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SIMULAÇÃO DA PRODUTIVIDADE DE MANDIOCA PARA O ESTADO DO RIO GRANDE DO SUL

DISSERTAÇÃO DE MESTRADO

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Santa Maria, RS, Brasil
2013

SIMULAÇÃO DA PRODUTIVIDADE DE MANDIOCA PARA O ESTADO DO RIO GRANDE DO SUL

Luana Fernandes Gabriel

Dissertação apresentada ao Curso de Mestrado do Programa de Pós-graduação em Agronomia, Área de concentração em Produção Vegetal, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do grau de **Mestre em Agronomia**

Orientador: Prof. Nereu Augusto Streck

Santa Maria, RS, Brasil
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Universidade Federal de Santa Maria
Centro de Ciências Rurais
Programa de Pós-graduação em Agronomia

A Comissão Examinadora, abaixo assinada,
aprova a Dissertação de Mestrado

**SIMULAÇÃO DA PRODUTIVIDADE DE MANDIOCA PARA O ESTADO
DO RIO GRANDE DO SUL**

elaborada por
Luana Fernandes Gabriel

como requisito parcial para a obtenção do grau de
Mestre em Agronomia

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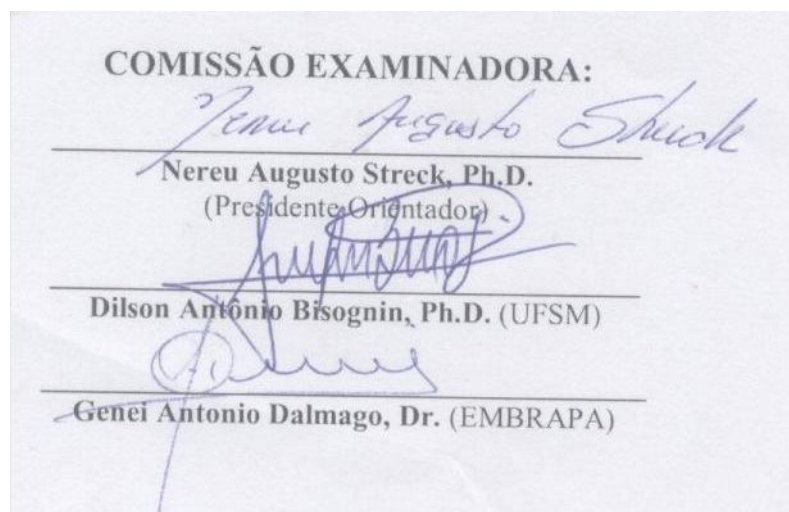
Santa Maria, 22 de fevereiro de 2013.

Aos meus pais Edson e Irma, ao meu marido Maicom e a todas as pessoas que sempre estiveram ao meu lado.

Dedico...

AGRADECIMENTOS

RESUMO

SIMULAÇÃO DA PRODUTIVIDADE DE MANDIOCA PARA O ESTADO DO RIO GRANDE DO SUL

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Local e data da defesa: Santa Maria, 22 de fevereiro de 2013

A mandioca tem um papel importante na segurança alimentar nas regiões tropicais, onde é a terceira maior fonte de alimentos. No Estado do Rio Grande do Sul é utilizada principalmente como cultura de subsistência nas pequenas propriedades familiares para a alimentação humana e animal. O objetivo nesta dissertação foi adaptar e testar um modelo baseado em processos para a cultura da mandioca em ambiente subtropical no Estado do Rio Grande do Sul. Foram realizadas três modificações no modelo em relação à versão original de Matthews e Hunt (1994): considerou-se um terceiro "relógio" independente no desenvolvimento de mandioca para o início da tuberização, substituímos o sub-modelo da taxa de aparecimento de folhas pelo modelo de Wang e Engel modificado para a mandioca, e foi modificado o sub-modelo de senescência foliar. A calibração do modelo foi realizada através do método dos mínimos quadrados (Matthews e Hunt, 1994), que minimizou o erro quadrático entre os valores observados e estimados, com um total de 16 parâmetros calibrados. Um total de 25 conjuntos de dados independentes de experimentos conduzidos em quatro locais no Estado do Rio Grande do Sul (Santa Maria, Glorinha, Vera Cruz e Rio Pardo) foram utilizados para testar o desempenho do modelo e uma análise de sensibilidade foi realizada no modelo GUMCAS para 17 locais em todo o Estado do Rio Grande do Sul. Em geral, a calibração e as modificações introduzidas no modelo GUMCAS resultou em boas simulações de processos ecofisiológicos chave, tais como o desenvolvimento e crescimento de folhas, bem como o rendimento de raízes tuberosas para um genótipo de mandioca adaptado à região subtropical. O modelo foi capaz de captar as diferentes condições ambientais encontradas no Rio Grande do Sul e com algumas adaptações na introdução dos dados foi capaz de simular diferentes práticas de manejo, tais como plantio, espaçamento, densidade de plantas, poda verde, dois ciclos de crescimento (mandioca de sobreano), bem como o efeito de eventos climáticos extremos, como o granizo.

Palavras-chave: GUMCAS. Modelagem. Segurança alimentar. Cultura energética.

ABSTRACT

Master of Science Dissertation
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SIMULATING CASSAVA YIELD FOR THE RIO GRANDE DO SUL STATE

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Location and date of presentation: Santa Maria, February 22th, 2013.

Cassava plays an important role for food security in the tropics, where it is the third main food source. In Rio Grande do Sul State, Brazil, cassava is a subsistence crop for small farms, who use cassava for human and livestock food. The objective of this dissertation was to adapt and test a process-based model for the cassava crop in subtropical environment of the State of Rio Grande do Sul. We made three modifications in the model compared to the original version in Matthews and Hunt (1994): we considered a third independent "clock" in the cassava development for the onset of starch accumulation, we replaced the rate of leaf appearance sub-model, by the Wang e Engel model modified for cassava, and we modified the leaf senescence sub-model. Calibration of the model was performed by estimating parameters using the trial and error approach (Matthews and Hunt, 1994) that minimized the root mean square error between observed and estimated values, with total of 16 parameters were calibrated. A total of 25 independent datasets from experiments conducted in four sites of Rio Grande do Sul State (Santa Maria, Glorinha, Vera Cruz and Rio Pardo) were used for testing the model performance and a sensitivity analysis was performed running the GUMCAS model for 17 locations throughout the State of Rio Grande do Sul. In general, the calibration and modifications introduced in the GUMCAS model resulted in good simulations of some key ecophysiological processes such as leaf development and growth as well as of storage roots yield for a cassava genotype adapted to the subtropics. The model was able to capture different environmental conditions accross the Rio Grande do Sul State and with some adaptations for inputting data was able to simulate different management practices such as planting date, plant spacing, plant density, partial above-ground pruning during the growing cycle and two growing cycles as well as the effect of extreme weather events such as hail.

Key-words: GUMCAS. Modeling. Food security. Energy crops.

LISTA DE FIGURAS

INTRODUÇÃO

REVISÃO BIBLIOGRÁFICA

ARTIGO

LISTA DE TABELAS

SUMÁRIO

1 INTRODUÇÃO

O aumento da população mundial, que chegou a 6,8 bilhões de pessoas, a expectativa de que atinja 9 bilhões de pessoas até 2050, e a má distribuição da renda, especialmente nos países em desenvolvimento e na África, indicam que a segurança alimentar será um dos principais desafios da humanidade nas próximas décadas, pois no cenário atual já existem pelo menos 800 milhões de pessoas subnutridas e outras 2 bilhões de pessoas com falta de alimentos intermitente ou em "fome silenciosa" (FAO, 2012). A mandioca tem um papel importante na segurança alimentar nas regiões tropicais, onde é a terceira maior fonte de alimentos, após arroz e milho (FAO, 2012) e seu cultivo se estende às regiões de clima subtropical, como o Rio Grande do Sul (SCHONS et al., 2009) onde é utilizada principalmente como cultura de subsistência nas pequenas propriedades familiares para a alimentação humana e animal (FAGUNDES et al., 2010a).

Até 2002, a mandioca foi considerada uma cultura órfã, negligenciada por parte dos investidores e pesquisadores na área científica. Na última década um esforço internacional iniciou para mudar este cenário, através da Reunião Estratégica da Parceria Global de Mandioca para o Século 21 (GCP21), com a qual a meta é melhorar a segurança alimentar global, a produção sustentável, e o desenvolvimento e uso de variedades melhoradas de mandioca. Assim, a mandioca passou a ter mais espaço nos grupos de pesquisa (FAUQUET et al., 2012). No Estado do Rio Grande do Sul, em Santa Maria, a pesquisa com a cultura da mandioca iniciou em 2005 pelo grupo de pesquisa de Agrometeorologia da Universidade Federal de Santa Maria, e se estende até o presente, com o intuito de caracterizar o crescimento e desenvolvimento dessa cultura em ambiente subtropical.

O Brasil é o segundo maior produtor mundial, atrás apenas da Nigéria (FAO, 2012). Na safra de 2011 foram colhidos 25.441.653 t de raízes numa área de 1.741.226 ha, com uma produtividade média de 14.611 t ha^{-1} (IBGE, 2012), bem abaixo do potencial produtivo que pode chegar até 60 t ha^{-1} (COCK, 1990). O Estado do Pará é o maior produtor nacional, o qual produz 4.647.552 t, seguido do Paraná com 4.179.245 t, da Bahia com 2.966.230 t, do Maranhão com 1.780.279, de São Paulo com 1.321.297 e do Rio Grande do Sul, que na safra de 2011 produziu 1.302.929 t (IBGE, 2012). Nos estados do Norte e Nordeste, a mandioca tem grande importância

cultural, sendo utilizada para consumo humano e animal, tanto as raízes quanto as folhas. No RS a cultura da mandioca tem maior expressão nas pequenas propriedades rurais da região Norte e Depressão Central do Estado (FAGUNDES et al., 2010a), como cultura de subsistência. Apesar da quantidade produzida e a área plantada ter decrescido da década de 90 para cá no Estado (Figura 1), a mandioca é uma cultura com grande potencial produtivo no Rio Grande do Sul, com produtividade de raízes tuberosas de até 30 a 36 t ha^{-1} em nível experimental em Santa Maria, Região Central do RS (SCHONS et al., 2009; FAGUNDES et al., 2010a). No Estado ainda não há uma cadeia agroindustrial estruturada, mas há uma mobilização e preocupação por parte dos pesquisadores e técnicos da extensão rural para o incentivo a produção de mandioca, e pelo grande potencial para a produção de etanol (SALLA; CABELLO, 2010).
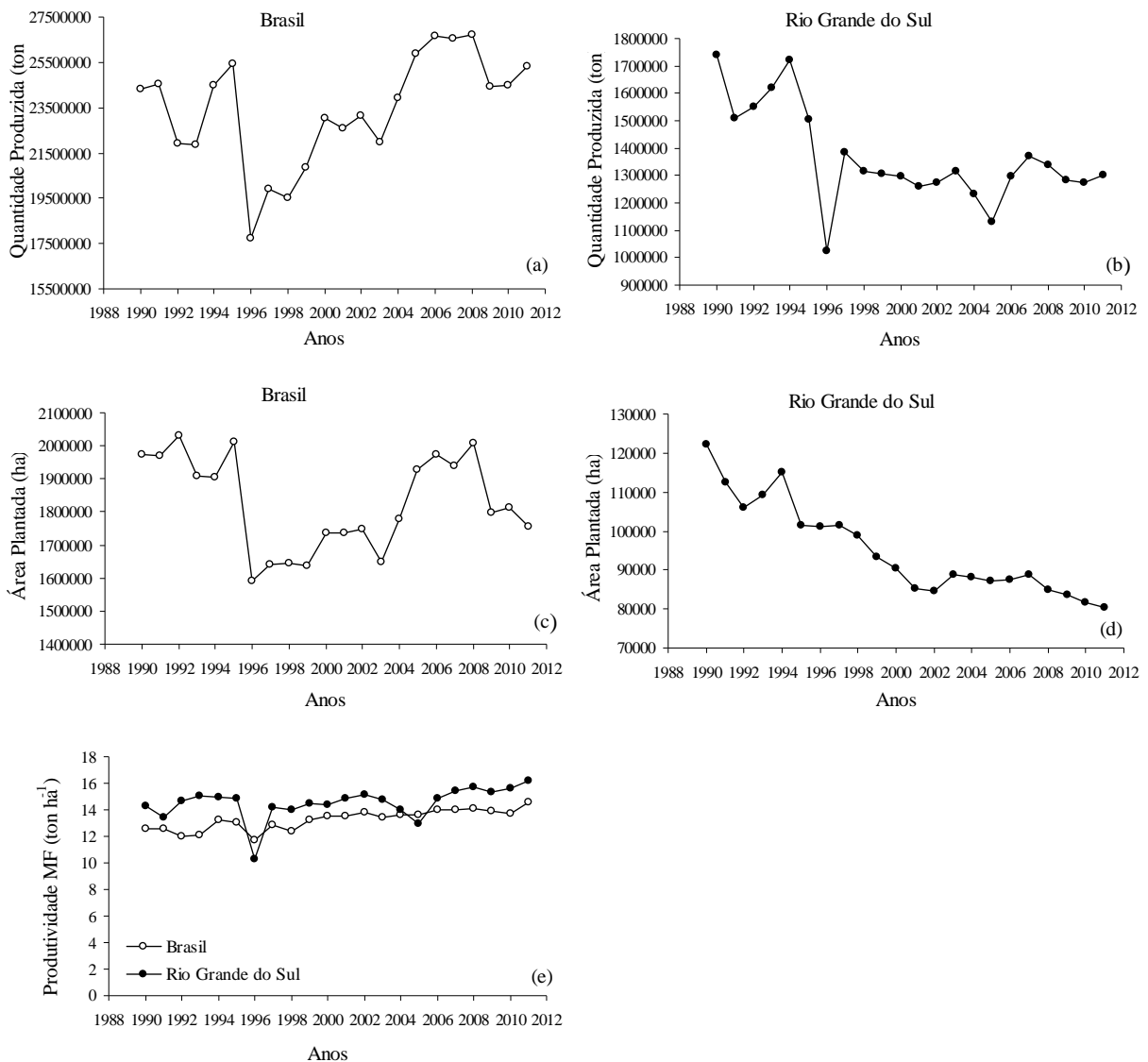
Figura 1- Quantidade produzida (ton), área plantada (ha) e produtividade de massa fresca de raízes tuberosas (ton ha^{-1}) de mandioca no Brasil e no Rio Grande do Sul de 1990 a 2011 (IBGE, 2012).

A modelagem matemática de uma cultura agrícola, mais especificamente o uso de modelos baseados em processos, ajudam a entender como uma planta de determinada cultura funciona, pois são modelos ecofisiológicos, além se ser uma ferramenta que pode auxiliar na tomada de decisões referentes ao manejo, no agendamento de práticas culturais como aplicação de fertilizantes, herbicidas, de acordo com a fase de desenvolvimento da cultura (STRECK et al., 2003a,b), como em conhecer a influência de diferentes espaçamentos, épocas de plantio no crescimento e desenvolvimento das culturas, pode auxiliar em programas de melhoramento, através da seleção de linhagens avançadas de acordo com a resposta a diferentes ambientes (BANTERNG et al., 2006; HAMMER et al., 2010), na previsão sazonal de safra (BANNAYAR et al., 2003; SHIN et al., 2010), e no estudo do impacto de cenários climáticos futuros nessas culturas (STRECK et al., 2006; LAGO et al., 2008; WALTER et al., 2010; STRECK et al., 2010; FAGUNDES et al., 2010b).

Para usar um modelo matemático de uma cultura que foi desenvolvido e calibrado em outra região diferente da qual pretende-se realizar o estudo, com outros genótipos, é necessário que esse modelo seja devidamente calibrado e testado para as condições da região a ser estudada, e que ele consiga captar as características fisiológicas que essa planta apresenta quando são cultivadas em diferentes regiões.

Portanto, os objetivos nesta dissertação foram:

1- Selecionar um modelo matemático baseado em processos com a cultura da mandioca;

2- Calibrar o modelo de mandioca para ser sensível a diferentes manejos que são realizados na cultura da mandioca, como diferentes densidades populacionais, diferentes épocas de plantio, cultivo de ano e sobreano, efeito da poda verde e de eventos meteorológicos como o granizo;

3- Testar o modelo de mandioca com dados de experimentos realizados em diferentes anos agrícolas, diferentes manejos e diferentes locais do Estado do Rio Grande do Sul.

4- Realizar uma análise de sensibilidade do modelo às variações das condições meteorológicas existentes em diferentes anos agrícolas para todas as regiões climáticas do Estado do Rio Grande do Sul em ambiente subtropical.

2 REVISÃO DE LITERATURA

2.1 Caracterização e uso da mandioca

A mandioca (*Manihot esculenta* L. Crantz) é originária da América do Sul, da região sul da Amazônia (LEOTARD et al, 2009) e nos séculos XVI e XVII foi amplamente disseminada pelos portugueses para áreas tropicais e subtropicais da África, Ásia e Caribe. Além disso, a mandioca se tornou rapidamente um alimento básico em muitos destes lugares devido a tolerância às condições adversas de clima e solo (ALVES, 2002). Pertence à família Euphorbiaceae, a qual tem como característica a presença de látex e glicosídeos cianogênicos. A planta de mandioca é um arbusto perene de hábito indeterminado propagado vegetativamente através de pedaços do caule denominados manivas (CÂMARA; GODOY, 1998). Condições ambientais (baixas temperaturas e déficit hídrico prolongado) levam a planta a um período dormente ou de repouso (CONCEIÇÃO, 1987; ALVES, 2006), e neste caso, a cultura é geralmente cultivada de forma anual, com plantio no início do período das chuvas nas regiões tropicais e na primavera em regiões subtropicais como no Sul do Brasil.

A estrutura morfológica da planta de mandioca pode diferir de acordo com o genótipo. Alguns apresentam o caule ereto (monopodial), enquanto outros possuem caule ramificado com inflorescência (simpódio) com duas, três ou quatro hastes, denominadas ramificações simpodiais (PEIXOTO, 1999; CARVALHO; FUKUDA, 2006), conforme ilustrado na Figura 2. O número de ramificações simpodiais pode ainda depender da sensibilidade do genótipo ao fotoperíodo, de modo que fotoperíodos longos estimulam a produção de ramificações simpodiais (KEATING et al., 1982). Dependendo do genótipo, a planta pode apresentar brotações laterais, que se originam da axila das folhas da haste principal, produzindo novas hastes laterais (MATTHEWS; HUNT, 1994).
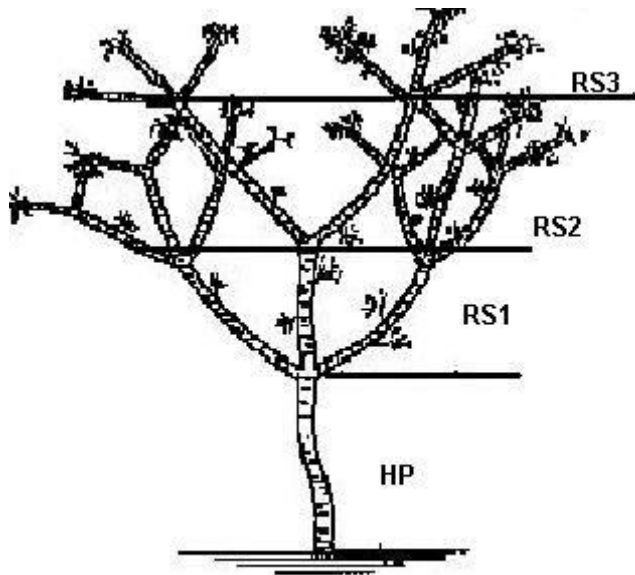
Figura 2- Estrutura de uma planta de mandioca, sendo HP a haste principal, RS1 a primeira ramificação simpodial, RS2 a segunda ramificação simpodial e RS3 a terceira ramificação simpodial. Adaptado de Fagundes et al. (2009).

A parte mais importante da planta é a raiz, rica em fécula, utilizada tanto na alimentação humana e animal quanto como matéria prima para diversas indústrias (CEPLAC, 2012). A mandioca classificada como de mesa na sua maioria é comercializada in natura, mas também vem crescendo a comercialização da mandioca pré-cozida e congelada. A mandioca classificada para indústria tem uma variedade de usos, dos quais as farinhas e a fécula são as mais importantes (CARDOSO; GAMEIRO, 2006). Na indústria, tem larga utilização farmacêutica, podendo substituir derivados de trigo na indústria alimentar (INTERLICHE, 2002). A parte aérea pode ser utilizada na alimentação animal, onde as folhas e hastes são utilizadas na forma de silagem, feno, ou mesmo frescas, e também na alimentação humana, na preparação de alimentos típicos das Regiões Norte e Nordeste do Brasil (CARDOSO; GAMEIRO, 2006). Ainda, devido ao elevado teor de amido nas suas raízes, a mandioca é uma cultura com bom potencial para produção de etanol (FUKUDA; OTSUBO, 2003), sendo que a mandioca consome menos energia do que a cana-de-açúcar e o milho considerando o sistema de produção agronômico (SALLA; CABELLO, 2010).

2.2 Zoneamento Agroclimático da cultura da mandioca no Estado do Rio Grande do Sul

Para o Zoneamento Agroclimático da cultura da mandioca no Estado do Rio Grande do Sul (MALUF et al., 2011), para a delimitação das regiões de maior aptidão agroclimática e de menores riscos climáticos para cultivo de mandioca no Rio Grande do Sul, foram usados como índices a temperatura média de verão (dezembro, janeiro e fevereiro) e a deficiência hídrica mensal. Foi considerado 21 ºC como a temperatura média de verão, a partir da qual ocorreram as maiores disponibilidades térmicas para crescimento. Considerou-se 150 mm como valor de deficiência hídrica anual, acima do qual podem ocorrer limitações ao rendimento da mandioca. Também foi utilizado, como índice de zoneamento, a temperatura média do solo desnudo a 5 cm de profundidade a partir do 3º decêndio de agosto. Foi usada a temperatura do solo desnudo a 5 cm de profundidade de 16 ºC, considerada a temperatura a partir da qual o enraizamento e brotação é satisfatória e uniforme das manivas. É considerado ainda como índice de zoneamento a ocorrência de temperatura mínima do ar de 3 ºC no abrigo meteorológico (1,5 m), como condição de formação de geada.

As áreas de zoneamento são classificadas para plantio de mandioca de 1º ciclo e 2º ciclo (ano e sobreano), e para cada município dentro do zoneamento agroclimático de mandioca no Estado é indicado o período recomendado de plantio (MALUF et al., 2011). Os municípios indicados para o plantio no início do período recomendado (de 21/08 a 10/09) e que pode ser realizado cultivo de ano e sobreano são as regiões que compreendem grande parte do Alto Uruguai e parte das Missões e uma faixa que vai da metade da Depressão Central até o Litoral norte. Os municípios indicados para o plantio no meio do período recomendado (de 11/09 a 20/09) e que pode ser realizado cultivo de ano é a maior parte do Estado, com exceção de parte do litoral Sul e grande parte do Planalto Superior e Serra do Nordeste. Para o fim do período de plantio recomendado (21/09 a 30/11) algumas cidades da Serra do Nordeste e Planalto Superior tornam-se aptas para o plantio de mandioca de ano, sendo que as demais cidades dessas regiões e do litoral Sul continuam inaptas para o plantio.

2.3 Modelos de simulação de crescimento, desenvolvimento e produtividade da mandioca

Modelos de simulação do crescimento, desenvolvimento e produtividade tem sido propostos para várias culturas, inclusive a mandioca (BOERBOOM, 1978; COCK et al., 1979; FUKAI; HAMMER, 1987; GUTIERREZ et al., 1988; GIJZEN et al., 1990; MATTHEWS; HUNT, 1994). Esses modelos foram sendo aperfeiçoados com o tempo, a medida que mais conhecimento sobre a fisiologia e a resposta em diferentes condições ambientais eram obtidos na pesquisa sobre a cultura. Esses modelos podem ser divididos de acordo com a forma que é calculada a partição de matéria seca, se é particionada de acordo com um valor fixo ou se são modelos "spill-over", no qual o crescimento de folhas e haste são calculados independentemente do total produzido no dia, e possuem prioridade na produção de novos assimilados, sendo que raízes tuberosas recebem o restante do total que foi produzido no dia. Esses últimos modelos são mais responsivos às variações meteorológicas, sendo assim mais representativos da interação planta-ambiente.

