UNIVERSIDADE ESTADUAL DO MARANHÃO - UEMA
CENTRO DE CIÊNCIAS AGRÁRIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM AGROECOLOGIA

LORENA SILVA CAMPOS

RESPOSTAS ECOFISIOLÓGICAS EM MILHO CULTIVADO COM GESSO E BIOMASSA DE LEGUMINOSA EM UM AGROSSISTEMA TROPICAL

SÃO LUÍS - MA
2020

LORENA SILVA CAMPOS

Engenheira Agrônoma

RESPOSTAS ECOFISIOLÓGICAS EM MILHO CULTIVADO COM GESSO E BIOMASSA DE LEGUMINOSA EM UM AGROSSISTEMA TROPICAL

Dissertação apresentada à Universidade Estadual do Maranhão, como parte das exigências do Programa de Pós-Graduação em Agroecologia, para obtenção do título de Mestre em Agroecologia.

Orientador: Prof. Dr. Tiago Massi Ferraz

SÃO LUÍS - MA
2020

Campos, Lorena Silva.

Respostas ecofisiológicas em milho cultivado com gesso e biomassa de leguminosa em um agrossistema tropical / Lorena Silva Campos. – São Luís, 2020.

65 f.

Dissertação (Mestrado) – Curso de Agroecologia, Universidade Estadual do Maranhão, 2020.

Orientador: Prof. Dr. Tiago Massi Ferraz.

1.Biomassa de leguminosa. 2.Manejo do solo. 3.Fotossíntese. 4.Milho. 5.Adaptação às mudanças climáticas. I.Título.

CDU: 633.15

UNIVERSIDADE ESTADUAL DO MARANHÃO - UEMA
CENTRO DE CIÊNCIAS AGRÁRIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM AGROECOLOGIA
LORENA SILVA CAMPOS

RESPOSTAS ECOFISIOLÓGICAS EM MILHO CULTIVADO COM RESÍDUOS DE LEGUMINOSAS E GESSO EM UM AGROSSISTEMA TROPICAL

Dissertação apresentada à Universidade Estadual do Maranhão, como parte das exigências do Programa de Pós-Graduação em Agroecologia, para obtenção do título de Mestre em Agroecologia.

Orientador: Prof. Dr. Tiago Massi Ferraz

Aprovado em: 14 / 08 / 2020

BANCA EXAMINADORA

Tiago Massi Ferraz
Prof. Dr. Tiago Massi Ferraz (Orientador)
Universidade Estadual do Maranhão – UEMA

Emanoel Gomes de Moura
Prof. Dr. Emanoel Gomes de Moura (Membro 1)
Universidade Estadual do Maranhão – UEMA

Weverton Pereira Rodrigues
Prof. Dr. Weverton Pereira Rodrigues (Membro 2)
Universidade Estadual da Região Tocantina do Maranhão - UEMASUL

AGRADECIMENTOS

A Deus, Gratidão !

Aos meus pais, Ana Celeste Silva Campos e Adelman Silva Campos por sempre me incentivarem;

Aos meus familiares, especialmente minhas tias Francy Maia e Conceição Maia;

Aos meus padrinhos Maria Raimunda e Vitorino Machado;

À minha irmã Larissa e meu querido sobrinho Ryan e meu irmão Leandro;

Ao meu companheiro, Luciano Barros, por todo apoio e incentivo;

A minha tia Cléa Fideles;

Ao professor e orientador Tiago Ferraz;

Ao professor Emanoel Moura;

À professora Kátia Coelho;

Ao professor João Reis, chefe do laboratório de Química;

À amiga e técnica do laboratório de Química, Kelen Ruth;

Ao professor Fabrício Reis pelo empréstimo dos aparelhos para a realização da pesquisa;

À Jéssica Freitas, Stéffany Portela, Virley Sena, Rones Castro, Maylson Cunha, Weydson Bello, Walisson Araújo, Luciene Souza, Gabriel Coelho, Edésio Rafael, Karina Pimentel, Tharcísio Campos, Mauriana Rocha, Tácila Marinho, Raysa Valéria, Francisneide Lourenço e Thiago Mendes pela amizade e cooperação nas atividades desenvolvidas;

À Rayanne Cristine, secretária do Programa de Pós-Graduação;

Ao Núcleo Geoambiental (NuGeo) da Universidade Estadual do Maranhão;

A Carlos Wendell pela cessão de dados climatológicos do NuGeo e esclarecimento de dúvidas;

Aos funcionários Neto, João e Renato pela ajuda na realização dos trabalhos em campo;

À Universidade Estadual do Maranhão (UEMA), ao Programa de Pós Graduação em Agroecologia (PPGA) e a Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

“*A menos que modifiquemos a nossa maneira de pensar, não seremos capazes de resolver os problemas causados pela forma como nos acostumamos a ver o mundo*”.

Albert Einstein

SUMÁRIO

LISTA DE FIGURAS

LISTA DE TABELAS

RESUMO

Os modelos climáticos consistentemente projetam aumentos na variabilidade da temperatura nos países tropicais nas próximas décadas, com a Amazônia como um ponto de preocupação. Os limites para os quais os sistemas agrícolas podem se adaptar ao aquecimento global dependem, em parte, das melhorias das propriedades físicas do solo que favoreçam o aumento da absorção de água e nutrientes. Utilizamos gesso e biomassa de leguminosa para melhorar a zona radicular do solo e nossa hipótese é que tais alterações podem melhorar as condições físicas do solo tropical propenso à coesão e aumentar as respostas ecofisiológicas no milho. O estudo teve quatro repetições dos seguintes tratamentos: controle (C), gesso (G), nitrogênio (N), biomassa de leguminosa (L), nitrogênio + gesso (NG), biomassa de leguminosa + gesso (LG) e biomassa de leguminosa + nitrogênio + gesso (LNG). Os tratamentos foram submetidas ao regime sequeiro em 2018 e irrigação em regime de restrição hídrica em 2019. Os resultados das melhorias nos atributos do solo tiveram efeitos positivos nas respostas ecofisiológicas do milho**,** com uma redução no estresse das plantas principalmente no índice de performance (PI_{abs}) que mostrou ser um índice sensível às adições de gesso e nitrogênio. Essas mudanças foram capazes de produzir diferenças na absorção de N, produção de biomassa e rendimento de grãos de milho, mesmo em regime de restrição de água. Sob regime de restrição de água, o rendimento de grãos de milho no tratamento LNG foi 41% maior do que no tratamento N e 151% maior do que no tratamento C. Além disso, a adição de nitrogênio diminuiu consideravelmente o estresse das plantas, com efeitos positivos nas respostas fisiológicas e no aumento da produção de biomassa. Esses resultados destacam o papel do nitrogênio em conjunto com a biomassa de leguminosa e o gesso na melhoria do solo, especialmente no contexto da adaptação às mudanças climáticas.

Palavras-chave: biomassa de leguminosa; manejo do solo; fotossíntese; milho; adaptação às mudanças climáticas

ABSTRACT

Climate models consistently project increases in temperature variability in tropical countries over the coming decades, with the Amazon a particular hotspot of concern. The extent to which agricultural systems can adapt to global warming depends in part on physical improvements to soil that enhance water and nutrient uptake. We use gypsum and leguminous residue to improve the soil root zone, hypothesizing that such changes may improve the physical conditions of tropical soil prone to hardness and enhance the ecophysiological responses in maize. The study consisted of four replicates using the following treatments: control (C), gypsum (G), nitrogen (N), legume residue (L), nitrogen + gypsum (NG), legume residue + gypsum (LG) and legume residue + nitrogen + gypsum (LNG). The study plots were rainfed in 2018 and used a restricted irrigation regime in 2019. The soil improvements studied had positive effects on the physiological parameters of maize, with a reduction in stress mainly in performance index (PI_{abs}) which indicated the sensitivity of maize plants to gypsum and nitrogen addition. More specifically, we observed changes in N uptake, biomass production and maize grain yield, even in the restricted irrigation regime. Under a restricted irrigation regime, maize grain yield in the LNG plots was 41% higher than in N plots and 151% higher than the C plots. Interestingly, additions of nitrogen considerably decreased plants stress, improving physiological parameters and increasing biomass production. These results highlight the role for added nitrogen alongside soil improvement measures such as leguminous residues and gypsum, especially in the context of climate change adaptation.

Keywords: legume residue; soil management; photosynthesis; maize; climate change adaptation.

CAPÍTULO I

1 INTRODUÇÃO GERAL

Com o aquecimento global é previsto que o rendimento das culturas nas regiões de clima tropical e subtropical seja reduzido como resultado de uma aceleração do desenvolvimento fenológico (TURNER e RAO, 2013). Modelos climáticos projetam diferenças nas características climáticas regionais entre os dias atuais e o aquecimento global de 1,5°C a 2°C. Essas diferenças incluem aumentos na temperatura média na maioria das regiões terrestres e oceânicas, nos extremos de calor na maioria das regiões habitadas, na ocorrência de chuva intensa em diversas regiões e na probabilidade de seca e déficits de chuva em algumas regiões (IPCC, 2019)

O déficit hídrico é a causa mais grave de redução da produção agrícola global e as mudanças climáticas tendem a agravar esse efeito. Além disso, existe o desafio de aumentar a oferta de alimentos nos cenários de estresse em cerca de 60% para atender o aumento da população mundial, que excederá 9 bilhões de pessoas até 2050 (GRASSINI et al., 2015). Com os adventos climáticos, o desenvolvimento da agricultura terá o desafio de buscar a economia de água e o aumento da eficiência do seu uso. Os ambientes tropicais que apresentam períodos de estiagem estão mais sujeitos a fatores estressantes, com a consequente diminuição da produção de biomassa (TURNER e RAO, 2013).

Outro fator de elevada importância que induz a diminuição e limita o crescimento e a produção das culturas é a baixa disponibilidade de nutrientes (VANCE et al., 2003). Em condições meteorológicas tropicais, devido à interação negativa entre a inadequada condição do solo e a alta demanda evaporativa da atmosfera, as culturas nem sempre alcançam seu potencial de produtividade, tornando esses agrossistemas inviáveis, favorecendo a insegurança alimentar (MOURA et al., 2013).

A maioria dos solos da região tropical não possui alta resiliência intrínseca à degradação física devido ao baixo conteúdo de elementos agregadores, como carbono, cálcio e magnésio (MOURA et al., 2018). Nesse solo, também conhecido como solo coeso (DANIELLS, 2012), as raízes das plantas podem explorar apenas uma fina camada superficial para sustentar o desenvolvimento e a produtividade das culturas. Portanto, a melhoria das propriedades físicas do solo para aumentar o aproveitamento da água no solo será crucial para diminuir o efeito deletério do aquecimento global sobre a produtividade das culturas na agricultura tropical (EBSA, 2019). O plantio direto com o uso de biomassa de leguminosas é um sistema em que utilizam-se ramos e folhas de leguminosas aplicados à superfície para inicialmente servir de cobertura e posterior retorno de nutrientes ao solo durante a decomposição (TSONKONVA et al., 2012). Essa camada protetora permite que o solo permaneça úmido reduzindo a evaporação a partir da superfície por mais tempo o que favorece a disponibilidade de água para as culturas e com isso possa aumentar a taxa fotossintética (KADER et al., 2019).

Segundo Kluge et al. (2015), o dióxido de carbono (CO_2) entra na folha ao mesmo tempo que a água, na forma de vapor, é perdida através dos estômatos da epiderme. Como planta C4, o milho (*Zea mays* L.) possui alta eficiência fotossintética mesmo com intensidade luminosa elevada. No entanto, quando ocorre o déficit hídrico, os estômatos se fecham para conservar água, reduzem a difusão de CO_2 nos locais de fixação no mesofilo foliar nas proximidades da enzima ribulose 1,5-bifosfato carboxilase oxigenase (Rubisco), o que diminui a fotossíntese pois esta é indiretamente afetada pela sensibilidade estomática e, assim, consequentemente poderá haver perdas na produtividade (SILVA et al., 2013). Entretanto, o rendimento em determinadas culturas, não depende apenas da taxa fotossintética, mas também do comprimento da fase ativa da fotossíntese das folhas e da capacidade de realocação para os grãos (FUHRER, 2003). Boretti e Florentine (2019) alertam que embora o aumento da concentração de dióxido de carbono no contexto do aquecimento global possa contribuir para um maior crescimento das plantas, sob condições meteorológicas tropicais isso pode não ocorrer devido ao déficit hídrico.

A cobertura morta de biomassa de árvores leguminosas tem sido especialmente recomendada como alternativa para o manejo dos solos coesos por diminuir a evaporação, mantendo a umidade do solo mesmo sob alta taxa de evaporação da água (MOURA et al., 2018; KADER et al., 2019). No entanto, o efeito a curto prazo da cobertura morta tende a se concentrar nas camadas superficiais do solo (BLANCO-CANQUI et al., 2007).

Para aumentar a captação de água pelas raízes em camadas mais profundas do solo, o uso do gesso tem sido recomendado devido à sua alta solubilidade e rápido enriquecimento por cálcio das camadas inferiores do perfil (SUMNER, 2009). Entretanto, para garantir a produção das culturas agrícolas destinadas a alimentar uma população em crescimento e em cenários de crescente falta de água, é necessário ampliar o conhecimento acerca das práticas que minimizem a perda e aumente o aproveitamento da água nos cultivos afim de evitar o estresse pela falta de água na planta.

O nitrogênio (N) faz parte dos principais componentes do sistema fotossintético, tais como clorofilas, rubisco e fosfoenolpiruvato carboxilase – PEPcase. O incremento na disponibilidade de nitrogênio geralmente traz efeitos benéficos na taxa de assimilação de carbono, já que esse nutriente faz parte dos principais componentes do sistema fotossintético (CORREIA et al., 2005). Em solo tropical intemperizado, os serviços fornecidos pelos ecossistemas naturais, como a ciclagem de nutrientes na zona das raízes e fixação do nitrogênio são essenciais para a manutenção da estrutura e aumento da fertilidade do solo. Esses processos impulsionam a eficiência pela qual as plantas adquirem o N, que foi apontado como um dos mais importantes para melhorar a eficiência de absorção de raízes (Chapman et al. 2012). Isso é particularmente verdadeiro em condições tropicais úmidas, onde a eficiência do uso do nitrogênio é geralmente muito baixa devido às altas taxas de volatilização da amônia e ao aumento da remoção da água de drenagem devido às altas temperaturas e altas precipitação (Jabloun et al. 2015).

A hipótese deste trabalho é que a utilização de gesso e biomassa de leguminosa poderá melhorar as condições físicas da zona radicular do solo tropical e elevar as respostas ecofisiológicas do milho, como estratégia para aumentar a adaptação às mudanças climáticas na agricultura tropical. Portanto, este estudo teve como objetivo avaliar como as respostas ecofisiológicas do milho são afetadas pelos efeitos combinados do gesso com biomassa de leguminosa como cobertura morta no solo. O objetivo final é contribuir para a adaptação da agricultura familiar ao aquecimento global previsto na periferia da Amazônia.

2 REVISÃO DE LITERATURA

2.1 Milho: Características gerais

O milho é uma planta monoica, membro da Família Poaceae e pertence ao gênero *Zea*, um grupo de gramíneas anuais e perenes, nativas do México e da América Central. É um dos principais cereais cultivados no mundo e os grãos podem ser consumidos diretamente, sem a necessidade de processamento para remover a "casca", como é feito com outros cereais, como arroz e trigo. A partir do milho são originados vários produtos destinados à alimentação humana e animal. Além disso, é matéria prima para a agroindústria. Em termos nutricionais, o milho possui uma composição rica em carboidratos, principalmente na forma de amido, além de proteínas, lipídios, vitaminas e minerais (OLIVEIRA et al., 2014; LANGNER et al., 2019).

O rendimento de grãos de milho é determinado pelo resultado da interação de genótipo, manejo e fatores ambientais. Os fatores ambientais mais importantes são radiação solar, precipitação e temperatura. Esses fatores não podem ser controlados pelo produtor e variam com a época do ano (FAGERIA et al., 2006). A fotossíntese durante a fase de crescimento e a eficiência com que o fotossintato é realocado para os grãos são processos fundamentais na determinação do desenvolvimento da planta de milho e consequentemente no seu rendimento. Práticas de manejo como plantio direto, irrigação, suprimento de nutrientes e manejo de pragas são utilizados para maximizar o rendimento econômico, mas as respostas a essas práticas variam entre os ambientes.

O milho tem um grande impacto na economia dos países desenvolvidos assim como dos países em desenvolvimento. É cultivado em todas as regiões do território brasileiro e sua produção ocorre em diferentes épocas, a depender das condições climáticas das regiões. Devido a uma gama de cultivares disponíveis no mercado com grande adaptabilidade é possível o cultivo do milho em épocas distintas. Considerado como uma das principais culturas da agricultura brasileira, o milho está presente em diversos sistemas de cultivo como em consórcio com gramíneas forrageiras para compor sistemas integrados de produção lavoura-pecuária, em cultivo consorciado com espécies arbóreas leguminosas, em esquema de rotação de culturas no sistema de plantio direto, etc. (CONTINI et al., 2019). A produtividade média do milho no Brasil está por volta de 5,3 t/ha e encontra-se abaixo da produtividade mundial que é de aproximadamente 5,65 t/ha (USDA, 2019).

