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ECOFISIOLOGIA E MODELO LOGÍSTICO NA DINÂMICA DE CRESCIMENTO E DESENVOLVIMENTO DE SOJA EM CONDIÇÕES DE EXCESSO HÍDRICO

Santa Maria, RS, Brasil
2022

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Tese apresentada ao Curso de Pós-Graduação em Agronomia, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do título de **Doutora em Agronomia.**

Orientador: Prof. Dr. Sidinei José Lopes

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Patrícia Carine Hüller Goergen

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Aprovado em 17 de julho de 2022:

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Santa Maria, RS
2022

DEDICATÓRIA

Aos meus pais Vicente Luiz e Odete Goergen pela educação, apoio e exemplo de vida.

DEDICO.

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MUITO OBRIGADA.

RESUMO

ECOFISIOLOGIA E MODELO LOGÍSTICO NA DINÂMICA DE CRESCIMENTO E DESENVOLVIMENTO DE SOJA EM CONDIÇÕES DE EXCESSO HÍDRICO

AUTORA: Patrícia Carine Hüller Goergen
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A soja é a principal leguminosa cultivada no mundo. O Rio Grande do Sul é um importante produtor nacional do grão e no Estado vem ocorrendo a expansão da cultura para áreas de terras baixas onde tradicionalmente é cultivado monocultivo de arroz irrigado. A ocorrência de excesso hídrico é prejudicial para o crescimento e desenvolvimento das plantas, e compromete a produção, gerando grandes perdas de produtividade de grãos. No entanto, o período de duração do estresse, o estágio de desenvolvimento das plantas e as condições meteorológicas durante a inundação influenciam na severidade do estresse. Assim, o presente estudo teve por objetivo avaliar a ecofisiologia e caracterizar o crescimento de cultivares de soja pelo modelo logístico submetidas a dias de inundação em épocas de semeadura. Para alcançar tal objetivo foram realizados dois experimentos em duas épocas de semeadura (outubro e novembro) nos anos agrícolas 2018/2019 e 2019/2020. O delineamento experimental foi o inteiramente casualizado com quatro repetições, cada repetição constituindo-se de um vaso com uma planta. Foram utilizadas 2 cultivares (NA 5909 RG e TEC IRGA 6070 RR) de soja com grupo de maturidade relativa próximo de 6.0. O experimento I visou estudar o excesso hídrico em cultivares de soja em distintas fases do desenvolvimento durante a fase vegetativa e o experimento II, estudar dias de inundação em cultivares de soja, sem e com uma segunda inundação a partir da fase vegetativa V6-V7. Em cada experimento foram determinados: a área foliar, massa seca, número de nós, estatura das plantas, teor de clorofila e medidas de trocas gasosas. A fase mais sensível ao excesso hídrico para as cultivares de soja é a SE-EM, pois não ocorreu a germinação das sementes, nas duas épocas de semeadura e anos estudados. Foi observado que a cultivar NA 5909 RG é mais sensível ao excesso hídrico em dias de inundação para as variáveis estudadas. Para cada grupo (3, 6, 9 e 12) de dias de inundação avaliado observou-se que quando a soja foi submetida a uma segunda inundação ela apresentou um desempenho pior do que quando somente imposta a um único evento de estresse hídrico, o que demonstra não ter aclimatação. A segunda época de semeadura potencializou o efeito do estresse hídrico sobre a soja devido as médias de temperaturas do ar mais elevadas. O modelo logístico se ajustou à variável área foliar, em função dos graus-dias acumulados. A área foliar pode ser estimada a partir de modelos de relação com a temperatura média do ar, através do acúmulo de graus-dia.

Palavras-chave: *Glicyne max* L., Excesso hídrico. Aclimatação. Fases de desenvolvimento. Datas de semeadura. Produtividade. Modelo logístico.

ABSTRACT

ECOPHYSIOLOGY AND LOGISTICS MODEL IN THE DYNAMICS OF SOYBEAN GROWTH AND DEVELOPMENT UNDER EXCESS WATER CONDITIONS

AUTHOR: Patrícia Carine Hüller Goergen
ADVISOR: Sidinei José Lopes

Soybean is the main legume grown in the world. Rio Grande do Sul is an important national producer of the grain and the expansion of the crop to lowland areas where irrigated rice is traditionally cultivated in the state. The occurrence of excess water is harmful to the growth and development of plants, and compromises production, generating large losses of grain productivity. However, the duration of the stress, the phase of plant development and the weather conditions during the flood influence the severity of the stress. Thus, the present study aimed to evaluate the ecophysiology and characterize the growth of soybean cultivars by the logistic model subjected to flooding days in sowing seasons. To achieve this objective, two experiments were carried out at two sowing times (October and November) in the 2018/2019 and 2019/2020 crop years. The experimental design was completely randomized with four replications, each repetition consisting of a pot with one plant. Two soybean cultivars (NA 5909 RG and TEC IRGA 6070 RR) with relative maturity group close to 6.0 were used. The experiment I aimed to study the water excess in soybean cultivars in different phases of development during the vegetative phase and the experiment II, to study days of flooding in soybean cultivars, without and with a second flood from the vegetative phase V6-V7. In each experiment the following were determined: leaf area, dry mass, number of nodes, plant height, chlorophyll content and gas exchange measurements. The most sensitive phase to excess water for soybean cultivars is SE-EM, as there was no seed germination in both sowing dates and years studied. It was observed that the cultivar NA 5909 RG is more sensitive to excess water on days of flooding for the variables studied. For each group (3, 6, 9 and 12) of days of flooding evaluated, it was observed that when the soybean was submitted to a second flood it presented a worse performance than when only imposed to a single event of water stress, which shows no acclimatization. The second sowing season potentiated the effect of water stress on soybeans due to higher average air temperatures. The logistic model was adjusted to the leaf area variable, as a function of the accumulated degree-days. Leaf area can be estimated from models of relationship with mean air temperature, through the accumulation of degree-days.

Keywords: *Glicyne max* L., Water excess. Acclimate. Development phases. Sowing dates. Productivity. Logistic model.

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LISTA DE ABREVIATURAS E SIGLAS

Amax	Maximum Photosynthesis
C1	Cultivar 1
C2	Cultivar 2
E	Leaf Transpiration
EM-VC	Emergence – Cotyledons
DM	Dry matter
FC	Field Capacity
GDD	Growing Degree-days
GMR	Relative Maturity Group
Gs	Stomatal Condutance
INMET	Brazilian National Weather Service
IRGA	Portable Photosynthesis System LICOR
LA	Leaf Area
PH	Plant Height
S1	Season 1
S2	Season 2
SO-EM	Sowing - Emergence
Sta	Accumulated Thermal Sum
Tb	Lower Basal Temperature
Tm	Average Air Temperature
Tmax	Temperature maximum air
Tmin	Temperature minimum air
VC-V2	Cotyledons - First Fully Expanded Trifoliate Leaf
V2-V4	First Fully Expanded Trifoliate Leaf - Third Fully Expanded Trifoliate Leaf
V6-V8	Fifth Fully Expanded Trifoliate Leaf - Seventh Fully Expanded Trifoliate Leaf

SUMÁRIO

1. INTRODUÇÃO E JUSTIFICATIVA

A soja (*Glycine max* (L.) Merril) é uma leguminosa de alto valor proteico e um dos produtos agrícolas de maior importância no mundo e também no Brasil (JUHÁSZ et al., 2014; TAGLIAPIETRA et al., 2022). O excesso hídrico é um estresse de ocorrência frequente que reduz o rendimento de grãos da cultura em muitas áreas produtoras desta oleaginosa no mundo. A ocorrência de eventos extremos de disponibilidade hídrica, como o excesso hídrico, é comum no Rio Grande do Sul no inverno e no início da primavera (BORTOLUZZI et al., 2017; CARDOSO, 2005; HELDWEIN; BURIOL; STRECK, 2009), onde impacta principalmente o estabelecimento da cultura da soja.

Espera-se aumento na frequência destes eventos extremos de precipitação pluvial como resultado do aquecimento global (FIELD et al., 2012). Além disso, vem crescendo na região sul do Brasil o cultivo da soja em solos hidromórficos. Nestas regiões, a soja é cultivada em rotação de culturas com o arroz irrigado, pela possibilidade de diminuição do banco de sementes de plantas daninhas nas lavouras de arroz, especialmente de arroz vermelho, além do aumento e diversificação de renda na propriedade rural (TAGLIAPIETRA et al., 2022; ZANON et al., 2015). Contudo, os solos de áreas de terras baixas apresentam reduzida drenagem natural e estão sujeitos à ocorrência de períodos temporários de alagamento, especialmente após eventos de precipitação pluvial intensa (MUNDSTOCK et al., 2017; ZANON et al., 2018). Nesse contexto, existe crescente demanda por genótipos de soja adaptados às condições de solos de terras baixas e há necessidade de determinar quais as cultivares ou quais características conferem as mesmas maior tolerância ao estresse por excesso hídrico.

As plantas, quando submetidas a condição de estresse, apresentam alterações morfológicas e fisiológicas. As alterações fisiológicas são notadas poucas horas após o início do estresse, enquanto as alterações morfológicas ocorrem em resposta ao estresse fisiológico na tentativa da planta tolerar o estresse, cuja capacidade varia entre espécies e entre cultivares (TAIZ; ZEIGER, 2017). Em plantas de soja, a ocorrência de excesso hídrico é prejudicial para o crescimento das raízes, formação de nódulos para a fixação biológica de nitrogênio atmosférico e assimilação de carbono (CHO; YAMAKAWA, 2006; FANTE et al., 2010). Além disso, ocorre a redução na taxa fotossintética das folhas, atribuída parcialmente à diminuição da condutância estomática (GARCIA et al., 2020). A diminuição das taxas de assimilação líquida e a expansão foliar provocam modificações no crescimento das plantas, na partição de matéria seca, na relação parte aérea/raiz, na distribuição do sistema radicular e redução da produtividade de grãos (TAIZ; ZEIGER, 2017).

O efeito do estresse por saturação hídrica do solo sobre as plantas é complexo e dependente da genética da cultivar, do estágio de desenvolvimento da planta, da duração desse estresse (GARCIA et al., 2020) e da influência dos elementos meteorológicos no período de estresse da planta. Algumas espécies de plantas têm capacidade para suportar essas condições adversas, sendo que a tolerância ao excesso hídrico pode variar entre cultivares e entre os estágios de desenvolvimento (BAILEY-SERRES; VOESENEK, 2008). Os elementos meteorológicos, principalmente temperatura do ar e radiação solar, variam de acordo com as estações do ano, e podem ter influência na intensidade do estresse por excesso hídrico das culturas agrícolas, maximizando ou retardando o efeito nas plantas (BERGAMASCHI; BERGONCI, 2017). Assim, o entendimento da ecofisiologia de plantas em ambientes propensos à inundações e dos aspectos de aclimatação, são importantes, principalmente para a identificação de genótipos mais tolerantes, e os modelos de crescimento podem ser uma ferramenta de auxílio para diferenciar as respostas das plantas sobre diferentes condições de excesso hídrico. Carecem de informações na literatura sobre a influência da radiação solar e da temperatura do ar em função das épocas de semeadura na potencialização do estresse por excesso hídrico, e qual subfase durante a fase vegetativa em que as plantas são mais tolerantes à saturação hídrica do solo, assim como, o período em dias de estresse tolerável pelas cultivares de soja a partir do estágio V6. Por isso, é necessário verificar a tolerância das plantas de soja a inundação em diferentes fases de desenvolvimento, épocas de semeadura, e se as mesmas apresentam diferentes respostas e grau de aclimatação quando submetidas a número de dias e a uma segunda inundação.

1.1. HIPÓTESES

A resposta das variáveis de crescimento e desenvolvimento das cultivares de soja ao excesso hídrico varia em função das fases de desenvolvimento durante a fase vegetativa da cultura e do tempo em dias de inundação.

Cultivares de soja submetidas a uma segunda inundação estariam mais aclimatadas ao excesso hídrico.

A tolerância das cultivares de soja à inundação em diferentes épocas de semeadura varia em função da alteração da temperatura do ar e da radiação solar.

O modelo de crescimento logístico é eficiente para caracterizar as diferenças no crescimento das cultivares de soja submetidas a dias de inundação.

1.2. OBJETIVOS

Os objetivos desta tese foram (i) avaliar a tolerância de cultivares de soja ao excesso hídrico em fases de desenvolvimento e épocas de semeadura, (ii) avaliar a tolerância de cultivares de soja ao excesso hídrico em diferentes dias de inundação, com e sem uma segunda inundação, em duas épocas de semeadura e anos agrícolas, e (iii) avaliar os ajustes do modelo logístico à variável de crescimento, área foliar, em função dos graus-dias acumulados após a emergência, em diferentes cultivares de soja e datas de semeadura da cultura da soja em dois anos agrícolas.

2. REVISÃO DE LITERATURA

2.1. A CULTURA DA SOJA

A soja (*Glycine max* L.) pertencente à família Fabaceae (leguminosa) tem como centro de origem a China, é uma planta de metabolismo fotossintético tipo C3, suas características morfológicas apresentam raiz pivotante, caule herbáceo e folha trifoliolada (FERRARI; PAZ; SILVA, 2015). O grão possui elevado teor de óleo e proteína, contendo todos os aminoácidos essenciais necessários ao corpo humano, sendo bastante utilizado na alimentação animal e humana (CUNHA et al., 2015). Apresenta ciclo anual, com grande capacidade de se adaptar a diferentes ecossistemas, propiciando a disseminação do seu cultivo em diversos ambientes agricultáveis do mundo (TAGLIAPIETRA et al., 2022; ZANON et al., 2018).

A produção mundial de grãos de soja na safra 2020/2021 foi de 252,8 milhões de toneladas (USDA, 2021). No Brasil, a produção na mesma safra foi de 135,9 milhões de toneladas e estima-se a produção de 142,8 milhões de toneladas na safra 2021/2022 (CONAB, 2022). Além do aumento na área plantada, o investimento em pesquisa e no desenvolvimento de cultivares mais adaptadas às condições de cultivo têm melhorado a produtividade e ajudado a alavancar a produção (ZANON et al., 2018).

Quanto à disponibilidade hídrica a soja necessita de aproximadamente 450 a 700 mm de água durante todo o seu desenvolvimento, além de uma boa distribuição das chuvas ao longo do ciclo (PARDO et al., 2015). Por outro lado, assim como a maioria das espécies produtoras de grãos, a soja é considerada sensível ao estresse causado pelo excesso hídrico (GARCIA et al., 2020; ZHOU et al., 2020), sendo que períodos de alagamentos ou inundações podem afetar o crescimento e a produtividade de grãos da cultura (CHO; YAMAKAWA, 2006).

O excesso hídrico afeta diversas áreas produtoras desta oleaginosa no mundo, tais como a região sul do Brasil (BAILEY-SERRES et al., 2012; BORTOLUZZI et al., 2017; RHINE et al., 2010; ZANON et al., 2015). Nessa região, vem se intensificando as áreas de soja cultivadas em áreas de terras baixas em rotação de culturas com o arroz irrigado (PUIG et al., 2020; THEISEN et al., 2017) onde a partir do ano agrícola 2009/2010 observou-se um aumento significativo da área semeada com soja em terras baixas, passando de 10 para 408 mil ha no ano agrícola 2021/2022 (IRGA, 2021). Contudo, os solos de áreas de terras baixas apresentam reduzida drenagem natural e estão sujeitos à ocorrência de períodos temporários de alagamento, especialmente após eventos de precipitação pluvial intensa (ROCHA et al., 2017).

2.2. EFEITOS DO EXCESSO HÍDRICO NAS PLANTAS

A ocorrência de excesso hídrico é frequente no RS, sendo de curta ou longa duração, e o período entre outubro e dezembro é o de maior intensidade de influência do fenômeno ENOS no estado (BORTOLUZZI et al., 2021a, b; FONTANA; BERLATO, 1997). Em anos de El Niño é comum regiões com relevo ondulado apresentarem excesso hídrico de curta duração após chuvas em dias consecutivos (GRIMM; BARROS; DOYLE, 2000), enquanto regiões mais planas (terras baixas) estão sujeitas a períodos mais prolongados de saturação do solo (STRECK et al., 2008). Em regiões que recebem um grande volume de chuvas e de relevo plano, é comum a ocorrência de excesso hídrico, o que reduz, consequentemente, a produtividade de grãos.

O excesso hídrico ocorre quando o volume de água decorrente de precipitação e/ou irrigação excede a quantidade de água percolada e drenada. Quando isto ocorre, o espaço poroso do solo é preenchido com água e, desta maneira, as trocas gasosas são reduzidas a níveis extremamente baixos (CARLESSO; ZIMMERMANN, 2000). O consumo de O_2 pelas raízes, fauna e microrganismos do solo pode resultar no esgotamento de O_2 do solo em período de até 24 h após início da inundação (THOMAS; GUERREIRO; SODEK, 2005). Nestas condições, a disponibilidade de oxigênio é muito baixa e o ambiente radicular torna-se hipóxico, sendo hipoxia o termo utilizado quando há deficiência de oxigênio e anoxia quando em completa falta de oxigênio (LICAUSI, 2011). O dano causado pelo excesso hídrico depende do tempo de ocorrência do estresse, da temperatura média do ar e da fase de desenvolvimento da soja.

As plantas necessitam de certa quantidade de oxigênio que é necessário para seu metabolismo e crescimento, tolerando a anoxia apenas por curtos períodos de tempo antes da ocorrência de um dano irreversível. A partir de 15 horas de anoxia, podem ocorrer danos irreversíveis à estrutura mitocondrial, ao metabolismo energético e à viabilidade celular

(ANDREEV; GENEROZOVA; VARTAPETIAN, 1991). Somente as espécies que são originárias de ambientes de solos úmidos evoluíram para germinar e crescer em condição de anoxia (WAMPLE; DAVIS, 1983). Apesar da cultura da soja ser uma espécie originária de áreas alagadas do norte da China e apresentar variabilidade genética em relação à tolerância ao excesso de umidade no solo, os períodos e a duração do alagamento do solo durante o ciclo de desenvolvimento da cultura causam alterações anatômicas, morfológicas e fisiológicas nas plantas que, na maioria dos casos, levam à redução no potencial produtivo da cultura (MUNDSTOCK et al., 2017).

O primeiro sintoma das plantas ao excesso hídrico é o fechamento estomático, induzido pelo acúmulo de ácido abscísico (TAIZ; ZEIGER, 2017). Havendo o fechamento estomático, as folhas murcham e com o passar do tempo reduzem a concentração de clorofila e proteínas nas folhas levando a drástica redução da fotossíntese (TAIZ; ZEIGER, 2017; YORDANOVA; POPOVA, 2007). Podem ocorrer danos foto-oxidativos nas folhas da planta pelo acúmulo de água oxigenada (H_2O_2) cujo excesso é um potencial causador de danos nas células foliares (BANSAL; SRIVASTAVA, 2012).

Em girassol, o crescimento de raízes seminais pode ser paralisado em poucas horas após a ocorrência do encharcamento do solo, podendo haver até senescência de raízes. Em contrapartida, plantas com raízes submetidas à hipoxia ou anoxia podem evitar o estresse, facilitando a difusão de oxigênio da parte aérea para o sistema radicular, tendo a formação de aerênquima e produção de raízes adventícias e secundárias próximas a superfície do solo. Além disso, a capacidade da planta entrar em estado quase de dormência e a capacidade de fechamento de estômatos e curvatura das folhas parece estar relacionada aos mecanismos de tolerância em plantas (LOOSE, 2013).

Outro fator comum às plantas na falta de oxigênio, segundo Kolb e Loly (2009), é o desvio do metabolismo aeróbio para a via anaeróbia, o que induz mudanças no metabolismo respiratório do sistema radicial produzindo substâncias tóxicas como o etanol e o lactato, além de baixo rendimento energético.

Como consequência do excesso hídrico, em diferentes culturas agrícolas de terras baixas, as biomassas da parte aérea e raiz são reduzidas e a relação parte aérea/raiz afetada, a área foliar das plantas é reduzida e, consequentemente, os componentes da produtividade de grãos são prejudicados (MUNDSTOCK et al., 2017; TAIZ; ZEIGER, 2017). Em soja ainda, o excesso hídrico é prejudicial para o crescimento das raízes e formação de nódulos para a fixação biológica de nitrogênio atmosférico (CHO; YAMAKAMA, 2006; THOMAS; GUERREIRO; SODEK 2005).

2.3. SINALIZAÇÃO DA OCORRÊNCIA DE ESTRESSE E MECANISMOS DE TOLERÂNCIA DAS PLANTAS AO EXCESSO HÍDRICO

A maioria das respostas das plantas a estresses abióticos é controlada pelos hormônios vegetais. Existem hormônios responsáveis por estimular o crescimento e o desenvolvimento vegetal, enquanto outros são responsáveis pela estagnação do crescimento, equilíbrio entre parte aérea/raiz, estimulação do crescimento de raízes, maturação e até senescência de folhas e de raízes. Os hormônios vegetais mais conhecidos e estudados são as giberelinas, as citocininas, as auxinas, o ácido abscísico (ABA), e o etileno. A formação desses hormônios é dada pela sequência de DNA que é intrínseca da espécie e da própria cultivar, e define o grau de tolerância e de adaptabilidade da espécie ou da cultivar à condição adversa de disponibilidade hídrica imposta pelo ambiente (TAIZ; ZEIGER, 2017).

Quando as plantas estão sob excesso hídrico ocorre a sinalização química para o fechamento estomático, e há um maior acúmulo de ácido abscíssico (ABA) no xilema, sendo transportado para as folhas de plantas estressadas. Nas células-guarda dos estômatos existe uma proteína receptora do ABA, que ao recebê-lo muda de configuração ativando a abertura dos canais de $Ca^{2+,}$ que é o mensageiro secundário no citoplasma (TAIZ; ZEIGER, 2017). Esse aumento da concentração de Ca^{2+} no citoplasma faz com que a célula perca solutos e turgor celular, fechando o estômato. Entretanto, em dias de alta demanda hídrica o fechamento estomático pode ocorrer pelo incremento de pH da seiva no xilema e não apenas pelo ABA, que levaria mais tempo para ser translocado (WILKINSON; DAVIES, 2002).

Em plantas sob excesso hídrico o estresse não ocorre pela limitação de água no solo, mas sim pela baixa atividade radicular em decorrência da hipoxia das células radiculares causada pela exposição ao excesso hídrico (TAIZ; ZEIGER, 20117). A redução da produção de ATP e a desnaturação de proteínas levam à drástica redução da atividade de raízes, que não absorvem e conduzem a água na quantidade demandada pela parte aérea (TAIZ; ZEIGER, 2017; YORDANOVA; POPOVA, 2007). Nessa condição o fechamento estomático também ocorre em resposta à concentração de ABA nas folhas.

Hormônios como as auxinas e as citocininas possuem relação com a abertura estomática, atuando assim, de forma antagônica ao ABA (ACHARYA; ASSMANN, 2009). As citocininas atuam na expansão celular e na divisão celular estimulando o desenvolvimento dos diferentes órgãos dos vegetais, além de opor a senescência foliar e a invasão de patógenos (TO; KIEBER, 2008). O incremento da concentração de citocinina no xilema leva a redução da sensibilidade dos estômatos ao ABA promovendo a abertura estomática (TAIZ; ZEIGER, 2017). As auxinas promovem a divisão celular, elongação celular, diferenciação dos tecidos vasculares, elongação de hastes e dominância apical (KEPINSKI, 2007). Ambos os hormônios podem ser sintetizados em qualquer célula, mas as citocininas são sintetizadas em maior concentração nos meristemas radiculares e as auxinas nos meristemas apicais da parte aérea (ALONI et al., 2006; TAIZ; ZEIGER, 2017).

