Maize yield and rainfall on different spatial and temporal scales in Southern Brazil

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Abstract – This study aimed to establish relationships between maize yield and rainfall on different temporal and spatial scales, in order to provide a basis for crop monitoring and modelling. A 16-year series of maize yield and daily rainfall from 11 municipalities and micro-regions of Rio Grande do Sul State was used. Correlation and regression analyses were used to determine associations between crop yield and rainfall for the entire crop cycle, from tasseling to 30 days after, and from 5 days before tasseling to 40 days after. Close relationships between maize yield and rainfall were found, particularly during the reproductive period (45-day period comprising the flowering and grain filling). Relationships were closer on a regional scale than at smaller scales. Implications of the crop-rainfall relationships for crop modelling are discussed.

Index terms : *Zea mays*, rainfall, water deficit, crop models, critical period.

Rendimento de milho e chuva em diferentes escalas espaço-temporais no Sul do Brasil

Resumo – Este trabalho teve como objetivo estabelecer relações entre rendimentos de milho e totais de chuva em diferentes escalas temporais e espaciais, com a finalidade de fornecer bases para modelagem e monitoramento de safras. Utilizou-se uma série de 16 anos de rendimento de milho e dados diários de chuva de 11 municípios e microrregiões do Estado do Rio Grande do Sul. Análises de correlação e regressão foram utilizadas para determinar associações entre rendimento e total de chuva no ciclo do milho, do pendoamento até 30 dias depois, e de 5 dias antes a 40 dias após o pendoamento. Altas relações foram encontradas entre rendimento de milho e chuvas do período reprodutivo, em particular dos 45 dias que englobam florescimento e enchimento de grãos. Essas relações foram mais elevadas em escala regional do que em nível de município. São discutidas implicações das relações clima-chuva para modelagem de cultivos.

Termos para indexação: *Zea mays*, chuva, deficit hídrico, modelagem, período crítico.

Introduction

The Southeast region of South America is responsible for producing a great part of grains and animal foods exported by the Continent. Rio Grande do Sul, State of Brazil, is one of the most important producers of grains in the Region. The greatest part of the maize produced in this State is used to feed chickens, pigs and dairy cows, as well as for human consumption. Currently, poultry and pork meat are very important commodities to export abroad (Conab, 2007).

The annual yield of maize grain has ranged in the last decade from less than 1.5 t ha^{-1} (in 1991 and 2005) to about 3.5 t ha^{-1} (in 2001 and 2003) in Rio Grande do Sul State (IBGE, 2006). The irregular distribution of rainfall, during the crop cycle, may explain a lot of the yield variability attributed to crop growing conditions. Berlato et al. (2005) showed relationships between maize yield and the El Niño Southern Oscillation, through the influence of this phenomenon on rainfall patterns in the State.

Other studies have revealed an extreme sensitivity of maize plants to water deficit, during a very short critical period, from flowering to the beginning of the grain-filling phase (Bergonci et al., 2001; Bergamaschi et al., 2004). Maize crops have also the highest water requirement during the critical period, when the maximum leaf area index combines with the highest evaporative demand

(Bergamaschi et al., 2001; Radin et al., 2003). Thus, maize crops are very sensitive to water deficits during its critical period (flowering to beginning of grain filling) for two reasons: high water requirement, in terms of evapotranspiration, and high physiological sensitivity when determining its main yield components, as number of ears per plant and number of kernels per ear.

Field experiments have shown increases and a stabilizing of maize yield, when water deficit is reduced using irrigation. In a 10-year set of experiments, Bergamaschi et al. (2006) obtained an average grain yield of around 10 t ha^{-1} in irrigated maize plots, with a high level of management, in Rio Grande do Sul State; meanwhile, the average grain yield was less than 6 t ha^{-1} in nonirrigated plots, and ranged from 1.5 to 10 t ha^{-1}. The fluctuation in rainfed conditions reflects the high variability of the rainfall regime, which is typical of summer seasons in most of the subtropical region. Otherwise, the high performance of grain production in irrigated plots reflects the capacity of maize crops to respond to the use of high level technology in nonlimiting weather conditions.

Techniques of modelling have been used recently to describe crop-weather relationships, in order to quantify and understand the impacts of weather hazards on cropping systems, and to identify new technological alternatives to mitigate their effects. Crop models are becoming more and more an important tool for decision-makers. According to Thornley (2006), the type and complexity of models depend on how complex are the processes, as well as the scope of their practical use. It is not necessary to understand how something works in order to be able to predict behaviour by using an empirical model. However, prediction with understanding always offers more options than empirical prediction alone. Mechanistic models can provide the understanding needed for intelligent and flexible management, given the near certainty of changing environmental and economic conditions (Thornley, 2006).

Numerical models comprise mathematical functions for estimating or predicting the impacts of adverse conditions on a wide range of time and spatial scales. Challinor et al. (2004) considered that understanding the impacts of current subseasonal and interannual climate variability on crop yields would support agricultural planning over different timescales. Therefore, the relationships between seasonal weather and yield data must be determined before developing such models, in order to proceed the modelling on spatial scales on which an observed relationship has been shown. Challinor et al. (2003) considered that data on a large (countrywide) scale could be used in food balance sheets, allowing government agencies to plan economic policy. Data on smaller scales (e.g. farm or regional scale) can be used to detect local crop stress and, hence, to enable effective mitigation strategies to be employed.