2.2 Parâmetros fisiológicos

2.2.1 Trocas gasosas no milho

A fotossíntese é o processo usado pelas plantas para capturar energia da luz solar e convertê-la em energia bioquímica, que é posteriormente usada para suportar quase toda a vida na Terra. Esse processo é complexadamente regulado por fatores biofísicos, bioquímicos, fisiológicos e estruturais das folhas assim como alguns órgãos fotossintetizantes. Apesar de muitos avanços alcançados neste campo, nossa compreensão dos processos regulatórios da fotossíntese ainda é insatisfatório (EVANS, 2013). Os fatores que causam a variação genética na fotossíntese também permanecem amplamente desconhecidos (FLOOD et al., 2011).

O milho pode suportar luz de alta intensidade ao meio-dia e o padrão diurno de sua taxa fotossintética corresponde à curva da intensidade da luz diurna com um pequeno atraso, ou seja, a sua taxa fotossintética tem uma curva de pico único. Plantas com esse padrão de taxa de fotossíntese na forma de um pico podem abrir mais os estômatos e sofrer menos fotoinibição do que aquelas com padrões de taxa de dois picos, como as de arroz por exemplo, que sofre fotoinibição ao meio-dia, quando a alta intensidade luminosa causa fechamento dos estômatos e baixa eficiência nos cloroplastos (VAN et al., 2011; FENG et al., 2017).

Um importante mecanismo regulador da fotossíntese é o controle dos níveis de proteínas enzimáticas. Durante um ciclo diurno com intensidade luminosa variável, as folhas otimizam a assimilação fotossintética de CO_2 para se adaptar ao ambiente, ajustando os níveis de enzimas. Porém, entre as proteínas relacionadas à fotossíntese identificadas no estudo feito por Feng et al. (2017), as de antenas da fotossíntese das folhas de milho permanecem em níveis quase constantes durante todo o ciclo diurno, indicando que a captação de luz na clorofila não muda com a intensidade de luz variável. Os autores concluem que as folhas de milho não ajustam os níveis de proteína da antena da fotossíntese em resposta à mudança da intensidade da luz. No entanto, proteínas no fotossistema exibem expressão diferencial durante o dia.

Sabe-se que as plantas C4, como o milho, têm maior assimilação fotossintética de CO_2 e maior produtividade biológica do que as plantas C3 em condições tropicais (BROWN, 1999). Isso é obtido por um mecanismo de concentração de CO_2 que atua em plantas C4. Nas folhas de plantas C4, as células do mesófilo e da bainha são diferenciadas e envolvem os feixes vasculares. Na fotossíntese C4, o CO_2 atmosférico que entra nos estômatos é fixado pela PEP_{case} nas células do mesofilo. Os ácidos C4 produzidos são transportados para as células da região interna da bainha do feixe vascular (células BS), onde são descarboxilados pela descarboxilase do ácido C4. O CO_2 liberado é fixado pela rubisco. Esse processo bioquímico aumenta a concentração de CO_2 em torno da Rubisco nas células da bainha do feixe vascular e reduz a fotorrespiração (HATCH, 1987).

A abertura estomática está diretamente ligada à regulação das trocas gasosas, de modo que por meio da variação na abertura estomática é possível controlar o fluxo de CO_2 e água da folha. Conforme descrito por Kluge et al. (2015), o CO_2 entra na folha e a água, na forma de vapor, é perdida através dos estômatos da epiderme. Os estômatos podem fechar se o suprimento de água for insuficiente, podendo reduzir o suprimento de CO_2 para a fotossíntese.

Fatores como luz, temperatura, concentração de CO_2, teor de nitrogênio da folha e umidade do solo afetam a atividade fotossintética dos vegetais, sendo que, o processo de abertura e fechamento dos estômatos está relacionado principalmente com a intensidade e qualidade de luz, concentração de CO_2 e o teor de água na folha. Assim, a abertura estomática e a área foliar influenciam diretamente a produtividade do vegetal, o primeiro porque controla a absorção de CO_2 e o segundo porque determina a interceptação luminosa (COSTA e MARENCO, 2007). Lopes et al. (2009) avaliaram a taxa fotossintética líquida na cultura de milho no sudeste brasileiro em plantio convencional e direto com biomassa de triticale (X

Triticosecale) e obtiveram valor máximo de 48 µmol $CO_2m^{-2}s^{-1}$ por volta das 11h e valor mínimo de 20 µmol m^{-2} s^{-1} por volta das 7h para ambos os tipos de plantio no estádio V8 e concluíram que esses manejos não afetaram essa variável.

A demanda por água da atmosfera pode ser avaliada pela diferença de déficit de pressão de vapor entre a folha e o ar ($DPV_{folha-ar}$), que envolve a temperatura da folha e a temperatura do ar e essa variável pode afetar a saída de água da folha, por ação negativa sobre a condutância estomática (FRANKS e FARQUHAR, 2007; REIS et. al., 2009). De acordo com Taiz et al. (2017), quanto maior o $DPV_{folha-ar}$, maior a tendência da planta em perder água. Por intermédio da análise quantitativa do crescimento e de avaliações de trocas gasosas periódicas pode-se avaliar os efeitos dos tipos de manejo sobre as plantas, pois as mudanças nas características do crescimento são observadas em função do tempo, o que não é possível somente com o registro do rendimento do grão (URCHEI et al., 2000).

2.2.2 Fluorescência da clorofila

Embora a fotossíntese possa ser medida diretamente pela absorção de CO_2, para melhor compreensão, o desempenho fotossintético pode ser avaliado juntamente com outros parâmetros. Medidas da fluorescência da clorofila *a* apresentam-se como um complemento em estudos ecofisiológicos de plantas. O rendimento da fluorescência da clorofila nos informa o nível de excitação da energia no sistema de pigmentos que comandam a fotossíntese e é uma excelente ferramenta de monitoramento para tolerância de plantas de milho a condições adversas, principalmente estresse hídrico (MAGALHÃES et al., 2013).

Em outras palavras, as moléculas de clorofila são capazes de reemitir, na forma de fluorescência, uma porcentagem da luz absorvida que não é transformada em energia química. Assim, a intensidade da fluorescência pode ser correlacionada com a atividade do transporte fotossintético de elétrons (CARELLI, 2017**.** Um dos parâmetros mais frequentemente empregados para esta medida é o rendimento quântico máximo do fotossistema II (relação Fv/Fm), que fornece informações sobre a proporção da luz absorvida pela clorofila no PSII usada em processos fotoquímico (LEPEDUŠ et al., 2012).

Pinto et al. (2012) afirmaram que reduções significativas nos valores dos rendimentos quânticos máximos do fotossistema II, bem como nos valores do índice de desempenho - PI, indicam efeito de fotoinibição. Tais mudanças podem representar perda de eficiência fotoquímica pelas plantas e, como consequência, a diminuição da fotossíntese. Valores baixos do índice de desempenho indicam que apenas uma pequena proporção dos fótons absorvidos foi usada no transporte de elétrons, a maioria sendo dissipada como calor. O índice de performance (PI) vem sendo utilizado com mais intensidade para avaliar plantas sob condições adversas. Ele reflete a funcionalidade de ambos os fotossistemas (I e II) e fornece informações quantitativas sobre o estado atual do desempenho da planta. (ŽIVČÁK et al., 2008).

O índice de desempenho é obtido com emprego de fluorímetros, que integra três variáveis independentes sendo: a densidade dos centros de reação ativos (RC) por unidade de moléculas de clorofilas no sistema antena do PSII (RC/ABS); a eficiência do elétron que reduziu Quinona A (Qa) e entrou na cadeia transportadora de elétrons (ET/(TR-ET); a relação entre a capacidade de redução de Qa pelo fóton absorvido, e a energia dissipada na forma de calor (Fv/F_0). Silva et al. (2013) afirmam que a alta correlação entre os sintomas de estresse e a redução da performance fotossintética em plantas reforça a utilidade do índice de performance como indicador de estresse.

2.3 Estresse em plantas de milho

A definição de estresse é complexa porém é um conceito de grande importância para a ecologia e agricultura. Uma motivação para o estudo do estresse na ecofisiologia das plantas é a consideração sobre os padrões de distribuição e desempenho das plantas ao longo dos gradientes ambientais (OSMOND et al., 1987). Nas culturas, os efeitos estressantes dos ambientes afetam o rendimento de grãos a partir da diminuição dos componentes de rendimento. O estresse durante o crescimento vegetativo afeta o número de grãos devido ao fato de que o tamanho da espiga e o número de óvulos formados são determinados durante esse estágio (ABENDROTH et al., 2011).

O déficit hídrico é a causa mais grave e limitante de redução da produção agrícola global e as respostas das plantas à escassez de água são diferentes e dependem da intensidade e do tempo de estresse. O déficit hídrico em baixa intensidade leva à redução da transpiração, falha na translocação da água das raízes para os rebentos, presença de menos pigmentos fotossintéticos, limitação dos produtos fotossintéticos (HOSSEINZADEH et al., 2017). O déficit hídrico em alta intensidade resulta na formação de espécies reativas de oxigênio (ROS) nas plantas, que tem um efeito prejudicial sobre a proteína D1 do PSII, conteúdo de clorofila, transporte de elétrons e produção de moléculas como o trifosfato de adenosina (ATP) (PAGTER et al., 2005). Lu et al. (2002) relataram que o milho sob estresse hídrico teve uma diminuição em Fv/Fm em relação aos tratamentos sob estresse não hídrico. Sob condições de estresse hídrico, a proteína D1 do PSII e os centros de reação do PSII são destruídos. Bolhàr-

Nordenkampf et al. (1989) relatam que a razão Fv/Fm varia entre 0,75 e 0,85 quando a planta está com seu aparato fotossintético intacto e uma queda nesta razão reflete a presença de dano nos centros de reação do PSII por algum estresse.

Como planta C4, o milho possui alta eficiência fotossintética mesmo com intensidade luminosa elevada. No entanto, a fotossíntese é particularmente sensível ao déficit hídrico, pois os estômatos tendem a fechar para conservar água interna, com isso reduzem a difusão de CO_2 nos locais de fixação no mesofilo foliar nas proximidades da enzima rubisco. Esse processo diminui a fotossíntese e, consequentemente, reduz a produtividade. Entretanto, os estômatos podem ser regulados com base no nível de déficit hídrico fechando apenas parcialmente, levando a alguma fixação de carbono durante condições de seca e assim um aumento na eficiência do uso da água (SILVA et al., 2013).

O resultado da escassez de água é importante principalmente nos seguintes estádios de desenvolvimento da planta de milho: I - iniciação floral e surgimento da inflorescência, período em que o número potencial de grãos é estabelecido; II - época da fertilização, quando o potencial de produção é determinado e a presença da água evita o dessecamento do grão de pólen e assegura o desenvolvimento e a penetração do tubo polínico; III- enchimento dos grãos, quando há o acréscimo na deposição de matéria seca, processo diretamente ligado à fotossíntese. O estresse nesta fase culminaria na menor produção de fotossintatos, o que acarretaria menor quantidade de matéria seca nos grãos (MAGALHÃES et al., 2003).

Os efeitos da condutância estomática na tolerância do déficit de água na planta são complexos. Em algumas dicotiledôneas C4, modificações na arquitetura do xilema, incluindo vasos mais estreitos e mais curtos, diminuem a condutividade do caule por unidade de área foliar, o que fornece proteção contra cavitação e, portanto, melhora a tolerância à seca (SAGE et al., 2012). Pode-se supor que a maior eficiência no uso da água conferida pela fisiologia das C4 permitiu uma evolução no sentido de reduções na condutividade do caule por unidade de área foliar (CHRISTIN e OSBORNE, 2014).

2.4 Manejo do Solo: O uso de biomassa vegetal e gesso

O manejo do solo tem grandes efeitos na melhoria das suas propriedades físicas e químicas na qualidade das terras agrícolas e na eficiência fotossintética do milho (SUN et al., 2019). Estratégias para facilitar a penetração e alcance da raiz no solo e para aumentar a absorção de nutrientes incluem o seguinte: I) uso apropriado da cobertura morta; II) a aplicação de biomassa para aumentar a matéria orgânica do solo; III) a adição de cátions básicos, como cálcio e magnésio; e IV) estabelecimento de equilíbrio iônico adequado do solo.

As coberturas mortas podem atrasar o endurecimento do solo e favorecer o crescimento das raízes, reduzindo a evaporação da superfície do solo (MULUMBA E LAL, 2008). Além disso, a aplicação contínua de biomassa, como ocorre com a cobertura morta, pode aumentar as frações lábeis da matéria orgânica, criando agregados que, embora instáveis, melhoram a porosidade e, portanto, o ambiente do solo para o crescimento radicular (PASSIOURA et al., 1991). Infelizmente, nas regiões tropicais, o acúmulo de matéria orgânica, que poderia mitigar os efeitos negativos da coesão do solo na região da raiz, é prejudicado por condições que favorecem a rápida deterioração da biomassa incorporada (HIJBEEK et al., 2018).

O uso do gesso também vem sendo recomendado para os solos tropicais, pois o cálcio compreende um nutriente importante para o crescimento radicular das plantas. Para estender a capacidade das raízes nas camadas mais profundas do solo, pesquisas sugerem o uso de cálcio e magnésio como “agentes floculantes” para melhorar a estrutura do solo e reduzir a dispersão da argila (ANIKWE et al., 2016).

A aplicação de gesso com biomassa de leguminosas modifica a zona radicular, aumentando o teor de cálcio e matéria orgânica e reduzindo a resistência do solo (MOURA et al., 2018). Alguns autores enfatizam interações positivas entre o cálcio e a matéria orgânica composta a partir do resíduo aplicado como cobertura morta (WUDDIVIRA e CAMPS-ROACH, 2007). A formação de pontes de cátions com produtos derivados da decomposição da biomassa aplicada pode ser formada entre partículas carregadas negativamente, essencialmente ligando moléculas orgânicas em conjunto com os minerais (WHITTINGHILL e HOBBIE, 2012). A relação entre a melhoria da capacidade de suporte do solo, os fatores físicos e fisiológicos que sustentam o crescimento das plantas deve ser esclarecida para apoiar os esforços para evitar o desperdício de água e nutrientes e garantir a viabilidade dos sistemas agrícolas tropicais.

Em estudo realizado por Kusumah et al. (2019), a média total da produção de milho com cobertura morta aplicada de gliricidia (*Gliricida sepium*) foi de 4,43 ton/ha. A produção obtida foi muito maior em comparação à média da produção de milho dos agricultores de Merauke (Indonésia) que nos últimos 5 anos atingiram apenas 3,53 ton/ha. Os autores relatam que a maioria dos cultivos é de sequeiro e as altas temperaturas resultam em maior evaporação no solo, de modo que o estresse causado pela seca ocorre com frequência. Aguiar et al. (2018) obtiveram 4,1 ton/ha de rendimento de grãos quando utilizaram biomassa de gliricidia e clitoria

(*Clitoria fairchildiana*) com ureia no cultivo de milho em sistema de aleias no município de Chapadinha, MA, Brasil. O tratamento que recebeu somente ureia teve rendimento de grãos de 0.6 ton/ha. Sena et al. (2020) obtiveram 70% a mais de rendimento na produtividade de milho no leste maranhense no tratamento com biomassa de gliricidia e adição de ureia (5,3 ton/ha) em comparação ao solo desnudo com adição de ureia (3,1 ton/ha).

2.5 Aquecimento global

O clima é governado por influências naturais, mas as atividades humanas têm um impacto sobre ele também. O principal impacto que os humanos exercem sobre o clima é através da emissão de gases de efeito estufa. Gases capazes de absorver a energia radiante são chamados gases de efeito estufa (GEE). O desmatamento é outro exemplo de atividade que influencia o clima. As emissões globais antropogênicas de GEE têm aumentado desde os tempos pré-industriais, com um aumento de 90% entre 1970 e 2011, impulsionados pelo uso de combustíveis fósseis, mudanças no uso da terra e intensificação da agricultura (CLARKE et al., 2015).

O aquecimento global e as mudanças climáticas devido a processos naturais e fatores antropogênicos são as principais e mais importantes questões ambientais que afetarão o mundo (ALEXANDROV e HOOGENBOOM, 2000). Alimentar um mundo com nove bilhões de pessoas até 2050 exigirá um aumento substancial na produção de alimentos. A produção agrícola pode ser aumentada através da expansão da área cultivada ou pela intensificação da produção na área em uso. Em termos de eficácia da mitigação, a intensificação tende a ser preferível à expansão. A expansão pode causar emissões substanciais a partir da conversão de terras com altos estoques de carbono. Se bem administrada, a intensificação pode evitar a conversão de novas áreas em terras cultivadas, porque pressupõe maior produção agrícola na mesma área de terra (DICKIE et al., 2014).

