygw (1%) but a high Ygm (57%).

Maize, the main crop in CS4, had high Yp (15.8 Mg ha^{-1}) and Yw (12.4 Mg ha^{-1}) values. However, considerable variability was observed between the different sites and years, as shown by the scatter of the data and the standard deviation. Remarkably, maize in this region, similar to the PR region, had the highest Yg values (Ygw = 21% and Ygm = 58%).

3.3 | Soybean System (CS2) Versus Soybean–Wheat (CS3) and Soybean–Maize (CS1) Systems

When comparing the CS2 and CS3 systems (Figure 6), a significant correlation was found that favours CS2, as shown by the red dashed line. However, the statistical analysis with the Tukey test at a significance level of 5 (see Figure 6) showed no significant difference between CS2 and CS3, but only a difference of 0.2 Mg ha^{-1}. In contrast, when comparing CS2 with CS1, both a significant correlation and a statistical difference of 0.89 Mg ha^{-1} were found, which is in favour of CS2.

3.4 | Return on Investment in Cropping Systems

The analysis of ROI (Figure 7) reveals that soybean cultivation offers the highest ROI based on current average yield, with an average ROI of 0.75 and a variation between years ranging from −0.28 to 2.55. Maize follows with an average ROI of 0.24 (variation between years: −0.35 to 2.3), while wheat has the lowest average ROI at −0.24 (variation between years: −0.67 to 0.08) (Figure 7A). However, when considering ROI in terms of water-limited yield potential, the average ROI values were 1.18 for soybeans, 1.52 for maize and 0.80 for wheat (Figure 7A).

Examining ROI by cropping system (Figure 7B,C), CS1 demonstrated the highest ROI for both actual yield (Ya) and water-limited yield potential (Yw) in the PR region, with ROIs of 0.94 and 2.81, respectively. In the RSC region, the ROI values were 0.83, 0.56 and 0.23 for the CS2, CS3 and CS4 systems, respectively, based on Ya. For Yw, the ROI values were 1.80, 2.53 and 1.37 for CS2, CS3 and CS4, respectively.

4 | Discussion

This study quantified energy yield gaps and risks across major cropping systems in Southern Brazil, showing how system design shapes yield, stability and profitability. Beyond environmental constraints, results indicate that the current dominance of soybean monoculture (CS2) (Tables 1 and 2) limits regional energy production and increases vulnerability to climate variability. In contrast, diversified systems (CS1 and CS3) provide higher energy output, reduce interannual variability and improve return on investment (ROI), pointing to clear opportunities for cropping intensification. These findings emphasise not only the role of climate as a stress factor but also the management and design choices that determine the capacity of farming systems to adapt and buffer against climate variability.

Soybean monoculture (CS2) remains the most widespread system in both Paraná (PR) and Rio Grande do Sul/Santa Catarina (RSC) (Tables 1 and 2). However, CS2 consistently delivered lower annual energy yields (40–85 GJ ha^{-1}year^{-1}) and the highest yield

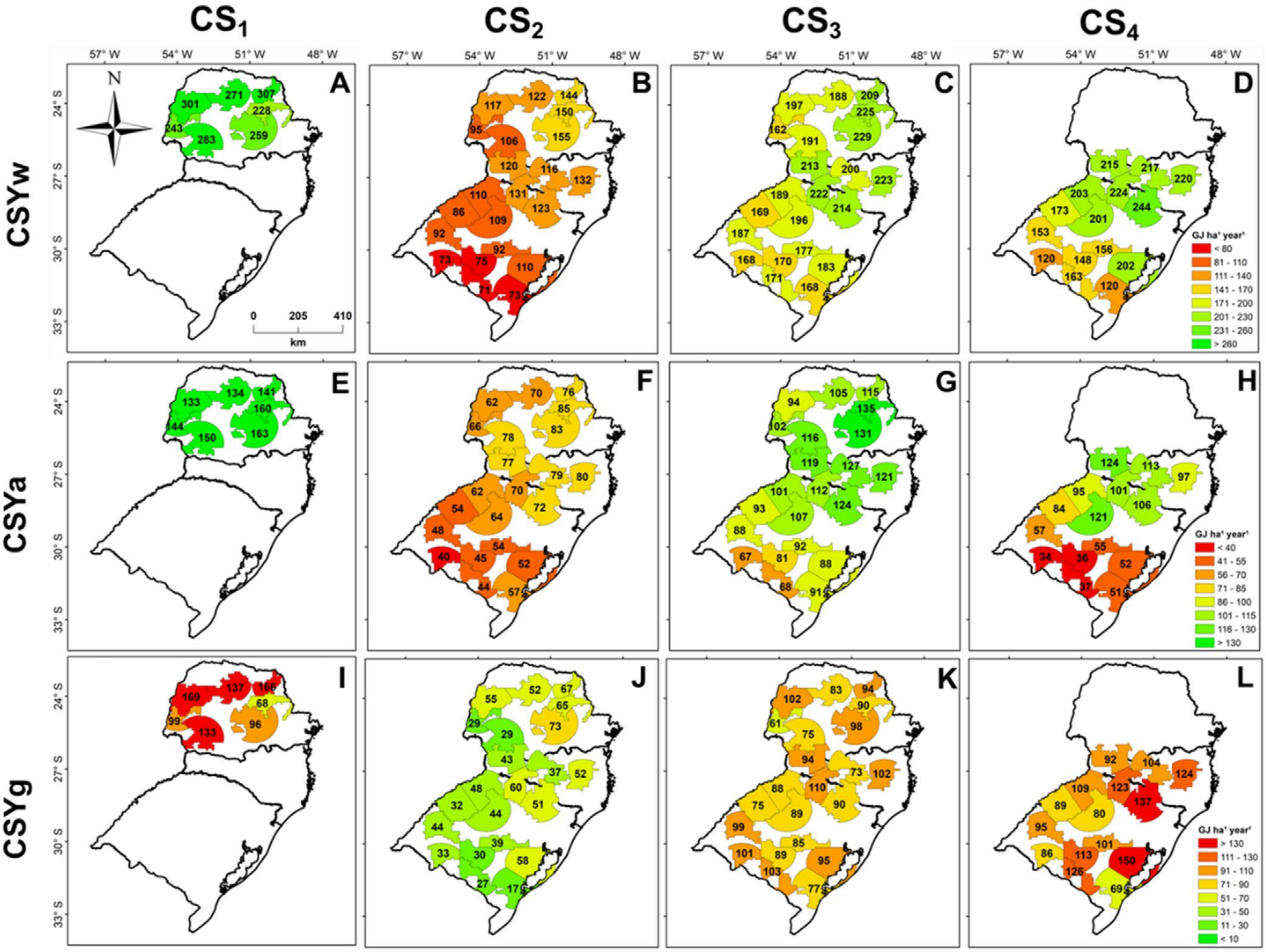

FIGURE 3 | Water-limited energy potential (CSYw), actual energy yield (CSYa) and energy gaps (CSYg), all expressed in energy units (GJ ha^{-1} year^{-1}) for the regions with different cropping systems in southern Brazil: CS1 (soybean–maize), CS2 (soybean), CS3 (soybean–wheat) and CS4 (maize).

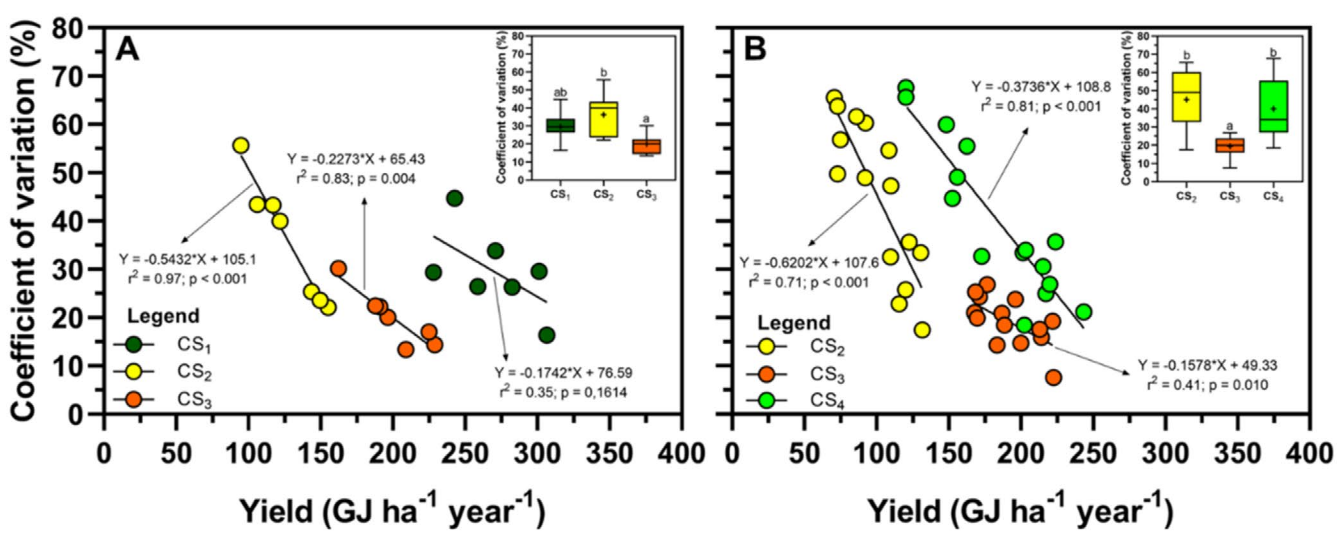

FIGURE 4 | The water-limited energy potential (CSYw) of cropping systems and the interannual coefficient of variation for different buffer zones within each system in southern Brazil. (A) The Paraná region (CS PR) and (B) the Santa Catarina and Rio Grande do Sul regions (CS RSC). The inset shows the differences in the coefficient of variation between the systems in each region, represented by a box plot, followed by a test of means (Tukey test) at a significance level of 5. In the box 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. The cropping systems are labelled as follows: CS1 (soybeans–maize), CS2 (soybeans), CS3 (soybeans–wheat) and CS4 (maize).

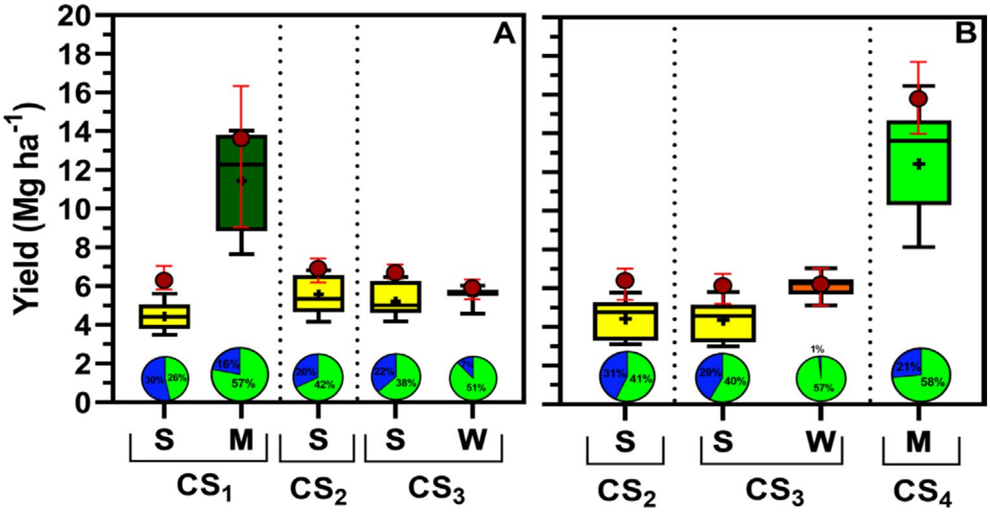

FIGURE 5 | Yield potential (Yp) and water-limited yield potential (Yw) for crops within individual cropping systems in southern Brazil, shown as a boxplot (coloured yellow/green/orange). The boxes show the 25th and 75th percentiles, the whiskers represent the maximum and minimum values, the horizontal line shows the median and the + symbol indicates the mean value. The red circles show the yield potential (Yp), while the red error bars represent the standard deviation of Yp. The pie chart-like circles at the bottom of each box illustrate the water gap (Ygw = Yp—Yw) in blue and the management gap (Ygm = Yw—Ya) in green, both expressed as percentages for each crop within each system. Field (A) represents the state of Paraná (CS PR) and field (B) represents the states of Santa Catarina and Rio Grande do Sul (CS RSC). The cropping systems include CS1 (soybeans–maize), CS2 (soybeans), CS3 (soybeans–wheat) and CS4 (maize).

variability (CV up to 56%) (Figures 3 and 4). Its profitability depends largely on high market prices rather than agronomic efficiency (Figure 7A). These results highlight the high exposure of soybean-based systems to climatic risks, particularly ENSO-related droughts, which can reduce water-limited yield (Yw) by up to 50% in subtropical regions (Tagliapietra et al. 2021; Winck et al. 2023). Thus, while CS2 supports short-term income, its long-term resilience is highly uncertain under intensifying climate variability (Battisti and Sentelhas 2019; Nóia Júnior and Sentelhas 2019). On the other hand, double-cropping systems significantly improve yield and stability. In PR, soybean–maize (CS1) achieved the highest energy production, with CSYw values of 208–307 GJ ha^{-1} year^{-1} (Figure 3A), and the highest ROI (0.94 for actual yield, 2.81 for Yw) (Figure 7B). CS1 is predominantly practiced in the western part of Paraná, covering 43% of the cultivated area, where warmer conditions allow timely soybean sowing followed by maize, reducing the risk of cold stress during grain filling. Despite a yield penalty for soybean due to delayed sowing (Figure 6), the inclusion of maize offsets this loss through higher system-level energy and income. In RSC, soybean–wheat (CS3) reached 149–209 GJ ha^{-1} year^{-1} (Figure 3C), combined with low CV values (7%–27%) (Figure 4B) and high ROI under Yw conditions (2.53) (Figure 7C). These results show that diversification buffers systems against climatic stress by spreading risks across crops with different seasonal sensitivities (Caviglia 2005; Calviño and Monzon 2009; Ribas et al. 2021).

Yield gap analysis reinforces these patterns. Soybean presented a small management gap (average 38%), but remained highly sensitive to water deficits during reproductive stages, especially in RSC, where Yw averaged only 4.3 Mg ha^{-1} (Figure 5B). This lower potential is explained by the reduced rainfall in RSC (741 mm) compared with PR (847 mm) during the growing season, consistent with regional findings by Marin et al. (2022). Similar soybean responses to climate and management interactions in

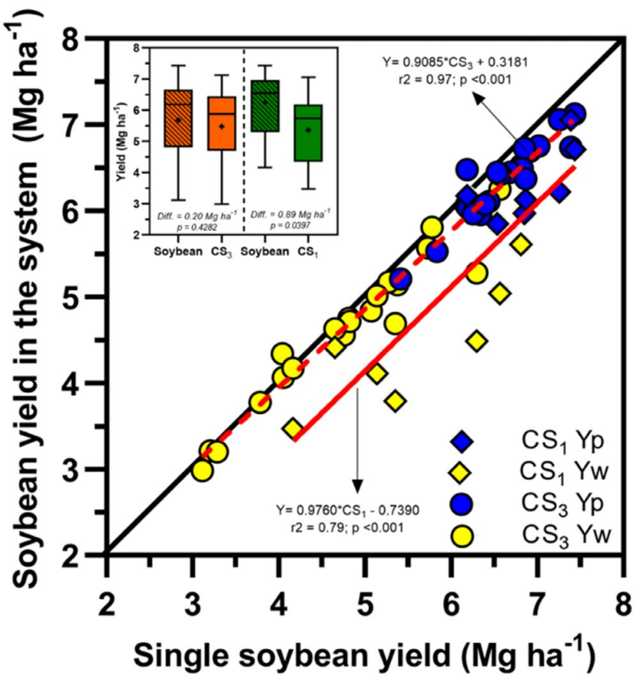

FIGURE 6 | Comparison of soybean yields (CS2) with cropping systems with maize (CS1) and wheat (CS3). The circles show the comparison of soybeans (CS2) with soybean-wheat (CS3), while the squares represent soybeans (CS2) with soybean-maize (CS1). Blue indicates yield potential (Yp) and yellow for the yield potential limited by water (Yw). The solid black diagonal line shows the line of equality ($y = x$). The fitted linear regression parameters are shown with a red solid line for the fit and a red dashed line for the 95% confidence interval together with the coefficient of determination (R^2). The boxplot 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 indicating the median and the + symbol denoting the mean.

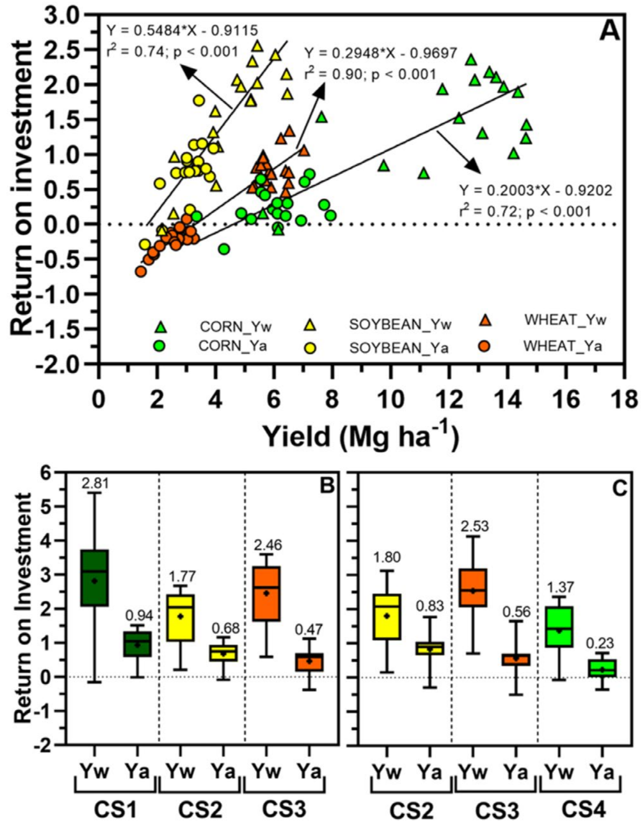

FIGURE 7 | Return on investment (ROI) for different crops in southern Brazil, compared to current yield (circles) and water-limited yield potential (triangles) over different years (2013–2021) for soybeans (yellow), maize (green) and wheat (orange) (A). The box plots illustrate the ROI for each cropping system in the region of the state of Paraná (CS PR) (B) and the region of Santa Catarina and Rio Grande do Sul (CS RSC) (C). In the box plots, the boxes delimit the 25th and 75th percentiles, the whiskers represent the maximum and minimum values, the horizontal line indicates the median and the + symbol denotes the mean value. The crop systems shown include CS1 (soybean–maize), CS2 (soybean), CS3 (soybean–wheat) and CS4 (maize).

subtropical regions have been reported by Zanon et al. (2016). Wheat exhibited large management gaps (51%–57%), linked to low investments in fertilisation and harvest losses from excessive spring rainfall. This aligns with reports from Argentina and the USA, where wheat gaps also reflected management limitations (Merlos et al. 2015; Edreira et al. 2017). Maize showed the widest gaps, both water- and management-related, reflecting its vulnerability when grown as a second crop under low temperatures or in rainfed conditions (Figure 5). These results are consistent with global findings where maize reaches only ca. 50% of its potential in China (Meng et al. 2013) and similar levels worldwide (Licker et al. 2010), compared to 80% of potential in the US Corn Belt under irrigated conditions (Grassini et al. 2011).

Return on investment (ROI) further clarifies system performance. Soybean achieved the highest ROI among crops (0.75), primarily due to its elevated market price (USD 315 ton^{-1} in 2013/2014–2021/2022), which is roughly double that of wheat (USD 160 ton^{-1}) and maize (USD 150 ton^{-1}) (CONAB, 2023). This economic advantage explains the persistence of soybean monoculture despite its lower energy efficiency and higher production risk. At the system level, however, diversified systems achieved superior ROI: in PR, CS1 reached 0.94 for actual yields (Figure 7B), while in RSC, CS3 achieved 2.53 for Yw (Figure 7C), confirming the combined energetic and economic benefits of diversification.

Adaptation options emerge from these findings. At the system level, replacing soybean monoculture with diversified double crops could increase annual energy output by up to 151 GJ ha^{-1}year^{-1} in PR and 87 GJ ha^{-1}year^{-1} in RSC, while reducing gaps by 50 and 41 GJ ha^{-1}year^{-1}, respectively (Figures 3 and 4). At the crop level, targeted improvements in wheat management and maize risk mitigation would further enhance system profitability. Technically, growers could buffer systems against climate variability by adopting flexible sowing windows, selecting drought- and temperature-resilient cultivars and considering supplemental irrigation during ENSO-related drought years (Nóia Júnior et al. 2020). Maintaining soil fertility through crop rotation and integrated nutrient management is also critical for long-term system resilience (Guilpart et al. 2017; Silva et al. 2017, 2022; Marin et al. 2022).

Although this study provides valuable insights, some limitations should be acknowledged. Crop simulation models, while robust, rely on assumptions regarding crop physiology, soil properties and management that may not fully capture on-farm variability (Edreira et al. 2017). In addition, interannual climate variability, especially extreme events related to ENSO, poses challenges for long-term predictions and may cause deviations between simulated and actual yields under specific scenarios. Expanding model validation with field data across diverse environments will be essential to refine predictions and guide adaptive management.

Overall, this study shows that system diversification offers a pathway to both agronomic and energetic gains in Southern Brazil. While soybean monoculture remains profitable in the short term, its instability under climate variability limits its long-term sustainability. By contrast, double-cropping systems such as soybean–maize and soybean–wheat combine higher energy yields, lower variability and improved ROI. These systems should therefore be prioritised in regional strategies for cropping intensification. Future research should also integrate on-farm trials, socioeconomic assessments, environmental indicators and modelling approaches that couple biophysical and economic risks in order to validate these findings under field conditions and support policies that foster broader adoption of diversified systems.

5 | Conclusions

In this study, the energy efficiency, stability and production risk of different cultivation systems were evaluated. In the PR region, the most energy-efficient system is CS1 (soybean-maize), while in the RSC region, CS4 (maize) and CS3 (soybean-wheat) have the highest energy efficiency.

In southern Brazil, multi-crop systems have lower coefficients of variation (7%–27%), which leads to greater inter-annual yield stability. The highest economic return was observed in the CS1 system in the PR region (ROI = 0.94), while CS2 achieved the highest ROI in the RSC region (0.83), based on the current yield. However, reducing the management gap in wheat cultivation could position the CS3 system as a viable alternative to improve economic yield, production stability and energy efficiency.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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