This study aimed to establish relationships between maize yield, rainfall and air temperature at different spatial scales, considering the entire crop cycle and the critical period. The hypotheses were: rainfall was the main weather variable in determining variability of maize yield; the relationships between maize yield and rainfall are closer during the reproductive period than in the entire crop cycle; and relationships between maize yield and rainfall are closer, when using data from a large scale than from a small spatial scale.

Material and Methods

A 16-year series of annual maize yield (1990 to 2005) was collected from 347 municipalities located in the North and Northwest of Rio Grande do Sul State, where around 83% of the State production of maize took place in that period (IBGE, 2006). Annual data of maize yield for the same period were collected from 11 specific municipalities, as well as from the neighbouring municipal areas surrounding each of them, so providing 11 microregions. Figure 1 shows the main producer region of maize in the State, with the 11 municipalities and microregions. Annual data of maize yield were also collected from the entire Rio Grande do Sul State, comprising 496 municipalities.

Daily data of rainfall and mean air temperature, from each growing season, were also collected from 11 meteorological stations available in each of the 11 chosen municipalities (Figure 1). The weather stations belong to the official networks of Fepagro – Fundação Estadual de Pesquisa Agropecuária (Cruz Alta, Erechim, Ijuí, Julio de Castilhos, Santa Rosa, São Borja, Taquari and Veranópolis) and Inmet – Instituto Nacional de Meteorologia (Iraí, Passo Fundo and São Luiz Gonzaga).

Average phenological phases were established for maize crops in each municipality or microregion. The mean time for 50% of maize sowing was considered as the starting point, according to the annual evaluations of the State extension service (Emater, 2005) from 2002 to 2005. Once the beginning of the crop cycle was established, it was possible to estimate the mean date of tasseling, milky maturity and physiological maturity by the use of experimental data, summarized by Matzenauer (1994) from a set of field experiments conducted during several years within sites of the same region. According to the author, those results are suitable for short and normal season maize hybrids, the prevailing genotypes used by farmers in the region during the 1970s and 1980s.

Preliminary analyses evaluated the relationships between annual grain yield of maize, mean air temperature, and rainfall. The entire crop cycle or a critical 30-day period, comprising tasseling stage to 30 days after, were used. According to Matzenauer (1994), the stage of 30 days after tasseling corresponds roughly to milky grain for maize crops in the region. A third phenological interval was introduced to the statistical analyses, by expanding the critical period to a 45-day period. The 45-day period corresponds to the interval from 5 days before flowering to 40 days after tasseling stage, which comprises the main processes of grain-setting and filling. The critical periods of 30 days, from tasseling to 30 days after that, as well as the entire crop cycle, were also used.

Each relationship was fitted by regression analyses. Deviations between annual yields and a linear historical trend (when significant) were subtracted from the observed data, to minimize the increasing effects of technology on grain yields.