Embora os pesquisadores ofereçam cenários diferentes, o consenso é de que a produtividade das culturas e dos animais pode diminuir devido às altas temperaturas e ao estresse relacionado à seca, mas esses efeitos serão variados entre diferentes regiões (ALTIERI et al., 2015). Alguns trabalhos baseados em modelagens, afirmam que temperaturas mais quentes podem fazer com que muitas culturas cresçam mais rapidamente, mas podem também reduzir o rendimento de outras muitas culturas. Para qualquer cultura em particular, o efeito do aumento da temperatura dependerá da temperatura ideal para crescimento e reprodução; em áreas onde o aquecimento excede a temperatura ideal de uma espécie, os rendimentos daquela espécie podem diminuir (LOBELL e FIELD, 2011).

Meza et al. (2008) relataram que o milho pode ser afetado pelas mudanças climáticas, com reduções de produtividade entre 10% e 30%, dependendo do cenário das mudanças climáticas e do tipo de cultivar utilizada. As mudanças climáticas também afetarão outras variáveis relevantes da cultura como a taxa de desenvolvimento e a eficiência do milho para completar seu ciclo de crescimento em períodos mais curtos. Mudanças na precipitação sazonal total ou em seu padrão de variabilidade também afetarão a produção agrícola, mas grande parte dos modelos afirma que a maioria dos impactos é causada principalmente por tendências de temperatura e não por precipitação. As mudanças no rendimento das culturas de sequeiro serão impulsionadas por mudanças na precipitação e na temperatura, enquanto as mudanças no rendimento em áreas irrigadas serão impulsionadas apenas pelas mudanças de temperatura (ALTIERI et al. 2015).

Projeções futuras através de modelo climático mostram uma redução de até 46% na produtividade de milho na agricultura de sequeiro da China (TONG et al., 2016). Para o nordeste do Brasil, os resultados de um trabalho desenvolvido por Martins et al. (2019) apontam que os efeitos das mudanças climáticas na produtividade do milho na agricultura de sequeiro será negativo. As projeções sugerem que essas mudanças podem afetar a produção de milho nos dois cenários avaliados, resultando em um declínio na produção entre 30 e 60%. Os autores argumentam que para mitigar a situação a utilização de cultivares de ciclo longo trarão maior vantagem juntamente com a introdução da irrigação durante os períodos mais secos. Afirmam ainda que a irrigação e o desenvolvimento de novas variedades de milho seriam essenciais para sustentar a produtividade em cenários adversos de mudanças climáticas. No entanto, a manutenção de tais níveis de produção requer um aumento significativo no consumo de água (até 140%). Ahmed et al. (2019) sugerem o desenvolvimento de cultivares tolerantes ao calor e a modificação nas atuais tecnologias de produção agrícola para compensar os efeitos negativos das mudanças climáticas.

REFERÊNCIAS BIBLIOGRÁFICAS

ABENDROTH, Lori J. **Corn Growth and development**. PMR 1009. Iowa State University Extension, Ames, Iowa. 2011.

AGUIAR, Alana C. F. *et al*. How leguminous biomass can increase yield and quality of maize grain in tropical agrosystems. **Legume Research**. 2018.

AHMED, Ishfaq *et al*. Climate change impacts and adaptation strategies for agronomic crops. In: Climate Change and Agriculture. **IntechOpen**, 2019.

ALEXANDROV, V. A.; HOOGENBOOM, Gerrit. Vulnerability and adaptation assessments of agriculturalcrops under climate change in the Southeastern USA. **Theoretical and Applied Climatology**, v. 67, n. 1-2, p. 45-63, 2000. https://doi.org/10.1007/s007040070015

ALTIERI, Miguel A. *et al*. Agroecology and the design of climate change-resilient farming systems. **Agronomy for sustainable development**, v. 35, n. 3, p. 869-890, 2015. https://doi.org/10.1007/s13593-015-0285-2

ANIKWE, M. A. N.; EZE, J. C.; IBUDIALO, A. N. Influence of lime and gypsum application on soil properties and yield of cassava (Manihot esculenta Crantz.) in a degraded Ultisol in Agbani, Enugu Southeastern Nigeria. **Soil and Tillage Research**, v. 158, p. 32-38, 2016.

BLANCO-CANQUI, Humberto; LAL, Rattan. Soil and crop response to harvesting corn residues for biofuel production. **Geoderma**, v. 141, n. 3-4, p. 355-362, 2007.

BOLHAR-NORDENKAMPF, H. R. *et al*. Chlorophyll fluorescence as a probe of the photosynthetic competence of leaves in the field: a review of current instrumentation. **Functional Ecology**, p. 497-514, 1989.

BORETTI, Albert; FLORENTINE, Singarayer. Atmospheric CO_2 Concentration and Other Limiting Factors in the Growth of C3 and C4 Plants. **Plants**, v. 8, n. 4, p. 92, 2019.

BROWN, R. H. A difference in N use efficiency in C3 and C4 plants and its implications in adaptation and evolution. **Crop Science**, v. 18, n. 1, p. 93-98, 1978. https://doi.org/10.2135/cropsci1978.0011183X001800010025x

CARELLI, M. L. C. **Taxa de Fotossíntese e Problemas**. Disponível em: https://fenix.isa.ulisboa.pt/qubEdu/conteudos-publicos/ficheiros?oid=3972844763477 Acesso em: 13/11/2019. 2017.

CHAPMAN, Nick *et al*. Roots, water, and nutrient acquisition: let's get physical. **Trends in plant science**, v. 17, n. 12, p. 701-710, 2012.

CHRISTIN, Pascal-Antoine; OSBORNE, Colin P. The evolutionary ecology of C4 plants. **New Phytologist**, v. 204, n. 4, p. 765-781, 2014. https://doi.org/10.1111/nph.13033

CLARKE, Leon E. *et al*. **Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change**. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2015.

CONTINI, Elisio *et al*. **Milho: caracterização e desafios tecnológicos**. Brasília: Embrapa. (Desafios do Agronegócio Brasileiro, 2), 2019.

CORREIA, Carlos M. *et al*. Ultraviolet-B radiation and nitrogen affect the photosynthesis of maize: a Mediterranean field study. **European journal of agronomy**, v. 22, n. 3, p. 337-347, 2005.

COSTA, Gracilene Fernandes da; MARENCO, Ricardo A. Fotossíntese, condutância estomática e potencial hídrico foliar em árvores jovens de andiroba (*Carapa guianensis*). **Acta Amazonica**, v. 37, n. 2, p. 229-234, 2007.

DANIELLS, Ian G. Hardsetting soils: a review. Soil Research, v. 50, n. 5, p. 349-359, 2012.

DICKIE, A. *et al*. **Strategies for mitigating climate change in agriculture: Abridged report**. Climate focus and california environmental associates, prepared with the support of the climate and land use Alliance, 2014.

EBSA, Abdeta Jembere *et al*. The Fate of Soil Resource in Response to Global Warming. **International Journal of Environmental Sciences & Natural Resources**, v. 16, n. 4, p. 78-82, 2019.

EVANS, John R. Improving photosynthesis. **Plant physiology**, v. 162, n. 4, p. 1780-1793, 2013.

FAGERIA, Nand Kumar; BALIGAR, Virupax C.; CLARK, Ralph. **Physiology of crop production**. CRC Press, 2006.

FENG, Dan *et al*. Proteomics analysis reveals a dynamic diurnal pattern of photosynthesis-related pathways in maize leaves. **PloS one**, v. 12, n. 7, 2017. https://doi.org/10.1371/journal.pone.0180670

FLOOD, Pádraic J.; HARBINSON, Jeremy; AARTS, Mark GM. Natural genetic variation in plant photosynthesis. **Trends in plant science**, v. 16, n. 6, p. 327-335, 2011.

FRANKS, P.J. e FARQUHAR, G.D. The mechanical diversity of stomata and its significance in gas-exchange control. **Plant Physiol**. 143: 78–87. 2007.

FUHRER, Jürg. Agroecosystem responses to combinations of elevated CO2, ozone, and global climate change. **Agriculture, Ecosystems & Environment**, v. 97, n. 1-3, p. 1-20, 2003.

GRASSINI, Patricio *et al*. How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. **Field Crops Research**, v. 177, p. 49-63, 2015. https://doi.org/10.1016/j.fcr.2015.03.004

HATCH, Marshall D. C4 photosynthesis: a unique elend of modified biochemistry, anatomy and ultrastructure. Biochimica et Biophysica Acta (BBA)-**Reviews on Bioenergetics**, v. 895, n. 2, p. 81-106, 1987.

HIJBEEK, R. *et al*. What drives farmers to increase soil organic matter? Insights from the Netherlands. **Soil Use and Management**, v. 34, n. 1, p. 85-100, 2018. https://doi.org/10.1111/sum.12401

HOSSEINZADEH, Saeed Reza; AMIRI, Hamzeh; ISMAILI, Ahmad. Nutrition and biochemical responses of chickpea (*Cicer arietinum* L.) to vermicompost fertilizer and water deficit stress. **Journal of Plant Nutrition**, v. 40, n. 16, p. 2259-2268, 2017. https://doi.org/10.1080/01904167.2016.1262412

IPCC, I.P. on C.C., 2019. Technical Summary, 2019, in: **Climate Change and Land**: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.

JABLOUN, Mohamed *et al*. Effect of temperature and precipitation on nitrate leaching from organic cereal cropping systems in Denmark. **European Journal of Agronomy**, v. 62, p. 55-64, 2015.

KADER, Mohammad Abdul *et al*. Mulching as water-saving technique in dryland agriculture. **Bulletin of the National Research Centre**, v. 43, n. 1, p. 1-6, 2019.

KLUGE, Ricardo Alfredo; TEZOTTO-ULIANA, Jaqueline V.; DA SILVA, Paula PM. Aspectos fisiológicos e ambientais da fotossíntese. **Revista virtual de química**, v. 7, n. 1, p. 56-73, 2015.

KUSUMAH, R. *et al*. Utilization of gamal biomass (*Gliricidia sepium*) as organic mulch on corn (*Zea mays* L.) plants on dry land. In: **IOP Conference Series: Earth and Environmental Science**. IOP Publishing, 2019. p. 012182.

LANGNER, Josana A. *et al*. Maize: Key agricultural crop in food security and sovereignty in a future with water scarcity. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v. 23, n. 9, p. 648-654, 2019. https://doi.org/10.1590/1807-1929/agriambi.v23n9p648-654

LEPEDUŠ, Hrvoje *et al*. Chlorophyll fluorescence analysis of photosynthetic performance in seven maize inbred lines under water-limited conditions. **Periodicum biologorum**, v. 114, n. 1, p. 73-76, 2012.

LOBELL, David B.; FIELD, Christopher B. California perennial crops in a changing climate. **Climatic Change**, v. 109, n. 1, p. 317-333, 2011.

LOPES, João Paulo *et al*. Análise de crescimento e trocas gasosas na cultura de milho em plantio direto e convencional. **Bragantia**, v. 68, n. 4, p. 839-848, 2009. https://doi.org/10.1590/s0006-87052009000400003

LU, Qingtao *et al*. Photosynthesis and chlorophyllafluorescence during flag leaf senescence of field-grown wheat plants. **Journal of Plant Physiology**, v. 159, n. 11, p. 1173-1178, 2002.

MAGALHÃES, P.C. *et al*. **Fisiologia do milho**. 1 ed. Sete Lagoas: Ministério da Agricultura, Pecuária e Abastecimento, 23p, 2003. (Circular técnica n.º22)

MARTINS, Minella Alves; TOMASELLA, Javier; DIAS, Cássia Gabriele. Maize yield under a changing climate in the Brazilian Northeast: Impacts and adaptation. **Agricultural water management**, v. 216, p. 339-350, 2019.

MEZA, Francisco J.; SILVA, Daniel; VIGIL, Hernán. Climate change impacts on irrigated maize in Mediterranean climates: evaluation of double cropping as an emerging adaptation alternative. **Agricultural systems**, v. 98, n. 1, p. 21-30, 2008. https://doi.org/10.1016/j.agsy.2008.03.005

MOURA, Emanoel G. *et al*. The importance of an alternative for sustainability of agriculture around the periphery of the amazon rainforest. **Recent patents on food, nutrition & agriculture**, v. 5, n. 1, p. 70-78, 2013. https://doi.org/10.2174/2212798411305010011

MOURA, Emanoel G. *et al*. Gypsum and legume residue as a strategy to improve soil conditions in sustainability of agrosystems of the humid tropics. **Sustainability**, v. 10, n. 4, p. 1006, 2018. https://doi.org/10.3390/su10041006

MULUMBA, Lukman Nagaya; LAL, Rattan. Mulching effects on selected soil physical properties. **Soil and Tillage Research**, v. 98, n. 1, p. 106-111, 2008.

OLIVEIRA, Daniel Emanuel Cabral; DOS SANTOS, Maria Nalbaline Sampaio; RUFFATO, Solenir. Forma e tamanho dos grãos de milho da cultivar p3646 submetidos a diferentes condições de ar de secagem. **Nativa**, v. 2, n. 3, p. 162-165, 2014. https://doi.org/10.14583/2318-7670.v02n03a06

OSMOND, C. B. *et al*. Stress physiology and the distribution of plants. **Bioscience**, v. 37, n. 1, p. 38-48, 1987. https://doi.org/10.2307/1310176

PAGTER, Majken; BRAGATO, Claudia; BRIX, Hans. Tolerance and physiological responses of Phragmites australis to water deficit. **Aquatic Botany**, v. 81, n. 4, p. 285-299, 2005. https://doi.org/10.1016/j.aquabot.2005.01.002

PASSIOURA, J. B. Soil structure and plant growth. **Soil Research**, v. 29, n. 6, p. 717-728, 1991.

PINTO, D. G. *et al*. Alterações fisiológicas após aplicação de silício em cacau e sua influência na preferência por pulgões. **Rev. Ceres**, Viçosa, v. 59, n.3, p. 360-367, mai/jun, 2012.

SAGE, Rowan F.; SAGE, Tammy L.; KOCACINAR, Ferit. Photorespiration and the evolution of C4 photosynthesis. **Annual review of plant biology**, v. 63, p. 19-47, 2012.

SILVA, Marcelo de Almeida *et al*. Photosynthetic capacity and water use efficiency in sugarcane genotypes subject to water deficit during early growth phase. **Brazilian archives of biology and technology**, v. 56, n. 5, p. 735-748, 2013.

SUMNER, Malcolm. Gypsum improves subsoil root growth. In **International Symposium Root Researcher and Application**. Vienna, Austria. p. 1-4. 2009.

SUN, Jiying *et al*. Maize canopy photosynthetic efficiency, plant growth, and yield responses to tillage depth. **Agronomy**, v. 9, n. 1, p. 3, 2019. https://doi.org/10.3390/agronomy9010003

TAIZ, Lincoln *et al*. Fisiologia e desenvolvimento vegetal. Artmed Editora, 2017.

TONG, D. *et al*. Modelling the impacts of climate change on spring maize yield in Southwest China using the APSIM model. **Resources Science**, v. 1, p. 017, 2016.

TSONKOVA, Penka *et al*. Ecological benefits provided by alley cropping systems for production of woody biomass in the temperate region: a review. **Agroforestry Systems**, v. 85, n. 1, p. 133-152, 2012. https://doi.org/10.1007/s10457-012-9494-8

TURNER, Neil C.; RAO, K. P. C. Simulation analysis of factors affecting sorghum yield at selected sites in eastern and southern Africa, with emphasis on increasing temperatures. **Agricultural Systems**, v. 121, p. 53-62, 2013. https://doi.org/10.1016/j.agsy.2013.06.002

URCHEI, Mário Artemio; RODRIGUES, João Domingos; STONE, Luis Fernando. Análise de crescimento de duas cultivares de feijoeiro sob irrigação, em plantio direto e preparo convencional. **Pesquisa Agropecuária Brasileira**, v. 35, n. 3, p. 497-506, 2000. https://doi.org/10.1590/s0100-204x2000000300004

USDA. United States Department of Agriculture. **Grain: world markets and trade**. Disponível em: https://www.fas.usda.gov/data/grain-world-markets-and-trade. Acesso em: 23/01/2020.

VAN HEERWAARDEN, Joost *et al*. Genetic signals of origin, spread, and introgression in a large sample of maize landraces. **Proceedings of the National Academy of Sciences**, v. 108, n. 3, p. 1088-1092, 2011. https://doi.org/10.1073/pnas.1013011108

VANCE, Carroll P.; UHDE-STONE, Claudia; ALLAN, Deborah L. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. **New phytologist**, v. 157, n. 3, p. 423-447, 2003. https://doi.org/10.1046/j.1469-8137.2003.00695.x

WHITTINGHILL, Kyle A.; HOBBIE, Sarah E. Effects of pH and calcium on soil organic matter dynamics in Alaskan tundra. **Biogeochemistry**, v. 111, n. 1-3, p. 569-581, 2012.