O primeiro modelo de mandioca foi descrito por Boerboom (1978), o qual apresenta uma relação linear entre a massa seca de raízes tuberosas e a massa seca total da planta para algumas cultivares em diferentes condições. Cock et al. (1979) apresentam um modelo calibrado com cultivares colombianas no qual a taxa de crescimento da cultura é uma função do Índice de Área Foliar (IAF), e o crescimento de folhas é calculado em função da taxa de aparecimento de folhas por ápice, número de ápices por área, tamanho de folha e longevidade da folha. Nesse trabalho após vários experimentos pode-se perceber que o crescimento de folhas e haste tem prioridade, e o excesso de fotoassimilados adquiridos no dia serão translocados para o acumulo nas raízes. Nesse modelo ainda não se considera o efeito da temperatura, radiação solar ou stress hídrico, os quais foram incluídos no modelo de Fukai e Hammer (1987), que foi calibrado e testado para estimar a produtividade de mandioca no norte da Austrália. O modelo de Gutierrez et al. (1988) é baseado na dinâmica do carbono, nitrogênio e balanço hídrico, com a massa seca alocada de acordo com padrões fixos, que eram alterados a proporção de acordo com o estagio de desenvolvimento. A desvantagem de utilizar um modelo de padrão fixo é que dessa maneira não

vai considerar os processos fisiológicos que podem ser alterados pelas condições ambientais e que irão contribuir para o rendimento final, e, portanto, tem a aplicação desses modelos mais limitada. Gijzen et al. (1990) modificaram o modelo SUCROS, que é usado para modelar o crescimento de várias culturas, para a cultura da mandioca, no qual descreveram os processos de fotossíntese, respiração de crescimento e de manutenção e simularam a produção e distribuição de massa seca dos experimentos conduzidos na Colômbia, descritos por Veltkamp (1986). O modelo de mandioca GUMCAS foi desenvolvido por Matthews e Hunt (1994) e será descrito com maiores detalhes no subitem 2.3.1 dessa seção. Em outros locais do mundo como na Índia também estão sendo concentrados esforços para produzir modelos que representem os genótipos daquela região (MITHRA et al., 2000). Também o grupo de modeladores do CIAT (Centro Internacional de Agricultura Tropical), fisiologistas de mandioca e os modeladores responsáveis pelo DSSAT-CROPSIM-CASSAVA estão trabalhando em conjunto para realizar melhorias no módulo DSSAT-Mandioca podendo esse futuramente ser usado em cenários de mudança climática, com a ajuda também do grupo de modelagem de mandioca APSIM (Simulador de Sistemas de Produção Agrícola) desenvolvido pela Unidade de Pesquisa Agropecuária em Sistemas de Produção na Austrália, e o grupo de modelagem de mandioca "MunThaiDSS: A Decision Support System for Cassava Production" (Departamento de Agricultura, Centro de Pesquisas de Culturas Agrícolas Khon Kaen, Tailândia) (HOOGENBOOM et al., 2012).

2.3.1 O Modelo GUMCAS

O modelo GUMCAS (MATTHEWS; HUNT, 1994) é um modelo baseado em processos para mandioca, tendo como base os conhecimentos usados nos modelos anteriores, e no qual foram aperfeiçoados alguns processos para melhorar o desempenho do modelo, além de incluir componentes extras, como um sub-modelo de balanço hídrico do solo, com o qual pode-se considerar stress hídrico na cultura. Na publicação original há a identificação dos parâmetros com maior sensibilidade, ou seja, os parâmetros que quando modificados seus valores alteravam mais sensivelmente a produção de raízes tuberosas, e a identificação dos parâmetros que eram específicos para cada cultivar, permitindo a simulação para diferentes cultivares. É

disponibilizado nesse artigo valores dos parâmetros calibrados para algumas cultivares colombianas e australianas, e também uma tabela com a análise de sensibilidade com valores mínimos, máximos e padrão dos parâmetros (esse último corresponde aos valores dos parâmetros de uma cultivar que produz 28,5 ton ha^{-1} de massa seca total e 16,4 ton ha^{-1} de produtividade em massa seca de raízes tuberosas) obtidos para uma cultivar "média" (considerada representativa) cultivada no CIAT, Colômbia. O teste do modelo foi realizado com os conjuntos de dados disponíveis, também de cultivares colombianas e australianas, com boa concordância entre valores observados e simulados. Os autores ressaltam que para a aplicação em outros ambientes é necessário uma validação.

Esse modelo foi desenvolvido para a inclusão no aplicativo Decision Support System for Agrotechnology Transfer (DSSAT), para simular os processos de crescimento e desenvolvimento de diferentes cultivares de mandioca em diferentes condições de solo, clima e manejo das plantas. O modelo DSSAT-GUMCAS foi testado com conjuntos de dados de quatro cultivares de mandioca amplamente utilizadas durante 1996-1999 em Khon Kaen, na Tailândia. O modelo teve boa estimativa da fenologia, mas superestimou o crescimento e a produção das cultivares (SARAWAT et al., 2000). Isso indica que quando trabalhamos com um modelo com o código fechado como é no DSSAT é permitido a entrada de alguns parâmetros, realizar a calibração através de testes de sensibilidade, porém não é permitido acesso ao código, ver as equações que constituem o modelo, entender como o modelo funciona e encontrar qual o processo que não está simulando adequadamente e propor melhorias.

O que comanda o crescimento e o desenvolvimento da cultura da mandioca no modelo são os dois "relógios" da planta: o relógio do desenvolvimento vegetativo (faz aparecer folhas) e do desenvolvimento reprodutivo (faz aparecer as ramificações simpodiais). O relógio do desenvolvimento vegetativo é influenciado pela temperatura e stress hídrico (por falta de água), este último se houver restrição hídrica, e inicia a contabilizar o desenvolvimento diário (Dd) a partir da data de plantio. A partir da temperatura mínima e máxima diária do ar é calculada a temperatura horária para as 24 horas do dia (Td), e com base nas temperaturas cardinais da cultura (temperatura base (Tbase)= 13ºC, temperatura ótima (Topt)= 30ºC e temperatura máxima (Thigh)= 42,5ºC) (MATTHEWS; HUNT, 1994) é calculado o desenvolvimento horário (HD) e realizada a média diária a partir desses 24 valores de HD, resultando na função de temperatura

(f(Tmin, Tmax)) que é a taxa diária de progressão do desenvolvimento vegetativo (Rv, Dd/day), sendo essa acumulada diariamente (somaRv).

Todas as equações que serão apresentadas nessa seção fazem parte do artigo de Matthews e Hunt (1994), e por isso estão na sua versão original, em inglês.

$$Td = (Tmin+Tmax)/2 + (Tmax-Tmin)*cos(0.2618*(h-14))/2 \tag{1}$$

em que h é a hora do dia, Tmax é a temperatura máxima (ºC) e Tmin é a temperatura mínima (ºC).

$$\text{Se } Td \leq Tbase \text{ ou } Td \geq Thigh \text{ então } HD=0; \tag{2}$$

$$\text{Se } Tbase < Td \leq Topt \text{ então } HD = (Td-Tbase)/(Topt-Tbase); \tag{3}$$

$$\text{Se } Topt < Td < Thigh \text{ então } HD = (Thigh-Td)/(Thigh-Topt) \tag{4}$$

$$f(Tmin,Tmax) = \sum (HD/24) \tag{5}$$

$$Rv = \sum f(Tmin,Tmax) \tag{6}$$

$$somaRv = \sum Rv \tag{7}$$

É esse relógio do desenvolvimento vegetativo (somaRv) que depois de acumular o desenvolvimento diário (Dd) necessário para a emergência, que vai comandar todos os processos de crescimento (folhas, haste e raízes fibrosas). Após a emergência, o relógio do desenvolvimento reprodutivo (somaRr) (influenciado pelos mesmos fatores citados anteriormente e pelo fotoperíodo (Ø)) é acionado e começa a contabilizar e acumular a taxa diária de progressão do desenvolvimento reprodutivo (Rr, Dd/day) suficiente para ramificar, e a partir deste período esse relógio vai comandar as subseqüentes ramificações.

$$\text{Para } Ø \geq Øo \text{ então } g(Ø) = 1; \tag{8}$$

$$\text{Para } Ø < Øo \text{ então } g(Ø) = 1 - S_Ø*(Øo - Ø), \quad g(Ø) \geq 0. \tag{9}$$

em que Ø é o fotoperíodo (h), Øo é o fotoperíodo ótimo mínimo (15,5 h) (MATTHEWS; HUNT, 1994), $S_Ø$ é a sensibilidade do genótipo ao fotoperíodo (0,25 h^{-1}) e g (Ø) é a função de fotoperíodo.

$$Rr = f(Tmin,Tmax)*g(Ø) \tag{10}$$

$$somaRr = \sum Rr \tag{11}$$

Esse relógio do desenvolvimento reprodutivo é muito importante, pois a cada ramificação vai aumentar o número de hastes por m² que irá influenciar o crescimento e desenvolvimento de folhas e hastes (maior número de hastes, maior área foliar fotossinteticamente ativa, maior índice de área foliar, maior taxa de crescimento da cultura).

A produção de biomassa total da cultura (CG, g m^{-2}) é calculada pela taxa de crescimento total da cultura (CGR, g m^{-2} dia^{-1}), e esta é influenciada pela taxa máxima de crescimento da cultura (CGR$_{max}$), pelo Índice de Área Foliar (LAI), por uma função não linear de temperatura (f(T)) e radiação solar (f(RS)) descritas em Fukai e Hammer (1987) (Figura 3) e pelo stress hídrico quando este for um fator limitante.

$$CGR= CGR_{max}*(1-exp(-0.27*LAI)*f(T)*f(RS) \tag{12}$$

$$CG= \sum CGR \tag{13}$$
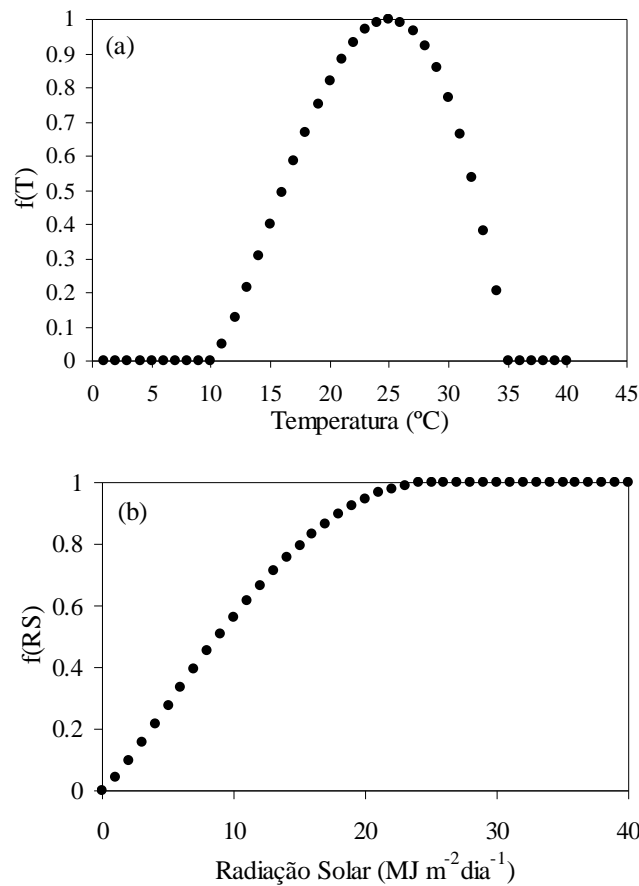
Figura 3- Função de temperatura (f(T)) (a) e de radiação solar (f(RS)) (b) utilizadas no cálculo da taxa de crescimento total da cultura (CGR) no modelo GUMCAS. Adaptado de Fukai e Hammer (1987).

O índice de área foliar é um produto da taxa de crescimento de folhas (LGR, g m^{-2} dia^{-1}) e da área foliar específica (SLA, cm² g^{-1}) (FUKAI; HAMMER, 1987).

$$LAI = LGR*SLA/10000 \qquad (14)$$

Na partição da biomassa, o crescimento da parte aérea (folhas e hastes) e das raízes fibrosas tem prioridade na distribuição dos fotoassimilados, sendo que o restante da produção de biomassa total será acumulado nas raízes tuberosas.

No crescimento de folhas (LG, g m^{-2}), a taxa de crescimento de folhas diária (LGR, g m^{-2} dia^{-1}) depende do número de hastes por m² (Nb), da taxa de aparecimento de folhas (LAR, folhas dia^{-1}), do tamanho da folha (LS, cm² folha^{-1}) e da área foliar específica (SLA, cm² g^{-1}).

$$LGR= Nb*LAR*LS/SLA \qquad (15)$$
$$LG= \sum LGR \qquad (16)$$
$$Nb(t)= Nb(t-1)*Nf \qquad (17)$$

em que Nb(t-1) é o número total de ápices (m^{-2}) antes da ramificação, e Nf é o número de hastes de cada ramificação.

$$LAR= Rv*LAR_0 (1-t_{ve}/A_{L0}) \qquad (18)$$

em que Rv é a taxa diária de progressão do desenvolvimento vegetativo, LAR$_0$ é a taxa de aparecimento de folhas na emergência, t$_{ve}$ é o desenvolvimento diário (Dd) desde a emergência, e A$_{L0}$ é o desenvolvimento diário (Dd) da emergência até o estágio em que a produção de folhas cessa.

O tamanho final de folha (LS) em dias após a emergência (t) é calculado a partir de uma adaptação da equação empírica descrita por Cock et al. (1979):

$$LS= (t*LS_{300}*LS_{max}*(t_{LS}-300)^2)/t_m*(LS_{max}-LS_{300})*(t_{LS}-t)^2.)+(t*LS_{300}*(t_{LS}-300)^2 \qquad (19)$$

em que LS$_{300}$ é o tamanho de folha aos 300 dias após a emergência, no final do período de crescimento, LS$_{max}$ é o máximo tamanho de folhas alcançado no t$_{LS}$ dias após a emergência, e t$_{LS}$ é o dia em que ocorre o LS$_{max}$. A variável tm não está especificada no artigo original, portanto foi adotado um valor para esse coeficiente pela calibração do LS.

A área foliar específica (SLA) (Figura 4) em mandioca varia normalmente de 200-300 cm² g^{-1}, dependendo da cultivar, temperatura, luz, disponibilidade de água e idade da planta. Baseada na equação usada por Fukai e Hammer (1987), a seguinte equação foi estimada:

$$SLA = SLA_0*(0.396+0.025*T_{mean}) \qquad (20)$$

em que SLA$_0$ é a área foliar específica para uma determinada cultivar a uma temperatura de 24ºC sem stress hídrico.
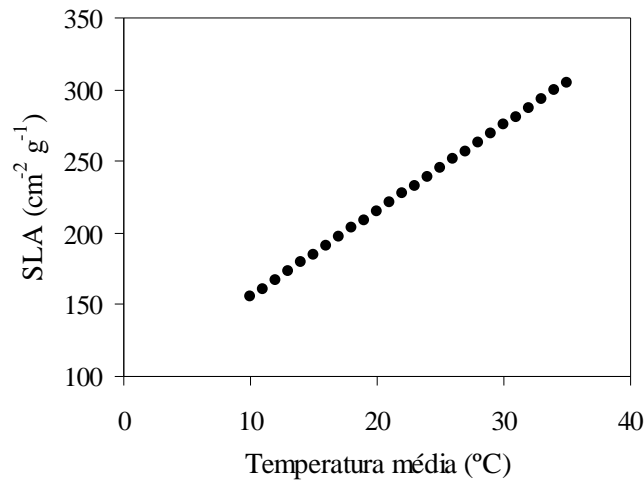
Figura 4- Relação entre área foliar específica (SLA) e temperatura média do ar (ºC) usada no modelo GUMCAS. Adaptado de Matthews e Hunt (1994).

O processo de senescência foliar é controlado pelo método "box-car", no qual a área foliar emergida cada dia ("cohort") é marcada ("tagged"). No primeiro dia dessa área foliar, a idade foliar (A_{leaf}) é igual a longevidade foliar potencial (P_{leaf}), e a cada dia essa idade é recalculada (atualizada) em função da temperatura média do ar (t_{mean}) (Figura 5a). Quando o Índice de área foliar (LAI) ultrapassa o Índice de área foliar crítico (L_{sen}) é adicionado uma segunda penalização na idade foliar (A_{leaf}) representada pelo coeficiente de sensibilidade ao sombreamento (Υs) (Figura 5b).

$$A_{leaf} = A_{leaf} - (15 - 1.45 * t_{mean} + 0.035 * (t_{mean})^2) \tag{21}$$

$$\text{Se } LAI \leq L_{sen} \quad \text{então} \quad A_{leaf} = A_{leaf} \tag{22}$$

$$\text{Se } LAI > L_{sen} \quad \text{então} \quad A_{leaf} = A_{leaf} - \Upsilon s (LAI - L_{sen}) \tag{23}$$
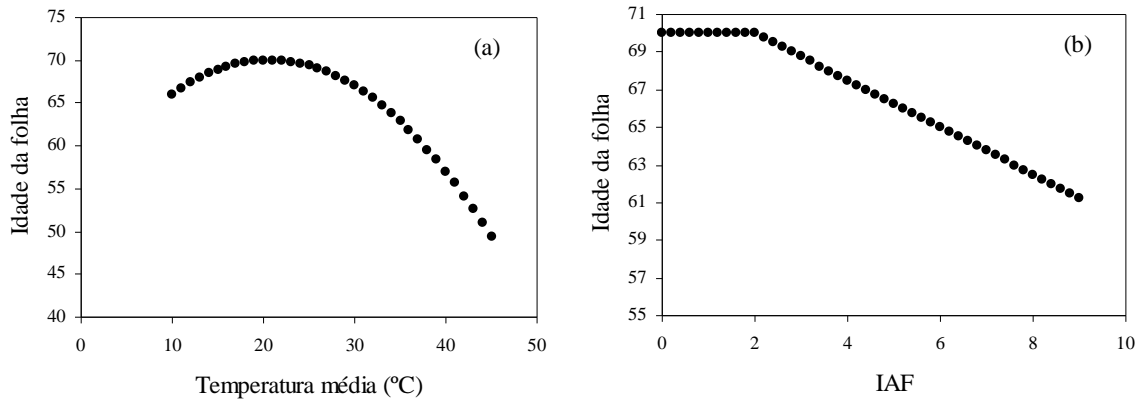
Figura 5. Idade foliar em função da temperatura média do ar (ºC) (a) e do Índice de Área foliar (IAF) (b) usada no modelo GUMCAS. Adaptado de Matthews e Hunt (1994).

No crescimento de haste (SG, g m^{-2}) é assumido que a fração haste/parte aérea (sf) aumenta linearmente de 0,2 na emergência (FUKAI; HAMMER, 1987) até um valor máximo de 0,6-0,7 dependendo da cultivar quando atinge o desenvolvimento vegetativo de 120 Dd, permanecendo constante até o final. A taxa de crescimento de haste (SGR, g m^{-2}dia^{-1}) depende dessa fração haste/parte aérea e da taxa de crescimento de folhas diária.

$$SGR= sf*LGR/(1-sf) \tag{24}$$

$$SG= \sum SGR \tag{25}$$

No crescimento das raízes fibrosas (RG, g m^{-2}), responsáveis pela absorção de água e nutrientes, é assumido que a razão raiz fibrosa/parte aérea (RSR) começa em 0,15 e declina exponencialmente para 0,05 no final do ciclo da cultura (Figura 6). A taxa de crescimento de raízes fibrosas (RGR, g m^{-2}dia^{-1}) é calculada por:

$$RGR= (LGR+SGR)*(0.05+0.10exp(-0.05*t_{ve}) \tag{26}$$

$$RG= \sum RGR \tag{27}$$

Onde LGR é a taxa de crescimento de folhas (g m^{-2}dia^{-1}), SGR é a taxa de crescimento de haste (g m^{-2}dia^{-1}) e t$_{ve}$ é o desenvolvimento diário (Dd) desde a emergência.
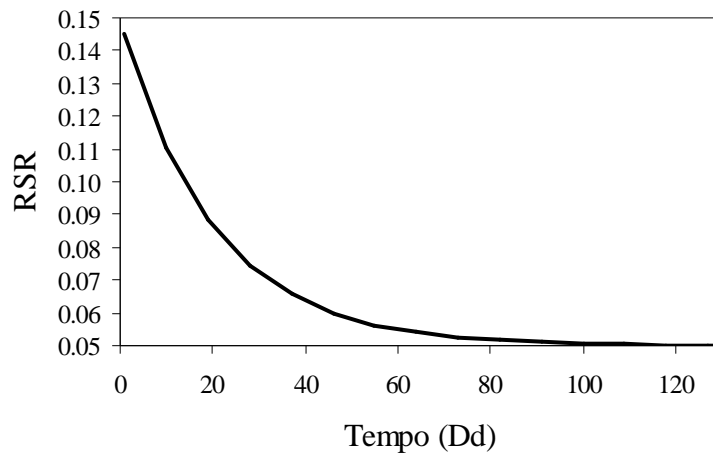
Figura 6. Razão raiz fibrosa/parte aérea em função do tempo (Dd) usada no modelo GUMCAS. Adaptado de Matthews e Hunt (1994).

Após ser calculada a taxa e acumulado diariamente o crescimento de folhas (LG, g m^{-2}), de hastes (SG, g m^{-2}) e raízes fibrosas (RG, g m^{-2}), o que sobrar da produção de biomassa total da cultura (CG, g m^{-2}) é acumulado nas raízes tuberosas (SRG, g m^{-2}):

SRG= CG – (LG+SG+RG)   (28)

A seguir, é apresentada a seção Desenvolvimento da dissertação na forma de artigo, segundo a MDT/UFSM, em inglês. A numeração das Figuras, também segundo a MDT/UFSM, neste formato é independente e, portanto, inicia em Figura 1 novamente. A formatação do texto segue as normas da revista Agronomy Journal, para a qual o manuscrito será submetido.

3 ARTIGO

TRABALHO A SER ENVIADO PARA PUBLICAÇÃO:

Simulating cassava growth and yield with a process-based model in

Southern Brazil

Agronomy Journal, 2013

Simulating cassava growth and yield with a process-based model in Southern Brazil

ABSTRACT

Cassava plays an important role as staple food in the tropics and is also produced for industrial purposes. The GUMCAS model is widely used as a process-based dynamic simulation model for cassava and is the cassava model in DSSAT. While GUMCAS has been used in some tropical locations, it was not used in the subtropical Southern Brazil. The objective of this study was to calibrate and evaluate the GUMCAS model in the subtropical environment of Rio Grande do Sul State, Brazil. We made three modifications in the model compared to the original version in Matthews and Hunt (1994): we considered a third independent "clock" in the cassava development for the onset of starch accumulation, we replaced the rate of leaf appearance sub-model, by the Wang e Engel model modified for cassava, and we modified the leaf senescence sub-model. Calibration of the model was performed by estimating parameters using the trial and error approach (Matthews and Hunt, 1994) that minimized the root mean square error between observed and estimated values, with total of 16 parameters were calibrated. A total of 25 independent datasets from experiments conducted in four sites of Rio Grande do Sul State (Santa Maria, Glorinha, Vera Cruz and Rio Pardo) were used for testing the model performance and a sensitivity analysis was performed running the GUMCAS model for 17 locations throughout the State of Rio Grande do Sul. In general, the calibration and modifications introduced in the GUMCAS model resulted in good simulations of some key ecophysiological processes such as leaf development and growth as well as of storage roots yield for a cassava genotype adapted to the subtropics. The model was able to capture different environmental conditions accross the Rio Grande do Sul State and with some adaptations for inputting data was able to simulate different management practices such as planting date, plant spacing, plant density, partial above-ground pruning during the growing cycle and two growing cycles as well as the effect of extreme weather events such as hail.