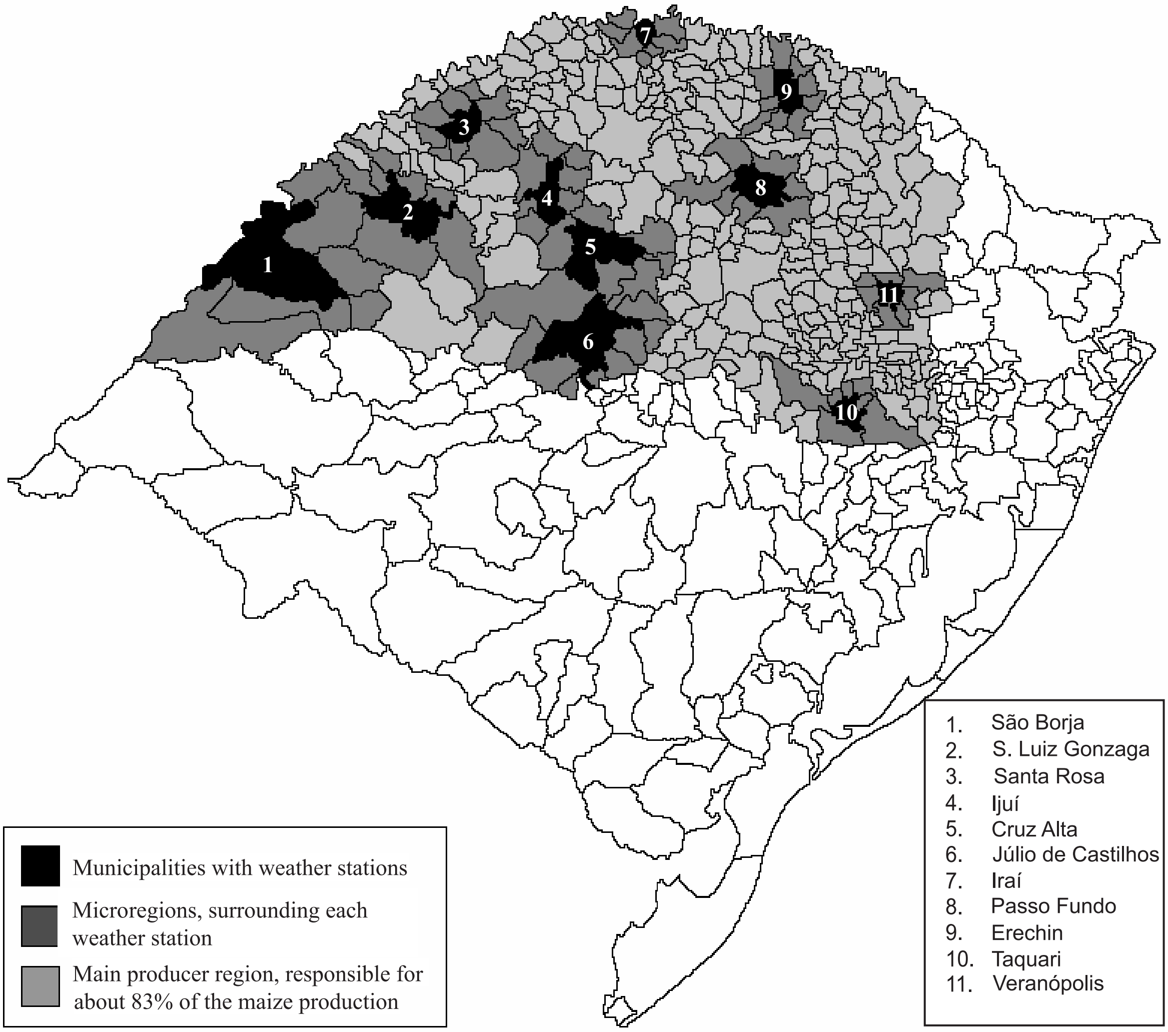

Figure 1. Map of the 11 municipalities and the 11 microregions of this study, and the main producer region of maize and the entire Rio Grande do Sul State, Brazil.

Adjustments were made to the crop calendar, considering the variability among the correlation coefficients for municipalities and microregions, in particular for the 30-day critical period. The recent use of short and very-short season hybrids by farmers in the region (during the 1990s and after) was also considered. Results from 10-years field experiments presented by Müller et al. (2005) and Bergamaschi et al. (2006), for short and very-short season hybrids, were used to match phenological stages to regional conditions. The mean phenology for these genotypes in the 11 municipalities and microregions is shown in Table 1.

Asymptotic models were fitted by exponential regression analyses to estimate the annual average maize yield as function of rainfall amount for different spatial scales, in which a linear model was not adequate. The amounts of rainfall, in the entire crop cycle and in the 30-day and 45-day periods, were considered for each spatial scale. The equation used was:
$y = A + B(C^x)$ where y is the annual yield (kg ha^{-1}); x is rainfall (mm); and A, B and C are fitted parameters.

Results and Discussion

Regression analyses showed close relationships among annual average maize yields, on the four spatial scales analysed in Rio Grande do Sul State (Figure 2). This suggests similar causes of variability in maize yield in all production zones of the State. In addition, high coherence among these different spatial scales indicates the possibility to estimate the variability of maize yields on a regional scale, or even on a State level, by using weather data collected only in the main production region.

There were only weak relationships between maize yield and air temperature. For the 11 municipalities, the mean correlation coefficients were -0.094 and -0.041 (not significant) for the entire crop cycle and for the period from tasseling to 30 days after, respectively. The mean correlation coefficients for the 11 microregions were -0.093 and -0.023 (not significant) for the crop cycle and the 30-day period, respectively. These results suggest that variability in air temperature has little or no effect on maize yield variability. Therefore, maize genotypes are well adapted to the thermal conditions of the region. Since maize is a C_4 species, it is reasonable to consider its adaptability to mean temperatures of summer seasons of Southern Brazil, at least on a macroclimate scale. This confirms the hypothesis that the water deficit is the main limiting weather condition for maize yields in Rio Grande do Sul State, as several authors have demonstrated previously (Matzenauer et al., 2002; Bergamaschi et al., 2004, 2006; Berlato et al., 2005).

The variability of annual grain yield on different spatial levels in Rio Grande do Sul State, together with the variability of rainfall in the entire crop cycle and in the 30-day and 45-day periods are shown in Figure 3. Correlation and linear regression revealed high levels of significance for yield, as function of rainfall at most of the municipalities and microregions (Table 2). The correlation coefficients and the significance of regressions increased from municipalities to microregions and from microregions to the main producer region, suggesting a decreasing variability in maize yield with increasing spatial scale. The significance had a small reduction from the main producer region to the entire

Table 1. Date and duration of development stages of short and very-short season maize hybrids, in different microregions of Rio Grande do Sul State, Brazil, according to Matzenauer (1994), Emater-RS (2005), Müller et al. (2005) and Bergamaschi et al. (2006).

Microregion	Sowing date (50%)	Tasseling (flowering)	Milky stage	Physiological maturity	Sowing – tasseling (days)	Crop cycle (days)
São Borja	Sept. 12	Nov. 30	Dec. 30	Jan. 30	79	140
S. L. Gonzaga	Sept. 12	Nov. 30	Dec. 30	Jan. 30	79	140
Santa Rosa	Sept. 22	Dec. 3	Jan. 2	Jan. 31	72	131
Ijuí	Sept. 30	Dec. 9	Jan. 8	Feb. 8	70	131
Iraí	Sept. 20	Dec. 1	Dec. 31	Jan. 28	72	130
Cruz Alta	Oct. 5	Dec. 10	Jan. 9	Feb. 10	66	138
J. Castilhos	Oct. 5	Dec. 10	Jan. 9	Feb. 10	66	138
Passo Fundo	Oct. 10	Dec. 17	Jan. 16	Mar. 7	68	138
Erechim	Oct. 10	Dec. 19	Jan. 18	Mar. 7	70	138
Veranópolis	Oct. 21	Dec. 30	Jan. 29	Mar. 10	70	140
Taquari	Oct. 15	Dec. 22	Jan. 21	Feb. 22	68	130

State, because all the weather data were collected in that region. The relationships were closer when analysing the critical period of the crop compared to the entire crop cycle, which can be attributed to the high sensitivity of maize plants to water deficits, during flowering and the beginning of grain filling, as showed Bergonci et al. (2001), Matzenauer (1994) and Bergamaschi et al. (2004, 2006).