As giberelinas são hormônios promotores de crescimento, que atuam na quebra de dormência, germinação de sementes e no desenvolvimento de folhas, flores e frutos (YAMAGUCHI, 2008). Em plantas sob estresse hídrico, tanto por déficit quanto por excesso, a concentração de giberelinas diminui, reduzindo o desenvolvimento das plantas (ACHARYA; ASSMANN, 2009).

A senescência foliar e radicular se dá pela presença do hormônio gás etileno, que além de atuar na senescência dos órgãos vegetais, atua na queda de folhas, no amadurecimento de frutos, no desenvolvimento dos pelos radiculares e na formação de raízes adventícias. O etileno possui também uma função crucial na sinalização do estresse hídrico, mais significativo em plantas sob excesso hídrico do que déficit hídrico (ACHARYA; ASSMANN, 2009). Entretanto, para não haver uma excessiva produção de etileno e ocorrer uma rápida morte dos tecidos da planta, um aumento da concentração de ABA é necessário, sendo que os dois hormônios são antagônicos (TAIZ; ZEIGER, 2017).

Além dos hormônios atuarem na sinalização de um estresse abiótico, eles também atuam na adaptação das plantas a essa condição ambiental adversa, visando garantir a sobrevivência da espécie. Tanto as citocininas quanto as auxinas são extremamente importantes para a adaptação das plantas à condição de excesso hídrico. As citocininas auxiliam provendo o aprofundamento radicular e as auxinas auxiliam no desenvolvimento das raízes secundárias e pelos radiculares importantes na absorção de nutrientes (ALONI et al., 2006; TAIZ; ZEIGER, 2017). O gás etileno é outro hormônio que auxilia as plantas pela adaptação com formação de raízes secundárias e adventícias. Isso faz com que o etileno seja mais importante na condição de excesso hídrico, pois além de acelerar a senescência das raízes asfixiadas pela falta de O_2, promove a formação de raízes secundárias e adventícias próximas à superfície do solo (ACHARYA; ASSMANN, 2009).

Alguns mecanismos de tolerância das plantas a estresses hídricos são: a capacidade de entrar em estado de quase dormência com inibição do crescimento da parte aérea; a maior formação de raízes (adventícias e secundárias); e a capacidade de regenerar novas raízes, além do fechamento de estômatos e a mudança da curvatura das folhas (TAIZ; ZEIGER, 2017). A interação entre os diferentes hormônios e o equilíbrio entre eles definem o potencial de cada espécie e, dentro da espécie, de cada cultivar de adaptar-se a essa condição hídrica do solo (MUNDSTOCK et al., 2017).

Os efeitos nocivos do excesso hídrico para as plantas são dependentes dos dias de excesso hídrico a que foi submetida e do estágio de desenvolvimento em que se encontra no momento do estresse. Para a cultura da soja essas informações são restritas, além do que, pouco se sabe o grau de adaptabilidade das cultivares modernas de soja a esse estresse, em distintas condições de solo e condições meteorológicas prevalecentes durante a ocorrência do estresse, como temperatura do ar e radiação solar.

2.4 TOLERÂNCIA E ACLIMATAÇÃO DAS PLANTAS AO EXCESSO HÍDRICO

À medida que a planta tolera mais o estresse se torna aclimatada, porém não adaptada, pois adaptação se refere a um nível de resistência geneticamente determinado, adquirido por processos de seleção durante muitas gerações (TAIZ; ZEIGER, 2017). Alguns mecanismos de tolerância das plantas a estresses hídricos são: a capacidade de entrar em estado de quase dormência com inibição do crescimento da parte aérea; a maior formação de raízes (adventícias e secundárias); e a capacidade de regenerar novas raízes, além do fechamento de estômatos e a mudança da curvatura das folhas (TAIZ; ZEIGER, 2017). A interação entre os diferentes hormônios e o equilíbrio entre eles definem o potencial de cada espécie e, dentro da espécie, de cada cultivar de adaptar-se a essa condição hídrica do solo (MUNDSTOCK et al., 2017).

Quando a planta é submetida a um estresse ambiental ocorre um armazenamento dessa informação, que pode ser recuperada em um novo evento estressante, em reações à sinalização gerada por estímulos ambientais, e esse fenômeno é conceituado como resposta adaptativa (*stress imprint*) da planta (THELLIER; LÜTTGE, 2012; TREWAVAS, 2003). De acordo com alguns autores, as plantas que sofreram estresse prévio respondem mais rápido e/ou mais forte a um estresse subsequente, seja ele biótico ou abiótico (CONRATH et al., 2006).

Existem dois mecanismos de respostas adaptativas, um por acúmulo de proteínas sinalizadoras e outro por acúmulo de fatores de transcrição (CONRATH et al., 2006). Além desses, Bruce et al. (2007) acrescentaram o mecanismo epigenético, que envolve mudanças na atividade do DNA através da metilação do DNA ou modificação de histonas (HAUSER et al., 2011). Modificações epigenéticas são induzidas por sinalização hormonal e bioquímica em resposta ao estresse e tais alterações na cromatina auxiliariam na aclimatação das plantas a um novo evento estressante (CHINNUSAMY; ZHU, 2009). Muitos genes estão ligados à resposta a estresses abióticos, alguns deles dependentes da ação do ABA, ou de outros hormônios, ou ainda de outras moléculas como cálcio, ácido jasmônico e ácido salicílico (CONRATH et al., 2006).

As plantas desenvolvem complexos mecanismos em resposta ao estresse hídrico, e a regulação da metilação do DNA desempenha um papel fundamental na regulação da expressão gênica. Ao estudar o estado de metilação de uma única citosina em todo o genoma sob estresse hídrico, o nível geral de metilação das plantas sob estresse hídrico são maiores do que as plantas controle, como 8,64% maior na amoreira (*Morus alba*) e 2,29% maior em *Populus trichocarpa*. (SUN et al., 2022). A metilação do DNA tem múltiplos efeitos sobre os genes de expressão sob estresse hídrico, indicando que afeta direta ou indiretamente a expressão através de múltiplas vias regulatórias. As plantas tolerantes à seca têm um metiloma mais estável em condições de seca, morte celular programada, e outras vias em arroz (*Oryza sativa* L.), amoreira (*Morus alba* L.), feijão mungo (*Vigna radiata* L.) e milho (*Zea mays* L.) (SUN et al., 2022).

Estudos nos quais as plantas são submetidas a estresses recorrentes fornecem evidências interessantes para a abordagem fisiológica da aclimatação vegetal. Plantas de *Cistus albidus* apresentaram maior conteúdo relativo de água (CRA) nas folhas superiores no segundo ciclo de seca, em função de um possível ajuste osmótico após serem expostas a um ciclo de estresse hídrico e recuperação (GALLE et al., 2011). Numa condição de déficit hídrico, plantas de trevo que foram previamente submetidas a dois ciclos de estresse/recuperação apresentaram manutenção do status hídrico, evidenciado por maior potencial da água no xilema e maior CRA do que as plantas que foram submetidas à apenas um ciclo de estresse, sugerindo a ocorrência de aclimatação (IANNUCCI et al., 2000). Trabalhos que avaliam a aclimatação da planta com culturas em condições de excesso hídrico são bastante restritos na literatura, e há uma carência desses estudos no que se refere a cultura da soja.

O cultivo sob condições de alagamento requer estudos prévios de avaliação de cultivares que possuam capacidades diferenciadas de tolerância ou aclimatação ao alagamento, buscando a obtenção de maiores rendimentos nesta condição. As cultivares de soja que atualmente são recomendadas para o cultivo nesses solos não foram desenvolvidas para essas condições (MUNDSTOCK et al., 2017; ZANON et al., 2018), apenas foram brevemente comparadas com outros genótipos.

2.5. FATORES ECOLÓGICOS QUE AFETAM A INTENSIDADE DO ESTRESSE POR EXCESSO HÍDRICO

A produtividade da soja é muito dependente das condições ambientais prevalecentes durante o ciclo de desenvolvimento da cultura (TAGLIAPIETRA et al., 2022; ZANON et al., 2015, 2018). Assim, a escolha da cultivar em função da época de semeadura, da região de cultivo e das estratégias de manejo adotadas são de suma importância para a obtenção de altas produtividades (MUNDSTOCK et al., 2017; TAGLIAPIETRA et al., 2022; ZANON et al., 2018).

No Rio Grande do Sul, a amplitude de épocas de semeadura para a cultura da soja é grande, variando entre os meses de setembro a janeiro (TAGLIAPIETRA et al., 2022; MAPA, 2021), em virtude do zoneamento agroclimático da cultura da soja (MAPA, 2021) e da possibilidade de se ter safra e safrinha da cultura. Esses períodos diferem principalmente quanto à temperatura do ar, a disponibilidade de radiação solar e a disponibilidade hídrica. Na safra, a temperatura do ar é menor no início (setembro-outubro) e maior no final do período recomendado para a semeadura (novembro), enquanto no período de safrinha a temperatura é alta no início com diminuição ao longo do ciclo (TAGLIAPIETRA et al., 2022; ZANON et al., 2018; MUNDSTOCK et al., 2017; ZANON et al., 2015).

A disponibilidade de radiação solar e a temperatura do ar predominantes durante um período de saturação do solo podem retardar ou maximizar os efeitos do excesso hídrico na planta (BERGAMASCHI; BERGONCI, 2017; TAIZ; ZEIGER, 2017). Isso em razão de que quando a planta está sob excesso hídrico a respiração já está afetada pela ausência ou deficiência de O_2 no solo, e temperaturas do ar mais elevadas aumentam ainda mais as taxas respiratórias. A eficiência da respiração da planta é afetada sob altas temperaturas devido ao comprometimento ou danos a maquinaria enzimática da planta em consequência do rompimento das membranas e das organelas. A temperatura é um fator de grande influência na respiração principalmente durante os estádios iniciais de desenvolvimento da planta (TAIZ; ZEIGER, 2017). Nesse sentido, a planta vai gastar mais energia ainda nesse processo, reduzindo seu crescimento, desenvolvimento e consequentemente a produtividade de grãos. O que motiva avaliar as plantas em diferentes épocas de semeadura para caracterizar o efeito da temperatura do ar aliado ao excesso hídrico.

2.6. EXCESSO HÍDRICO EM DIFERENTES FASES DO DESENVOLVIMENTO DA CULTURA DA SOJA

A tolerância da cultura a estresses abióticos e bióticos e o potencial de redução da produtividade de grãos pode estar diretamente relacionada com a fase de desenvolvimento da planta quando submetida a esses eventos. Na literatura são encontrados alguns estudos que relatam os danos causados a soja se o excesso hídrico ocorrer nas fases vegetativa ou reprodutiva (CHO; YAMAKAMA, 2006; FANTE et al., 2010; THOMAS; GUERREIRO; SODEK, 2005). Porém não há relatos da tolerância das plantas ao excesso hídrico nas diferentes fases do desenvolvimento (FEHR & CANIVENS, 1977), principalmente durante a fase vegetativa, como por exemplo SE-EM, EM-VC, VC-V2, V2-V4, V6-V8, que é quando ocorre o estabelecimento inicial da cultura e a definição de alguns componentes do rendimento. Por isso, é de extrema importância realizar estudos que avaliem as modificações morfofisiológicas nas diferentes subfases de desenvolvimento da soja durante a fase vegetativa. Tais pesquisas resultam em melhoria das técnicas produtivas e eficiência no manejo da cultura no campo, como escolha das épocas de semeadura e uso de cultivares tolerantes ao excesso hídrico

Como em algumas regiões é difícil prever quando a planta sofrerá com o excesso hídrico e a intensidade desse estresse, principalmente em estágios mais críticos do desenvolvimento, cultivares de soja com tolerância genética é uma característica desejável. Conhecer a resposta de diferentes genótipos ao estresse hídrico, ou adaptação, é um fator crucial para a seleção e recomendações de cultivares mais adaptadas (FANTE et al., 2010; TREWAVAS, 2003).

Em soja, o estresse por excesso hídrico por 9 dias durante o período vegetativo impactou negativamente na estatura, área foliar e teor de nitrogênio (N) nas plantas (CHO; YAMAKAWA, 2006) em experimento conduzido na Coreia. Quando o estresse ocorre no período reprodutivo, ocorre maior redução no rendimento de grãos. Entretanto, plantas submetidas ao excesso hídrico por período curto (48 a 96 h) não apresentaram diferenças significativas das plantas não submetidas ao estresse (RHINE et al., 2010). Sendo assim, a redução do rendimento de grãos de soja varia conforme a intensidade e a fase da cultura em que ocorre o excesso hídrico, necessitando de mais estudos que comprovem quais as subfases durante a fase vegetativa de maior susceptibilidade da cultura e com potencial de causar reduções na produtividade de grãos, dias de inundações toleráveis pela cultura e grau de aclimatação quando submetida a um novo estresse.

2.7. MODELAGEM DO CRESCIMENTO DE PLANTAS

Modelos matemáticos têm sido desenvolvidos e utilizados fortemente nos últimos anos, com a finalidade de simular e descrever o crescimento, o desenvolvimento e a produtividade de grãos das culturas agrícolas. Um modelo é uma representação ou interpretação simplificada da realidade, ou uma interpretação de um fragmento de um sistema, como por exemplo: equações matemáticas de processos fisiológicos (SANQUETTA, 1996). Avaliar o crescimento das plantas no decorrer de diferentes períodos do ciclo da cultura é relevante, pois permite identificar características inerentes a cada cultivar estudada e selecionar aquelas que apresentam as características desejadas. A análise de crescimento de plantas é uma metodologia que avalia as bases fisiológicas da produção e a influência de variáveis genéticas, agronômicas e ambientais (SILVA et al., 2000).

Existem modelos simplificados e modelos mais complexos. Os modelos matemáticos simplificados são utilizados para simular o desenvolvimento da cultura, tendo como base a soma de unidades de calor necessárias para a cultura atingir determinado estádio fenológico ou completar o ciclo (STRECK et al., 2003; STRECK; BOSCO; LAGO, 2008). Esses modelos utilizam basicamente a temperatura do ar e o fotoperíodo (em culturas responsivas ao comprimento do dia), taxa de emissão de folhas e graus dias. Esses modelos são ferramentas que podem auxiliar no manejo das culturas, em programas de melhoramento e em estudos de impactos de mudanças climáticas sobre o desempenho de agroecossistemas.

Na área da agronomia, a análise dos dados em modelos de crescimento tem a vantagem econômica e administrativa em conhecer como a cultura cresce e como estes fatores respondem às condições ambientais ou aos tratamentos aplicados (LÚCIO et al., 2015; LÚCIO et al., 2016a). Estes modelos geralmente são expressos por meio de curvas de crescimento, e quando ajustados aos dados de peso, altura, comprimento e outras características quantitativas de interesse, ao longo do tempo, permitem sintetizar grande número de medidas e informações em apenas alguns parâmetros de interpretação biológica (LÚCIO et al., 2015; LÚCIO et al., 2016a; LÚCIO et al., 2016b). Para modelar este tipo de resposta, a literatura apresenta vários modelos de crescimento empíricos (SEBER; WILD, 2003), que descrevem o crescimento da planta com base na observação do próprio vegetal, relacionando as variáveis sem referências aos processos que possam estar correlacionados. O modelo logístico tem sido utilizado para descrever a produção de diversas hortaliças como abóbora e pimentão (LÚCIO et al., 2015), feijão verde (LÚCIO et al., 2016a) tomate cereja (*Lycopersicon esculentum* L. var. Cerasiforme) (LÚCIO et al., 2016b) e soja (GASO et al., 2021).

O modelo de crescimento logístico é um modelo de crescimento de plantas não linear amplamente utilizado, por ser o que mais reflete o que ocorre com as espécies no ambiente natural. O crescimento logístico assume que o crescimento das plantas não é exponencial ao longo do tempo, e que há um ponto máximo de crescimento das plantas e a partir daí um decréscimo (REGAZZI, 2003).

O desenvolvimento de modelos de crescimento é importante, e tem tido avanços consideráveis nos estudos da interação planta x solo x atmosfera, conferindo visão mais generalista e, fisiologicamente embasada para a estimativa do crescimento de diversas culturas (SPATHELF; NUTTO, 2000). Uma das principais vantagens de modelar as curvas de crescimento é o resumo das informações contidas nos dados, em apenas alguns parâmetros com interpretação prática, sendo que estes modelos fornecem um bom ajuste.

Os esforços de pesquisadores estão em melhorar os modelos de simulações de culturas pela incorporação de respostas ao estresse hídrico, além de interpretar e compreender o tempo térmico (MCMASTER; WILHELM, 2003). Também tem sido pesquisada a partição de fotoassimilados entre as partes da planta, o crescimento e distribuição de raízes (KAGE; KOCHLER; STÜTZEL, 2004). Esse conhecimento é importante pelo fato de que quando a planta sofre um estresse, tanto por déficit quanto por excesso hídrico, ocorrem respostas fisiológicas e morfológicas, na tentativa de contornar a situação de estresse. Existem alguns trabalhos na literatura que abordam modelos de crescimento em soja em área de terras altas, no entanto para áreas de várzea (terras baixas) essa informação ainda é restrita, o que motiva a realização deste trabalho. Assim, a partir da variável de partição de matéria seca, se pode ter uma melhor estimativa para condição de estresse por excesso hídrico.

3. ARTIGO 1

Tolerance of soybean cultivars to flooding stress in different vegetative development phases[1]

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[1] Artigo formatado nas normas da revista Pesquisa Agropecuária Brasileira (PAB)

Tolerance of soybean cultivars to flooding stress in different vegetative development phases

Abstract – Excessive water is the main factor responsible for soybean yield reduction in the crop rotation system with irrigated rice. This study aimed to evaluate the tolerance of soybean cultivars to flooding stress in different phases of development during the vegetative phase. The experiment was arranged in a factorial scheme, with two sowing dates (October and November), two soybean cultivars (TEC IRGA 6070 RR and NA 5909 RG), and five phases of development during the vegetative phase (SE-EM, EM-VC, VC-V2, V2-V4, V6-V8) in the 2018/2019 and 2019/2020 growing season. The experimental design was completely randomized with four replications. The most sensitive vegetative development phase to the flooding stress in soybean cultivars is the SE-EM (sowing-emergence), in which the seeds did not germinate in the two sowing dates and growing seasons. After the emergence, the V2-V4 (first and third fully expanded trifoliate leaf) phase were the most affected by flooding stress influencing leaf area and shoot dry matter in both cultivars. Under soil flooding conditions, the establishment of the crop (from sowing to the fourth leaf) is the period with higher damages in the growth and development caused by anaerobiosis. Sowing in October tends to reduce the impact of flooding stress on the plants

Keywords: *Glycine max*, phenology, rice-soybean rotation, soil flooding, sowing dates.

Tolerância de cultivares de soja ao excesso hídrico em estádios de crescimento vegetativo

Resumo - O excesso hídrico no solo é o principal fator que reduz a produtividade das lavouras de soja em rotação com arroz irrigado. O objetivo foi avaliar a tolerância de cultivares de soja ao excesso hídrico em fases do desenvolvimento vegetativo. O experimento realizado foi um trifatorial, sendo duas épocas de semeadura (outubro e novembro), duas cultivares de soja (TEC IRGA 6070 RR e NA 5909 RG) e cinco fases de desenvolvimento durante a fase vegetativa (SE-EM, EM-VC, VC-V2, V2-V4, V6-V8) nos anos agrícolas 2018/2019 e 2019/2020. O delineamento experimental foi o inteiramente casualizado com quatro repetições. A fase mais sensível ao excesso hídrico para as cultivares de soja é a SE-EM (semeadura-emergência), pois não ocorreu a germinação das sementes, nas duas épocas de semeadura e anos agrícolas. Após a emergência das plantas, a fase V2-V4 (primeira e terceira folha trifoliolada desenvolvida) foi a mais afetada pelo excesso hídrico para as variáveis AF e MS nas duas cultivares. Em condição de alagamento do solo, o estabelecimento da cultura (semeadura até a quarta folha) é o período que ocorrem os maiores prejuízos causados pela anaerobiose e a semeadura em outubro tende a reduzir o impacto do estresse de inundação nas plantas.

Palavras-chave: *Glycine max*, fenologia, rotação de arroz e soja, alagamento do solo, datas de semeadura.

3.1 Introduction

In the last ten years, due to the increased pressure of weeds and the higher costs of rice production, farmers started introducing soybean to the traditional system of continuous irrigated rice production in Latin America (Theisen et al., 2017, Ulguim et al., 2018; Ribas et al., 2021a, b). The adoption of the crop rotation system rice-soybean increased exponentially, from 10 thousand hectares in the 2009/2010 to 408 thousand hectares in the 2021/2022 growing season; that is, around 55% of the current irrigated rice area in the state of Rio Grande do Sul (RS), Brazil is adopting the crop rotation system (Irga, 2021).

Despite the vertiginous growth, the average yield of the soybean in the crop rotation system with rice (1.8 Mg ha^{-1}) is lower than the soybean cultivated in Brazilian highlands (3.4 Mg ha^{-1}) (Conab, 2021, Irga, 2021). The main challenges for soybean in rotation with irrigated rice are the soils, which present reduced natural drainage, and they are subject to temporary floodings, especially after heavy rains (Sartori et al., 2016; Zanon et al., 2018). Heavy rains usually occur in the Rio Grande do Sul at the beginning of the spring, which coincides with the start of soybean sowing (Bortoluzzi et al., 2021a; Tagliapietra et al., 2021).

Plants submitted to flooding conditions present biochemical, physiological, and morphological alterations. The biochemical and physiological alterations are noted a few hours after the beginning of the stress and the morphological alteration occurs as a response to the physiological stress in an attempt of the plant to aclimatizacion the stress, whose capacity varies according to the cultivar and the growth phase and it can be irreversible (Taiz et al., 2017). The meteorological elements also influence the intensity of the stress caused by flooding in the crops, maximizing or delaying their effect on the plants, because they influence the evapotranspiration of the system (Timm et al., 2014). Thus, understanding the ecophysiology of plants in environments prone to flooding is essential, especially to identify the more tolerant cultivars and adopt management strategies that mitigate the damages caused by flooding stress in the most sensible vegetative development phase of soybean plants.

An evaluation of the growth and development of soybean cultivars submitted to flooding stress in distinct environmental conditions and vegetative development phases will help understand the restriction and, especially, to indicate management strategies that intensify the rotation system with soybean and rice. This evaluation will also provide insights on other systems based on rice in the world that seeks opportunities to increase yield, profit and reduce environment impact. Therefore, this study aimed to evaluate the tolerance of soybean cultivars to flooding stress at different vegetative development phases.

3.2 Material and Methods

The experiment was conducted in two growing seasons, with two sowing dates in each – YEAR 1: E1 (10/12/10/2018) and E2 (11/28/2018), and YEAR 2: E1 (10/12/2019) and E2 (11/30/2019). Two soybean cultivars were used: one with a relative maturity group (RMG) close to 6.0; one of the most cultivars grown in the South of Brazil in the last ten years (Cultivar 1 - NA 5909 RG – RMG 6.2), and another characterized as tolerant to flooding stress (Cultivar 2 - TEC IRGA 6070 RR – RMG 6.3) (Irga, 2018). The experiment was conducted inside a structure with a transparent plastic polyethylene cover in the experimental area at the Plant Science Department from the Universidade Federal de Santa Maria, Santa Maria, RS, Brazil (29º43'S; 53º49'W at 90 m above sea level).

The experimental design was completely randomized with four replications. Each repetition composed of one plant grown in a plastic pot filled with 7.0 dm^3 of soil. The experiment was arranged in a factorial scheme with three factors: two sowing dates (E1 and E2), two soybean cultivars (C1 and C2), and five vegetative development phases (SE-EM; EM-VC; VC-V2; V2-V4; V6-V8). These phases were chosen because producers, consultants, and researchers report that they have higher losses by flooding (Irga, 2018). Moreover, in the vegetative development phases, SE-EM (sowing - emergence, treatment I), EM-VC (emergence - cotyledons, treatment II), and VC-V2 (cotyledons - first fully expanded trifoliate leaf, treatment III), the initial establishment of the crop and the definition of the number of plants per area (the main component of soybean yield) occur (Zanon et al., 2018). In the vegetative development phases, V2-V4 (first fully expanded trifoliate leaf - third fully expanded trifoliate leaf, treatment IV), and V6-V8 (fifth fully expanded trifoliate leaf - seventh fully expanded trifoliate leaf), the differentiation of the branches and the floral primordium occur. Treatment V was the control.

Five seeds were sown in each pot. They were previously treated and inoculated with *Bradirizobium elkani*. Then, they were sown at a 3 cm depth, and, after the seedling emergence, only one plant was kept per pot. The space between the pots in the row was 10 cm, and 40 cm between the rows. The external walls of the pots was painted white to reduce solar radiation absorption. The soil used came from the superficial layer (0-20 cm) of a Typic Albaqualf – 22 % of clay. Nutrients and soil acidity correction were conducted following the soil analysis results and the local recommendations for soybean crops to avoid nutritional limitations and toxicity to plants (Silva & Gatiboni, 2016).

When plants were submitted to flooding, the pots were individually put inside larger containers. Then the water was added, keeping a constant water column of 5 cm above the soil level. The same number of replications for each treatment with flooding stress was conducted for each vegetative development phases in the control treatment, with 90% of the field capacity. Maintenance irrigation of the control plants was performed through the weighing method. The pot was weighed when in the field capacity (100% of the available water capacity - AWC) and then daily weighed to quantify the consumption. Reposition was conducted daily to reach at least 90% of the AWC.

During the experimental period, data from air temperature was collected through a thermo-hygrometer HT-500 with an attached instrutherm mini datalogger inside a tiny shelter in the experiment site. Solar radiation was collected in the automatic meteorological station from the 8th District of Meteorology of the Instituto Nacional de Meteorologia (DISME/INMET), at 200 m from the experimental area. The daily global solar radiation incidence on plants was corrected based on the 80% transmissivity cover plastic.

The following variables were evaluated: plant height (PH) (length from the stem at the soil level until the last visible node), leaf area (LA), and shoot dry matter (SDM). All these evaluations were conducted before applying the flooding stress and on the last day of experimentation (in the treatments in which it was possible to evaluate these variables). To determine LA, the length and the width of the central leaflet of all leaves of each plant were measured, obtaining the leaf area (LA) of each leaf through the equation ((L*W) *2.0185) of the estimative (Richter et al., 2014). To obtain the shoot dry matter (SDM), the plants were collected and dried in a forced-air oven at 65ºC until constant weight.

In the analysis and interpretation of the results, the increase compared to the control treatment was calculated for all variables. For this calculation, the value obtained on the last day of the evaluation was considered to discount the value obtained on the first day of the experiment, resulting in the increase of each treatment with flooding stress for the variable analyzed. The increase obtained in the treatments with excess water was measured compared to the increase of control plants; this generated a coefficient. Coefficients higher than 1 are higher than the control; lower than 1, the coefficient is lower than the control.

The presuppositions of the model (normality, randomness, and homogeneity of the variances) were tested. Then, the data were analyzed through the analysis of variance by the RStudio software (R Core Team, 2020), using the Metan package (Olivoto & Lucio, 2020). The means were compared by the Tukey test at 0.05 error probability.

3.3 Results and Discussion

The description of the meteorological elements in the agricultural seasons and years are represented in Figure 1. In both agricultural years, plants that were sown in October were exposed to lower average air temperature than plants sown in November, possibly resulting in lower evaporative demand. This fact permits the verification of a direct effect of the air temperature and solar radiation on the morphological responses (growth and development) under flooding conditions. The minimum air temperature (Tmin) registered was 10.0 ºC (12/03/18) (Figure 1A) and 10.6 ºC (10/25/19) (Figure 1C), and the maximum air temperature (Tmax) was 38.6 ºC (12/11/18) (Figure 1A) and 37.9 ºC (12/29/19) (Figure 1C). The photoperiod (Figure 1B, D) to which the soybean plants were exposed ranged between 13.45

and 14.96 hours. For solar radiation, the periods of higher incidence were the end of October, November, and the beginning of December (Figure 1B, D).

The most sensitive vegetative development phases to flooding stress for the was SE-EM since seeds did not germinate in the two sowing dates (Figure 2A, B). This fact explained by an increase in the respiration rate and the enzymatic activity after the first peak of imbibition of seeds, causing a high O_2 demand, which increases seed damage (Taiz et al., 2017). Similar results were found by Zhou et al. (2021), where flooding decreases seed vigor and germination, because decrease in of sugar contents and an increase of cell conductivity as well as ethanol level.

After the emergence, there was no plant death in any other phase. Morphophysiological changes were observed in the plants submitted to flooding conditions, such as the formation of superficial roots and cracking of stem in the plant basis due to aerenchyma formation (Figure 2 C,D). This fact occurs because the plant develops strategies to capture O_2, aiming to address the minimum requirements of root respiration. The same happens with wheat (Araki et al. 2012) and sunflower (Loose et al., 2017).

In the analysis of variance, it was verified that the influence of the interaction among season, cultivar, and treatment on the leaf area was significant in the 2018/2019 growing seasons (Figure 3). At all phases, flooding stress reduced the leaf area in the two soybean cultivars and sowing dates. This behavior was also found in other studies as Ludwig et al. (2016) found higher reduction number of nodes on the main stem, plant heigh and rate of chlorophyll content of after eight days of flooding. Leaf growth depends mainly on cell division and expansion, which is noted by the inhibition in the growth rate of leaves in their initial development (Taiz et al., 2017). The phase EM-VC, in the sowing dates, cultivars, and growing seasons, was the least affected by flooding stress, presenting a similar leaf area to the control.

This behavior is explained by the short duration of this phase in the growth cycle (about three days), besides photoassimilates that permit growth mainly from cotyledons.

Cultivar 2 (TEC IRGA 6070 RR) had its leaf area significantly reduced at the V2-V4 phase when sown in October and at the V6-V8 phase when sown in November. Garcia et al. (2020) also describe the influence of flooding on the physiology and metabolism of roots and leaves of five soybean genotypes during and after flooding stress. They expressed late flowering and significantly reduced gas exchanges (photosynthesis, stomatal conductance, and leaf transpiration) in the leaves.

In the 2019/2020 growing seasons, there was no significant influence from any factor and interactions on leaf area. Regarding the increase of leaf area (cm²) (Figure 4A), it is verified that the cultivar 1 (NA 5909 RG), when sown in October or November in the 2019/2020, had a lower increase of leaf area than the control plants at all phases. However, cultivar 2 in the V6-V8 phase had a slightly higher leaf area increase than the control plants in the two sowing dates. The genetic tolerance of the cultivar can explain this response to the flooding stress. In this phase, the plants are larger, with a bigger root and shoot structure, which favors a better plant development in a stressful environment. The same behavior was observed by Kirkpatrick et al. (2006), who found that seven days of flooding at the V4 phase were not enough to reduce the plant stand, reducing the SDM in only one of the three years of study.

There was no significant effect of factors and their interactions on plant height in the two growing seasons. The means of plant height increase for cultivar 1 in the 2018/2019 were lower than the control in both sowing dates; the same occurred with cultivar 2, sown in October (Figure 4B). Flooding generates an environment with low aeration for plants, which favors the dissemination of diseases, dano oxidativo às células da raiz and nutrient loss by leaching, resulting in lower plant growth (Taiz et al., 2017). The flooding stress affects both the primary and secondary metabolism in soybean plants, change in carbon and nitrogen metabolism as well as the phenylpropanoid pathway (Coutinho et al., 2018).

Nevertheless, cultivar 2 sown in November had a higher plant growth at the vegetative development phases EM-VC, VC-V2, and V6-V8. The higher air temperature can explain the behavior in this period, which might have accelerated even more the duration of these phases that, on average, last few days during soybean development. The higher plant growth demonstrates the good tolerance to flooding stress of this cultivar. When analyzing the 2019/2020, cultivar 1 in sowing date 1 had a higher plant height at the VC-V2 phase and in sowing date 2 at the V6-V8 phase. Moreover, cultivar 2 in sowing date 1 grew more than the control at the VC-V2 phase and in sowing date 2 at all phases except for the V2-V4 phase. Zhou et al. (2020) state that, with higher stem growth, the plant can capture more light for photosynthesis and increase the energy storage for the primary life activities of the plant under flooding conditions. Thus, it contributes to the resistance to more extended flooding periods.

The influence of the interaction among sowing date, cultivar, and treatment was significant on SDM in the 2018/2019. The SDM accumulation (Figure 5A) in the first growing season was affected by flooding stress in both cultivars, sowing dates, and treatments, except for cultivar 2 in the sowing date 2 when the flooding was imposed at the V6-V8 phase. At the V6-V8 phase, the plants are larger and have a bigger root and shoot structure, which favors better plant development under stressful conditions. We highlight that cultivar 2 has higher genetic tolerance to flooding stress (Irga, 2018), which explains such results.

In the 2019/2020, the influence of the interaction among season, cultivar, and treatment on the SDM was not significant, being significant only for the interactions between season and treatment and cultivar and treatment. The flooding stress reduced plant growth in the 2019/2020, observed by the SDM (Figure 5B) at all phases and growing seasons. This demonstrates that the soybean plants under flooding or hypoxia conditions have lower biomass production (Zhou et al., 2020). The V6-V8 phase, when the cultivar 2 was sown in October (E1), presented a better performance under flooding conditions with a higher increase in the SDM than the control plants.

Cultivar 1 (Figure 5C) had reduced growth at all phases compared to the control plants under field capacity conditions. However, cultivar 2 endured well the flooding conditions in the V6-V8 phase, presenting better growth than the control plants. Two primary alterations occur in plants while responding to flooding conditions: low-oxygen quiescence syndrome (LOQS) and low-oxygen escape syndrome (LOES) through phytohormone-mediated pathways involved in plant waterlogging stress (Sharma, 2018; Zhou et al., 2020). The characteristics of LOES include fast stem, internodes, and petioles growth under flooding conditions. This structural modification permits plants to reach the water surface quickly, reestablishing gas exchanges between the plant tissues and the atmosphere. For instance, this mechanism occurs with irrigated rice (Sharma, 2018).

For the application of our results in the rotation system with rice and soybean, farmers must be alert to meteorological broadcasts and the possibility of soil flooding, avoiding sowing during periods of excess rain because, regardless of the year, there will be germination and emergence problems for soybean in anaerobic environments (Bortoluzzi et al., 2021b). This result explains why many soybean producers in the crop rotation system with rice need to resow the crops when there is flooding during the soybean germination phase. Moreover, there are problems with the plant stand, which explains why soybean yield in lowlands (1.8 Mg ha^{-1}) is 30% lower than in highlands (3.4 Mg ha^{-1}) (Conab, 2021; Irga, 2021).

In lowlands soybean, producers must plan and invest in drainage systems to reduce the risks associated with excess soil water, especially at the initial phases (VE-V4), the most susceptible period. We highlight that even without plant death after the emergence, in field conditions, the cracking of the epidermis due to aerenchyma formation contributes to soil fungi infection in the plant, which is responsible for plant death in the crop rotation system with soybean and irrigated rice (Irga, 2018; Goulart, 2020; Bortoluzzi et al., 2021b). From the V4 phase, soybean has a higher tolerance to flooding stress; however, significant losses in the yield potential occur due to the anaerobic environment inducing the plant to adopt a metabolism with lower energy gain (Taiz et al., 2017).

Due to the lower air temperatures, sowing in October have a lower potentiation of the effects of flooding stress on the plant (Figure 1A, C). The availability of solar radiation and the predominant air temperature during a period of soil saturation may delay or maximize the effects of flooding stress on the plant (Taiz et al., 2017). This fact happens because when the plant is under flooding conditions, the respiration is already affected by O_2 absence or deficiency in the soil, and higher air temperatures increase the respiratory rates. The respiration efficiency of plants is affected by higher temperatures due to membranes and cell organelle disruption. In this sense, the plant will spend more energy in this process, reducing its growth, development, and, consequently, yield (Taiz et al., 2017; Rajendran & Lal, 2020).

3.4 Conclusions

1.The more vegetative development phase to flooding in the soybean cultivars is SE-EM.

2.After the seedling emergence, the V2-V4 phase had the highest reductions of LA and SDM in all cultivars, sowing dates, and growing seasons evaluated. From the V4 phase, the soybean has a higher tolerance to flooding conditions.

3.After the seedling emergence, the cultivar TEC IRGA 6070 RR had the highest tolerance to flooding stress than NA 5909 RG.

4. Sowing in October tends to reduce the impact of flooding stress on the plants.

3.5 Acknowledgements

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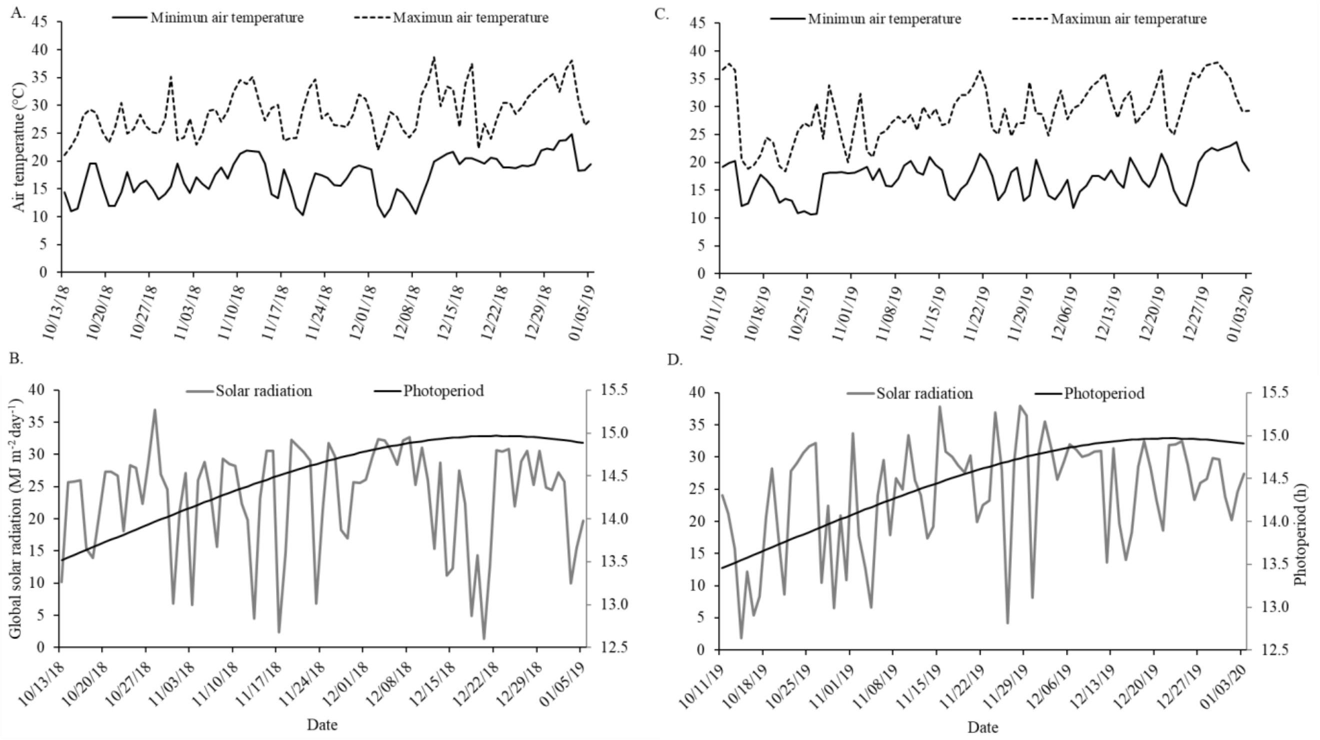

Figure 1. Minimum (Tmin, °C) and maximum (Tmax, °C) air temperatures (A, C), Global solar radiation (MJ m^{-2} day^{-1}), and Photoperiod (h) (B, D) inside the greenhouse during the experiment in 2018/2019 (A, B) and 2019/2020 (C, D) growing seasons, in Santa Maria, RS, Brazil.

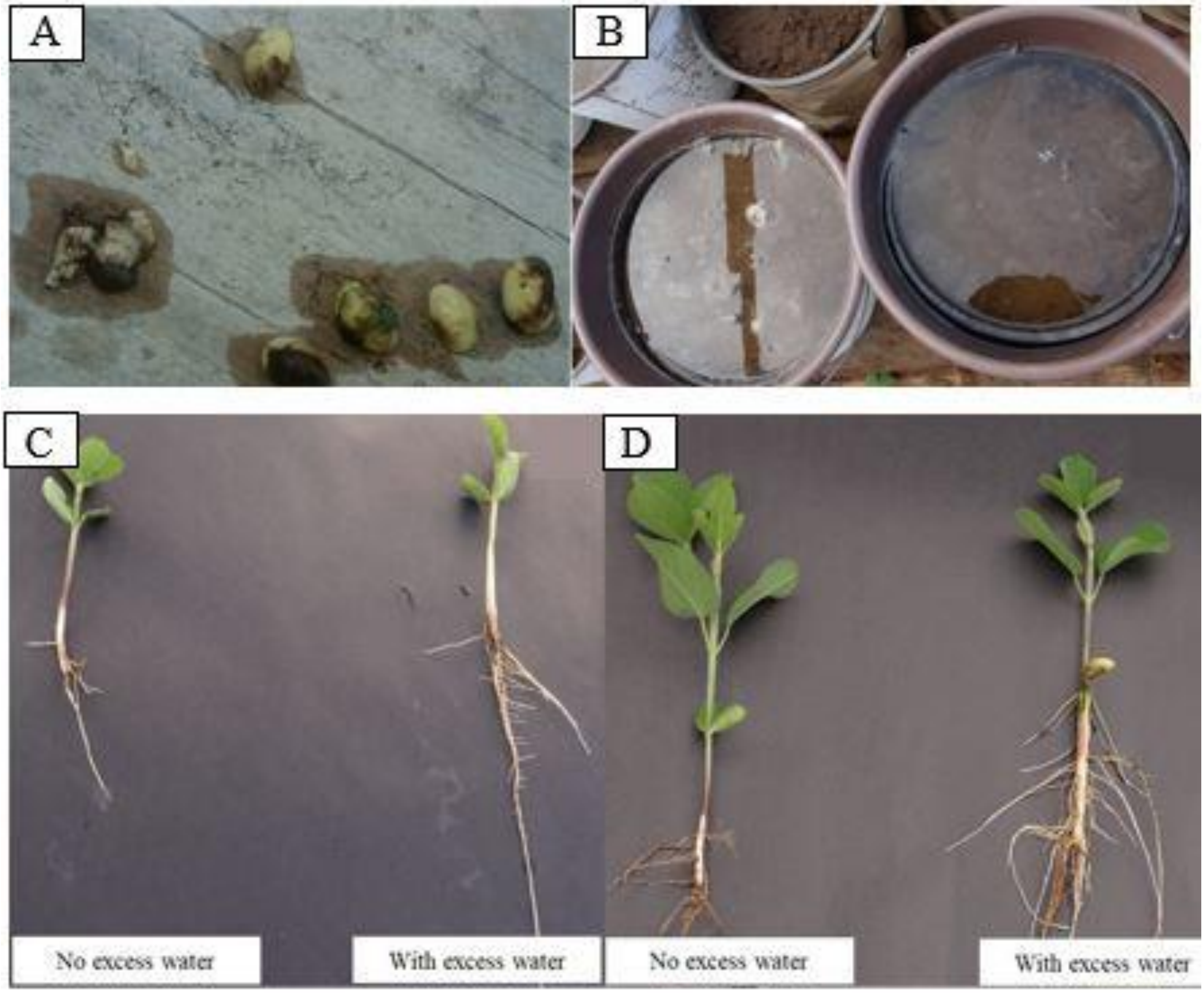

Figure 2. Soybean seeds after flooding in the phase SE-EM in the A: image of the damages in the seeds; B: image of the pots after the end of SE-EM with no seedling emerged. Comparison of soybean plants of the control treatment and after flooding at the different vegetative development phases in the C: phase EM-VC; D: phase VC-V2.

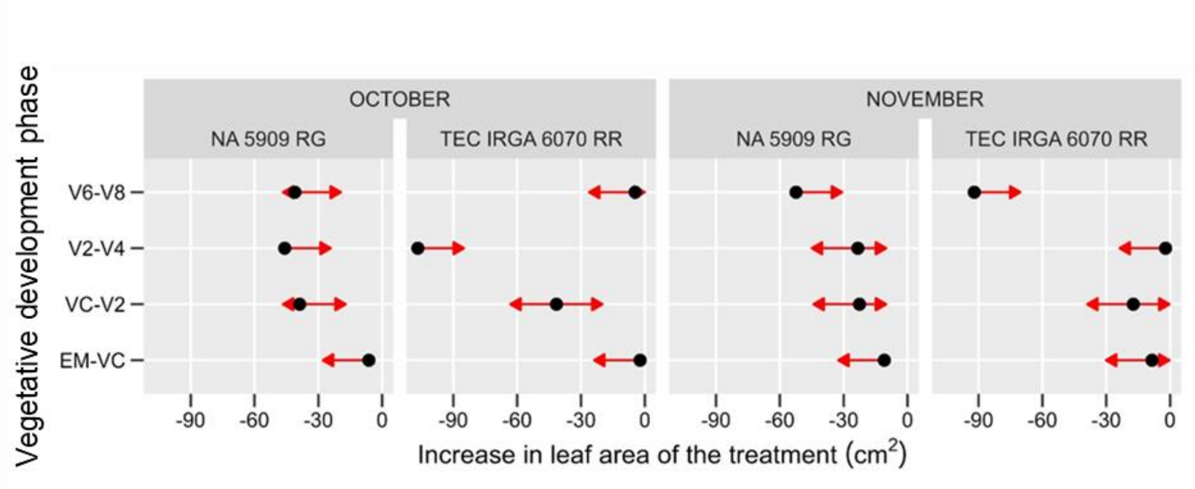

Figure 3. Test of means comparison at 0.05 % error probability for the increase of leaf area (cm²) of soybean under flooding conditions at the vegetative development phases EM-VC, VC-V2, V2-V4, V6-V8 compared with the control plants in the cultivars 1 (C1 - NA 5909 RG) and 2 (C2 - TEC IRGA 6070 RR) in the sowing dates 1 (E1 - October) and 2 (E2 - November) in the 2018/2019 growing seasons. *The arrows are the Tukey test DMS.

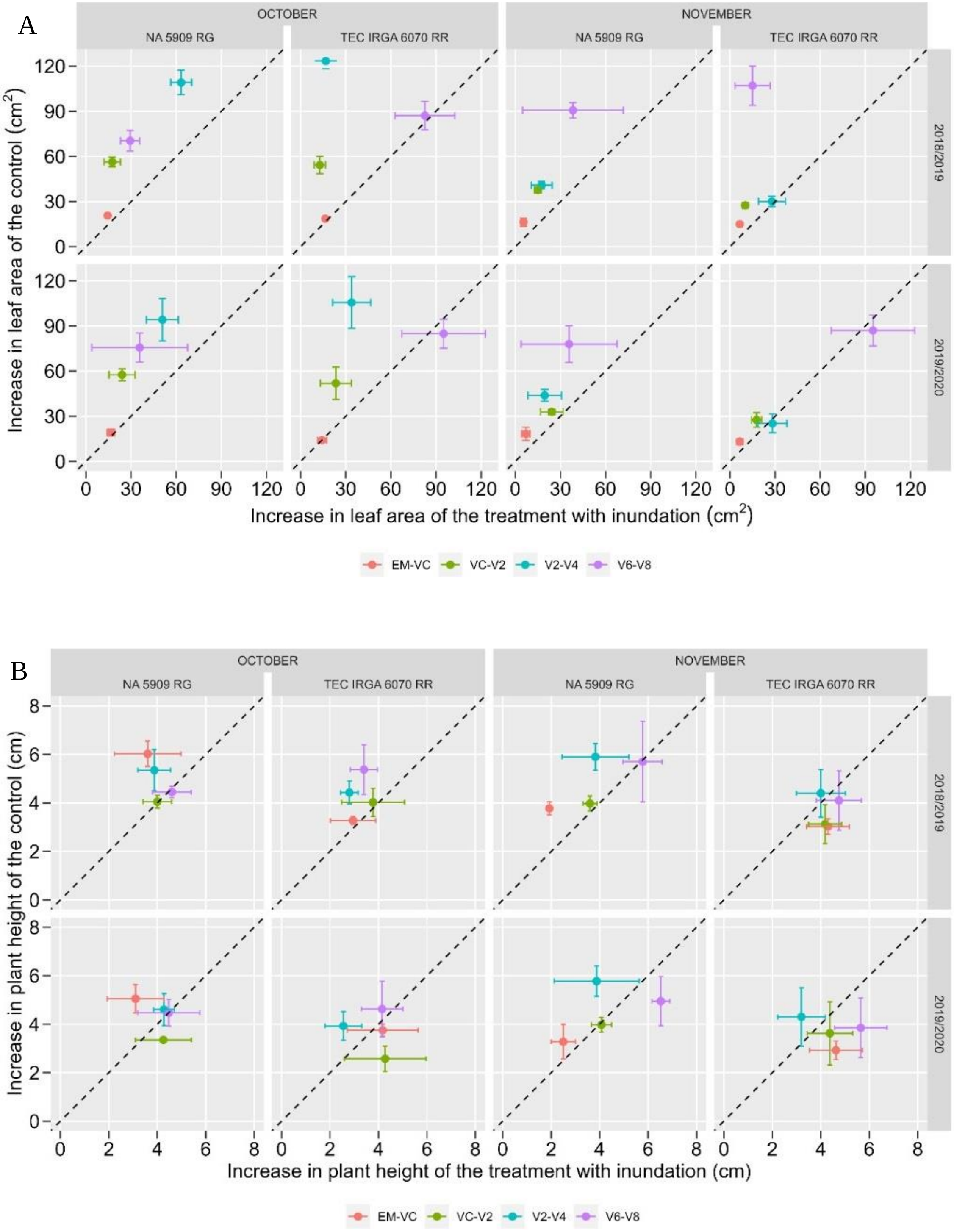

Figure 4. Means of the leaf area (cm²) increase (A) and Height (cm) increase (B) and average standard deviation of soybean under flooding conditions at the phases EM-VC, VC-V2, V2-V4, V6-V8, and the control plants of the cultivars 1 (C1 - NA 5909 RG) and 2 (C2 - TEC IRGA 6070 RR) in the sowing dates 1 (E1 - October) and 2 (E2 - November) in the growing seasons, 1 (Year 1 - 2018/2019) and 2 (Year 2 - 2019/2020).

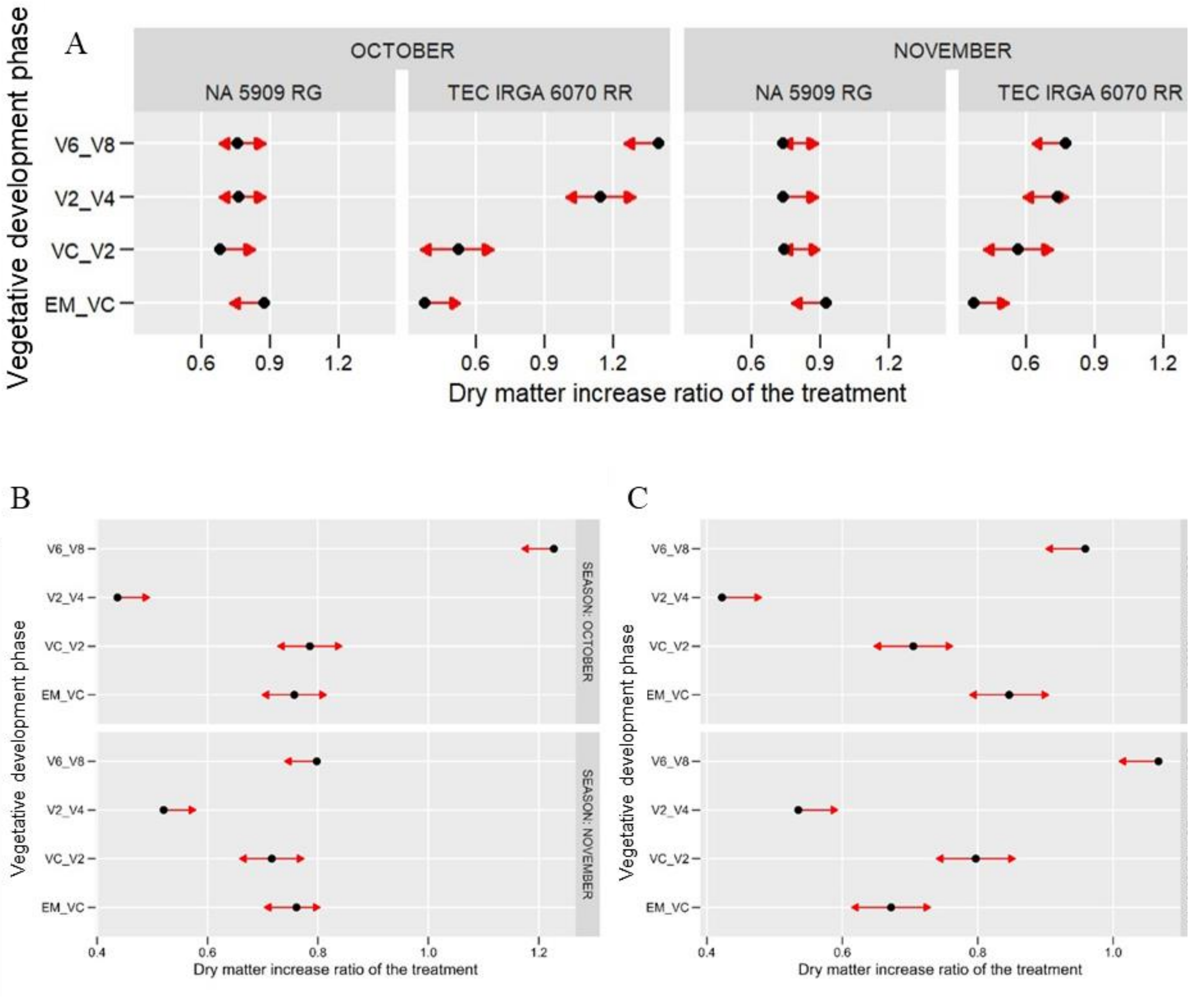

Figure 5. (A) Test of means comparison at 5% error probability for the dry matter (cm²) of soybean plants under flooding conditions at the phases EM-VC, VC-V2, V2-V4, V6-V8 compared with the control plants of the cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) in the sowing dates 1 (E1 - October) and 2 (E2 - November) in the growing seasons 1 (2018/2019). Test of means comparison at 5% error probability for the interactions Season*Treatment (B) and Cultivar*Treatment (C) for soybean dry matter (g) the growing season 2 (2019/2020). *Treatments: phases EM-VC, VC-V2, V2-V4, V6-V8; Cultivars 1 (C1 - NA 5909 RG) and 2 (C2 - TEC IRGA 6070 RR); Sowing dates 1 (E1 - October) and 2 (E2 - November). *The arrows are the Tukey test DMS.

4. ARTIGO 2

Excess water stress in soybean on different flooding times[2]

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[2] Artigo formatado nas normas da revista Agronomy Journal.

Core ideas

1. Identification of a soybean cultivar sensitive to soil waterlogging by flooding cycles
2. Identification of the most sensitive phenological stage to water deficit by flooding in soybean cultivars
3. Excess water reduces photosynthesis, stomatal conductance and leaf transpiration

Excess water stress in soybean on different flooding times

Abbreviations: DFL, distance from the flag leaf to the first branch of the tassel; DLN, distance for the last node to the first branch of the tassel; EH. Ear height; GY, grain yield; KD, kernel depth; LRT, Likelihood ratio test; MPE, mean performance and stability; MTSI, multi-trait stability index; NKE, number of kernels per ear; PH, plant height; SG, selection gains; TBN, tassel branch number; TKW, thousand-kernel weight; TL, tassel length.

ABSTRACT

The present study aimed to evaluate the tolerance of soybean cultivars to waterlogging on different flooding days, with and without a forced second flood, and in two sowing dates and crop years. A trifactorial experiment was carried out, with two sowing dates (October and November), two soybean cultivars (TEC IRGA 6070 RR and NA 5909 RG), and 10 and 13 flood periods in the 2018/2019 and 2019/2020 agricultural years. The following variables were evaluated: shoot dry mass, leaf area, plant height, total chlorophyll content, and in the 2018/2019 crop year: maximum photosynthesis, stomatal conductance, and leaf transpiration. Except for shoot dry matter, all evaluations were performed on the water excess (before flooding) imposition day, on the drainage (before draining) day, on the second flood day, on the second drainage day, and 7 days after the last drain. The NA 5909 cultivar showed more sensitivity to excess water stress on flooding days for the variables studied. When plants were exposed to 24 days of water excess (12 days + 7 drainage + 12 days) during the development cycle, the greatest decrease in leaf area, chlorophyll content and shoot dry mass occurred. For each group (3, 6, 9, and 12) evaluated, there was no acclimatization for the two cultivars and the sowing dates studied. For the two sowing dates the maximum photosynthesis, stomatal conductance, and foliar transpiration were reduced concerning the control. The second sowing period increased the influence of water stress on soybeans due to higher average air temperatures.

4.1 INTRODUCTION

Soybean (Glycine max L.) requires roughly between 650 to 860 mm of water during its development cycle and in a well-distributed way to reach its yield potential (Grassini et al., 2017; Zanon et al., 2016; Tagliapietra et al., 2021). On the other hand, like most grain-producing species, soybean is considered sensitive to stress caused by excess water (Fante et al., 2010; Garcia et al., 2020; Zhou et al., 2020), periods of flooding or inundation that frequently occur during the lowland soybean development cycle can alter grain growth and yield (Cho and Yamakawa, 2006; Garcia et al., 2020; Zhou et al., 2020).

The excess of water distresses numerous producing areas of this oil seed in the world, such as the southern region of the Rio Grande do Sul state (Brazil) (Zanon et al., 2018; Sartori et al., 2016a, b; Irga, 2018; Bortoluzzi et al., 2017; Zanon et al., 2015; Bailey-Serres et al., 2012; Rhine et al., 2010). In this region, lowland cultivated soybean crop areas in rotation with irrigated rice have been escalating to a significant increase in soybean sown area, passing from 10 thousand hectares in the 2009/2010 agricultural year to 408 thousand hectares in the agricultural year 2021/2022 (Irga, 2021). However, lowland soils have reduced natural drainage and are subjected to the incidence of temporary flooding periods, especially after intense precipitation events (Zanon et al., 2018; Irga, 2018; Rocha et al., 2017; Sartori et al., 2016a, b).

The effect of soil water saturation stress on plants is multifaceted and varies on genetics, plant development stage, stress duration, and the influence of meteorological elements on a plant's stress period (Garcia et al., 2020; SchoffeL et al., 2001). Some plant species can withstand these hostile conditions, and tolerance to excess water may diverge between cultivars and between flood periods (Garcia et al., 2020; Bailey-Serres; Voesenek, 2008). Meteorological elements, mainly air temperature and solar radiation, vary according to the year season and can influence the stress intensity caused by water excess, maximizing, or delaying the consequence on crops (Bergamaschi and Bergonci, 2017; Taiz and Zeiger, 2017). Thus, understanding the ecophysiology of plants in environments prone to flooding and characteristics of acclimatization are important, especially for the identification of the more tolerant genotype.

When the plant is exposed to environmental stress this information is stored as an experienced memory and can be recalled in a new stressful event, in response to the signaling generated by environmental stimuli, this phenomenon is conceptualized as the plant adaptive response (*stress imprint*) (ThellieR and Lüttge, 2012; Trewavas, 2003). In other words, plants that have experienced stress respond faster and/or stronger to subsequent stress, whether biotic or abiotic (Conrath et al., 2006). These characteristics have already been studied in bananas (Willadino et al., 2017), potatoes (Teixeira and Pereira, 2007), rice (Reddy et al., 2017), corn (Hu et al., 2007), and sugarcane cultivars under stress (Avinash et al., 2012; Inheiro et al., 2014). According to the available information in the literature, no studies were carried out to assess the adaptive response of the plant in a subtropical environment with two floods, which is what happens customarily in lowland soybean farming.

The available results on the influence of solar radiation and air temperature as a function of sowing dates and the period of days of tolerable water stress for soybean cultivars from the

V6 stage forward are limited in the literature. Consequently, the objective of this work was to evaluate the tolerance of soybean cultivars to excess water stress on different flood days, with and without an imposed second flood and different sowing dates.

4.2 MATERIALS AND METHODS

The experiment was conducted in two agricultural years (YEAR 1: 2018/2019 and YEAR 2: 2019/2020), with two sowing times each: YEAR 1: E1 (10/12/2018) and E2 (11/28/2018) and YEAR 2: E1 (10/12/2019) and E2 (11/30/2019). Two soybean cultivars with relative maturity group (GMR) close to 6.0 were used, one of the most cultivated in southern Brazil (Cultivar 1 - NA 5909 RG - GMR 6.2) and another described as a tolerant to water excess (Cultivar 2 - TEC IRGA 6070 RR - GMR 6.3) (Irga, 2018). A field experiment was carried out in a structure with a translucent polyethylene plastic cover located at the Federal University of Santa Maria, Santa Maria, RS, Brazil (latitude: 29º 43'S, longitude: 53º 43'W and altitude: 95 m). The regional climate according to the Köppen classification is Cfa, which means humid subtropical without a defined dry season with hot summers (Kuinchtner and Buriol, 2001).

The experimental design was completely randomized with four replications, each replication consisted of a plant grown in a 7-liter capacity plastic pot filled with soil. The experiment was carried out in a trilevel factorial as follows: two sowing seasons (E1 and E2), two soybean cultivars (C1 and C2), and 10 (2018/2019 agricultural year) and 13 (2019/2020 agricultural year) flood periods (Table 1). In the experiment, the effect of was studied of flooding days in soybean cultivars with and without a second flood.

Table 1. Description of excess water treatments used for soybean cultivars.

Treatments			
1	**Control**		
2	3 flood days imposition		
3	3 flood days imposition +	7 days drainage +	3 flood days imposition
4			3 flood days imposition
5	Imposition of 6 flood days		
6	Imposition of 6 flood days +	7 days drainage +	Imposition of 6 flood days
7			Imposition of 6 flood days
8	9 flood days imposition		
9	9 flood days imposition +	7 days drainage +	9 flood days imposition
10			9 flood days imposition
11	12 flood days imposition		
12	12 flood days imposition +	7 days drainage +	12 flood days imposition
13			12 flood days imposition

*** Agricultural year 2018/2019: T1 to T10; agricultural year 2019/2020: T1 to T13.**

Up to 9 and 12 days of excess water were studied in 2018/2019 and in the 2019/2020 agricultural years, respectively, therefore there were 10 and 13 periods of excess water in 2018/2019 and 2019/2020 individually. Due to the first-year experiment results, the plants were forced to water excess for a longer period of days.

Five seeds per pot, previously treated with insecticide and fungicide, were sown, and inoculated with *Bradirizobium elkani* at a depth of sowing of 3 cm and after the emergence of the plant, thinning was performed to preserve only one plant per pot. The spacing of the pot was 10 cm in rows and 40 cm between rows. Pots' external walls were white painted to reduce the solar radiation absorption. The soil used in the experiment came from the upper layer (from 0 to 20 cm) of a HAPLIC GLEISSOLO: Ta typical dystrophic (Typic Albaqualf) with 22% clay. Nutrients and soil acidity correction were performed according to laboratory soil analysis and soybean recommendations (Silva and Gatiboni, 2016).

When plants were subjected to flooding, the pots were individually placed inside larger containers (buckets), and then water was added, keeping a continuous depth of 5 cm above the ground level. For each excess water treatment, a similar number of plant repetitions, for each flooding period, were maintained at control conditions with 90% of field capacity. Maintenance irrigation in control plants was performed using the weighing method, in which the pot was weighed when it was in field capacity [100% of the available water capacity (AWC)] and then daily weighing to quantify consumption. The replacement was daily aiming to reach at least 90% of AWC.

The first flood was imposed when the plants were between V6 and V7. To evaluate the soybean cultivars' excess water acclimatization potential, the treatments that were submitted to a second flood were drained for seven days after the first flood and then were flooded again. At the time the treatments were flooded, there was a treatment group that received the first flood.

Meteorological air temperature Variable during the experimental period was collected using a digital thermo-hydrometer [Instrutherm (HT-500)] with a mini data logger attached to a shelter positioned in the experiment. Solar radiation was collected at the automatic meteorological station belonging to the eighth meteorological district of the Brazilian National Institute of Meteorology (DISME/INMET), located 200 m from the experimental area. The daily global incident solar radiation on the plants was corrected based on the plastic (covering 80%) transmissivity (Buriol et al., 1995).

Plant height (PH) (stem length from ground level to the base of the last visible node) and leaf area (LA) were evaluated. To determine LA, the length and width of the central leaflet of all leaves of each plant were measured, and consequently, the LA of each leaf was estimated through the Richter et al. (2014) equation: $LA=(L*W)*2.0185$ (1), where LA is the leaf area, L is the measured length, W is the measured width and 2.018 is the model constant. The LA of each plant was calculated by the sum of the LA of all the individual leaves of the plant. All these assessments were performed on the excess water day imposition (before flooding), on the drainage day (before draining), on the day of the second flood, on the day of the second drainage, and 7 days after the last drainage. At the beginning and the end of each experiment, the plant aerial dry biomass was determined in all repetitions. To obtain the total dry matter (TDM) of the shoot, the plants were collected and oven dried at a constant temperature of 65 ° C until a constant weight is reached.

In the 2018/2019 season, gas exchange measurements were carried out in the last expanded leaf of the plant using an infrared gas analyzer (IRGA) (LI-COR Portable Photosynthesis System, Nebraska, USA), from 9 am to 2 pm. The highest amounts of photosynthesis rate (Amax), stomatal conductance (gs), and leaf transpiration (E) were obtained. IRGA assessments were not possible to carry out in the 2019/2020 season, as the equipment was not available. In the two agricultural years studied, chlorophyll meter readings were done with a Falker SPAD-502 chlorophyll meter, in the middle third of the plant, operated according to the manufacturer's stipulations. The chlorophyll meter reading was made on the central trifoliate at points located in the center of the sampled leaf.

To quantify the soybean cultivars' acclimatization to excess water stress, growth variables (PH, LA, and TDM), chlorophyll content, maximum photosynthesis rate, stomatal conductance, and leaf transpiration were compared between treatments that received one flood with those that received two floods. In the analysis and interpretation of the results, the relative increase to the control was calculated for the growth variables. For this calculation, the value of the last day of the evaluation was considered minus the value obtained on the day of the beginning of the experiments, therefore having the increase in excess water treatment for each variable analyzed. This increment obtained in the water excess treatments was calculated about the increment of the control, which generated a coefficient, in which values greater than 1 mean that the increase was more than the control, and for values to a lesser extent than 1 the increment was smaller than that of the control. The assumptions of the model were tested (normality, randomness, and homogeneity of variances) and subsequently the data were analyzed using analysis of variance (ANOVA) with the aid of the RStudio program (R Core Team, 2020) using the Metan package (Olivoto and Lucio, 2020), and the means were compared using the Tukey test at 5% error probability using the emmeans package (Lenth, 2021). A simple linear correlation analysis was also performed between the variables TDM, Amax, E and gs in the 2018/2019 season. Furthermore, for variables LA, PH and chlorophyll index, a simple linear regression was performed between the total number of days the plants were flooded and the number of times [one (beginning and end) and two] they were under flood conditions during the development cycle.

4.3 RESULTS

The description of the meteorological elements in both agricultural seasons is represented in Figure 1. In both agricultural years, plants that were sown in October were exposed to a lower minimum and maximum air temperatures than plants sown in November, possibly resulting in lower evaporative demand. This allowed us to identify the effect of air temperature and solar radiation on morphological responses (growth and development) to the excess intensity of soil water. The lowest minimum air temperature values (Tmin) recorded were 10.0 ºC (12/03/18) (Figure 1A) and 10.6 ºC (10/25/19) (Figure 1C) and the highest maximum air temperature values (Tmax) were 38.6°C (12/11/18) (Figure 1A) and 37.9°C (12/29/19) (Figure 1C). The photoperiod (Figure 1 B, D) to which the soybean plants were exposed fluctuated from 13.45 to 14.96 hours. For solar radiation, the months with the highest incidence were late October [36.93 MJ m^{-2} (2018/2019) and 32.16 MJ m^{-2} (2019/2020)], November [32.24 MJ m^{-2} (2018/2019) and 37.83 MJ m^{-2} (2019/2020)] and early December [32.71 MJ m^{-2} (2018/2019) and 35.50 MJ m^{-2} (2019/2020)], (Figure 1B, D).

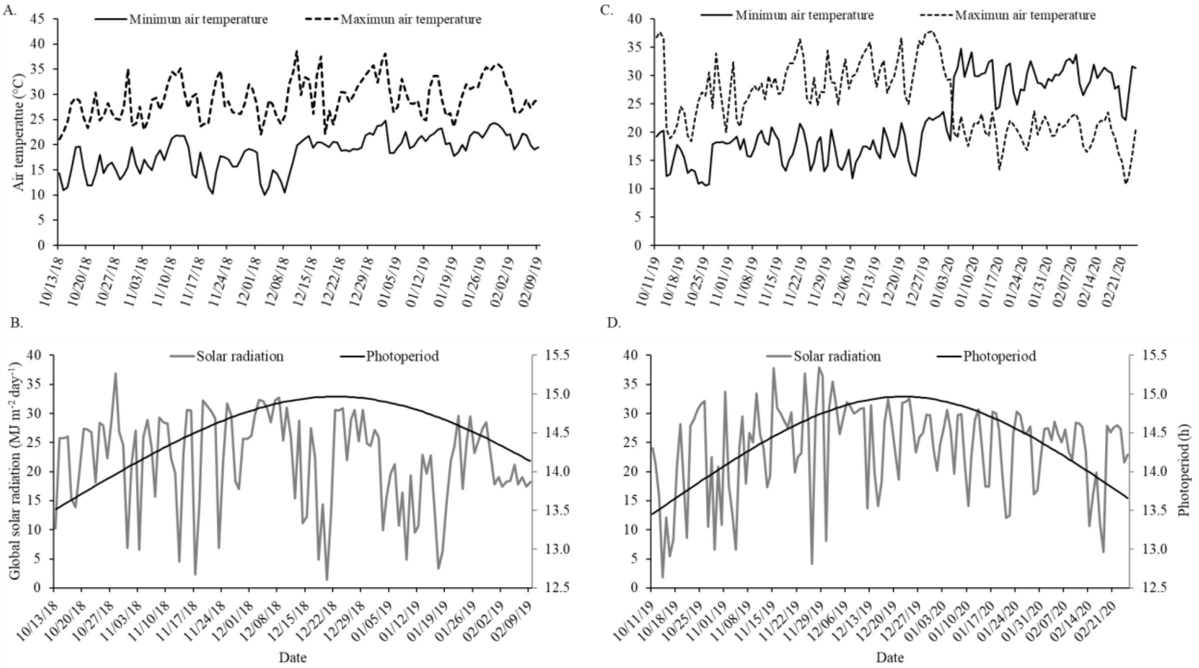

Figure 1. Daily minimum (Tmin, °C) and maximum (Tmax, °C) air temperature (A, C), global solar radiation (MJ m^{-2} day^{-1}), and photoperiod (h) (B, D) during the experiment in the seasons 2018/2019 (A, B) and 2019/2020 (C, D), in Santa Maria, RS, Brazil.

In the 2018/2019 season, when analyzing the LA of the two soybean cultivars sown in October, the longer the water excess stress period, the greater the reduction of LA, as farther away from the 1:1 line these treatments are found (Figure 2A).

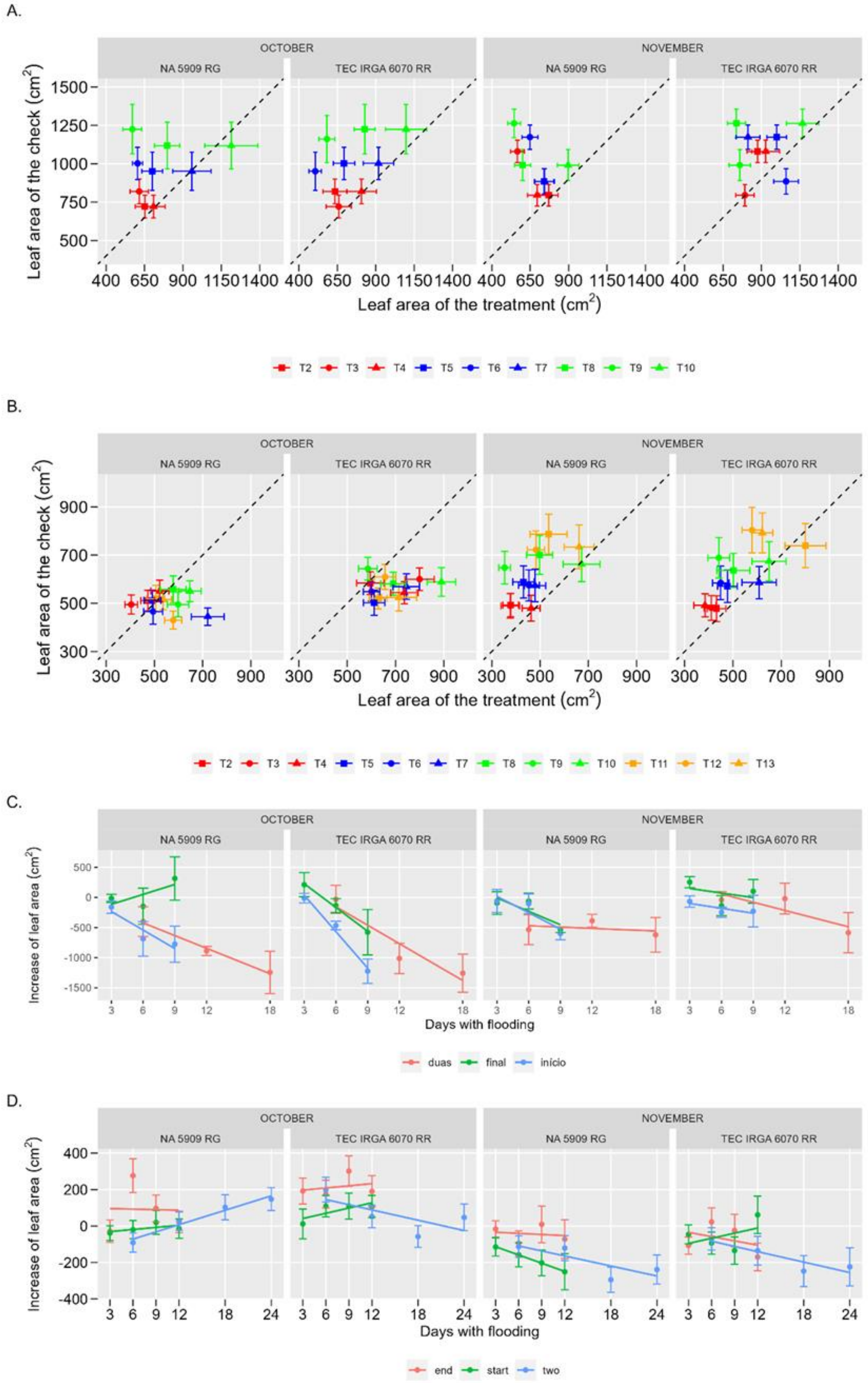

Figure 2. 1: 1 line for the leaf area (cm^2) of the control in relation to the leaf area of the treatments (A, B) and simple linear regression (C, D) between the total days the plants were in excess of water versus how many times (once (beginning and end) and two) were under

waterlogging conditions during the development cycle to increase the leaf area (cm²) in cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) in sowing seasons 1 (E1 - October) and 2 (E2 - November) in crop years 2018/2019 (A and C) and 2019/2020 (B and D).

For C1, the treatment that most reduced the LA concerning the control was T9, when the plants were 18 days in water excess with two impositions of 9 days, with a reduction of 7.33 cm² of leaf per day of water excess and total in the period of the experiment of 600 cm² with the control (Figure 2C). The same occurred for C2, with a reduction of 7.25 cm² per day of excess water and total in the experiment period of 570 cm² leaf. This is justified by the greater maximum air temperature in December when the water excess imposition on plants occurred, which delivered a greater pressure on the plants due to the possibly superior evaporative demand. When the water excess was at the end of the vegetative phase and the beginning of the reproductive phase (T10) the plants tolerated a 9-day flooding condition, expressed by the higher leave production concerning the control. As for cultivar 2, no treatment had higher leaf production than the control, but it can be seen that when the plants received only a flood of 3 (T4), 6 (T7), or 9 days (T10), when the plants were in at the end of the vegetative phase and beginning of the reproductive phase, the LA reduction with the control was minor.

In season 2, the highest LA decrease for C1 and C2 was also with 18 days of water excess (T9), nevertheless, it was significantly lower than in the first sowing season. This is because when the plants were exposed to flooding (V6-V8 (first imposition) and the beginning of the reproductive period (second imposition)) the average air temperatures were lower, causing less stress to the plant (Figure 1A).

In the 2019/2020 crop year, when sown in season 2, for the two cultivars there was a greater LA reduction in the water excess treatments when compared to the control due to higher air temperature and solar radiation in the period that the experiment was initiated. (V6-

V8), which increases plant stress (Figure 2 B). However, in the first sowing season, as the air temperature was milder in the V6-V8 phase for the plants that were sown in the November season, the plants did not suffer much from the water excess imposition, presenting a greater total LA than the control.

C1 had acclimatization to excess water with two impositions during the cycle when it was sown in October, presenting the highest daily increase in LA with control of 13.17 cm² (Figure 2 D). In season 2, the greatest daily LA reduction was observed when the excess water was imposed at the beginning of the experiment (V6-V8) with a daily leaf reduction of 15.09 cm². In C2E1, the major daily increase in LA was recorded when excess water occurred at the beginning of the cycle, with a daily increase in leaf of 9.57 cm² and the main reduction in season 2 was when there were two water impositions during the cycle, which reduced 9.55 cm² of leaf per day.

For the variable PH, in the 2018/2019 crop year, it is possible to confirm that C1, in both sowing seasons, showed a higher evolution than the control (Figure 3A), denoting the etiolation of the plants and an attempt to escape the anaerobic environment. For PH in seasons 1 and 2, 9 days of excess water at the beginning of the cycle (T8), E1 was 6 cm higher than the control and showed a daily growth rate also greater than 0.20 cm day^{-1} (Figure 3C), and in season 2, the plants grew around 3 cm more than the plants in field capacity and showed a daily growth greater than the control of 0.60 cm day^{-1} (Figure 3C).

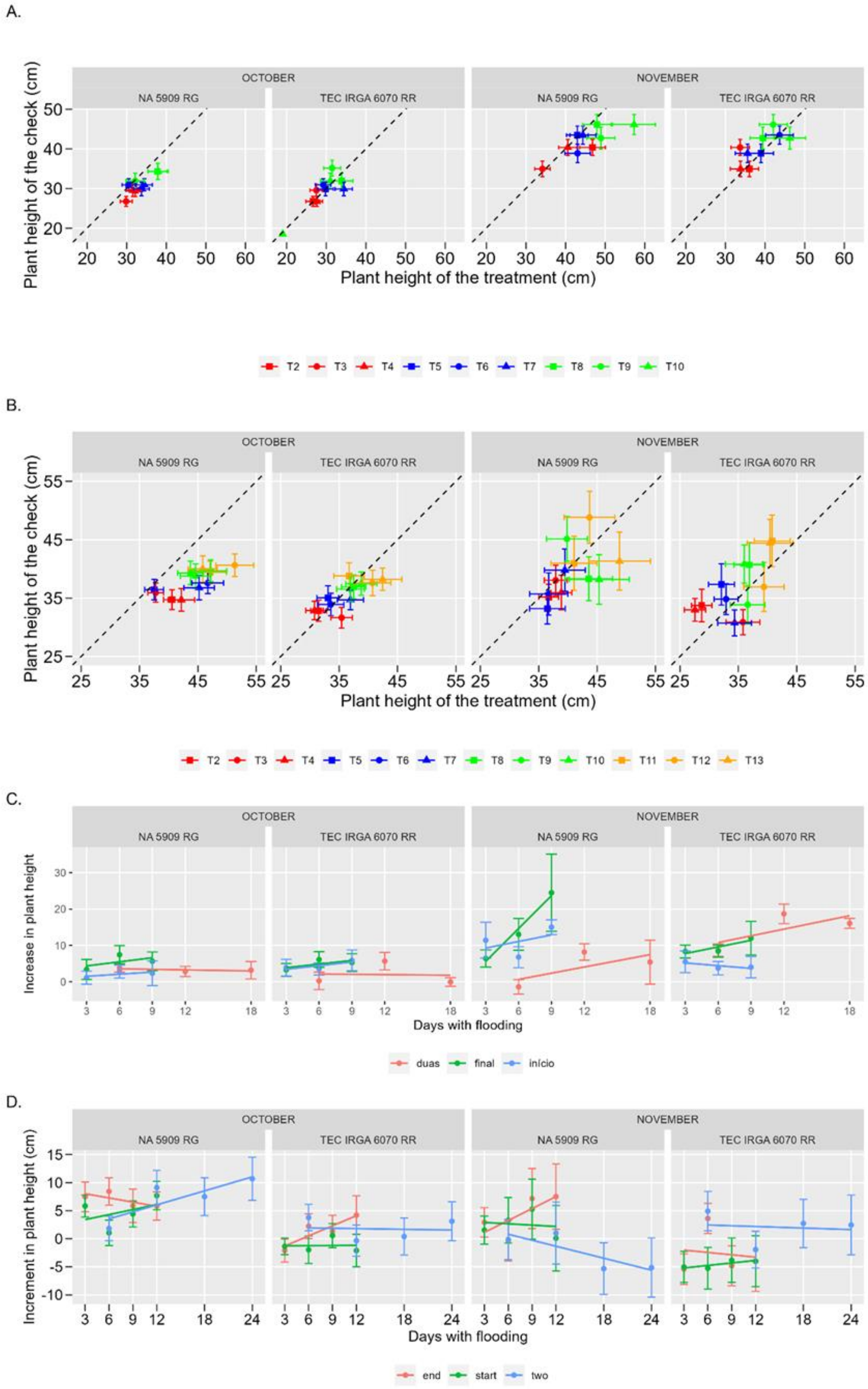

Figure 3. 1:1 line for the height of the control plant (cm) in relation to the height of the plants treated (A, B) and simple linear regression (C, D) between the total days when the plants were in excess water stress versus how many times (one (beginning and end) and two) were under

waterlogging conditions during the development cycle to increase the height of the plant (cm) in cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) in sowing seasons 1 (E1 - October) and 2 (E2 - November) in crop years 2018/2019 (A and C) and 2019/2020 (B and D).

For cultivar 2, it is noteworthy that plants in excess water displayed lower growth than the control in field capacity, in most treatments, which implies that the etiolation of this cultivar is lower in anaerobic circumstances. T9 was the one that most reduced plant growth in E1 and E2, with an average of 5 and 4 cm less than the control, correspondingly.

When comparing the effects of the sowing season, season 2, which had higher maximum air temperatures and higher incidence of solar radiation, favored the two soybean cultivars to grow more in height, despite being in excess water condition.

C1 had the greatest plant growth reduction per water excess day in 2018/2019, 0.05 cm day^{-1}, when sown in October and exposed twice to water excess. The reduction in plant growth was higher in C2 at the beginning of the experiment (V6-V8) when sown in E2 and when exposed only once to excess water, showing a daily decrease of 0.25 cm. C1 reduces plant growth the greater the number of times it stays in an anaerobic condition, and C2, in order, is more sympathetic to flooding when in early development stages and when the maximum air temperature is higher, by the number of abiotic stresses. However, it tolerated well two water impositions of up to 9 days, as its height growth was nearly unaltered.

In the 2019/2020 crop year, C1 and C2 growth were also more affected by water excess when was sown in November, with smaller PH when compared to the control (Figure 3B). C1 had the greatest plant growth reduction in 2019/2020 when sown in November and exposed twice to water excess for 12 days (T12), 0.05 cm day^{-1}, with an average of 15 cm less height than the control (Figure 3D). C2, on the other hand, reduced plant growth when sown in E2 and exposed only once to water excess at the beginning of the experiment (V6-V8) showing a daily reduction of 0.25 cm.

C1 reduces plant growth the greater the number of times it stays in an anaerobic condition, and C2, in turn, is more sensitive to flooding when it is younger and when air temperatures are higher, due to the sum of abiotic pressures. However, it stranded well two water impositions of up to 9 days, as its height growth was practically unaffected.

The total chlorophyll content (chlorophyll A + chlorophyll B) in both crop years, cultivars and seasons was considerably reduced when plants were under excess water conditions (Figures 4A and 4B). In this sense, the longer the number of days that the plants were in excess of water, the greater the reduction of this photosynthetic pigment, which favored the anaerobic plants to present chlorosis. The greatest daily reduction in chlorophyll was in the second agricultural year when the plants were twice exposed to excess water for 12 days (T12), presenting a total chlorophyll index reduction of 10 compared to the control, in both the cultivars studied and the sowing times.

When observing the daily reduction of chlorophyll of plants, it is evident that in the 2018/2019 crop year C1 showed the greatest daily reduction in chlorophyll in the two sowing times (Figure 4C), and for C1 and C2 when they were sown in November. For C1E1, C1E2, and C2E1, the greatest daily chlorophyll reduction was observed in treatments that were twice subjected to excess water during the development cycle, showing a reduction of 0.59, 0.93, and 0.18 on day 1 chlorophyll, respectively. For C2E2 the biggest chlorophyll daily reduction was when the plants were submitted to water excess at the end of the development cycle, presenting a reduction of 0.60 chlorophyll day^{-1}.

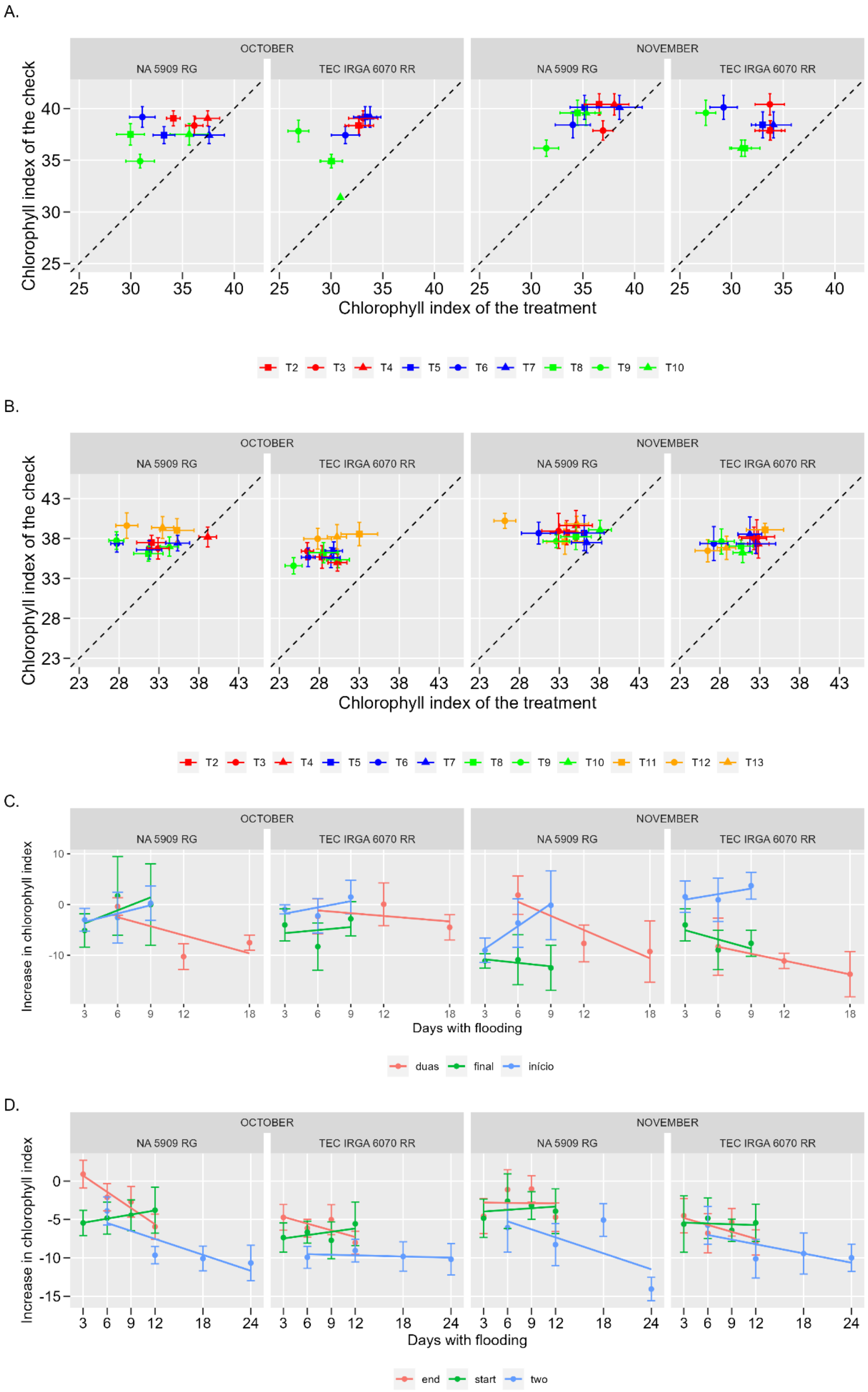

Figure 4. 1: 1 line for the total chlorophyll content of the control in relation to the chlorophyll content of the treatments and simple linear regression (C, D) between the total days that the plants were in excess of water versus how many times (one (beginning and end) and two)

were in waterlogging condition during the development cycle to increase chlorophyll in soybean cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) on sowing dates 1 (E1 - October) and 2 (E2 - November) in the agricultural years 2018/2019 (A and C) and 2019/2020 (B and D).

In the 2019/2020 crop year (Figure 4B) the greatest chlorophyll daily reduction was also observed in C1 in both sowing seasons. For C1E1, C2E1 and C2E2, the greatest daily chlorophyll reduction was observed when the plants were subjected to excess water at the end of the development cycle, showing a reduction of 0.7, 0.29, and 0.3 of chlorophyll day 1 related to the control, respectively (Figure 4D). For C1E2, the largest reduction in chlorophyll was recorded when plants were subjected twice to excess water during the development cycle, showing a reduction of 0.35 chlorophyll day^{-1}.

There was a positive correlation (0.21, $p < 0.01$) only between the dry matter and leaf transpiration (Figure 5). Stomatal conductance presented a positive simple linear correlation with photosynthesis and leaf transpiration of 0.28 and 0.53, respectively. The longer the plant has its stomata open, the greater the gas exchange and consequently the higher the performed photosynthetic rate, which leads to greater productivity. On the contrary, there is a positive correlation (0.51) between photosynthesis and leaf transpiration.

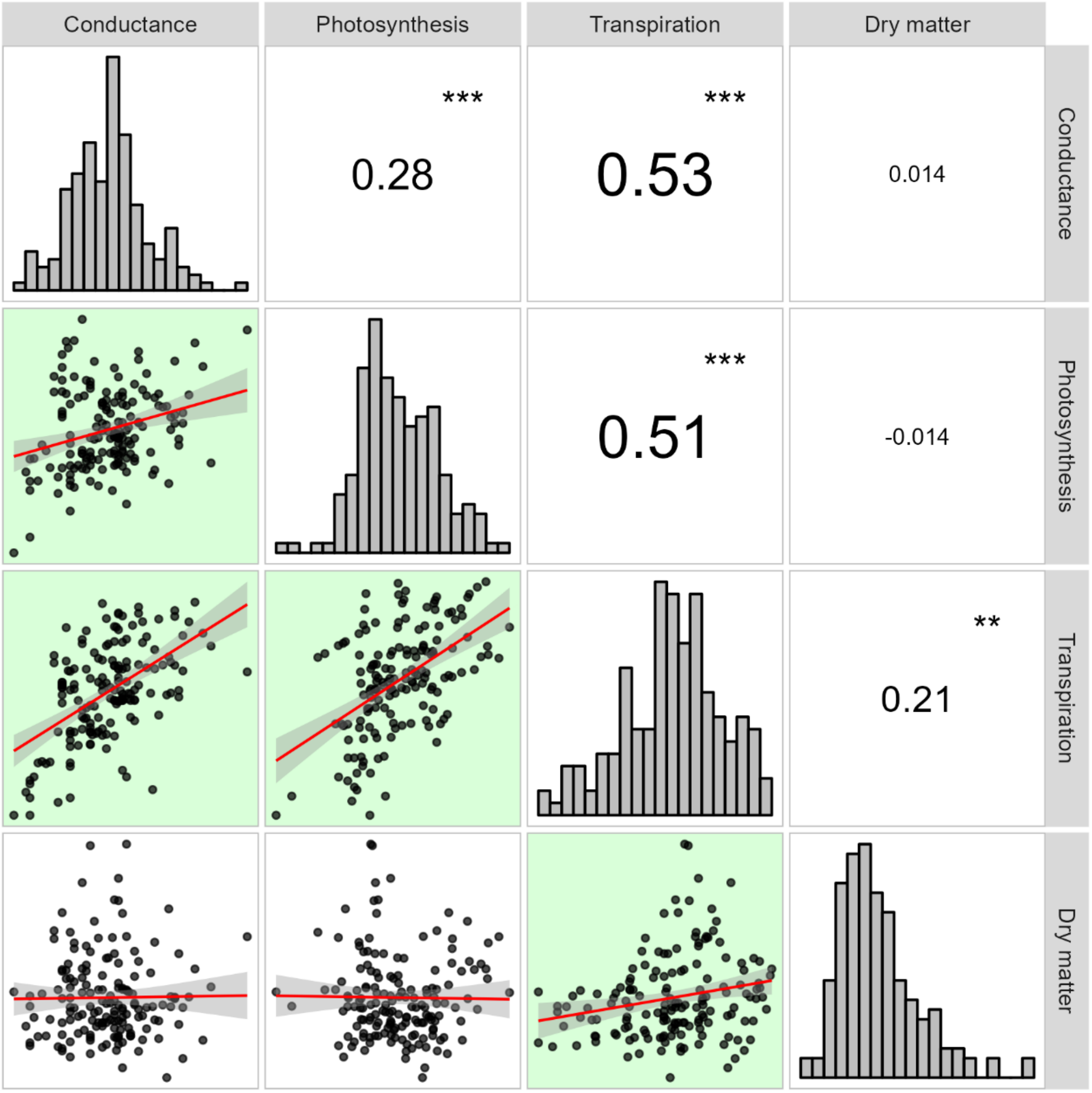

Figure 5. Simple linear correlation (n= 368) between TDM, Amax, E, and gs in soybean cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) at sowing dates 1 (E1 - October) and 2 (E2 - November) in the 2018/2019 agricultural year.

In the ANOVA, it was possible to validate that for TDM (2018/2019 agricultural year) the triple interaction Season x Cultivate x Treatment was not significant, however, the double interactions between Season x Cultivate (Figure 6A) and Season x Treatment (Figure 6B) presented statistical significance. In both cultivars and sowing times, the increase in TDM was greater than the control, because the plant thickens the stem base and develops aerenchyma, as well as it grows more in PH due to etiolation, and this favors greater plant mass. C2 is more stable than C1 under water stress conditions, showing equal growth at higher and milder temperatures since C1 increased less dry mass when it was sown in November and persisted in a higher air temperature environment.

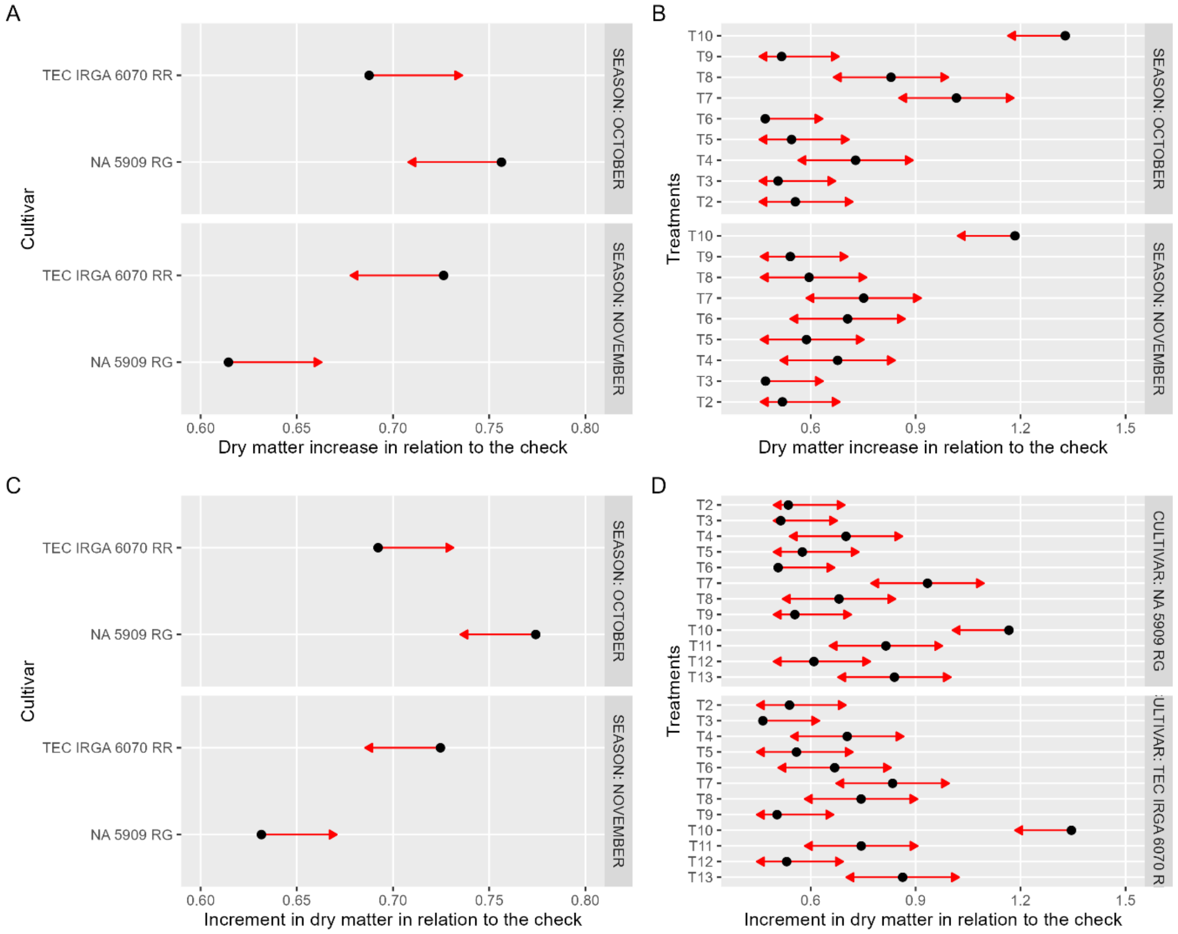

Figure 6. Means comparison test with 0.05% error probability for the increase in dry matter (g) of soybean in excess water relative to the control in cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) in sowing seasons 1 (E1 - October) and 2 (E2 - November) in crop years 2018/2019 (A, B) and 2019/2020 (C, D). *The arrows represent the DMS values for the Tukey test at (α = 0.05).

In season 1 there was a greater rise in treatments in water excess than in season 2, mainly T7, T8, and T9, which persisted in an anaerobic environment for a longer period. This is predictable because, in November, when the plants were imposed excess water, the maximum air temperatures were not high, which eases the stress of the plants, compared to E2 that had the water imposition at the beginning of January when the maximum air temperatures were higher.

In the ANOVA, it was possible to verify that in the 2019/2020 crop year, the double interactions between the Cultivar x season and the Cultivar x treatment were significant. We can verify that C1, when it is in a milder environment, suffers less excess water due to lower air temperatures. In turn, C2, regardless of the predominant weather conditions, presented statistically equal mean TDM (Figures 6C and 6D).

When plants subjected to different days of excess water stress behavior were analyzed, a significant difference was observed for T7 and T10 in C1 and T10 in C2. This shows that both cultivars stand water excess at the end of the cycle (close to the reproductive phase), showing plant growth in up to 9 days of water excess imposition.

The treatment that had the greatest reduction in the photosynthesis rate in the 2018/2019 crop year was T10 (Figure 7), which validates that the more days the plant is under a pressure condition, the greater the effect on photosynthesis and that a second stress condition, measured by replacing excess water, also affects the gas exchange of the plant.

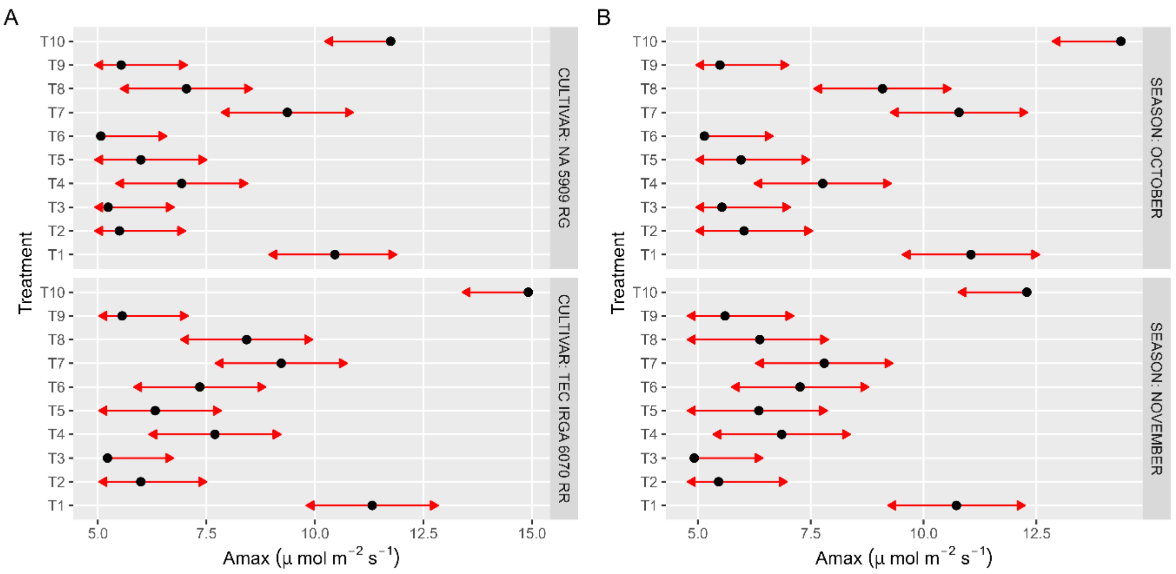

Figure 7. Mean comparison test at 0.05% error probability for maximum photosynthesis (μ mol m^{-2} s^{-1}) of soybean in water excess concerning the control in cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) in sowing seasons 1 (E1 - October) and 2 (E2 - November) in the 2018/2019 crop year. *The arrows represent the DMS values for the Tukey test at (α = 0.05).

When sowing dates are examined, the photosynthetic rate of treatments did not differ when the soybean was sown in October or November and what influenced photosynthetic efficiency was the number of days in an anaerobic environment. The same response was shown for the leaf transpiration variable. Leaf transpiration was affected by excess water, with a reduction in the control (Figure 8).

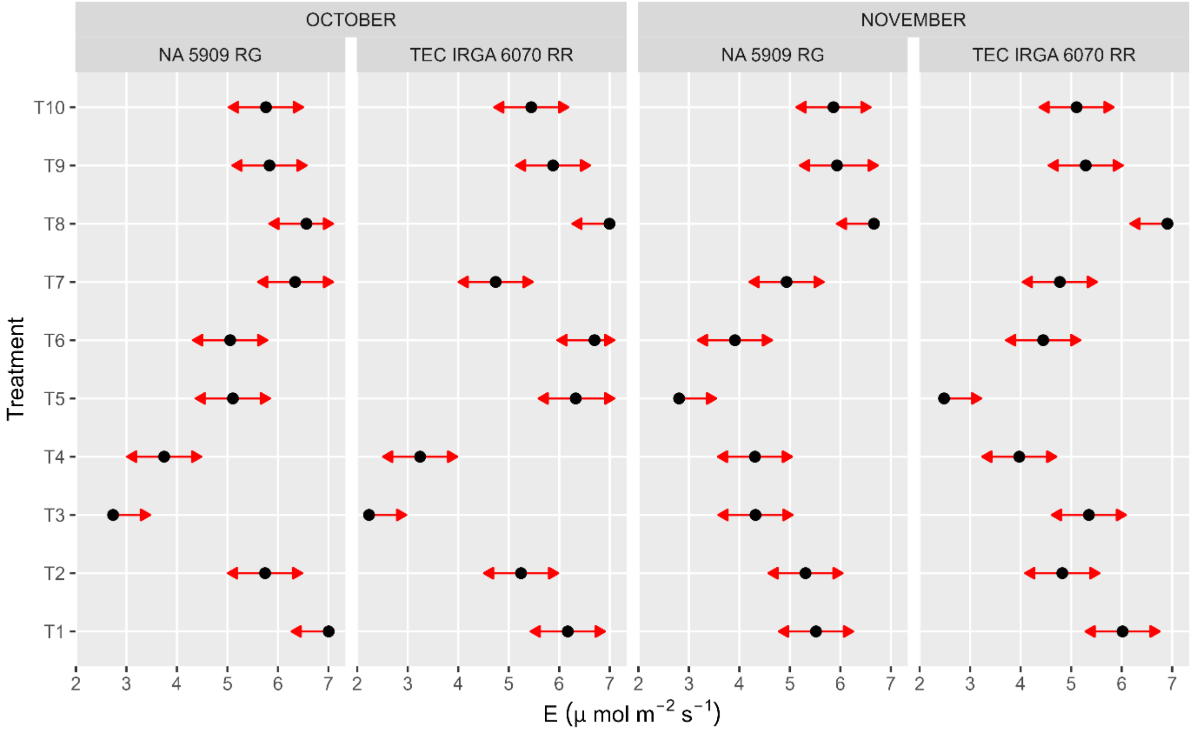

Figure 8. Mean comparison test at 0.05% error probability for foliar transpiration (μ mol m-2 s-1) of soybean in excess water to the control in cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) in sowing seasons 1 (E1 - October) and 2 (E2 - November) in the 2018/2019 crop year. * The arrows represent the DMS values for the Tukey test at (α = 0.05).

After seven days of drainage, for C1 and C2 and for both periods studied, treatments T2, T3, T4 and T5 showed the lowest foliar transpiration with respect to the other treatments with an excess of water. This response demonstrates that when soybean is still in the vegetative phase, it is more sensitive to water excess than when the reproductive phase starts.

Concerning stomatal conductance, gas exchange was significantly lower when associated with the control for T8, T9, and T10 in C1E2 (Figure 9). Indicating once again that C1 when in higher air temperatures and a greater number of days in water excess conditions (9 days) experiences superior abiotic stress. Notwithstanding the interaction of numerous factors that act on stomata and, therefore, on stomatal conductance, the effect of water stress on this parameter is evident, noticing that it can be used as an indicator of water stress.

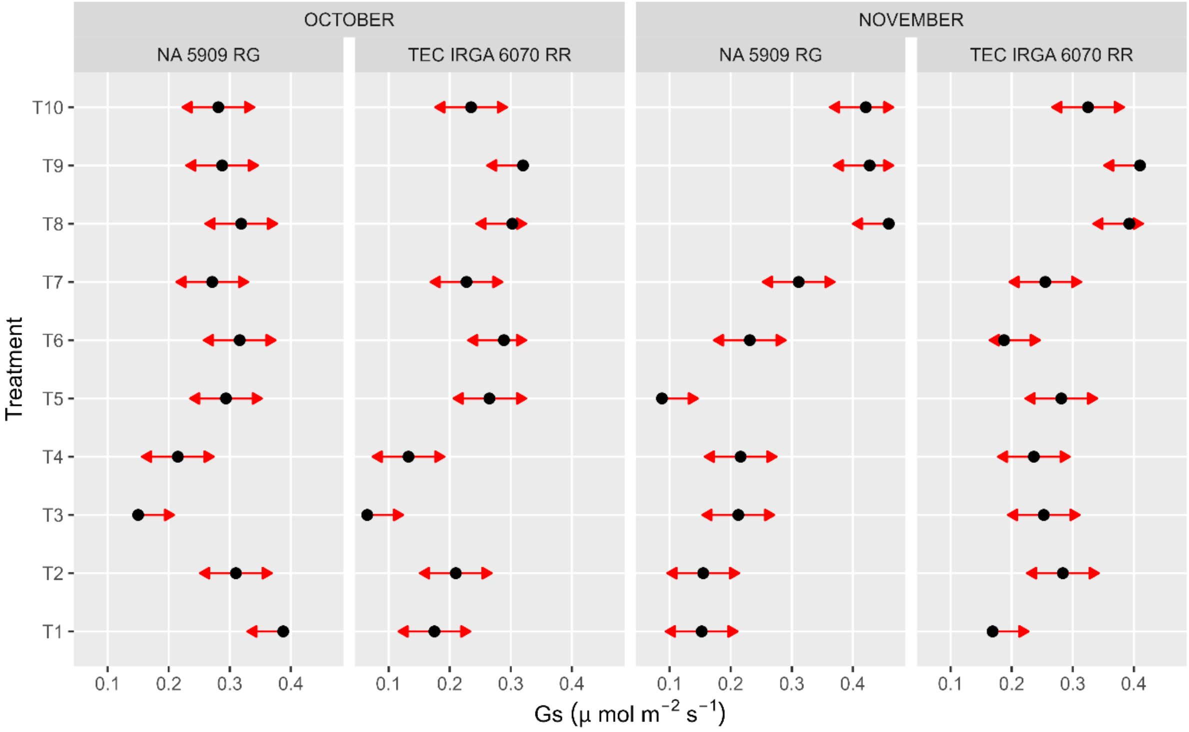

Figure 9. Mean comparison test with 0.05% error probability for soybean stomatal conductance (µ mol m-2 s-1) of water in relation to control in cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) in sowing seasons 1 (E1 - October) and 2 (E2 - November)

in the 2018/2019 crop year. * The arrows represent the DMS values for the Tukey test at ($\alpha = 0.05$).

During the entire experiment process, there was no death of plants regarding water excess conditions, conversely, it was possible to confirm plants' morphophysiological changes (Figures 10 and 11). When subjected to excess water, soybean plants are in a hypoxic environment, leading to stress, and to find an environment with greater availability of O_2, they undergo morphophysiological modifications. This is observed by the thickening and cracking of the base of the main stem (Figure 10B), development of adventitious roots (Figure 10A, 10B and 10D), and the formation of aerenchyma (Figure 10B), as can be seen in treatments with nine and twelve days of excess water.

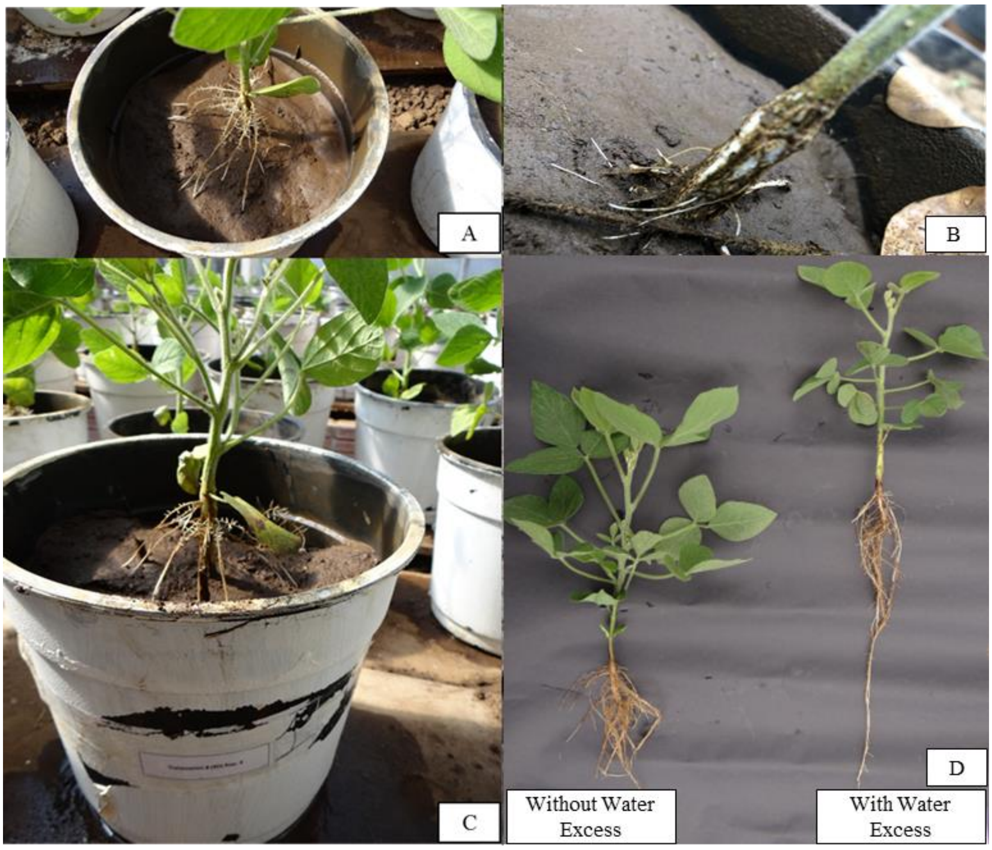

Figure 10. Morphophysiological changes in soybean plants after water excess imposition. A, C: superficial roots formation; B: stem base enlargement and splitting, and probable aerenchyma formation; D: plants root system with and without water excess imposition.

In addition, when they are in excess water (Figure 11A, B), there is a lower total leaf chlorophyll content and greater plant leaf senescence compared to plants that are in a soil condition close to field capacity (Figure 11C, D).

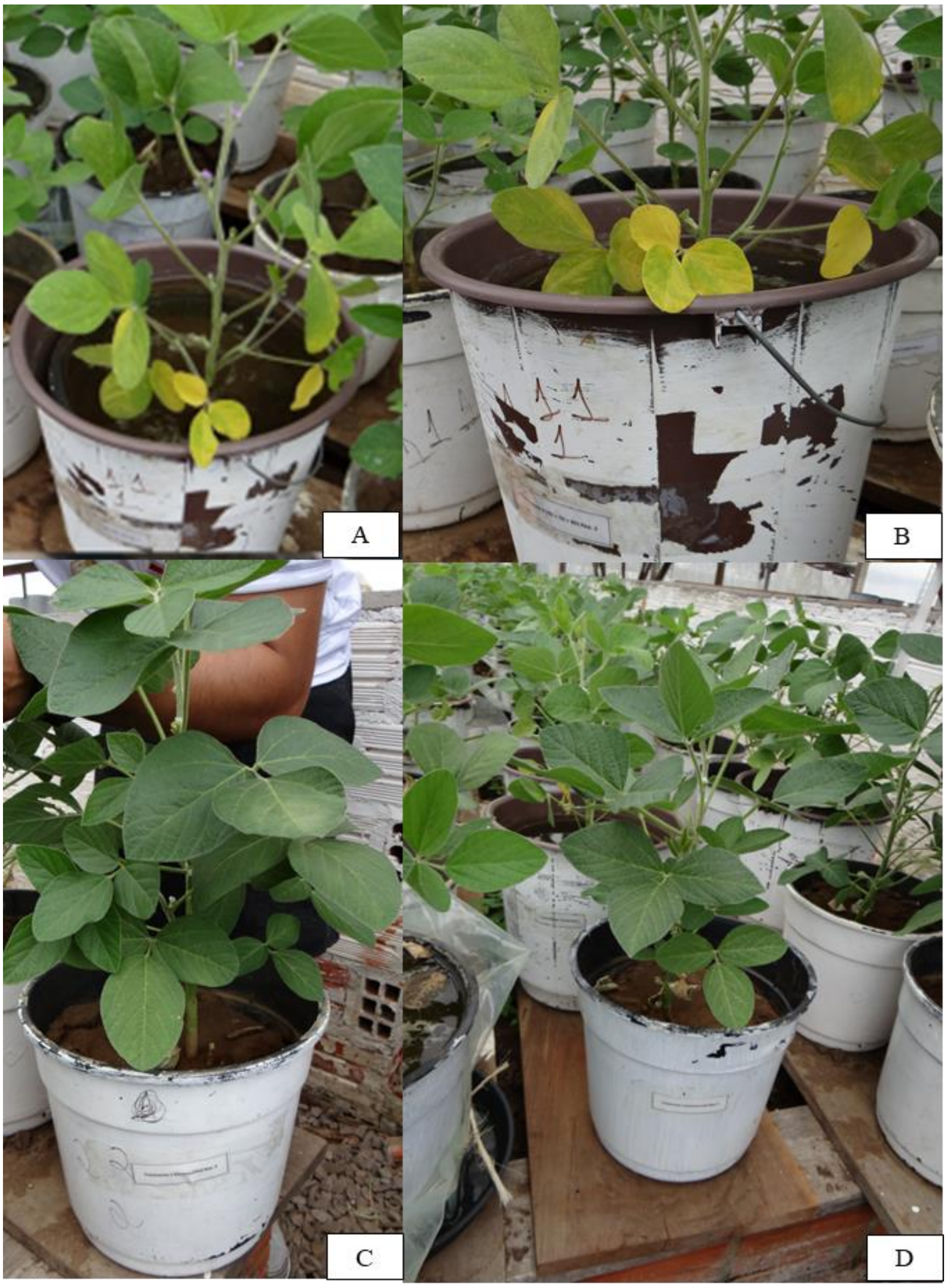

Figure 11. Morphophysiological changes in soybean plants after the water excess imposition. A, B: early yellowing of the basal leaves; C, D: plants close to soil field capacity conditions (control group).

Abiotic stresses are environmental factors that cause the greatest damage to the physiological and metabolic plant processes, causing harm to agriculture, and this is one of the reasons that has aroused great research interest. In this experiment, excess water triggered some morphophysiological changes in soybeans in response to flooding, specifically in the most severe stress circumstances (T10 and T13), such as rearrangement of photoassimilates into the root system, enlargement of the base of the stem, formation of aerenchyma, and lateral and adventitious growth of the roots, and for these reasons, researchers have been continually looking for more productive cultivars under hostile growing conditions.

4.4 DISCUSSION

Leaf growth depends primarily on cell division and development, noting that its inhibition caused by excess water can lead to a decrease in leaf growth rate at the beginning of their development (Taiz and Zeiger, 2017). Garcia et al. (2020) who also denote that soybean plants are more vulnerable to water excess at the beginning of the development cycle (Tagliapietra et al., 2022).

Zhou et al. (2020) stated that in excess water conditions, larger stem development may allow greater light to be absorbed for photosynthesis and increase the energy stock for basic plant life activities. Therefore, it helps to long resist flooding episodes. However, the comprehensive molecular mechanism is still largely unspecified.

Higher average daily air temperatures stimulate plant growth, up to a certain threshold of higher basal temperature, when compared to lower temperatures that constrain plant growth (Bergamaschi and Bergonci, 2017).

This confirms once again that the soybean when under excessive water conditions and a higher maximum air temperature environment has greater stress, because with increased atmospheric demand, plant transpiration increases to regulate internal temperature, and, in addition, lack of oxygen intensifies stress. Soil water excess causes a lack of aeration for plants' environment, as well as assists the spread of diseases and nutrient losses by leaching, leading to inferior plant growth (Santana, 2007).

Under three-day flooding conditions, Sullivan et al. (2001) found a 20% average productivity reduction, reaching up to 93% for the six days flooding condition, and attribute the yield drop to the plant population reduction, height, and pods number per soybean plant.

This is explained by the fact that the first process that is affected in a water excess condition is the nitrogen biological fixation, consequently, there is little nitrogen accessibility for the plant (GARCIA et al., 2020), because, under these conditions, the nodule decomposition occurs, which probably determines an atmospheric nitrogen fixation reduction (Taiz and Zieger, 2017).

This is clarified because plant processes that depend on the increase of cell volume are the most sensitive to water stress, LA depends on cell growth, and leaf gas exchange (transpiration and CO_2 assimilation) depends on the volume of the guard cell (Taiz and Zieger, 2017). Instead, a reticence of these processes can cause a considerable productivity reduction (dry mass) and production quality. The more available water in the environment, the less the plant transpires and therefore spends less energy on gas trade, which contributed to dry mass accumulation (Taiz and Zieger, 2017).

From a physiological point of view, the more the plant transpires, the more energy it employs and, consequently, the net photosynthesis is lower, demonstrating that in flooding or hypoxia conditions soybean plants' biomass production declines (Zhou et al., 2020).

When responding to excessive soil water conditions, two main alterations occur in plants: low oxygen quiescence syndrome (LOQS) and low oxygen escape syndrome (LOES) (Bailey-Serres an Voesenek, 2008; Colmer and Lacj, 2009). The characteristics of LOES comprise rapid growth of stems, internodes, and petioles under flooding conditions, and this physical alteration allows plants to rapidly reach the water surface and restore gas exchange between plant tissues and the atmosphere. For example, this mechanism occurs in irrigated rice (Bailey-Serres and Voesenek, 2008).

Significant drops in plant photosynthetic rate also occurred in the sunflower crop 48 hours after excess water application (Grassini et al., 2007; Loose et al., 2017, 2019).

The first plants' symptoms triggered by water excess are stomatal closure and photosynthesis rate reduction (Oosterhuis et al., 1990; Taiz and Zieger, 2017), this behavior was observed at the end of the experiment with water excess in both cultivars and sowing dates studied (Figure 8A, 8B). In plants under water excess stress, there was an important photosynthesis rate decrease, observed by the control and the treatments response to flooding, where even after 7 days of drainage the plants did not return to normal condition, showing a photosynthesis rate diminution.

Coffee sprouts exposed to intermittent and continuous waterlogging suffered strong decreases in environment gas exchange, such as net photosynthesis, stomatal conductance, and leaf transpiration (Silveira et al., 2011), as observed in this work.

According to Vartapetian and Jackson (1997), stomatal closure is a premature reaction of the plant to water stress. Roots are incapable to meet the plant leaves water demand due to cellular anoxia.

The plants' water condition is closely linked to the vital plant physiological processes. Processes such as transpiration, photosynthesis, respiration, and growth are significantly induced by changes in the water status of the leaves (Taiz and Zieger, 2017).

The practical application of this study for soybean producers in lowlands is that when the soil is water-logged, drainage should be performed, and when possible, sowings should be complete in October due to the lower minimum air temperatures that could lead to less plant stress potentiation effect.

4.5 CONCLUSIONS

The cultivar NA 5909 was more sensitive to water excess on flooding days for plant height, dry matter, and leaf area variables.

When plants were exposed to 24 days of water excess (12 days + 7 drainage + 12 days) during the development cycle, the greatest reduction in leaf area, total chlorophyll content and shoot dry mass occurred.

For each group (3, 6, 9, and 12) days of flooding evaluated, it was observed that when plants were exposed to a second flood, they performed worse than when forced into a single water stress episode, which validates that no acclimatization occurred, for the two cultivars and sowing dates planned.

Maximum photosynthesis, stomatal conductance, and foliar transpiration in both cultivars and two sowing dates were inferior compared to the control, with a superior reduction in treatments with 3 days of excess water (T2, T3, and T4).

The second sowing time potentiated the effect of water stress on soybean plants due to the higher minimum and maximum air temperature values compared to the first sowing time.

4.6 SUPPLEMENTARY MATERIAL

The authors declare no conflict of interest.

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5. ARTIGO 3

Logistic growth model of soybean cultivars subjected to flooding days[3]

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[3] Artigo formatado nas normas da revista Agriambi

Logistic growth model of soybean cultivars subjected to flooding days

ABSTRACT: The occurrence of excess water is recurrent in the Rio Grande do Sul (Brazil) state, being short or long-lasting, and the period between October and December is the one with the highest influence and intensity of the El Niño Southern Oscillation (ENSO) phenomenon in the state. In flat relief regions that receive a considerable rainfall volume, excess water is common, consequently reducing plant growth and grain productivity. The study aimed to assess the adjustments of the logistic model to leaf area growth variable, as a function of accumulated growing degree days after the emergency, in different soybean cultivars and seeding dates in two agricultural years exposed to flood days. The experiment carried out was a tri-factorial; two sowing seasons (October and November), two soybean cultivars (TEC IRGA 6070 RR and NA 5909 RG), and 10 and 13-day flooding periods, in two agricultural years 2018/2019 and 2019/2020. The experimental design was completely casualized with four repetitions, each repetition comprising a 7 liters capacity container with one plant. The first flood was set when the plants were between V6 and V7. The logistic model was adjusted to the dependent variable (leaf area), based on accumulated degree days. The leaf area was reduced in excess water treatments compared to the control, due to the anaerobic stress caused to plants. Treatments that received two floods during the development cycle had a lower accumulated leaf area in both cultivars and seeding seasons.

Key words: *Glycine max* L., logistic model, leaf area, water stress, sowing dates

Modelo de crescimento logístico de cultivares de soja submetidas a dias de inundação

RESUMO: A ocorrência de excesso hídrico é frequente no Rio Grande do Sul, sendo de curta ou longa duração, e o período entre outubro e dezembro é o de maior intensidade de influência do fenômeno ENOS no estado. Em regiões que recebem um grande volume de chuvas e de relevo plano, é comum a ocorrência de excesso hídrico, o que reduz consequentemente, o crescimento da planta e a produtividade de grãos. O objetivo foi avaliar os ajustes do modelo logístico à variável de crescimento, área foliar, em função dos graus-dias acumulados após a emergência, em diferentes cultivares de soja e datas de semeadura em dois anos agrícolas submetidas a dias de inundação. O experimento realizado foi um trifatorial, sendo duas épocas de semeadura (outubro e novembro), duas cultivares de soja (TEC IRGA 6070 RR e NA 5909 RG) e 10 e 13 dias períodos de inundações, nos anos agrícolas 2018/2019 e 2019/2020. O delineamento experimental foi o inteiramente casualizado com quatro repetições, cada repetição constituindo-se de um vaso com capacidade de 7 litros com uma planta. A primeira inundação foi imposta quando as plantas estavam entre V6 e V7. O modelo logístico foi ajustado à variável dependente área foliar, em função dos graus-dias acumulados. A área foliar foi reduzida nos tratamentos em excesso hídrico comparado à testemunha, devido ao estresse que a anaerobiose provoca nas plantas. Os tratamentos que receberam duas inundações durante o ciclo de desenvolvimento tiveram a menor área foliar acumulada em ambas as cultivares e épocas de semeadura.

Palavras-chave: *Glycine max* L.; Modelo logístico. Área foliar. Estresse hídrico. Datas de semeadura.

5.1 INTRODUCTION

In the last 10 years, due to amplified weed pressure coupled with abnormal rice production budgets, farmers began to introduce soybeans to the old-fashioned continuous irrigated rice cultivation system in southern Brazil (THEISEN et al., 2017, ULGUIM et al., 2018, RIBAS et al., 2021 a, b) and in subtropical and temperate regions such as Uruguay (PUIG et al., 2020). The main challenge of growing soybeans in rotation with irrigated rice is related to soils that have reduced usual drainage and are subject to the occurrence of temporary periods of flooding, especially after severe rainfall events (ZANON et al., 2018; SARTORI et al., 2018; SARTORI et al., 2016a, b; MUNDSTOCK et al., 2018). These strong precipitation events are common in the Rio Grande do Sul state, Brazil, in early spring, a period that coincides with soybean crop sowing (BORTOLUZZI et al., 2021a, b; TAGLIAPIETRA et al., 2021).

Meteorological elements, mainly air temperature and solar radiation, similarly influence the intensity of water stress in crops, amplifying or deferring its effect on plants (BERGAMASCHI; BERGONCI, 2017). Therefore, understanding plant ecophysiology in environments prone to flooding is important, principally, for the identification of more tolerant cultivars and the adoption of management approaches to mitigate damage caused by excess water in the soil.

An evaluation of the growth and development of soybeans exposed to excess soil water content in different environmental conditions and plant cycle phases will be valuable to understand boundaries and essentially to point out management strategies to strengthen the soybean and rice rotation system. In this sense, growth models can be useful in illustrating the differences in the growth of soybean cultivars subjected to flooding days.

Modeling the plant growth and development processes means presenting a synthesis of the physical and biochemical mechanisms amid the plant and the environment, characterizing them through mathematical functions (SETYIONO et al., 2007). Plant growth analysis is a methodology that assesses the physiological bases of production and the impact of genetic, agronomic, and environmental variables (SILVA et al., 2000). Evaluating plant growth during crop phases is significant, as it allows categorizing the intrinsic characteristics of each studied cultivar and choosing those that present the required features.

The analysis of data from growth models has the economic and administrative advantage of understanding how the crop grows and how these factors react to environmental conditions or experimental treatments LÚCIO et al., 2015; LÚCIO et al., 2016a). These models are usually communicated through growth curves, and when adjusted to weight, height, length, and other important quantitative characteristics over time, they allow the amalgamation of many measurements and information in just a few parameters of biological interpretation. (LÚCIO et al., 2015; LÚCIO et al., 2016a; LÚCIO et al., 2016b). To model this sort of answer, the literature presents several empirical growth models (SEBER; WILD, 2003), which describe plant growth based on the observation of the plant itself, linking the variables deprived of reference to processes that may be associated. The logistic model has been extensively used to describe the production of numerous vegetables such as pumpkin and pepper (LÚCIO et al., 2015), green beans (LÚCIO et al., 2016a) cherry tomato (*Lycopersicon esculentum* L. var. Cerasiforme) (LÚCIO et al., 2016a; 2016b) and soybeans (GASO et al., 2021).

Some works in the literature address soybean growth models in upland areas; however, for floodplain areas (lowlands), this information is still narrow, which encourages this work. Plant growth models deliver significant approximations for agronomical research, helping to understand critical points of plant development restricted to biotic and abiotic stresses, which contributes to crop decision-making.

Thermal sum (TS) is commonly used to model plant growth because it has a biotic impact on plants. TS considers the influence of air temperature on plant growth and development (MCMASTER; SMIKA, 1988). In addition to this, using the accumulated thermal sum, it is possible to obtain pertinent information and identify possible crop development problems. Therefore, the objective of this study was to evaluate the adjustments of the logistic model to the leaf area as a function of the accumulated growing degree-days after emergence, in different soybean cultivars subjected to flooding and sowing dates in two agricultural years.

5.2 MATERIALS AND METHODS

The experiment was conducted in two agricultural years (S1: 2018/2019 and S2: 2019/2020), with two sowing dates each year - YEAR 1: E1 (10/12/2018) and E2 (11/28/2018) and YEAR 2: E1 (10/12/2019) and E2 (11/30/2019). Two soybean cultivars with a relative maturity group

(RMG) close to 6.0 were used, one of the most cultivated in southern Brazil [Cultivar 1, NA 5909 RG GMR 6.2 (C1)] and another classified as tolerant to excess water stress (EWS) [Cultivar 2, TEC IRGA 6070 RR-GMR 6.3(C2)] (MUNDSTOCK et al., 2018). The experiment was carried out in a greenhouse with a synthetic translucent polyethylene cover located in the experimental area of the Department of Plant Science of the Federal University of Santa Maria, Santa Maria, Rio Grande do Sul state, Brazil (latitude: 29º 43’S, longitude: 53º 43 'W and altitude: 95 m). According to the Köppen classification, the climate of the region is Cfa, which means humid subtropical without a well-defined dry season with hot summers (KUINCHTNER; BURIOL, 2001).

The experimental design was completely randomized with four replications, each replication comprised of a plant grown in a 7 liters capacity plastic pot filled with soil. The experiment was implemented in a trifactorial statistical arrangement as follows: two sowing seasons (E1 and E2), two soybean cultivars (C1 and C2), and 10 flood periods (2018/2019 agricultural year) and 13 (2019/2020 agricultural year) flooding periods (Table 1).

Table 1. Description of excess water treatments used for soybean cultivars

		Treatments	
1	Control		
2	Imposition of 3 flood days		
3	Imposition of 3 flood days +	7 days drainage +	Imposition of 3 flood days
4			Imposition of 3 flood days
5	Imposition of 6 flood days		
6	Imposition of 6 flood days +	7 days drainage +	Imposition of 6 flood days
7			Imposition of 6 flood days
8	Imposition of 9 flood days		
9	Imposition of 9 flood days +	7 days drainage +	Imposition of 9 flood days
10			Imposition of 9 flood days
11	Imposition of 12 flood days		
12	Imposition of 12 flood days	7 days drainage +	Imposition of 12 flood days
13			Imposition of 12 flood days

* Agricultural year 2018/2019: T1 to T10; agricultural year 2019/2020: T1 to T13.

Due to the results of the S1 experiment, we decided to impose EWS for a longer period of days. Consequently, in S1, up to 9 days of EWS were studied, and in S2 12 days, there were 10 and 13 EWS periods for S1 and S2, respectively.

Five seeds, previously treated and inoculated with *Bradirizobium elkani*, were sown per pot at a 3 cm sowing depth, and after emergence, thinning was performed to keep only one plant per pot. The spacing between the pots was 10 cm and between the rows was 40 cm. The outside walls of the pots were white painted to disparage the solar radiation absorption. The soil used in the experiment came from the upper layer of the experimental site (from 0 to 20 cm) of a HAPLIC GLEISSOLO: Ta typical dystrophic (Typic Albaqualf) with 22% clay. Soil acidity and nutrient corrections were completed according to laboratory analysis and local soybean recommendations (SILVA; GATIBONI, 2016).

When the plants were subjected to EWS, pots were separately positioned inside larger containers (buckets), and then water was added, preserving a constant depth of 5 cm above ground level. For each EWS treatment, the same number of plant repetitions was maintained, for each flood period, in the control condition with 90% field capacity. Maintenance irrigation on the control plants was performed using the weighing method, in which the pot was weighed when it was at field capacity [100% of soil water storage capacity (WSC)] and then daily weighing to quantify consumption. The replacement was daily aiming to reach at least 90% of the WSC.

The first flood was inflicted when the plants were between V6 and V7. To evaluate the acclimatization potential of soybean cultivars to EWS, treatments that were submitted to a second flood were drained for seven days after the first flood and then flooded again. The moment the treatments were flooded again, there was a treatment group that received the first flood.

Air temperature during the experimental period was collected using a thermo-hygrometer (Instruthem® HT-500) with a datalogger coupled to a mini shelter located inside the greenhouse.

Leaf area (LA) was estimated using Richter's et al. (2014) model using the equation ((C*L) *2.0185) (1), where C and L are the length and width of the central leaflet. All leaves of each plant were measured. The LA of each plant was calculated by the sum of the LA of all the leaves of the plant.

All these calculations were carried out on the day of EWS (before flooding), on the day of drainage (before draining), on the day of the second flood, on the day of the second drainage, and 7 days after the last drainage.

To determine the accumulated growing degree-days needed for the soybean crop, the following model was used:

$$GDD = \sum_{i=1}^{n} \left(T_{m,1} - T_b \right) \text{ (2)}$$

where: GDD (°C) represents the accumulated growing degree-days; Tm (ºC) is the average air temperature of day i, with i ranging from 1 (emergence date) to n days (harvest) and Tb (ºC) is the basal temperature. Tm was determined by the extremes of daily air temperature [(Tx + Tn)/2], where Tx and Tn (ºC) are, respectively, the maximum and minimum daily air temperatures. Tb = 7.6°C was adopted (SETYONO et al., 2007). The logistic model was adjusted to the dependent variable LA, as a function of the GDD as follows:

$$Y_i = \frac{\beta_1}{1+e^{\beta_2 - \beta_3 t_i}} + \varepsilon_i \text{ (3)}$$

where Yi is the dependent variable (LA, cm^2); ti is the independent variable (GDD, °C); β1 is the horizontal asymptote, e.g. the total LA production when ti $\rightarrow +\infty$; β2 is the parameter that indirectly reflects the distance (with the abscissa) between the initial value and the inflection point; β3 is the parameter that reflects the increase in the production rate; and εi is the random error assumed to be independent, identically and normally distributed εi $\sim$ N(0,σ2).

The models were generated from a planned experiment (December) with a trifactorial adjustment for S1 and S2, the estimation parameter was obtained using the ordinary least squares (OLS) method using the Gauss-Newton algorithm. The normality, heteroscedasticity, and independence of the residues were verified by the Shapiro-Wilk (SHAPIRO; WILK, 1965), Breusch-Pagan (BREUSCH; PAGAN, 1979), and Durbin-Watson (DURBIN; WATSON, 1950) tests, respectively. The goodness of fit was evaluated by the coefficient of determination (R^2) and by the Akaike information criterion (AIC). R^2 close to one and lower AIC values indicated a good fit of the model to the data.

5.3 RESULTS AND DISCUSSION

In S1 and S2, the maximum LA occurred at the beginning of the reproductive period (R1-R3), with accumulated GDD of 1800 ° C and 1000 ° C, respectively. The EWS promoted the reduction of LA in E1, E2, C1, C2, S1, and S2. In S1, the EWS treatments that had the smallest accumulation of LA in both cultivars and sowing dates were T3, T6, and T9 (Figure 1). These treatments received two floods during the development cycle, which corroborates that when the soybean does not become acclimatized when it is reimposed to an EWS event, there is a LA reduction. Garcia et al. (2020) also defined the effect of flooding on the physiology and metabolism of leaves from five soybean genotypes during and after EWS, expressing late growth in terms of flowering and an important reduction in leaf gas exchange (photosynthesis, stomatal conductance and leaf transpiration).

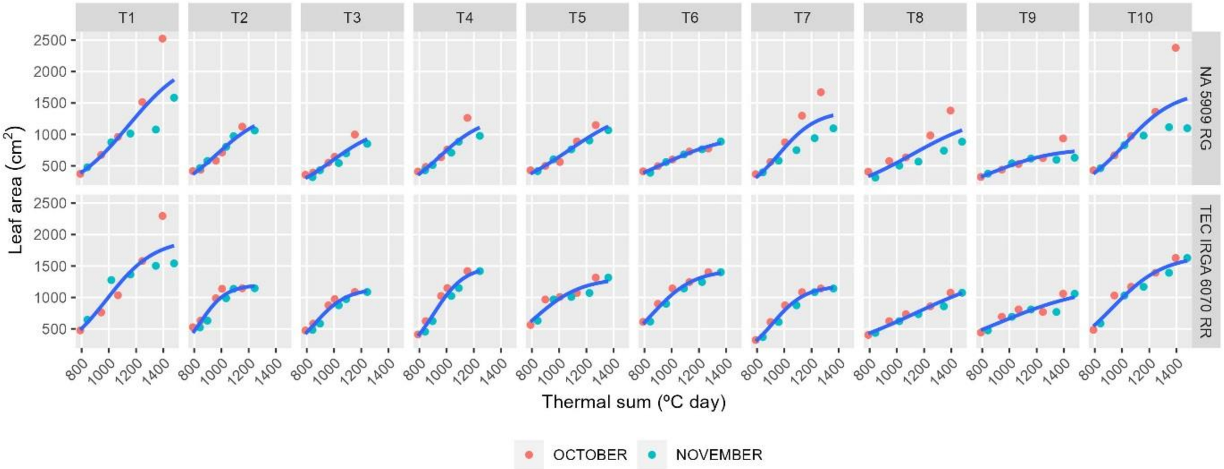

Figure 1. Relationship between leaf area (cm²) and accumulated thermal sum (°C day^{-1}) in excess water treatments in two soybean cultivars: 'NA 5909 RG' (C1), 'TEC IRGA 6070 RR' (C2) and sowing times (E1 - October and E2 - November) in the 2018/2019 season

In S2 (Figure 2) the treatments (T3, T6, T9, and T12) that received two floods during the development cycle also had the lowest accumulation of LA, and this answer was comparable between C1 and C2.

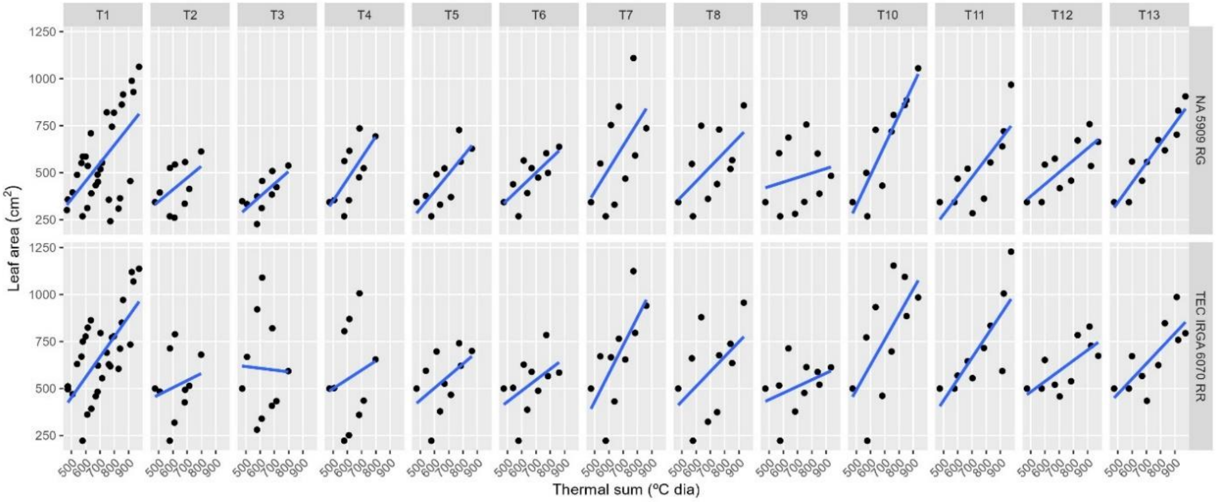

Figure 2. Relationship between leaf area (cm²) and accumulated thermal sum (°C day^{-1}) in excess water treatments in two soybean cultivars: 'NA 5909 RG' (C1), 'TEC IRGA 6070 RR' (C2), in the 2019/2020 agricultural year

When analyzing season and cultivar interaction, we can observe that for both C1 and C2, the highest LA production occurred in S2 (Figure 3), with approximately 900 and 1000 cm^2 of leaf at 1000 °C day of the thermal sum for C1 and C2, respectively. This is because the maximum air temperatures in December and January were higher than the maximum air temperatures of the plants seeded in October, which stimulated superior plant growth. On the other hand, E1, for having milder temperatures in October and November, had the maximum LA production of 600 cm².

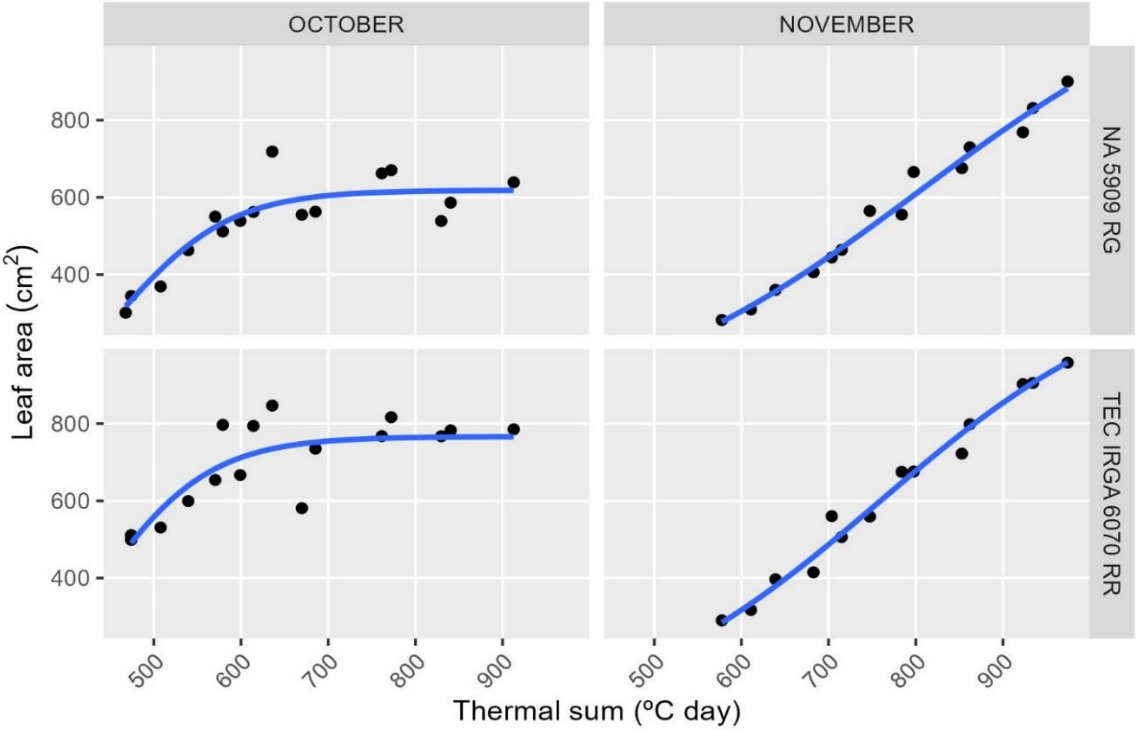

Figure 3. Relationship between leaf area (cm²) and accumulated thermal sum (°C day^{-1}), on two sowing dates (E1 - October and E2 - November) and soybean cultivars: NA 5909 RG (C1), TEC IRGA 6070 RR (C2), in the 2019/2020 season

The parameter β1 represents the estimated asymptote and is the point at the ordinate where the curve stabilizes. Changes in β1values change the value of the ordinates, the production, and acceleration rates, moving them up or down, but do not distress the moment (abscissa) at which these points occur. In practical terms, β1 may be related to the total production of the crop.

Analyzing the confidence intervals of the β1 parameter, in C1, treatments T5, T8 and T10 were equal to the control for LA production (Figure 4), indicating that EWS at 6 or 9 days between V6-V7 or 9 days in the reproductive phase does not imply a decrease in LA. In C2, only in treatments that received 9 days of EWS, leaf production did not reduce compared to the control, even when it received two EWS impositions (T9).

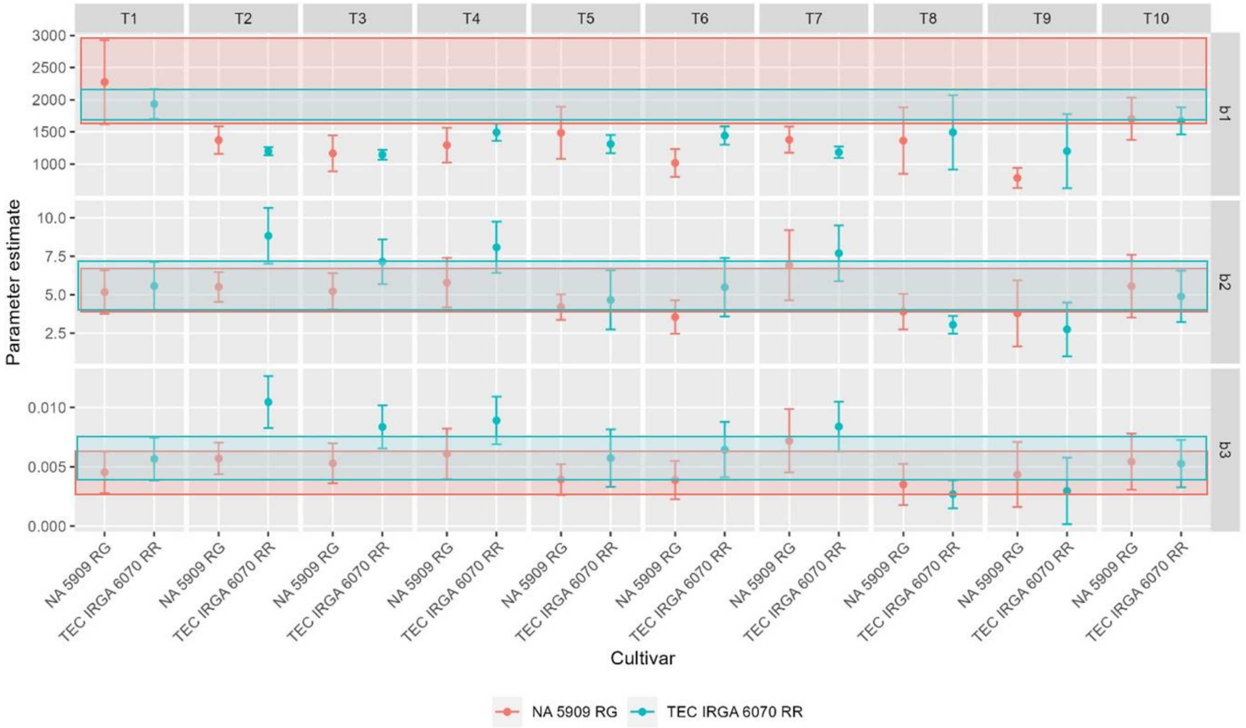

Figure 4. Parameter estimates for the Cultivar X Treatment interaction based on the logistic model adjusted to the leaf area and the accumulated thermal sum for treatments with excess water stress, in the 2018/2019 season. Cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR)

In a study by Bem et al. (2018), the β2 parameter is considered not to have a direct biological/practical explanation, but, when the β2 value is inferior, LA is reached earlier, representing greater plant growth. The parameter β3 is related to the production rate. Greater values of β3 increase the model curve slope and characterize the point between maximum and minimum acceleration of the LA growth. In practice, β3 can be used to understand how early the production was and how long this production was strong.

When analyzing the β2 parameter for C1, there is no statistical difference in the confidence interval of T1 with the other treatments, indicating that the maximum LA is reached in the same period, demonstrating a similar growth for all treatments. In C2, only T2 varied from T1, this higher value validates that the maximum LA was reached later, indicating a lower plant growth degree. The β3 value for C1 was statistically equal for all treatments and C2 only diverged for T2, showing that the leaves production was deferred for these plants.

The slope means the LA increase for each unit change in x (GDD). For T1 in both cultivars, the angular coefficient was 1, which means an LA increase of 1 cm2 for each accumulated GDD (Figure 5). Treatments that have an angular coefficient less than or equal to zero reduced LA production with respect to control. In S2, in which treatments were added and plants received 12 days of EWS, in C1 only treatments T9, T10, and T12 statistically differed from the control in the accumulated LA. In T9 and T12, LA was reduced for each accumulated GDD in the control and in T10 the increase was superior to the control, this treatment was the least affected by the EWS for leaf production.

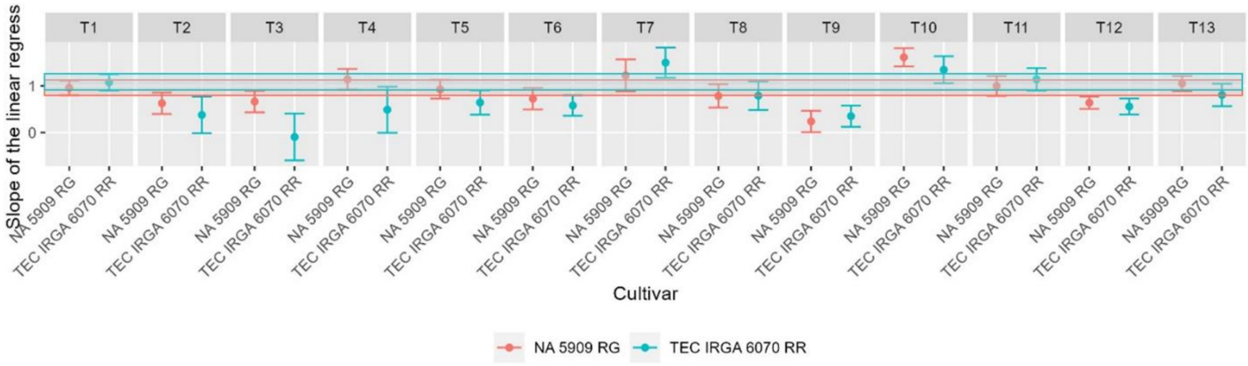

Figure 5. The angular coefficient for the Cultivate x Treatment interaction based on the logistic model adjusted to the leaf area and accumulated thermal sum for excess water stress treatments, in the 2019/2020 season. Cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR)

In C2, leaf production significantly reduced concerning the control in treatments T3, T9, and T12, although treatments T9 and T12 received 9 and 12 EWS days for two moments, T3 showed the greatest reduction in leaf production due to plant precociousness (V8). LA depends on cell growth, and leaf gas exchange (transpiration and CO_2 assimilation) depends on the volume of the guard cell (TAIZ; ZEIGER, 2017). Inhibition of these processes can cause a substantial LA reduction.

When analyzing the interaction of E * C (Figure 6) it is observed that the total leaf (β1) for both cultivars was significantly higher in E2, reaching around 1250 cm^2 of leaves, while in E1 C1 produced 550 cm^2 of leaf and C2 750 cm^2. This is because in E2 the plants were exposed to higher average air temperatures, which favored higher plant growth. The solar radiation availability and the dominant air temperature during a soil saturation period can interrupt or amplify the effects of EWS on the plant (BERGAMASCHI; BERGONCI, 2017; TAIZ; ZEIGER, 2017). This is because when the plant is under EWS, respiration is already affected by the lack or deficit of O_2 in the soil, and higher air temperatures rise respiration rates even more. Plant respiration efficiency is affected at high temperatures due to compromise or injury to the plant's enzymatic machinery due to membrane and organelles disturbance. Temperature is a factor of great influence on respiration, particularly throughout plant development's early stages (TAIZ; ZEIGER, 2017). In this sense, the plant will employ more energy in this process, reducing its growth, and development and consequently affecting productivity.

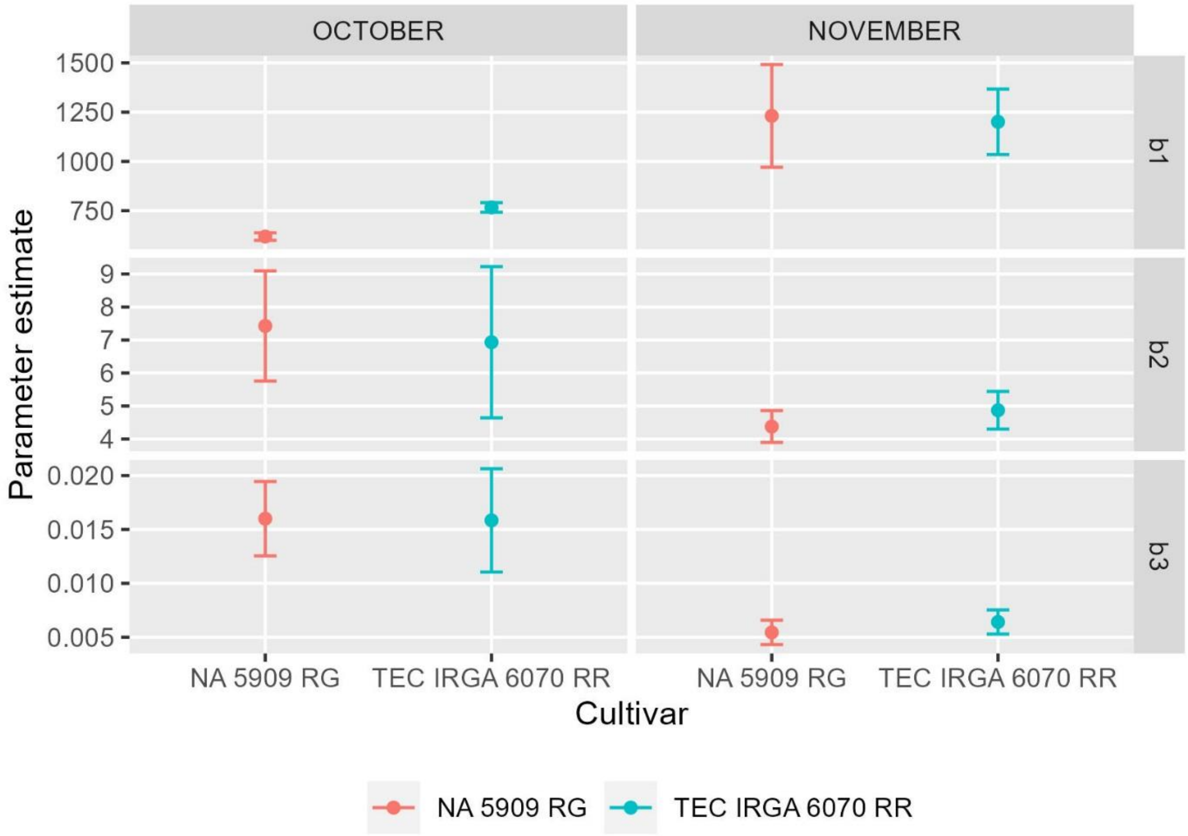

Figure 6. Parameter estimates for the Season x Cultivar interaction based on the logistic model adjusted to the leaf area and accumulated thermal sum. Cultivars 1 (C1 - NA 5909 RG) and 2 (C2- TEC IRGA 6070 RR) in sowing seasons 1 (E1 - October) and 2 (E2 - November) in the agricultural year 2019 / 2020

When the β2 parameter 2 is analyzed in E1, the values are higher than in E2 for both cultivars, which establishes that the maximum LA was reached later, indicating a lower degree of plant growth. The same pattern was observed for the β3 parameter, indicating that due to the lower average air temperatures in E1, leaf production was later for these plants.

An interesting aspect of growth models is that their parameters have a biological explanation that can be used to define and associate the growth behavior of living organisms. As parameters can be used to clarify productive conduct, the bias assessment, and if necessary, bias correction, in parameter estimates is critical. Soybean models such as SOYSIM and SOYDEV (SETYIONO et al., 2007; 2010) and CROPGRO-Soybean (BOOTE et al., 1998) usually do not present adjustment for EWS conditions (lowlands soybeans), so these results may be valuable to be combined into these process-based models, which is very significant given the soybean-irrigated rice intensive crop rotation agricultural model systems in Southern Brazil.

Using the logistic model (but not restricted to it), it is shown that lower β2 values are linked to an earlier maximum production rate and higher β3 values are related to earlier and concentrated in fewer days of production. These models provide key approximations for agronomic research, helping to infer critical points of plant growth limited to water excess, which contributes to decision-making in agricultural management.

5.4 CONCLUSION

1. The logistic model was adjusted to the leaf area variable, as a function of the accumulated growing degree-days.

2. Through the accumulation of growing degree-days, by the relationship with mean air temperature, leaf area can be modeled.

3. LA was reduced in the treatments in EWS compared to the control, due to the stress caused by anaerobiosis in plants.

4. Treatments that received two floods during the development cycle had the lowest accumulated leaf area in both cultivars and sowing dates.

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6. DISCUSSÃO GERAL

O produtor rural deve ficar atento às previsões meteorológicas e a possibilidade de encharcamento do solo, evitando assim, a semeadura da cultura da soja, pois independente do ano de cultivo não há germinação e emergência de plântulas de soja em um ambiente anaeróbico. Se ocorrer excesso hídrico durante a fase de germinação da cultura da soja o produtor corre sérios riscos de ter que fazer a ressemeadura da área. Além disso, ocorrem falhas nas lavouras, o que explica a produtividade da soja em terras baixas (1,8 Mg ha^{-1}) ser 30% menor que a de terras altas (3,4 Mg ha^{-1}).

Em lavouras de soja em terras baixas os produtores devem planejar e investir em sistemas de drenagem para reduzir riscos de excesso hídrico no solo, principalmente na fase de plântula (VE-V4) por ser o período de maior susceptibilidade. Destaca-se que mesmo não tendo ocorrido morte de plantas após a emergência, em condições de lavoura o rompimento da epiderme devido a formação de aerênquima, facilita a entrada de fungos de solo que são os responsáveis pela morte de plantas em lavouras de soja em rotação com arroz irrigado. A partir de V4 a soja tem uma maior tolerância ao excesso hídrico, porém ocorrem perdas significativas no potencial de produtividade da planta em virtude do ambiente anaerobiótico induzir a planta a realizar metabolismos com maior ganho energético.

As plantas de soja quando submetidas ao excesso hídrico ficam em condição de estresse pois se encontram em um ambiente hipóxico, e na tentativa de encontrar um ambiente com maior disponibilidade de O_2 sofrem alterações morfofisiológicas. Isso é observado pelo engrossamento e rachadura na base da haste principal, formação de raízes adventícias e formação de aerênquimas. Além disso, há um menor teor de clorofila total na folha e maior senescência das folhas da planta, e quanto maior o período de dias em excesso hídrico maior a intensidade destes sintomas na cultura da soja. Por isso, quando a cultura ficou exposta a 24 dias de excesso hídrico ao longo do ciclo de desenvolvimento (12dias + 7 drenagem + 12 dias) demonstrou o pior desempenho para as variáveis analisadas de crescimento e desenvolvimento. É importante ressaltar também que quando a soja foi submetida a uma segunda inundação ela apresentou um desempenho pior do que quando somente imposta a um único evento de estresse hídrico, o que demonstra não ter aclimatação.

Semeaduras que ocorrerem no mês de outubro pelas menores temperaturas do ar, em relação a novembro, tem menor efeito sobre a potencialização do estresse hídrico na planta. A disponibilidade de radiação solar e a temperatura do ar predominantes durante um período de saturação do solo podem retardar ou maximizar os efeitos do excesso hídrico na planta. Isso em razão de que quando a planta está sob excesso hídrico a respiração já está afetada pela ausência ou deficiência de O_2 no solo, e temperaturas do ar mais elevadas aumentam ainda mais as taxas respiratórias. A eficiência da respiração da planta é afetada sob altas temperaturas devido ao comprometimento ou danos a maquinaria enzimática da planta em consequência do rompimento das membranas e das organelas. A temperatura é um fator de grande influência na respiração principalmente durante os estádios iniciais de desenvolvimento da planta. Nesse sentido, a planta vai gastar mais energia ainda nesse processo, reduzindo seu crescimento, desenvolvimento e consequentemente a produtividade de grãos.

É importante também que os produtores de soja de áreas de várzea analisem a tolerância genética das cultivares de soja ao excesso hídrico antes de realizarem a escolha da cultivar, pois a tolerância genética influencia diretamente o potencial de crescimento, desenvolvimento e produtividade de grãos da soja em condições de excesso hídrico.

A ocorrência de excesso hídrico é frequente no estado do Rio Grande do Sul, sendo de curta ou longa duração, e o período entre outubro e dezembro é o de maior intensidade de influência do fenômeno ENOS no estado. Em anos de El Niño é comum regiões com relevo ondulado apresentarem excesso hídrico de curta duração após chuvas em dias consecutivos, enquanto regiões mais planas (terras baixas) estão sujeitas a períodos mais prolongados de saturação do solo. Em regiões que recebem um grande volume de chuvas e de relevo plano, é comum a ocorrência de excesso hídrico, o que pode reduzir, consequentemente, a produtividade de grãos.

7. CONCLUSÕES

A fase mais sensível ao excesso hídrico para as cultivares de soja é a SE-EM.

Após a emergência das plantas, a fase V2-V4 apresentou maior redução de AF e MS nas duas cultivares, épocas de semeadura e anos estudados. A partir de V4 a cultura da soja tem uma maior tolerância ao excesso hídrico.

A cultivar TEC IRGA 6070 RR apresentou uma maior tolerância ao excesso hídrico após a emergência das plantas.

A disponibilidade de radiação solar e a temperatura do ar ocorrentes durante um período de saturação do solo podem retardar ou maximizar os efeitos do excesso hídrico na planta. Semeaduras no mês de outubro, pela menor temperatura do ar e disponibilidade de radiação solar, tendem a ter menor efeito do excesso hídrico na planta em comparação às de novembro.

A cultivar NA 5909 se mostrou mais sensível ao excesso hídrico em dias de inundação para as variáveis estudadas estatura de plantas, massa de matéria seca, área foliar e número de nós.

O tratamento que demonstrou o pior desempenho foi o T12 (12dias + 7 drenagem + 12 dias) para as variáveis AF, teor de clorofila total e MS.

Para cada grupo (3, 6, 9 e 12) dias de inundação avaliado observou-se que quando a soja foi submetida a uma segunda inundação ela apresentou um desempenho pior do que quando somente imposta a um único evento de estresse hídrico, o que demonstra não ter aclimatação, para as duas cultivares e épocas de semeadura estudadas.

A fotossíntese máxima, condutância estomática e a transpiração foliar das cultivares de soja nas duas épocas de semeadura foram reduzidas em relação à testemunha, com maior redução nos tratamentos com 3 dias de excesso hídrico (T2, T3 e T4).

A segunda época de semeadura potencializou o efeito do estresse hídrico sobre a soja devido as temperaturas mínimas e máximas do ar mais elevadas.

O modelo logístico se ajustou à variável área foliar, em função dos graus-dias acumulados.

A área foliar pode ser estimada a partir de modelos de relação com a temperatura média do ar, através do acúmulo de graus-dia.

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