CASSAVA (*Manihot esculenta* L. Crantz) is native of South America and now plays a key role for food security, mainly in the tropics where it is the third major food source after rice and maize (Faostat, 2012). Cassava is a staple food in many of these regions because of its

tolerance to low soil water and fertility (Tafur et al., 1998; Alves, 2002). It is also a very important crop in regions with armed conflicts when the above ground part of the crops is destroyed and below ground (roots) can stay viable for several months (Rosenthal and Ort, 2012). The plant part of highest interest is the storage roots, rich in starch, which is used for food to humans and livestock and for industrial purpose (Ceplac, 2012). Furthermore, cassava is also an energy crop as roots may be used for ethanol production (Thu Lan Thi et al., 2007; Jansson et al., 2009, Li et al., 2010), requiring less energy compared with sugarcane and maize considering the whole agronomic system (Salla and Cabello, 2010).

Brazil is the second largest cassava producer worldwide, only behind Nigeria (Faostat, 2012). In 2011, 25.44 million tons of cassava roots were produced in Brazil, with the Pará State being the largest producer with 4.65 milion ton, followed by Paraná (4.18 milion ton), Bahia (2.97 milion ton), Maranhão (1.78 milion ton), São Paulo (1.32 milion ton) and by Rio Grande do Sul with 1.30 milion ton (Ibge, 2012). Rio Grande do Sul State is the southern most State in Brazil (Figure 1), located between about 27°S and 34°S latitude, which is at the edge of the latitude range (30° N to 30°S) where cassava can be grown (El Sharkawy, 2004). Because the State is located in the subtropics, low freezing temperatures during winter months (June, July, August) limit cassava growth. A typical timeline for cassava in the State is planting cuttings in late September or early October and harvesting plants in May or June. Usually in May farmers prune stems and storage them during the winter months and use them as propagules (cuttings) the following growing season. As in most parts of Brazil, in Rio Grande do Sul State, cassava is a low-technology crop, mainly grown in small farms, who use storage roots as a staple food and above-ground parts (stems and leaves) for feeding livestock, thus playing an important social role for farmer's sustainability (Chielle et al., 2009).

Process-based crop dynamic (PBCD) simulation models are currently widely used tools in many applications. They can be used to learn how a plant grows and develops, how fotoassimilates are partitioned within the plant among the sinks and how biotic and abiotic stresses affect crop yield (Alberto et al., 2006; Setiyono et al., 2010; Kim et al., 2012). They can also help in field management practices like fertilize side dressing and pest control (Streck et al., 2003a,b), plant breeding programs (Banterng et al., 2006; Hammer et al., 2010), yield forecasting (Bannayar et al., 2003; Shin et al., 2010) and in studies of crops response to climate change (Aggarwal and Mall, 2002; Tubiello et al., 2002; Weiss et al., 2003; Lago et al., 2008; Streck et

al., 2010). A major advantage of PBCD models compared to other approaches such as simple and multi regression models is that the formers are based on the biology of processes that comprise an agroecossystem whereas the latter are more based on empirical relationships between crop yield and climate variables (Lee et al., 2013). This advantage make PBCD models more likely to work properly in situations different from those that the model was developed and calibrated.

A number of cassava PBCD models are available in the literature. These cassava models can be grouped into two groups that differ in the approach on how dry matter is partitioned among to plant compartments. One group of models assume that dry matter is partitioned following a fixed pattern (Boerboom; 1978; Gutierrez et al., 1988; Gijzen et al., 1990). The other group of models uses a "spill-over" approach of dry matter partitioning so that the growth of leaves and stems is assumed to take place independently and have priority on new assimilates, and storage roots receive the remaining assimilates (Cock et al., 1979; Fukai and Hammer, 1987; Matthews and Hunt, 1994). The latter approach is more realistic for cassava, and among those models the GUMCAS model (Matthews and Hunt, 1994) combines knowledge into a process-based dynamic model and constitutes the most complete cassava model available. GUMCAS was developed for inclusion in the Decision Support System for Agrotechnology Transfer (DSSAT) suite for simulating cassava growth and development under a with range of cultivars, soils, climates and crop management (Sarawat et al., 2000; Mithra et al., 2000). The GUMCAS model was calibrated and validated using trials and cassava genotypes in Australia and Colombia (Matthews and Hunt, 1994) and later on was tested using the DSSAT-GUMCAS with four cassava genotypes in Thailand (Sarawat et al., 2000). Indeed, a recent meeting held at CIAT headquarters in Cali, Colombia, during the week of August 7-10, 2012, between CIAT crop modeless and physiologists and the maintainers and developers of DSSAT highlighted the need for improving the DSSAT/GUMCAS model in order improve the ability of the model to describe the crop under a wider variety of environments and management practice (Hoogenboom et al., 2012).

Even though PBCD models can be used in regions different from those where they were developed, some calibration is still needed, mainly because crop genotype differences among regions do exist (Marin et al., 2011; Kim et al., 2012). As model calibration implies in new parameterization of some processes, the predictions of the new version of the model need to be evaluated. To our knowledge, GUMCAS has not been tested in Brazil, and cassava cultivars

grown in Brazil, mainly those adapted to the subtropics of the Rio Grande do Sul State, greatly differ in growth habit and number of simpodial branches from the ones previously used for calibrating and testing the GUMCAS model, which constituted the rationale for this effort.

The objective of this study was to calibrate and evaluate the GUMCAS model in the subtropical environment of Rio Grande do Sul State, Brazil.

MATERIAL AND METHODS

Area of study

The domain area of this study is the State of Rio Grande do Sul, Brazil, located in the Southeast part of South America (Fig. 1). Annual minimum and maximum temperature vary from 11ºC in the Northeast to 27ºC in the Northwest of the State, respectively, (Fig. 2a and 2b) and monthly temperature varies from 7 and 11 ºC in July to 26 and 33 ºC in January (Fig. 2c and 2d), and annual precipitation, which varies from 1,200 to 2,000 mm, is well distributed accross seasons, i.e. there is not a dry season (Fig. 3a, 3b, 3c, 3d).

The agroclimatic zoning for cassava in the State takes into account three planting date periods (21 Aug to 10 Sep, 11 Sep to 20 Sep and 21 Sep to 30 Nov), the risk of frost during August, September and October, and only areas with seasonal average temperature during Summer (DJF) greater than 21ºC are recommended for growing cassava. The spatial distribution of the areas recommended for cassava in Rio Grande do Sul State in the three planting periods is in Figure 4 (a, b, c).

Cassava model

The cassava model used in this study was the GUMCAS model (Matthews and Hunt, 1994). GUMCAS is a process-based model in which different processes that describe growth, development and yield of cassava are considered. The priority in the model is the growth of above ground parts (leaves and stems), and growth of fiber roots (which are responsible for water and nutrients absorption) depend on above-ground growth and decreases as plant ages. These processes are calculated independently from the calculation of total plant biomass, and the growth of tuber (storage) roots is calculated as the difference between total plant biomass and the

biomass of leaves, stems and fiber roots. The model outputs the dry matter of different plant parts in g m^{-2} day^{-1}.

We made three modifications in the model compared to the original version in Matthews and Hunt (1994). The first modification was to incorporate the developmental time to the onset of starch accumulation, i.e. we considered a third independent "clock" in the cassava development (the other two "clocks" are the vegetative development, which makes leaf number progress, and the reproductive development, which makes progression towards simpodial branching). This third clock is represented in our version by the parameter A_{b0} (developmental time from emergence to onset of starch accumulation).

The second modification was to replace the rate of leaf appearance sub-model, which in the original version of the GUMCAS model is described by a bi-linear temperature response and has two coefficients, by a WE model (Wang and Engel, 1998) that has only one cultivar specific parameter (LAR_{max}) and uses a non-linear temperature response function adapted for cassava by Samboranha et al. (2013):

$LAR= LAR_{max}*f(T)$ [1]

$f(T) = [2(T-T_{base})^{\alpha}(T_{opt}-T_{base})^{\alpha}-(T-T_{base})^{2\alpha}]/(T_{opt}-T_{base})^{2\alpha}$ [2]

when $T_{base} \leq T \leq T_{high}$

$f(T) = 0$ [3]

when $T < T_{base}$ ou $T > T_{high}$

$\alpha = \ln2/\ln[(T_{high}-T_{base})/(T_{opt}-T_{base})]$ [4]

where LAR is the daily leaf appearance rate (leaves per day), LAR_{max} is the maximum leaf appearance rate (leaves per day), T_{base} (14ºC (Schons et al., 2007)), T_{opt} and T_{high} (30ºC and 42.5ºC, respectively (Matthews and Hunt, 1994)) are the cardinal temperatures for LAR, T is the daily air temperature, and f(T) is a temperature response function, which varies from 0 to 1. The f(T) was calculated using daily minimum (Tmin) and daily maximum (Tmax) air temperature and, then, the mean of the resulting daily values of f(T) were calculated, corresponding to the daily mean f(T). This approach was used, because in a nonlinear function it is more appropriate to calculate the minimum and the maximum daily mean temperature first, and then to calculate the f(T). The accumulated number of leaves per apex (NL) was calculated by accumulating LAR, i.e. NL=∑LAR. The values of LAR_{max} have specific values for the main stem (MS) and simpodial branches (SB1, SB2, etc.).

The third modification was in the leaf senescence sub-model: we kept the approach from the original model that uses a "box-car" method the track age, dry matter, area and longevity of each cohort of leaf area produced on a daily basis. We modified the code by assuming that each cohort progresses towards its senescence by a daily rate of aging (r) until the leaf completes its lifetime (A_{leaf}). A_{leaf} is updated daily (decreased) as a function of temperature by the same temperature function given in the original model. For the temperature function we introduced the threshold of 5ºC for daily minimum temperature (Tmin) below which the decrease in A_{leaf} is maximum, to account for an increase in leaf senescence under low non-freezing temperatures in subtropical regions. Shading also fastens leaf aging in cassava and in the GUMCAS model (Mathews and Hunt, 1994), and we incorporated this effect by increasing daily aging rate due to shading after a threshold LAI (L_{sen}) using the same response function as in the original model. Once the effects of temperature and shading on leaf rate aging are accounted for, the daily aging rates are accumulated (DA) and when DA completes 1.0 the cohort senesces and falls off. The modified senescence sub-model is:

While Tmin > 5.0ºC

$$A_{leaf} = P_{leaf}- (15-1.45*t_{mean}+0.035*(t_{mean})^2) \qquad [5]$$

$$\text{If } LAI \leq L_{sen} \quad \text{then } r= 1./ A_{leaf} \qquad [6]$$

$$\text{If } LAI > L_{sen} \quad \text{then } r =(1./A_{leaf})*(\Upsilon_{s1}(LAI-L_{sen})+1) \qquad [7]$$

While tmin ≤ 5.0ºC

$$A_{leaf} = P_{leaf}-(15.) \qquad [8]$$

$$\text{If } LAI \leq L_{sen} \quad \text{then } r=(1./ A_{leaf}) \qquad [9]$$

$$\text{If } LAI > L_{sen} \quad \text{then } r =(1./ A_{leaf})*(\Upsilon_{s2}(LAI-L_{sen})+1) \qquad [10]$$

$$DA = \sum r \qquad [11]$$

In our version of the model, we did not include the effect of vapor pressure deficit (VPD) on crop growth rate (CGR), as indicated in Matthews and Hunt (1994), because climate in the State of Rio Grande do Sul is humid throughout the entire year (above 70%, Fig. 5) and therefore we do not expect VPD being a limiting factor for cassava in this region. Furthermore, the incorporation of VPD effects on stomata aperture is currently being revised by the DSSAT team because this part is very week in the GUMCAS model (Hoogenboom et al., 2012). The model was coded in Fortran 77 using the Force Compiler version 3.0.

The inputs for the model were planting date, harvest date, plant density (plants m^{-2}), daily weather data (minimum and maximum temperature and total solar radiation) and latitude. Solar radiation was calculated from sunshine hours. When harvest date was unknown, the model stopped, it was assumed that crop was killed by frost when minimum temperature was equal to or lower than 3°C (Heldwein et al., 1988). Solar radiation (MJ m^{-2} day^{-1}) was calculated from daily sunshine hours using the Angstrom modified by Prescott and Penman model with local coefficients adjusted for different locations accross the Rio Grande do Sul State given in Fontana and Oliveira (1996).

The GUMCAS model was run without water stress. This condition was chosen because we were not able to have a desirable description of different soils throughout the State and because precipitation is not a limiting factor for cassava in Rio Grande do Sul State during most of the years and throughout the cassava growing season, from September to May (Fig. 3). Therefore, the GUMCAS version used here calculates storage roots yield under near-optimum conditions.

Model calibration

The GUMCAS model was calibrated for the cultivar Fepagro - RS 13. This cultivar is widely grown by farmers in the State, because of its excellent below and above ground growth, allowing high storage roots and stems and leaves yield. Its growth habit is three-stem simpodial branching, producing three to four simpodial branches during one growing season.

A field experiment was conducted in Santa Maria, RS, Brazil (29.7ºS, 53.7ºW, 95m) during the 2011/2012 growing season. Planting of 5 to 7-node stem cuts was on 27 Sept 2011 in a 0.8 x 0.8m spacing (plant density of 15,625 plants ha^{-1}), in an area of 23.2 x 9.6m (223 m^2), with 12 rows of plants (total of 348 plants). Agronomic practices included fertilization, weed control (by manual hoeing), and insects control (with chemicals) were performed as recommended in order to have plants growing without biotic or abiotic stresses. During short periods without rainfall, water was supplied by irrigation, so water was also not a limiting factor either. These experimental conditions was to ensure that the calibration of the model was under near-optimum conditions.

Beginning on 27 Oct 2011, ten plants were sampled every two or three weeks. On each of the sampled plants, the following variables were measured: length of the longest foliolate (L), number of accumulated leaves per apex (NL), apex number, total number of accumulated leaves

per plant (NLT), and fresh and dry matter of leaves, stems, roots (fibrous + storage). Individual leaves area (LA) was calculated as $LA=a*(L)^b$, where a and b are empirical coefficients, which were estimated using 50 leaves as a=0.1774 and b=2.4539 (R^2=0.9644). Leaves, stem, roots and total plant fresh and dry matter were converted into g/m². Leaf area index (LAI) was calculated as the ratio of plant LA/soil area, specific leaf area (SLA) was calculated as the ratio of LA/leaf dry matter, and the stem/shoot fraction (sf) was calculated as the ratio of stem dry matter/above ground (leaves + stem) dry matter.

A second experiment was conducted in an adjacent area under the same conditions (including same planting date) in order to monitor plant phenology. This experiment had four plots, each plot with five rows of eight plants in a 0.8 x 0.8 m plant spacing. In each plot, six plants (two plants in each of the three central rows) were tagged (total of 24 plants). The date of the first simpodial branching (SB1), the second simpodial branching (SB2), the third simpodial branching (SB3) and the fourth simpodial branching (SB4) were determined on the tagged plants by observing plants daily. Leaf longevity (days) was measured on leaves located at nodes 10, 20, and 30 on the main stem, SB1, SB2, and SB3 of the tagged plants as the difference between the date of leaf emergence and the date of leaf senescence. An additional plot in this experiment was used to measure the date of the onset of starch accumulation (OSA). In this plot, four plants were sampled every other day and the date of OT was considered when at least two of the sampled plants had one root with diameter greater than 1cm (Schons et al., 2007). Emergence day in both experiments was considered when 50% of the plants were visible at the soil surface.

Calibration of the model was performed by estimating parameters using the trial and error approach (Matthews and Hunt, 1994) that minimized the root mean square error between observed and estimated values. A total of 16 parameters were calibrated: P_{leaf}, SLA_0, A_{b1}, CGR_{max}, LS_{max}, A_b (A_{b1-2}, A_{b2-3}, A_{b3-4}), A_e, N_f, LS_{300}, t_{LS}, T_{base}, S_Φ, sf_{em}, tm, L_{sen} e Υ_s (see Appendix A for description). The other model parameters given in the article of Matthews and Hunt (1994) were not changed because the original values worked well for this cultivar.

Test with independent experimental data

A total of 25 independent datasets from experiments conducted in four sites in the State of Rio Grande do Sul (Santa Maria, Glorinha, Vera Cruz and Rio Pardo), located in a main region were cassava is grown in the State (Fig. 1) were used for evaluating the model performance.

These experiments include different growing seasons, years, and managements practices such as plant densities, planting dates, one and two growing cycles, and above ground pruning (Table 1). One dataset (Dataset 11) had plants hit by hail during the growing season.

The experiments in Santa Maria were conducted from 2005/2006 to 2010/2011. In the 2005/2006 growing season cassava was grown as a monoculture in single rows spacing (0.8 x 0.78 m plant spacing; 16,025 plants ha^{-1}) or in a double row spacing (1.60 x 0.5 x 0.6 m plant spacing; 15,873 plants ha^{-1}) and intercropped with maize (1.60 x 0.78 m plant spacing; 8,012 plants ha^{-1} (Datasets 1, 2 and 3 in Table 1). More details on this experiment are in Schons et al. (2009). In the 2006/2007 growing season, there were four planting dates (26 Sep 2006, 18 Oct 2006, 08 Nov 2006 and 28 Nov 2006) in a 0.8 x 0.8 spacing (Datasets 4, 5, 6 and 7 in Table 1) and details can be found in Fagundes et al. (2010).

In the 2007-2008 and 2008-2009 growing seasons, the experiments that constituted Datasets 9 and 11 (Table 1) were set up to study the effect of stem cuts size (4 to 13 nodes and diameter varying from 1 to 4 cm). The experimental design was a complete randomized block, with four replications. Each plot had five rows with eight plants per row (40 plants and 25.6 m² per plot) in a 0.8 x 0.8 m spacing. Because there was no statistical difference in storage roots fresh and dry matter yield in these experiments, the storage root dry matter of all treatments were averaged and compared with a single run of the model each year. On 08 Jan 2009 a severe weather event, with hail and wind gusts up to 113 km/h, severely damaged the plants (leaf area and the upper portion of stems were destroyed). Plants returned growth and were harvested in the following fall. When running the model for the 2008/2009 growing season, on the day of the severe weather event NL, LAI, accumulated leaf dry matter and leaf size was set to zero, leaf dry matter was subtracted from the total plant dry matter and on the day after the event the model was restarted from SB1 because in the field plants restarted growing with three shoots that developed from the upper three nodes at the position of the first simpodial branching.

Dataset 10 (Table 1) was planted on 26 Sep 2006 in a complete randomized block design with four replications. Each plot had five rows with 11 plants in a 0.8 x 0.8 m plant spacing (8.8 m x 4.0 m). On 19 Jun 2007, half of the plants in each plot were harvested and the other half of the plants had the stem pruned at 20 cm above soil surface and let grow one more growing season. Sprouting occurred on 08 Oct 2007 (378 days after planting). On 17 Sep 2007, a new planting was made in half of the plots that were harvested on 19 Jun 2007 (which constituted

Dataset 8), and harvesting of both one and two growing cycles was on 16 Jun 2008. During the winter period, dormant cassava plants that were not harvested use reserves from the storage roots for maintenance and sprouting (Andrade et al., 2011). We assumed in the model that fresh roots contains 30% starch (Mendonça et al., 2003), and that during the dormant period the starch content in the storage roots reduced to 20% (i.e., one third) due to reserve use (Andrade et al., 2011). Assuming that storage roots dry matter has 70% starch (Curvelo-Santana et al., 2010), 23% of the starch in the storage roots dry matter was used during the dormant period, which corresponds to a reduction in 33% of the roots dry matter produced after the first growing season. For this two-year experiment, the model was run for the first growing season and stopped on the first harvesting date, which is also the date of above-ground pruning (19 Jun 2007). The model restarted again on 08 Oct 2007 (observed day of sprouting) and stopped on 16 Jun 2008 (harvesting day).

During the 2009/2010 growing season, treatments were four plant spacings (plant densities): 0.8 x 0.8 m (15,625 plants ha^{-1}) (Dataset 12); 1.0 x 1.0 m (10,000 plants ha^{-1}) (Dataset 14); 1.2 x 1.2 m (6,944.45 plants ha^{-1}) (Dataset 15) and 1.5 x 1.5m (4,444.45 plants ha^{-1}) (Dataset 16). Dataset 13 consisted of a 0.8 x 0.8 m (15,625 plants ha^{-1}) with pruning treatment. The pruning consisted of cutting the upper part of the canopy on 10 Feb 2010 (140 DAP) right above the second node of the first simpodial branch (SB1). The pruned material (leaves and stems) was collected and oven dried for dry matter. The goal of this pruning treatment was to maintain LAI within the optimum, between 3.0 and 3.5 (Cock et al., 1979), for a longer period throughout the growing season. Local farmers use to do this management practice, in order to use the pruned material for feeding livestock. Leaf area was measured every other week, including the day right after pruning. The experimental design in both Datasets 12 and 13 was a complete randomized block with five replications (plots with five rows, 8 plants per row, 40 plants per plot).

In Dataset 16, plants of the 1.5x1.5 m treatment had lateral branches on the main stem (average 3.1 branches per plant main stem) probably because of the low competition by light among plants. This lateral main stem branching was considered in the simulation by adding 3.1 in the number of branches (Nb) to SB1, i.e., the lateral branching on the main stem started at the same time as the first simpodial branching, as observed in the field. The additional lateral branches had smaller leaves compared to SB1 leaves. To take into account the smaller leaves on

the lateral branching, we reduced the average leaf size by reducing the coefficient LS_{max} of the model when running the model for this Dataset 16 to $LS_{max}=130$.

When running the model for the pruned experiment (Dataset 13), we used an $LAR_{max} = 0.8045$ leaves day^{-1} (average between the LAR_{max} of SB1 and SB2), because the observed rate of leaf appearance of the stems that grew after pruning was intermediate between the rate of leaf appearance of the stems on SB1 and SB2 of the no pruned plants. In the simulation for this experiment, on the pruning date the LAI was set to the observed LAI (1.35), the observed leaf number and leaf and stem dry matter removed by pruning was subtracted from the accumulated LN and from the accumulated leaf, stem and total dry matter, respectively. It was assumed that two stems grow from each simpodial branch after pruning, as observed in the field, totaling six new stems per plant (three simpodial branches). In the field experiment, these new stems did not produce a new simpodial branching until the end of the growing season, so no branching was considered in the simulation.

Dataset 17 was conducted during the 2010/2011 growing season with cultivars Fepagro - RS 13 and Fepagro - RS 14 (a cultivar similar to Fepagro – RS 13 in growth habit). The experimental design was a complete randomized block, with four replications (plots with five rows, eight plants per row, 0.8 x 0.8 m plant spacing). The model was run for cultivar Fepagro - RS 14 with the coefficients calibrated for cultivar Fepagro – RS 13.

The experiments in Vera Cruz (29.71°S, 52.51°W, 68m altitude) were conducted during the 1999/2000 (Dataset 18) and 2002/2003 (Dataset 20) growing seasons in single row spacing (1.0x0.6m; 16,666 plants ha^{-1}) (Dataset 18) with details given in Cardoso et al. (2004a), and during the 2004/2005 and 2005/2006 growing seasons in single row spacing (1.0 x 0.6 m; 16,666 plants ha^{-1}) with one growing cycle (Dataset 21) and two growing cycles (Dataset 22) with details given in Chielle et al. (2007). The day of sprouting in the second growing cycle was not observed by Chielle et al. (2007), and in the simulation we assumed that sprouting occurred at 340 DAP (01 Sep 2005), when typically sprouting takes place in the field in this region.

Experiment in Glorinha (29.88°S, 50.78°W, 58m altitude) was conducted during the 1999/2000 growing season in single row spacing (1.0 x 0.8m plant spacing; 12,500 plants ha^{-1}) (Dataset 19) and more details are in Cardoso et al. (2004b). Experiments in Rio Pardo (29.99°S, 52.38°W, 47m altitude) were conducted during the 2007/2008 growing season in single row spacing (1.2x0.6m; 13,889 plants ha^{-1}) and described in Chielle et al. (2009) (Dataset 23), during

the 2008/2009 growing season were in single row spacing (1.0 x 0.6 m; 16,666 plants ha^{-1}) and described in Morales et al. (2009) (Dataset 24), and during the 2009/2010 growing season were in single row spacing (0.8 x 0.8 m; 15,625 plants ha^{-1}) and described in Morales et al. (2010) (Dataset 25). Results from these experiments are with the cultivar Fepagro - RS 13, except the experiment by Cardoso et al. (2004b) which are with cultivar Fepagro - RS 14.

Datasets 1, 2, 3 and 18 to 25 had storage roots yield reported only on a fresh weight basis. These data were divided by 2.65 in order to have storage roots on a dry weight basis, which were then compared with dry matter simulated with the model, i.e., assuming that fresh storages have 62.2% of water, an average water content at harvesting found in the experiments conducted in Santa Maria from 2006 to 2011. Furthermore, only one value (average yield) is reported for these datasets. For all the other datasets listed in Table 1, average and standard deviations of the observed data are presented and compared with simulated data.

Meteorological data needed to run the model for the experiments in Santa Maria were from a conventional weather station of the Brazilian National Weather Service (INMET) located 100 to 150m from the plots. For the other three sites, there were no weather stations near the experiments. For running the model for these sites we used meteorological data from a conventional weather station of INMET located in Porto Alegre (30.05ºS, 51.17ºW, 46.97m), which is located in the same climatic region of these sites (Fig. 6), 167 km from Vera Cruz, 44 km from Glorinha and 140 km from Rio Pardo.

In the simulations for each site and experiments, the model was initialized three times (three members): at the day of 10%, 50% and 90% emergence. These days were defined on the basis of the parameter A$_e$ (5.94 Dd, 7.08 Dd, and 10.21 Dd, respectively). In doing this three-member simulation, we had an envelope (or variability) of the simulated values.

Sensitivity analysis for the State of Rio Grande do Sul and county data

A sensitivity analysis was performed running the GUMCAS model for 17 sites accross the State of Rio Grande do Sul (Table 2). These sites were selected for having meteorological data from the Brazilian National Weather Service (daily minimum and maximum temperature and solar radiation), which are inputs for the model, and because they are located in different regions accross the State (Fig. 6). This sensitivity analysis aimed to show how the model simulates potential yield as a function of different environments (temperature and solar radiation)

accross the State. For each location, the model was run for seven growing seasons (from 2004/2005 to 2010/2011). These 7-year period has a considerable interannual variability in terms of solar radiation and temperature, linked to the El Niño Southern Oscillation phases: 2004/2005, 2006/2007 and 2009/2010 were El Niño years, 2005/2006, 2007/2008, 2010/2011 and 2011/2012 were La Niña years and 2008/2009 were Neutral years. The idea was to test how the model predicts cassava yield affected by interannual variability in climate. For each growing season and site, the model was run twice: one run with planting on the first day and one run with planting on the last day of the recommended period according to the Agroclimate Zoning (Fig. 4).

Observed cassava storage roots fresh yield on a county level for each of these locations during the seven years were from the Brazilian Agriculture Statistics Service (Ibge, 2012). These county-level observed data are an ensemble of cultivars, planting and harvesting date, and technologies used by local farmers and were used as a reference to show average and interannual variability during the 2004/2005-2010/2011 period as a direct comparison between simulated and observed yield is not the case because the GUMCAS model has been calibrated for one cultivar under "high" technology (fertilizers were applied as recommended) where as farmers use several cultivars and low technology (little or no fertilizers). In order to have a more broad sample of observed data for each of the 17 sites, the data from nearby counties were also used so that each observed data its an average of several counties around the county where the weather station is located. County-level yield data are fresh storage roots yield. Simulated dry yield of storage roots by GUMCAS model was multiplied by 2.65 to retrieve simulated fresh yield.

For the sites where growing cassava is not recommended by the Agroclimate Zonin (Bom Jesus, Lagoa Vermelha and Santa Vitória do Palmar), planting dates were late in the simulation (Table 2) because of the low temperatures during winter and early spring. In all simulations, harvesting was assumed on the day of the first frost (minimum air temperature lower than 3ºC) or on 15 June (which occurred first), because farmers usually harvest cassava in June and little or no growth is expected during winter time in the State.

Model Evaluation

The evaluation of the performance of the model with the 25 independent Datasets (Table 1) was with the statistics root mean square error (RMSE), BIAS index, correlation coefficient (r), index of agreement (dw) and model efficiency (EF). The RMSE indicates the average error of the

model and the lower the RMSE the better the model (Janssen and Heuberger, 1995). The BIAS index shows the bias of the average deviation of the observed from the simulated values, and negative BIAS indicate that the model underestimates the observed values whereas positive BIAS indicates that the model overestimates the observed values (Wallach, 2006). The correlation coefficient allows to quantify the degree of association between observed and simulated values, so that r approaching 1 ou -1 indicates that the model is good. The index of agreement indicates the degree of accuracy of the model (Willmott, 1981), varying from zero (no agreement) to one (perfect agreement). The model efficiency (EF) is a measure of the deviation between simulated and the observed values relative to the scattering of the measured data. The value of EF is 1 if simulated values match the observed values perfectly (Kim et al., 2012). The equations to calculate each of the above statistics are:

$$RMSE = [\ \sum(S_i - O_i)^2 / n]^{0,5} \qquad\qquad [10]$$

$$BIAS = (\ \sum S_i - \sum O_i)\ /\ \sum O_i \qquad\qquad [11]$$

$$dw = 1 - [\ \sum(S_i - O_i)^2] / [\sum(|S_i - \bar{O}|) + (|O_i - \bar{O}|)]^2 \qquad\qquad [12]$$

$$r = \sum(O_i - \bar{O})\ (S_i - S) / \{[\ \sum(O_i - \bar{O})^2][\ \sum(S_i - S)^2]^{0,5} \qquad\qquad [13]$$

$$EF = 1 - [\ \sum(S_i - O_i)^2] / \sum(|O_i - \bar{O}|)^2 \qquad\qquad [14]$$

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

RESULTS

Model calibration

The biweekly sampling of plants and the daily monitoring of crop phenology provided a detailed dataset for calibrating the GUMCAS model for the cultivar Fepagro – RS 13. The 16 parameters calibrated with the optimization procedure are listed in Table 3. In general, development parameters decreased while some growth parameters increased or decreased compared to default parameters given in Matthews and Hunt (1994) (Table 3). In Figure 7 are presented some of the parameters or processes after parameter optimization. The three modifications in our version of the GUMCAS model compared to the original version are shown in Figure 7: the third developmental "clock" delayed the beginning of starch accumulation in 15

days (Fig. 7m), the new leaf appearance model described better the dynamics of leaf number during most of the growing season (Fig. 7g) and the new leaf senescence submodel was efficient to describe the intense leaf fall off late in the season (Fig. 7b and 7f).

The photoperiod sensitivity coefficient (S_Φ) estimated for this cultivar is lower than the default value (Table 3). Cassava is a long-day plant, i.e. long days favor simpodial branching (Keating et al., 1982), and from our experience, the cultivar Fepagro – RS 13 continues its branching during the end of Summer and Fall when photoperiod is decreasing in Santa Maria, thus explaining the lower sensitivity coefficient estimated in the parameter optimization procedure.

In the calibration of leaf size (Fig. 7e), the optimization was efficient only after a 70% reduction in the size of the leaves on the fourth simpodial branching (SB4) (Fig. 7e), to represent an increase in the sink strength for growing about 34 new stems from SB4, which decreases photoassimilates available for leaf expansion.

The threshold LAI (L_{sen}) estimated for the cultivar was 2.0. In our experiments, this value is usually achieved in February, and leaf senescence increases rapidly in March due to shading, indicating that the optimization procedure estimated this parameter properly. We noted in the field during the experiment for calibration an intense leaf senescence of about two-thirds of the canopy that occurred 5-7 days after a minimum temperature of 4ºC on 01 May 2012, even though in the following days the temperature was above 8 (first next day) and 10ºC (the following nine days). We interpreted this rapid senescence as a result of an intensification of the shading effect at low non-freezing temperatures. During the calibration process (described in 2.3) we noted that the model was not able to describe this intense leaf senescence with the optimized Υ_{s1}. In order to take into account this intense leaf fall, we ran a second optimization procedure for the calibration of leaf growth and LAI considering an higher Υ_s when minimum temperature was below 5ºC, which we called Υ_{s2} (Table 3). This second optimization for the parameter Υ_s (Υ_{s2}) properly adjusted the model to the observed leaf dry matter and LAI late in the season compared to the optimization of only one Υ_s, i.e. Υ_{s1} (Fig. 7b and 7f).

Test with independent experimental data

In the simulation of the dates of different cassava developmental stages (Fig. 8), the RMSE was lower for emergence (EM) and OSA (RMSE of 3.44 e 3.91 days, respectively),

followed by SB2 (6.98 days) and SB3 (7.20 days). These RMSE values are below the ones reported by Sarawat et al. (2000) for cassava (12.8 days for cultivar Rayong 90 and 44.5 days for cultivar Rayong 5 both for SB1) and by Streck et al. (2007) for potato (from 10.4 to 19.1 days for several developmental stages) and similar to the ones reported by Streck et al. (2011) for rice. The statistics BIAS indicates that the model slightly underestimated the date of emergence (-0.03), SB1 (-0.03), SB2 (-0.09) e SB3 (-0.01) and slightly overestimates OSA (0.01). The degree of association between simulated and observed data was above 0.9 for EM and OSA (r=0.92 and r=0.95, respectively) and above 0.8 for SB2 and SB3 (r=0.84 and r=0.82, respectively). The index of agreement was greater than 0.9 for EM and OSA (dw=0.91 e 0.96, respectively), and greater than 0.8 for SB2 and SB3 (dw=0.87 and 0.86, respectively). Model efficiency was greater than 0.9 for the prediction of the dates of EM, OSA, SB2 and SB3 (EF=0.98, 0.97, 0.95 and 0.94, respectively).

The high value of RMSE (14.66 days) and low values of the other statistics (r=0.24, dw=0.52 e EF=0.73) (Fig. 8c) for the prediction of the date of the first branching (SB1) was mainly due to an underestimation (model went too fast) in the predicted dates of this developmental stages in Datasets 6 and 7, which correspond to the two late planting dates (08/11 and 28/11) during the 2006/2007 growing season. We were not able to come up with a reasonable hypothesis to explain the low ability of the model to simulate SB1 in these two dataset as the model did an excellent job in simulating the date of SB1 in the other two planting dates of this experiment (Datasets 4 and 5). Therefore, an additional effort may be worthy in the future to have more experiments with different planting dates, mainly late planting dates, to test the model. Excluding these two datasets, the RMSE is 5.37 days, i.e in the range of the error of the other developmental stages. Interestingly, the model did a good job in predicting the date of SB2 in these two datasets (Fig. 8d).

The test of the model for stem and storage roots dry matter with datasets from different experiments under different environmental conditions and management practices indicated that the model was able to capture a major part of the variability in the data (Fig. 9a and 9b). The overall RMSE for the 14 datasets of stem dry matter was 1.48 Mg ha^{-1} while for the 25 datasets of storage roots the RMSE was 1.97 Mg ha^{-1}. The RMSE for stem dry matter without Dataset 4 (the worst performance of the model) is 1.00 Mg ha^{-1}, and for roots dry matter without dataset 4 is 1.80 Mg ha^{-1}. These RMSE values for storage roots yield are above the ones reported by the

cultivar cassava Rayong 90 (0.87 Mg ha^{-1}) and below the ones for Rayong 5 (13.0 Mg ha^{-1}) grown in Khon Kaen, Thailand (Sarawat et al., 2000). The model slightly underestimated stem dry matter, with BIAS of -0.11 and overestimated storage roots dry matter yield with BIAS of 0.05. The correlation coefficient (r) was above 0.8 for stem and storage roots, which are similar to the ones reported by Marin et al. (2011) for sugarcane with the DSSAT/CANEGRO model. The index of agreement (dw) was greater than 0.8 for stems and greater than 0.9 for storage roots, also similar to the ones reported by Marin et al. (2011) and the ones reported by Kim et al. (2012) for maize with the MAIZSIM. Model efficiency (EF) was high, 0.96 for stem and 0.99 for roots, much higher than those reported by Marin et al. (2011) for sugarcane (0.72) and by Kim et al. (2012) for maize (from 0.63 to 0.95). Noticeable is that the simulated envelope created by the different initialization times of the model (10% and 90%) is narrower for stem (Fig. 9a) and broader for storage roots (Fig. 9b), i.e. roots growth is more sensitive to the initialization time than stem growth in the model. The explanation for the greater sensitivity of roots growth in the model is that the difference of developmental days between the 10% and 90% emergence members (4.27 Dd) is small for a considerable growth of stems, but for storage roots this difference renders a higher growth as roots grow as a result of the remaining of photoassimilates that were not used for above ground growth (stems, leaves and fiber roots) and when senescence starts at the end of Summer, a greater portion of daily assimilation rate is partitioned to storage roots (Matthews and Hunt, 1994), and therefore, the earlier the model is initialized the earlier senescence due to shading starts and the more dry matter is daily partitioned to roots.

Datasets 1, 2 and 3 are a test of the model for different plant arrangements (single row spacing, double row spacing and intercropped with maize, respectively), which in the model are represented by plant density. The model slightly underestimated the observed data in Datasets 1 and overestimated Dataset 3, but the model was able to capture the decrease in root yield of cassava when intercropped with maize at a plant density of 8,012 plants ha^{-1} (Dataset 3, Fig. 9b).

Comparing different planting dates (Datasets 4, 5, 6 and 7), under near-optimum conditions the GUMCAS model "sees" that earlier planting dates allow plants to grow for a longer period until growth is reduced by low temperatures in late Fall, resulting in greater stem and storage roots the earlier the planting. The observed data for stem yield follow this pattern (Fig. 9a) and for storage roots yield, the first planting date (Dataset 4) that had root yield similar to the third planting date (Dataset 6) (Fig. 9b). The observed lower root yield in the Dataset 4

compared to Dataset 5 was attributed by Fagundes et al. (2010) to a high above ground and LAI growth early in the season that caused excessive shading in plants from Dataset 4 and thus decreasing storage roots. Indeed, the model underestimated stem growth and overestimated root growth for this dataset, indicating the model underestimated the shading effect observed in the field. The dynamics of leaf development and growth during the growing season of these datasets are in Figure 10. The model captured the decrease in the number of leaves and LAI as planting date was later, but with some delay in the simulated values compared to the observed data, which led to an underestimation of NL and overestimation of LAI towards the end of the growing season, with negative BIAS values (Fig. 10a, 10c, 10e, 10g).

For different plant densities in the 2009-2010 growing season in Santa Maria (Datasets 12, 14, 15, 16), the observed data showed a decrease in stem dry matter yield as plant density decreased from 15,625 plants ha^{-1} (0.8 x 0.8 m plant spacing, Dataset 12) to 6,944.45 plants ha^{-1} (1.2 x 1.2 m plant spacing, Dataset 15) and an increase in the 4,444.45 plants ha^{-1} (1.5 x 1.5m plant spacing) treatment (Dataset 16) and the model captured this trend properly (Fig. 9a). For storage roots yield, observed values decreased as plant density decreased from 15,625 plants ha^{-1} (0.8 x 0.8 m plant spacing, Dataset 12) to 4,444.45 plants ha^{-1} (1.5 x 1.5m plant spacing, Dataset 16) and so did the model (Fig. 9b). The dynamics of leaf development and growth during the 2009/2010 growing season for the four plant densities are in Figure 11. The model captured very well the trend of decreasing LAI as plant density decreased (Fig. 11b, 11d, 11f, 11h). Leaf number was better simulated for the higher plant density treatments (0.8x0.8 e 1.0x1.0 plant spacing, Fig. 11a and 11c) while in the two other treatments (1.2 x 1.2 m = 6,944.45 plants ha^{-1} and 1.5 x 1.5m = 4,444.45 plants ha^{-1}) the model overestimated LN in the first half of the growing period and underestimated LN in the second half of the growing period (Fig. 11e and 11f). These results indicate that our version of the GUMCAS model is able to describe the effect of plant density properly.

Another field management used by some local farmers is to harvest only the above ground part of the plant and let the roots grow during a second growing cycle. This situation is represented by Dataset 10 and Dataset 8 is one growing cycle. Observed stem growth during the second growing season (Dataset 10) was similar to the stem growth during the one-growing season crop (Dataset 8) whereas root growth increased two-fold after the second growing cycle (Dataset 10) compared to one growing cycle (Dataset 8), and the model did a good job in

simulating both stem and roots (Fig. 9a and 9b). The biannual dynamics of leaf development and growth, and stem and storage roots growth of Dataset 10 is in Figure 12. During the first growing cycle, stem growth was higher than roots growth while during the second growing period stem growth was lower, and the model properly simulated the leaf number during and stem and roots dry matter at the end of the second growing period. The steep drop in LAI simulated by the model at the end of the second growing period (Fig. 12b) was due to a 4.9ºC temperature on 15 Apr 2008 (568 DAP), and after that temperature persisted low but greater than during the end of the first growing cycle due to some relatively high temperatures for this time of the year until 30 May 2008 (613 DAP), when minimum temperature dropped again to 2.1ºC (frost).

The pruning treatment (Dataset 13) decreased observed stem and storage roots dry matter compared to the treatment without pruning (Dataset 12), and the model simulated this decrease properly (Fig. 9a, 9b). The dynamics of leaf development and growth and stem and roots growth during the growing period of the pruned plants is in Figure 13. Leaf appearance was well simulated both prior to and after pruning (Fig. 13a). Leaf area was well simulated before pruning whereas after pruning the model overestimated LAI but simulated values are within the error of the observed values at the end of the growing season (Fig. 13b). Simulated final stem and storage roots growth was within the error of the observed values (Fig. 13c, 13d). The model simulated a lower root yield compared to the non pruned plants because after pruning the plant had to invest more photoassimilates to grow new stems and new leaves, so there was no enough time to translocate extra photoassimilates to roots. Note that, after pruning, the simulated roots growth was very slow, which delayed the accumulation of photoassimilates to roots at the end of the growing season (Fig. 13d).

In the experiment during the 2007/2008 growing season in Santa Maria with two planting dates (Datasets 8 and 9) the model simulated stem dry matter within the error of the observed values (Fig. 9a) whereas storage roots dry matter yield was overestimated by the model (Fig. 9b). Leaf appearance was well simulated during the two planting dates (Fig. 14a, 14b).

Dataset 17 was an experiment during the 2010/2011 growing season, a year with above-normal solar radiation due to La Niña. Observed stem growth was higher compared to other years and datasets and the model captured this higher stem growth (Fig. 9a). Observed storage roots yield was also higher and the model under estimated root yield for this dataset (Fig. 9b). Leaf development and growth was well simulated throughout the growing season (Fig. 15a, 15b). In

this experiment another cultivar (Fepagro – RS 14) was also grown and the dynamics of leaf development and growth for this cultivar is also plotted in Figure 15 (c,d). The model was run with the coefficients calibrated for the cultivar Fepagro – RS 13 and simulation was quite good, mainly for LAI (Fig. 15d), indicating that the coefficients presented in Table 3 work for both cultivars, as they have a similar growth habit and the observed roots yield did not differ between them in the 2010/2011 growing season.

The ability of the model to simulate the effect of the hail event in the 2008/2009 growing season was tested with Dataset 11. Stem and storage roots dry matter at harvest was lower than Datasets 10 and 12, and the model captured well this decrease (Fig. 9a, 9b). The simulated dynamics of the leaf number and LAI and stem and roots growth during the experiment is in Figure 16. Before the hail event, leaf number was very well simulated by the model (Fig. 16a) and on the day of hail (95 DAP) plants had 44 leaves and the model simulated a LAI of 1.0 (Fig. 16b). After the hail, there were no observed data on leaf number and LAI, and the model simulated a total of 68 leaves at harvest and a maximum LAI of 5.5. Simulated stem and roots slowly recovered after the hail and ended within the error of observed stem and root dry matter at harvest (Fig. 16 c,d). The model was also run without inputing the hail event (no drop of leaves) (dashed lines in Fig. 16) and the difference between the two lines is what was lost due to hail in this experiment. The simulated effect of hail represented a decrease in 36% of stem dry matter and 58% of storage roots dry matter, indicating that after the hail the plant was able to recover more above ground than below ground growth, i.e. roots yield was much more affected by defoliation than stem and leaves.

The simulation of root yield for the experiments in the other three locations (Datasets 18 a 25) were in general also good as observed data are close or within the simulated envelope (Fig. 9b). Dataset 22 corresponds to a two-year growing period, and the model captured the increase in root yield (Fig. 9b). In Dataset 25, the simulated root yield was greater than the observed data, probably because there was above-normal precipitation during November which, according to Morales et al. (2010), delayed crop emergence and initial establishment and below-normal precipitation in March-April that may have caused some water stress, and these two factors were not considered in the simulation. The simulated dynamics of leaf number, LAI, stem and roots growth during the experiments conducted in Glorinha during the 1999/2000 growing season (Dataset 19), in Vera Cruz during the 2004/2005 growing season (Dataset 21) and in Rio Pardo

during the 2008/2009 growing season (Dataset 24) are in Figure 17. Besides differences in meteorological conditions among the three growing seasons, which are inputs to the model (minimum and maximum temperature, and solar radiation) (Fig. 17a, b e c), the model captured the differences in plant densities among these experiments, i.e. 1.0x0.8m (12,500 plants ha^{-1}) in Glorinha and 1.0x0.6m (16,666.67 plants ha^{-1}) in Vera Cruz and Rio Pardo, which resulted in very different LAI and stem yield (Fig. 17 g, h, i, j, l, m) and root yield among them. These results indicate that the model was able to describe the interaction response of plant growth and development to environment and management.

Sensitivity analysis for the State of Rio Grande do Sul and county data

Model runs for the 17 locations (average of the seven growing seasons 2004/2005-2010/2011 growing seasons) accross the State are in Figure 18. Simulated cassava root fresh yield was very different accross the State, with greater values in the Central, Northwest and East parts of the State (Depressão Central, Missões and Alto Vale do Uruguay regions) whereas the lowest values are in the Northeast of the State (Serra do Nordeste and Planalto Superior regions). This spatial distribution of cassava yield simulated by the model accross the State was correlated with temperature (Fig. 19a) but not with solar radiation (Fig. 19b) during the growing period (from planting to harvesting). This results indicate that cassava potential yield accross the State is not limited by radiation, only by temperature. The greater simulated root yield in the warmest regions, such as Porto Alegre, Iraí and São Luiz Gonzaga, and lower in the coldest regions such as Bom Jesus, Caxias do Sul and Bento Gonçalves. Potential simulated fresh storage roots yield varied from 6.6 to 44.5 Mg ha^{-1} when the simulation started on the first date of the recommended planting period.

Observed cassava yield data varied little accross the State and are low, from 9.1 to 23.6 Mg ha^{-1} (average of seven growing seasons, Fig. 19). The seven-year average observed yield data was below the simulated yield in most of the sites except for Bom Jesus, Lagoa Vermelha and Caxias do Sul (Fig. 18), being two of these sites located in a region not recommended for cassava (Serra do Nordeste region) according to the Agroclimatic Zoning (Fig. 4). Comparing the observed data with the envelope of the simulated data (model initialized on the first and on the last day of the recommended planting period), 7 out of 16 observed data are within the envelope and 8 out of 16 observed data are out and below the envelope, indicating that farmers yield is far from the potential yield in most of the State.

The interannual variability of observed and simulated cassava yield during the 2005-2011 period for the State and for the different regions is in Figure 20. For the average of the State, simulated storage roots yield varied from 28.3 to 33.1 Mg ha^{-1} when simulation began on the first planting date, and from 12.4 to 16.6 Mg ha^{-1} when simulation began on the last planting date (Fig. 20a). Planalto Superior, Serra do Nordeste and Serra do Sudeste were the regions with lower yields and Missões, Alto and Médio Vale do Uruguai and Depressão Central regions had the highest simulated yields. For the State, average yield was greater during the 2008-2009 growing season (2009 yield in panels of Fig. 20), a year with high solar radiation accross the State. Among the State regions, interannual variability was greater in the Serra do Sudeste (Fig. 20d), Planalto Médio (Fig. 20e), Planalto Superior (Fig. 20f), Litoral (Fig. 20h), Missões (Fig. 20i) and Alto e Médio Vale do Uruguai (Fig. 20f) regions, while interannual variability was lower in the Campanha (Fig. 20b), Depressão Central (Fig. 20c) and Serra do Nordeste (Fig. 20g) regions. The low yield simulated for year 2008 in the Planalto Superior region (Fig. 20f) was because an early frost on 15 Apr 2008 that "killed" the plant, shortening the growing period, which decreased storage root yield. On the other hand, observed data had much less interannual variability, probably because the data are an ensemble of cultivars, planting dates, management practices and low technology used by local farmers.

DISCUSSION

The calibration of the version of the GUMCAS model we used in this study was based on a field experiment specifically designed and conducted for this purpose. This experiment provided a comprehensive data set on key ecophysiological processes that drive canopy growth and development in a cassava ecosystem such as leaf appearance (Fig. 7g), leaf area index (Fig. 7f) and leaf (Fig. 7b), stem (Fig. 7a) and roots (Fig. 7c) growth. The calibration procedure we used for genotype-specific coefficients estimation, was a traditional optimization approach based on minimizing the error between observed and simulated values (Xue et al., 2004; Setiyono et al., 2008). We acknowledge that other approaches for calibrating crop models have been recently proposed such as the cross-validation and bootstrap approaches (Marin et al., 2011), but we understand that these alternative approaches are more suitable when models are calibrated based on experiments that were not designed for being used as dataset in simulation studies. When an

experiment can be designed to provide data on key components of the model, than the traditional fitting approach still is appropriate and used (Kim et al., 2012). The use of field data proved to be useful to calibrate the GUMCAS model for modeling the dynamics of the components of a cassava plant such as simpodial branching (Fig. 7h), and leaf senescence (Fig. 7b and 7f) at the end of the growing season in a subtropical environment.

The modifications we introduced in the GUMCAS model represent, from our perspective, a better representation of some ecophysiological processes of a cassava plant. Setting the onset of starch accumulation as a developmental stage seems to be reasonable because cassava, as a perennial, has the priority of fibrous root growth during the first couple of weeks after plant emergence, which are responsible for uptaking water and nutrients, allowing plant to explore a maximum soil volume early in the season. Only after a minimum fibrous root system is established, storage roots begin to grow. The second modification was the leaf appearance model with a multiplicative approach that uses a non-linear response function to temperature as an alternative to the thermal time approach originally used in GUMCAS. Incorporating non-linear response of plant processes to ambient temperature, mainly plant development, has been widely tested and successfully achieved in several crops (Streck et al., 2003a; 2003b; 2007; 2008; 2011; Setiyono et al., 2007; 2010; Kim et al., 2012) and recently also proposed for cassava (Samboranha et al., 2013). In our calibration procedure, the non-linear approach better described the leaf number dynamics for the cultivar Fepagro – RS 13 (Fig. 7g). The third modification we made in the model was in the leaf senescence sub-routine, where leaf aging was treated as a rate and the sensitivity coefficient (Υ_s) was 0.25 and 20 at the end of the growing season when temperature was equal to or lower than 5ºC. This was a key modification to take into account the interaction of low temperature and shading effects that accelerate leaf senescence when cassava is grown in the subtropics (Fig. 7b and 7f), which greatly differs from senescence when cassava is grown in the tropics.

Overall, the version of the GUMCAS model we calibrated in this study was able to describe the effects of environmental changes caused by within and among season differences in environmental changes (different planting dates in the same location, different locations in the same growing season and different years in the same location), climate variability (the 2008/2009 growing season had greatest solar radiation accross the Rio Grande do Sul State), and agricultural management practices like plant spacing, plant density, intercropping, in-season partial above-ground pruning and cassava grown during two growing cycles (which led to a two-fold increase in storage roots yield). Furthermore, by imputing some

appropriate parameters, the model was also able to simulate the effect of a hail event that destroyed leaf area completely and the recovery of leaf area and plant growth after the hail, so that we were able to estimate the losses in stem and storage roots yield caused by the hail event. Because the model was calibrated under near-optimum conditions, we were also able to simulate how far from the potential yield are the yields obtained by farmers in different regions of the Rio Grande do Sul State. These results indicate that we have an explanatory dynamic cassava simulation model capable and suitable to be used in the subtropics of Southern Brazil.

In many regions around the world where cassava is a major crop, soil water shortage can be a major limiting factor for cassava yield (El-Sharkawy and Cock, 1987; Baker et al., 1989; El-Sharkawy and Cadavil, 2002), including Northeast Brazil. The county-level data during seven years accross the Rio Grande do Sul State (Fig. 20) indicate no apparent effect of soil water shortage (little interannual variability), even thought during this period there were three years (2004/2005, 2005/2006 and 2008/2009) with below-normal precipitation during spring and /or summer months, when cassava was growing in farms. An additional growing season with very below-normal precipitation was 2011/2012, but no major changes in State and county-level cassava yield was observed (data not's shown). These results indicate that, different from other regions where cassava is grown and that the GUMCAS model was development and has been used (Matthews and Hunt, 1994; Sarawat et al., 2000), soil water is not a major limiting factor for cassava yield in the State. The dry spells that occured during the growing season do not cause water deficit enough to reduce yields. Cassava is particularly dry-soil tolerant (Tafur et al., 1998; El-Sharkawy, 2007) compared to most of annual crops, like maize and soybean, which are highly affected by dry spells in Southern Brazil (Berlato and Fontana, 1999; Berlato et al., 2005; Alberto et al, 2006; Bergamaschi et al., 2006). This is not to say that there is no need to account for water deficits effects in cassava models for Southern Brazil. In fact, the next step in our research program is to incorporate water effects in this version of the GUMCAS model. A major challenge we are facing in this task is the lack of a comprehensive datasets on soil properties for an accurate soil water model for the whole State.

Given the low cassava yields on a county-level accross the State, and that soil water shortage is not a major factor for explaining these low yields, low technology is very likely the major factor to explain low cassava yields. Major agricultural crops in the State are soybean and maize in the upper lands and rice in the low lands. Cassava is grown in marginal areas of the farms, with no fertilizers and not rarely with old cultivars, not well adapted to the subtropics.

Experimental data used to calibrate and evaluate the model (Fig. 7 and 9) and simulations accross the State (Fig. 19) indicate that cassava yield can increase by at least two-fold if farmers use more technology in their cassava fields, mainly fertilizers (according to recommendation by soil analysis) and cultivars adapted to the subtropical environment of the State.

We are unaware of any previous attempt to use the GUMCAS model to simulate cassava growth and yield in Brazil, the second largest cassava producer worldwide. The model was calibrated for a single cultivar (Fepagro RS -13), which is well adapted to the subtropics (Chielle et al., 2007; 2009; Morales et al., 2009; 2010) and is well adapted for small farmers because of its below and above-ground excellent growth. This cultivar produces up to four simpodial branching, similar in growth habit to another cultivar, Fepagro – RS 14. Not surprising, some other cultivars also currently grown in the State (like Estrangeira, Fécula Branca and Cascuda) differ from Fepagro – RS 13 and Fepagro – RS 14 both in below and in above-ground growth as they produce only one or two simpodial branching (Chielle et al., 2007; Morales et al., 2009; Morales et al., 2010). Therefore, genetic-dependent coefficients have to be calibrated for these other cultivars, which is currently under way by our research team.

CONCLUSIONS

In general, the calibration and modifications introduced in the GUMCAS model resulted in good simulations of some key ecophysiological processes such as leaf development and growth as well as of storage roots yield for a cassava genotype adapted to the subtropics. The model was calibrated under near-optimum conditions and was able to capture different environmental conditions accross the Rio Grande do Sul State. With some adaptations by inputting data, the model was also able to simulate the effect of different management practices such as planting date, plant spacing, plant density, partial above-ground pruning during the growing cycle and two growing cycles as well as the effect of extreme weather events such as hail.

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Table 1. Datasets used testing the GUMCAS model.

Dataset	Site	Growing season	Plant density (plants ha^{-1})	Planting date	Harvesting date	Variables measured
1	Santa Maria	2005/2006	16,025	27/09/2005	06/06/2006	Roots
2	Santa Maria	2005/2006	15,873	27/09/2005	06/06/2006	Roots
3	Santa Maria	2005/2006	8,012	27/09/2005	06/06/2006	Roots
4	Santa Maria	2006/2007	15,625	26/09/2006	19/06/2007	NL, LAI, Stem, Roots
5	Santa Maria	2006/2007	15,625	18/10/2006	19/06/2007	NL, LAI, Stem, Roots
6	Santa Maria	2006/2007	15,625	08/11/2006	19/06/2007	NL, LAI, Stem, Roots
7	Santa Maria	2006/2007	15,625	28/11/2006	19/06/2007	NL, LAI, Stem, Roots
8	Santa Maria	2007/2008	15,625	17/09/2007	16/06/2008	NL, Stem, Roots
9	Santa Maria	2007/2008	15,625	03/10/2007	02/07/2008	NL, Stem, Roots
10	Santa Maria	2006/2008	15,625	26/09/2006	16/06/2008	NL, LAI, Stem, Roots
11	Santa Maria	2008/2009	15,625	06/10/2008	19/07/2009	NL, Stem, Roots
12	Santa Maria	2009/2010	15,625	24/09/2009	09/06/2010	NL, LAI, Stem, Roots
13†	Santa Maria	2009/2010	15,625	24/09/2009	09/06/2010	NL, LAI, Stem, Roots
14	Santa Maria	2009/2010	10,000	24/09/2009	09/06/2010	NL, LAI, Stem, Roots
15	Santa Maria	2009/2010	6,944.45	24/09/2009	09/06/2010	NL, LAI, Stem, Roots
16	Santa Maria	2009/2010	4,444.45	24/09/2009	09/06/2010	NL, LAI, Stem, Roots
17	Santa Maria	2010/2011	15,625	06/10/2010	16/06/2010	NL, LAI, Stem, Roots
18	Vera Cruz	1999/2000	16,666	15/10/1999	15/05/2000	Roots
19	Glorinha	1999/2000	12,500	29/10/1999	15/05/2000	Roots
20	Vera Cruz	2002/2003	16,666	15/10/2002	15/05/2003	Roots
21	Vera Cruz	2004/2005	16,666	27/09/2004	22/04/2005	Roots
22	Vera Cruz	2004/2006	16,666	27/09/2004	29/03/2006	Roots
23	Rio Pardo	2007/2008	13,889	17/09/2007	13/05/2008	Roots
24	Rio Pardo	2008/2009	16,666	03/10/2008	21/05/2009	Roots
25	Rio Pardo	2009/2010	15,625	06/10/2009	08/06/2010	Roots

13† Dataset with above groung prunning on 10 Feb 2010.

Table 2. Regions, sites, their coordinates and planting dates (day/month) used for the sensitivity analysis of the GUMCAS model.

Region	Site	Geographic Coordinates	Planting dates
Campanha	Bagé	31.33ºS, 54.1ºW, 242.31m	11/09, 30/11
	Santana do Livramento	30.83ºS, 55.6ºW, 328m	11/09, 30/11
Depressão Central	Santa Maria	29.7ºS, 53.7ºW, 95m	11/09, 30/11
	Porto Alegre	30.05ºS, 51.17ºW, 46.97m	21/08, 30/11
Serra do Sudeste	Encruzilhada do Sul	30.53ºS, 52.52ºW, 427.75m	11/09, 30/11
Planalto Médio	Cruz Alta	28.63ºS, 53.6ºW, 472.5m	11/09, 30/11
	Passo Fundo	28.22ºS, 52.4ºW, 684.05m	11/09, 30/11
Planalto Superior	Bom Jesus†	28.67ºS, 50.43ºW, 1047.5m	01/11, 30/11
	Lagoa Vermelha†	28.22ºS, 51.5ºW, 840m	01/11, 30/11
Serra do Nordeste	Caxias do Sul	29.17ºS, 51.2ºW, 759.6m	21/09, 30/11
	Bento Gonçalves	31.78ºS, 52.41ºW, 13m	21/09, 30/11
Litoral	Pelotas	29.15ºS, 51.51ºW, 640m	11/09, 30/11
	Rio Grande	32.03ºS, 52.12ºW, 2.46m	21/09, 30/11
	Santa Vitória do Palmar†	33.52ºS, 53.35ºW, 24.01m	01/11, 30/11
	Torres	29.35ºS, 49.73ºW, 4.66m	21/08, 30/11
Missões	São Luiz Gonzaga	28.4ºS, 55.02ºW, 245.11m	11/09, 30/11
Alto Vale do Uruguai	Irai	27.18ºS, 53.23ºW, 247.10m	21/08, 30/11
Médio Vale do Uruguai	Uruguaiana	29.75ºS, 57.08ºW, 62.31m	11/09, 30/11

† These sites are not located in recomended regions for cassava according to the Agroclimatic Zoning (Maluf et al. 2011).

Table 3. Modified processes in the GUMCAS model and optimized parameters for the cassava cultivar Fepagro – RS 13 resulted from the calibration procedure.

| Parameter or Process	Default GUMCAS	Calibrated or modified GUMCAS
LAR	$LAR=Rv*LAR_0*(1-t_{ve}/A_{L0})$	$LAR=LARmax*f(T)$
T_{base}	13ºC	14ºC (Schons et al., 2007)
A_e	11.80 Dd	7.08 Dd
A_{b0}	Not considered	23.60 Dd
A_{b1}	44.10 Dd	27.60 Dd
A_{b1-2}	35.30 Dd	31.51 Dd
A_{b2-3}	35.30 Dd	17.67 Dd
A_{b3-4}	35.30 Dd	7.22 Dd
S_Φ	$0.25.h^{-1}$	$0.15.h^{-1}$
N_f	3.00	SB1: 2.75; SB2: 2.65; SB3: 2.34; SB4: 2.0
CGR_{max}	27.5 g $m^{-2}day^{-1}$	31.5 g $m^{-2}day^{-1}$
sf_{em}	0.20	0.30
t_{LS}	60	100
LS_{max}	300	220
LS_{300}	50	35
t_m	Not specified	35
SLA_0	240	220
LAR_{maxMS}	-	0.95313
LAR_{maxSB1}	-	0.96502
$LAR_{maxSB2,3,4}$	-	0.64398
P_{leaf}	70 days	140 days
L_{sen}	Not specified	2
Υ_{s1} e Υ_{s2}	Not specified	0.25 and 20.0
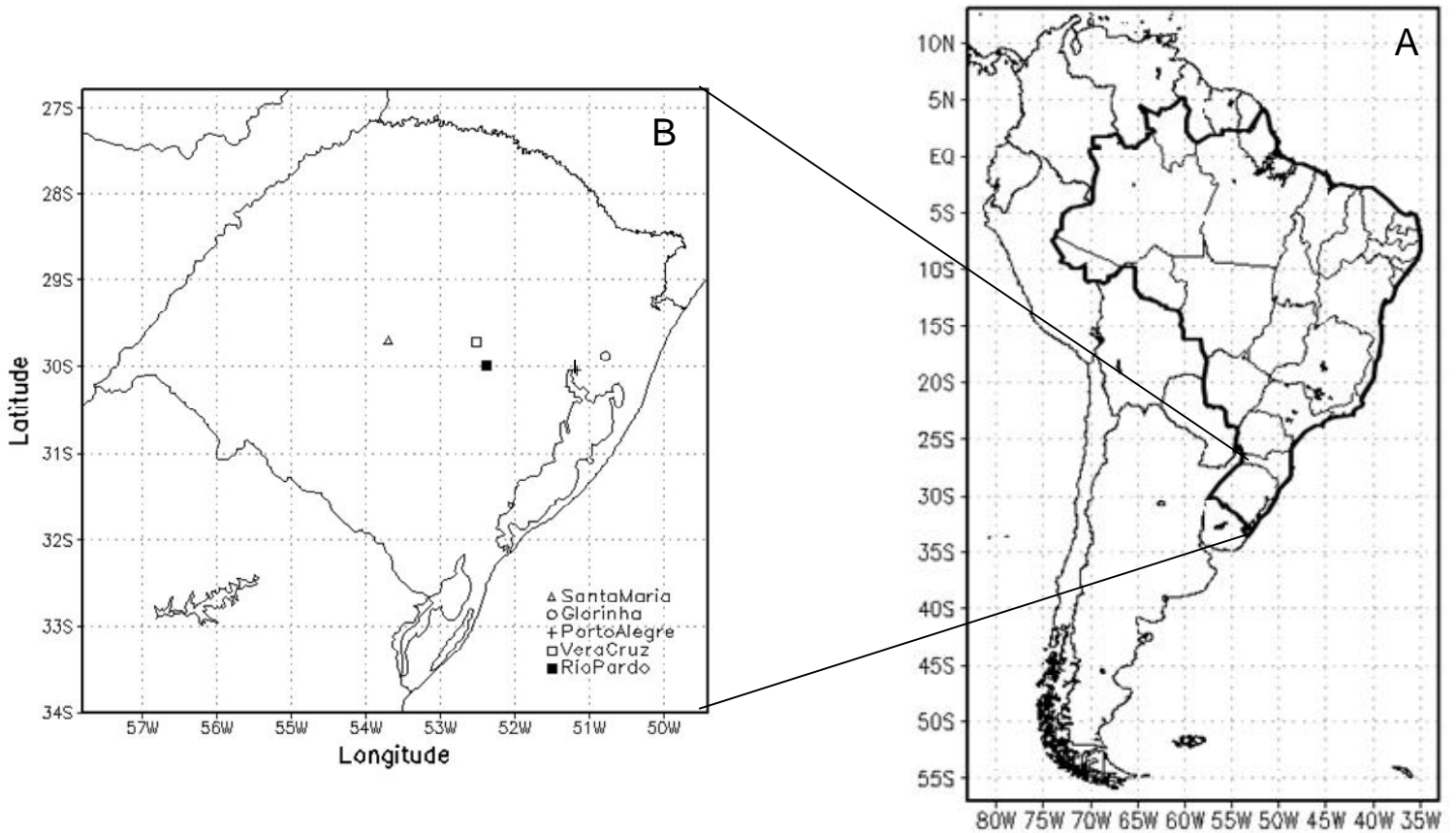
Figure 1. Map of South America and Brazil (A) and the domain (Rio Grande do Sul State) of this study (B) with the sites used for model calibration (Santa Maria) and model testing (Santa Maria, Vera Cruz, Rio Pardo and Glorinha) and the site used for source of meteorological data (Porto Alegre) to run the GUMCAS model in Vera Cruz, Rio Pardo e Glorinha.
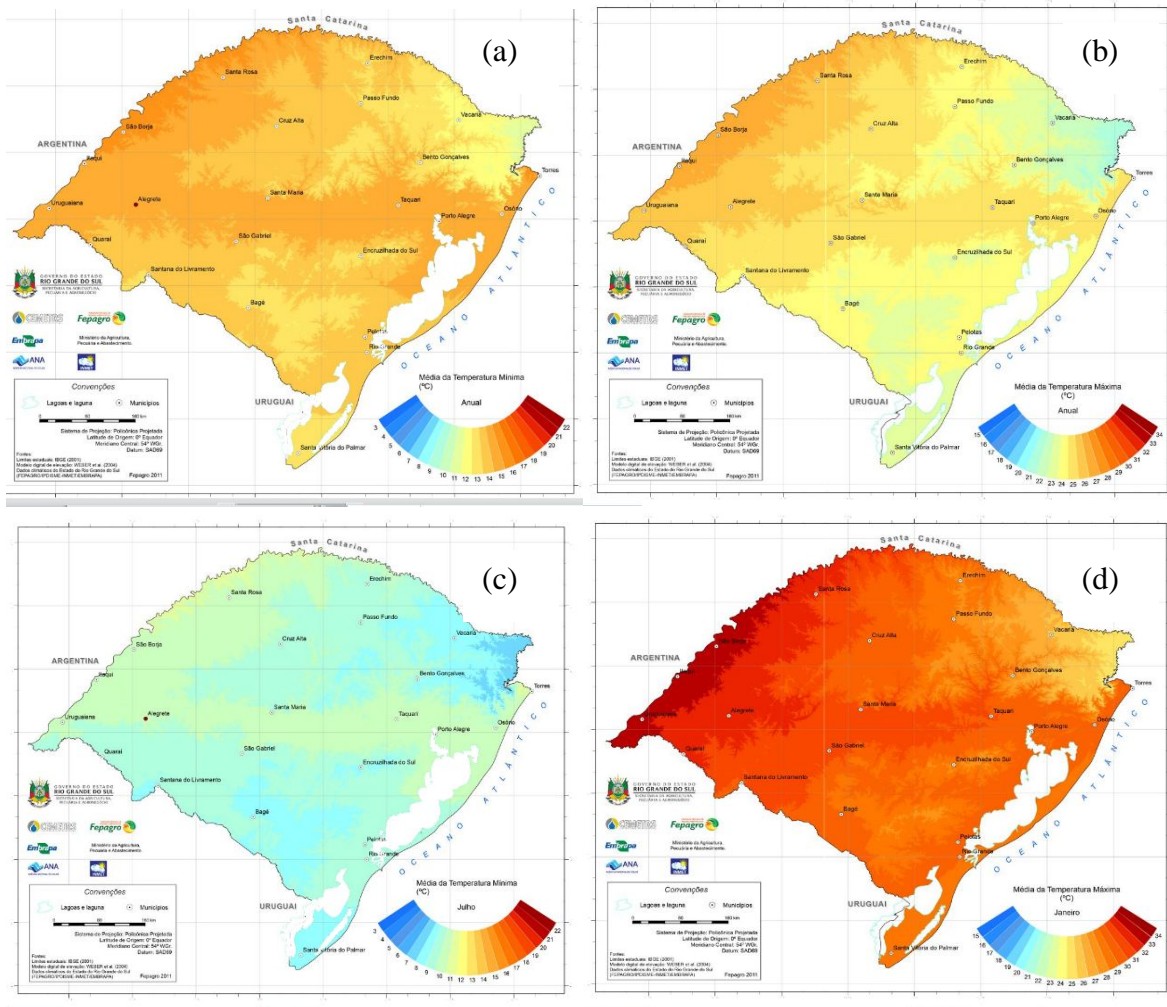
Figure 2. Annual normal minimum (a) and maximum (b), monthly normal minimum temperature in July (c) and monthly normal maximum temperature in January (d) in the State of Rio Grande do Sul, Brazil. Source: Matzenauer et al. (2011).
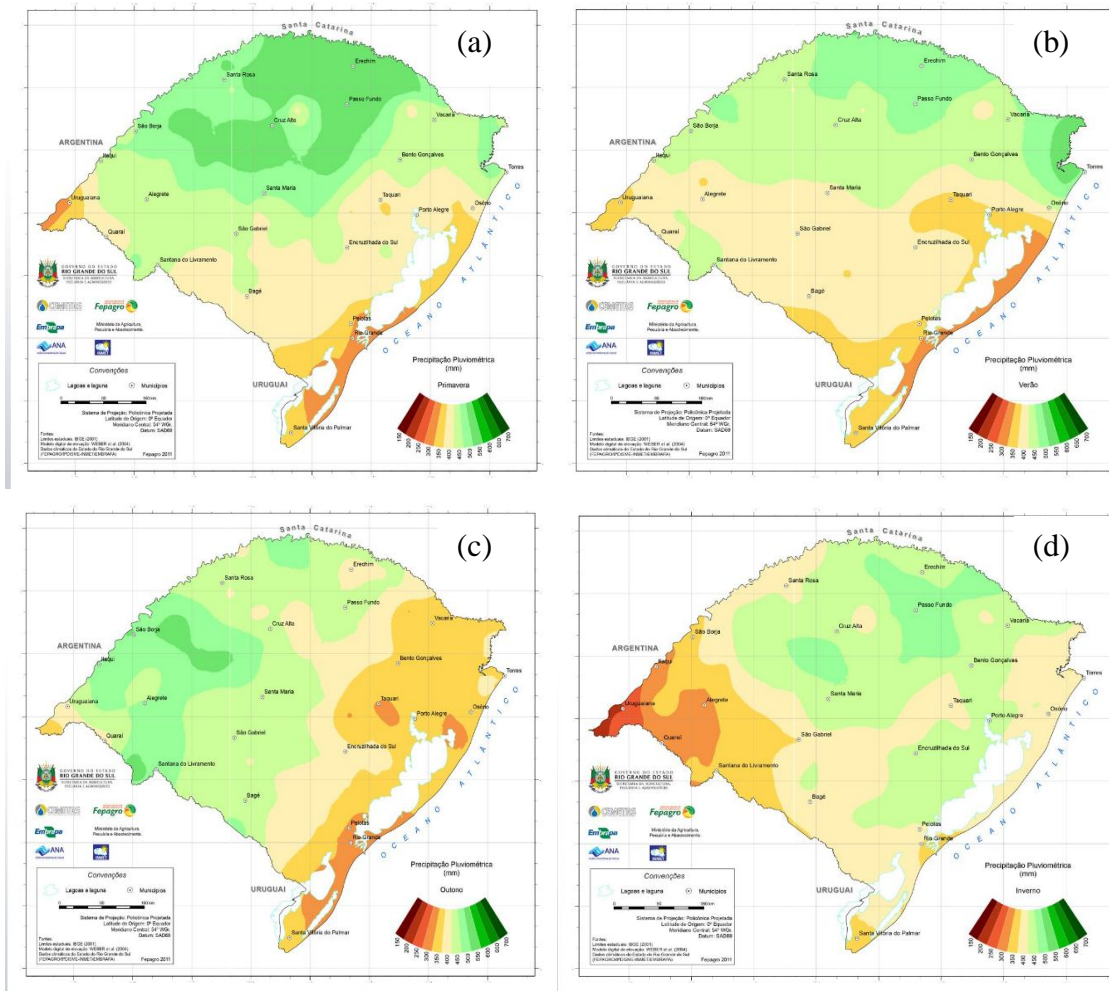
Figure 3. Seasonal normal precipitation in the State of Rio Grande do Sul, Brazil: (a) Spring, (b) Summer, (c) Fall, (d) Winter. Source: Matzenauer et al. (2011).
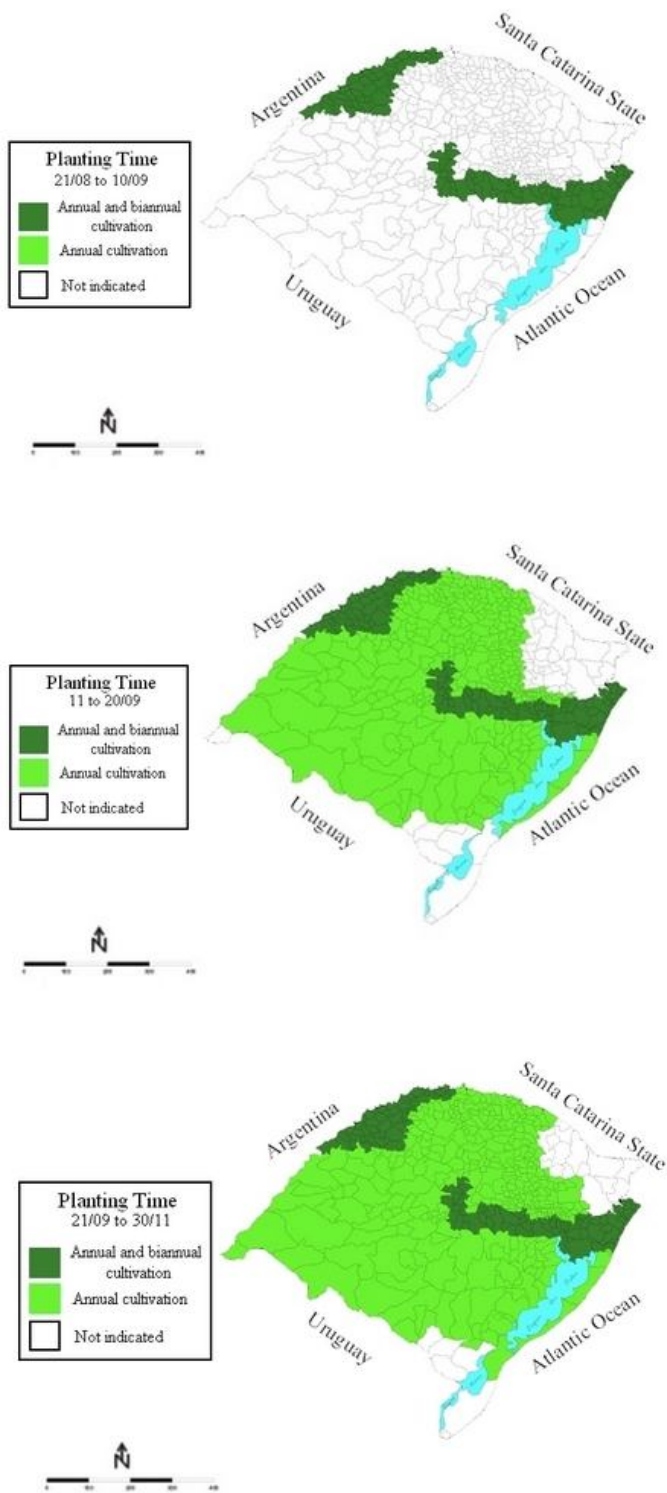
Figure 4. Map of the State of Rio Grande do Sul, Brazil, showing the Agroclimatic Zoning for cassava in the State (Maluf et al., 2011).

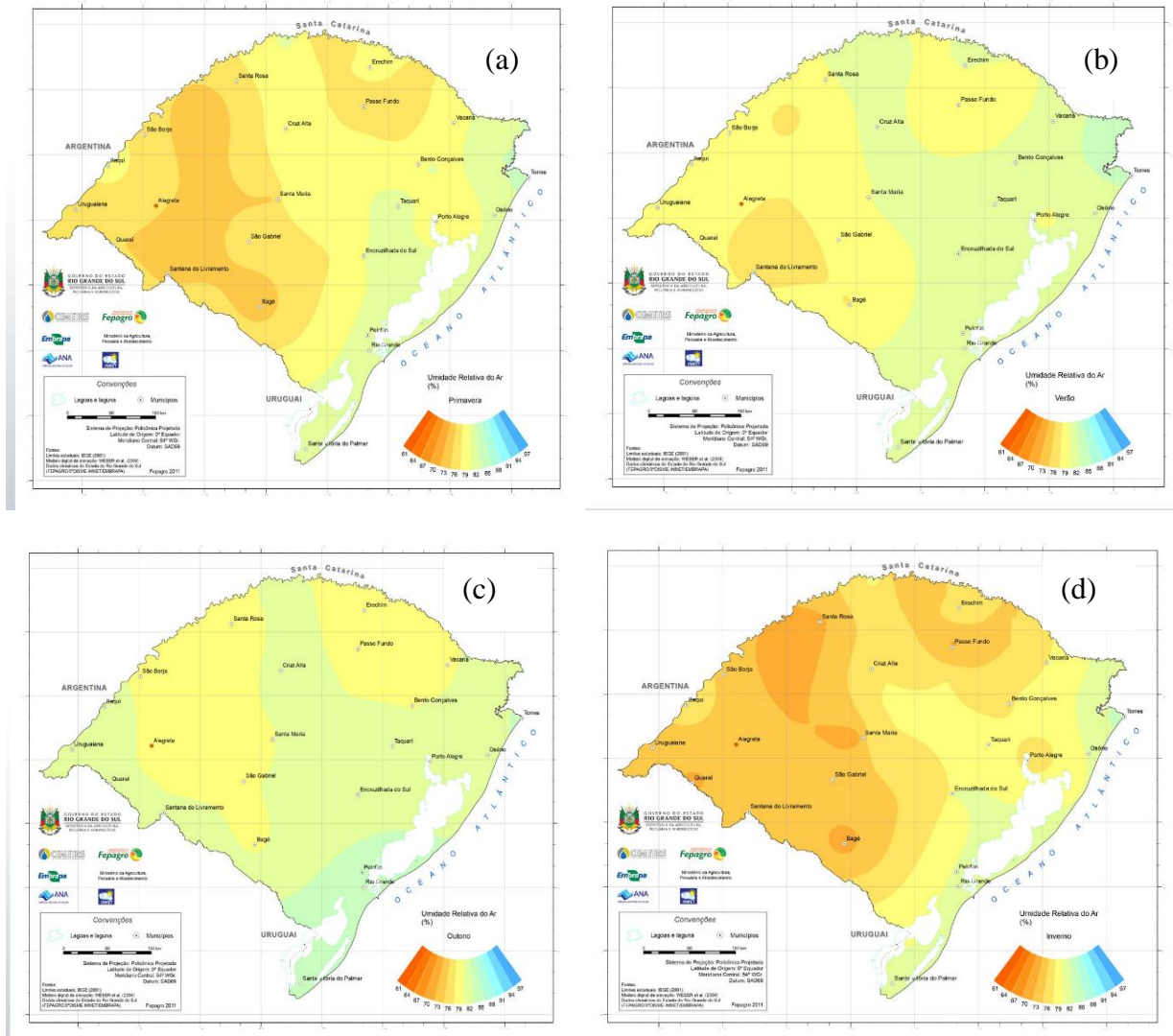Figure 5. Seasonal relative humidity in the State of Rio Grande do Sul, Brazil: (a) Spring, (b) Summer, (c) Fall, (d) Winter. Source: Matzenauer et al. (2011).
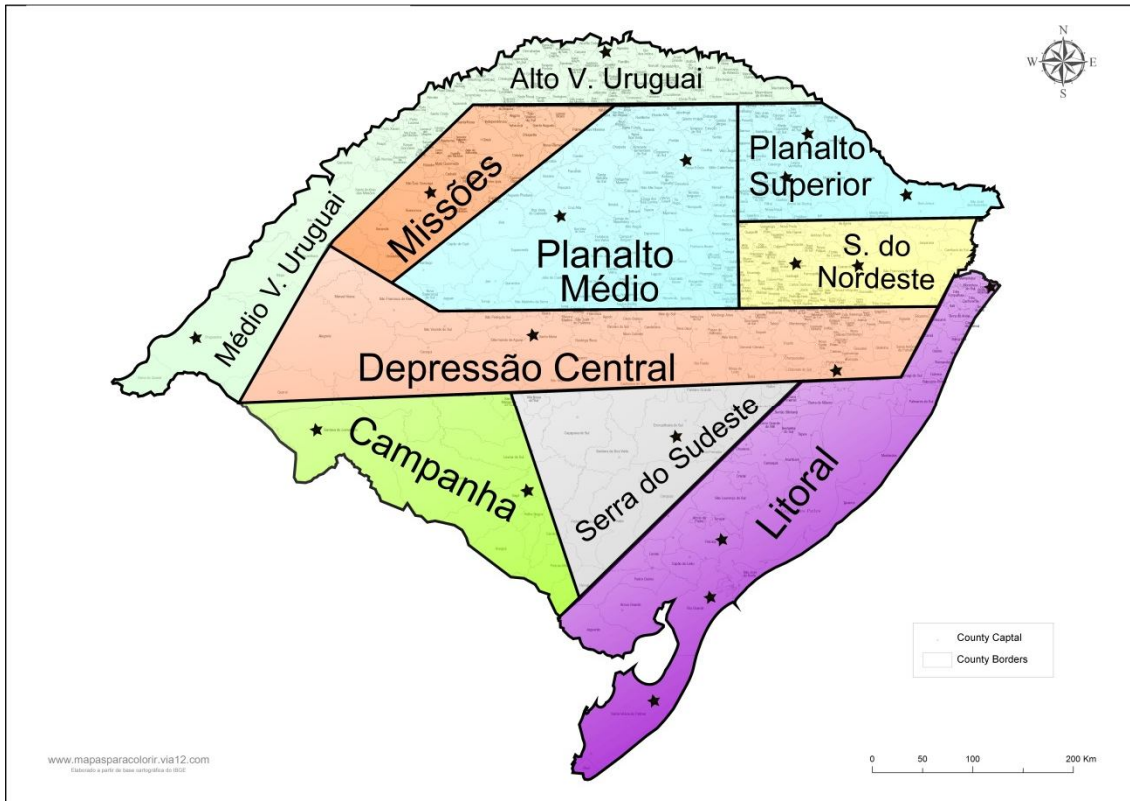
Figure 6. Climatic regions in the Rio Grande do Sul State, Brazil, and the locations (stars) with weather stations used for the sensitivity analysis of the GUMCAS model. Adapted from http://www.mapasparacolorir.com.br/mapa-estado-rio-grande-do-sul.php
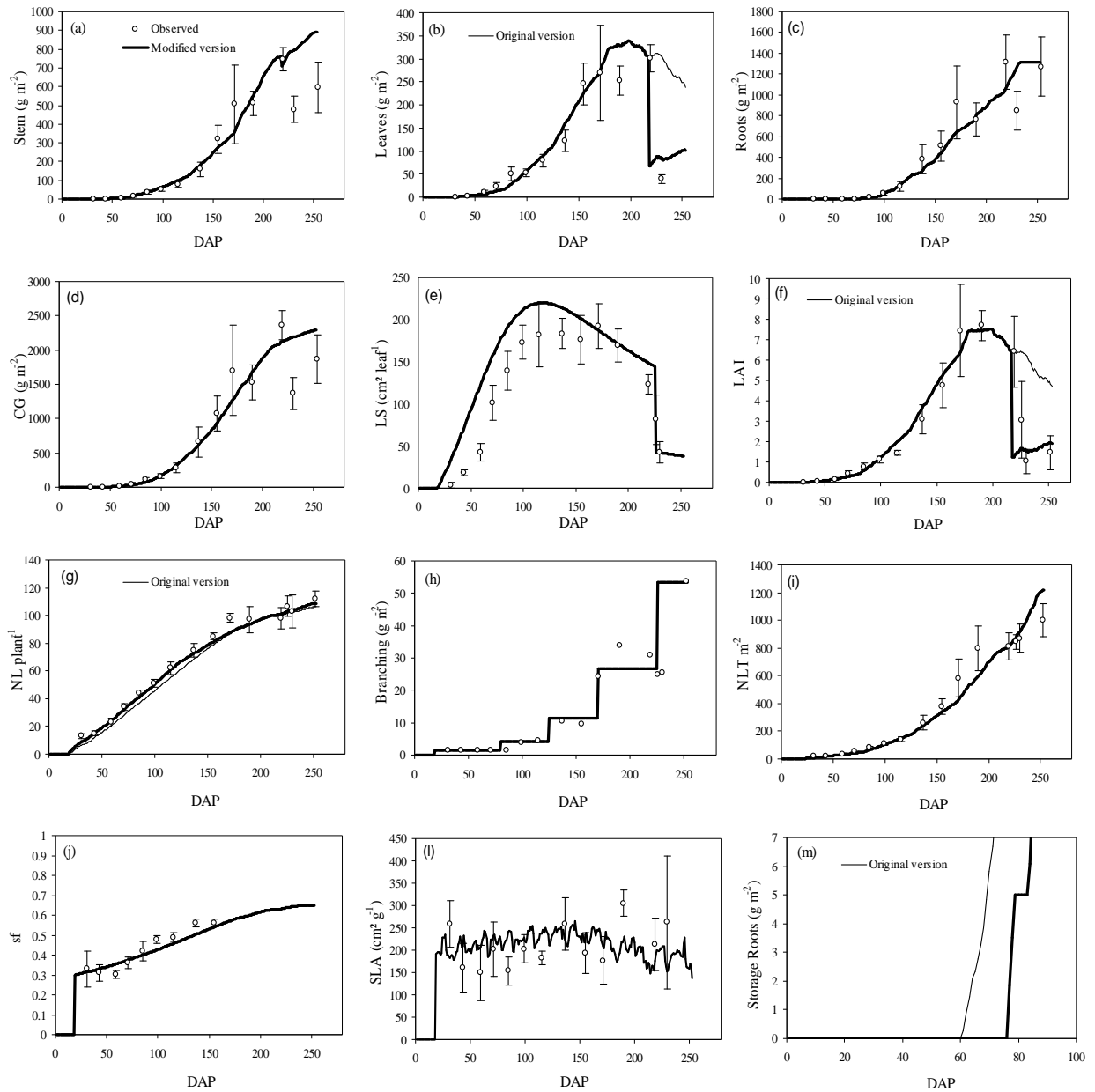
Figure 7. Parameters and processes calibrated for cassava cultivar Fepagro - RS 13 during the 2011/2012 growing season resulted from the optimization procedure. Observed data (average and standard deviation) are represented by open circles with error bars. Simulated data with the GUMCAS model are represented by the curves (thick line is the calibrated model with the modified version and thin line is the calibrated model with the original version).
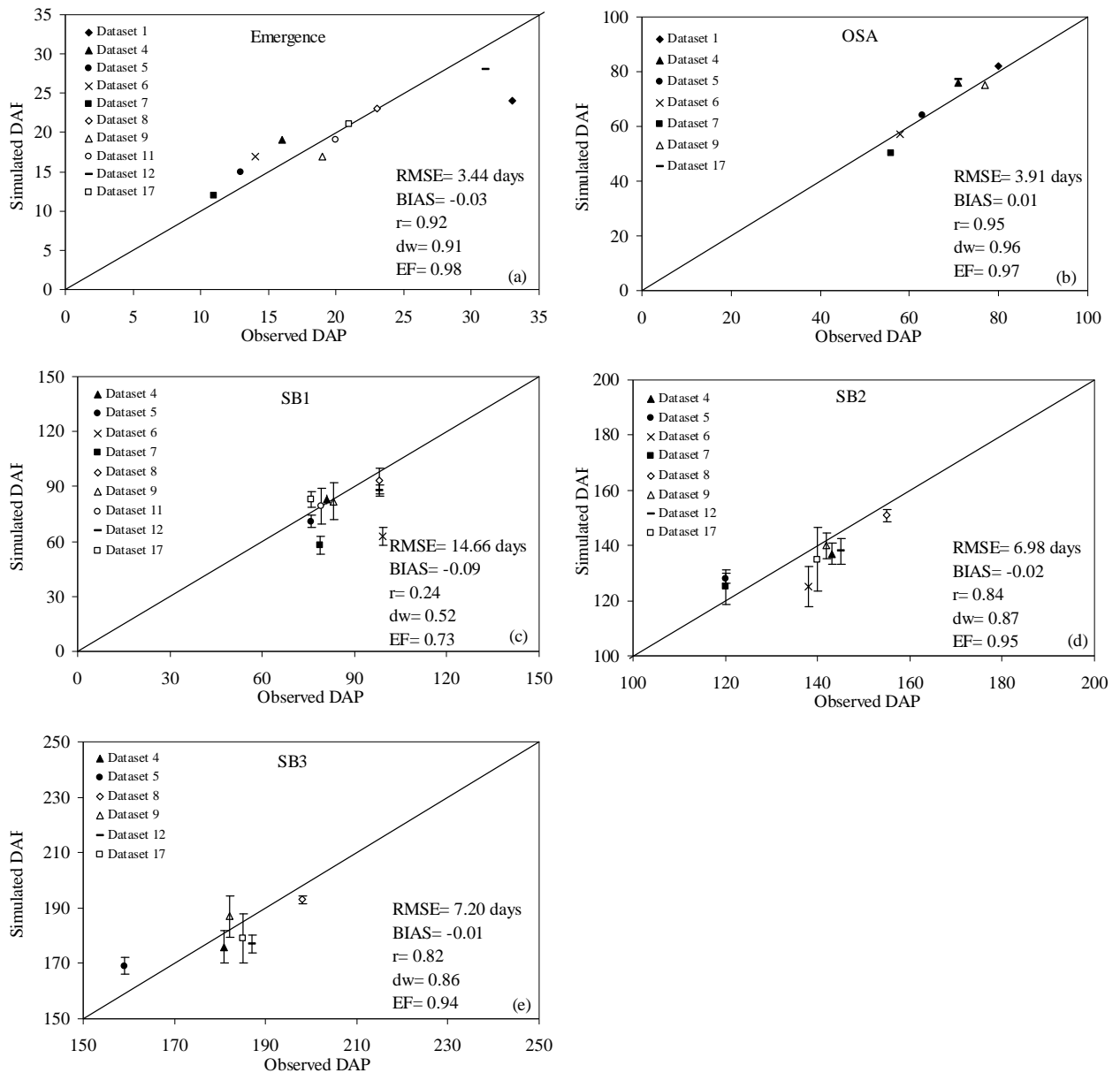
Figure 8. Observed versus simulated day after planting (DAP) of emergence (a), onset of starch accumulation (b), first simpodial branching (c), second simpodial branching (d) and third simpodial branching (e) of cassava, cultivar Fepagro - RS 13, with the GUMCAS model in several datasets in Santa Maria, RS, Brazil. Statistics are shown in each panel: RMSE=Root Mean Square Error, BIAS=BIAS index, r=correlation coefficient, dw=index of agreement, EF=model efficiency.
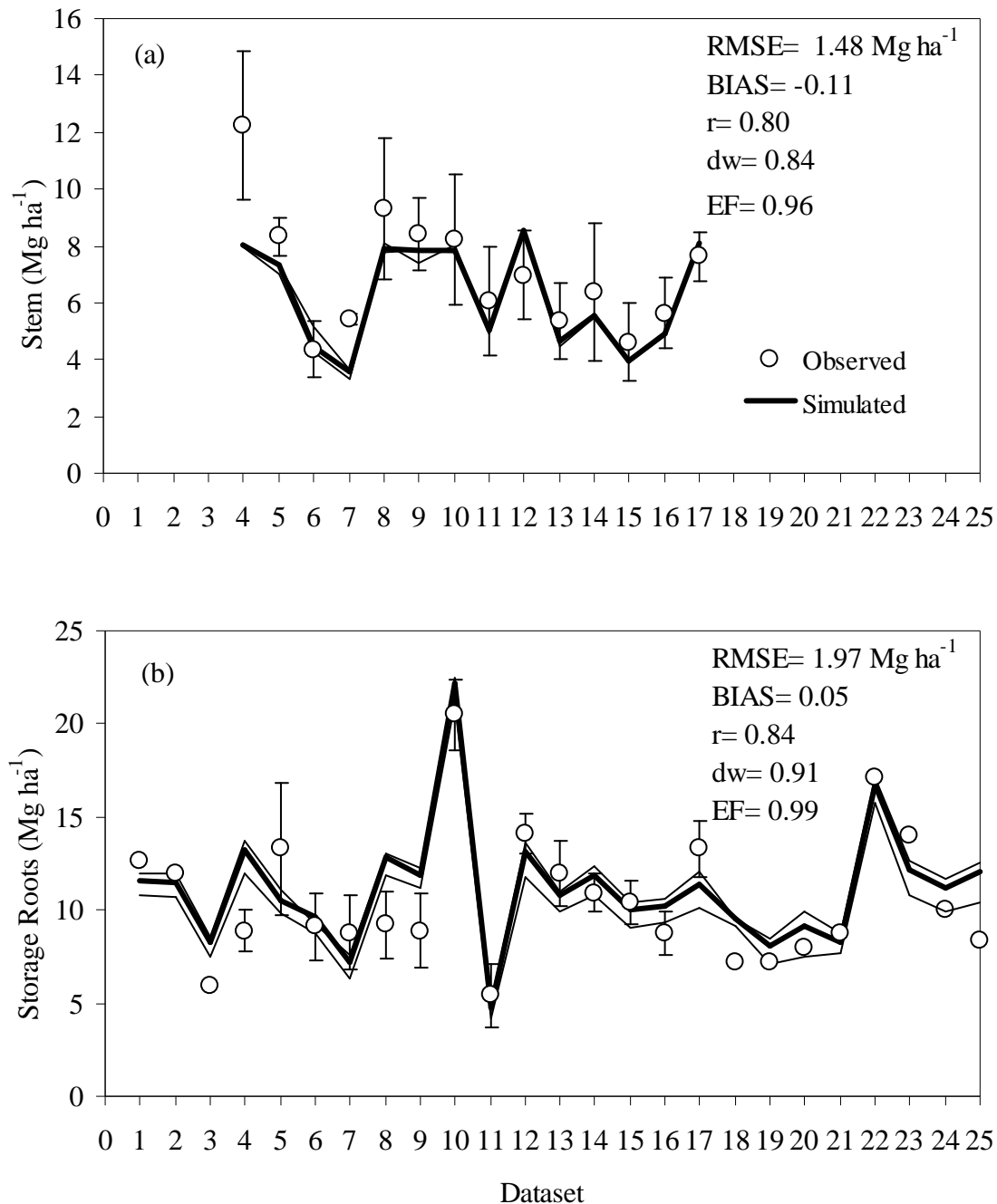
Figure 9. Observed and simulated yield of stem (a) and storage roots (b) dry matter of cassava with the GUMCAS model. Stem data are from cultivar Fepagro - RS 13 grown in Santa Maria, RS, tuber roots data are from varieties Fepagro - RS 13 and Fepagro - RS 14 grown in Santa Maria, Vera Cruz, Glorinha and Rio Pardo, RS, Brazil, in several datasets described in Table 1. RMSE is the root mean square error. Error bars are presented for observed data from experiments at Santa Maria. Thick solid line is simulated with the model set at 50% emergence and thin solid lines with the model set at 10% and 90% emergence. Statistics are shown in each panel: RMSE=Root Mean Square Error, BIAS=BIAS index, r=correlation coefficient, dw=index of agreement, EF=model efficiency.

Figure 10. Observed and simulated number of leaves per plant (NL pl^{-1}) and leaf area index (LAI) of cassava, cultivar Fepagro - RS 13, with the GUMCAS model as a function of days after planting (DAP), grown in Santa Maria, RS, Brazil, on four planting dates: 26 Sep 2006 (a,b), 18 Oct 2006 (c,d), 08 Nov 2006 (e,f) e 28 Nov 2006 (g,h). Error bars are presented for observed data from experiments at Santa Maria. Thick solid line is simulated with the model set at 50% emergence and thin solid lines with the model set at 10% and 90% emergence. Statistics are shown in each panel: RMSE=Root Mean Square Error, BIAS=BIAS index, r=correlation coefficient, dw=index of agreement, EF=model efficiency.

Figure 11. Observed and simulated number of leaves per plant (NL plant^{-1}) and leaf area index (LAI) of cassava, cultivar Fepagro- RS 13, with the GUMCAS model as a function of days after planting (DAP), grown in Santa Maria, RS, Brazil, during the 2009/2010 growing season in four plant spacings: 0.8x0.8m (a,b), 1.0x1.0m (c,d), 1.2x1.2m (e,f), and 1.5x1.5m (g,h). Planting was on 24 Sep 2009. Error bars are presented for observed data from experiments at Santa Maria. Thick solid line is simulated with the model set at 50% emergence and thin solid lines with the model set at 10% and 90% emergence. Statistics are shown in each panel: RMSE=Root Mean Square Error, BIAS=BIAS index, r=correlation coefficient, dw=index of agreement, EF=model efficiency.
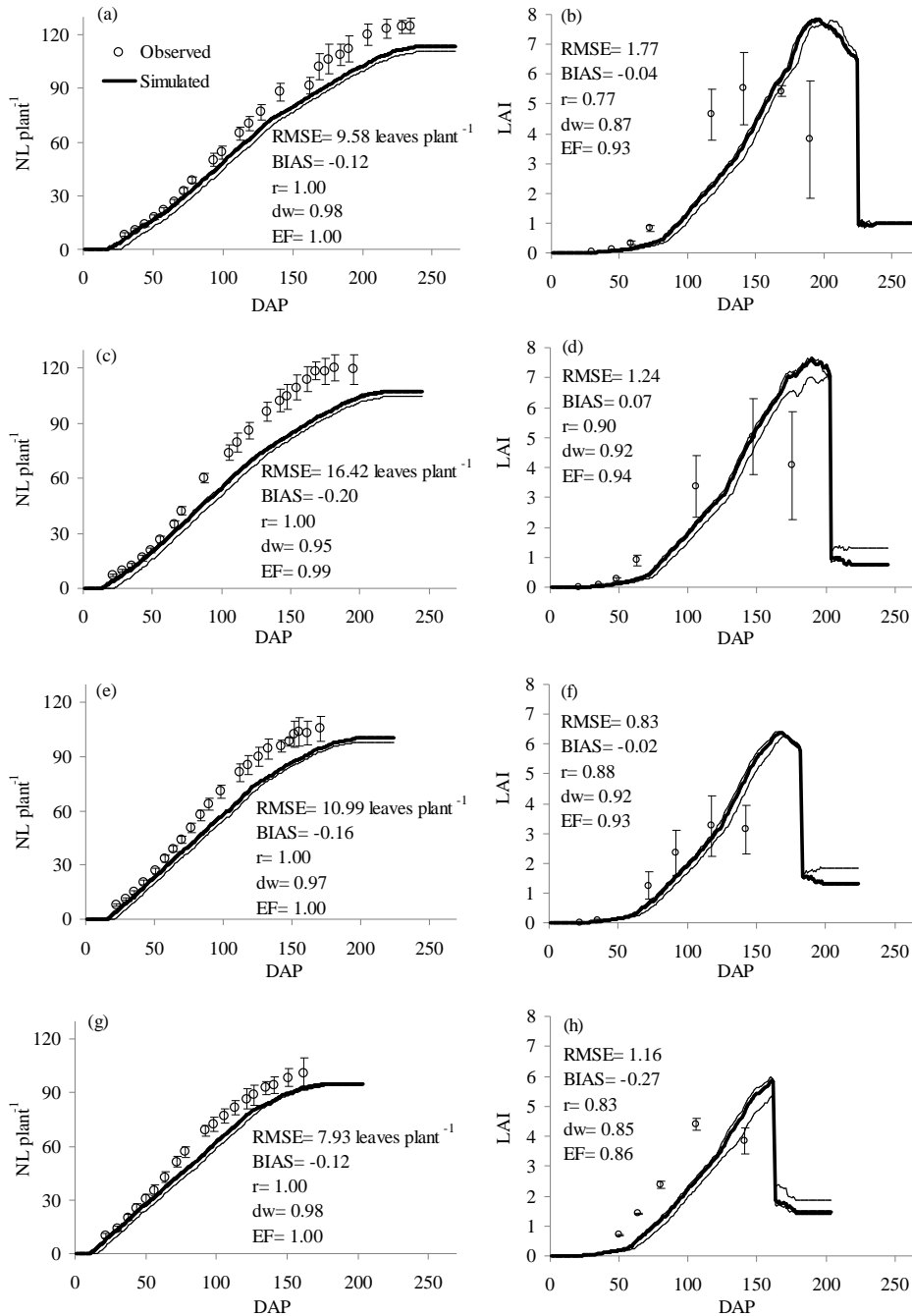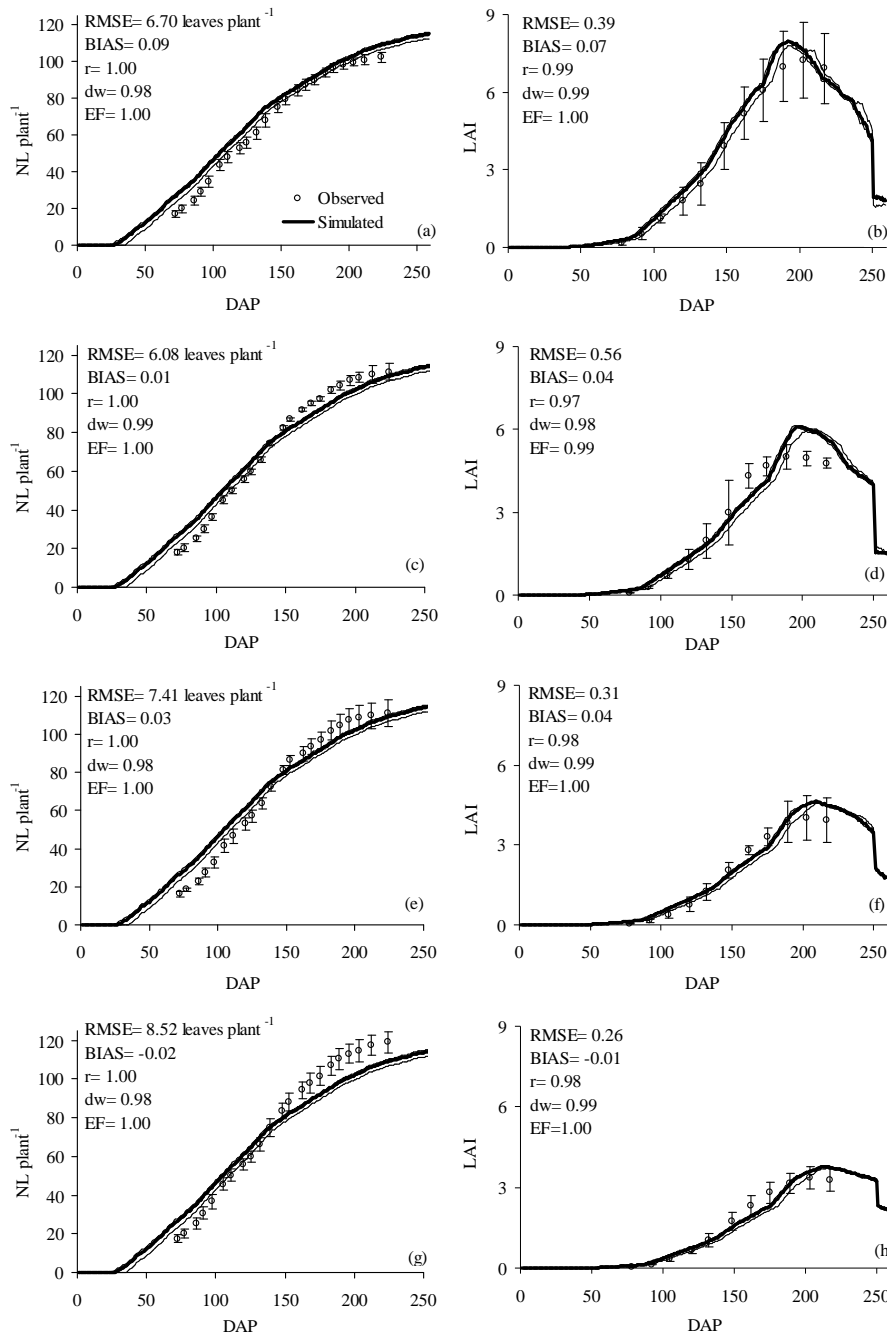
Figure 12. Observed and simulated number of leaves per plant (NL pl⁻¹) (a), leaf area index (LAI) (b), stem dry matter (DM) (c), and tuber roots DM (d) of cassava, cultivar Fepagro - RS 13, with the GUMCAS model as a function of days after planting (DAP), grown in Santa Maria during two growing cycles (2006/2007 and 2007/2008). Planting was on 26 Sep 2006. Error bars are presented for observed data from experiments at Santa Maria. Thick solid line is simulated with the model set at 50% emergence and thin solid lines with the model set at 10% and 90% emergence.
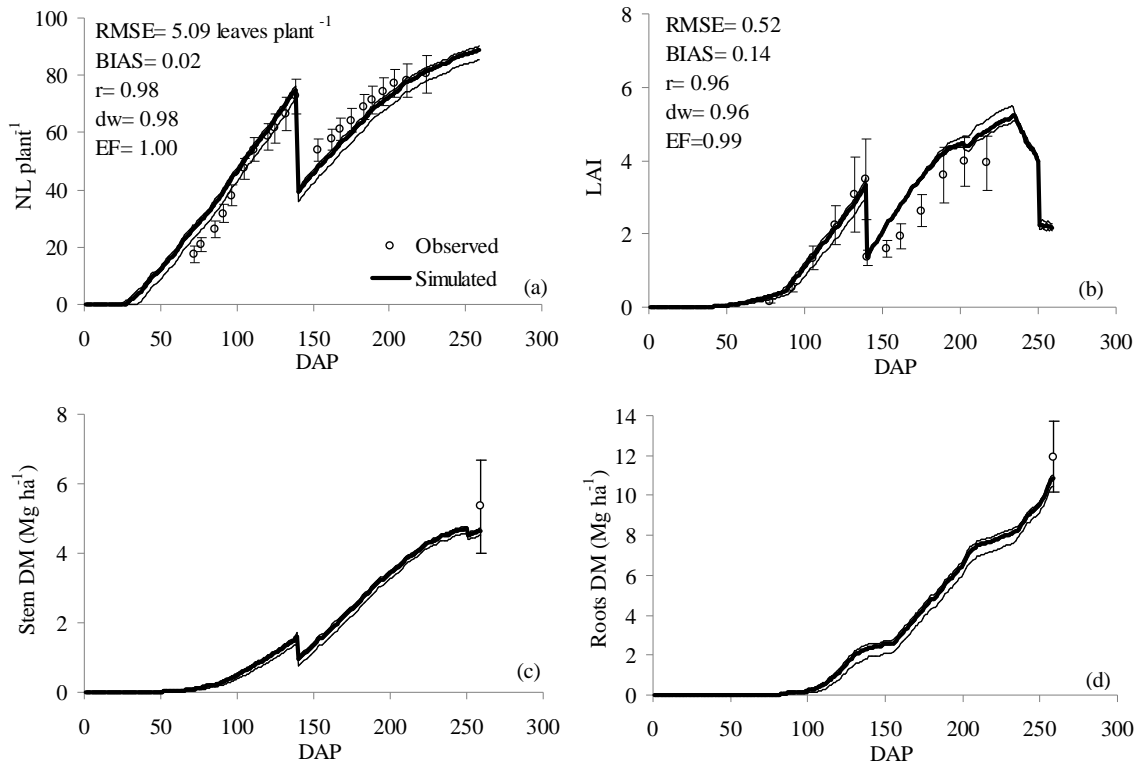
Figure 13. Observed and simulated number of leaves per plant (a), leaf area index (b), stem dry matter (DM) (c) and storage roots DM (d), of cassava cultivar Fepagro - RS 13, with the GUMCAS model as a function of days after planting (DAP), grown in Santa Maria, RS, Brazil during the 2009/2010 growing season. Plants were cut a two nodes of the first simpodial branches on 10 Feb 2010 (DAP= 140). Planting was on 24 Sep 2009 and plant spacing was 0.8x0.8m. Error bars are presented for observed data from experiments at Santa Maria. Thick solid line is simulated with the model set at 50% emergence and thin solid lines with the model set at 10% and 90% emergence. Statistics are shown in each panel: RMSE=Root Mean Square Error, BIAS=BIAS index, r=correlation coefficient, dw=index of agreement, EF=model efficiency.
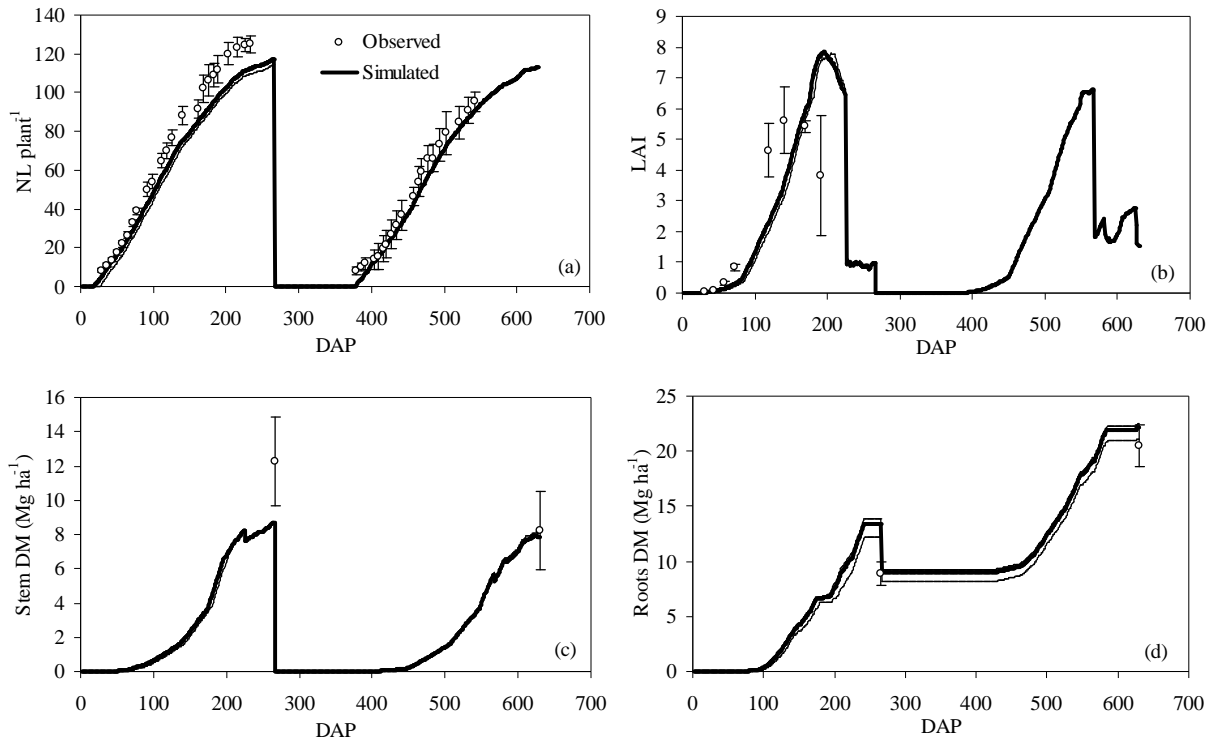
Figure 14. Observed and simulated number of leaves per plant (NL pl^{-1}) cultivar Fepagro - RS 13, with the GUMCAS model as a function of days after planting (DAP), grown in Santa Maria, RS, Brazil, during the 2007/2008 growing season. Planting was on 17 Sep 2007 (a) and 03 Oct 2007 (b). Error bars are presented for observed data from experiments at Santa Maria. Thick solid line is simulated with the model set at 50% emergence and thin solid lines with the model set at 10% and 90% emergence. Statistics are shown in each panel: RMSE=Root Mean Square Error, BIAS=BIAS index, r=correlation coefficient, dw=index of agreement, EF=model efficiency.

Figure 15. Observed and simulated number of leaves per plant (NL pl⁻¹) (a and c) and leaf area index (LAI) (b and d) of cassava, cultivar Fepagro - RS 13 (a,b) and Fepagro - RS 14 (c,d), with the GUMCAS model as a function of days after planting (DAP), grown in Santa Maria, RS, Brazil, during the 2010/2011 growing season. Planting was on 06 Oct 2010. Error bars are presented for observed data from experiments at Santa Maria. Thick solid line is simulated with the model set at 50% emergence and thin solid lines with the model set at 10% and 90% emergence. Statistics are shown in each panel: RMSE=Root Mean Square Error, BIAS=BIAS index, r=correlation coefficient, dw=index of agreement, EF=model efficiency.
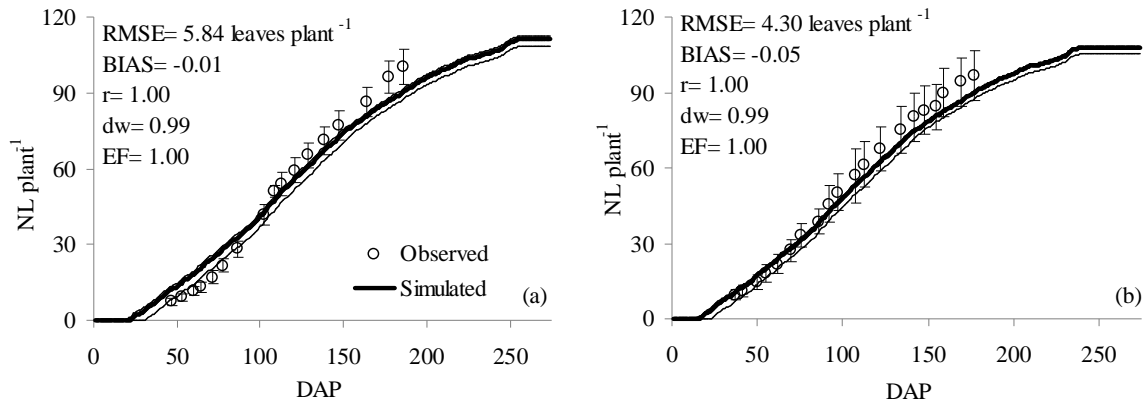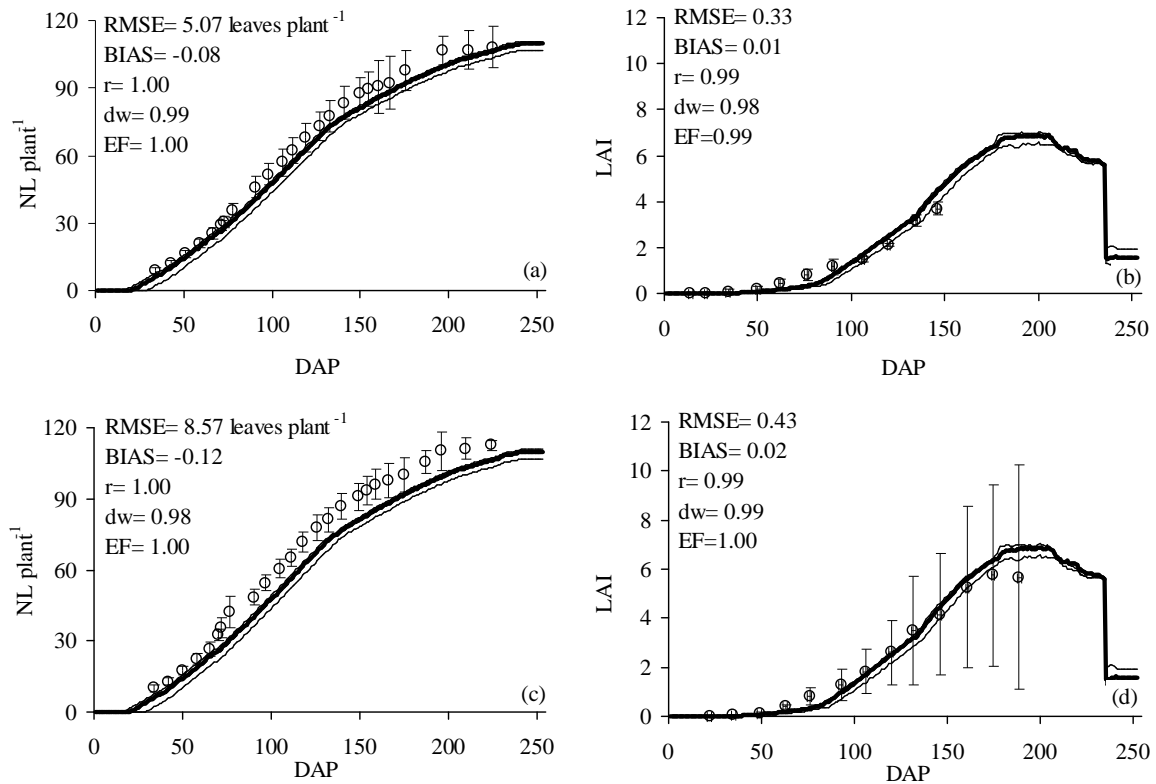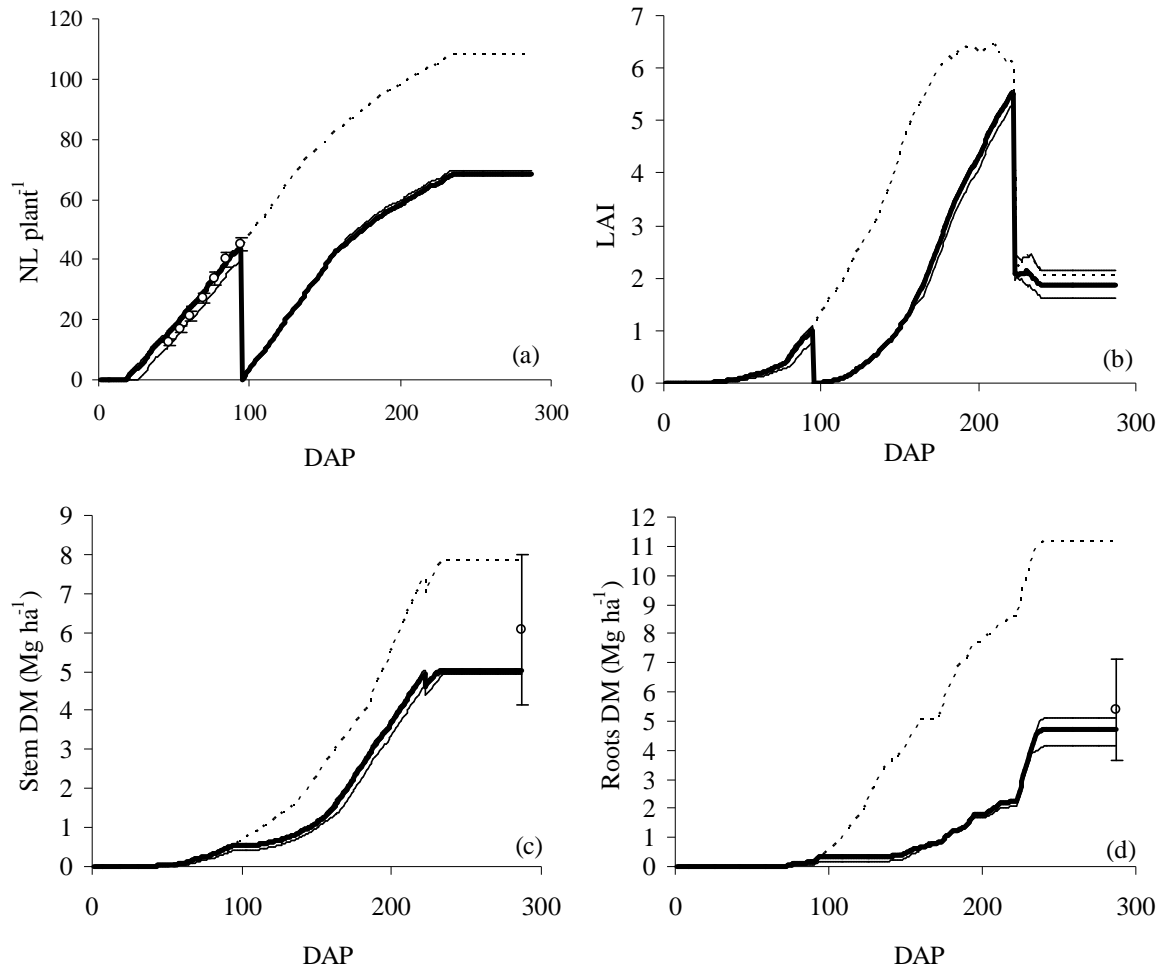
Figure 16. Observed and simulated number of leaves per plant (NL pl^{-1}) (a), leaf area index (b), tuber roots dry matter (DM) (c), and stem DM (d) of cassava, cultivar Fepagro - RS 13, with the GUMCAS model as a function of days after planting (DAP), grown in Santa Maria, RS, Brazil during the 2008/2009 growing season. A hail event took place on 08 Jan 2009 (DAP=95) that destroyed the whole leaf area of plants, and after that plants restarted growing. Planting was on 06 Oct 2008. Error bars are presented for observed data from experiments at Santa Maria. Thick solid line is simulated with the model set at 50% emergence and thin solid lines with the model set at 10% and 90% emergence. Dashed line is the simulated curve without the hail event.
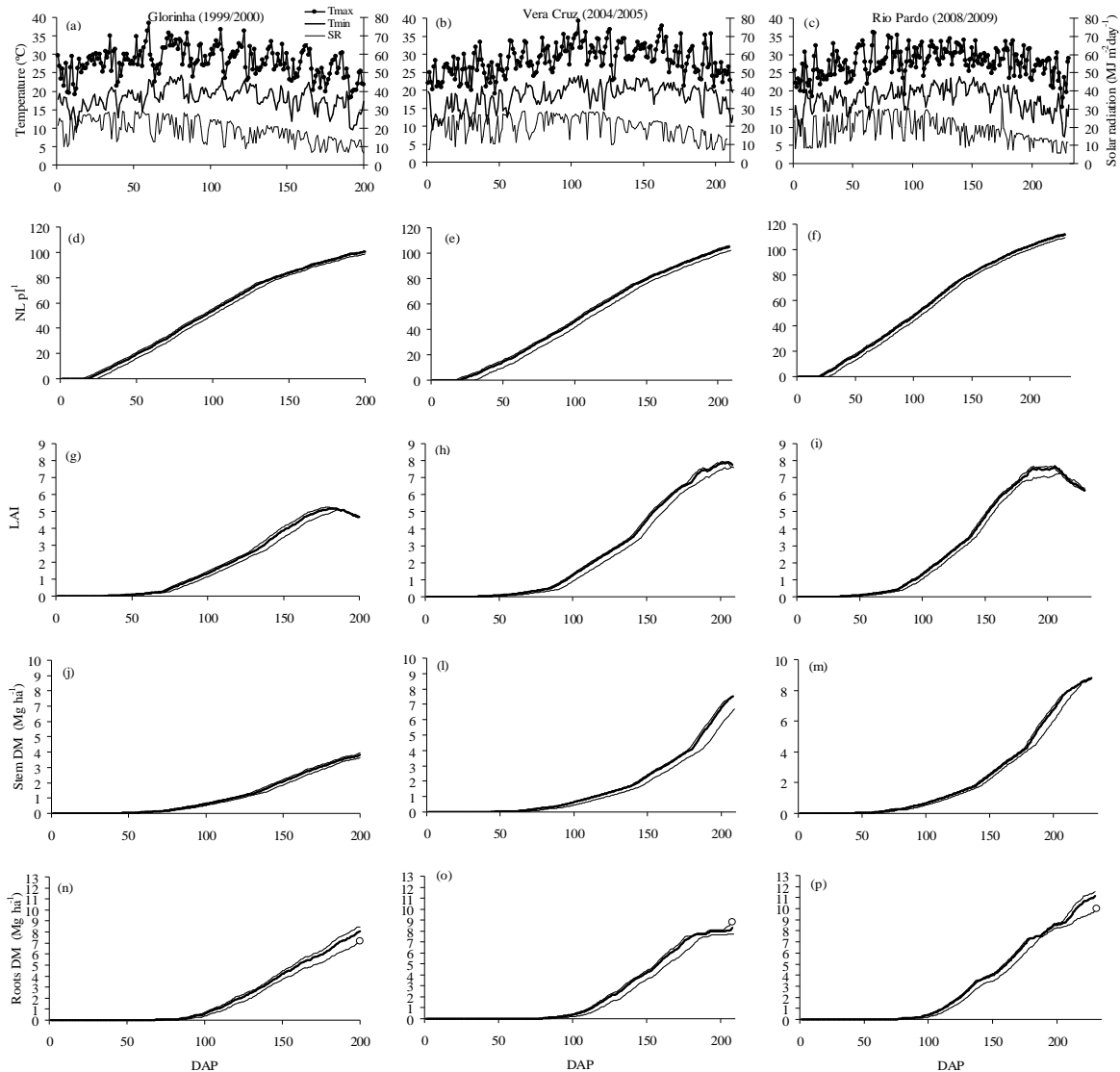
Figure 17. Daily minimum (Tmin) and maximum (Tmax) temperature, and solar radiation (SR) (a,b,c), observed and simulated number of leaves per plant (NL plant[-1]) (d,e,f) leaf area index (LAI) (g,h,i), stem dry matter (DM) (j,l,m) and tuber roots DM (n,o,p) of cassava, cultivar Fepagro - RS 13, with the GUMCAS model as a function of days after planting (DAP), for experiments run in Glorinha during the 1999/2000 growing season (left hand panels), in Vera Cruz during the 2004/2005 growing season (center panels) and in Rio Pardo during the 2008/2009 growing season (right hand panels). Planting date was on 29 Oct 1999, 27 Sep 2004 and 03 Oct 2008, and harvesting was on 15 May 2000, 22 Apr 2005 and 21 Sep 2009 in Glorinha, Vera Cruz and Rio Pardo, respectively. Single row spacing was 1.0x0.8m (12,500 plants ha^{-1}) in Glorinha and 1.0x0.6m (16,666 plants ha^{-1}) in Vera Cruz and Rio Pardo. Thick solid line is simulated with the model set at 50% emergence and thin solid lines with the model set at 10% and 90% emergence.
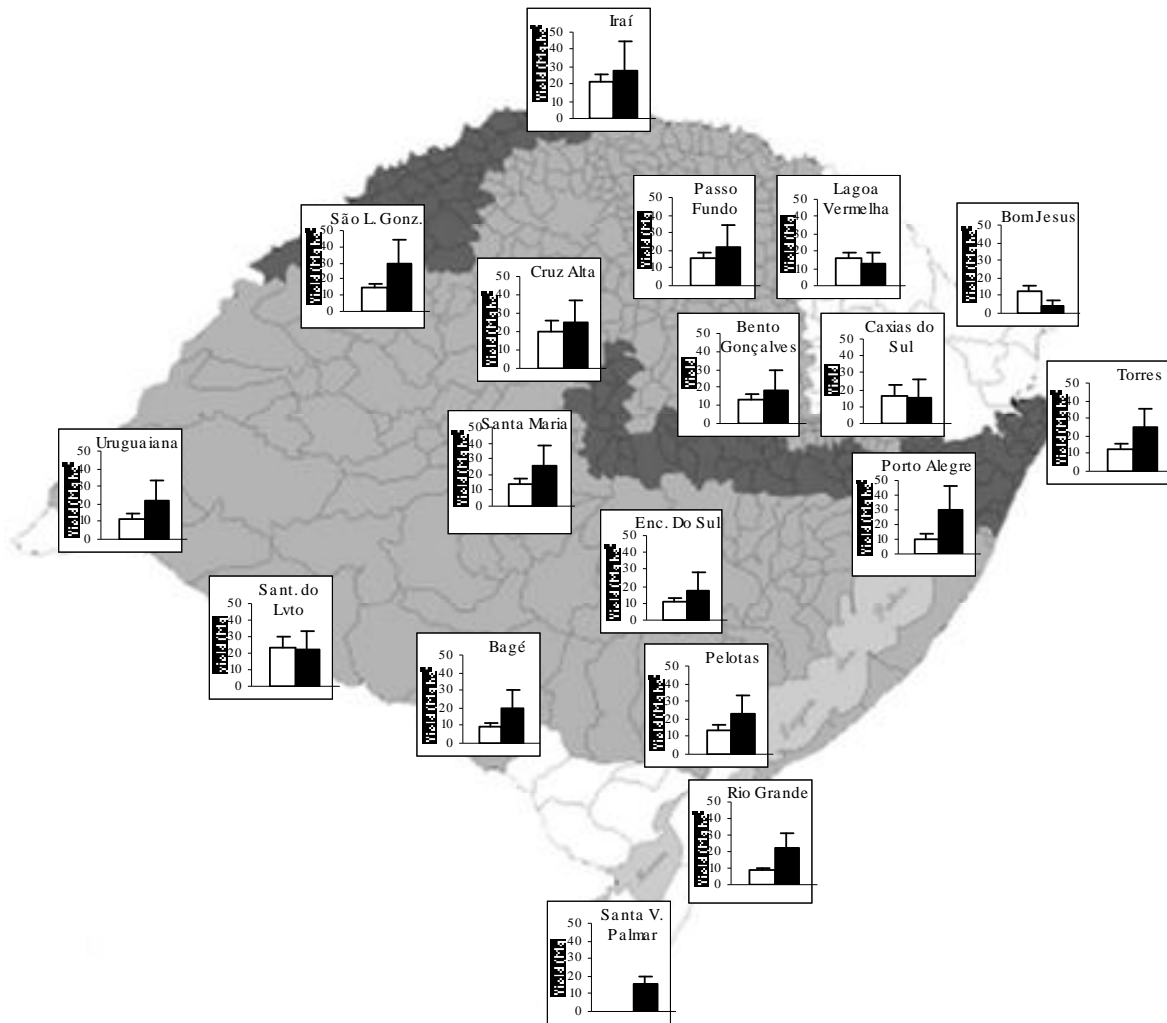
Figure 18. Observed (open bars) and simulated (solid bars) fresh storage roots yield of cassava, for different locations accross the State of Rio Grande do Sul, Brazil. Both observed and simulated bars are the mean and standard deviation for the 2004/2005-2010/2011 growing seasons period. Simulated values are the mean of the seven years and two runs (two planting dates) of the model each year.
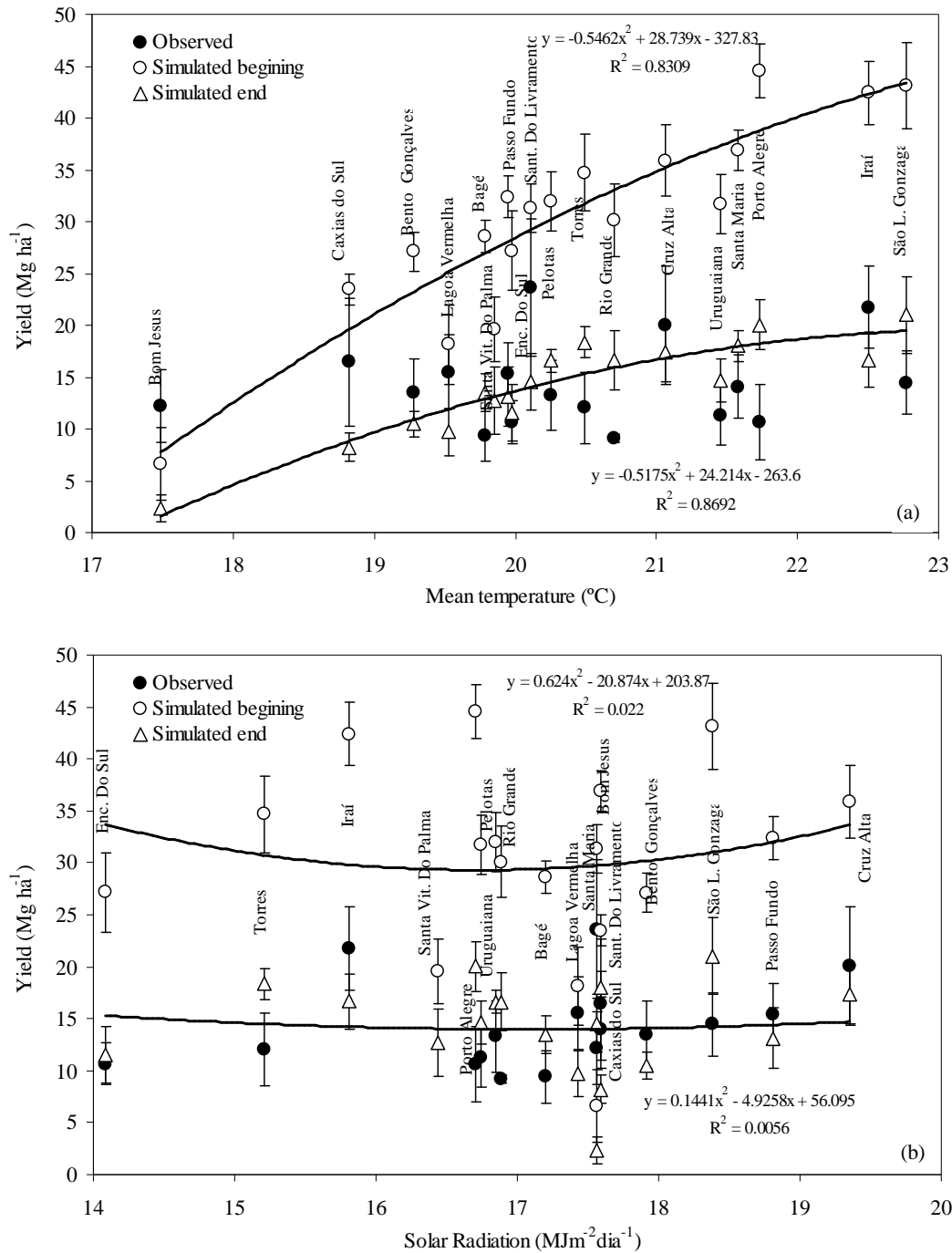
Figure 19. Simulated fresh storage roots yield of cassava with the GUMCAS model runs starting at the beginning and at the end of the recommended planting period as a function of the mean air temperature (a) and mean solar radiation (b) during the growing season for several locations in the Rio Grande do Sul State. Solid circles are the observed fresh yields from the Brazilian Agricultural Statistics Service. Both simulated and observed points are the mean and standard deviation (error bars) for the 2004/2005-2010/2011 growing seasons period. Curves and equations are regression fits for the simulated data.
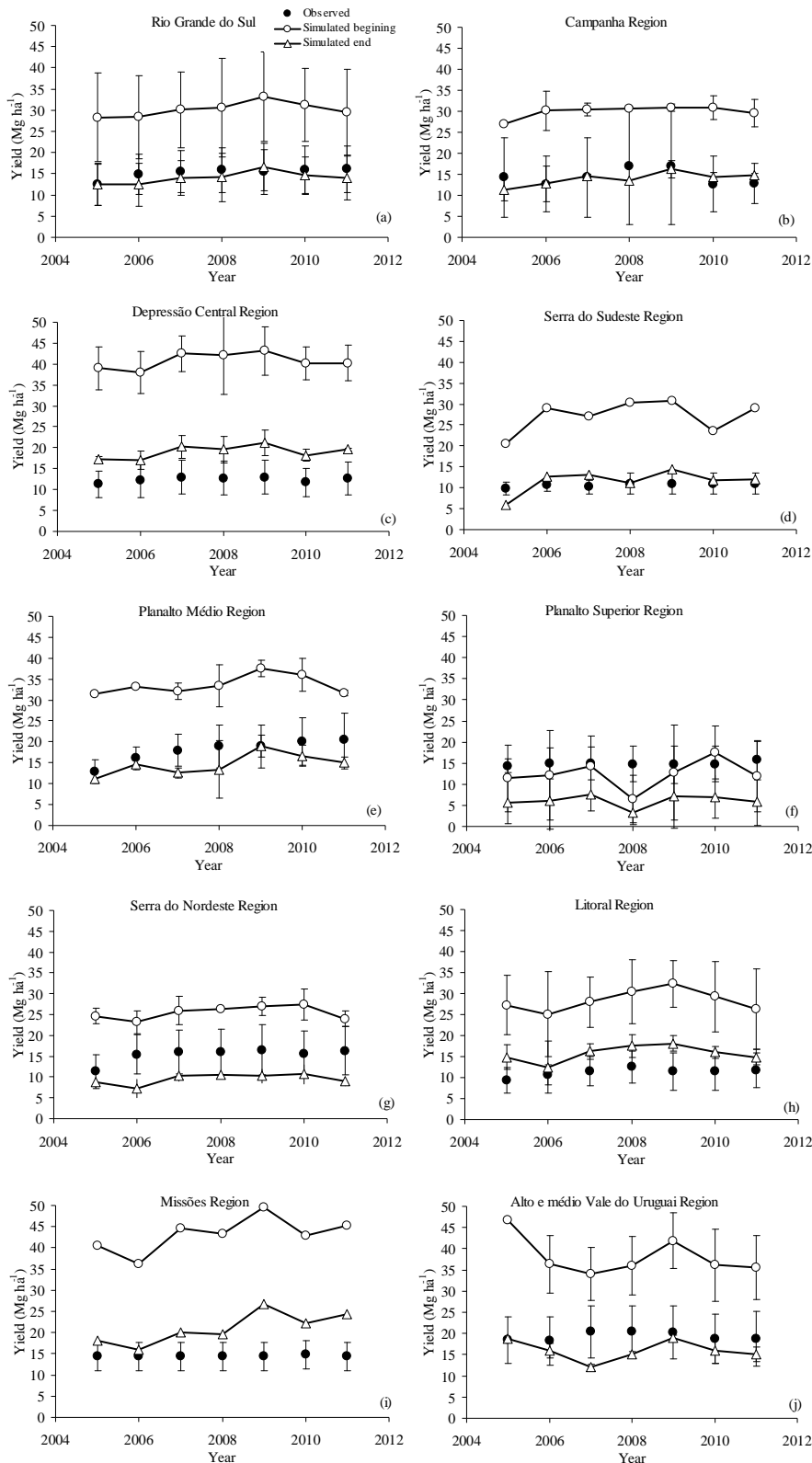
Figure 20. Simulated fresh storage roots yield of cassava with the GUMCAS model runs starting at the beginning and at the end of the recommended planting period as a function of years during the 2005-2011 period for the Rio Grande do Sul State (a), and for different State regions (b to j). Solid circles are the observed yields from the Brazilian Agricultural Statistics Service. Errors bars are one standard deviation of the mean of several locations in each region.

Appendix A. Crop parameters, their description and units.

Parameter	Description	Units
T_{base}	Cardinal minimum temperature	°C
T_{opt}	Cardinal optimum temperature	°C
T_{high}	Cardinal maximum temperature	°C
A_e	Developmental time from sprouting to emergence	Dd
A_{b1}	Developmental time from emergence to first branching	Dd
SB1	Date First Simpodial Branching	Dd
A_b	Developmental time between subsequent branching levels	Dd
A_{b1-2}	Developmental time from first branching to second branching	Dd
A_{b2-3}	Developmental time from second branching to third branching	Dd
A_{b3-4}	Developmental time from third branching to fourth branching	Dd
S_Φ	Sensitivity to photoperiod	h^{-1}
N_f	Number of branches at each branch point	dimensionless
CGR_{max}	Maximum crop growth rate	$gm^{-2}dia^{-1}$
Sf_{em}	Stem/shoot fraction at emergence	dimensionless
t_{LS}	Date at which max leaf size occurs	DAE
LS_{max}	Maximum leaf size	cm^2
LS_{300}	Leaf size at 300 DAE	cm^2
t_m	Shape coefficient in the leaf size equation	dimensionless
A_{leaf}	Lifetime of the cohort	days
P_{leaf}	Maximum leaf age	days
L_{sen}	Critical LAI for leaf aging relationship	$m^2\,m^{-2}$
Υ_{s1}	Sensitivity of senescence to shading coefficient when tmin>5.0°C	$day\,m^2\,m^{-2}$
Υ_{s2}	Sensitivity of senescence to shading coefficient when tmin≤5.0°C	$day\,m^2\,m^{-2}$
r	Daily rate of aging	dimensionless
Rv	The rate of progression vegetative	Dd
LAR_0	Leaf appearance rate at time of emergence	leaves Dd^{-1}
t_{ve}	Crop developmental age since emergence	Dd
A_{L0}	Developmental age at which leaf production ceases	Dd
A_{b0}	Developmental time from emergence to Onset of starch accumulation	Dd
LAR_{maxMS}	Maximum leaf appearance rate for the main stem (MS)	leaves day^{-1}
LAR_{maxSB1}	Maximum leaf appearance rate for the first simpodial branch (SB1)	leaves day^{-1}
$LAR_{maxSB2,3,4}$	Maximum leaf appearance rate for the 2°,3° and 4° simpodial branch	leaves day^{-1}
f(T)	Temperature response function	dimensionless

4 CONCLUSÕES

- Esse trabalho permitiu realizar a seleção de um modelo matemático baseado em processos com a cultura da mandioca, a calibração e teste do modelo, além de uma análise de sensibilidade do modelo a diferentes condições ambientais encontradas em todo o Estado do Rio Grande do Sul. Em geral, a calibração e as modificações introduzidas no modelo GUMCAS resultou em boas simulações de processos ecofisiológicos chave, tais como o desenvolvimento e crescimento de folhas, bem como o rendimento de raízes tuberosas para um genótipo de mandioca adaptado à região subtropical. O modelo foi capaz de captar as diferentes condições ambientais encontradas no Rio Grande do Sul e com algumas adaptações na introdução dos dados foi capaz de simular diferentes práticas de manejo, tais como plantio, espaçamento, densidade de plantas, poda verde, dois ciclos de crescimento (mandioca de sobreano), bem como o efeito de eventos climáticos extremos, como o granizo.

- As recomendações para pesquisas futuras são melhorar e modificar o relógio do desenvolvimento da cultura, adaptando o modelo de desenvolvimento de Wang e Engel e a interação com o fotoperíodo, e modificar a equação que calcula o tamanho de folha para considerar como tempo de desenvolvimento em graus dia, e não em dias do calendário civil.

- As próximas etapas de pesquisa com o modelo GUMCAS na UFSM são a calibração do modelo para outras cultivares de mandioca (Cascuda, Estrangeira e Fécula Branca) e seu acoplamento a um modelo de balanço hídrico no solo.

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