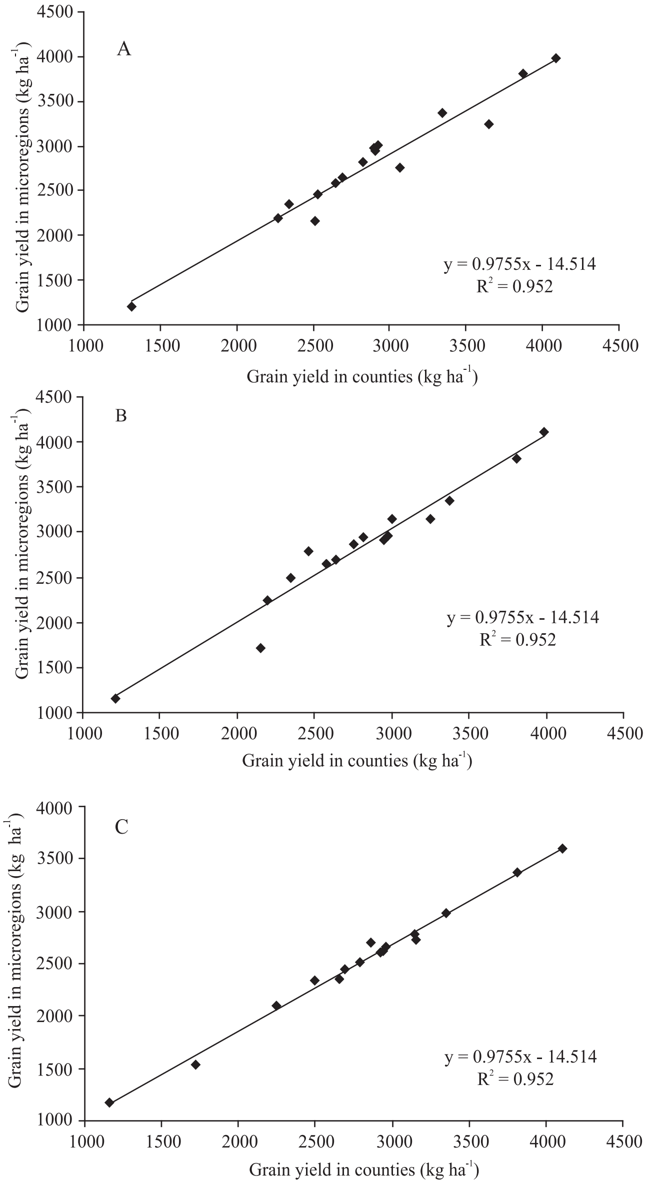

Figure 2. Relationships between annual average yield of the period 1990–2005 for: A) 11 municipalities and microregions; B) microregions and main producer region; and C) main producer region and Rio Grande do Sul State.

Analyses of the exponential regressions revealed significant asymptotic relations between the annual maize yield and rainfall in the 30-day and 45-day critical periods (Figures 4 and 5). Relations between annual maize yield and rainfall in the entire crop cycle were only significant as linear functions (Figure 6). The estimated parameters of equation and the probability of significance for each function are given in Table 3. Annual yield for each municipality and microregion were associated with rainfall in each site. Annual yields from

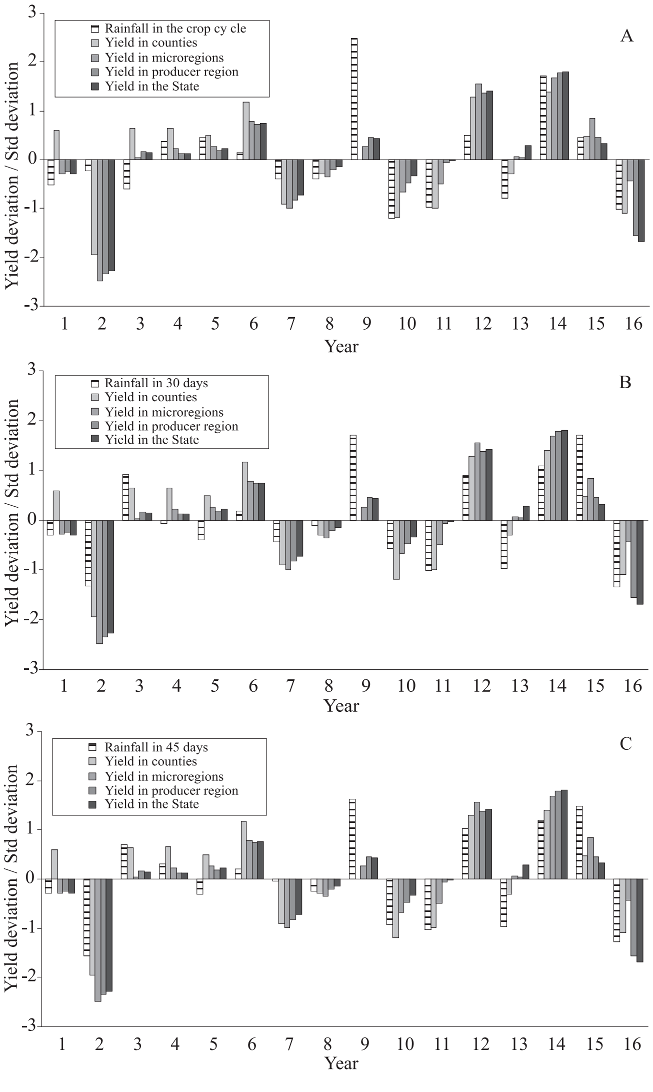

Figure 3. Variability of maize grain yields in 11 municipalities, 11 microregions, main producer region, and Rio Grande do Sul State, for rainfall in 11 sites, during: A) the entire crop cycle; B) 30 days of the reproductive phase; and C) 45 days of the reproductive phase, for 16 years, from 1990 to 2005.

the main producer region and the State were related to the average rainfall in the 11 sites. Therefore, annual yields and rainfall were analyzed at different degrees of association, depending on the level of aggregation (small or large spatial scales), since rainfall data changed from single values for each site and microregion to average values of 11 sites for the main region and State.

Asymptotic models were significant ($p \leq 0.05$) when relating the annual maize yield to rainfall, in both the 30-day and 45-day critical periods of maize. However, the significance of these models was low ($p \geq 0.1$) when rainfall, during the entire crop cycle, was used for any spatial scale (Table 3). The significance of the exponential functions also increased, as the critical period was extended from 30-day (Figure 4) to 45-day (Figure 5), during flowering and grain-filling. The 45-day period comprises almost all the processes of formation of yield components, and it showed a better association between yields and rainfall than the 30-day period, on a large spatial scale. This decrease in variability occurred because the longer period encompassed small variations in crop durations within the time series, which arose because data were taken on a municipality level, and so they contain all the variability among crop systems and years.

The shape of the asymptotic functions showed an initial increase in maize yields as rainfall increased, and, then, a plateau above some limit (Figures 4 and 5). The plateau in grain yield occurred as the rainfall was around 200 and 300 mm for the 30-day and 45-day periods, respectively. The proportion between the two limits is coherent, if considering the time length of the respective periods. It is possible to suppose those amounts of rainfall as necessary to supply the water requirements of maize crops, at a high level of technology, during maximum leaf area index in the region. Field measurements in a weighing lysimeter, during four cropping seasons, detected a maximum evapotranspiration (ETm) of about 7 mm per day, in maize crops at maximum leaf area index, in the subtropical conditions of Rio Grande do Sul (Radin, 1998; Bergamaschi et al., 2001; Radin et al., 2003). The rainfall amounts of 200 and 300 mm for the 30-day and 45-day periods, respectively, are in accordance with those crop water requirements. In practical terms, they represent the rainfall to meet maize water demand in the region necessary to avoid water deficit during the reproductive period. The limit of about 200 mm, in a 30-day period after flowering, is also in agreement with results of Matzenauer et al. (2002). They verified that monthly means of rainfall (around 110 to 130 mm) are lower than the water necessity in the critical stages of maize crops in the region, which represents a limiting factor for maize production in Rio Grande do Sul State.

The high variability in grain yields in the wettest cropping seasons may be attributed to the effect of other

Table 2. Analyses of correlation and linear regressions for yield deviations of maize (kg ha^{-1}) as a function of rainfall deviations (mm), for the entire crop cycle, 30-day and 45-day periods in the reproductive period, in 11 municipalities, 11 microregions, the main producer region, and the Rio Grande do Sul State, Brazil, 1990-2005.

Municipality or microregion	Correlation coefficients (r)						Significance of regressions					
	Municipalities			Microregions			Municipalities			Microregions		
	Cycle	30 d	45 d	Cycle	30 d	45 d	Cycle	30 d	45 d	Cycle	30 d	45 d
São Borja	0.224	0.198	0.212	0.228	0.292	0.404	0.404	0.462	0.431	0.395	0.273	0.121
Taquari	0.456	0.445	0.509	0.507	0.379	0.396	0.076	0.084	0.044	0.045	0.147	0.129
Santa Rosa	0.457	0.303	0.501	0.486	0.253	0.505	0.075	0.254	0.048	0.056	0.345	0.046
S.L. Gonzaga	0.241	0.256	0.293	0.530	0.532	0.587	0.369	0.344	0.271	0.035	0.034	0.017
Passo Fundo	0.380	0.768	0.705	0.346	0.716	0.605	0.147	0.001	0.002	0.189	0.002	0.013
J. Castilhos	0.273	0.357	0.452	0.249	0.405	0.445	0.307	0.175	0.079	0.353	0.120	0.084
Iraí	0.0389	0.456	0.501	0.565	0.608	0.685	0.137	0.076	0.048	0.023	0.012	0.003
Erechim	0.268	0.404	0.451	0.370	0.460	0.491	0.315	0.121	0.079	0.159	0.073	0.054
Cruz Alta	0.262	0.381	0.478	0.455	0.659	0.733	0.327	0.146	0.061	0.077	0.001	0.006
Ijuí	0.416	0.535	0.621	0510	0.643	0.695	0.109	0.033	0.010	0.044	0.007	0.003
Veranópolis	0.526	0.368	0.371	0.505	0.363	0.300	0.036	0.161	0.157	0.046	0.167	0.259
Aver. yield	0.484	0.659	0.702	0.529	0.695	0.741	0.056	0.005	0.002	0.033	0.004	0.001
Periods	Cycle		30 days		45 days		Cycle		30 days		45 days	
Main region	0.564		0.724		0.759		0.023		0.002		0.001	
State	0.541		0.690		0.724		0.031		0.003		0.002	

factors rather than the water availability to the crop (Figures 4, 5 and 6). It is reasonable to expect higher correlations between maize yields and rainfall amounts in dry seasons than in rainy conditions. Therefore, estimating models tend to be more precise as the water deficit increases, in particular during the critical periods of the crops.

High significance of adjusted functions, for flowering and grain filling, reflects the high efficiency of rainfall, during the critical period of maize crops, due to fewer losses of water by runoff or evaporation on the soil surface. In contrast, for the entire crop cycle the relationships are not close, which may represent high losses of water, in particular at the beginning of plant growth. The shape of the asymptotic functions for the critical period, by increasing and then tending to a plateau, shows saturation in the crop response as the water requirement is achieved. A similar trend was observed

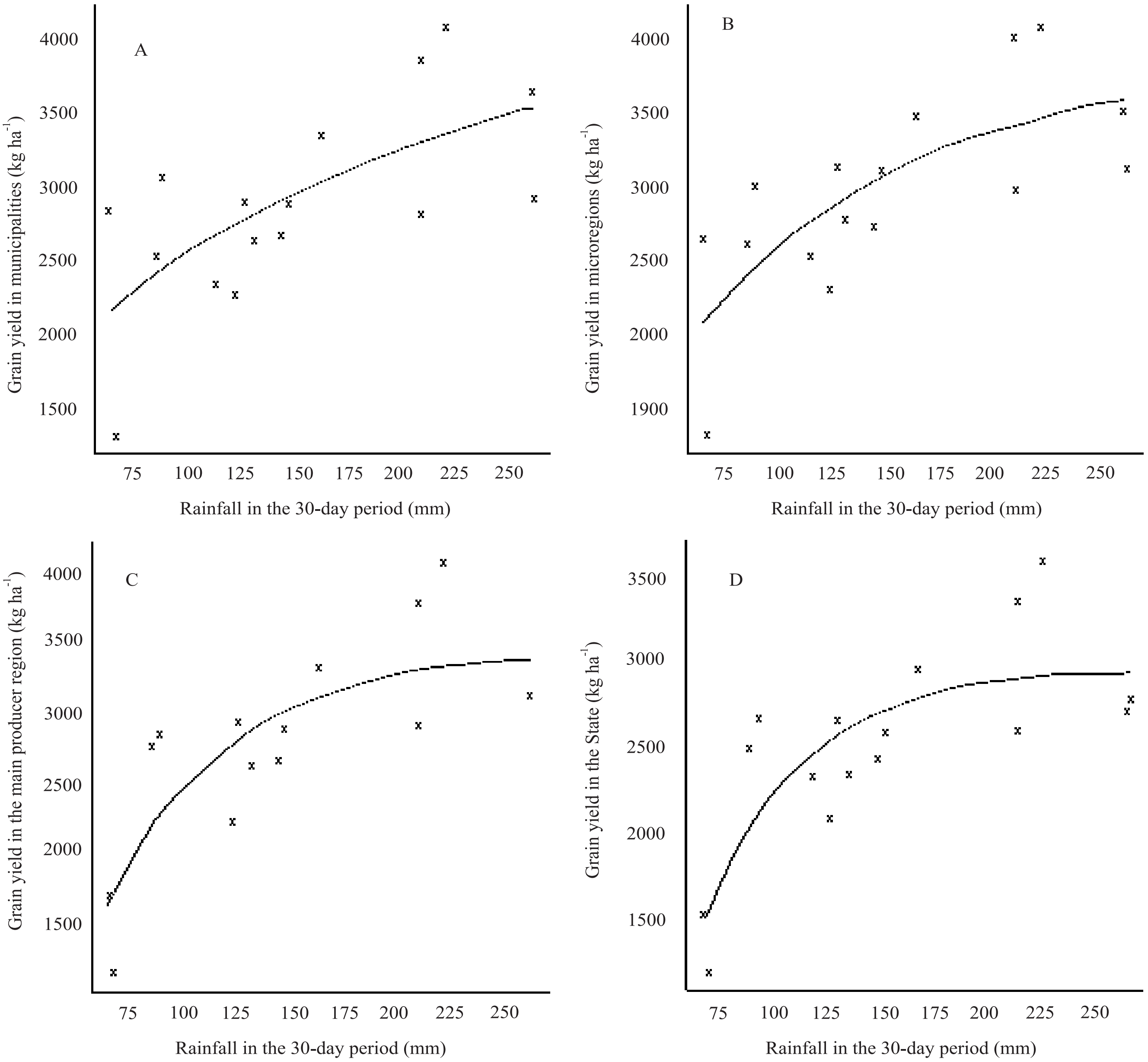

Figure 4. Relationships between the average 30-day period of rainfall from tasseling and maize yields (1990–2005) for the: A) 11 municipalities; B) 11 microregions; C) main producer region; and D) whole State.

by Bergonci et al. (2001) and Bergamaschi et al. (2006), who analysed the effect of irrigation and water deficit on maize yields in the field.

This set of results supports the modelling of maize crops on a large scale, in accordance to Challinor et al. (2003). High associations in the critical period suggest also the possibility to establish models for diagnosis of crops, or even yield, forecasting by using simply the rainfall of December and January. This may represent a promising aspect for crop monitoring in the region, since most of the maize crops are harvested in February and March.

According to the regression analyses between the annual yields and the rainfall, the highest significance occurred generally in the North and Northwest plateau of Rio Grande do Sul State (Table 2). Those areas

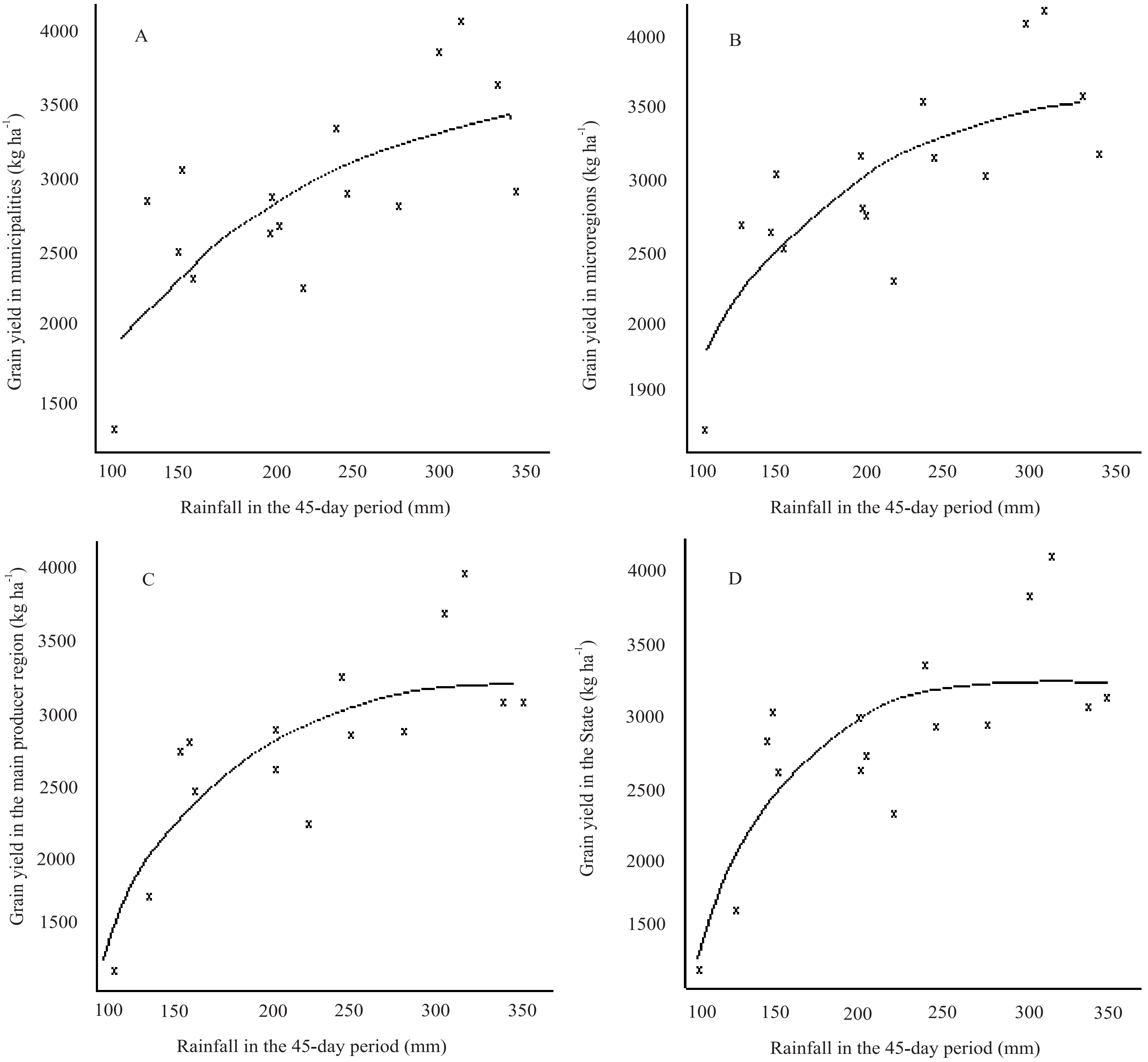

Figure 5. Relationships between the average 45-day period of rainfall from tasseling and maize yields (1990–2005) for the: A) 11 municipalities; B) 11 microregions; C) main producer region; and D) whole State.

comprise the Planalto Médio and Missões regions, where the pattern of climate, soil and topography is more homogeneous than in other municipalities and microregions. This should reduce the variability of yields and, hence, increase the precision of estimating crop yields on a municipal or regional scale. In addition, in the plateau of Planalto Médio and Missões, the farms and maize crops are of medium to large sizes and highly mechanised, so allowing high and uniform production. In contrast, in the other municipalities and microregions, in particular in the South and South eastern parts of the main producer region, soils and weather conditions tend to a high variability, because of the irregular relief. Farms and maize fields are mostly of small size, and the technological level is lower than in the plateau region. These factors may increase the variability of yield data in time and space, so reducing the precision in estimating grain yields on small scale.

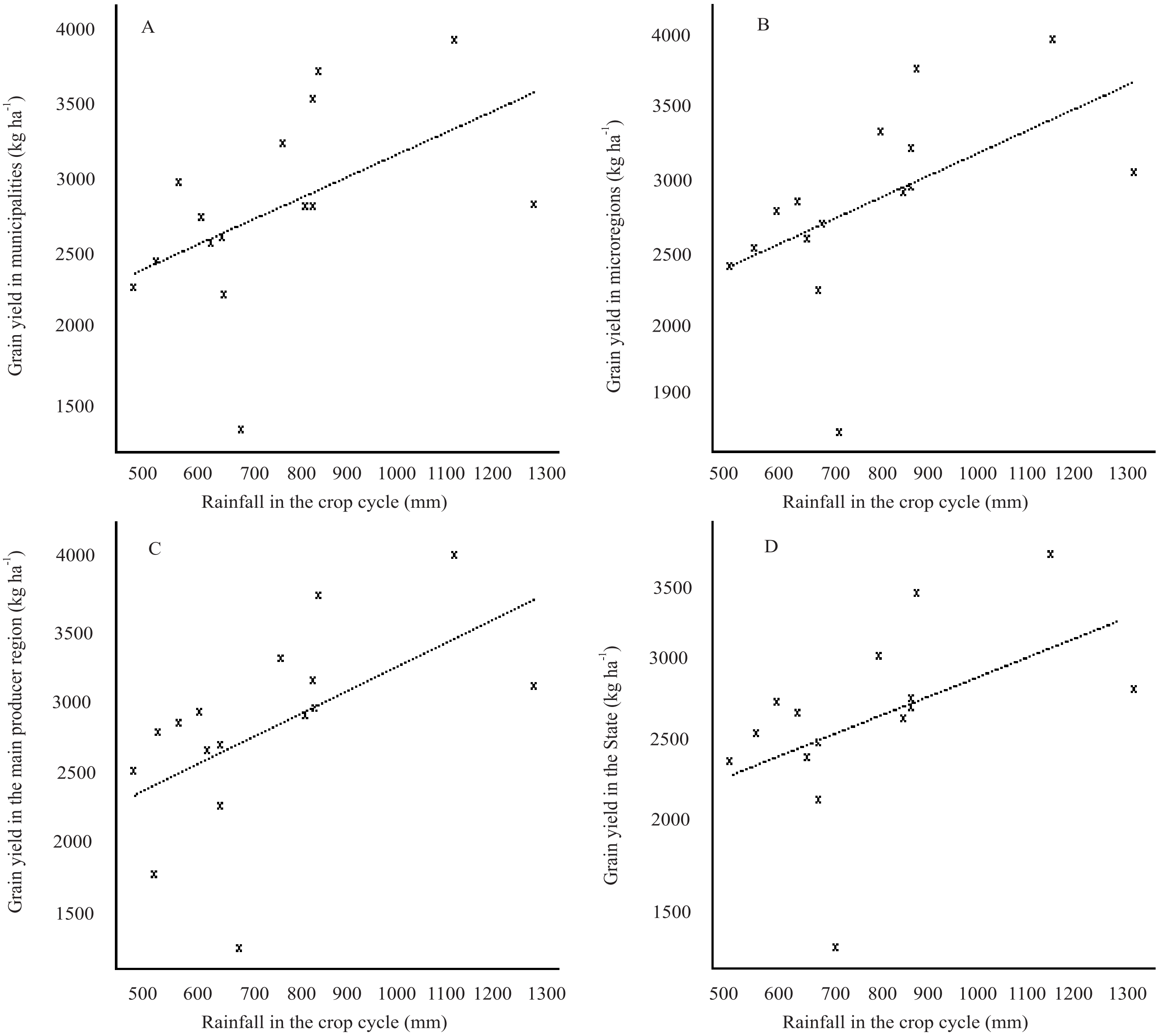

Figure 6. Relationships between the average rainfall in the crop cycle and maize yields (1990–2005) for the: A) 11 municipalities; B) 11 microregions; C) main producer region; and D) whole State.

Table 3. Parameters of asymptotic models of grain yield of maize (kg ha^{-1}), in 11 municipalities, 11 microregions, the main producer region, and the whole State, as function of average rainfall (mm) at the 11 sites, from 1990 to 2005, for the entire crop cycle, 30-days and 45-days in the reproductive period.

Spatial scale	Parameters						Significance probability F test
	A		B		C		
	Estimate	Std error	Estimate	Std error	Estimate	Std error	
			All crop cycle				
Municipalities	3,875	1,682	-4,167	4,740	0.99795	0.00398	0.138
Microregions	4,149	2,780	-3,865	2,141	0.99852	0.00347	0.101
Main region	4,426	3,485	-4,120	1,654	0.99866	0.00325	0.072
State	4,894	15,313	-3,479	13,199	0.99943	0.00401	0.191
			Period of 30 days				
Municipalities	3,625	575	-4,009	2,426	0.98760	0.01050	0.010
Microregions	3,428	366	-5,031	3,269	0.98416	0.00987	0.004
Main region	3,472	334	-5,841	3,516	0.98295	0.00922	0.001
State	3,003	277	-4,543	4,082	0.98130	0.01300	0.015
			Period of 45 days				
Municipalities	3,722	689	-5,148	3,157	0.99138	0.00702	0.005
Microregions	3,455	397	-6,733	4,651	0.98856	0.00670	0.002
Main region	3,407	298	-9,409	7,498	0.98559	0.00729	<0.001
State	2,894	188	-12,814	14,968	0.98010	0.01030	0.007

Conclusions

1. The variability of annual maize yields is closely related to the rainfall amount in Rio Grande do Sul State.
2. Relationships between maize yield and rainfall are closer for rainfall in the reproductive period than for rainfall in the entire crop cycle.
3. Relationships between maize yield and rainfall are closer on a regional scale than on a municipality level.
4. The impact of variability of rainfall on maize yield, during short critical periods of crop cycle, can be detected even at large scales of aggregation such as region or State.

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