WUDDIVIRA, M. N.; CAMPS-ROACH, G. Effects of organic matter and calcium on soil structural stability. **European Journal of Soil Science**, v. 58, n. 3, p. 722-727, 2007.

ŽIVČÁK, M. et al. Performance index as a sensitive indicator of water stress in Triticum aestivum L. **Plant Soil Environ**, v. 54, n. 4, p. 133-139, 2008.

CAPÍTULO II

Ecophysiological response of maize to soil management in the Amazonian periphery in the context of climate change adaptation

Lorena Silva Campos[1*], Emanoel Gomes de Moura[1], Jéssica de Freitas Nunes[1], Stefanny Barros Portela[1], Weverton Pereira Rodrigues[2], Fabrício de Oliveira Reis[1], Helen West[3], Tiago Massi Ferraz[1]

[1] Programa de Pós-Graduação em Agroecologia, Universidade Estadual do Maranhão, São Luís, MA 65080-970, Brasil.

[2] Centro de Ciências Agrárias, Naturais e Letras. Universidade Estadual da Região Tocantina do Maranhão, Estreito, MA, 65975-000, Brasil.

[3] Division of Agricultural and Environmental Sciences, School of Biosciences, University of Nottingham, Sutton Bonington Campus, Leicestershire LE12 5RD, United Kingdom.

*Corresponding author:
Lorena Silva Campos
Professional address: Programa de Pós-Graduação em Agroecologia, Universidade Estadual do Maranhão, São Luís, MA 65080-970, Brasil.
E-mail address: lorena7campos@gmail.com
Telephone number: +55 98 98348-6481

Emanoel Gomes de Moura
egmoura@elointernet.com.br

Jéssica de Freitas Nunes
jessnunes.24@gmail.com

Stefanny Barros Portela
stefannyportela@hotmail.com

Weverton Pereira Rodrigues
weverton.rodrigues@uemasul.edu.br

Fabrício de Oliveira Reis
fareoli@gmail.com

Helen West
helen.west@nottingham.ac.uk

Tiago Massi Ferraz
ferraztm@gmail.com

Abstract

Climate models consistently project increases in temperature variability in tropical countries over the coming decades, with the Amazon a particular hotspot of concern. The extent to which agricultural systems can adapt to global warming depends in part on physical improvements to soil that enhance water and nutrient uptake. We use gypsum and leguminous residue to improve the soil root zone, hypothesizing that such changes may improve the physical conditions of tropical soil prone to hardness and enhance the ecophysiological responses in maize. The study consisted of four replicates using the following treatments: control (C), gypsum (G), nitrogen (N), legume residue (L), nitrogen + gypsum (NG), legume residue + gypsum (LG) and legume residue + nitrogen + gypsum (LNG). The study plots were rainfed in 2018 and used a restricted irrigation regime in 2019. The soil improvements studied had positive effects on the physiological parameters of maize, with a reduction in stress which indicated the sensitivity of maize plants to gypsum and nitrogen addition. More specifically, we observed changes in N uptake, biomass production and maize grain yield, even in the restricted irrigation regime. Under a restricted irrigation regime, maize grain yield in the LNG plots was 41% higher than in N plots and 151% higher than the C plots. Interestingly, additions of nitrogen considerably decreased plants stress, improving physiological parameters and increasing biomass production. These results highlight the role for added nitrogen alongside soil improvement measures such as leguminous residues and gypsum, especially in the context of climate change adaptation.

Keywords: legume residue; soil management; photosynthesis; maize; climate change adaptation.

Introduction

Climate models consistently project increases in temperature variability in tropical countries over the coming decades, with the Amazon a particular hotspot of concern (Bathiany et al. 2018). A number of harmful effects on agricultural production are predicted due to global warming, including extreme events such as heatwaves, excessive drying of soils, increased rainfall intensity and higher total precipitation (Gupta et al. 2020, Kamphorst et al. 2020). All of these mechanisms contribute to soil degradation in the humid tropics, particularly the leaching of base cations and increased rates of soil organic matter decomposition (Senna et al. 2020).

Although increased CO_2 concentrations [CO_2] is predicted to impact on C3 plants to greater extent, recent studies have demonstrated postivie effects of increased [CO_2] in C4 plants such as maize (*Zea mays* L.) especially under adequade water supply (Meng et al. 2014). Therefore, improving the physical properties of soil to increase soil water uptake will be crucial to decrease the deleterious effect of global warming on tropical crop productivity (Ebsa 2019).

Overall, soils in Amazon region do not have a high intrinsic resilience against physical degradation due to the low content of aggregator elements like soil carbon, calcium and magnesium (Moura et al. 2018). In the natural conditions of the Amazonian periphery, the soil-vegetation system is resilient against physical degradation due to complete soil cover at ground level combined with the perforating activity of the soil fauna (Brinkman and Sombroek 1996). In agroecosystems, strategies using mulch application as a ground cover increase organic matter and avoid soil degradation by reducing cohesion and improving the root zone (Sena et al. 2020). Mulching with plant residues decreases the rate of evaporation from the soil, delaying soil moisture loss, and improving rootability (Blanco-Canqui and Lal 2007). Such improvements, however, may be limited to the soil surface (Moura et al. 2012). One solution to extend soil rootability to lower depths is using calcium in the form of gypsum, which acts as a "flocculating" agent to improve the soil structure by reducing the dispersion of clay at deeper layers (Sumner 2009). In addition, polyvalent cations like calcium derived from gypsum may interact with organic matter from decomposing plant residue, which further contributes to a favorable environment for root growth (Ellerbrock and Gerke 2018). These bonds prevent the biological, chemical, and physical breakdown of organic matter, leading to reduced losses of organic matter and soil base cations (Whittinghill and Hobbie, 2012).

Although environmental stresses are one of the most important factors that limit crop production, the responses of plants to water scarcity can be different depending on the intensity and time of stress (Kamphorst et al. 2020). Low-intensity water deficit leads to reduced transpiration, failure to translocate water from roots to shoots, decreased photosynthetic pigments and limiting production of photosynthetic products (Hosseinzadeh et al. 2017). High-intensity water deficit creates reactive oxygen species (ROS) in plants with detrimental effect on the D1 protein of photosystem II, chlorophyll content, electron transport, and the production of molecules such as adenosine triphosphate (ATP) (Pagter et al. 2005). Therefore, improvements to soil physical characteristics that enhance water and nutrient uptake are an important component of climate change adaptation for tropical agricultural systems (Moura et al. 2012). We hypothesize that improvements in the soil root zone from using gypsum along with leguminous residue might improve the physical conditions of tropical soil prone to hardening and enhance crop physiological performance. Therefore, this study aimed to evaluate the combined effects of gypsum with leguminous residue on changes in soil properties and how these changes could affect maize physiological performance. The ultimate objective is to contribute to family farm adaptation to global warming predicted to the Amazonian periphery.

Materials and Methods

Study Site

The field experiment was conducted in 2018 and 2019 at the Universidade Estadual do Maranhão, São Luís, Maranhão, Brazil (2°30'4" S, 44°18'33" W). The region's climate is hot and humid equatorial. Its rainy season extends from January to June and its dry season, with a pronounced water deficit, which lasts from July to December. The annual average temperature is approximately 27°C, the maximum temperature is 37°C, and the minimum temperature is 23°C. The total rainfall during the experimental periods of October to January of each year was 528.6 mm in 2018 and 53.6 mm in 2019 (Fig. 1). The soil in the experimental area is an sandy loan Arenic Hapludult (Smith 2014) with hard-setting characteristics (Daniells 2012).

Fig. 1 Precipitation, daily maximum, mean and minimum temperature and relative humidity at the study site, 2018–2019

History of the experimental area

The area was fallow since 1990 and supported a native species of grass, which was removed using glyphosate. In January 2011, lime was applied to the surface at a rate of 1 t ha^{-1}. During this period, natural gypsum was applied at a rate of 6 t ha^{-1} to plots designated for this treatment. Maize (cultivar AG 7088) was sown in 2011–2013 and 2015–2017. Gypsum was applied again in 2016 at a rate of 4 t ha^{-1}. Residues from *Gliricidia sepium* (Gliricidia) was applied in the form of fresh branches at 12 t ha^{-1} each year.

Field trial and treatments

The experiment was conducted under no-tillage mulch system, with maize planted and harvested in 2018 and 2019. We used Pioneer 30f35, a commercial maize cultivar. Each experimental plot measured 4 x 8 m, with a total of 28 plots in a randomized block arrangement. Plots consisted of 5 rows, spaced 0.80 m apart with an intra-plant spacing of 0.25 m. The planting density was 50,000 plants ha^{-1}. Gliricidia mulch was applied at a rate of 12 t ha^{1} per year. The study had four replicates of each of the following treatments: control (C), gypsum (G), nitrogen (N), legume residue (L), nitrogen + gypsum (NG), legume residue + gypsum (LG) and legume residue + nitrogen + gypsum (LNG). Chemical fertilizer was applied to maize at a rate of 100 kg ha^{-1} of P in the form of triple superphosphate, 180 kg ha^{-1} of K as potassium chloride, 5 kg ha^{-1} of Zn in the form of zinc sulphate and 180 kg ha^{-1} of N in the form of urea. Phosphorus and zinc were applied as basal fertilizer once before planting. Nitrogen (only in the plots that received nitrogen) and potassium were applied at a rate of 60 kg ha^{-1} at planting, 60 kg ha^{-1} at the V6 stage (six leaves with collars visible) and 60 kg ha^{-1} at the V11 stage (11 leaves with collars visible). The plots used a rainfed system in 2018 and a restricted irrigation regime in 2019. In 2019, water was supplied by drip tape irrigation with one tape per row with emitters spaced 25 cm apart delivering 1.25 L h^{-1} for 4 h, resulting in a total of 20 mm of water applied per irrigation.

Measured Parameters and Analyses

Soil Samples

We collected soil samples for chemical analysis at the end of the second-year experiment at depths of 0–20 and 20–40 cm. A total of four simple samples per plot were collected using a Dutch auger with a 3 inch diameter. Samples from each plot were passed through a 2 mm screen mesh and air-dried before the analyses. Each sample was analysed using an exchangeable ion resin (Raij et al. 1986) as an extractor for Ca, Mg, and K, which were measured using a Varian 720-ES ICP Optical Emission Matter Analysis Spectrometer (Walnut Creek, CA, USA).

Soil penetration resistance (SPR) and soil moisture

The SPR measurements were collected at depths of 0–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40m with three replicates per plot. In 2019, these measures were taken 4 days after irrigation (or 4 days without water) and immediately before the irrigation (or 7 days without water). SPR was measured using a digital penetrometer (Falker, Porto Alegre, Brazil) with 1 cm gradations. The bars of critical level defined by Hazelton and Murphy (2016) was used to construct the graph of the soil penetration strength. We calculated soil moisture content using the gravimetric method with the following formula: soil moisture (g/g) = (weight of fresh soil – weight of oven-dried soil)/weight of oven-dried soil.

Physical fractionation of soil organic matter

The soil organic matter in the 0–20 cm layer of the soil profile was physically fractionated following Cambardella and Elliott (1992). After drying, a soil sample was ground in a porcelain mortar, after which an aliquot was collected, weighed, and analysed for its C content, which represented the soil particulate organic carbon (POC) in the particulate organic matter, according to the Walkley and Black (1934) method. An aliquot of the 2 mm sieved subsample was ground in a porcelain mortar and weighed and analysed for total organic carbon (TOC). Soil mineral-associated carbon (MOC) was calculated as the difference between TOC and POC. The total organic carbon stock (TOCS) of each of the 0–30 cm layers was calculated with the following expression (Veldkamp 1994): C stock = (TOC x ρs x E) /100, where C stock = organic C stock at a given depth (t ha^{-1}); OC = organic C content at the sampled depth (g kg^{-1}); ρs = soil bulk density (kg dm^{-1}); and E = thickness of the layer (30 cm).

Plant and nitrogen analysis

Total N content were measured in 2018 and 2019 at the physiological maturity stage. Five plants from each plot were randomly selected. All plant material was dried at 60°C for 6 days to a constant weight in an oven and was then ground for analysis. Total nitrogen content in each sample was determined from the mass of dried plant matter by digestion in sulfuric acid ($H_2SO_4 – H_2O_2$), according to the standard distillation method described by Cottenie (1980).

Gas exchanges

Gas exchange measurements were performed using a portable LI-6400XT open gas exchange system (Li-Cor Inc., Lincoln, NE, USA) that included a 6400-02B LED light source. These two accessories were used to maintain a constant CO_2 concentration of 400 ± 10 μmol mol^{-1} and a constant incident photosynthetic active radiation (PAR) of 1500 μmol m^2 s^{-1} in the leaf chamber during instantaneous measurements. A flow rate to chamber was 500 μmol s^{-1}. Net photosynthetic rate (P_N), stomatal conductance (g_s) and transpiration (E) were obtained from the instantaneous measurements. The measurements were taken on three randomly selected and marked plants on the middle rows of each plot in 2018 and 2019, between 7:30 am and 9:30 am at the V6 (six leaves with collars visible) and VT (tasseling) stages on the third fully matured leaf from the top. In 2018, the first measurement was done 6 days after rainfall and the second measure was performed 1 day after rainfall. In 2019 the first and second measures were done 6 days after the irrigation (or 6 days without water). The instantaneous water use efficiency (WUE) at leaf level was calculated as the ratio between photosynthesis and transpiration (instantaneous WUE = P_N / E).

Fluorescence measurements

The performance index (PI_{abs}) was measured at the same time and on the same leaves as the gas exchange measurements. Maize leaves were adapted to darkness for 30 minutes using a light-with-holding clips. Chlorophyll *a* fluorescence was measured with a portable non-modulated fluorimeter Pocket-PEA (*Plant Efficiency Analyser* - Hansatech, Norfolk, UK). After the adaptation of leaves to darkness, a single strong light pulse lasting one second (3500 μmol m^2 s^{-1}) was applied using three light-emitting diodes (650 nm). The measurements were taken on three randomly selected and marked plants in the middle rows of each plot.

Statistical Analysis

An analysis of variance (ANOVA) was performed on the data to evaluate treatment effects and means were compared using the Tukey's HSD test ($p < 0.05$) using R program. The data from the each year were analysed separately because of significant ($p < 0.05$) season year interactions.

Results

Changes in SOC and SBC

Total organic carbon (TOC) was higher in the N (11%), G (13%) and L (60%) treatments compare to the control, while the LNG treatment was 81% higher (Table 1). These results were primarily driven by mineral associated carbon (MOC), whose values and differences between treatments were higher than particulate organic carbon (POC).

Table 1 Soil organic carbon (SOC) fractions: particulate organic carbon (POC), mineral associated-organic carbon (MOC) and total organic carbon (TOC). Notes: Values followed by different letters in the same line indicate a significant difference at the 5% level by the Tukey's HSD test. C: control; N: nitrogen; G: gypsum; NG: nitrogen+gypsum; LG: legume residue+gypsum; L: legume residue; LNG: legume residue+nitrogen+gypsum

Calcium (Ca) content was also increased by legume and gypsum in the soil profile. In the 0–20 cm layer, the effect of the legume to calcium content was greater than the gypsum effect (Table 2). There was no significant difference between the L, NG, LG, and LNG treatments, though they all had higher calcium levels than the other treatments. Notably, calcium levels were higher in plots with only legume mulch than in plots with only gypsum (L > G). Similar results were obtained for the sum of base cations (SBC). In contrast, magnesium (Mg) content was lowest in the G and NG treatments, in which Mg content was three times lower than in the L plots. Potassium (K) content was higher in L and LNG than in N and NG.

In contrast, gypsum was more effective in increasing Ca levels in the 20–40cm layer than legume residue, which was reflected in higher overall Ca levels in treatments with gypsum. The increase in SBC was also greater in gypsum treatments than in those with legume residue. Indeed, SBC was lower in the L plots than in treatments with gypsum, though not as low as the C and N treatments.

Table 2 Exchange base cations ($mmol_c\ m^3$) and sum of base cation (SBC). Notes: Values followed by different letters in the same line indicate a significant difference at the 5% level by the Tukey's HSD test. Notes: C: control; N: nitrogen; G: gypsum; NG: nitrogen+gypsum; LG: legume residue+gypsum; L: legume residue; LNG: legume residue+nitrogen+gypsum

Legume residue application positively affected soil moisture, with higher levels than the control in the 0–20 cm layer, even after 7 days without rain (Table 3). In this layer, only treatments with residue maintained soil moisture above the critical level of 5%. On the whole, soil moisture in the 20–40 cm layer was higher in the L and LNG treatments than in treatments without legume residue.

Table 3 Gravimetric soil moisture (g/g) 7 days without water in 2019. Notes: Values followed by different letters in the same line indicate a significant difference at the 5% level by the Tukey's HSD test. C: control; N: nitrogen; G: gypsum; NG: nitrogen+gypsum; LG: legume residue+gypsum; L: legume residue; LNG: legume residue+nitrogen+gypsum

Our results showed that impact of water scarcity on treatments without legume residue was greater than in treatments with mulch cover. This can be seen in the penetration resistance curves on the 4th and 7th days after irrigation. Figure (2a) and (2b) provide insights on the intensity (distance between curves of the same treatment) and duration of water stress (time spent in the stress range). After four days without irrigation, soil penetration resistance was under 1 MPa up to 20 cm and lower than 2 MPa up to 30 cm in treatments with legume residues (Fig. 2a). Meanwhile, SPR was higher than 1 MPa in the 10–20 cm layer (Fig. 2b) in treatments without legume mulch. After seven days without irrigation, SPR was higher than critical level of 2.0 MPa in the 0–30 cm layer in the LG and L treatments, as well as all treatments without leguminous mulch. Only in the LNG treatment SPR was lower than 1 MPa in the 0–20cm layer and lower than 2 MPa in the 0–30 cm layer.

Fig. 2 Response of different treatments with legume residue (a) and without legume residue (b) in soil penetration resistance (MPa). Notes: C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum; 4: four days without water; 7: seven days without water

Maize physiological response to soil improvement

There were no significant differences in stomatal conductance (g_s) in 2018 at the VT stage, though g_s was higher in LG (0.53 mol m^{-2} s^{-1}) than in G (0.34 mol m^{-2} s^{-1}) at the V6 stage (Fig. 3a). In 2019, the LNG treatment had a higher g_s at the V6 stage than all other treatments, with no difference between the remaining treatments (Fig. 3b). At VT stage, however, the NG, LG, and LNG treatments were greater than the control. There was no difference between the other treatments.

The net photosynthetic rate (P_N) was also different in each year of the experiment. In 2018, P_N ranged from 38.72 to 52.17 µmol m^{-2} s^{-1}, while the range was larger in 2019, varying between 13.45 and 39.45 µmol m^{-2} s^{-1}. There was no difference between treatments at the VT stage in 2018, while G (38.72 µmol m^{-2} s^{-1}) had lower P_N than LG (44.64 µmol m^{-2} s^{-1}) at the V6 stage (Fig. 3c). In contrast, in 2019 LNG had the highest photosynthetic rate at the V6 stage, with no difference among the others treatments, except for LG (36.16 µmol m^{-2} s^{-1}) being higher than L (31.49 µmol m^{-2} s^{-1}) (Fig. 3d). At the VT stage, all treatments with added urea had a higher P_N than the remaining treatments and L had a higher P_N than C. All of the treatments had low P_N values at the VT stage (with means under 23 µmol m^{-2} s^{-1}).

Fig. 3 Stomatal conductance, g_s (mol m^{-2} s^{-1}) in 2018 (a) and in 2019 (b) and net photosynthetic rate, P_N (µmol m^{-2} s^{-1}) in 2018 (c) and 2019 (d). Notes: Different lower-case letters at the V6 stage and different capital letters at the VT stage in each graph indicate significant differences at the 5% level per Tukey's HSD test. Notes: C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum

There was large variation in the performance index (PI_{abs}) between 2018 and 2019. In 2018 at V6 stage, PI was higher in LNG than in C, G, and N, while at the VT stage, PI was higher in NG and LNG than in C and G (Fig. 4a). In 2019, there were no significant differences among treatments at the V6 stage, but at VT the NG and LNG treatments were had higher PI values than the other treatments (Fig. 4b).

Fig. 4 Performance Index (PI_{abs}) in 2018 (a) and 2019 (b). Notes: Different lower-case letters at the V6 stage and different capital letters at the VT stage in each graph indicate significant differences at the 5% level per Tukey's HSD test. Notes: C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum

As for instantaneous water use efficiency (A/E) there was no difference between treatments at the V6 stage in 2018 and 2019 (Fig. 5a). However, at VT stage in 2018 instantaneous water use efficiency was higher in LNG than in N, G and C. In 2019 it was higher in the treatments LNG, NG and N than in all other treatments (Fig. 5b).

Fig. 5 Instantaneous leaf water use efficiency (Ins WUE) in 2018 (a) and 2019 (b). Notes: Different lower-case letters at the V6 stage and different capital letters at the VT stage in each graph indicate significant differences at the 5% level per Tukey's HSD test. Notes: C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum

Nitrogen uptaken and maize grain yield (GY)

Legume residue affected total N uptake when used alone, though only in the rainfed system (2018), in which the LG and L treatments had higher N uptake than C and G (Fig. 6a). The LNG and NG treatments had higher N uptake than in the other treatments, while total N was not different from the LG and L treatments than in plots with only urea (N treatment). In 2019, all treatments with added urea (N, NG, and LNG) had considerably higher nitrogen uptake than other treatments, with no difference between the remaining treatments. In 2018, GY was the lowest in the G, C, and N treatments (Fig. 6b). There were no significant differences between the L, NG and LG treatments, while LNG had the highest GY of any treatment. In 2019, added urea had the greatest effect on GY. In the N treatment, GY was up to 78% higher than in treatments without added urea. The LNG treatment had the highest yield, which was 151% greater than the control and 41% higher than the N treatment.

Fig. 6 Effects of different treatments on total N (g kg^{-1}) in 2018 (=1) and 2019 (=2) (a) and maize grain yield (GY) in 2018 (1) and 2019 (2). Notes: Different letters in each graph indicate significant differences at the 5% level per the Tukey's HSD test. C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum

Discussion

Soil improvement and nitrogen uptake

Our results showed that interactions between legume residue, gypsum and N application can improve the soil root zone, reducing the effect of drought conditions on physiological parameters in maize while also increasing nitrogen uptake. The observed soil improvements can be explained through specific interactions between polyvalent cations and compounds derived from the decomposition of legume residues (Ellerbrock and Gerke 2018). In turn, synthetic N inputs increase microbial activity and thereby increase soil organic matter transformation and microbial biomass if N is a soil limiting resource (Chen et al. 2014). Gypsum and N application appear to have complementary effects that help capture the benefits of leguminous mulch application to ensure an adequate content of soil organic carbon. The predominance of mineral-associated organic carbon in our samples may be due to the fast decomposition of POC the more labile SOC fraction (Hijbeek et al. 2018).

Treatments with mulch had higher moisture levels and lower SPR. Straw mulches are commonly used because of their ability to reduce soil evaporation by preventing capillarity (Jimenez et al. 2017). Furthermore, the increase in water holding capacity may be directly related to increased soil organic carbon observed in treatments with legume mulch. The presence of SOM plays a key role in altering the pore size distribution of sandy loam soils, as a result of decreased bulk density (Robin et al. 2018). In turn, the increased number of small pores and higher specific surface area increases water holding capacity at low tensions such as field capacity, increasing water availability for plants (Moura et al. 2009).

In addition to the positive effect of increased soil moisture, decreased impedance is due to a dilution effect caused by mixing of the biomass with the denser mineral fraction of the soil (Maltas et al. 2018). In soil prone to cohesion, increased SOM decreases SPR indirectly by affecting the stability of soil aggregates (Tarkiewicz and Nosalewicz 2005). Added calcium has both direct (increasing flocculation and aggregation in the subsoil) and indirect (improving root activity, which leads to greater soil aggregation) effects on SPR (Sumner et al. 2009). Thus, the interaction between legume residues and added calcium can increase SOM, soil moisture and SBC while decreasing SPR. These effects encourage plant growth while increasing the availability of water in drought scenarios (Lynch and Wojciechowski 2015).

Maize physiological response to soil improvement

The changes in maize physiological parameters observed in this experiment are driven principally by variations in SPR. According to Ley et al. (1995) in soil that tend to harden, effects on root growth are common when the water potential approaches -100 kPa. In these circumstances, SPR is a better proxy for plant water stress rather than the permanent wilting point, as proposed by Letey (1985). Therefore, the decreased intensity and duration of water stress in the LNG treatment, as shown in Figure 2a, can account for its improved performance in all physiological parameters evaluated in this experiment. In this experiment, the LNG treatment resulted in higher stomatal conductance and net photosynthetic rate in both years, but the effect was greatest in 2019, the year in which drip irrigation was used. Soil improvement as reflected by lower penetration resistance and higher soil moisture can partially account for these results.

Environmental stress results in lower stomatal conductance and net photosynthetic rate, as shown in Figure 3, which is reflected in lower growth (Ripley et al. 2007). Under both soil and atmosphere water stress, this decrease in stomatal conductance may be attributed to limited root system capacity to meet leaf water demand (Lopes et al. 2019; Brodribb et al. 2020). The combined effect of gypsum and legume residue to decrease root stress in LG and LNG can explain higher g_s and P_N values in these treatments. Indeed, the reduction in photosynthetic electron consumption, an important consequence of the drought-induced decrease in CO_2 supply, causes a decrease in photosynthetic efficiency and an increased requirement for additional electron sinks such as photorespiration (Ripley et al. 2017).

Differences in performance index (PI_{abs}) shown in Figure 4 confirm the effectiveness of the LNG treatment to reduce stress in maize plants. PI_{abs} reflects the functionality of both photosystems I and II and gives us quantitative information on the current state of plant performance under stress conditions (Živčák, et al. 2008). Therefore, the PI_{abs} provides a proxy for plant vitality as well as indicating stress in plants even before visible symptoms appear on the leaves (Christen et al. 2007). Indeed, even in 2018, PI_{abs} was able to detect higher vitality in LNG treatment at the earlier V6 stage. Again, lower penetration resistance, higher soil moisture and higher nitrogen contents in leaves can explain higher PI_{abs} due to lower stress in plants in LNG plots.

Differences in instantaneous water user efficiency were just verified in water restrict regime, when it was higher in treatments with N, demonstrating that maize performance could be increased with no change in water use rate. Water shortage can lead to N deficiency and a decline in transpiration efficiency strictly proportional to the N deficiency induced by drought. Therefore, interaction between water and N deficit could be analysed by the N uptake/transpiration ratio indicator (Kunrath et al. 2018).

Nitrogen uptake and grain yield (GY)

Due to differences in the rainfall regime, harnessing of N from urea and legume residue was more dependent on the water supply regime than the soil structure. This can be seen in the higher uptake of N from decomposing legume residue in 2018 but not in 2019, when legume residues had no effect on N uptake. In contrast, under intense rain regime the effect of urea on N uptake decreased in 2018 and was enhanced in 2019 under irrigation regime. The LNG treatment showed the highest N content in both years, which is consistent with findings by Senna et al. (2020).

Our results showed that maize production can be increased by soil improvements resulting from legume residue and gypsum in both water regimes. Since legume residue contributed relatively little to N uptake in the restricted irrigation regime, the 35% difference in grain yield between the N and LNG treatments in 2019 is due mainly to soil improvement caused by soil management (Moura et al. 2020). This result confirms that the combination of legume residues with gypsum and urea application can be a good strategy to maintain crop productivity in cohesive soil and drought conditions.

Conclusions

Our results showed the possibility of improving crop management in conditions of cohesive tropical soil with an irregular water regime. These improvements were primarily apparent in certain key areas, including soil organic matter, water holding capacity, penetration resistance and calcium content. This underscores the importance of soil management for the adaptation of tropical agroecosystems to climate change. The improvements in soil attributes resulted in positive effects in physiological parameters, with a reduction in plant stress reflected mainly in the performance index (PI_{abs}). These changes resulted in increased biomass and maize grain yield, even in a restricted irrigation regime. However, it is worth highlighting the significant contribution of added nitrogen to decreasing plant stress, increasing soil organic carbon, enhancing physiological parameters, and increasing biomass production. Therefore, the inclusion of nitrogen alongside gypsum and legume residue should be part of new research on climate change adaptation strategies for tropical agriculture.

Conflict of Interest: The authors declare that they have no conflict of interest.

Acknowledgments

This study was funded by Capes and FAPEMA-Maranhão Research Foundation [grant number RCUK-02771/16]; and in the United Kingdom by the Biotechnology and Biological Sciences Research Council [grant number BB/N013201/1] under the Newton Fund Scheme.

References

Bathiany S, Dakos V, Scheffer M, Lenton TM (2018) Climate models predict increasing temperature variability in poor countries. Sci Adv 4: eaar5809. https://doi.org/10.1126/sciadv.aar5809

Blanco-Canqui H, Lal R (2007) Soil and crop response to harvesting corn residues for biofuel production. Geoderma 141: 355-362. https://doi.org/10.1016/j.geoderma.2007.06.012

Brinkman R, Sombroek WG (1996) The effects of global change on soil conditions in relation to plant growth and food production. In F. and W.G. Sombroek eds. Global Climate Change and Agricultural Production. Bazzaz FAO and Wiley, Chichester, UK, pp 49-64

Brodribb TJ, Powers J, Cochard H, Choat B (2020) Hanging by a thread? Forests and drought. Science 368: 261 – 266. https://doi: 10.1126/science.aat763

Cambardella CA, Elliot ET (1992) Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci Soc Am J 56: 777-783

Chen R, Senbayram M, Blagodatsky S, Myachina O, Dittert K, Lin X, Blagodatskaya E, Kuzyakov Y (2014) Soil C and N availability determine the priming effect: microbial N mining and stoichiometric decomposition theories. Glob Chang Biol 20: 2356-2367

Christen D, Schönmann S, Jermini M, Strasser RJ, Défago G (2007) Characterization and early detection of grapevine (*Vitis vinifera*) stress responses to esca disease by *in situ* chlorophyll fluorescence and comparison with drought stress. Environ Exp Bot 60: 504-514. https://doi.org/10.1016/j.envexpbot.2007.02.003

Cottenie A (1980) Soil and plant testing as a basis of fertilizer recommendations. FAO Soil Bulletin. Rome, Italy, pp 1-119

Daniells IG (2012) Hardsetting soils: A review. Soil Res 50: 349-359

Ebsa AJ (2019) The Fate of Soil Resource in Response to Global Warming. Int J Environ Sci Nat Resour 16: 78-82. http://doi.org/10.19080/IJESNR.2019.16.555944

Ellerbrock RH, Gerke HH (2018) Explaining soil organic matter composition based on associations between OM and polyvalent cations. J Plant Nutr Soil Sci 181: 721-736. https://doi.org/10.1002/jpln.201800093

Gupta A, Rico-Medina A, Caño-Delgado AI (2020) The physiology of plant responses to drought. Science 368: 266 LP – 269. https://doi:10.1126/science.aaz7614

Hazelton P, Murphy B (2016) Interpreting soil test results: What do all the numbers mean?. CSIRO publishing

Hijbeek R, Pronk AA, van Ittersum MK, ten Berge HFM, Bijttebier J, Verhagen J (2018) What drives farmers to increase soil organic matter? Insights from the Netherlands. Soil Use Manag 34: 85-100. https://doi.org/10.1111/sum.12401

Hosseinzadeh SR, Amiri H, Ismaili A (2017) Nutrition and biochemical responses of chickpea (*Cicer arietinum* L.) to vermicompost fertilizer and water deficit stress. J Plant Nutr 40: 2259-2268. https://doi.org/10.1080/01904167.2016.1262412

Jimenez MN, Pinto JR, Ripoll MA, Sánchez-Miranda A, Navarro FB (2017) Impact of straw and rock-fragment mulches on soil moisture and early growth of holm oaks in a semiarid area. Catena 152: 198-206

Kamphorst SH, Amaral Júnior AT, Lima VJ, Santos PHAD, Rodrigues WP, Vivas JMS, Gonçalves GMB, Schmitt KFM, Leite JT, Vivas M, Mora-Poblete F, Vergara-Dıaz O, Araus Ortega JL, Ramalho JC and Campostrini E (2020) Comparison of selection traits for effective popcorn (*Zea mays* L. var. Everta) breeding under water limiting conditions. Front Plant Sci 11:1289. https://doi.org/10.3389/fpls.2020.01289

Kunrath TR, Lemaire G, Sadras VO, Gastal F (2018) Water use efficiency in perennial forage species: Interactions between nitrogen nutrition and water deficit. F Crop Res 222, 1–11. https://doi.org/10.1016/j.fcr.2018.02.031

Ley GJ, Mullins CE, Lal R (1995) The potential restriction to root growth in structurally weak tropical soils. Soil Tillage Res 33: 133–142

Lynch JP, Wojciechowski T (2015) Opportunities and challenges in the subsoil: pathways to deeper rooted crops. J Exp Bot 66: 2199-2210. https://doi.org/10.1093/jxb/eru508

Lopes ECS, Rodrigues WP, Fraga KR, Machado Filho JA, Silva JR, Assis-Gomes MM, Figueiredo FAMMA, Gresshoff PM, Campostrini E (2019). Hypernodulating soybean mutant line nod4 lacking 'Autoregulation of Nodulation' (AON) has limited root-to-shoot water transport capacity. Annals Bot 124: 979–991. https://doi.org/10.1093/aob/mcz040

Mahal NK, Osterholz WR, Miguez FE, Poffenbarger HJ, Sawyer JE, Olk DC, Archontoulis SV, Castellano MJ (2019) Nitrogen fertilizer suppresses mineralization of soil organic matter in maize agroecosystems. Front Ecol Evol 7: 59. https://doi.org/10.3389/fevo.2019.00059

Maltas A, Kebli H, Oberholzer HR, Weisskopf, P, Sinaj S (2018) The effects of organic and mineral fertilizers on carbon sequestration, soil properties, and crop yields from a long-term field experiment under a Swiss conventional farming system. L Degrad Dev 29: 926-938

Meng F, Zhang J, Yao F, Hao C (2014) Interactive effects of elevated CO_2 concentration and irrigation on photosynthetic parameters and yield of maize in northeast China. PLoS One 9: e98318. https://doi: 10.1371/journal.pone.0098318

Moura ED, Moura, NG, Marques ES, Pinheiro KM, Costa Sobrinho JRS, Aguiar ACF (2009) Evaluating chemical and physical quality indicators for a structurally fragile tropical soil. Soil Use Manag 25: 368-375. https://doi.org/10.1111/j.1475-2743.2009.00238.x

Moura EG, Oliveira AKC, Coutinho G, Pinheiro KM, Aguiar ACF (2012) Management of a cohesive tropical soil to enhance rootability and increase the efficiency of nitrogen and potassium use. Soil Use Manag 28: 370-377. https://doi.org/10.1111/j.1475-2743.2012.00424.x

Moura EG, Portela, SB, Macedo VRA, Sena VGL, Sousa CCM, Aguiar ADCF (2018) Gypsum and legume residue as a strategy to improve soil conditions in sustainability of agrosystems of the humid tropics. Sustainability, 10: 1006. https://doi.org/10.3390/su10041006

Moura EG, Hallett PD, Mooney SJ, Silva FR, Macedo VRA, Aguiar ACF (2020) Physiological and yield response in maize in cohesive tropical soil is improved through the addition of gypsum and leguminous mulch. J Agric Sci pp 1-8. https://doi.org/10.1017/S0021859620000192

Pagter M, Bragato C, Brix H (2005) Tolerance and physiological responses of *Phragmites australis* to water deficit. Aquat Bot 81: 285-299. https://doi.org/10.1016/j.aquabot.2005.01.002

Poffenbarger HJ, Barker DW, Helmers MJ, Miguez FE, Olk DC, Sawyer JE, Six J, Castellano, MJ (2017) Maximum soil organic carbon storage in Midwest US cropping systems when crops are optimally nitrogen-fertilized. PLoS One 12: e0172293. https://doi.org/10.1371/journal.pone.0172293

Raij BV, Quaggio JA, Silva NM (1986) Extraction of phosphorus, potassium, calcium, and magnesium from soils by an ion-exchange resin procedure. Commun Soil Sci Plant Anal 17: 547-566. https://doi.org/10.1080/00103628609367733

Ripley BS, Gilbert ME, Ibrahim DG, Osborne CP (2007) Drought constraints on C-4 photosynthesis: stomatal and metabolic limitations in C-3 and C-4 subspecies of *Alloteropsis semialata*. J Exp Bot 58: 1351–1363. https://doi.org/10.1093/jxb/erl302

Robin P, Morel C, Vial F, Landrain B, Toudic A, Li Y, Akkal-Corfini N (2018) Effect of Three Types of Exogenous Organic Carbon on Soil Organic Matter and Physical Properties of a Sandy Technosol. Sustainability 10: 1146. https://doi.org/10.3390/su10041146

Sarker JR, Singh BP, He X, Fang Y, Li GD, Collins D, Cowie AL (2017) Tillage and nitrogen fertilization enhanced belowground carbon allocation and plant nitrogen uptake in a semi-arid canola crop–soil system. Sci Rep 7: 1-13. https://doi.org/10.1038/s41598-017-11190-4

Sena VG, Moura EG, Macedo VR, Aguiar AC, Price AH, Mooney SJ, Calonego JC (2020) Ecosystem services for intensification of agriculture, with emphasis on increased nitrogen ecological use efficiency. Ecosphere 11: e03028. https://doi.org/10.1002/ecs2.3028

Smith DW (2014) Soil survey staff: keys to soil taxonomy. Natural Resources Conservation Service, Washington USA, pp 1-360

Sumner ME (2009). Gypsum improves subsoil root growth. In: Proceedings of the International Symposium Root Reseacher and Aplications. Viena, Austria, pp 2-4

Tarkiewicz S, Nosalewicz A (2005) Effect of organic carbon content on the compactibility and penetration resistance of two soils formed from loess. Int Agrophysics 19: 345

Veldkamp E (1994) Organic carbon turnover in three tropical soils under pasture after deforestation. Soil Sci Soc Am J 58: 175-180.

Walkley A, Black IA (1934) An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 79: 459-465.

Whittinghill KA, Hobbie SE (2012) Effects of pH and calcium on soil organic matter dynamics in Alaskan tundra. Biogeochemistry 111: 569-581. https://doi.org/10.1007/s10533-011-9688-6

Živčák M, Brestič M, Olšovská K, Slamka P (2008) Performance index as a sensitive indicator of water stress in *Triticum aestivum* L. Plant Soil Environ 54: 133-139. https://doi.org/10.17221/392-PSE

Ecophysiological response of maize to soil management in the Amazonian periphery in the context of climate change adaptation

Regional Environmental Change

Lorena Silva Campos
lorena7campos@gmail.com

Programa de Pós-Graduação em Agroecologia, Universidade Estadual do Maranhão, São Luís, MA 65080-970, Brasil.

Table 1. Soil organic carbon (SOC) fractions: particulate organic carbon (POC), mineral associated-organic carbon (MOC) and total organic carbon (TOC).

SOC fractions	Treatments						
(g/kg)	C	N	G	NG	LG	L	LNG
POC	1.13 b	1.55 ab	1.83 a	1.86 a	1.71 ab	1.81 a	2.00 a
MOC	5.76 b	6.13 b	5.64 b	6.94 b	9.23 a	9.33 a	10.62 a
TOC	6.91 e	7.68 d	7.80 d	8.76 c	10.99 b	11.09 b	12.53 a

Table 2. Exchange base cations (mmol$_c$ m^3) and sum of base cation (SBC).

Cations content (mmol$_c$ m^3)	Treatments						
	C	N	G	L	NG	LG	LNG
	0 - 20 cm						
Ca	5.46 c	5.51 c	9.75 b	11.92 a	13.13 a	12.73 a	14.49 a
Mg	2.22 bc	1.46 c	1.08 d	3.59 a	1.01 d	2.41 b	2.16 bc
K	0.44 ab	0.37 b	0.42 ab	0.48 a	0.37 b	0.44 ab	0.46 a
SBC	8.25 c	7.34 c	11.24 b	16.00 a	14.50 a	15.57 a	17.10 a
	20 - 40 cm						
Ca	2.83 c	2.75 c	8.27 a	4.67 b	8.47 a	7.82 a	7.83 a
Mg	0.86 b	0.79 bc	0.54 bc	1.45 a	0.48 c	0.86 b	0.76 bc
K	0.53 a	0.32 c	0.60 a	0.50 ab	0.37 b	0.50 ab	0.35 bc
SBC	4.62 c	3.85 c	9.74 ab	6.62 b	9.86 a	9.57 ab	9.34 ab

Table 3. Gravimetric soil moisture (g/g) 7 days without water in 2019.

	Treatments						
	(kg/kg)						
Layer (cm)	C	N	G	L	NG	LG	LNG
0 - 10	0.022 b	0.021 b	0.023 b	0.052 a	0.026 b	0.051 a	0.044 a
11 - 20	0.024 c	0.026 c	0.041 bc	0.056 ab	0.042 b	0.059 ab	0.069 a
21 - 30	0.052 ab	0.041 b	0.068 ab	0.098 a	0.051 ab	0.057 ab	0.087 a
31 - 40	0.051 bc	0.043 c	0.040 c	0.089 a	0.045 c	0.073 b	0.086 a

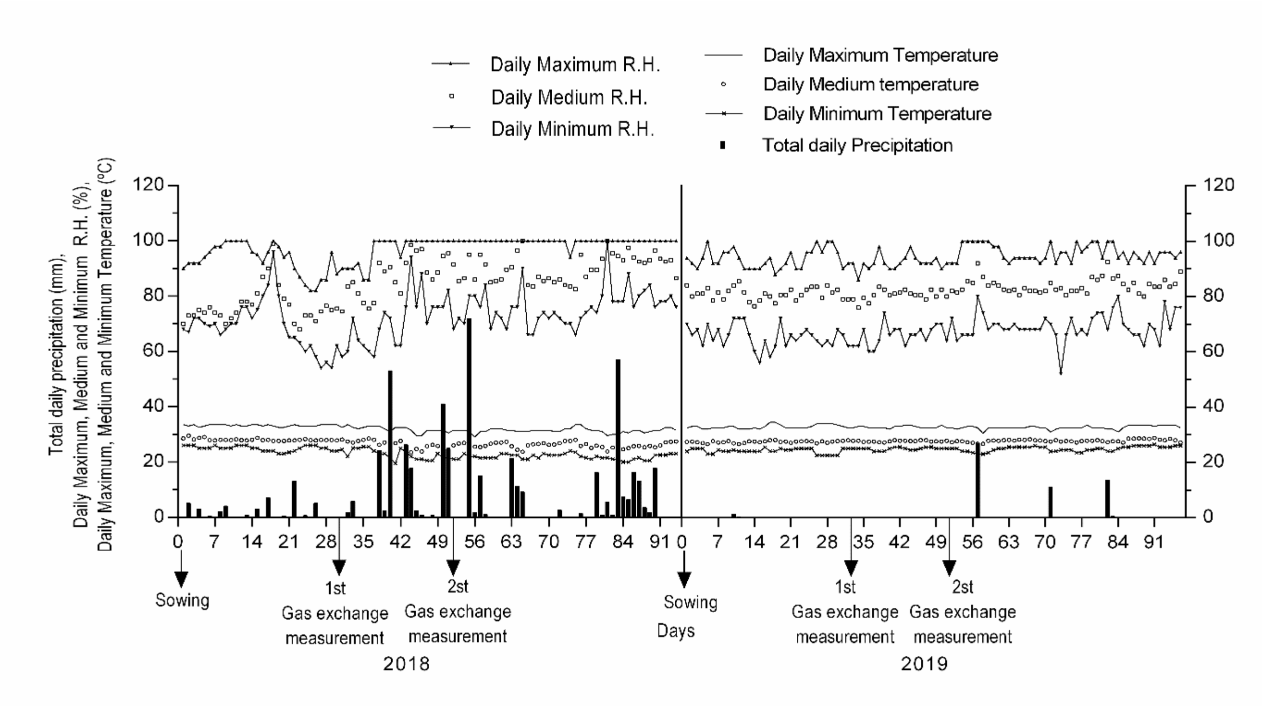


Fig. 1 Precipitation, daily maximum, mean and minimum temperature and relative humidity at the study site, 2018–2019

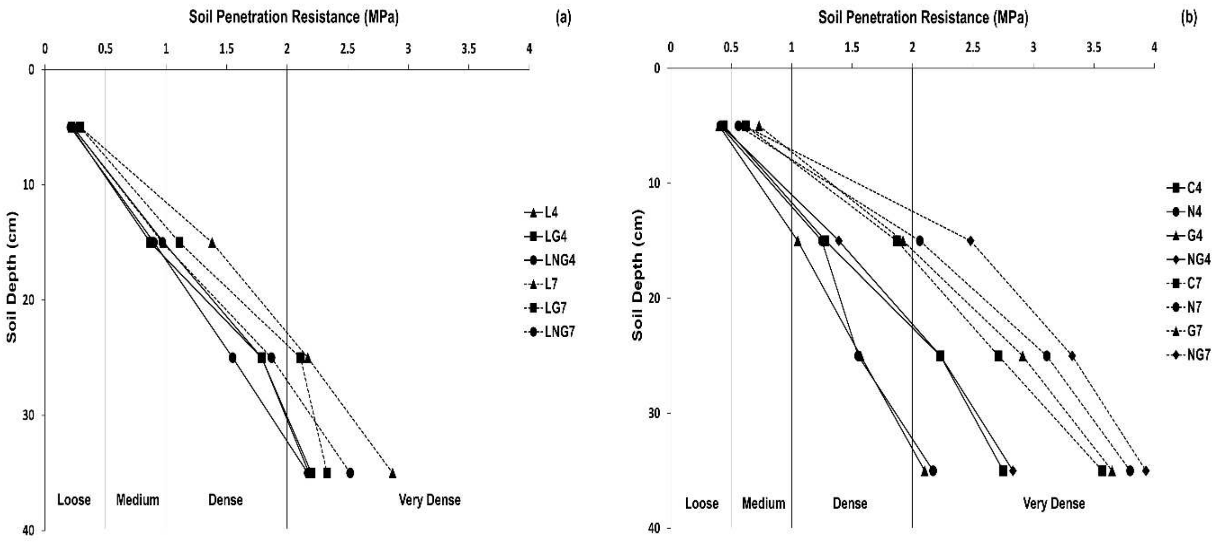


Fig. 2 Response of different treatments with legume residue (a) and without legume residue (b) in soil penetration resistance (MPa). C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum; 4: four days without water; 7: seven days without water. Vertical bars mean the critical levels by Hazelton &Murphy (2007)

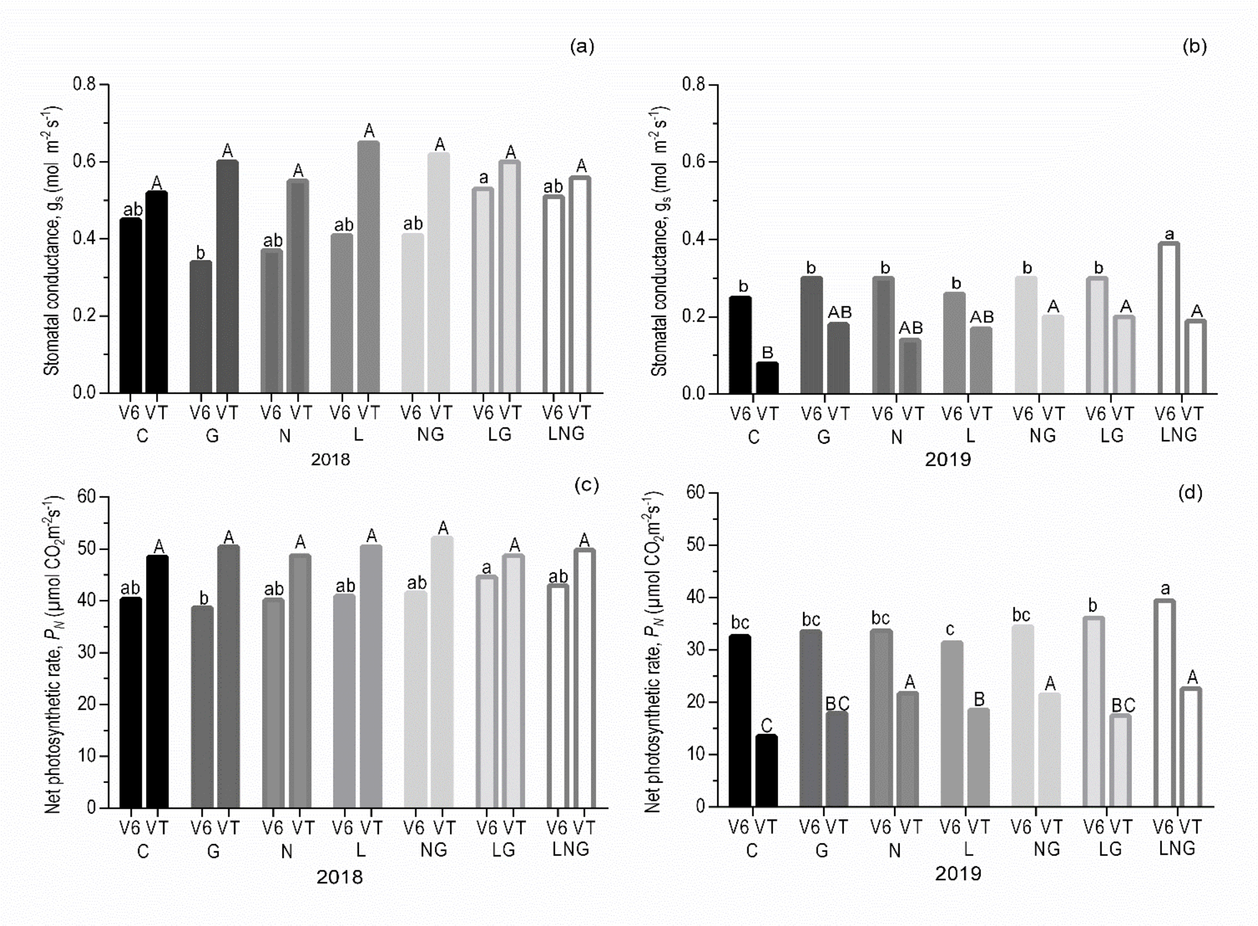


Fig. 3 Stomatal conductance, g_s (mol m^{-2} s^{-1}) in 2018 (a) and in 2019 (b) and net photosynthetic rate, P_N (µmol m^{-2} s^{-1}) in 2018 (c) and 2019 (d). Notes: Different lower-case letters at the V6 stage and different capital letters at the VT stage in each graph indicate significant differences at the 5% level per Tukey's HSD test. C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum

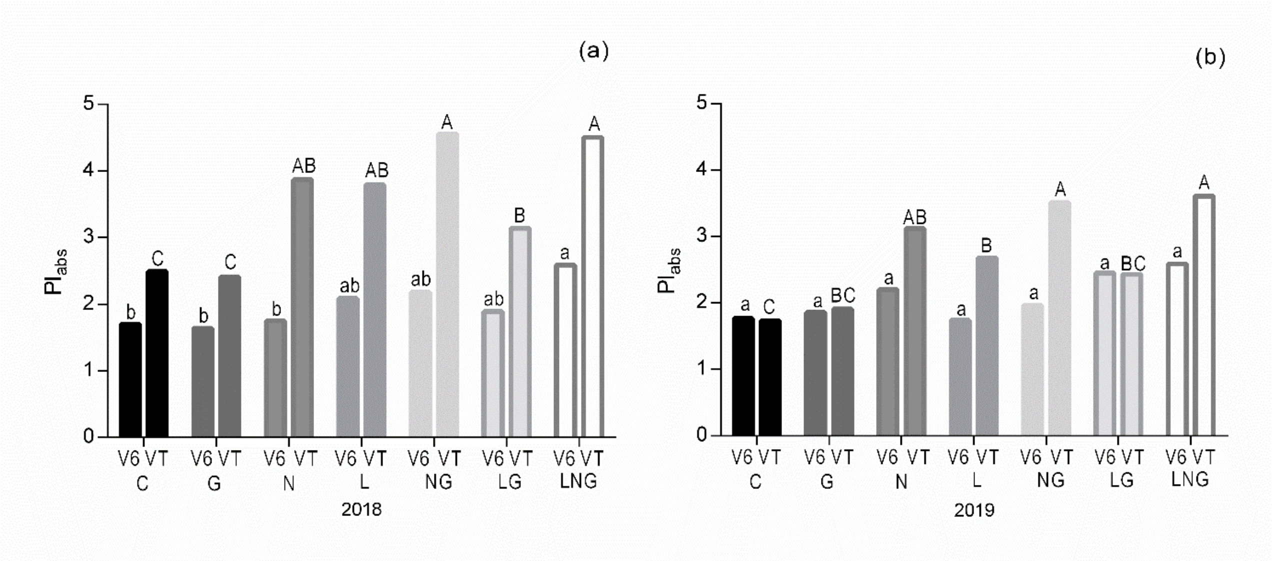


Fig. 4 Performance Index (PI_{abs}) in 2018 (a) and 2019 (b). Notes: Different lower-case letters at the V6 stage and different capital letters at the VT stage in each graph indicate significant differences at the 5% level per Tukey's HSD test. C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum

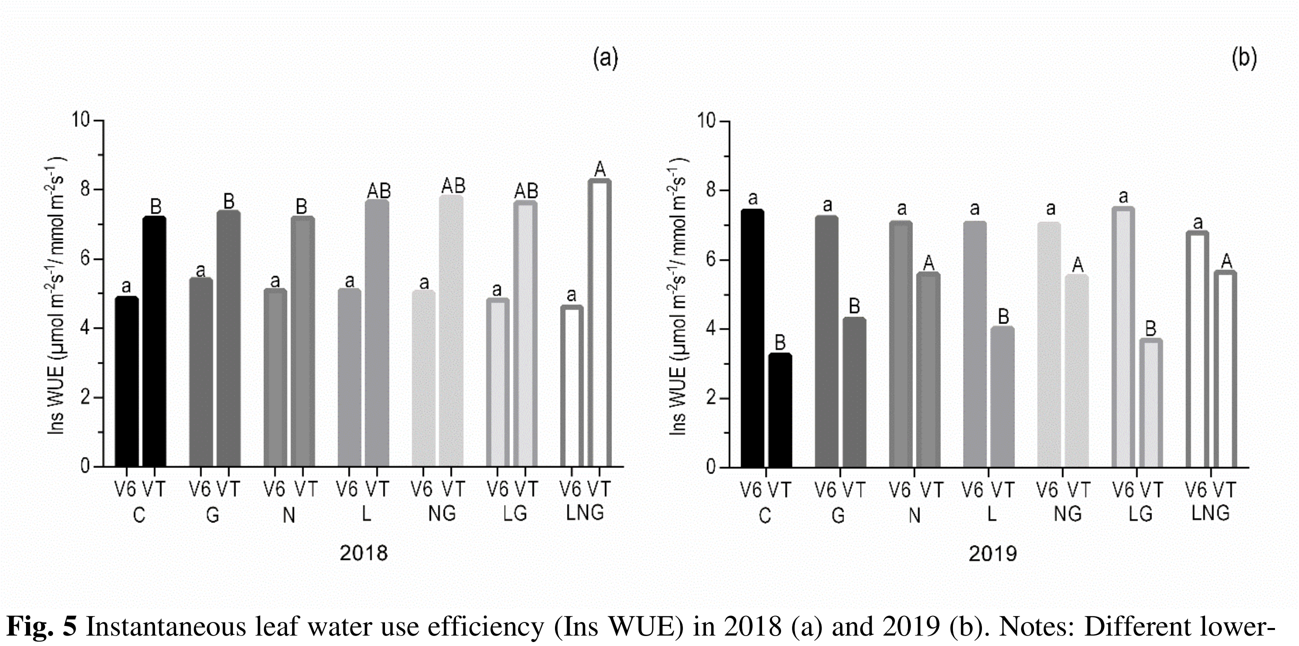


Fig. 5 Instantaneous leaf water use efficiency (Ins WUE) in 2018 (a) and 2019 (b). Notes: Different lower-case letters at the V6 stage and different capital letters at the VT stage in each graph indicate significant differences at the 5% level per Tukey's HSD test. C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum

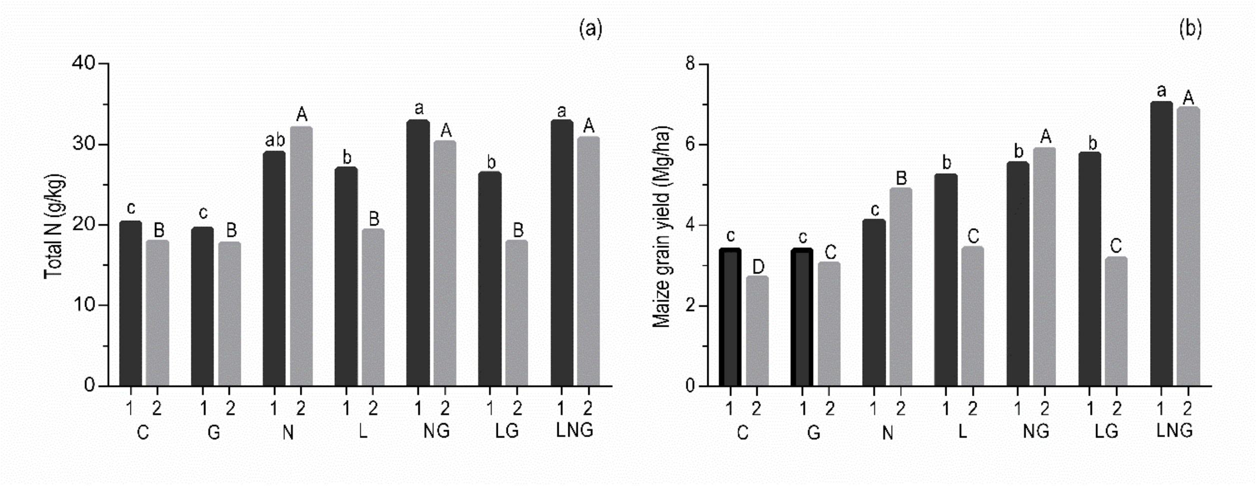


Fig. 6 Effects of different treatments on total N (g kg^{-1}) in 2018 (=1) and 2019 (=2) (a) and maize grain yield (GY) in 2018 (1) and 2019 (2). Notes: Different letters in each graph indicate significant differences at the 5% level per the Tukey's HSD test. C: control; G: gypsum; N: nitrogen; L: legume residue; NG: nitrogen+gypsum; LG: legume residue+gypsum; LNG: legume residue+nitrogen+gypsum

ANEXO

Springer Journal – Regional Environmental Change

LENGTH OF PAPER

Our goal is to encourage original research articles of up to 12 published pages, inclusive of all text, references, figures and tables, which is equivalent to approximately 8,000 words if the manuscript were composed of text alone. Figures and tables are counted as 300 words each. Some leniency in the length upto the equivalence of 9,000 words is permitted subject to editorial discretion; however, submissions excessively over the limit will be returned to the authors before review

LANGUAGE

We appreciate any efforts that you make to ensure that the language is corrected before submission. This will greatly improve the legibility of your paper if English is not your first language. British English or American English spelling and terminology may be used, but either one should be followed consistently throughout the article.

ARTICLE TYPE

1. ***Review Articles*** (upto 9000 words of text), summarizing an important area of science concerning regional environmental change. Editors suggest that authors contact them to discuss proposed review topics with them before finalization and submission of reviews papers.
2. ***Original Research Articles*** (upto 8000), presenting new evidence from analyses of empirical data or else more theoretical investigations of regional environmental change. The findings should always be of interest to an international research community.
3. ***Short Communications*** (up to 3000 words, max 1 figure and 1 table), presenting important findings of similar nature. These submissions will receive high review priority and are, after acceptance, normally published in the next available issue of the journal.
5**. *An Essay*** is a submitted opinion or think piece, subject to review, which has a lower standard of evidence required to justify conclusions than a research article. Essays are published rarely and at the complete discretion of the editors.
4. ***A Commentary*** is an unsolicited and uninvited critique of a paper previously published in Regional Environmental Change. Authors of the original piece are generally invited to prepare a response to the critique, which would be published concurrently with the Commentary. Commentaries and responses are reviewed on the basis of fairness, balance and scientific merit.

5. Editorial

By invitation only.

MANUSCRIPT SUBMISSION

- **Manuscript Submission**
  Submission of a manuscript implies: that the work described has not been published before; that it is not under consideration for publication anywhere else; that its publication has been approved by all co-authors, if any, as well as by the responsible authorities – tacitly or explicitly – at the institute where the work has been carried out. The publisher will not be held legally responsible should there be any claims for compensation.
- **Permissions**
  Authors wishing to include figures, tables, or text passages that have already been published elsewhere are required to obtain permission from the copyright owner(s) for both the print and online format and to include evidence that such permission has been granted when submitting

their papers. Any material received without such evidence will be assumed to originate from the authors.

- **Online Submission**
  Authors should submit their manuscripts online. Electronic submission substantially reduces the editorial processing and reviewing times and shortens overall publication times. Please follow the hyperlink "Submit online" on the right and upload all of your manuscript files following the instructions given on the screen.
- **Proceedings, etc**
  In the case that parts of the text have been published as conference proceedings, project reports, working papers or similar, this needs to be declared during submission - editors will then assess on a case by case basis whether the paper may still be considered original.

PREPARING THE MANUSCRIPT

Title Page

- The title page is part of the manuscript and must include:
  - The full name(s), professional affiliations and e-mail addresses of all author(s)
  - A concise and informative title, indicating the specific region the work relates to (consider Search Engine Optimization when choosing the title)
  - The full professional address, e-mail address and telephone number of the corresponding author
  - Abstract and keywords (see below)
  - Length of the manuscript (see below)

Abstract

Please provide an abstract of 150 to 250 words. The abstract should be highly informative about the findings and conclusions from the paper, and it should not contain any undefined abbreviations or unspecified references.

Keywords

Please provide 4 to 6 keywords which can be used for indexing purposes.

Length of the manuscript

The length of the manuscript must be indicated, consisting of

- The number of words, counting from the top of the title page, including abstract, keywords and acknowledgements to the end of text (before the reference list)
- The number of figures and tables (counting as 300 words each)
- The number of words, including the count for the figures and tables, must not exceed the length of text permitted for the article type
- We urge authors to take full advantage of our capacity for Electronic Supplemental Material. Authors who find the page limit to be particularly restrictive, especially as a result of disciplinary differences, are encouraged to contact the journal office (reec@imbe.fr) for guidance.

Text

Text Formatting

Manuscripts should be submitted in Word.

  - Use a normal, plain font for text.
  - Use italics for emphasis.

  - Use the automatic page numbering function to number the pages.
  - Use the automatic line numbering function to number all lines of the text.
  - Do not use any field functions.
  - Use tab stops or other commands for indents, not the space bar.
  - Use the table function, not spreadsheets, to make tables.
  - Use the equation editor or MathType for equations.
  - Save your file in docx format (Word 2007 or higher) or doc format (older Word versions).

Manuscripts with mathematical content can also be submitted in LaTeX.

  - LaTeX macro package (zip, 182 kB)

Headings

Please use no more than three levels of displayed headings. Do not use acronyms.

Abbreviations

Abbreviations should be defined at first mention and used consistently thereafter.

Footnotes

Footnotes can be used to give important additional information, which may include the citation of a reference included in the reference list. They should not consist solely of a reference citation, and they should never include the bibliographic details of a reference.

Footnotes should not contain any figures or tables.

Footnotes to the text are numbered consecutively; those to tables should be indicated by superscript lower-case letters (or asterisks for significance values and other statistical data).

Footnotes to the title or the authors of the article are not given reference symbols.

Always use footnotes instead of endnotes.

Acknowledgments

Acknowledgments of people, grants, funds, etc. should be placed in a separate section before the reference list. The names of funding organizations should be written in full.

Scientific Style

Please always use internationally accepted signs and symbols for units (SI units).

REFERENCES

Citation

Cite references in the text by name and year in parentheses. Some examples:

- Negotiation research spans many disciplines (Thompson 1990).
- This result was later contradicted by Becker and Seligman (1996).
- This effect has been widely studied (Abbott 1991; Barakat et al. 1995; Kelso and Smith 1998; Medvec et al. 1999).

Reference list

The list of references should only include works that are cited in the text and that have been published or accepted for publication. Personal communications and unpublished works should only be mentioned in the text. Do not use footnotes or endnotes as a substitute for a reference list.

Reference list entries should be alphabetized by the last names of the first author of each work.

Journal article

Gamelin FX, Baquet G, Berthoin S, Thevenet D, Nourry C, Nottin S, Bosquet L (2009) Effect of high intensity intermittent training on heart rate variability in prepubescent children. Eur J Appl Physiol 105:731-738. doi: 10.1007/s00421-008-0955-8
The names of all authors should be provided, the usage of "et al" in long author lists will not be accepted. The doi-number should always be indicated when it exists.
Book

South J, Blass B (2001) The future of modern genomics. Blackwell, London
Book chapter

Brown B, Aaron M (2001) The politics of nature. In: Smith J (ed) The rise of modern genomics, 3rd edn. Wiley, New York, pp 230-257
Online document

Cartwright J (2007) Big stars have weather too. IOP Publishing PhysicsWeb. http://physicsweb.org/articles/news/11/6/16/1. Accessed 26 June 2007

Dissertation

Trent JW (1975) Experimental acute renal failure. Dissertation, University of California
Always use the standard abbreviation of a journal's name according to the ISSN List of Title Word Abbreviations, see
ISSN.org LTWA
If you are unsure, please use the full journal title.
For authors using EndNote, Springer provides an output style that supports the formatting of in-text citation list.
EndNote style (zip, 2 kB)

Request Figures and Tables

Authors are required to separate figures and tables from the main text file.
Any figure captions containing acronyms should be explained.

Tables

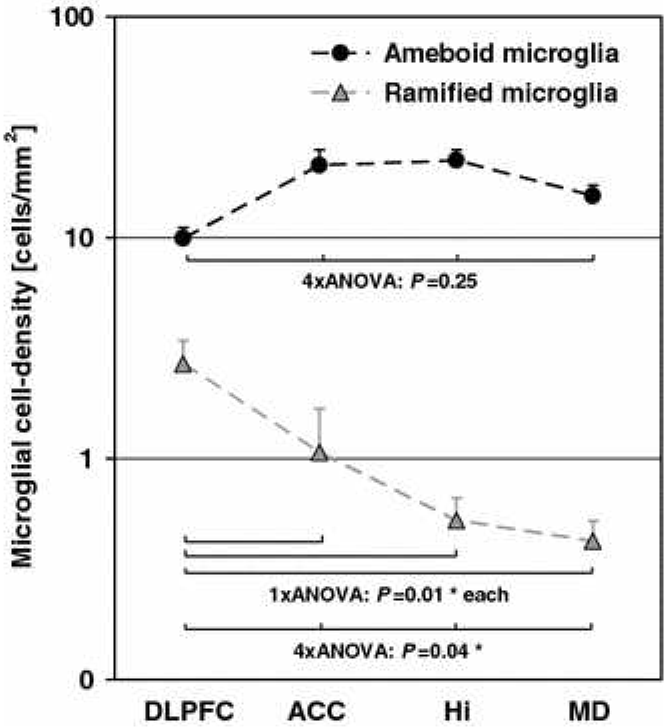
- All tables are to be numbered using Arabic numerals.
- Tables should always be cited in text in consecutive numerical order.
- For each table, please supply a table caption (title) explaining the components of the table.
- Identify any previously published material by giving the original source in the form of a reference at the end of the table caption.
- Footnotes to tables should be indicated by superscript lower-case letters (or asterisks for significance values and other statistical data) and included beneath the table body.

Artwork and Illustrations Guidelines

- Electronic Figure Submission
    - Supply all figures electronically.
    - Illustrations should only contain essential content for the topic of the paper.
    - All lettering should be scaled such as to allow the smallest possible printing of the illustration.

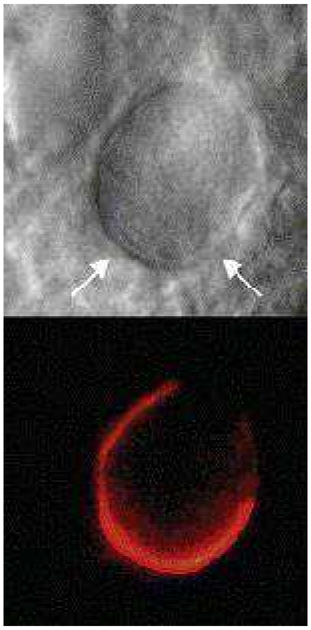
- For vector graphics, the preferred format is EPS; for halftones, please use TIFF format. MSOffice files are also acceptable. (Indicate what graphics program was used to create the artwork.)
- Vector graphics containing fonts must have the fonts embedded in the files.
- Name your figure files with "Fig" and the figure number, e.g., Fig1.eps.

Line Art



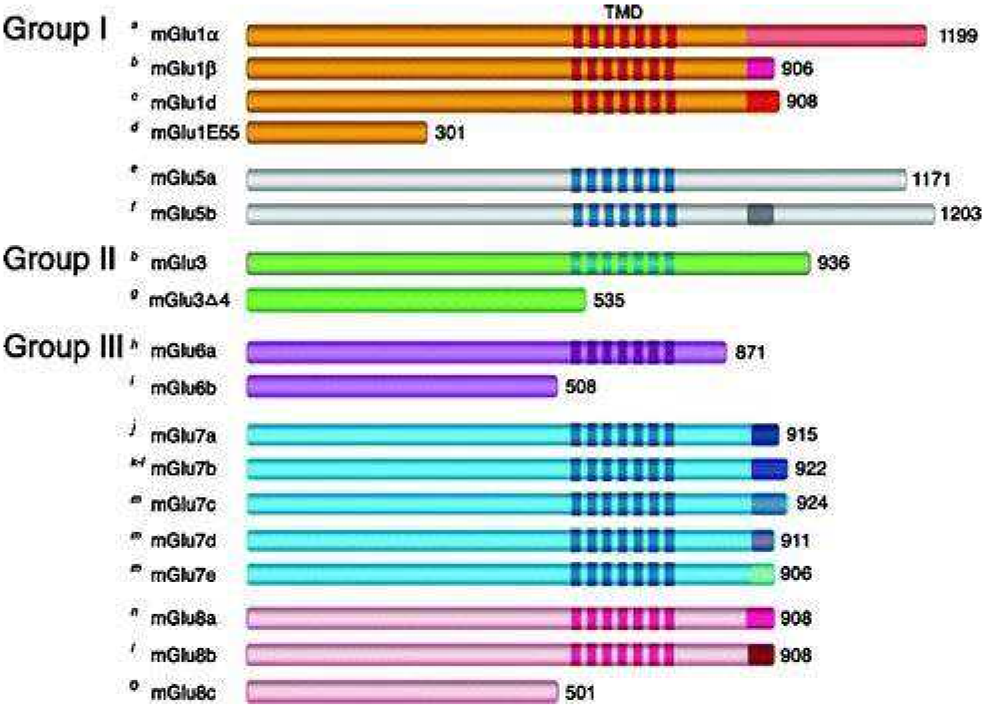
- Definition: Black and white graphic with no shading.
- Do not use faint lines and/or lettering and check that all lines and lettering within the figures are legible at final size.
- All lines should be at least 0.1 mm (0.3 pt) wide.
- Scanned line drawings and line drawings in bitmap format should have a minimum resolution of 1200 dpi.
- Vector graphics containing fonts must have the fonts embedded in the files.

Halftone Art



- Definition: Photographs, drawings, or paintings with fine shading, etc.
- If any magnification is used in the photographs, indicate this by using scale bars within the figures themselves.
- Halftones should have a minimum resolution of 300 dpi.

Combination Art



- Definition: a combination of halftone and line art, e.g., halftones containing line drawing, extensive lettering, color diagrams, etc.
- Combination artwork should have a minimum resolution of 600 dpi.

Colour Art

- Colour art is free of charge for online and print publication.
- If black and white will be shown in the print version, make sure that the main information will still be visible. Many colours are not distinguishable from one another when converted to black and white. A simple way to check this is to make a xerographic copy to see if the necessary distinctions between the different colours are still apparent.
- If the figures will be printed in black and white, do not refer to colour in the captions.
- Colour illustrations should be submitted as RGB (8 bits per channel).

Figure Lettering

- To add lettering, it is best to use Helvetica or Arial (sans serif fonts).
- Keep lettering consistently sized throughout your final-sized artwork, usually about 2–3 mm (8–12 pt).
- Variance of type size within an illustration should be minimal, e.g., do not use 8-pt type on an axis and 20-pt type for the axis label.
- Avoid effects such as shading, outline letters, etc.
- Do not include titles or captions within your illustrations.

Figure Numbering

- All figures are to be numbered using Arabic numerals.

- Figures should always be cited in text in consecutive numerical order.
- Figure parts should be denoted by lowercase letters (a, b, c, etc.).
- If an appendix appears in your article and it contains one or more figures, continue the consecutive numbering of the main text. Do not number the appendix figures, "A1, A2, A3, etc." Figures in online appendices (Electronic Supplementary Material) should, however, be numbered separately.

Figure Captions

- Each figure should have a concise caption describing accurately what the figure depicts. Include the captions in the text file of the manuscript, not in the figure file.
- Figure captions begin with the term Fig. in bold type, followed by the figure number, also in bold type.
- No punctuation is to be included after the number, nor is any punctuation to be placed at the end of the caption.
- Identify all elements found in the figure in the figure caption; and use boxes, circles, etc., as coordinate points in graphs.
- Identify previously published material by giving the original source in the form of a reference citation at the end of the figure caption.

Figure Placement and Size

- When preparing your figures, size figures to fit in the column width.
- For most journals the figures should be 39 mm, 84 mm, 129 mm, or 174 mm wide and not higher than 234 mm.
- For books and book-sized journals, the figures should be 80 mm or 122 mm wide and not higher than 198 mm.

Permissions

If you include figures that have already been published elsewhere, you must obtain permission from the copyright owner(s) for both the print and online format. Please be aware that some publishers do not grant electronic rights for free and that Springer will not be able to refund any costs that may have occurred to receive these permissions. In such cases, material from other sources should be used.

Accessibility

In order to give people of all abilities and disabilities access to the content of your figures, please make sure that

- All figures have descriptive captions (blind users could then use a text-to-speech software or a text-to-Braille hardware)
- Patterns are used instead of or in addition to colors for conveying information (colorblind users would then be able to distinguish the visual elements)
- Any figure lettering has a contrast ratio of at least 4.5:1

ELECTRONIC SUPPLEMENTARY MATERIAL

Springer accepts electronic multimedia files (animations, movies, audio, etc.) and other supplementary files to be published online along with an article or a book chapter. This feature can add dimension to the author's article, as certain information cannot be printed or is more convenient in electronic form.

Submission

- Supply all supplementary material in standard file formats.
- Please include in each file the following information: article title, journal name, author names; affiliation and e-mail address of the corresponding author.
- To accommodate user downloads, please keep in mind that larger-sized files may require very long download times and that some users may experience other problems during downloading.

Audio, Video, and Animations

- Always use MPEG-1 (.mpg) format.

Text and Presentations

- Submit your material in PDF format; .doc or .ppt files are not suitable for long-term viability.
- A collection of figures may also be combined in a PDF file.

Spreadsheets

- Spreadsheets should be converted to PDF if no interaction with the data is intended.
- If the readers should be encouraged to make their own calculations, spreadsheets should be submitted as .xls files (MS Excel).

Specialized Formats

Specialized format such as .pdb (chemical), .wrl (VRML), .nb (Mathematica notebook), and .tex can also be supplied.

Collecting Multiple Files

- It is possible to collect multiple files in a .zip or .gz file.

Numbering

- If supplying any supplementary material, the text must make specific mention of the material as a citation, similar to that of figures and tables.
- Refer to the supplementary files as “Online Resource”, e.g., "... as shown in the animation (Online Resource 3)", “... additional data are given in Online Resource 4”.
- Name the files consecutively, e.g. “ESM_3.mpg”, “ESM_4.pdf”

Captions

- For each supplementary material, please supply a concise caption describing the content of the file.

Processing of supplementary files

- Electronic supplementary material will be published as received from the author without any conversion, editing, or reformatting.

Accessibility

In order to give people of all abilities and disabilities access to the content of your supplementary files, please make sure that:

- The manuscript contains a descriptive caption for each supplementary material
- Video files do not contain anything that flashes more than three times per second (so that users prone to seizures caused by such effects are not put at risk

DOES SPRINGER PROVIDE LANGUAGE SUPPORT?

Manuscripts that are accepted for publication will be checked by our copyeditors for spelling and formal style. This may not be sufficient if English is not your native language and substantial editing would be required. In that case, you may want to have your manuscript edited by a native speaker prior to submission. Clear and concise language is required for acceptance of your paper.

The following editing service provides language editing for scientific articles in all areas Springer publishes in:

Edanz English editing for scientists

Use of an editing service is neither a requirement nor a guarantee of acceptance for publication.

Please contact the editing service directly to make arrangements for editing and payment.

For Authors from China

文章在投稿前进行专业的语言润色将对作者的投稿进程有所帮助。作者可自愿选择使用Springer**推荐的**编辑服务，使用与否并不作为判断文章是否被录用的依据。提高文章的语言质量将有助于审稿人理解文章的内容，通过对学术内容的判断来决定文章的取舍，而不会因为语言问题导致直接退稿。作者需自行联系Springer**推荐的**编辑服务公司，协商编辑事宜。

理文编辑

For Authors from Japan

ジャーナルに論文を投稿する前に、ネイティブ・スピーカーによる英文校閲を希望されている方には、Edanz社をご紹介しています。サービス内容、料金および申込方法など、日本語による詳しい説明はエダンズグループジャパン株式会社の下記サイトをご覧ください。

エダンズグループジャパン

For Authors from Korea

영어 논문 투고에 앞서 원어민에게 영문 교정을 받고자 하시는 분들께 Edanz 회사를 소개해 드립니다. 서비스 내용, 가격 및

신청 방법 등에 대한 자세한 사항은 저희 Edanz Editing Global 웹사이트를 참조해 주시면 감사하겠습니다.

Edanz Editing Global

Please contact the editing service directly to make arrangements for editing and payment.

ETHICAL RESPONSIBILITY OF THE AUTHORS

This journal is committed to upholding the integrity of the scientific record. As a member of the Committee on Publication Ethics (COPE) the journal will follow the COPE guidelines on how to deal with potential acts of misconduct.

Authors should refrain from misrepresenting research results which could damage the trust in the journal, the professionalism of scientific authorship, and ultimately the entire scientific endeavour.

Maintaining integrity of the research and its presentation can be achieved by following the rules of good scientific practice, which include:

- The manuscript has not been submitted to more than one journal for simultaneous consideration.
- The manuscript has not been published previously (partly or in full), unless the new work concerns an expansion of previous work (please provide transparency on the re-use of material to avoid the hint of text-recycling ("self-plagiarism")).
- A single study is not split up into several parts to increase the quantity of submissions and submitted to various journals or to one journal over time (e.g. "salami-publishing").
- No data have been fabricated or manipulated (including images) to support your conclusions.
- No data, text, or theories by others are presented as if they were the author's own ("plagiarism"). Proper acknowledgements to other works must be given (this includes material that is closely copied (near verbatim), summarized and/or paraphrased), quotation marks are used for verbatim copying of material, and permissions are secured for material that is copyrighted.

  Important note: the journal may use software to screen for plagiarism.

  - Consent to submit has been received explicitly from all co-authors, as well as from the responsible authorities - tacitly or explicitly - at the institute/organization where the work has been carried out, **before** the work is submitted.
  - Authors whose names appear on the submission have contributed sufficiently to the scientific work and therefore share collective responsibility and accountability for the results.

In addition:

- Changes of authorship or in the order of authors are not accepted **after** acceptance of a manuscript.
- Requesting to add or delete authors at revision stage, proof stage, or after publication is a serious matter and may be considered when justifiably warranted. Justification for changes in authorship must be compelling and may be considered only after receipt of written approval from all authors and a convincing, detailed explanation about the role/deletion of the new/deleted author. In case of changes at revision stage, a letter must accompany the revised manuscript. In case of changes after acceptance or publication, the request and documentation must be sent via the Publisher to the Editor-in-Chief. In all cases, further documentation may be required to support your request. The decision on accepting the change rests with the Editor-in-Chief of the journal and may be turned down. Therefore authors are strongly advised to ensure the correct author group, corresponding author, and order of authors at submission.
- Upon request authors should be prepared to send relevant documentation or data in order to verify the validity of the results. This could be in the form of raw data, samples, records, etc.

If there is a suspicion of misconduct, the journal will carry out an investigation following the COPE guidelines. If, after investigation, the allegation seems to raise valid concerns, the accused author will be contacted and given an opportunity to address the issue. If misconduct has been established beyond reasonable doubt, this may result in the Editor-in-Chief's implementation of the following measures, including, but not limited to:

- If the article is still under consideration, it may be rejected and returned to the author.
- If the article has already been published online, depending on the nature and severity of the infraction, either an erratum will be placed with the article or in severe cases complete

retraction of the article will occur. The reason must be given in the published erratum or retraction note.

- The author’s institution may be informed.

COMPLIANCE WITH ETHICAL STANDARDS

To ensure objectivity and transparency in research and to ensure that accepted principles of ethical and professional conduct have been followed, authors should include information regarding sources of funding, potential conflicts of interest (financial or non-financial), informed consent if the research involved human participants, and a statement on welfare of animals if the research involved animals. Authors should include the following statements (if applicable) in a separate section entitled “Compliance with Ethical Standards” before the References when submitting a paper:

- Disclosure of potential conflicts of interest
- Research involving Human Participants and/or Animals
- Informed consent

Please note that standards could vary slightly per journal dependent on their peer review policies (i.e. double blind peer review) as well as per journal subject discipline. Before submitting your article check the Instructions for Authors carefully.

The corresponding author should be prepared to collect documentation of compliance with ethical standards and send if requested during peer review or after publication.

The Editors reserve the right to reject manuscripts that do not comply with the above-mentioned guidelines. The author will be held responsible for false statements or failure to fulfill the above-mentioned guidelines.

DISCLOSURE OF POTENTIAL CONFLICTS OF INTEREST

Authors must disclose all relationships or interests that could have direct or potential influence or impart bias on the work. Although an author may not feel there is any conflict, disclosure of relationships and interests provides a more complete and transparent process, leading to an accurate and objective assessment of the work. Awareness of a real or perceived conflicts of interest is a perspective to which the readers are entitled. This is not meant to imply that a financial relationship with an organization that sponsored the research or compensation received for consultancy work is inappropriate. Examples of potential conflicts of interests **that are directly or indirectly related to the research** may include but are not limited to the following:

- Research grants from funding agencies (please give the research funder and the grant number)
- Honoraria for speaking at symposia
- Financial support for attending symposia
- