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Stefanía Dalmolin da Silva

SIMULAÇÃO DO CRESCIMENTO, DESENVOLVIMENTO E PRODUTIVIDADE DE MILHO EM CLIMA PRESENTE E FUTURO

Santa Maria, RS
2018

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Tese apresentada ao curso de Pós-Graduação em Engenharia Agrícola da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do título de **Doutor em Engenharia Agrícola.**

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Nereu Augusto Streck

Nereu Augusto Streck, Dr. (UFSM)
(Presidente/Orientador)

Simone Ferraz

Simone Erotildes Teleginski Ferraz, Dra. (UFSM)

Alencar Junior Zanon

Alencar Junior Zanon, Dr. (UFSM)

Cleber Maus Alberto, Dr. (UNIPAMPA)

Diogo A Arsego

Diogo Alessandro Arsego, Dr. (CPTEC)

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RESUMO

SIMULAÇÃO DO CRESCIMENTO, DESENVOLVIMENTO E PRODUTIVIDADE DE MILHO EM CLIMA PRESENTE E FUTURO

AUTORA: Stefanía Dalmolin da Silva
ORIENTADOR: Nereu Augusto Streck

O milho é uma das principais culturas de verão ao redor do mundo e este grão desempenha um papel importante na sustentabilidade e segurança alimentar da população mundial. A modelagem agrícola é uma importante ferramenta no planejamento das atividades agrícolas. Dos modelos de milhos existentes, os modelos CSM-Ceres-Maize e Hybrid-Maize, são modelos de milho baseados em processos, de fácil utilização, que são capazes de simular o crescimento, o desenvolvimento e produtividade de milho. Os objetivos desta tese foram (a) comparar diferentes métodos de estimativa de parâmetros genéticos do modelo CSM-Ceres-Maize, (b) comparar a capacidade dos modelos CSM-Ceres-Maize e Hybrid-Maize em simular o crescimento, o desenvolvimento e produtividade de milho com diferente variabilidade genética em ambiente subtropical e (c) simular a produtividade de milho no Estado do Rio Grande do Sul em cenários futuros de mudança climática utilizando o modelo Hybrid-Maize. Para a realização da calibração dos modelos, foram realizados experimentos a campo durante os anos agrícolas 2013/14 e 2014/15, e para o teste destes modelos, foram coletados dados em experimento a campo nos anos 2015/16 e 2017/18. Foram utilizadas duas cultivares melhoradas de milho, uma variedade de polinização aberta ‘BRS Planalto’ e um híbrido simples ‘AS 1573PRO’, e duas cultivares crioulas de milho ‘Bico de Ouro’ e ‘Cinquentinha’. Para simular a produtividade de milho com diferente variabilidade genética diante a cenários climáticos futuros, foram utilizados os cenários RCP 2.6, RCP 4.5 e RCP 8.5 do quinto relatório do IPCC, utilizando o modelo Hybrid-Maize. As simulações mostraram diminuição da produtividade na metade norte do estado, e, até 5,5 Mg ha^{-1}, enquanto que na metade sul mostraram um aumento na produtividade de milho no período de 2070-2098 em relação ao período de 1975-2005.

Palavras-chanve: *Zea Mays* L., CSM-Ceres-Maize, Hybrid-Maize, cenários climáticos futuros, cultivares crioulas

ABSTRACT

SIMULATING GROWTH, DEVELOPMENT AND YIELD OF MAIZE UNDER CURRENT AND FUTURE CLIMATE

AUTHOR: Stefanía Dalmolin da Silva
ADVISOR: Nereu Augusto Streck

Corn is one of the most important summer crops around the world and this grain plays an important role in the sustainability and food security of the world's population. Agricultural modeling is an important tool in planning agricultural activities. Of the existing maize models, the CSM-Ceres-Maize and Hybrid-Maize models are easy-to-use process-based models that can simulate maize growth, development and yield. The objectives of this dissertation were (a) to compare different methods of estimating genetic parameters in the CSM-Ceres-Maize model, (b) to compare the capacity of the CSM-Ceres-Maize and Hybrid-Maize models to simulate growth, development and productivity of maize with different genetic variability in a subtropical environment and (c) to simulate maize productivity in the Rio Grande do Sul State under future climate change scenarios using the Hybrid-Maize model. For the calibration of the models, field experiments were carried out during the 2013/14 and 2014/15 growing seasons, and for the evaluation of these models, data were collected in field experiment in the 2015/16 and 2017/18 growing seasons. Two improved maize cultivars, one of open pollination variety 'BRS Planalto' and one simple hybrid 'AS 1573PRO', and two 'Bico de Ouro' and 'Cinquentinha' were used. To simulate maize yields with different genetic variability in relation to future climatic scenarios, the scenarios RCP 2.6, RCP 4.5 and RCP 8.5 of the fifth IPCC report using the Hybrid-Maize model, were used. Simulations showed a decrease in maize yield in the northern half of the state, and up to 5.5 Mg ha^{-1}, while in the southern half showed an increase in maize productivity in the period 2070-2098 in relation to the period 1975-2005.

Key words: *Zea Mays* L., CSM-Ceres-Maize, Hybrid-Maize, future climate scenarios, landrace cultivars.

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O Rio Grande do Sul (RS) é um Estado da Federação com economia fortemente baseada no Agronegócio. O milho é uma das três principais culturas agrícolas de verão, sendo o Brasil o terceiro maior produtor mundial e o estado do Rio Grande do Sul o segundo maior produtor da região sul do país (CONAB, 2018). A agricultura familiar ocupa um importante espaço no agronegócio, pois compõem a base da alimentação da população mundial e, principalmente, em países em desenvolvimento como, México, países do continente Africano e o Brasil (MDA, 2012). Em vários destes países em desenvolvimento são utilizadas cultivares crioulas de milho, pois apresentam alta variabilidade genética e rusticidade, além de proporcionar ao agricultor produzir sua própria semente, reduzindo custos a cada nova semeadura (PATERNIANI et al., 2000).

A modelagem agrícola é uma ferramenta que possibilita simular o crescimento, o desenvolvimento e a produtividade de culturas diante de diferentes condições meteorológicas e de manejo (O'NEAL et al., 2002; STRECK et al., 2003,a,b; BERGAMASCHI et al., 2013). Por isso, os modelos agrícolas vêm sendo cada vez mais usados na pesquisa, na academia, na extensão rural e por consultores e empresas ligadas ao agronegócio.

Entre os modelos de milho, o CSM-Ceres-Maize (JONES; KINIRY, 1986) e o Hybrid-Maize (Yang et al., 2004) são modelos ecofisiológicos baseados em processos já bem consolidados na literatura. Esses modelos são capazes de simular o crescimento, o desenvolvimento e a produtividade da cultura do milho, assim como sua resposta a variabilidade climática e a resposta a mudança climática (SOUTHWORTH et al., 2000; TUBIELLO et al., 2002; ADVIENTO-BORBE et al., 2007; MEZA; SILVA, 2009; BASSU et al., 2011) e vem sendo utilizados no estudo da previsão de safra (SHIN et al., 2006; YANG et al., 2006).

Estudos sobre mudança climática vêm sendo realizados ao redor do mundo, e o IPCC reúne os resultados destes estudos (IPCC, 2013). Há previsões de que até o final do século a temperatura média do ar aumente entre 0,3 a 4,8°C e a concentração de CO_2 aumente entre 420 a 918 ppm, dependendo do cenário (IPCC, 2013). Países em desenvolvimento como México, em países da África e o Brasil estão entre as regiões condicionadas a sofrer riscos devido a mudança climática (IPCC, 2013). Ao mesmo tempo, há a projeção de que até 2050 a população mundial atinja a faixa de 9 bilhões de habitantes, comprometendo a segurança alimentar da humanidade nas décadas seguintes, principalmente em países em desenvolvimento e na África. (FAO, 2012). Nestes locais, o milho desenvolve um importante papel na sustentabilidade e segurança alimentar da população. Deste modo, com a confirmação de que ocorra aquecimento global até o final do século, é importante estudar e entender a resposta de cultivares de milho à mudança climática.

2 REVISÃO BIBLIOGRÁFICA

2.1 A CULTURA DO MILHO

O milho (*Zea mays* L.) é originário do México e da Guatemala, onde o registro mais antigo deste cereal data de 8000 anos, e ao passar dos anos foi se difundindo ao redor do mundo, sendo cultivado em diferentes regiões e clima (CIB, 2006). Por apresentar uma alta adaptabilidade representada pela vasta variabilidade genética, permite-se o seu cultivo desde o Equador até regiões temperadas, desde o nível do mar até altitudes superiores a 3600 metros, abrangendo diferentes limites de temperatura e precipitação, desde um clima tropical, subtropical e temperado (CORRAL et al., 2008). O milho pertence à família das Poaceae, sendo um cereal de importante qualidade nutricional devido a presença de carboidratos, proteínas e lipídios (PAES, 2006).

É o terceiro cereal mais cultivado e de importância socioeconômica no mundo devido a sua versatilidade no uso, abrangendo a alimentação humana e animal, assim como na indústria tecnológica, a partir da fabricação de etanol. O maior produtor de milho é os Estados Unidos, onde na safra 2017/2018 foram colhidos aproximadamente 362 milhões de toneladas (USDA, 2018). O Brasil se encontra na terceira posição do ranking mundial na produção deste grão, e na safra 2016/17 teve produtividade de aproximadamente 5,5 toneladas por hectare em uma área plantada de 17 milhões de hectares (CONAB, 2018). A nível nacional, a região Centro-Oeste é a maior produtora do grão, seguido pela Região Sul. Na Região Sul, o Rio Grande do Sul (RS) é o segundo maior produtor de milho, sendo que na safra 2016/17 teve uma produtividade de 7,5 toneladas por hectare em uma área plantada de aproximadamente 804 mil hectares (CONAB, 2017).

No Brasil, cerca de 84,0% dos estabelecimentos rurais são de agricultores familiares, e ocupam uma área de 80,25 milhões de hectares totalizando 24,3% da área total destinada à agricultura no país (FAO, 2012). Segundo o Censo Agropecuário de 2006, este setor é responsável pela geração de 38% do valor bruto da produção agrícola do país, e destaca-se pela agricultura familiar ser a principal fornecedora de alimentos básicos para a população brasileira. Os alimentos produzidos pela agricultura familiar correspondem cerca de 70% da produção nacional, ou seja, são essenciais para a sustentabilidade e segurança alimentar do país (MDA, 2009). Dentre os alimentos cultivados pela agricultura familiar, o milho se destaca por ser o terceiro mais produzido, sendo a agricultura familiar responsável por 46% da produção deste cereal.

Com relação aos grupos genéticos de milho, atualmente, a maior parte das lavouras de milho no RS e Brasil são cultivadas com cultivares híbridas tolerantes ao glifosato (tecnologia RR) e Spodoptera frugiperda (tecnologia Bt). Como são cultivares híbridas, a cada nova semeadura é necessário que os agricultores comprem novas sementes, e sendo cultivares transgênicas, o custo da semente é alto. Uma maneira para agricultores familiares contornarem o alto custo de sementes de milho é com o uso das cultivares crioulas de milho, que são variedades do tipo polinização aberta (VPA).

As cultivares crioulas de milho podem desempenhar um papel socioeconômico importante na agricultura familiar no Brasil. As cultivares de milho utilizadas por comunidades familiares rurais podem ser classificadas de várias formas: cultivar local, cultivar tradicional e cultivar crioula. Uma cultivar local é assim denominada quando, em um período de pelo menos cinco anos, aquela população é manejada por agricultores com ciclos de cultivos e de seleção. Uma cultivar tradicional é assim chamada quando, por pelo menos três gerações familiares, a cultivar é manejada em um mesmo local. A terminologia cultivares crioulas é utilizada por países de língua espanhola para denominar cultivares tradicionais (MACHADO et al., 2011; BERG, 2009).

A utilização de cultivares crioulas de milho pelos agricultores familiares se destaca por apresentarem grande variabilidade genética e alta rusticidade, sendo bastante resistentes a fatores bióticos e abióticos, permitindo que o agricultor realize o seu cultivo com baixo nível tecnológico e mesmo assim obtenha produtividade rentável (PATERNIANI; NASS, 2000; ARAÚJO; NASS, 2002; SANDRI; TOFANELLI, 2008). Mesmo não produzindo no mesmo nível que um híbrido, outra vantagem para o agricultor é a possibilidade de produzir sua própria semente, reduzindo significativamente o custo a cada nova semeadura (MACHADO et al., 2011). Além disso, essas cultivares desempenham um papel socioeconômico devido a riqueza do patrimônio genético e na preservação da biodiversidade na agroecologia, sendo uma estratégia de segurança nacional.

2.2 MODELOS AGRÍCOLAS

Modelos agrícolas são um conjunto de equações matemáticas que descrevem os diferentes processos das plantas, e nos últimos anos se tornaram indispensáveis nas diversas áreas, dando suporte para a pesquisa científica, para tomadas de decisões de agricultores e análises econômicas. Estes modelos, quando bem calibrados e testados para as condições de estudo, são ferramentas que podem auxiliar no manejo das culturas (STRECK et al., 2003,a,b), como a escolha da melhor data de semeadura, em programas de melhoramento genético (BANTERNG, 2006) e em estudos para avaliar a respostas de agroecossistemas diante de cenários de mudança climática (STRECK et al., 2006a; LAGO et al., 2008; WALTER et al., 2010a,b; FAGUNDES et al., 2010b; STRECK et al., 2011).

Modelos agrícolas que simulam o crescimento, desenvolvimento e produtividade têm sido propostos para várias culturas, incluindo o milho (LIU et al., 2011; KIM et al., 2012; BERGAMASCHI et al., 2013). Dentre os modelos de milho, os modelos CSM-Ceres-Maize e o modelo Hybrid-Maize são modelos ecofisiológicos baseados em processos utilizados mundialmente (JONES; KINIRY, 1986; YANG et al., 2004).

2.3 O MODELO CSM-CERES-MAIZE

O modelo CSM (Cropping System Models)-Ceres (Crop–Environment–Resource–Synthesis)-Maize foi desenvolvido pelo Departamento de Agricultura dos Estados Unidos - Serviço de Pesquisa Agrícola (USDA-ARS), Crop Systems Evaluation Unit, localizado em Grassland, Laboratório de Pesquisa de solo e água e colaboradores. É um modelo ecofisiológico dinâmico, determinístico, baseado em processos (Process-based model) bastante usado mundialmente (CARBERRY et al., 1989; ASADI; CLEMENTE, 2003; GEDANKEN et al., 2003). Com este modelo é possível simular o crescimento, desenvolvimento e produtividade da cultura do milho, considerando-se o efeito de cultivar, densidade de planta, clima, estresse hídrico e nutricional, efeito de pragas e doenças e eventos extremos do clima (JONES; KINIRY, 1986).

O modelo CSM-Ceres-Maize está disponível na plataforma DSSAT (Decision Support System for Agrotechnology Transfer), uma plataforma que hospeda 26 modelos de diferentes culturas agrícolas (JONES et al., 2003, HOOGENBOOM et al., 2012). O modelo necessita de *inputs* para realizar a simulação, como parâmetros agrícolas e parâmetros meteorológicos. Os parâmetros agrícolas necessários são informações sobre solo, irrigação e fertilização (os dois últimos podem estar na condição potencial), data de semeadura, densidade de plantas, profundidade de semeadura, etc. Os parâmetros meteorológicos necessários são temperatura máxima e mínima do ar diária (°C), radiação solar (Mj m-2 dia-1) e precipitação (mm).

Como qualquer modelo agrícola, no CSM-Ceres-Maize existem coeficientes genéticos que necessitam de calibração, para poder representar a genética de cada cultivar. Os coeficientes genéticos no CSM-Ceres-Maize estão apresentados na Tabela 1. Os coeficientes P1, P2, P5 e

PHINT são responsáveis por governar a fenologia, enquanto G2 e G3 governam a produtividade de grãos da cultura do milho no modelo.

Tabela 1 – Parâmetros genéticos específicos nos modelos CSM-Ceres-Maize e Hybrid-Maize.

Coeficiente	Descrição
P1	Graus-dia da emergência até o fim do estágio juvenil (Tb=8°C)
P2	Coeficiente de sensibilidade ao fotoperíodo
P5	Graus-dia do florescimento feminino até a maturidade fisiológica (Tb=8°C)
G2	Número potencial de grãos por planta
G3	Taxa potencial de enchimento de grãos (mg grão-1 dia-1)
PHINT	Filocrono (°C dia)

2.4 O MODELO HYBRID-MAIZE

O modelo Hybrid-Maize foi desenvolvido a partir da combinação de abordagens de três modelos, o Ceres-Maize, o WOFOST e o INTERCOM. Ele considera a parte de crescimento e desenvolvimento representados pelo Ceres-Maize., e mecanismos dos processos de fotossíntese e respiração do WOFOST e INTERCOM. WOFOST e INTERCOM são modelos mais genéricos que descrevem os processos da planta sem considerar uma cultura específica, abordando a mesma metodologia para diferentes tipos de culturas agrícolas (YANG et al., 2004). Já modelos mais complexos, como o Ceres-Maize, são capazes de simular o crescimento e desenvolvimento de uma cultura agrícola específica (JONES; KINIRY, 1986). Porém, com mais de 15 anos de pesquisa e diferentes abordagens de uso do modelo Ceres-Maize, foi relatado que o modelo Ceres-Maize não era capaz de simular a produtividade potencial. Desta forma, o modelo Hybrid-Maize foi desenvolvido com o principal objetivo ter um modelo que simule, principalmente, a produtividade potencial de milho (YANG et al., 2004).

Os dados de entrada meteorológicos necessários são a radiação solar, temperatura máxima e mínima do ar, umidade relativa (%), precipitação (mm) e evapotranspiração potencial (mm), todos em um passo de tempo diário. Os dados de entrada agrícolas são data de semeadura, genótipo e informações de solo. O modelo pode ser rodado na condição potencial ou com restrição hídrica.

Os coeficientes necessários para a calibração são os graus-dias até o florescimento e do ciclo total, assim como G2 e G3 (Tabela 1).

2.5 MUDANÇA CLIMÁTICA

Em 2013 um novo relatório do IPCC foi publicado, IPCC- AR5, que reúne resultado de estudos sobre a projeção do clima até o final do século (IPCC, 2013). Segundo este relatório, a temperatura média da superfície global teve um aumento de 0,85°C (0,65 a 1,06°C) no período de 1880 a 2012, e o maior aumento ocorreu entre 1967 e 2000, sendo que a década de 1990 foi a mais quente do último milênio (KERR, 2005; IPCC, 2013). Vale ressaltar que o aumento da temperatura máxima e mínima foi observado por ser assimétrico, ou seja, com a temperatura mínima aumentando a uma taxa maior que a máxima. Marengo; Camargo (2008) analisaram a tendência da temperatura do ar no Sul do Brasil no período de 1960 a 2002 e constataram que há um aumento na temperatura mínima maior que na temperatura máxima durante os meses de verão e inverno. Sansigolo; Kayano (2010) analisando a tendência da temperatura do ar em um período maior, de 1913 a 2006, no Sul do Brasil, observaram que a temperatura mínima do ar aumentou a uma taxa de 1,7^{o}C/100 ano.

Com relação às projeções até o final deste século, no último relatório do IPCC, as projeções de clima apontam para aumentos de 1,1 a 4,8°C na temperatura média do ar em vários locais do Planeta, incluindo o Brasil, dependendo do cenário (IPCC, 2013). As projeções para outros elementos climáticos como a precipitação, nebulosidade, radiação solar e evaporação apresentam tendências variáveis em função da escala, seja regional ou global (HULME et al., 1994; THOMAS, 2000; IPCC, 2013).

Além da projeção para esses elementos meteorológicos, também há evidências de aumento da concentração de CO_2 e outros gases do efeito estufa (WEISS et al., 2003; KERR, 2005; IPCC, 2013). Em 2011, as concentrações atmosféricas dos gases do efeito estufa como o Dióxido de Carbono (CO_2), Metano (CH_4) e Óxido Nitroso (N_2O) eram 391ppm, 1803ppb e 324ppb, respectivamente, e estas concentrações vem aumentando desde o início da Revolução Industrial, com aumento de 40% da concentração de CO2. As projeções até o final do século para aumento da concentração de CO_2 atmosférico variam de 420 a 918 ppm, dependendo do cenário (IPCC, 2013).

2.6 MUDANÇA CLIMÁTICA E SEU EFEITO NA CULTURA DO MILHO

Estudos numéricos onde o objetivo é entender a resposta da cultura do milho à mudança climática têm sido desenvolvidos ao redor do mundo. Delécolle et al. (1995) estudaram os possíveis efeitos das modificações climáticas induzido pelo aumento dos gases traços na atmosfera, em trigo e milho, na França. Utilizaram os modelos da família Ceres (Ceres-Wheat e Ceres-Maize) e os cenários climáticos foram gerados por modelos globais de clima. Entre os resultados, houve encurtamento do ciclo de desenvolvimento, diminuição da produtividade devido ao aumento da concentração de CO_2 e aumento de 5ºC na temperatura do ar.

Iglesias e Mínguez. (1995) estudaram a prospectiva da produtividade de milho na Espanha diante à mudança climática. Utilizaram cenários climáticos gerados por modelos globais de clima e o modelo CSM-Ceres-Maize. Constataram que com o aumento da temperatura há um encurtamento do ciclo de desenvolvimento e uma diminuição da produtividade, e que também algumas regiões da Espanha possam deixar de produzir milho.

No estudo de Conde et al. (1997) foram analisados os impactos potenciais na cultura do milho no México. Criaram duas séries de dados climáticos, uma com aumento de temperatura do ar de +2°C e outro com +4°C combinados com mudança na precipitação (±20%) e combinados com o dobro da concentração de CO_2. Concluíram que ambos os cenários causam impacto na cultura do milho para o local em estudo (ocorrência de seca ou enchentes).

Southworth et al. (2000) estudaram os impactos da mudança climática para três híbridos em 10 áreas agrícolas no meio-oeste dos Estados Unidos. Utilizaram o modelo Ceres-Maize como ferramenta e para os cenários climáticos futuros utilizaram o modelo 'HadCM2' desenvolvido na Inglaterra. Constataram que maiores impactos na produtividade foram observados para milhos de ciclo tardio, seguido de milhos de ciclo intermediário e precoce.

Chipanshi et al. (2003) analisaram a sensibilidade das culturas de milho e sorgo ao aquecimento global, em Botswana. A resposta destas duas culturas à mudança climática foi realizada por meio de modelos de simulação agrícola, sendo os cenários de mudanças climáticas sendo gerados a partir de Modelos de Circulação Global. Como resultados gerais encontram-se redução no rendimento do milho entre 10 e 36% e em sorgo entre 10 e 31%. Outro impacto encontrado foi no encurtamento do ciclo de 3 a 5 dias para milho e 4 a 8 dias para sorgo.

Streck e Alberto (2006) realizaram um estudo numérico avaliando o impacto da mudança climática sobre o rendimento de trigo, soja e milho para Santa Maria, RS. Os cenários utilizados foram com o dobro de aumento da concentração de CO_2 atmosférico, com diferentes aumentos da temperatura do ar e precipitação. Concluíram que a mudança climática influenciará no rendimento destas três culturas e que o aumento da temperatura do ar pode anular as vantagens do efeito de CO_2 para as culturas de milho, trigo e soja.

Minuzzi e Lopes (2015) estudaram o desempenho agronômico da 1ª e 2ª safra de milho no Centro-Oeste do Brasil, utilizando o cenário climático RCP 4.5 do IPCC. Constataram que a produtividade e o requerimento de irrigação do milho safrinha tendem a diminuir quanto maior for a redução na duração do ciclo da cultura, e que a primeira safra não teria estresse hídrico, mas haveria redução no seu ciclo.

Quanto ao estudo da mudança climática e a adaptabilidade de cultivares crioulas de milho, Hellin et al. (2014) mostram que pequenos agricultores localizados no México estarão mais vulneráveis aos impactos das mudanças climáticas. Além disso, abordam a importância dessas cultivares nestas propriedades familiares, que não aceitam a utilização de cultivares melhoradas, pois as cultivares crioulas de milho tem um papel muito maior que apenas a produção, destacando sua importância cultural e na culinária. Também ressaltam o importante papel que as cultivares crioulas representam em um ambiente de mudança climática, já que são cultivadas em condição de sequeiro e em todos locais espalhados no México. Existem mais de 41 raças de milho crioulo cultivadas no México, cultivadas desde regiões de altitude variando de 0 a 2900m, temperatura média anual variando de 11,3 a 26,6ºC e precipitação anual variando de 426 a 4245mm, mostrando que os agricultores tem um acesso a uma gama de diversidade nessas raças locais, que se tornam importantes para mitigar os impactos negativos das alterações climáticas nos seus meios de subsistência. Os autores também comentam que uma estratégia de adaptação seria melhorar as cultivares crioulas a partir do melhoramento genético.

3 OBJETIVO GERAL

Contribuir para o entendimento dos impactos da mudança climática sobre a cultura do milho no Rio Grande do Sul.

4 OBJETIVOS ESPECÍFICOS

Calibrar os modelos CSM-Ceres-Maize e Hybrid-Maize para cultivares com variabilidade genética.

Simular a produtividade potencial e com limitação por água para cultivares de milho com variabilidade genética no Estado do Rio Grande do Sul em cenários atual e futuros do IPCC com os modelos CSM-Ceres-Maize e Hybrid-Maize.

5 ARTIGO 1

A COMPARISON OF METHODS FOR ESTIMATING GENETIC PARAMETERS OF MAIZE CULTIVARS IN THE CSM-CERES-MAIZE MODEL

(Artigo Submetido para publicação na Revista Ciência Rural)

A Comparison of methods for estimating genetic parameters of maize cultivars in the CSM-Ceres-Maize model

Comparação de métodos de estimativa de parâmetros genéticos de cultivares de milho no modelo CSM-Ceres-Maize

Stefanía Dalmolin da Silva[I*] Nereu Augusto Streck[II], Josana Andreia Langner[II], Anderson Haas Poersch[II]

ABSTRACT

Crop models are useful tools and have been used in the last years to help decision makers and farmers to make the best decisions to achieve good production, as selecting the best sowing date and the best time to applicate fertilizers and also in irrigation management. For maize, the CSM-Ceres-Maize model is used worldwide and can simulate the development, growth and productivity of maize. The genetic parameters in the model must be calibrated and validated so the model can be as near the reality as possible. In the DSSAT platform, users can choose from two methods to calibrate the genetic parameters, Gencalc and GLUE, and also, the cross-validation is another method used to calibrate crop models. The objective of this study was to compare three calibration methods in CSM-Ceres-Maize model for maize cultivars with different genetic variability and select the best method. To calibrate the model, field experiments were conducted through the 2013/14 and 2014/15 growing seasons. To evaluate the model, two experiments was taken in the 2015/16 growing season, Experiment 1 with irrigated and rainfed treatments and Experiment 2 varying the row spacing among cultivars. In both experiments, the cross-validation was the method with the best performance in simulating development, growth and yield of the four maize cultivars used in this study.

Key words: calibration methods, crop models, DSSAT

RESUMO

Os modelos agrícolas são uma ferramenta útil e tem sido utilizada nos últimos anos para ajudar tomadores de decisão e agricultores a alcançarem boas produções, como selecionando a melhor data de semeadura, melhor época de aplicação de fertilizantes e, também, no manejo da irrigação. Para o milho, o modelo CSM-Ceres-Maize é utilizado em todo o mundo e é capaz de simular o desenvolvimento, crescimento e produtividade do milho. Os parâmetros genéticos no modelo devem ser calibrados e validados para que o modelo possa ser tão próximo quanto a realidade. Na plataforma DSSAT, os usuários podem escolher entre dois métodos para calibrar os parâmetros genéticos, Gencalc e GLUE, e também, a validação cruzada é outro método utilizado para calibrar os modelos agrícolas. O objetivo deste estudo foi comparar três métodos de calibração para cultivares de milho com diferente variabilidade genética e selecionar o melhor método. Para calibrar o modelo, foram conduzidos experimentos de campo nas safras 2013/14 e 2014/15. Para avaliar o modelo, foram realizados dois experimentos na safra 2015/16, Experimento 1 com tratamentos irrigado e não irrigado, e Experimento 2 variando o espaçamento entre cultivares. Em ambos os experimentos, a validação cruzada foi o método com melhor desempenho na simulação do desenvolvimento, crescimento e produtividade das quatro cultivares utilizadas neste estudo.

Palavras-chave: métodos de calibração, modelos agrícolas, DSSAT

INTRODUCTION

In the last years, crop models have been used for many different purposes. Decision makers and farmers can use crop models to assess field operations such as the best sowing time and the timing of crop management practices in order to optimize crop production. Crop models have also been used for yield forecasting (SHIN et al., 2009) and for assessing the impact of climate change on crops (SOUTHWORTH et al., 2000).

The Ceres-Maize model is a dynamic process-based model widely used in many countries, including Brazil (MONTEIRO et al., 2017), that can simulate the growth, development and yield of maize. This model is available in the DSSAT (Decision Support System for Agrotechnology Research) platform, that hosts other 25 different crop models (JONES et al., 2003). The CSM-Ceres-Maize model simulates growth and development in a daily basis time and allows to analyze the effect of management factors, such as water and fertilizer, the effect of soil and environment (JONES & KINIRY, 1986). The inputs necessary to run the model are divided into weather inputs (solar radiation, maximum and minimum air temperature and rainfall), soil input, cultivar and crop management (plant population, planting date, water and fertilizer applications).

In order to represent the field reality, crop models have genetic specific coefficients, that describes the environment x genotype interaction, and these genetic parameters must be calibrated and validated. The CSM-Ceres-Maize model has six genetic coefficients associated with development and growth: P1 is the thermal time from emergence to the end of the juvenile phase, P2 is a photoperiod sensitivity coefficient, P5 represents the thermal time from silking to physiological maturity, G2 is the maximum possible number of kernels per plant, G3 is the kernel filling rate during the linear grain filling stage and under optimum conditions and PHINT is the phylocron (JONES et al., 2003).

The calibration of these coefficients can be done with different methods. In the DSSAT platform there are two optimizations which users can estimate the best combination of the six genetic coefficients, called GLUE and Gencalc. Another calibration approach widely used is the cross-validation method, because this method is a better option when the data for calibration and validation is small (FENSTERSEIFER et al., 2017).

The objective of this study was to compare three calibration methods in CSM-Ceres-Maize model, GLUE, Gencalc and Cross-validation for maize cultivars with different genetic variability and select the best method.

MATERIAL AND METHODS

A field experiment was conducted during two growing seasons (2013/14 and 2014/2015) in Santa Maria, RS, Brazil (29°43‟S, 53°43‟W, and 95m altitude). Soil tillage was performed with plowing and disking. Soil acidity was corrected with limestone to reach a pH of 6.0. Fertilizer was applied at sowing with NPK 5-20-20 based on soil test at a rate of 750 kg ha-1 (30 kg of N, 105 kg of P2O5 and 150 kg of K2O) and nitrogen was side-dressed based on an expected yield of 8.0 Mg ha-1 with ureia at the V4 and V8 stages, totaling 239.1 kg of N as a side dressing. Supplementary irrigation was performed by a drip irrigation system to prevent water stress (no-water limiting conditions).

In each growing season had three sowing dates, 08/20/2013, 11/04/2013 and 02/03/2014 for the 2013/14 growing season and, 08/15/2014, 12/13/2014 and 01/07/2015 for the 2014/15 growing season. Four maize cultivars with different genetic variability were chosen. Two landrace maize cultivars, “Cinquentinha” (early maturity) and “Bico de Ouro” (late maturity), one open pollination variety “BRS Planalto” (early maturity) and a simple hybrid “AS 1573PRO” (early maturity).

The experiment was a two-factor in a randomized complete block design with four replications. Each replication was a 5.0x4.5 m plot with five rows. Plant spacing was 0.9 m among rows and 0.2 m among plants within rows (5.5 pl m^{-2}). In the landrace maize cultivars, a total of 45 plants per plot were tagged, and in the improved cultivars, 15 plants per plot were tagged. The following variables were evaluated on the tagged plants: tip leaf number (TLN) on a weekly basis, final leaf number (FLN) after tasseling (VT), emergence (EM) date, silking (R1) date, physiological maturity (R6) date and kernel yield components (number of ears per plant, number of kernels per ears and dry matter (g) of 100 kernels). The EM, R1 and R6 dates were considered when 50% of the tagged plants reached these developmental stages. Data collected in these experiments were used to calibrate and validate the Ceres-Maize model using the GLUE, Gencalc and cross-validation methods.

On the 2015/16 growing season, two field experiments were conducted to collect independent data to validate the calibration. In Experiment 1 the objective was to study the response of these cultivars under rainfed and irrigated conditions, and in Experiment 2 was conducted to evaluate the response of maize under different row spacing. In both experiments the experimental design was a randomized block with four replicates, and the plant population density used was 6.0 pl m^{-2}. The sowing date in Experiment 1 was on 10/23/2015, because this date is outside the agroclimatic zoning for maize, as there are risks of the critical period of maize to occur when there is water deficiency in the soil. In the Experiment 2 the sowing date was on 11/25/2015. Experiment 1 was composed of two treatments, one irrigated and one non-irrigated, and Experiment 2 was composed of three treatments, with row spacing of 0.5, 1.0 and 1.5m. The data collected in both experiments were: tip leaf number (TLN) on a weekly basis, final leaf number (FLN) after tasseling (VT), emergence (EM), silking (R1), physiological maturity (R6) dates and kernel yield components.

The evaluation of the performance of the CSM-Ceres-Maize model was with the statistics Root Mean Square Error (RMSE) (STRECK et al., 2008), Normalized RMSE (LOAGUE & GREEN, 1991), Pearson Correlation (WILLMOTT, 1981), and BIAS (WALLACH, 2006):

$$\mathrm{RMSE}=\left[\frac{\sum (s_i-O_i)^2}{n}\right]^{0.5} \qquad (1)$$

$$\mathrm{NRMSE}=\mathrm{RMSE}*\left(\frac{100}{\bar{O}}\right) \qquad (2)$$

$$\mathrm{BIAS}=\frac{\sum S_i-\sum O_i}{\sum O_i} \tag{3}$$

$$r=\frac{\sum(O_i-\bar{O})(S_i-S)}{\{[\sum(O_i-\bar{O}][\sum(S_i-S)^2]\}^{0.5}} \tag{4}$$

where S_i is the simulated values, S is the mean of the simulated values, O_i is the observed values, $\bar{O}$ is the mean of the simulated values, and n is the number of observations.

RESULTS AND DISCUSSION

In Table 1 are presented the calibrated parameters of the Ceres-Maize models for the four genotypes used in this study, using the three methods. Among methods, the value of P1 and P5 were similar through cultivars, with high value for the late maturity cultivar ‘Bico de Ouro’ and low value for the early maturity cultivars ‘AS 1573PRO’, ‘BRS Planalto’ and ‘Cinquentinha’ (Table 1). The estimated values of P2 were relatively small (0.0 – 0.34) in comparison with the results obtained by JONES & KINIRY. (1986) (P2 = 0.52) (Table 1). G2 was the same for all cultivars among methods, and G3 were higher for the improved maize cultivars ‘AS 1573PRO’ and ‘BRS Planalto’ (Table 1). PHINT varied from 41.29 to 51.92.

Evaluation of CSM-Ceres-Maize

Figure 1 shows the observed vs. simulated phenology for the Experiment 1. The RMSE between methods were similar, varying from 3.7 to 4.2 days (Figures 1A to 1F). Overall, all method overestimated the phenology (BIAS from 0.01 to 0.02), and other statistics showed that all three methods had a good performance in simulating the developmental stages (NRMSE varied from 5.4 to 6.2%; r varied between 0.996 and 0.997) (Figures 1A to 1F), with the cross-validation method that presented the best results between the methods (Figures 1A and 1B). In Experiment 2, all three methods had the same performance in simulating phenology, with a RMSE of 3 days (Figure 4A, 4B and 4C). Other statistics shown that the model could represent the development stage for the cultivars and treatments. These results are similar to studies reported by MUBEEN et al. (2016) (RMSE from 1.96 to 2.16 days).

For Experiment 1, the cross-validation and Gencalc method had the best performance in simulating FLN (Figure 2), with RMSE varying from 0.48 to 0.55, BIAS of -0.02, NRMSE from 2.2 to 2.5% (Figures 2A, 2B, 2E and 2F). For Experiment 2, the calibration with the cross-validation and Gencalc methods had better FLN estimative than the GLUE method (Figures 5D, 5E and 5F). The RMSE varied from 1 to 2.1 leaves and other statistics indicate that the three methods of calibration had good estimates of FLN (Figures 4D, 4E and 4F), with the cross-validation method had the best performance (Figure 4D).

Figures 3 and 4 show the observed vs. simulated for grain yield for Experiment 1 and 2. For Experiment 1, the RMSE varied from 0.36 to 1.9 Mg ha^{-2} (Figures 3A to 3F) between cultivars, treatments and methods, where cross-validation methods presented the smallest values (0.36 and 0.76 Mg ha^{-2}) (Figures 3A and 3B). Among all statistics, the cross-validation and GLUE methods shown the best performance. NRMSE varied from 4.7 to 27% (Figures 3A to 3F). Overall, the cross-validation was the methods with the best performance in simulating grain yield (Figures 3A and 3B). For Experiment 2, the method with the best performance in simulating grain yield was the cross-validation method, with an error of 0.7 Mg ha^{-1} (Figure 4G), followed by the Gencalc and GLUE. NRMSE varied from 8.7 to 22.3%, BIAS from -0.01 to -0.09, indicating that all method underestimated grain yield, and r varied from 0.864 to 0.916 (Figures 4G to 4I). These results are similar to the value of RMSE reported by FRAISSE et al. (2001) (RMSE=0.8 Mg ha^{-1}), XIE et al. (2001) (RMSE=0.83 Mg ha^{-1}), YANG et al. (2009) (RMSE=0.783 Mg ha^{-1}) and LANDRY & LOBELL. (2012) (NRMSE= 15 to 25%).

Crop models need constantly being revised and recalibrated because new cultivars are released every year. Field experiments set up to calibrate and validate models are usually costly and labor demanding. The cross-validation method is usually recommended when the number of experiments available for modelers is not high. In this study, this approach proved to be better than the two approached available in the DSSAT version of the CSM-Ceres-Maize model, indicating that calibration can be improved.

CONCLUSIONS

In both experiments, the cross-validation was the method with the best performance in simulating development, growth and yield of the four maize cultivars used in this study.

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Table 1 - Calibrated parameters for the optimization procedure of the Ceres-Maize for two maize landrace, “Cinquentinha” and “Bico de Ouro”, and two improved cultivars, an open pollination variety “BRS Planalto” and a transgenic simple hybrid “AS 1573PRO”.

	Genetic Coefficients					
Cultivar	P1	P2	P5	G2	G3	PHINT
Cross-validation Method						
‘Cinquentinha’	300.5	0.00	797.0	387.0	15.00	50.00
‘Bico de Ouro’	335.8	0.25	800.0	317.0	15.00	47.87
‘BRS Planalto’	301.5	0.07	700.0	515.0	17.00	48.11
‘AS 1573PRO’	323.1	0.10	723.7	575.0	21.00	50.69
Gencalc Method						
‘Cinquentinha’	302.5	0.24	809.4	251.4	11.96	51.92
‘Bico de Ouro’	335.8	0.25	785.6	251.7	13.38	47.87
‘BRS Planalto’	301.4	0.07	654.5	650.8	14.92	50.69
‘AS 1573PRO’	323.1	0.10	723.7	925.6	14.02	51.60
GLUE Method						
‘Cinquentinha’	303.5	0.33	809.4	251.4	11.96	41.29
‘Bico de Ouro’	338.0	0.34	785.6	251.7	13.38	49.20
‘BRS Planalto’	303.3	0.10	654.5	650.8	14.92	45.41
‘AS 1573PRO’	328.4	0.19	723.7	925.6	14.02	45.05

P1=Thermal time from seedling emergence to the end of the juvenile phase (°C day), P2=Extent to which development is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 hours) (day), P5=Thermal time from silking to physiological maturity (°C day), G2=Maximum possible number of kernels per plant (number), G3=Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day), PHINT=Phylocron interval; the interval in thermal time between successive leaf tip appearances (°C day), RUE=Radiation use efficiency (g plant dry matter/MJ PAR).

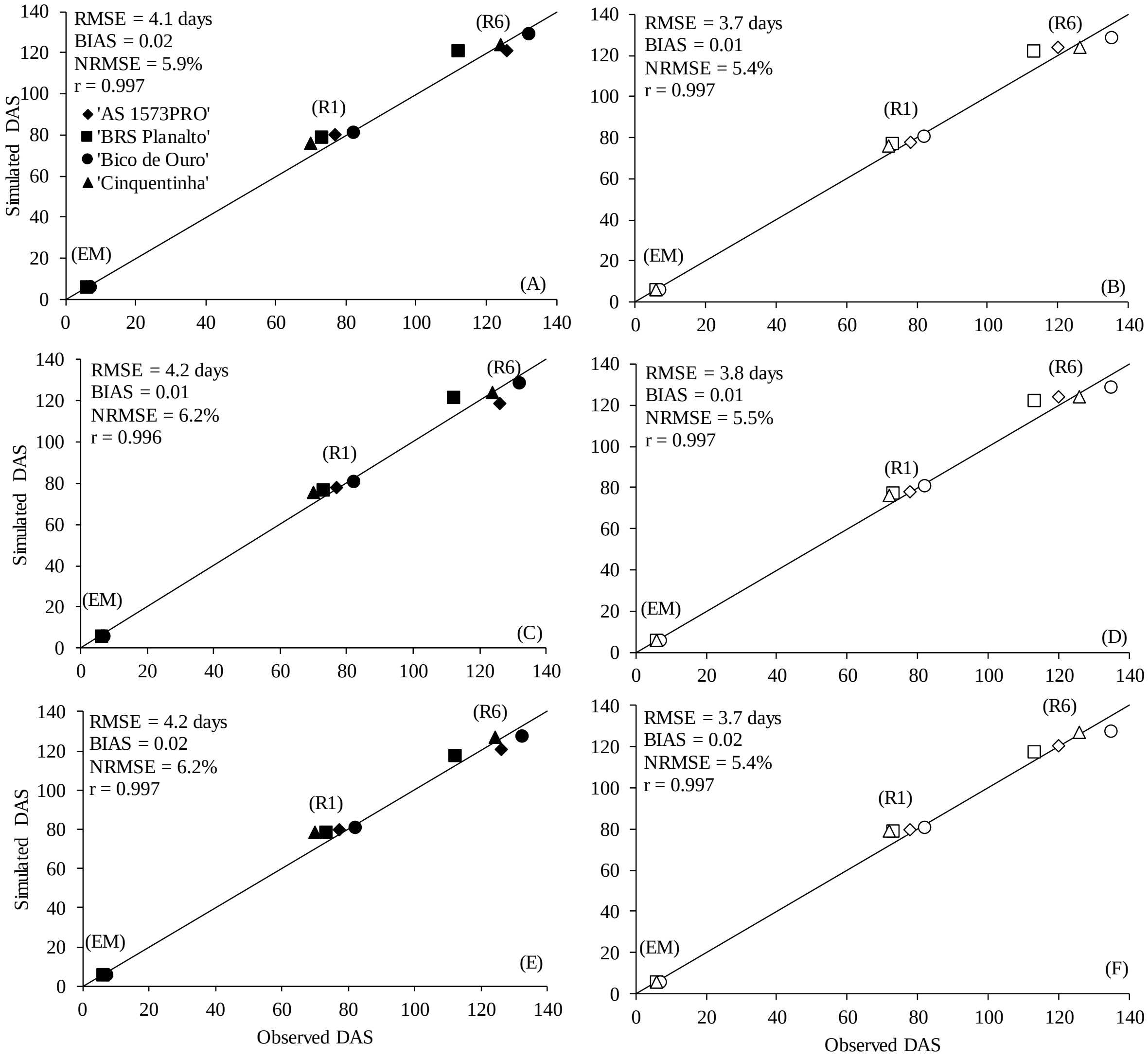

Figure 1 – Observed *vs*. Simulated days after sowing for emergence (EM), silking (R1) and physiological maturity (R6) for Experiment 1, for ‘AS 1573PRO’, ‘BRS Planalto’, ‘Bico de Ouro’ and ‘Cinquentinha’, for irrigated (A, C, E) and rainfed (B, D, F) conditions, with the calibrations of three methods, Cross-validation (A, B), GLUE (C, D) and Gencalc (E, F).

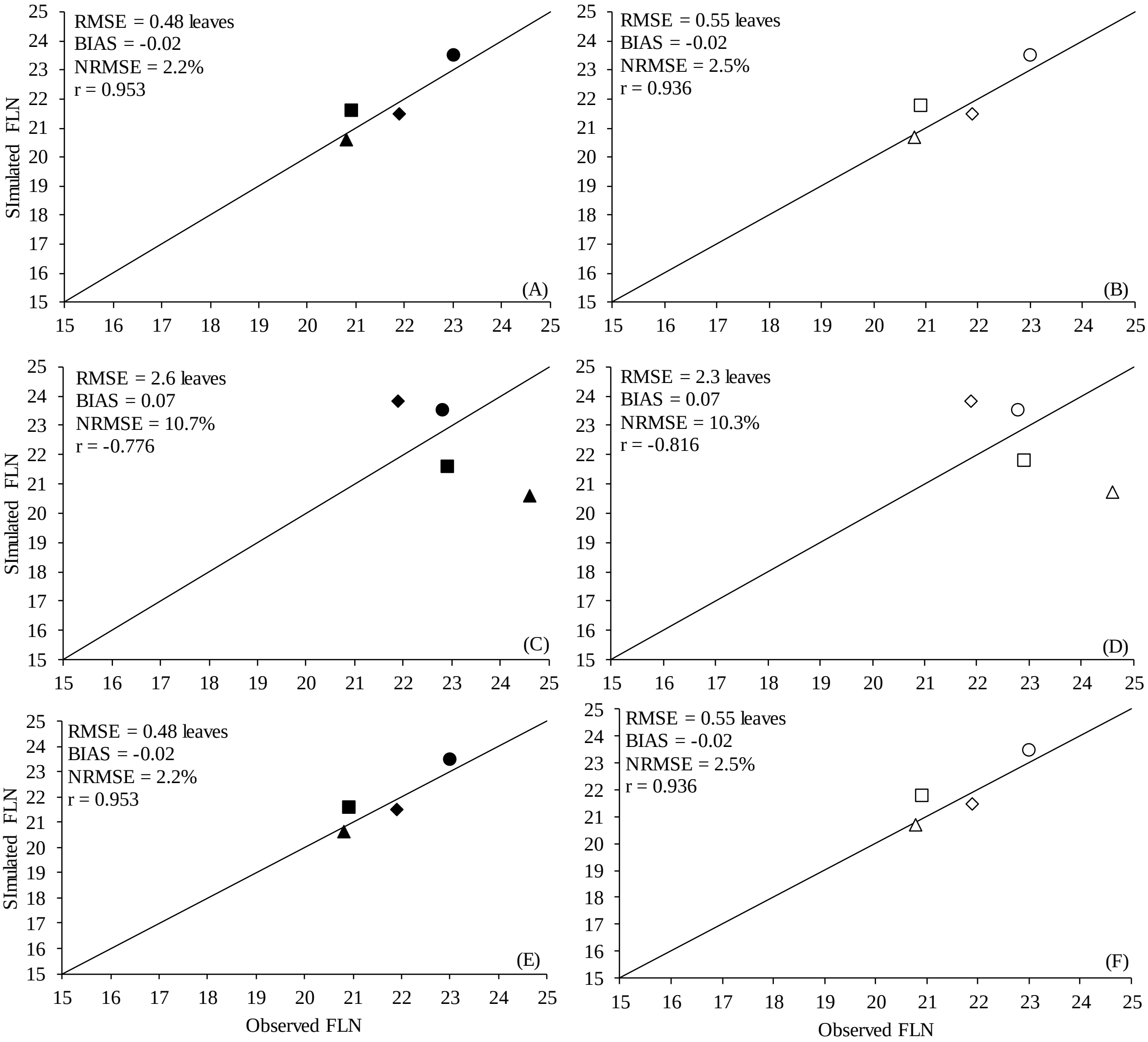

Figure 2 - Observed *vs*. Simulated Final Leaf Number (FLN) for Experiment 1, for ‘AS 1573PRO’, ‘BRS Planalto’, ‘Bico de Ouro’ and ‘Cinquentinha’, for irrigated (A, C, E) and rainfed (B, D, F) conditions, with the calibrations of three methods, Cross-validation (A, B), GLUE (C, D) and Gencalc (E, F).

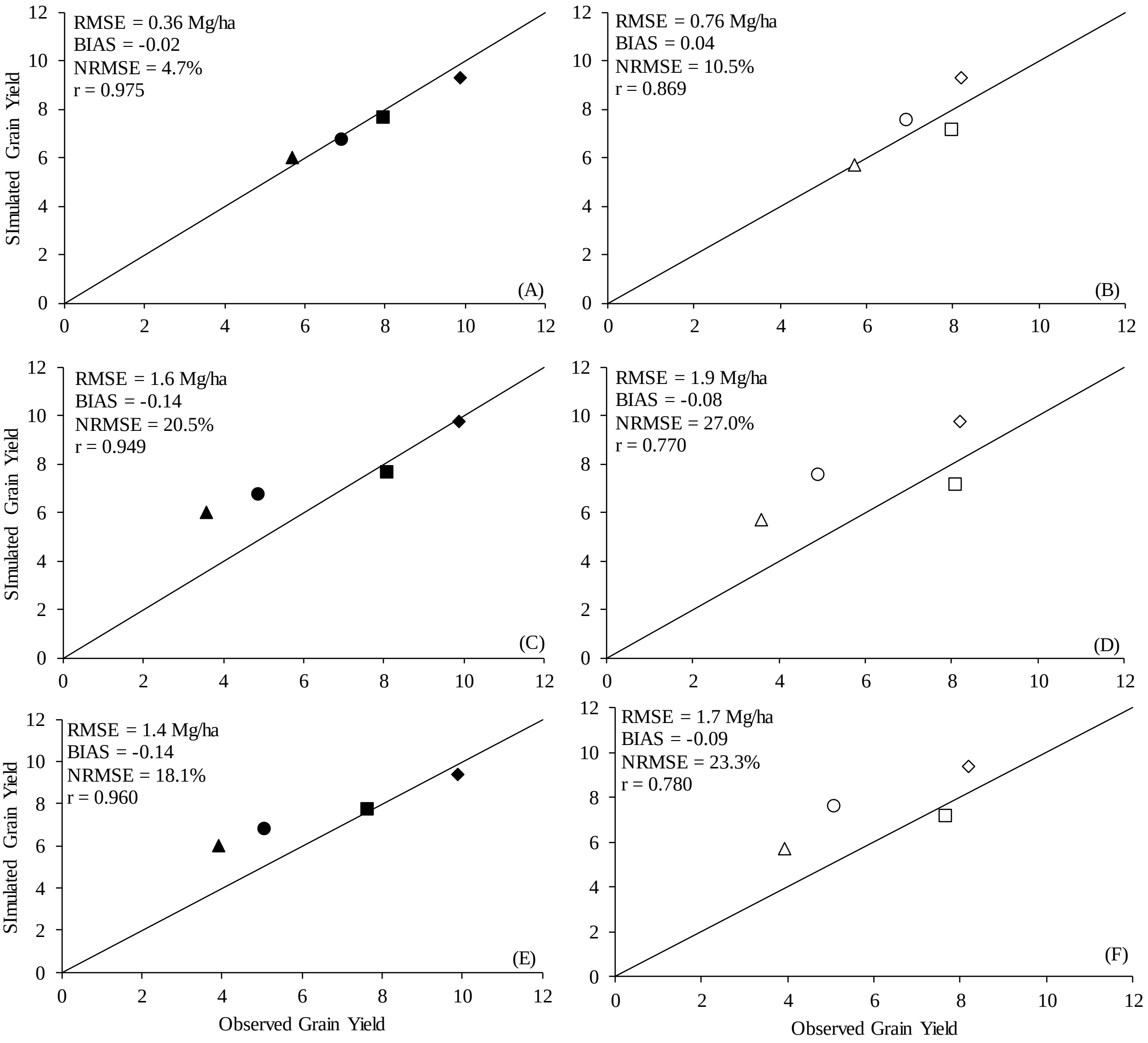

Figure 3 – Observed *vs*. Simulated Grain Yield for Experiment 1, for ‘AS 1573PRO’, ‘BRS Planalto’, ‘Bico de Ouro’ and ‘Cinquentinha’, for irrigated (A, C, E) and rainfed (B, D, F) conditions, with the calibrations of three methods, Cross-validation (A, B), GLUE (C, D) and Gencalc (E, F).

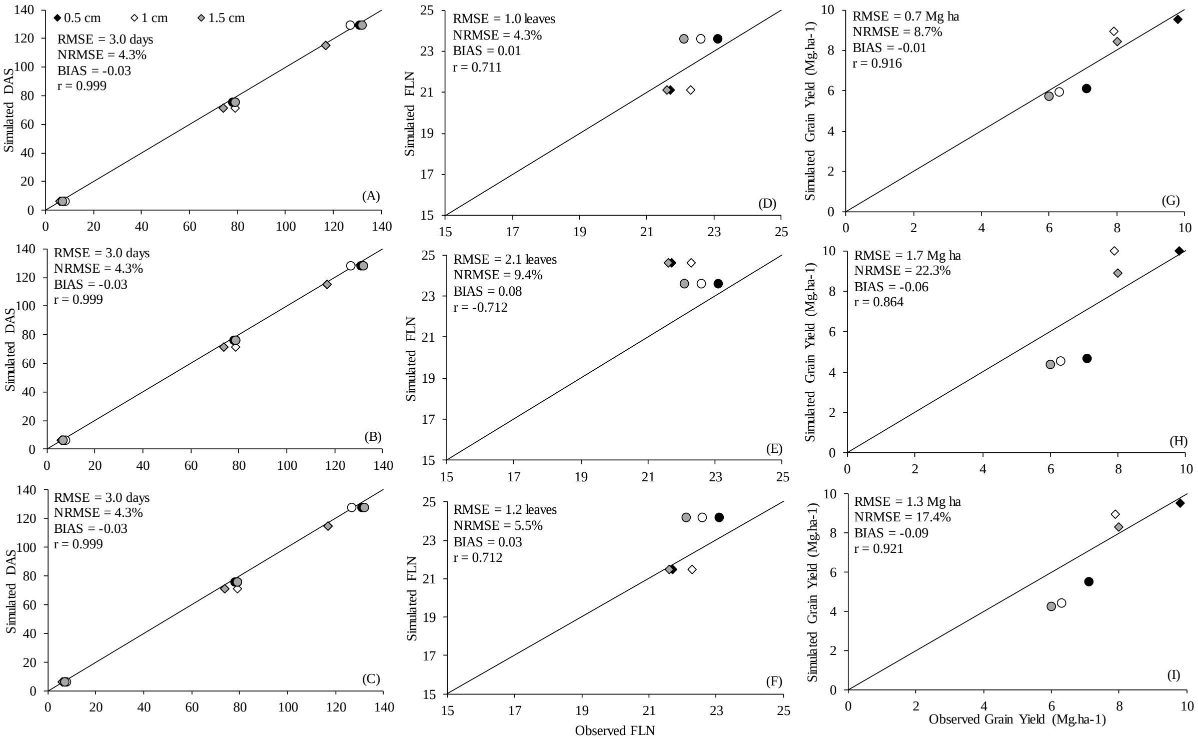

Figure 4 - Observed *vs*. Simulated days after sowing (DAS) (A, B, C) for emergence (EM), silking (R1) and physiological maturity (R6), Final Leaf Number (FLN) (D, E, F) and Grain Yield (G, H, I) for Experiment 2, for ‘AS 1573PRO’, ‘BRS Planalto’, ‘Bico de Ouro’ and ‘Cinquentinha’, with the calibrations of three methods, Cross-validation (A, D, G), GLUE (B, E, H) and Gencalc (C, F, I).

6 ARTIGO 2

EVALUATION OF HYBRID-MAIZE AND CSM-CERES-MAIZE MODEL IN SIMULATING GROWTH AND DEVELOPMENT OF MAIZE IN A SUBTROPICAL ENVIRONMENT

(Artigo será submetido para a Revista Brasileira de Meteorologia)

Evaluation of Hybrid-Maize and CSM-Ceres-Maize model in simulating growth and development of maize in a subtropical environment

Stefanía Dalmolin da Silva(1), Nereu Augusto Streck(1), Haishun Yang(2), Jossana Andreia Langner(1)

(1)Universidade Federal de Santa Maria (UFSM), Avenida Roraima, nº 1000, Cidade Universitária, Prédio 77, Sala 2, Camobi, CEP 97105-900 Santa Maria, RS, Brasil. E-mail: tefa.ds@hotmail.com, nstreck02@yahoo.com.br, lagnerja@gmail.com. (2)University of Nebraska, Lincoln, Nebraska, Estados Unidos.

ABSTRACT

The objective of this study was to demonstrate the ability of the Hybrid-Maize and CSM-CERES-Maize models in simulating growth and development in maize in a subtropical climate located in the southern region of Brazil. For calibration of the models, the data from a field experiment conducted during the 2013/14 and 2014/15 growing seasons in Santa Maria, RS, Brazil were used. The experiment was carried out using four maize cultivars, including two landraces maize cultivar ‘Bico de Ouro’ and ‘Cinquentinha’, and two improved cultivars ‘AS 1573PRO’ and ‘BRS Planalto’. For evaluation of the models, independent data was collected from another field experiment conducted in the same place, using the same cultivars, under two treatments, including irrigated and rainfed conditions. For both field experiments, the crop was managed for optimal nutrient supply, disease, pests and insects controls, and water for irrigated field to meet the requirements of the models. The Hybrid-Maize model had a better performance in simulating growth, development and grain yield of maize, and capturing the tendency between genotype x environment x growing season, and if a useful tool to assist farmers and researchers on field management decisions and yield forecast.

Keywords: modeling, process-based models, Southern Brazil, *Zea mays* L, yield, phenology.

Avaliação dos modelos Hybrid-Maize e CSM-CERES-Maize em simular o crescimento e desenvolvimento de milho em ambiente subtropical

RESUMO

O objetivo deste estudo foi demonstrar a capacidade dos modelos Hybrid-Maize e CSM-CERES-Maize em simular o crescimento e desenvolvimento de milho em clima subtropical localizado na região sul do Brasil. Para calibração, foram usados os dados de experimento de campo realizado durante as safras 2013/14 e 2014/15 em Santa Maria, RS, Brasil. O experimento foi realizado utilizando quatro cultivares de milho, incluindo duas cultivares crioulas de milho, 'Bico de Ouro' e 'Cinquentinha', e duas cultivares melhoradas, 'AS 1573PRO' e 'BRS Planalto'. Para a avaliação dos modelos, os dados independentes foram coletados de outro experimento de campo realizado no mesmo local, utilizando as mesmas cultivares, sob dois tratamentos, incluindo condições irrigadas e de sequeiro. Para ambos os experimentos de campo, a cultura foi administrada para o fornecimento ideal de nutrientes, controle de doenças, pragas e insetos, e água para campo irrigado para atender às exigências dos modelos. O modelo Hybrid-Maize teve um melhor desempenho na simulação do crescimento, desenvolvimento e rendimento de grãos de milho e capturou a tendência entre genótipo x ambiente x estação de crescimento e se mostrou ser uma ferramenta útil para auxiliar agricultores e pesquisadores em tomadas de decisões de gerenciamento de campo e previsão de safra.

Palavras-chave: modelagem, modelos baseados em processos, Sul do Brasil, Zea mays L, produtividade, fenologia.

1. Introduction

Agriculture has a high economic risk that is associated directly with climate variability and climate change. Crop models are important tools studying of the impact of resources, especially water and fertilizers (Cerrato and Blackmer, 1990; Hook, 1994; Streck et al., 2003a,b), responses to climate (Fagundes et al., 2010b; Streck et al., 2011, Walter et al., 2014, Cera et al., 2017), in education, and for crop consultants and insurance industry. Crop models can assist on decision making on field operations, such as the best sowing time, optimizing plant density, irrigation and fertilizer managements. Crop models have also been used for yield forecasting (Shin et al., 2006; Shin et al., 2009, Morell et al., 2016). To account for genetic differences among cultivars, crop models have parameters that reflex the general relationship between genotype and the environment. To increase the reliability of the crop models, however, these genetic parameters must be well calibrated for new cultivars or when models are used in new and untested.

There are several maize models, as the CSM-CERES-Maize (Hoogenboom et al., 2003), and more recently, the Hybrid-Maize model (Yang et al., 2004; 2017). They differ in complexity and their inputs. Both the CSM-CERES-Maize and Hybrid-Maize are process-based models and they simulate growth, development and grain yield. The Hybrid-Maize model was a hybridization of three models, INTERCOM including (Kropff and van Laar,1993; Lindquist, 2001), WOFOST (Van Diepenetal, 1989) and CERES-Maize (Jones and Kiniry, 1986), and had been gone through several revisions for improvements (Yang et al., 2017). Both models require two types of input data: daily weather data and agronomic data, from management and soil characteristics (Table 1). It is possible to notice that CERES-Maize model requires more input data than Hybrid-Maize and this can be a disadvantage, especially in regard to soil data, since soil information demands more work for collection. Among the genetic parameters in the CSM-CERES-Maize, P1 represents the thermal time from emergence to the end of the juvenile phase, P2 a photoperiod sensitivity coefficient, P5 the thermal time from silking to physiological maturity, G2 the maximum possible number of kernels per plant, G3 the daily kernel filling rate during the linear grain filling stage and under optimum conditions, and PHINT is the phylocron (Jones et al., 2003). For the Hybrid-Maize model in necessary to calibrate GDD of the whole cycle, G3 and G5 can be calibrated when necessary (Yang et al., 2004).

Brazil is the third largest maize producer. The CSM-CERES-Maize model have been tested in Southern Brazil in the past. Cardoso et al. (2004) used the CSM-Ceres-Maize to simulate yield and climatic risks on “off season” maize in Londrina – PR, Cardoso and Soccol (2008) studied how CSM-Ceres-Maize model simulated maize grown in late sowing date In Santa Catarina. There are no studies that have used the Hybrid-Maize model for Southern Brazil. Thus, the objective of this study was to compare the ability of these two models in simulating maize growth, development and yield in the subtropics of southern Brazil.

2. Material and Methods

A model calibration field experiment was carried out during the 2013/14 and 2014/15 growing seasons in Santa Maria (29°43“S, 53°43“W, and 95m altitude), Rio Grande do Sul State, Brazil. The average mean annual temperature is 18.8°C and total annual rainfall is 1,686 mm. Soil type at the experimental site is Rhodic Paleudalf (Embrapa, 2006).

The experimental field was with plowing and disking. Soil pH was corrected with limestone to a pH of 6.0. Based on soil test, 30 kg of N, 105 kg of P2O5 and 150 kg of K2O were applied at sowing using combined NPK fertilizer, and a total of 209 Kg ha^{-1} nitrogen was side-dressed based on an expected yield of 8.0 Mg ha-1 using ureia at the V4 and V8 stages.

For irrigation treatment, irrigation was performed using a drop irrigation system to prevent water stress.

The experiment was a two-factor in a randomized complete block design with four replications. Factor A was [two landrace maize cultivars: 'Cinquentinha' (early maturity) and 'Bico de Ouro' (late maturity); an open pollination maize cultivar: 'BRS Planalto' (early maturity), and a transgenic simple hybrid 'AS 1573PRO' (early maturity)], respectively. Factor B was four sowing (MM/DD/YYYY) dates (08/20/2013, 11/04/2013, 08/15/2015 and 12/13/2015). These sowing dates were chosen so the crops would be exposed to a wider range of the environment conditions.

Each plot was 5.0x4.5 with five rows. The row spacing was 0.9 m and the plant density of 5.5 plants m^{-2}. For the landrace maize cultivars, a total of 45 plants per plot were tagged, and for the improved cultivars, 15 plants per plot were tagged. The following observations or measurements were made for the tagged plants: emergence date (EM), flowering date (R1) and physiological maturity date (R6), final leaf number (FLN) (after tasseling (VT), and yield components. The EM, R1 and R6 dates were considered when 50% of the tagged plants reached these developmental stages.

A model testing field experiment was also conducted during the 2015/16 and 2016/17 growing season in the same experimental area, under rainfed and irrigated conditions using the same four cultivars as in the model calibration experiment. The sowing date in the 2015/16 growing season was 10/23/2015 for all cultivars, and in the 2016/17 was on 12/21/2016 for 'Bico de Ouro' and 12/28/2016 for the other three cultivars. The experiment was also a randomized complete block design with four replications and the plant density was 6.0 plants m^2. Because of the low soil moisture during the early part of the season, all plots in the experiment were irrigated till the V6 stage to help crop establishment. After that, irrigation was stopped for the rainfed treatment.

The model calibration was carried using the leave-one-out (LOO) cross-validation method (Efron and Gong, 1983; Fensterseifer et al., 2017). Performance of the two models was evaluated based on Root Mean Square Error (RMSE) (Streck et al., 2008), Normalized RMSE (Loague and Green, 1991), Pearson Correlation (r, Willmott, 1981), and BIAS (Wallach, 2006):

$$\mathrm{RMSE}=\left[\frac{\sum (s_i\text{-}O_i)^2}{n}\right]^{0.5} \tag{1}$$

$$\mathrm{NRMSE}=\mathrm{RMSE}^{*}\left(\frac{100}{\bar{O}}\right) \tag{2}$$

$$\mathrm{BIAS}=\frac{\sum S_i\text{-}\sum O_i}{\sum O_i} \tag{3}$$

$$r=\frac{\sum(O_i\text{-}\bar{O})(S_i\text{-}S)}{\{[\sum (O_i\text{-}\bar{O}][\sum (S_i\text{-}S)^2]\}^{0.5}} \tag{4}$$

where S_i is the simulated values, S the mean of the simulated values, O_i the simulated values, $\overline{O}$ the mean of the observed values, and *n* the number of pairs of observed and simulation variables. For the Normalized RMSE (NRMSE), a simulation is considered excellent when NRMSE is less than 10%, good if in between 10% and 20%, fair in between 20% and 30%, and poor if greater than 30% (Jamieson et al., 1991).

As an extra application of the model for the Rio Grande do Sul State, we ran both models for the four cultivars in the 2013/14, 2014/15, 2015/16, 2016/17 growing seasons for six locations (Uruguaiana, Passo Fundo, Porto Alegre, São Luiz Gonzaga, Santa Vitória do Palmar e Santa Maria) across Rio Grande do Sul State, starting in August until January, on the 1st, 11th and 21st day of each month, according to the Climatic Zoning Risk. These six locations were selected because they are located in different regions of RS (Figure 1), where soil and weather elements are different from each other, and also because to the period chosen (2013-17), these locations had the weather data without gaps. Observed yield data of the six locations in the four growing seasons were collected from IBGE, a federal public administration entity that unity various data about the country, and also, data from agriculture. Observed and simulated data were then compared.

3. Results and Discussion

Models Calibration

In table 2 and Figure 2 are presented the calibrated values of the genetic parameters for each model and results from phenology and grain yield, respectively. Between models, the CSM-CERES-Maize model requires two genetic parameters to simulate silking time (P1 and P2), and these parameters are difficult to measure, while Hybrid-Maize have the ability to predict silking time based on the total GDD (Table 2). For all sowing dates in both growing seasons, Hybrid Maize predicted silking within -8 to +6 days while CSM-CERES-Maize predicted silking within -11 to +4 days. The simulated phenology by both models was close with observed values, however, the Hybrid-Maize model had a smaller RMSE than CSM-CERES-Maize (Figures 2A and 2B). Predictions of yield by both models were, also, in close agreement with observed values, where CSM-CERES-Maize model had an RMSE of 0.9 Mg ha^{-1} and Hybrid-Maize of 1.1 Mg ha^{-1}, considering all cultivars and all growing seasons (Figures 2C and 2D). For the simulations of Final Leaf Number (FLN), both models had the same performance, with an RMSE of 1.0 leaf (Figures 2E and 2F).

Models evaluation

Figure 3 shows the observed vs. simulated days after sowing (DAS) for the phenology, pooling all cultivars, sowing dates and water conditions, for the CSM-Ceres-Maize and Hybrid Maize models. Comparing both models, the Hybrid-Maize model showed the best performance in simulating the phenology, with an RMSE of 1.9 days (Figure 3A), while the CSM-CERES-Maize model had an RMSE of 8 days (Figure 3B). The Hybrid-Maize models had excellent results in other statistics (Figure 3A). About the simulation of grain yield, the simulated values were with agreement with the observed values by both models, where the Hybrid-Maize models had an RMSE of 0.6 Mg ha^{-1} and the CSM-CERES-Maize of 0.7 Mg ha^{-1} (Figure 3C and 3D), capturing the difference between growing seasons, cultivars and water conditions. Looking at other statistics (NRMSE and r), both models had excellent performance in simulating maize grain yield (Figure 3C e 3D).

Figure 4 and 5 show the performance of the models in simulating Leaf Area Index (LAI). For the 2015/16 growing season, the RMSEs of LAI simulated by the Hybrid-Maize model were between 0.53 and 0.98 for the irrigated treatment (Figures 4A, 4B, 4C and 4D, Table 3), and for the rainfed treatment RMSE varied from 0.79 to 1.03 (Figures 4E, 4F, 4G and 4H, Table 3). The CSM-Ceres-Maize model presented higher values of RMSE, varying from 0.77 to 1.85 for the irrigated treatment (Figure 5A, 5B, 5C and 5D, Table 3) and between 0.72 to 1.47 for the rainfed treatment (Figure 5E, 5F, 5G and 5H, Table 3). For the 2016/17 growing season, the results were similar to the 2015/16, with Hybrid-Maize model better performance for simulating LAI evolution, with an RMSE varying from 0.6 to 1.2 Simulated LAI with the CSM-CERES-Maize model was close to the observed values for the first 40 days after sowings while the simulated values with the Hybrid-Maize captured the LAI better along the growing season (Figures 4 and 5). In the general, the Hybrid-Maize model simulated the trend of LAI for all cultivars among treatments.

The observed and simulated grain yield for the six locations across de RS State, during the 2013/14 to 2016/17 growing seasons, to the four cultivars are shown in Figure 7. The mean of the six locations was calculated to represent the entire state of RS. The Hybrid-Maize model had the best performance in simulating grain yield to RS State whereas the CSM-CERES-Maize model wasn’t able to predict well the grain yield on a state level (Figure 6). Also, the Hybrid-Maize model captured the genetic variability between cultivars, the difference between the elements of the climate of each region and also the difference between years.

Looking for the phenology, both models simulated with a good performance, with a NRMSE smaller than 20%. Both models have same basis to simulate phenology. The better performance of the Hybrid-Maize model can be explained by a smaller number of parameters to calibrate, and also, the phenology parameters in CSM-CERES-Maize models are difficult to calibrate using observed data. For LAI, the Hybrid-Maize model had the best performance comparing with the CSM-CERES-Maize, showing that the growth and phenology parameters are adequate. In grain yield simulations, on a site level, both models performed well, although in a county level, the CSM-CERES-Maize model did not show accuracy in the simulations. This can be explained by the soil characteristics in some sites in RS State located in the Southern. The situation in low lands is hardly to find around the world. In conclusion, the Hybrid-Maize model can be a useful tool to simulate growth, development, grain yield and also can assist in yield forecast and also in studies to evaluate the impact of climate change in maize.

4. Conclusions

On a site-specific scale, both models had a good performance in simulating maize phenology and grain yield. The Hybrid-Maize model had the best performance in simulating LAI.

On a count level, the Hybrid-Maize predicted well the grain yield in Rio Grande do Sul State.

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Table 1 – Input parameters required by the CSM-CERES-Maize and Hybrid-Maize models.

Input data	CERES-Maize	Hybrid-Maize
Daily weather	Solar radiation (Mj m^{-2} dia^{-1}), maximum and minimum temperatures (°C) and rainfall (mm), wind speed (m s^{-1})	Solar radiation (Mj m^{-2} dia^{-1}), maximum and minimum temperatures (°C) and rainfall (mm), relative humidity (%), evapotranspiration (mm)
Management data	Sowing date, plant density, planting method, distribution and depth, row spacing, irrigation management, genotype	Sowing date, plant density, irrigation management, genotype
Soil chatacteristics	Bulk density, soil layer L, Thickness of soil layer L, Soil water content at drained upper limit in soil layer L, Soil water content in soil layer L at lower limit of plant extractable soil water, Ammonium N in soil layer L, Actual number of soil layers, Root length density for soil layer L	Rooting depth, soils texture (top-soil and sub-soil), bulk density, soil moisture, soil surface residues coverage, field runoff

Table 2 – Values of the genetic parameters of the CSM-CERES-Maize models after calibration.

	Genetic Parameters					
	Hybrid-Maize Model					
Cultivar	P1	P2	P5	G2	G3	PHINT
‘AS 1573PRO’	-	-	1590	710	9.00	-
‘Bico de Ouro’	-	-	1790	500	8.50	-
‘Cinquentinha’	-	-	1670	485	8.50	-
‘BRS Planalto’	-	-	1520	700	8.90	-
	CSM-CERES-Maize					
‘AS 1573PRO’	323.1	0.102	723.7	575.0	21.00	51.60
‘Bico de Ouro’	335.8	0.250	800.0	317.0	15.00	47.87
‘Cinquentinha’	300.5	0.000	797.0	386.0	15.00	50.00
‘BRS Planalto’	301.50	0.075	700.0	515.0	17.00	50.69

Table 3 - Root Mean Square Error (RMSE) values of the simulation of leaf area index (LAI) of two landrace maize cultivars ‘Bico de Ouro’ and ‘Cinquentinha’, and two improved maize cultivars, one OPV ‘BRS Planalto’ and a transgenic simple hybrid ‘AS 1573PRO’ with the Hybrid-Maize and CSM-Ceres-Maize models, grown in Santa Maria, RS, Brazil in two sowing dates, under irrigated and rainfed conditions.

	RMSE			
	Simulated with Hybrid-Maize			
	2015/16 growing season		2016/17 growing season	
Cultivars	Irrigated	Rainfed	Irrigated	Rainfed
‘AS 1573PRO’	0.53	0.85	0.60	0.60
‘BRS Planalto’	0.58	0.79	0.70	0.70
‘Bico de Ouro’	0.54	0.76	0.70	0.70
‘Cinquentinha’	0.98	1.03	1.20	1.20
	Simulated with Hybrid-Maize			
	2015/16 growing season		2016/17 growing season	
	Irrigated	Rainfed	Irrigated	Rainfed
‘AS 1573PRO’	1.20	0.85	1.20	1.00
‘BRS Planalto’	1.18	0.92	1.30	1.30
‘Bico de Ouro’	1.85	1.47	1.50	1.50
‘Cinquentinha’	0.77	0.72	1.00	1.00

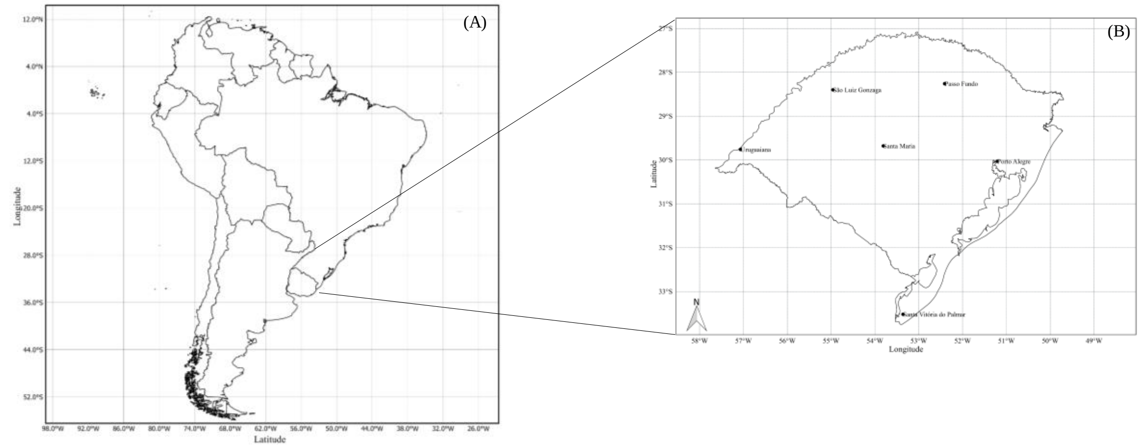

Figure 1 – Map of Southern America (A) and Rio Grande do Sul State (B), with the six location across the state selected to run the CSM-CERES-Maize and Hybrid-Maize models.

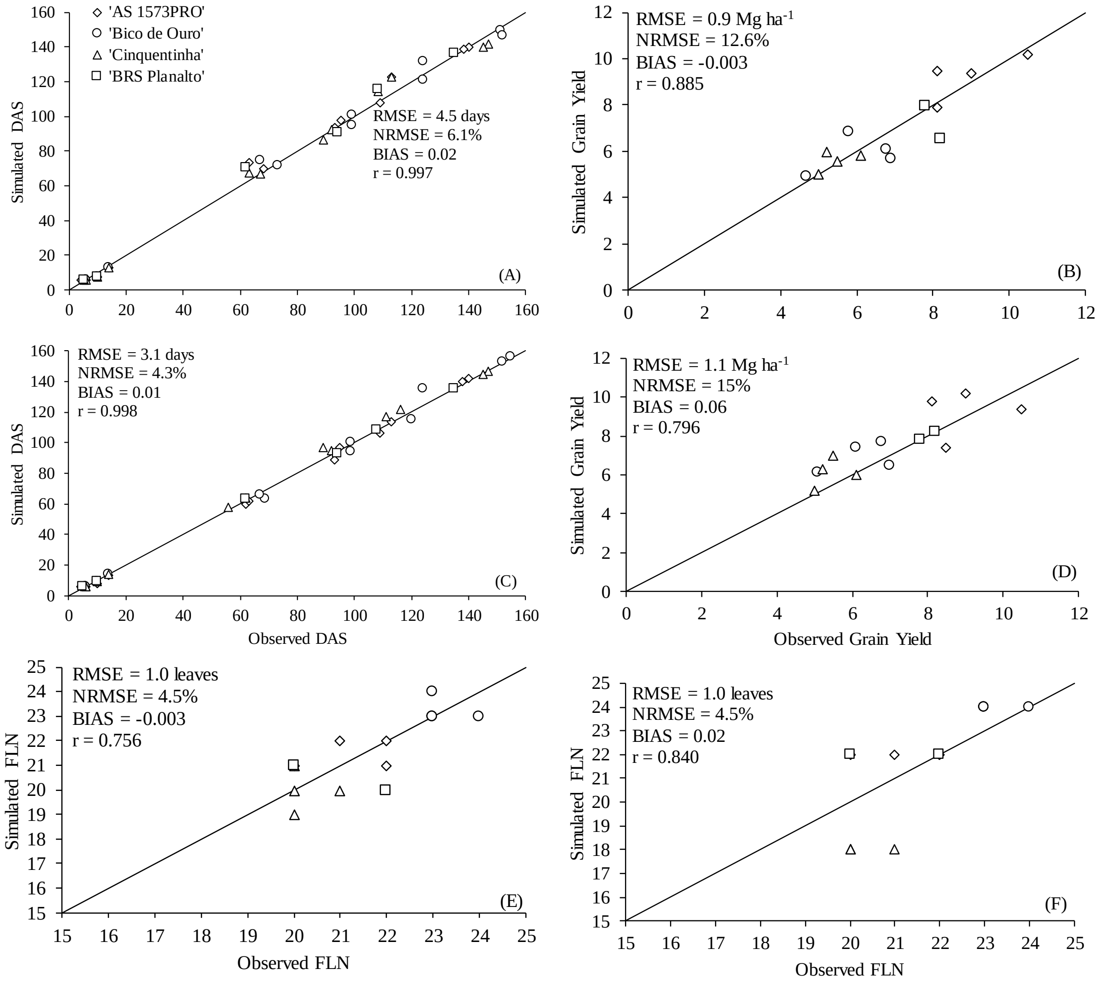

Figure 2 – Observed vs. Simulated days after sowing for emergence, silking and physiological maturity simulated with the CSM-CERES-Maize (A) and Hybrid-Maize (C) models and grain yield simulated with the CSM-CERES-Maize (B) and Hybrid-Maize (D) models and Final Leaf Number (FLN) simulated with CSM-CERES-Maize (E) and Hybrid-Maize (F) models, after calibration, during the 2013/14 and 2014/15 growing seasons, for Santa Maria, RS, Brazil.

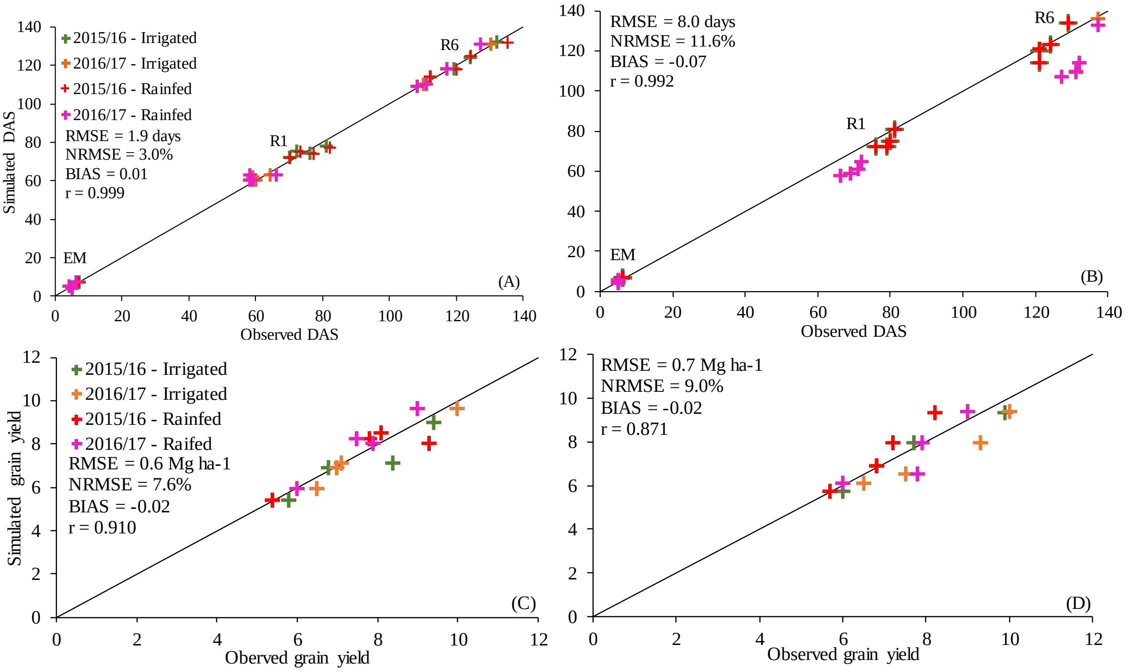

Figure 3- Observed and simulated days after sowing to emergence (EM), silking (R1) and physiological maturity (R6), to four cultivars (‘AS 1573PRO’, ‘BRS Planalto’, ‘Bico de Ouro’ and ‘Cinquentinha’), two growing seasons (2015/16 and 2016/17), and two treatments (Irrigated and Rainfed), with the Hybrid-Maize model (A) and with the CSM-Ceres-Maize model (B) and Observed and simulated grain yield (Mg ha^{-1}), to four cultivars (‘AS 1573PRO’, ‘BRS Planalto’, ‘Bico de Ouro’ and ‘Cinquentinha’), two growing seasons (2015/16 and 2016/17), and two treatments (Irrigated and Rainfed), with the Hybrid-Maize model (C) and with the CSM-Ceres-Maize model (D). Santa Maria, RS, Brazil.

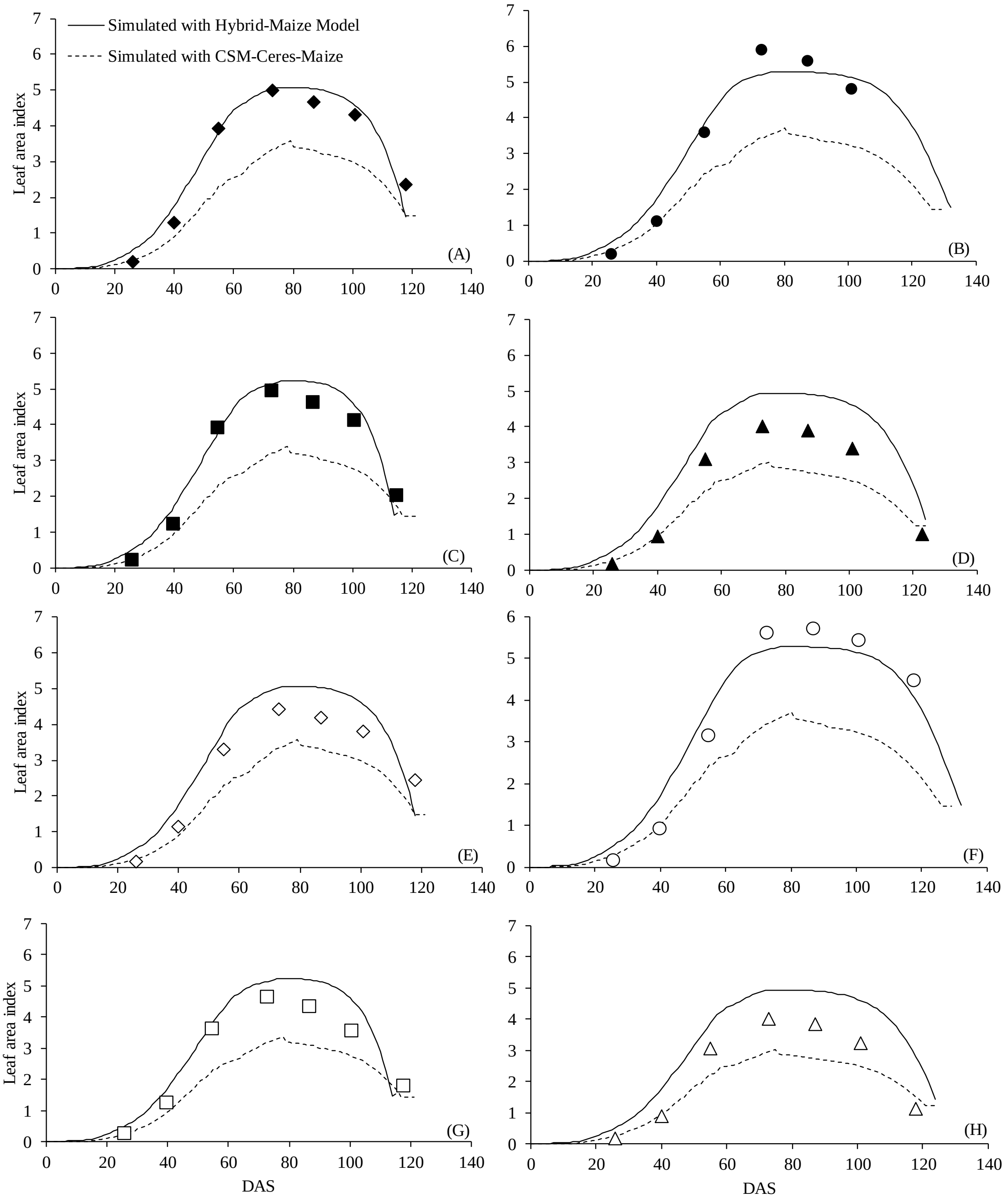

Figure 4 – Observed and simulated leaf area index (LAI) as a function of days after sowing (DAS) with the Hybrid-Maize and CSM-Ceres-Maize models to for cultivars, ‘AS 1573PRO’ (A and E), ‘BRS Planalto’ (C and G), ‘Bico de Ouro’ (B and F) and ‘Cinquentinha (D and H), during the 2015/16 growing season, in irrigated conditions (A, B, C and D) and rainfed conditions (E, F, G, H). Santa Maria, RS, Brazil.

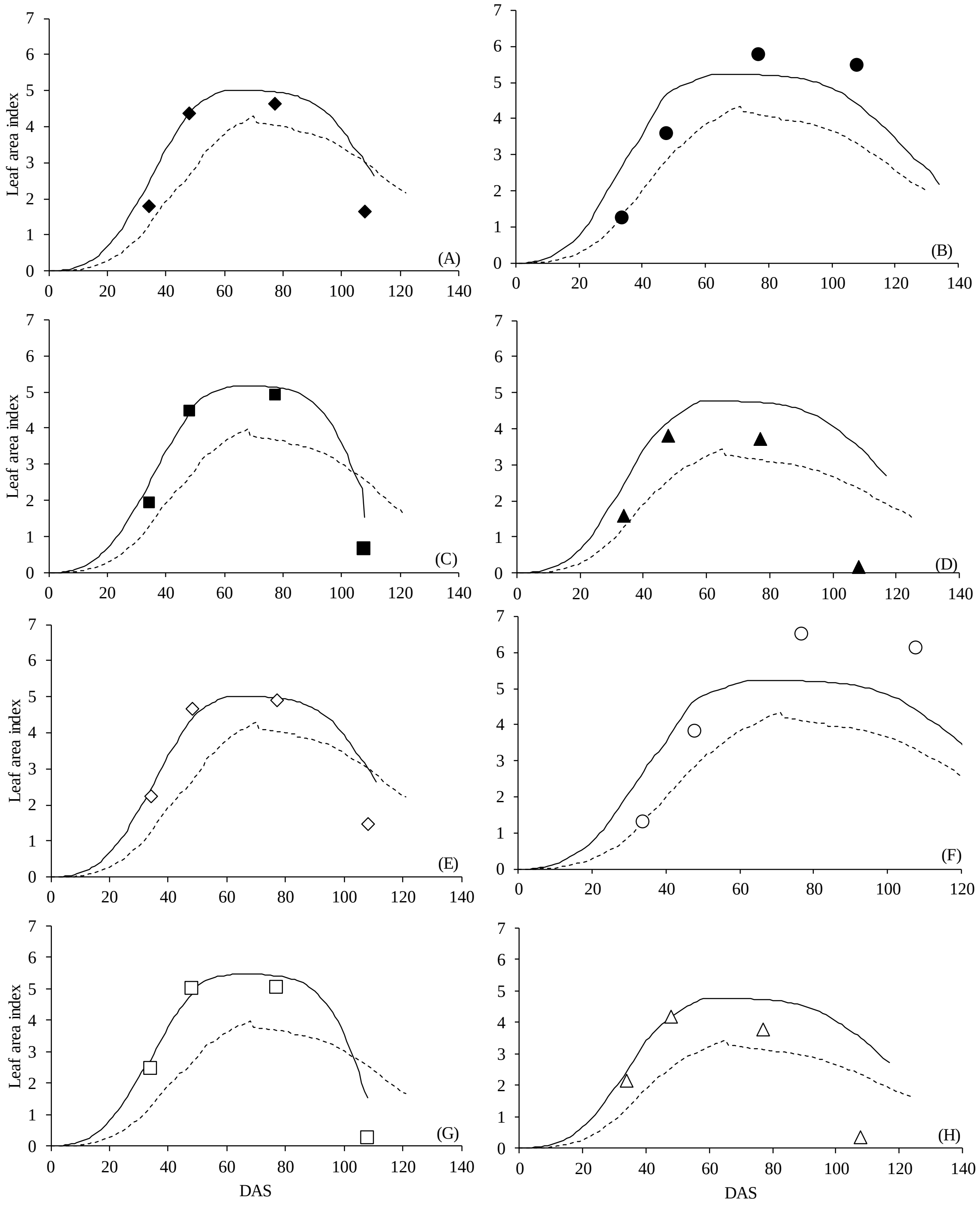

Figure 5 – Observed and simulated leaf area index (LAI) as a function of days after sowing (DAS) with the Hybrid-Maize and CSM-Ceres-Maize models for cultivars, ‘AS 1573PRO’ (A and E), ‘BRS Planalto’ (C and G), ‘Bico de Ouro’ (B and F) and ‘Cinquentinha (D and H), during the 2016/17 growing season, in irrigated conditions (A, B, C and D) and rainfed conditions (E, F, G, H). Santa Maria, RS, Brazil.

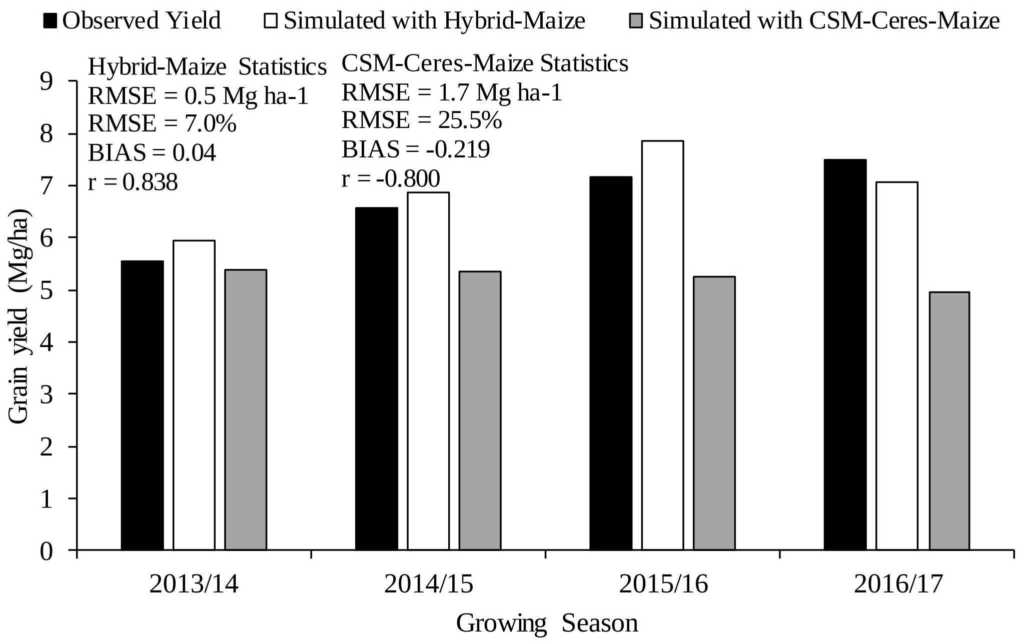

Figure 6 – Observed grain yield for six locations in Rio Grande do Sul State compared with the simulated by the Hybrid-Maize and CSM-Ceres-Maize model. Statistics of the models performance are in the inset: RMSE= Root Mean Square Error, NRMSE= Normalized Root Mean Square Error, BIAS= Bias Index, r = Pearson Correlation coefficient.

7 ARTIGO 3

MAIZE YIELD IN FUTURE CLIMATE SCENARIOS FOR RIO GRANDE DO SUL STATE, BRAZIL

(Intensão de submissão para revista internacional)

Maize yield in future climate change scenarios for Rio Grande do Sul State, Brazil

Stefanía Dalmolin da Silva[1], Nereu Augusto Streck[1], Haishun Yang[2], Anderson Haas Poersch[1]
[1]Departamento de Fitotecnia, Universidade Federal de Santa Maria, Santa Maria, RS, Brasil
[2]University of Nebraska – Lincoln, Lincoln, Estados Unidos

ABSTRACT

The objective of this study was to estimate maize yield using the climate projections of the RCP 2.6, RCP 4.5 and RCP 8.5 of the Intergovernmental Panel on Climate Change (IPCC) in the Hybrid-Maize model, to analyse the response of maize yield under the impact of climate change in Rio Grande do Sul State. The Hybrid-Maize model were run using two improved maize cultivars and two landrace maize cultivars, from August to January, considering the 1st, 11th and 21st days of each month as sowing dates, representing the 20, 30 and 40% of risk considered in the Agroclimatic Zoning Risk of this crop for the RS State. It was found a decrease in maize yield in the northern half region of the State in the period of 2070-2098, considered to be the region with significant production, while in the an increasing in maize yield was found in the southern region of the state.

Key words: Hybrid-Maize model, climate change, landrace maize, IPCC

INTRODUCTION

In 2013 was released the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013), evidencing that the planet has already warmed 0.85°C (0.65 to 1.06°C) in the period from 1880 to 2012, where the 90's decade was the warmer of the millennium (Kerr, 2005; IPCC, 2013). The temperature increasing projected by the end of the century (2081-2100) is to vary from 0.3 to 1.7°C for the RCP 2.6 (low forcing level of the greenhouse gas emissions), from 1.1 to 2.6°C (intermediate scenario) and from 2.6 to 4.8°C (very high forcing level of the greenhouse gas emissions) (IPCC, 2013). Besides the temperature increasing projections, there is an evidence of the increasing of CO_2 concentrations and other greenhouse gases (Weiss et al., 2003; Kerr, 2005; IPCC, 2013). The projections, by the end of the century, for the CO_2 concentrations vary from 420 to 918 ppm (IPCC, 2013).

Agriculture is an activity extremely sensitive do climate variability and climate change, since it depends on the environment conditions to growth (Watson et al., 1996; Kang et al., 2009). Maize (*Zea Mays* L.) is one of the main crops grown worldwide and it plays an important role in sustainability and food security of world population (Bruinsma et al., 2009). In the 2017/18 growing season, the world corn production was approximately 1.0 million of tons (USDA, 2018). The United States is the major maize producer, whose production in the last growing season was, approximately, 362 million of tons in a grown area of 36.489 thousand hectares (USDA, 2018). Brazil takes the third position in the ranking, with a production of 94 million of tons in a grown area of approximately 16 thousand hectares (CONAB, 2018). Between brazilian states, Rio Grande do Sul (RS) is the seventh largest corn producer and in the last growing season was responsible for a production of 4,827 thousand tons in a grown area of 728 thousand hectares (CONAB, 2018).

In developing countries like Mexico, countries of the African continent, and even Brazil, family farming is extremely important for the economy, but also for the sustainability and food security. In Around 84% of the rural establishments are family farming, and they occupy an area of 80 million of hectares, totaling 24.3% of the total area intended to agricultural in Brazil (FAO, 2012). The food produced by family farming accounts for about 70% of the national production, i.e, they are essential for the country's sustainability and food security (MDA, 2009). In this establishments, farmers have the habit of using landrace maize cultivars because it has high genetic variability and rusticity, being resistant to biotic and abiotic factors, allowing the farmer to carry out his cultivation in low technology and nevertheless obtain profitable productivity (Paterniani and Nass, 2000; Araújo and Nass, 2002; Sandri and Tofanelli, 2008).

Although not producing at the same level as a hybrid, another advantage for the farmer is the possibility of producing his own seed, significantly reducing the cost of each new sowing (Machado et al., 2011). Also, the high genetic variability and rusticity allow them to be grown under different climate conditions, from annual mean temperature varying between 11.3 to 26.6°C and rainfall varying from 426 to 3555mm during the growing season, showing the climate adaptation and stability of these cultivars (Corral et al., 2008). With a confirmation of the of climate change by the end of the century, small farmers will be the first to suffer by these effects and an effort to study adaptation strategies to mitigate these negatives effects is needed, as the landrace maize cultivars plays, also, an important role on breeding programs (Hellin et al., 2014).

The study of the effect of climate variability and climate change can be done using crop models (Streck and Alberto., 2006a; Walter et al., 2010; Cera et al., 2017). Muchow et al. (1989) studied the effect of temperature on potential maize yield among different locations of Florida. They found that temperature influence the growth duration, where high temperatures decreased the growth duration and, consequently, the maize yield. Also, Alberto et al. (2006) studied the effect of available soil water and crops yield, including maize, in Santa Maria, RS, Brazil, and associating to the EL Nino South Oscillation phenomena. They found that in El Niño years, where the rainfall in more frequent and regular in RS State, it benefits maize grain yield. Under a climate change environment, Delécolle et al. (1995) studied the effects of climate change on Wheat and Maize, in France. They found that a shortening of the growth duration occurred, mainly because of the temperature increasing. Streck and Alberto .(2006a) studied the impact of climate change on wheat, soybean and maize in Santa Maria, RS, Brazil, and found that the temperature increasing will influence the yield of these crops, and that the effect of temperature can annul the effect of $CO_{2.}$

The Hybrid-Maize model in a recent developed maize process-based model that can simulate growth, development and grain yield, under potential and water-limiting conditions (Yang et al., 2004). A recent study using the Hybrid-Maize model to analyses it response to climate change factors was done to locations in United States, France, Brazil and Tanzania, however was accounting for just one city in Brazil (Bassu et al., 2014). Also, this model was never used to study the impact of landrace maize cultivars under a climate change condition. The objective of this study was to estimate the potential and water-limiting maize grain yield in Rio Grande do Sul State under the RCP 2.6, RCP4.5 and RCP 8.5 of the AR5, using the Hybrid-Maize model.

MATERIAL AND METHODS

Study area

This study was performed for the Rio Grande do Sul State (RS), in the Southern Brazil (Figure 1). According to Köppen's climate classification, the State has areas with two climate zone, humid subtropical without dry season and hot summer (Cfa) and temperate summer (Cfab). During the year, temperature vary since negative values of -10 to 40°C, and annual precipitation through the state can vary from 1200 to 1800 mm.

Crop model

The maize model chosen to this study was the Hybrid-Maize model (Yang et al., 2004). The Hybrid-maize is a process-based model that simulate maize development, growth and yield under potential and water limiting conditions. The Hybrid-Maize model was developed in the United States and calibrated and evaluated in a subtropical environment in the Southern of Brazil (paper 2 of this dissertation), showing that this model can simulate, with a good performance, development, growth and yield of maize under potential and water limiting conditions, capturing the difference between genotype, environment and growing season.

There are three types of inputs required to run the model: weather, soil and agronomic inputs. The weather inputs are solar radiation (Mj m^{-2} day^{-1}), maximum and minimum air temperature (°C), relative humidity (%), rainfall (mm) and evapotranspiration (mm), all in a daily basis. The soil data required are soil texture, rooting depth, bulk density (g cm^{-3}), soil moisture and surface residues coverage, and field runoff. The agronomic inputs are date of planting, seed brand, information of duration of cycle and plant population. To represent cultivars, there are genetic parameter that must be calibrated: GDD to silking and GDD to maturity, potential number of kernels per ear and potential kernel filling rate (Yang et al., 2004).

Soil information required to run the model was from soil analysis from ta survey conducted throughout the Rio Grande do Sul State by EMBRAPA (http://library.wur.nl/isric/fulltext/isricu_i00003061_001.pdf).

Climate change scenarios and CO_2 concentrations

The climate scenarios used in this study were from the Fifth Assessment Report of the IPCC (IPCC, 2013), derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5). This recent report considers representative concentrations pathways scenarios (RCP), based on a relative radiative forcing (W m^{-2}) of the greenhouse gas emissions. This RCP are divided into RCP 2.5, RCP 4.5, RCP6.0 and RCP8.5, where RCP 2.6 correspond to a very low forcing level, i.e, an optimist scenario, RCP4.5 and 6.0 are both intermediate scenarios and RCP8.5 is a scenario with high emission of greenhouse gas. The data was generated by the HadGEM-ES model with a 250 km of spatial resolution and as made a downscaling to an 81km of resolution using the RegCM4 (Regional Climate Model v.4), totaling 61 grid points across the Rio Grande do Sul State (Figure 1B). The temperature and CO_2 concentrations projections until the end of the century is 1.7ºC and 420 ppm for the RCP2.6, 2.6ºC and 538ppm for the RCP4.5 scenario and 4.8ºC and 918ppm for the RCP8.5 (Figure 2b). The temperatures and rainfall were compared to see how they vary through scenarios (Figures 3, 4 and 5). Five points were selected, one located on West, North, East, Center and South. If we look to the temperatures, it is possible to notice that the minimum temperature increases in a higher level than the maximum temperature, showing that the increasing temperature in the scenarios is asymmetric (Figure 3 and 4). It is also possible to see that the RCP 8.5 scenario present lower maximum temperatures than the other scenarios (Figure 3). About the rainfall, the points located in the half south region of the state are more wet than in the half north in the RCP 2.6 and RCP 8.5 (Figure 5).

Two periods in the scenarios was considered: from 1976 to 2005 as the baseline scenario, and from 2070 to 2098 respective to the future period.

Simulations of maize yield

Four maize cultivars were used in this study, two landrace maize cultivars, ‘Bico de Ouro’ (late maturity) and ‘Cinquentinha’ (early maturity), and two improved maize cultivars, ‘BRS Planalto’ (OPV; early maturity) and ‘AS 1573PRO’ (simple hybrid; early maturity).

Maize yield was considered as dry matter (Mg ha^{-1}). To evaluate the performance of the model to simulate grain yield, the simulated yield data with the baseline scenario was compared to observed data of IBGE (Figure 2B), to the 2000/01, 2001/02, 2002/03, 2003/04 and 2004/05 growing season, considering 18 sowing dates, 1st, 11th and 21st, from August to January, period that is considered in the Agroclimatic Risk Zoning for maize in RS. These dates consider 20, 30 and 40% of risk. The simulated yield with the Hybrid-Maize model is a mean of the yield for the four cultivars and 18 sowing dates. The technologic tendency was removed from the observed grain yield, because the model was calibrated using cultivars and management different than that were used on the 2000`s.

The yields for each future scenario were presented as anomalies, calculated by the difference between the yield of each year of the future scenarios and the mean yield of the baseline scenario in each grid point (it was calculated the mean of the improved and landrace cultivars separately) for each sowing date, 1st, 11th and 21st, from August to January.

RESULTS AND DISCUSSION

Figure 2A shows the area cultivated with maize in the 2016/17 growing season. In Figure 2B is presented the observed grain yield (mean grain yield during five growing seasons – 2000/2001, 2001/2002, 2002/2003, 2003/2004, 2004/2005), with values 6.0 to 10.4 Mg ha^{-1} and located in the north region of the State. The simulated grain yield by the Hybrid-Maize model varied from 6.0 to 9.0 Mg ha^{-1} (Figure 2D) under rainfed conditions and 8.0 to 11.0 Mg ha^{-1} under potential conditions (Figure 2C). Comparing the observed and simulated grain yield, it is possible to see that the model had a good performance, with an RMSE of 1.2 Mg ha^{-1} and with a slightly underestimate of grain yield by the Hybrid-Maize model (Figure 2D).

Under potential conditions, the model is predicting good grain yield among all sowing dates, with higher yield on sowing dates in November, December and January, around 8.0 to 13.0 Mg ha^{-1} for improved maize cultivars and 6.0 to 9.0 Mg ha^{-1} for landrace maize cultivars (Figures 6G, 6I, 6K, 7G, 7I and 7K). Under water limiting conditions, the sowing dates in November, December and January, for both improved and landrace maize cultivars, have the higher yields, mainly in the half north region of the Stat (Figures 6H, 6J, 6L, 7H, 7J and 7L).

For the improved maize cultivars, under potential conditions, the scenario RCP 2.6 was the one with the lowest response. In the early sowing dates (August and September) occurred a decrease of 0.5 to 1.5 Mg ha^{-1} in the state, with higher anomalies in the northeast of the State (Figures 8A and 8D). If we look to the RCP 4.5, the decrease in yield is concentrated in the significant production region of the State (half north), with negative anomalies of -1.5 to -2.5 Mg ha^{-1} (Figures 8B and 8E). In the scenario RCP 8.5 the decrease extends to all regions of the State (Figures 8C and 8F). The sowing dates on October and November have some expressive decreases, mainly in the RCP 4.5 and RCP 8.5 scenarios, highlighting the negative anomalies (from -2.5 to -4.5 Mg ha^{-1}) in the North region of RS (Figures 8H, 8I, 8K and 8L). The sowing dates realized on the latest months of the Agroclimatic Zoning Risk (December and January) are the one with the more expressive decreases in grain yield, with anomalies of -0.5 to -2.5 Mg ha^{-1} (RCP 2.6) (Figures 8M and 8P), -0.5 to -5.5 (RCP 4.5) (Figures 8N and 8Q) and -2.5 to higher than -5.5 (RCP 8.5) (Figures 8O and 8R). As the model was run under no-water limiting, only the effect of the maximum and minimum temperatures was considered by the models. Under water limiting conditions, the RCP2.6 and RCP 4.5 presented the highest negative anomalies, mainly in the half north regions of the RS, varying from -0.5 to -5.5 Mg ha^{-1} (Figures 9A, 9B, 9D, 9E, 9G, 9H, 9J and 9K). The latest sowing dates, in January, occurred an increase of grain yield in almost the entire state among the future scenarios, with values varying from 0.5 to 4.5 Mg ha^{-1} (Figures 9P, 9Q and 9R).

For the landrace maize cultivars, under potential conditions, among sowing dates on August, September and October, it is observed the smallest anomalies, varying from -0.5 to -2.5 Mg ha^{-1}, decreasing in a rate of -0.8 Mg ha^{-1} through future scenarios. Also, the region that is more affected is the half north of RS State (Figures 10A, 10B, 10C, 10D, 10E, 10F, 10G, 10H and 10I). The sowing dates on November, December and January presented the highest negative anomalies, from -0.5 to higher than 5.5 Mg ha^{-1}, with the Northwest, Central and South regions being the areas with the more severe decreasing of grain yield (Figures 10J, 10K, 10L, 10M, 10N, 10O, 10P, 10Q and 10R). The area located far northeastern of the State, in the RCP 4.5 scenario during sowing in January, is observed positive anomalies of 0.5 Mg ha^{-1} (Figure 10Q). Under water limiting conditions, in the RCP 2.6 scenario, among the sowing dates from August to November, the negative anomalies are observed in the north region of the state, varying from -0.5 to -4.5 Mg ha^{-1} (Figures 11A, 11D, 11G and 11J). Among the RCP 4.5, mainly in sowing dates in November and December, an anomaly of -0.5 to -1.5 Mg ha^{-1} extends to the Central and South region od RS State (Figures 11K and 11N). In the latest sowing dates, in January, it is observed an increasing in maize grain yield, varying from 0.5 to 4.5 Mg ha^{-1} (Figures 11P, 11Q and 11R). In the RCP 8.5 scenario z negative anomaly is observed in the far north region of RS, from August to December, while in the other region of the state in observed anomalies varying from 0.5 to 4.5 Mg ha^{-1} (Figures 11C, 11F, 11I, 11L, 11O and 11R).

The positive effect in maize grain yield in the simulations under water limiting conditions can be attributed to the effect of the interactions of increasing temperature and rainfall (Figures 9 and 11), and the decreasing in the simulation under potential conditions can be explained by the shortening of the development cycle (Figures 8, 10 and 12D, 12E, 12F, 12J, 12K and 12L). In the literature was found studies that found the effect of the climate change scenario of the Fifth Assessment Report of the IPCC on maize yield. Lin et al. (2014) found a reduction of 11 to 46% of maize yield in a Province of China, mainly because of the temperature increasing and shorter maturity duration. Also, Araya et al. (2015) found the yield to be slightly higher than the baseline in southwestern Ethiopia, in the RCP 4.5 and 8.5 scenarios. Ma et al. (2017) also studied the effect of RCPs scenarios on maize grain yield in Colorado, USA. They found a reduction on grain yield of 21% and 14%, under full irrigation and water limiting conditions, respectively.

CONCLUSIONS

In general, under water limiting conditions, the climate changes projected by the RCPs scenarios of the Fifth Assessment Report of the IPCC (RCP 2.6, RCP 4.5 and RCP 8.5) affect negatively the maize grain yield in sites located in the north of Rio Grande do Sul State in the simulations with the Hybrid-Maize model. The sites located in the south of Rio Grande do Sul State shown to have an increasing in maize grain yield in the period of 2070-2098.

Under potential conditions, the asymmetric increasing of temperature affect maize grain yield by shortening the total duration of the developmental cycle, with negative anomalies reaching -5.5 Mg ha^{-1} by the end of period of 2070-2098.

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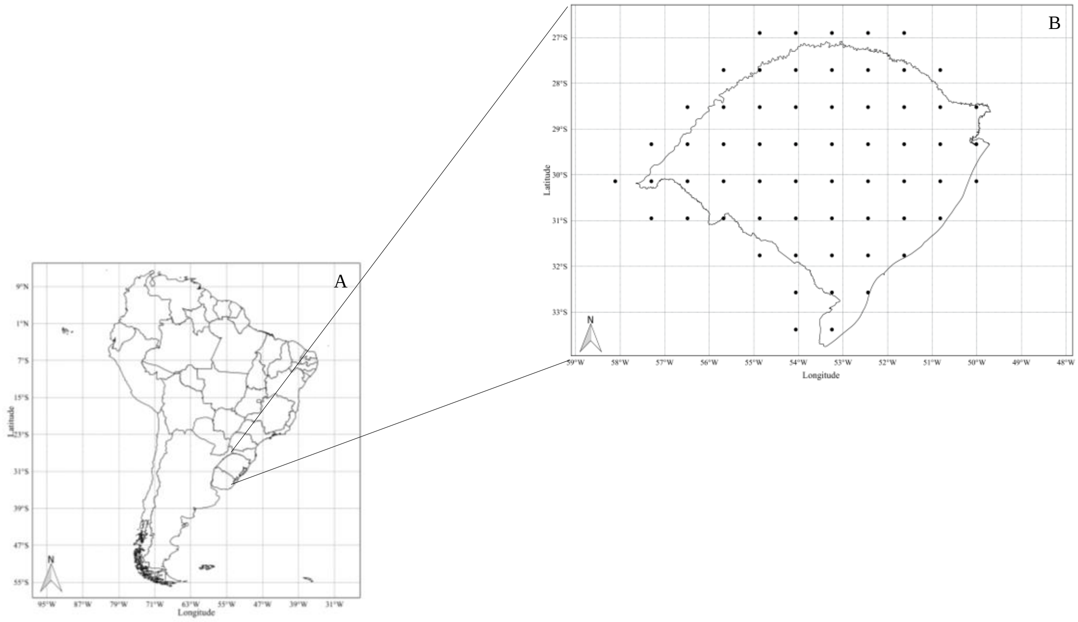


Figure 1 – Maps of South America and Brazil (A) and Rio Grande do Sul State (B).

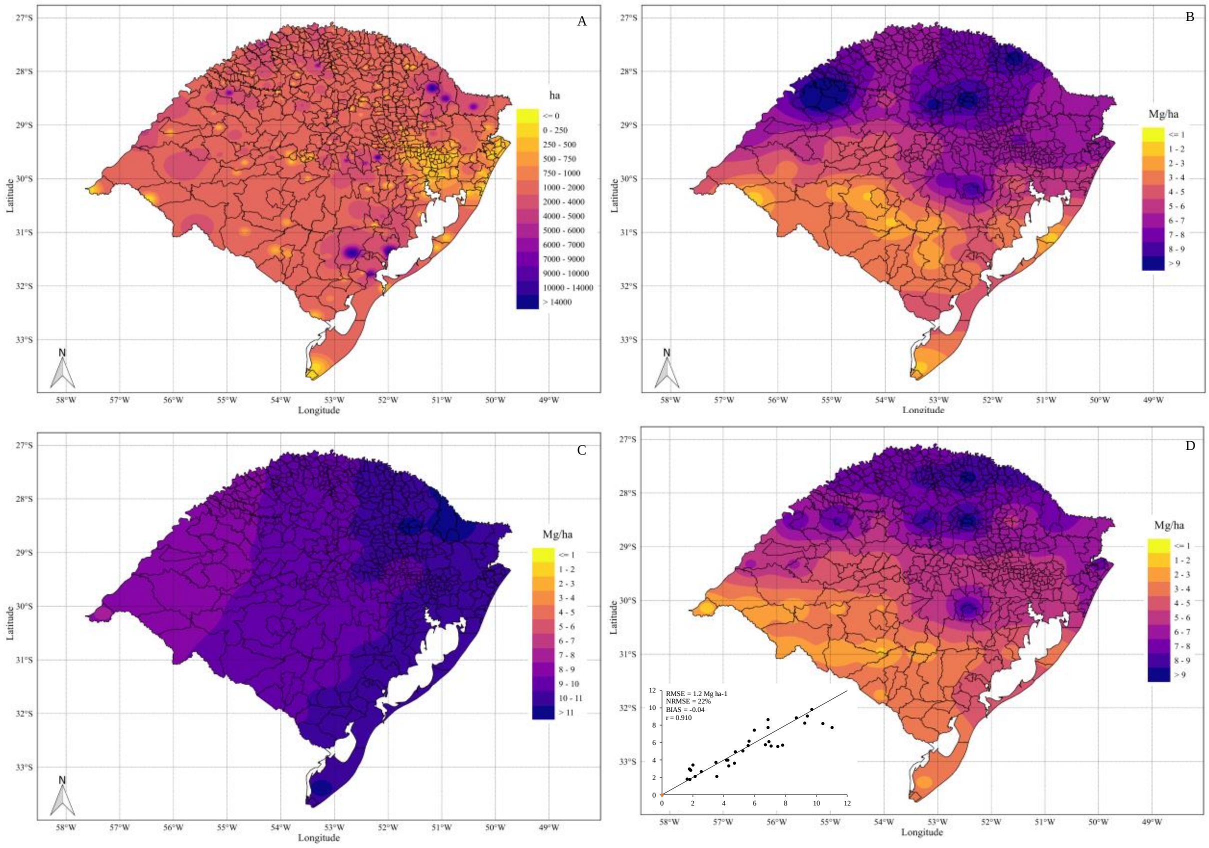


Figure 2 – Area cultivated with maize in the 2016/17 growing season (A), observed maize yield (Mg ha^{-1}) during 2000-2005 (B), potential maize yield simulated by the Hybrid-Maize model with the baseline scenario in the period of 2000-2005 (C) and maize yield under water limiting conditions simulated by the Hybrid-Maize model with the baseline scenario in the period of 2000-2005 (D) in Rio Grande do Sul State, Brazil. The simulated yield in the mean of the five growing seasons, the four cultivars and 18 sowing dates (1st, 11th, 21st) from August to January.

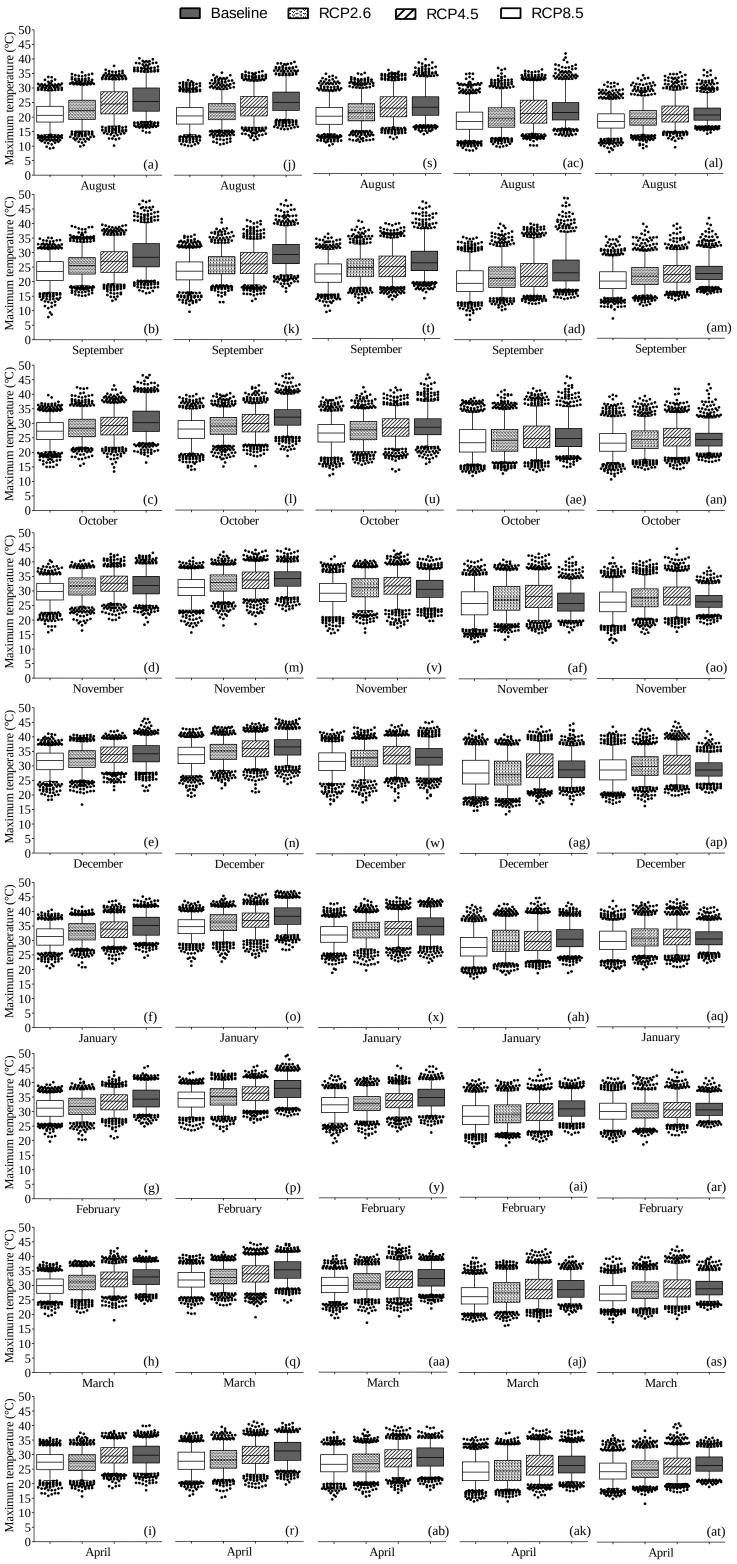


Figure 3 – The maximum daily temperature, in the baseline (1976-2005) and scenarios RCP 2.6, RCP 4.5 and RCP 8.5 (2070-2098) in north grid point (a-i), west (b-r), center (c-ab), east (d-ak) and south (e-at) of Rio Grande do Sul. In each box plot, horizontal lines represent, from bottom to top, the 5th percentile, 25th percentiles, median, 50th percentile and 95th percentile. The filles circles represent outliers.

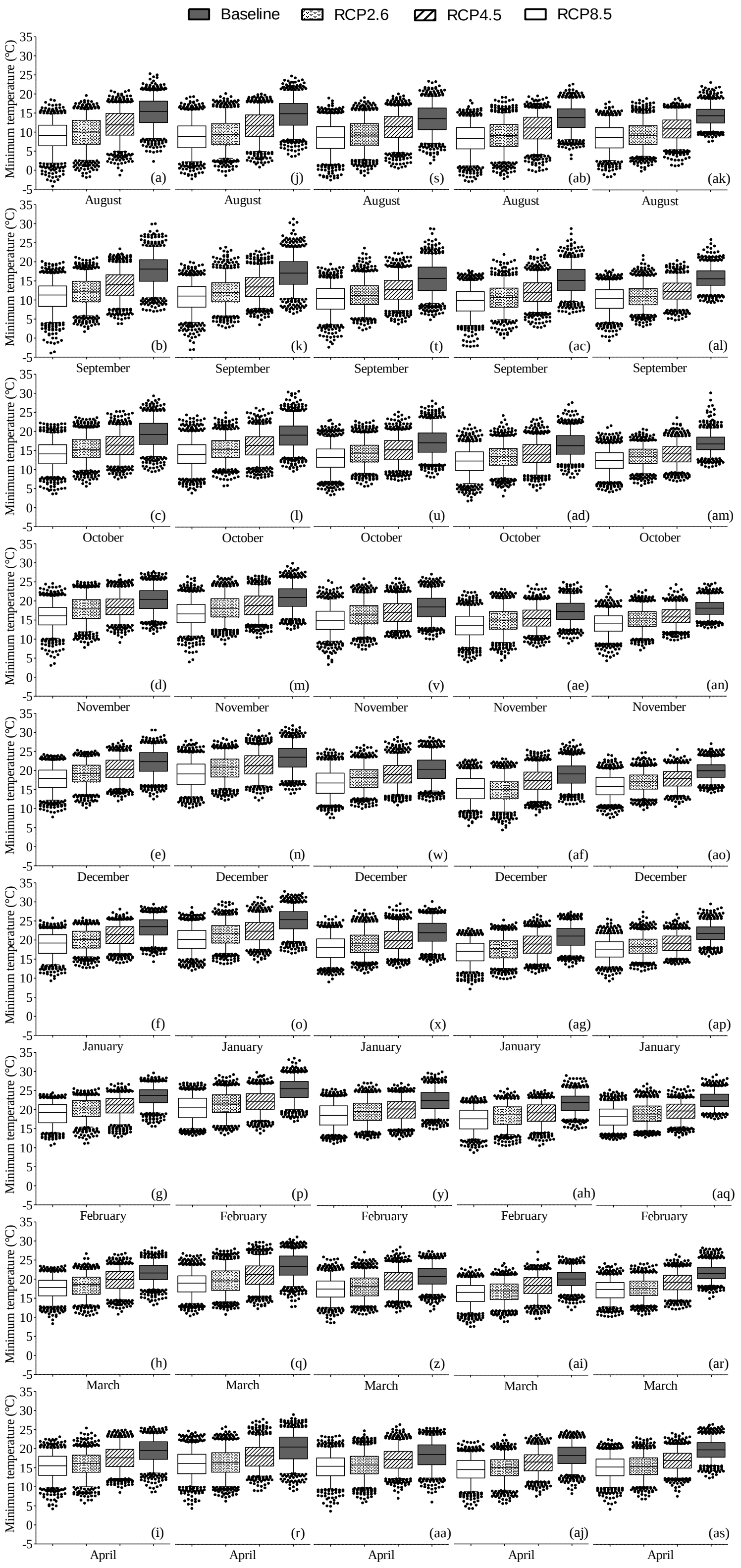


Figure 4 – The minimum daily temperature, in the baseline (1976-2005) and scenarios RCP 2.6, RCP 4.5 and RCP 8.5 (2070-2098) in north grid point (a-i), west (b-r), center (c-ab), east (d-ak) and south (e-at) of Rio Grande do Sul. In each box plot, horizontal lines represent, from bottom to top, the 5th percentile, 25th percentiles, median, 50th percentile and 95th percentile. The filles circles represent outliers.

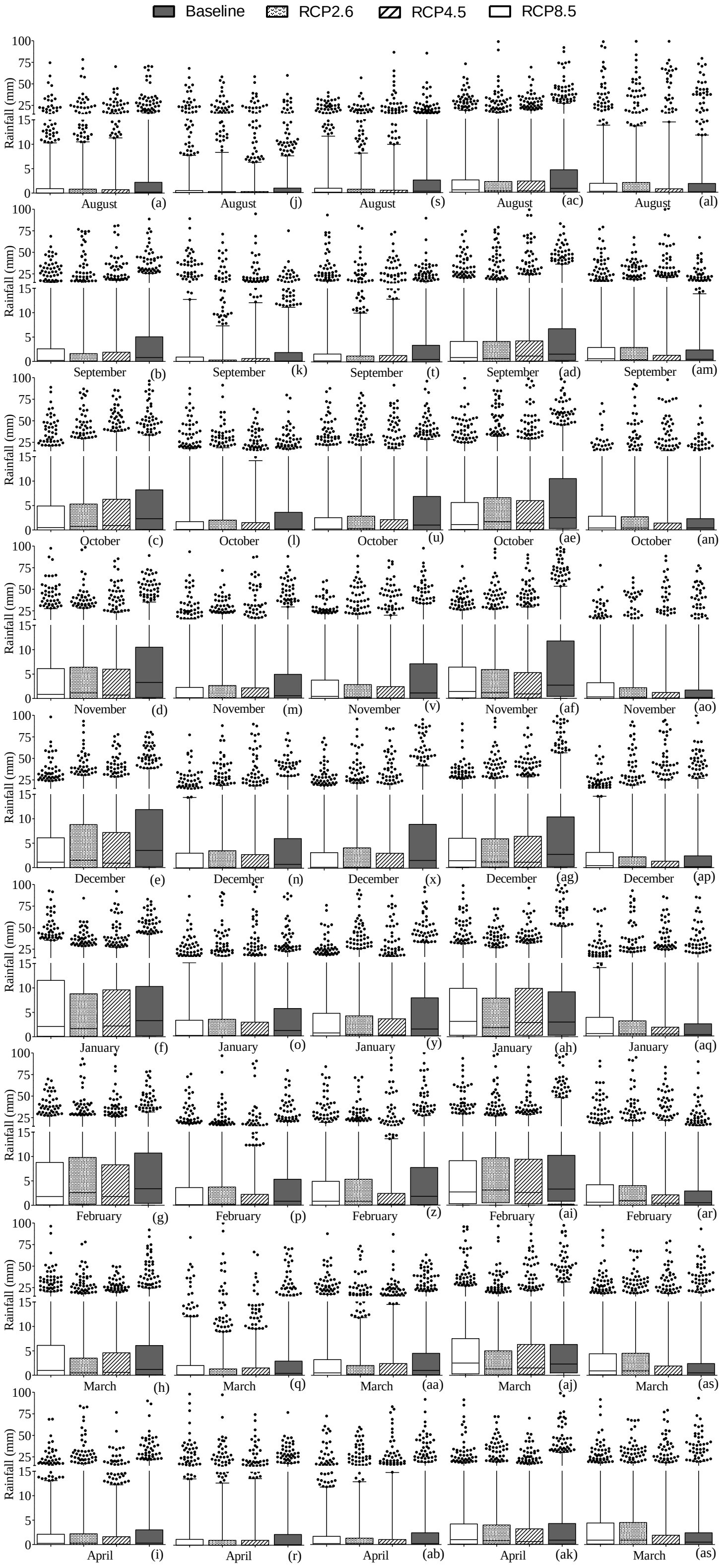


Figure 5 – The rainfall, in the baseline (1976-2005) and scenarios RCP 2.6, RCP 4.5 and RCP 8.5 (2070-2098) in north grid point (a-i), west (b-r), center (c-ab), east (d-ak) and south (e-at) of Rio Grande do Sul. In each box plot, horizontal lines represent, from bottom to top, the 5th percentile, 25th percentiles, median, 50th percentile and 95th percentile. The filles circles represent outliers.

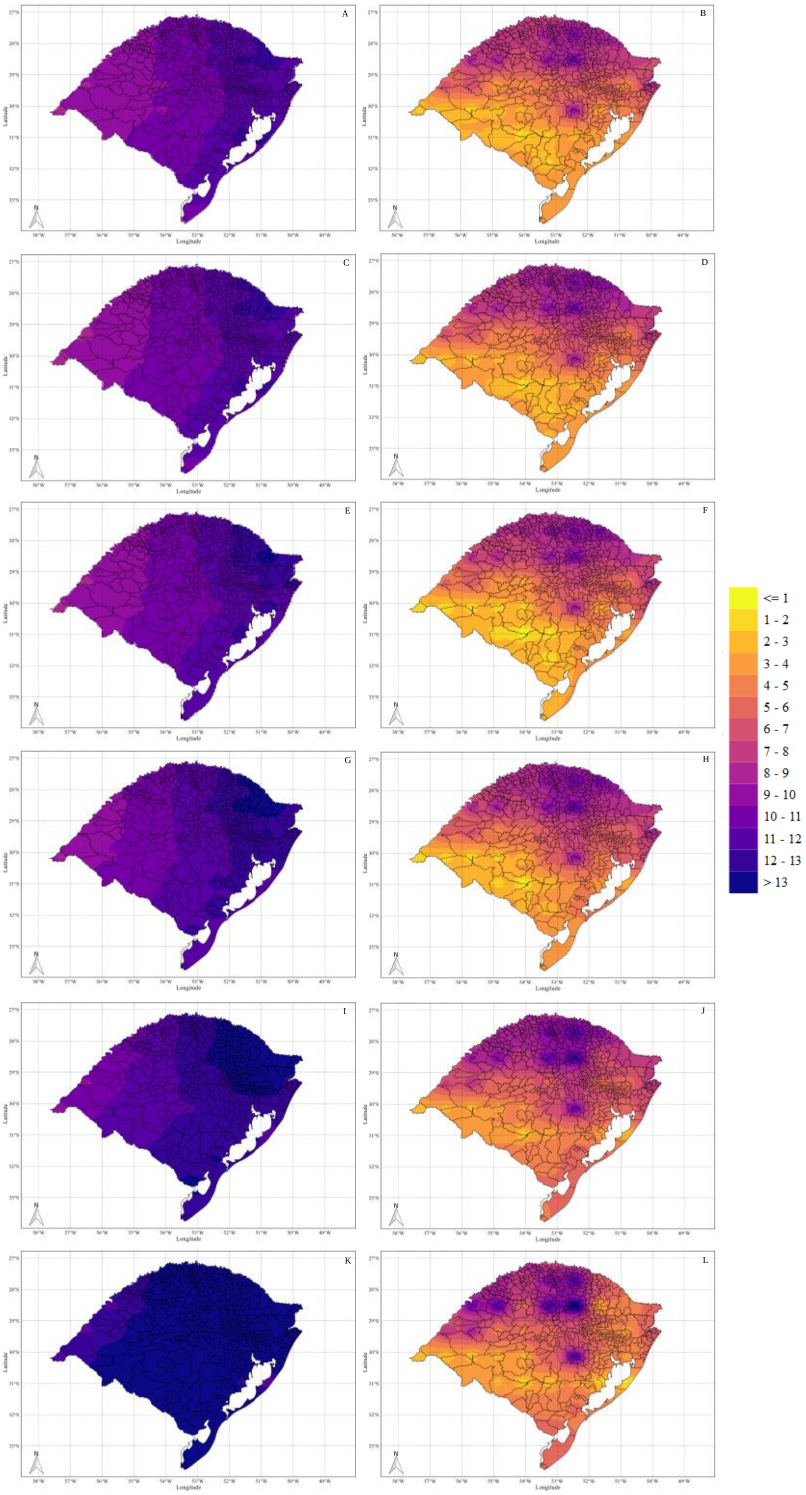


Figure 6 – Improved maize yield potential (Mg ha^{-1}) simulated by the Hybrid-Maize model in Rio Grande do Sul State, Brazil, for the baseline period (1976-2005) from August (A), September (C), October (E), November (G), December (I) and January (K), and under water limiting conditions from August (B), September (D), October (F), November (H), December (J) and January (L). Sowing dates were the 1st, 11th, and 21st of each month and the mean of the yield were calculated.

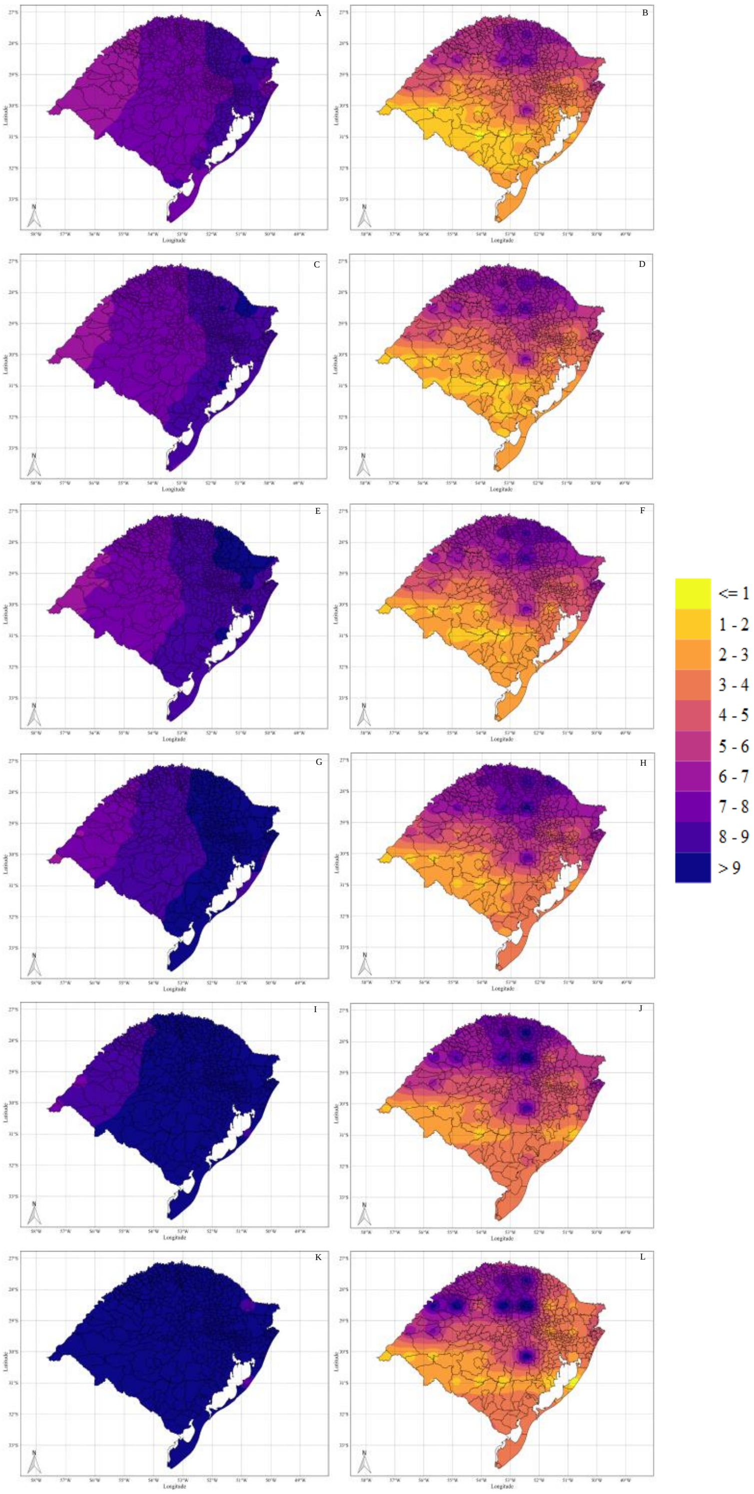


Figure 7 – Landrace maize yield potential (Mg ha^{-1}) simulated by the Hybrid-Maize model in Rio Grande do Sul State, Brazil, for the baseline period (1976-2005) from August (A), September (C), October (E), November (G), December (I) and January (K), and under water limiting conditions from August (B), September (D), October (F), November (H), December (J) and January (L). Sowing dates were the 1st, 11th, and 21st of each month and the mean of the yield were calculated.

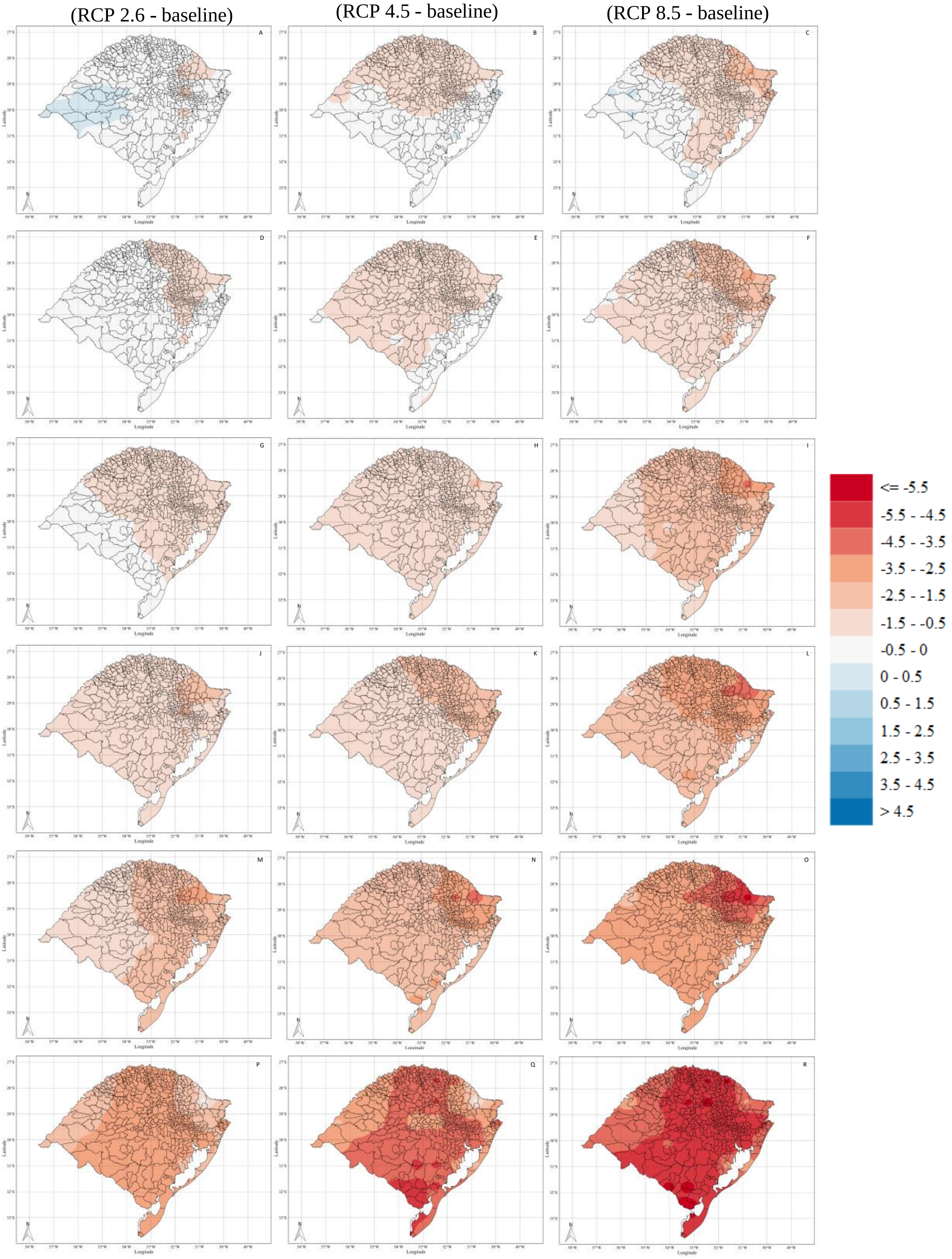


Figure 8 – Anomaly in potential improved maize yield (Mg ha^{-1}) in improved maize cultivars in Rio Grande do Sul State for three climate change scenarios in the period of 2070-2098, RCP 2.6 (A, D, G, J, M, P), RCP 4.5 (B, E, H, K, N, Q) and RCP 8.5 (C, F, I, L, O, R) from August (A-C), September (D-F), October (G-I), November (J-L), December (M-O) and January (P-R), for 18 sowing dates (1st, 11th and 21st of each month). Baseline in the period of 1976-2005.

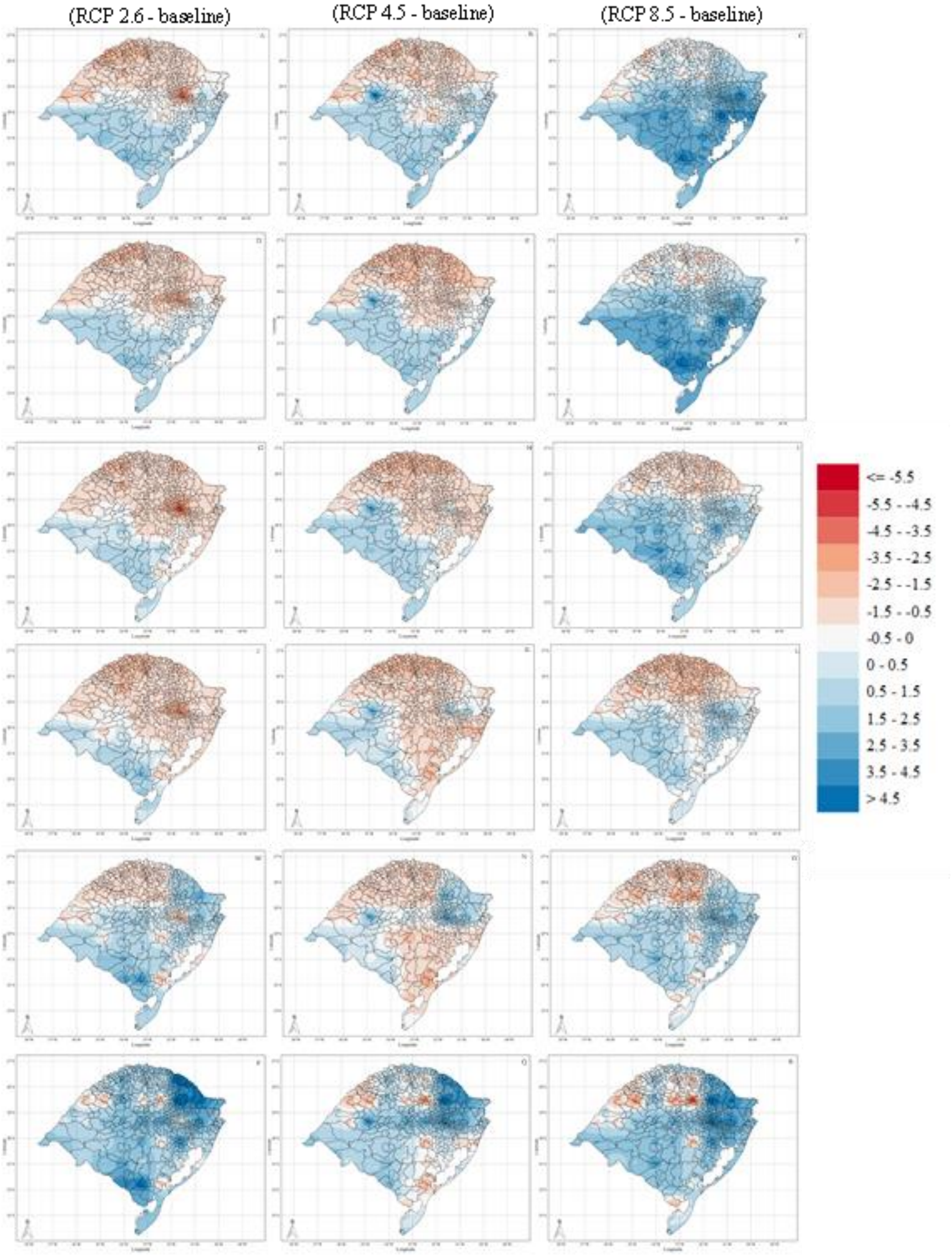


Figure 9 – Anomaly in improved maize yield under water limiting conditions (Mg ha^{-1}) in improved maize cultivars in Rio Grande do Sul State for three climate change scenarios in the period of 2070-2098, RCP 2.6 (A, D, G, J, M, P), RCP 4.5 (B, E, H, K, N, Q) and RCP 8.5 (C, F, I, L, O, R) from August (A-C), September (D-F), October (G-I), November (J-L), December (M-O) and January (P-R), for 18 sowing dates (1st, 11th and 21st of each month). Baseline in the period of 1976-2005.

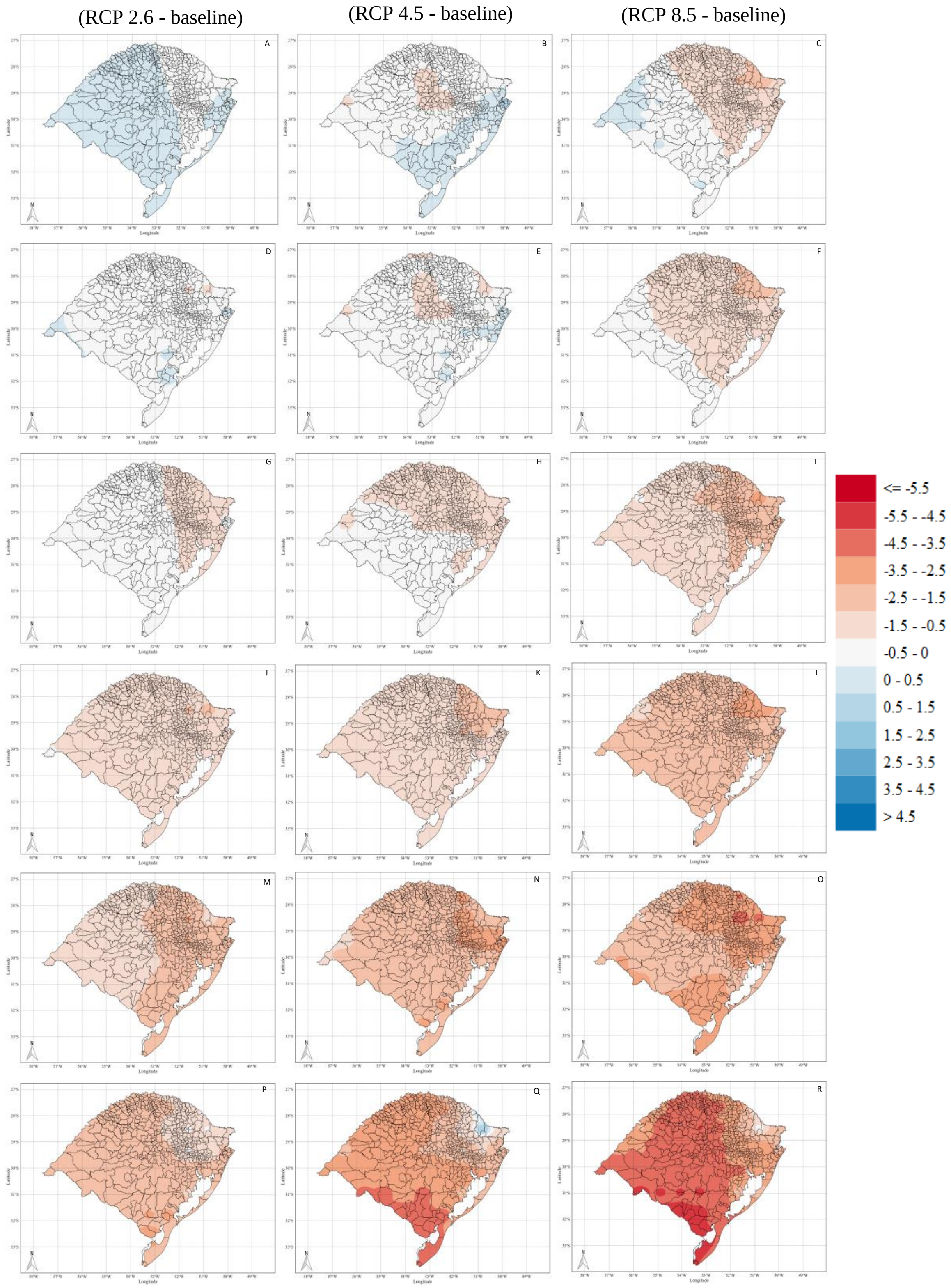
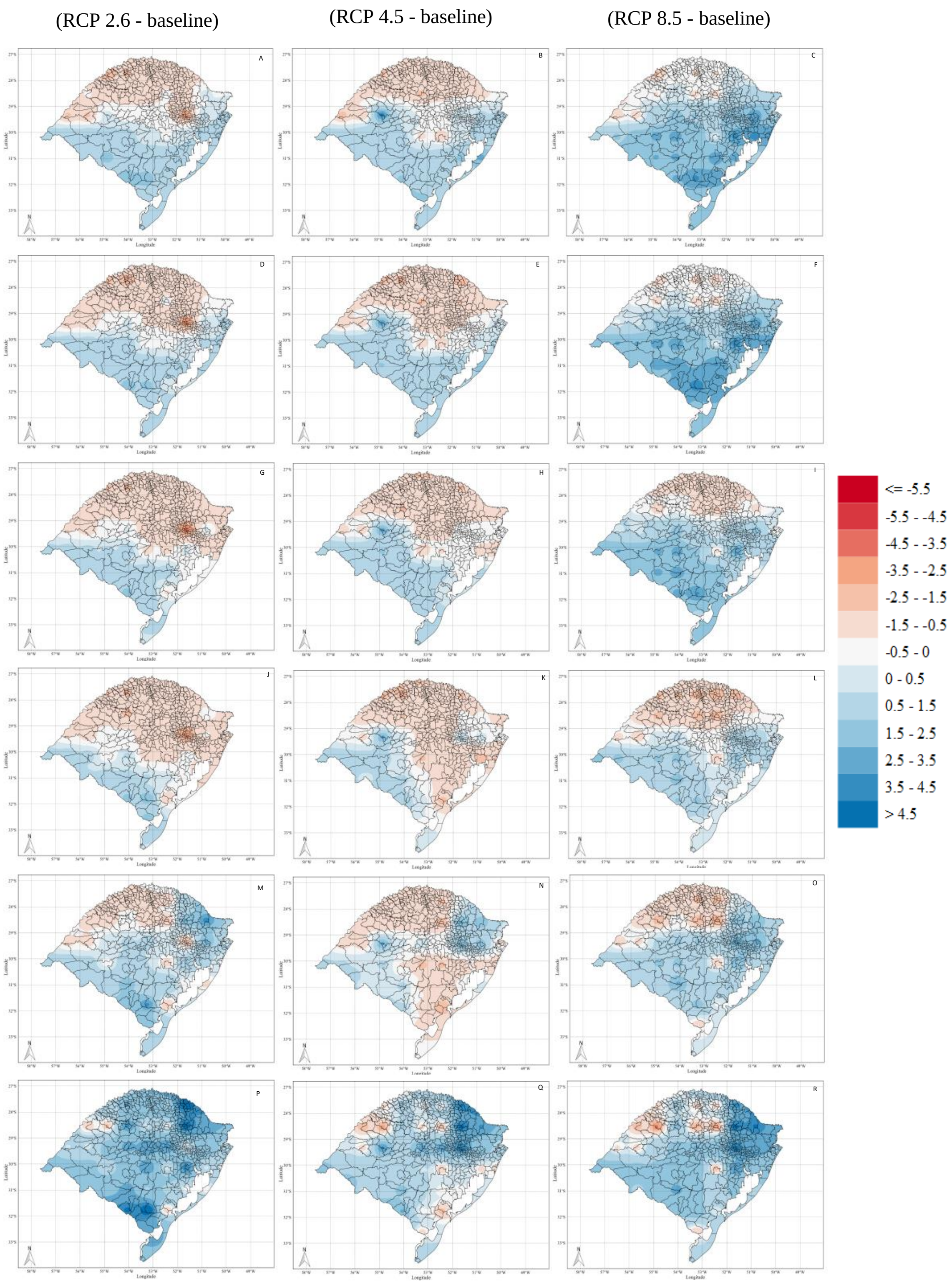


Figure 10 – Anomaly in potential landrace maize yield (Mg ha^{-1}) in improved maize cultivars in Rio Grande do Sul State for three climate change scenarios in the period of 2070-2098, RCP 2.6 (A, D, G, J, M, P), RCP 4.5 (B, E, H, K, N, Q) and RCP 8.5 (C, F, I, L, O, R) from August (A-C), September (D-F), October (G-I), November (J-L), December (M-O) and January (P-R), for 18 sowing dates (1st, 11th and 21st of each month). Baseline in the period of 1976-2005.


(RCP 2.6 - baseline)

(RCP 4.5 - baseline)

(RCP 8.5 - baseline)

Figure 11 – Anomaly in landrace maize yield under water limiting conditions (Mg ha^{-1}) in improved maize cultivars in Rio Grande do Sul State for three climate change scenarios in the period of 2070-2098, RCP 2.6 (A, D, G, J, M, P), RCP 4.5 (B, E, H, K, N, Q) and RCP 8.5 (C, F, I, L, O, R) from August (A-C), September (D-F), October (G-I), November (J-L), December (M-O) and January (P-R), for 18 sowing dates (1st, 11th and 21st of each month). Baseline in the period of 1976-2005.

8 DISCUSSÃO

O uso da modelagem matemática das culturas agrícolas tem aumentado nos últimos anos em diversos lugares do mundo devido a, principalmente, a esta ferramenta estar se tornando cada vez mais amigável e , também, por esta ferramenta auxiliar na melhoria de diversas áreas da agricultura, como por exemplo, na tomada de decisão e planejamento agrícola, visando sempre encontrar o manejo que irá otimizar os processos na planta e, consequentemente, aumentar a produtividade das culturas agrícolas, assim como é uma ferramenta muito útil no estudo da variabilidade e mudança climática e seus principais efeitos nas culturas.

Dentre os modelos de milho existentes, dois modelos agrícolas se sobressaem no meio científico, o modelo CSM-Ceres-Maize (Jones; Kiniry et al., 1986) e, um recente modelo, o Hybrid-Maize (Yang et al., 2004). Estes modelos são chamados modelos baseados em processos (*process-based models*) por considerarem processos que são responsáveis pela interação genótopo x ambiente das culturas em condições de campo. Nestes dois modelos utilizados nesta tese, são requeridos dezenas de parâmetros para rodar o modelo, enquanto que a para calibração de parâmetros genéticos, o modelo CSM-Ceres-Maize requer que sete parâmetros sejam calibrados, enquanto o modelo Hybrid-Maize apenas três (Tabela 1 desta tese).

Nesta tese, ambos os modelos foram calibrados utilizando o método da calibração cruzada, utilizada quando o número de amostrar para calibração é relativamente pequeno, o que foi o caso aqui. Os modelos foram testados para as condições de Santa Maria, RS, Brasil, a partir de dados coletados em experimento de campo. Após isso, outra análise foi realizada rodando para locais espalhados no estado e que fossem representativos ao estado, em diferentes anos agrícolas e datas de semeadura, para ver a capacidade dos modelos em simular a produtividade de milho para condições subtropicais do Brasil. Dentre os modelos, o modelo Hybrid-Maize apresentou a melhor performance em similar a fenologia, com RMSE de 1,8 das (Figura 1A, artigo 2), enquanto o CSM-Ceres-Maize apresentou erro de 8 dias (Figura 1B, artigo 2). Na simulação da produtividade de grãos, ambos os modelos apresentaram o mesmo RMSE de 0.7 Mg ha^{-1} (Figuras 2A e 2B, artigo 2). Com relação ao índice de área foliar (IAF), o modelo CSM-Ceres-Maize subestimou para todas as cultivares, enquanto o Hybrid-Maize conseguiu capturar a evolução do IAF (Figuras 3 e 4, artigo 2). Quando as rodadas para simular a produtividade de grãos foram realizadas para mais locais no estado do Rio Grande do Sul, o modelo Hybrid-Maize foi capaz de capturar a diferença entre locais, clima e solo, apresentando os melhores resultados nas simulações, comparado com o CSM-Ceres-Maize (Figura 5, artigo 2).

A partir do Painel Intergovernamental de Mudança Climática (IPCC) está relatado o aumento dos gases do efeito estufa e seus impactos no clima terrestre (IPCC, 2007, 2013). Recentemente, uma nova versão do relatório do IPCC foi lançada, considerando novos cenários de emissão, o AR (IPCC, 2013). Neste relatório foram formulados os cenários RCP 2,6, RCP 4,5, RCP 6,0 e RCP 8,5, desde um cenário otimista a um pessimista, com projeções de aumento de 1,1 a 4,8°C na temperatura média do ar em vários locais do Planeta. As projeções até o final do século para aumento da concentração de CO2 atmosférico variam de 420 a 918 ppm, dependendo do cenário (IPCC, 2013).

A produtividade de milho no Rio Grande do Sul é maior, e mais significativa, na metade norte do estado (Figura xxx, artigo 3). Em se confirmando a mudança climática até o final deste século, as propriedades nestes locais serão as mais prejudicadas devido ao efeito do aumento de temperatura e baixa precipitação (Figuras xxxxx, artigo 3), principalmente para semeaduras realizadas em agosto, setembro, outubro e novembro. Em alguns locais, dependendo da data de semeadura, há um aumento na produtividade de milho, dependente da interação do aumento da temperatura e precipitação disponível durante o ciclo da cultura (Figuras xxx, artigo 3).

Como no RS a agricultura familiar é bastante expressiva, e nestas propriedades são utilizadas cultivares crioulas de milho, é necessário um esforço no estudo da adaptabilidade destes materiais e, também, de como será a adaptação destes estabelecimentos rurais aos efeitos da mudança climática, a fim de mitigar os efeitos negativos da mudança climática.

9 CONCLUSÃO

A avaliação dos modelos CSM-Ceres-Maize e Hybrid-Maize indicaram que ambos os modelos são capazes de simular o crescimento, desenvolvimento e produtividade de milho com diferente variabilidade genética em escala local, porém em uma maior escala, o modelo Hybrid-Maize se sobressaiu em relação ao CSM-Ceres-Maize, capturando o efeito de data de semeadura, anos agrícolas, diferentes regiões e diferentes cultivares.

Nas simulações para a produtividade de milho no estado em cenários de mudança climática, o modelo Hybrid-Maize, na condição potencial prevê uma diminuição na produtividade para cultivares crioulas e melhoradas de milho, devido principalmente aio encurtamento do ciclo de desenvolvimento, que acarreta em uma diminuição da produtividade. Na condição com limitação de água, os modelos mostraram diminuição na produtividade na metade norte do estado, região mais significativa em produção de milho, e aumento de produtividade na metade sul do Rio Grande do Sul, devido ao efeito combinado de temperatura e disponibilidade de precipitação.

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