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Potential for growing Arabica coffee in the extreme south of Brazil in a warmer world

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Abstract Agriculture appears to be one of the human activities most vulnerable to climatic changes due to its large dependence on environmental conditions. However, the diversity of Brazilian environmental conditions could be of great advantage to adapting this sector to new climatic conditions, which should be assessed as in this study on shifting Arabica coffee cultivation to the extreme south of the country. The methodology applied is the same the one used to define climatic risks in current productive regions of Brazil and their vulnerability to climatic change predicted by IPCC reports. The basic climatic parameters applied were frost probability and annual average temperature, since annual water deficit did not prove to be a restricting factor for Arabica coffee cultivation in the study area. The climatic conditions suitable for coffee production are: annual average temperature between 18°C and 22°C, annual water deficit less than 100 mm and frost probability (risk of lowest annual temperature less than 1°C) less than 25%. An area is said to have "low climatic risks" for coffee production when these three climatic conditions are met. Current climatic conditions were used and simulations of four temperature increases between 1°C and 4°C were also performed. The results indicated a substantial increase in the size of low climatic risks areas for the production of Arabica coffee in the extreme south of Brazil, mainly for mean temperature increases of 3°C in

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the study area in relation to present conditions. Increases of 2°C and 4°C were also favorable, but not as good as those obtained for 3°C. It should be underscored that areas with low climatic risks will be able to be found mainly in the extreme south of the study region, the border with Uruguay and North of Argentina.

Abbreviations

lati Latitude in minutes with negative sign in the southern hemisphere;
long Longitude in minutes with negative sign in the western hemisphere;
alti Altitude in meters

1 Introduction

The fourth IPCC report (IPCC 2007) released during the year 2007 caught the interest of a large part of the World population, including several governments and governmental organizations, regarding climate change. It should be emphasized that this issue received special attention after the hurricanes in North America and the heatwave in Europe in 2003 and the involvement of the ex-vice president of America, Al Gore with his lectures around the World and the documentary "An Inconvenient Truth".

The ever eminent possibility of change in current climatic conditions, the effect on economic activities after the onset of the industrial era and the effects they may provoke in human activities and the Earth as a whole are some of the great concerns of present society in relation to a sustainable future.

The high dependence of agriculture on environmental conditions, particularly the climate, makes it one of the human activities most vulnerable to climatic change described by IPCC. According to Seguin (2007), climatic change will not be the only factor to affect the European economy during the coming years but will have a significant impact on crop productivity and geographic division of potential agricultural regions.

The climatic conditions suitable for coffee production are: annual average temperature between 18°C and 22°C, annual water deficit less than 100 mm and frost probability (risk of lowest annual temperature less than 1°C) less than 25%. An area is said to have "low climatic risks" for coffee production when these three climatic conditions are met. Low climatic risk areas are found in the south and southeast regions in Brazil, mainly in the states of Sao Paulo, Minas Gerais and Parana (Fig. 1).

Coffee is grown in Brazil since 1727 and is one of most important agricultural crops of the country, exporting two-thirds of its production which is 75% of type arabica. Brazil produced 30% of world production of seven billion tons in 2007, according to the International Coffee Organization (ICO), followed by Vietnam and Colombia. Based on this importance of coffee production to Brazilian economy and international market of coffee, Assad et al. (2004) assessed the impact of climate change described in the third report of IPCC on climatic risk zones of Arabica coffee in four main Brazilian producer states (shown in Fig. 1):

- São Paulo (between parallels 19° and 26° S and meridians 44° and 53° W);
- Minas Gerais (between parallels 14° and 23° S and meridians 40° and 52° W);
- Paraná (between parallels 22° and 27° S and meridians 48° and 55° W) and
- Goiás (between parallels 12° and 20° S and meridians 46° and 54° W).

Fig. 1 Map of South America, showing the four main Brazilian producer states of Arabica coffee (Minas Gerais, Goias, Sao Paulo and Parana) and the state of Rio Grande do Sul, in the extreme south of the country, focus of this paper

They concluded that 1°C, 3°C and 5.8°C increases in the mean temperature recorded between 1961 and 1990 may provoke a reduction in current low risk climatic areas and migration to higher elevation regions, considering the currently used commercial varieties and no adaptation or genetic modification. In the case of the state of São Paulo, specifically, Zullo et al. (2006) evaluated that the impact of 1°C, 3°C and 5.8°C increase in the mean temperature and 15% increased rainfall may provoke a climatic risk regarding the cultivation of Arabica coffee and concluded that the size of low risk climatic areas may decrease from 78.7% (current situation) of the total area of the state to 58.9% (1°C increase), 30.3% (3°C increase) and 3.3% (5.8°C increase). In the case of the corn crop, the mean estimated decrease in low climatic risk areas during the October to December planting period was 1% (1°C increase), 33% (3°C increase) and 84% (5.8°C increase), considering average soil texture.

Assad et al. (2007a) stated that the size of low climatic risk areas in the Agricultural Zoning Program of the Ministry of Agriculture (MAPA) regarding soybean, beans, corn and rice crops on higher elevation regions will decrease as the mean temperatures and rainfall increase for the main planting period: the month of November. Wrege et al. (2007) observed that temperature increases may reduce the size of current low climatic risk areas for fruit production in the temperate climate of the state of Rio Grande do Sul due to the decrease in the cold period required for their adequate development.

Despite the high vulnerability to climatic change detected in all these studies, agriculture has a great capacity of adapting to new climatic conditions as long as the existing technological challenges and limits, the natural resources available and the predicted period are taken into consideration. Assad et al. (2007b) highlighted the factors required for the adaptation of the main Brazilian crops: heat tolerance for the whole country, drought tolerance for the Southern and Northern regions and soil management to increase water conservation capacity. The biodiversity of the Cerrados and Amazon regions may contain genes that facilitate the adaptation of present crops to environmental stress and tolerate drought and heat.

The substitution of crops or the use of more resistant species may be another method of adapting agriculture to climatic changes. Pinto et al. (2007) observed that the loss of present low risk climatic areas of Arabica coffee in the southeast region of Brazil could be compensated with other species of coffee more resistant to elevated temperatures such as Roast coffee, currently planted in the lower regions of the state of Espírito Santo (between parallels 26° and 34° S and meridians 49° and 58° W). Likewise, current high risk climatic areas that present low temperatures for the development of Arabica coffee could, for example, benefit with the rise in global temperatures and reduced incidence of frost. In Brazil, these potential areas are in the states of Rio Grande do Sul, Santa Catarina and the south of Parana as well as in Uruguay and north of Argentina. The shifting of coffee production to current areas of high climatic risk, which may be caused by the global warming, agrees with the results presented by Pinto et al. (2007), Zullo et al. (2006) and Assad et al. (2004). All these papers indicate that the higher elevation regions, with colder and milder climate, may become low climate risk areas for coffee production, if the temperature increases.

Therefore, the general purpose of this study was to collaborate with the assessment of the current potential of national agriculture to adapt to climatic changes described by IPCC in two most recent reports (IPCC 2001, 2007) that evaluated the specific case of extending Arabica Coffee to the extreme south of Brazil in relation to rising global temperatures and rainfalls.

2 Materials and methods

The study region covers the state of Rio Grande do Sul, situated approximately between parallels 26° and 34° S and meridians 49° and 58° W. The methodology was based on the one used to define climatic risk zones for Arabica coffee crop (*Coffea* arabica) in the main coffee producing states of Brazil (Pinto et al. 2001; Caramori et al. 2001; Assad et al. 2001; Sediyama et al. 2001) and on an assessment of the impact of climatic changes on the coffee crop (Zullo et al. 2006; Assad et al. 2004; Pinto et al. 2007). These studies based the climatic needs of the coffee crop on three main

Table 1 Classes of climatic risks for Arabica Coffee

Climatic risk	Agrometeorological parameter		
	Mean annual temperature	Annual water deficit	Frost probability
Low risk (no restrictions)	≥18°C and ≤22°C	≥0 and ≤100 mm	≤25%
Risk of high temperatures	≥22°C and ≤23°C	≥0 and ≤100 mm	≤25%
Risks of frosts	≥18°C and ≤22°C	≥0 and ≤100 mm	>25%
High risk	≤18°C or ≥23°C	≥150 mm	>25%

parameters: annual mean temperature, frost probability (i.e. the risk of the lowest annual temperature being equal or less than 1°C) and water deficit. Four classes of climatic risks were defined based on these parameters as shown in Table 1.

Estimates of frost probability were based on values presented by de Oliveira (1997) for probability of minimum temperature equal or less than specific values (+4°C, +3°C, +2°C, +1°C, 0°C, –1°C, –2°C and –3°C) in 21 localities in the state of Rio Grande do Sul for each of the 21 10-day periods between the months of April and October. Figure 2 consists of a map of Rio Grande do Sul with the position of 21 locations used by de Oliveira (1997). Probability of the occurrence of minimum temperatures equal to or less than each of the values considered (+4°C, +3°C, +2°C, +1°C, 0°C, –1°C, –2°C and –3°C) between the months of April and October were calculated, considering all 21 original 10-day events. In reality, this corresponds to the probability of at least one of the 21 original events occurring, which is exactly the value used for zoning areas regarding frost risk assessment during a defined period of the year. It was also considered that the probability of a defined minimum atmospheric temperature occurring in a 10-day period did not depend on the probability of the same temperature occurring during a different 10-day period or

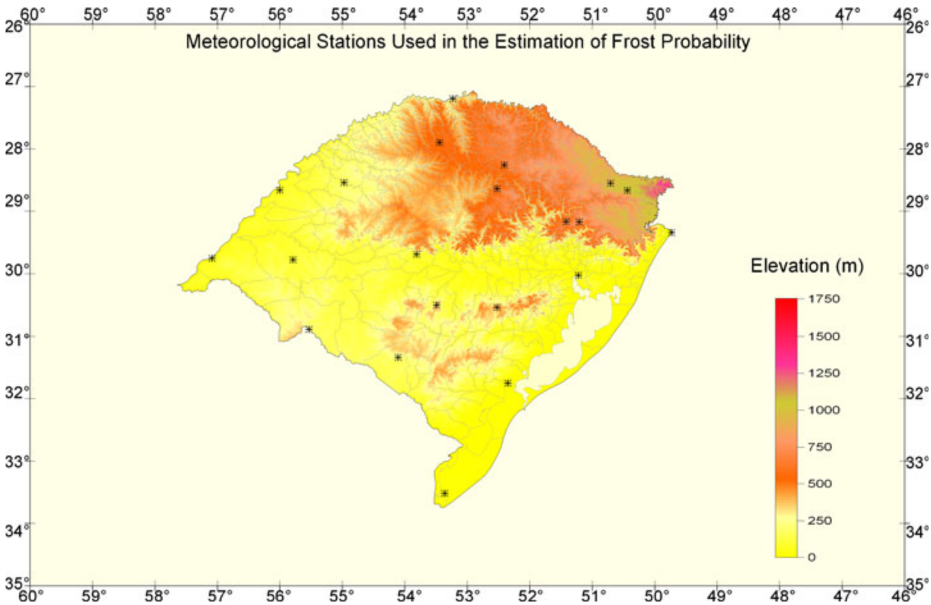

Fig. 2 Location of 21 meteorological stations used to estimate the frost probability

that the events were considered independent but not mutually exclusive. It should be emphasized that in the case of two independent and not mutually exclusive events, A and B, the probability of their union P(AUB) is given by Eq. 1 (de Bussab and Morettin 2003).

$$P(A \cup B) = P(A) + P(B) - P(A) * P(B) \quad (1)$$

After calculating the probability of the union of 21 events, regression equations were calculated to estimate the probability of the occurrence of minimum temperatures less than or equal to the eight minimum temperatures (+4°C, +3°C, +2°C, +1°C, 0°C, −1°C, −2°C and −3°C) between the months of April and October using the longitude, latitude and altitude of the 21 locations in the state of Rio Grande do Sul as parameters. The regression equations calculated are presented in Table 2 where *long* is the longitude (in minutes with negative sign in the western hemisphere), *lati* is the latitude (in minutes with negative sign in the southern hemisphere), *alti* is the altitude (in meters), *Multiple R* is the coefficient of multiple regression and *Std.Error of Estimate* is the standard error of the estimate. All *p* values are less than 0.01 (1%).

The annual water deficit was calculated based on the estimation of climatic water balance using the Thornthwaite and Mather (1955) method, considering 125 mm of water holding capacity in the soil. The total mean monthly rainfall used in the water balance were calculated based on daily values during the 1980–2003 period, obtained from 74 meteorological stations of FEPAGRO (Fundação Estadual de Pesquisa Agropecuária—Foundation for Agricultural Research in the state of Rio Grande do Sul) and ANA (Agência Nacional de Águas—National Water Agency). Figure 3 shows the spatial distribution of the 74 stations used.

Table 2 Regression equations for estimating the probability (values from 0% to 100%) of the occurrence of minimum temperatures less than or equal to a defined minimum temperature limit ($\overline{T_{\min}}$) in Rio Grande do Sul, between the months of April and October

$\overline{T_{\min}}$	Regression equation	Multiple *R*	*p* Value	Std.err. of estimate
−3°C	$P(T_{\min}\vert_{APR}^{OCT} \leq \overline{T_{\min}}) = 17.4662 + 0.0196 \times long - -0.0217 \times lati + 0.0614 \times alti$	0.7850	0.0008	17.20
−2°C	$P(T_{\min}\vert_{APR}^{OCT} \leq \overline{T_{\min}}) = -40.3657 - 0.0077 \times long - -0.0103 \times lati + 0.0736 \times alti$	0.8175	0.0002	17.32
−1°C	$P(T_{\min}\vert_{APR}^{OCT} \leq \overline{T_{\min}}) = -206.137 - 0.0636 \times long - -0.0135 \times lati + 0.0817 \times alti$	0.8091	0.0003	17.97
0°C	$P(T_{\min}\vert_{APR}^{OCT} \leq \overline{T_{\min}}) = -444.424 - 0.1291 \times long - -0.0424 \times lati + 0.0821 \times alti$	0.7936	0.0006	17.97
+1°C	$P(T_{\min}\vert_{APR}^{OCT} \leq \overline{T_{\min}}) = -583.054 - 0.1592 \times long - -0.0765 \times lati + 0.0735 \times alti$	0.8142	0.0003	15.57
+2°C	$P(T_{\min}\vert_{APR}^{OCT} \leq \overline{T_{\min}}) = -486.166 - 0.1361 \times long - -0.0710 \times lati + 0.0549 \times alti$	0.8113	0.0003	12.48
+3°C	$P(T_{\min}\vert_{APR}^{OCT} \leq \overline{T_{\min}}) = -243.067 - 0.0798 \times long - -0.0418 \times lati + 0.0308 \times alti$	0.7739	0.0011	8.15
+4°C	$P(T_{\min}\vert_{APR}^{OCT} \leq \overline{T_{\min}}) = -23.1271 - 0.0286 \times long - -0.0152 \times lati + 0.0109 \times alti$	0.7266	0.0044	3.35

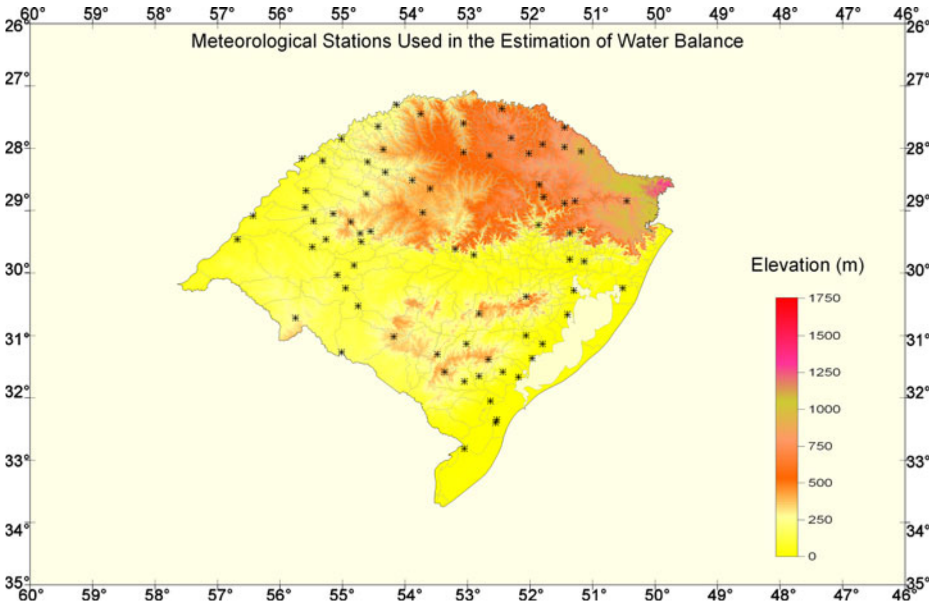

Fig. 3 Location of 74 meteorological stations used to estimate the water balance

The mean monthly temperatures of each station used in water balance were calculated applying equations proposed by Ferreira et al. (1971) based on the values of altitude (meters) and latitude (minutes) of each point of interest. The estimated mean annual temperature used in defining the climatic ability of Arabica coffee was also based on the equation proposed by Ferreira et al. (1971). Table 3 presents

Table 3 Regression equations for estimating annual and monthly mean temperatures

Month/year	Equation	Multiple R
January	$T_{MEAN}{}^{JAN} = 44.11 - 0.006673 \times alti + 0.010443 \times lati$	0.947
February	$T_{MEAN}{}^{FEB} = 42.46 - 0.006492 \times alti + 0.009752 \times lati$	0.960
March	$T_{MEAN}{}^{MAR} = 41.80 - 0.006062 \times alti + 0.010305 \times lati$	0.971
April	$T_{MEAN}{}^{APR} = 34.80 - 0.004970 \times alti + 0.008464 \times lati$	0.954
May	$T_{MEAN}{}^{MAY} = 31.85 - 0.004462 \times alti + 0.008540 \times lati$	0.946
June	$T_{MEAN}{}^{JUN} = 34.32 - 0.004066 \times alti + 0.011195 \times lati$	0.951
July	$T_{MEAN}{}^{JUL} = 32.65 - 0.003864 \times alti + 0.010495 \times lati$	0.924
August	$T_{MEAN}{}^{AUG} = 40.29 - 0.004248 \times alti + 0.014063 \times lati$	0.940
September	$T_{MEAN}{}^{SEP} = 45.06 - 0.004725 \times alti + 0.015784 \times lati$	0.935
October	$T_{MEAN}{}^{OCT} = 47.06 - 0.005501 \times alti + 0.015651 \times lati$	0.931
November	$T_{MEAN}{}^{NOV} = 48.52 - 0.006176 \times alti + 0.014888 \times lati$	0.959
December	$T_{MEAN}{}^{DEC} = 46.16 - 0.006311 \times alti + 0.012304 \times lati$	0.951
Year	$T_{MEAN}{}^{YEAR} = 40.46 - 0.005246 \times alti + 0.011661 \times lati$	0.959

Proposed by Ferreira et al. (1971)

equations used to estimate annual and monthly mean temperatures where *alti* is the altitude (in meters), *lati* is the latitude (in minutes with negative sign in the southern hemisphere) and *Multiple R* is the coefficient of multiple regression.

Five water balances were simulated for each of the 74 meteorological stations with original temperatures and rainfall data as well as raising the mean monthly temperatures by 1°C to 4°C and the mean monthly rainfall by 15%. These values of temperature and rainfall were based on the IPCC reports (2001 and 2007), mainly the scenarios for the south of Brazil. The water deficit is not a limiting factor for the development of Arabica coffee even without the increase of 15% used in this paper. The maximum annual water deficit in each one of the five simulated cases was 36.1, 17.3, 26.9, 38.4 and 76.9 mm, respectively, which was below the 100 mm used as reference to define the climatic risk of Arabica coffee as presented in Table 1. Since it wasn't a limiting factor, annual water deficit was not used in the definition of climatic risk of Arabica coffee in the state of Rio Grande do Sul and the focus was kept on calculating the estimated annual mean temperature and frost probability. These two parameters were calculated for five distinct climatic conditions for each of the 909,121 altimetric data (841 lines × 1081 columns) supplied by USGS (2001) in a regular grid delimited by the coordinates longitude 58° to 49° W and latitude 27° to 34° S with a spacing of 30 × 30°. Figure 4 presents a plani-altimetric map of Rio Grande do Sul based on USGS data (2001).

The climatic conditions used in the calculations were current climate and four cases of global warming corresponding to mean temperature increases of the Earth between 1°C and 4°C. The estimated annual mean temperature used in simulating

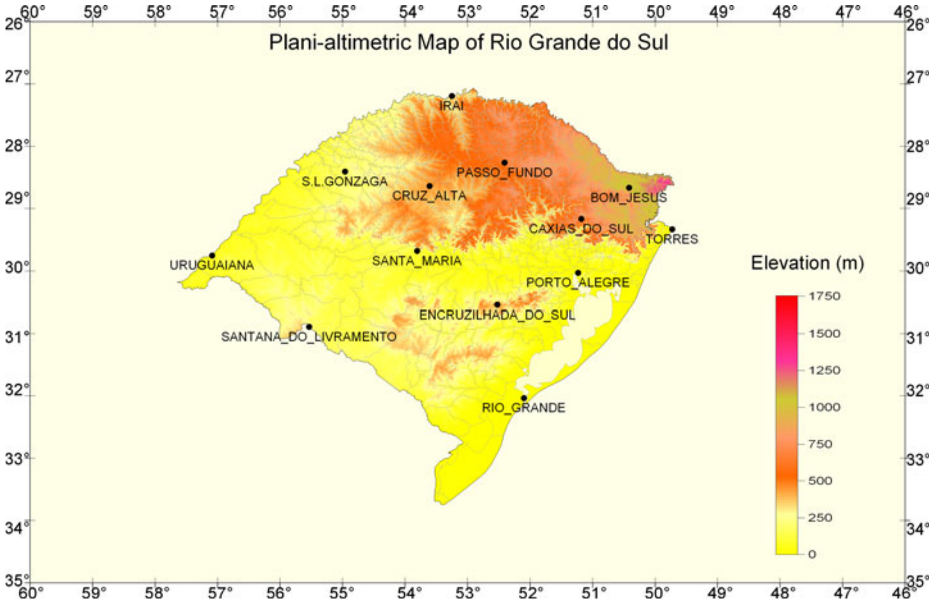

Fig. 4 Plani-altimetric map of Rio Grande do Sul

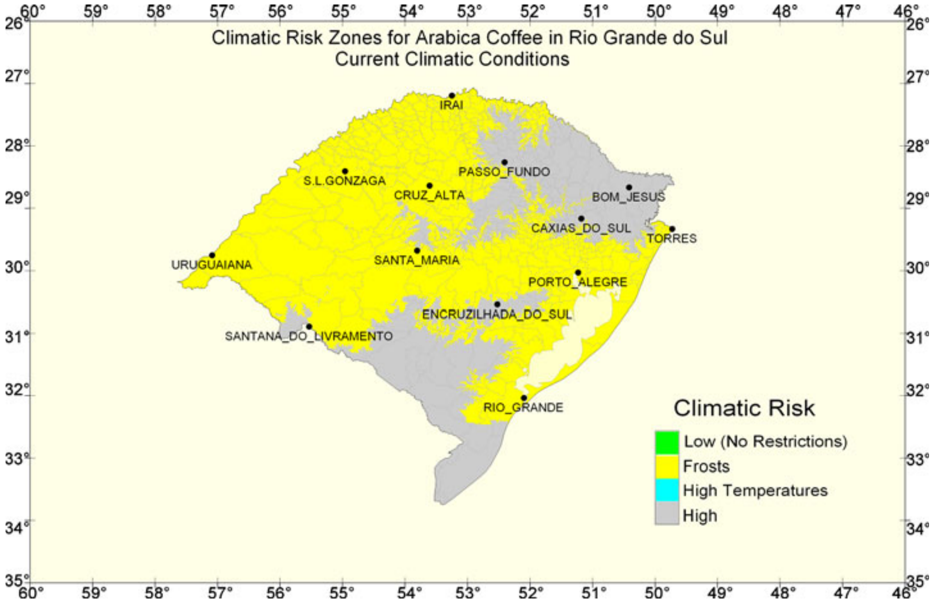

Fig. 5 Climatic risk zoning for Arabica coffee in Rio Grande do Sul, based on current climatic conditions

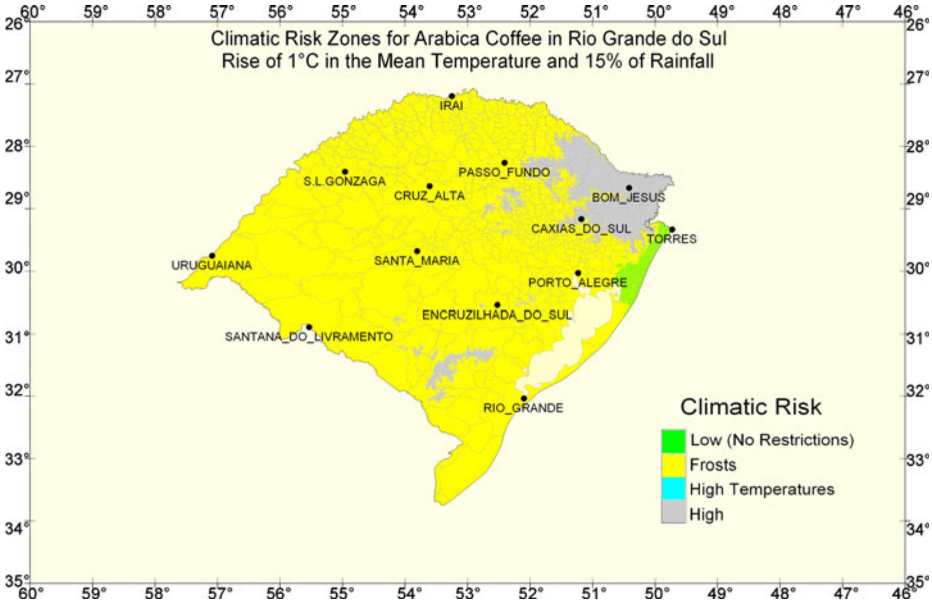

Fig. 6 Climatic risk zones for Arabica coffee in Rio Grande do Sul, considering a rise of 1°C in the mean temperature and 15% of rainfall

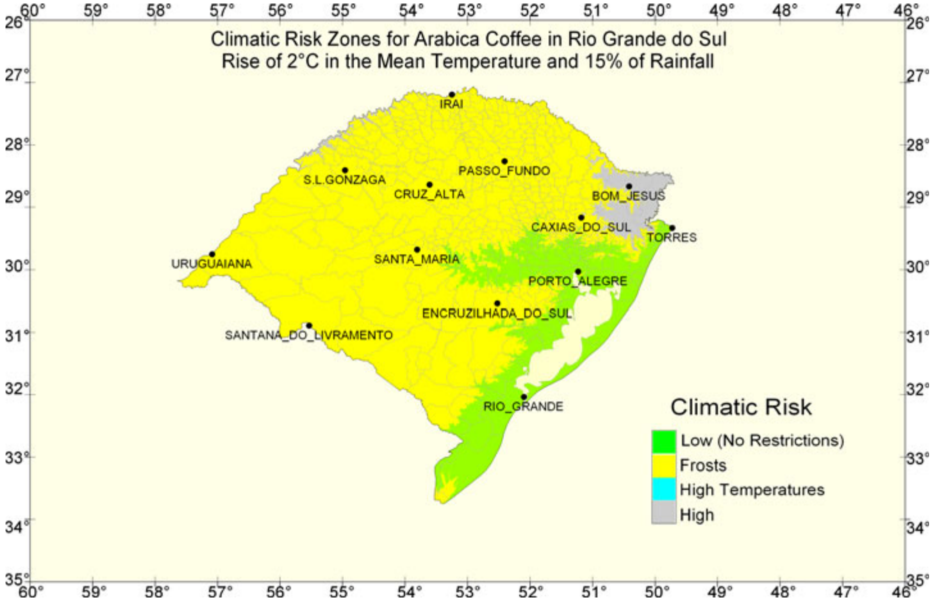

Fig. 7 Climatic risk zones for Arabica coffee in Rio Grande do Sul, considering a rise of 2°C in the mean temperature and 15% in rainfall

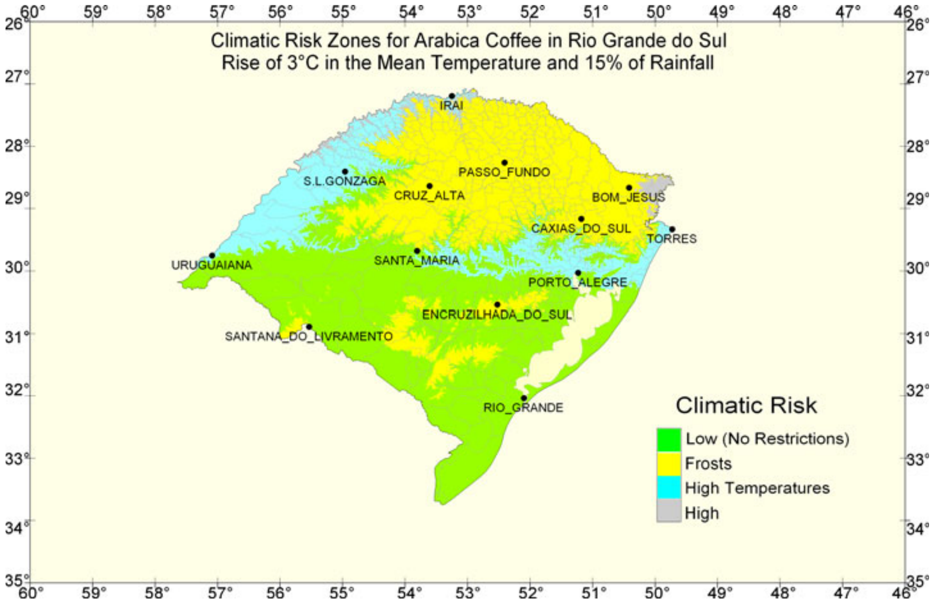

Fig. 8 Climatic risk zones for Arabica coffee in Rio Grande do Sul, considering a rise of 3°C in the mean temperature and 15% in rainfall

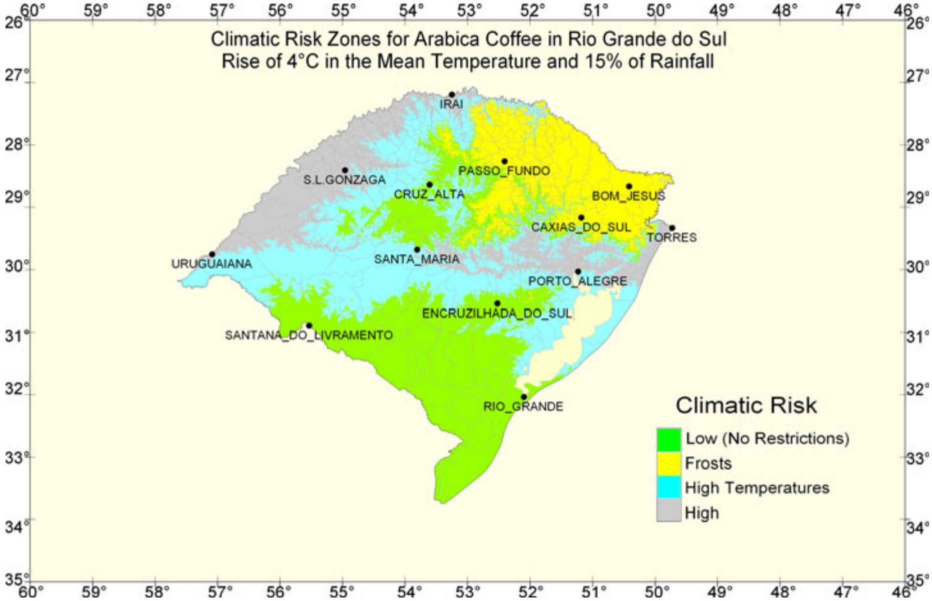

Fig. 9 Climatic risk zones for Arabica coffee in Rio Grande do Sul, considering a rise of 4°C in the mean temperature and 15% in rainfall

current climate was raised by 1°C to 4°C in the case of global warming simulations. The equations applied for frost probability were:

- $P(T_{\min}|_{APR}^{OCT} \leq +1°C)$ for current climate (that is, from 1980 to 2003);
- $P(T_{\min}|_{APR}^{OCT} \leq 0°C)$ for 1°C global warming;
- $P(T_{\min}|_{APR}^{OCT} \leq -1°C)$ for 2°C global warming;
- $P(T_{\min}|_{APR}^{OCT} \leq -2°C)$ for 3°C global warming; and
- $P(T_{\min}|_{APR}^{OCT} \leq -3°C)$ for 4°C global warming.

The tests performed to classify the climatic risks for Arabica coffee in Rio Grande do Sul are presented in Table 1, with the exception of annual water deficit, which was unnecessary since it was not a limiting factor as previously stated.

Table 4 Percentage of area in the state of Rio Grande do Sul for each type of risk defined in climatic risk zoning for Arabica coffee, considering the current climate and simulations of global warming

Climatic risk	Percentage of area in the state of Rio Grande do Sul for each type of risk				
	Current climate	Global warming			
		+1°C	+2°C	+3°C	+4°C
Low (no restrictions)	0.0	1.5	17.4	46.0	33.1
High temperatures	0.0	0.0	0.0	16.1	32.6
Frosts	67.0	89.3	78.7	36.0	16.8
High risk	33.0	9.3	3.9	1.9	17.6

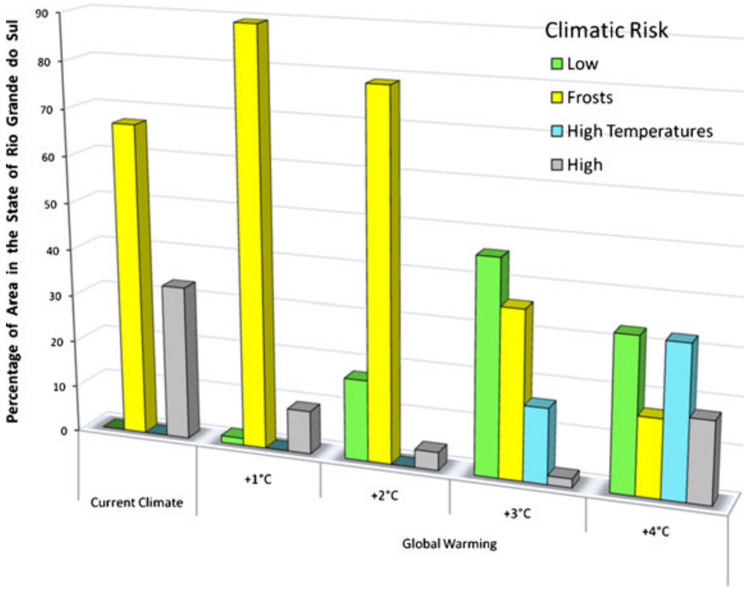

Fig. 10 Percentage of area in the state of Rio Grande do Sul for each class used in zoning climatic risks for Arabica coffee in relation to five distinct climatic situations

3 Results and discussion

Figures 5, 6, 7, 8 and 9 present climatic risk zone maps for Arabica coffee in Rio Grande do Sul, considering the current climate and four global warming simulations.

Table 4 presents the dimension of each risk class used in zoning, illustrated in Fig. 10. Tables 5 and 6 details the values of change from one type of risk to another.

According to Tables 4, 5 and 6, global warming may reduce the risk of frost and increase the size of low climatic risk areas, reaching a peak for the rise of +3°C (32.8%), decreasing significantly from this value (12.2%) when there is an increase in the size of areas with risk of high temperatures (27.7% and 6.9%) and high climatic risk (15.7%). The risk of frost decreases significantly and the risk of high temperatures is zero or low (16.1% at +3°C), until the rise of +3°C. From global warming +4°C, the risk of frost continues to decrease (unfavoring the increase of areas with low climatic risk) but the risk of high temperatures increases. This

Table 5 Net percentage change of area in the state of Rio Grande do Sul for each type of climatic risk, resulting from a change in the climate condition

Climatic risk	Net percentage change			
From	Current climate	Rise of +1°C	Rise of +2°C	Rise of +3°C
To	Rise of +1°C	Rise of +2°C	Rise of +3°C	Rise of +4°C
Low (no restrictions)	+1.5	+15.9	+28.6	−12.9
High temperatures	0.0	0.0	+16.1	+16.5
Frosts	+22.3	−10.6	−42.7	−19.2
High risk	−23.7	−5.4	−2.0	+15.7

Table 6 Percentage change of area in the state of Rio Grande do Sul transformed from one type of climatic risk to other, resulting from a change in the climate condition

Climatic risk		Percentage change			
From	To	From: Current climate To: Rise of +1°C	Rise of +1°C Rise of +2°C	Rise of +2°C Rise of +3°C	Rise of +3°C Rise of +4°C
High risk	Frosts	22.9	5.7	2.6	0.6
Frosts	Low (no restrictions)	1.5	18.9	32.8	12.2
	High temperatures	0.0	0.0	10.3	6.9
	High risk	0.0	0.5	0.7	0.2
Low (no restrictions)	High temperatures	0.0	0.0	5.4	27.7
High temperatures	High risk	0.0	0.0	0.0	15.7

explains the maximum value of 46% for areas with low climatic risk for the global warming +3°C.

4 Conclusions

The results indicate that a rise in mean temperatures and reduction of frost risk may favor an increase in the size of low risk climatic areas for the cultivation of Arabica coffee in the state of Rio Grande do Sul, especially if the rise in temperature is about 3°C in relation to current climatic conditions. An increase in temperature between 2°C to 4°C could favor an increase in the size of low risk climatic areas, but less than in the case of 3°C. The rise of +3°C was the simulation scenario in which the changes from “risk of frost” to “low climatic risk” were maximal and significantly greater than the changes from “low climatic risk” to “risk of high temperatures. Thus, even for a high climatic risk area for Arabica coffee production, global warming may be advantageous up to a certain limit. It should be underscored that areas classified as low climatic risk areas for temperature increases of 3°C to 4°C are situated in the south of Rio Grande do Sul, also indicating a possibility for neighboring regions like Uruguay and north of Argentina (as shown in Fig. 1). Although other simulations are needed, the results suggest that the Brazilian coffee sector has the potential to adapt to rising global temperatures by migrating the present low climatic risk areas to the extreme south of the country. It is important to emphasize that the agronomic and environmental parameters used in this paper to define the classes of climatic risk are consistent since Arabica coffee is one of the agricultural crops more traditional in Brazil, studied and cultivated since 1727. Moreover, the technology of agricultural zoning is being used by the Ministry of Agriculture as basis for its public policies since 1995, with a previous successful experience in the 1970s. The first simulations on possible impacts caused by climate changes in the production of Arabica coffee were prepared and published in 2001. These facts are of great importance to ensure the robustness of the results and make them useful for defining adaptation policies of a tropical agricultural so important as the Brazilian agricultural to possible climate changes in the coming decades. The methodology used in this paper to assess the impacts of climate changes may be useful for others agricultural crops and world regions with similar agronomical and environmental conditions.

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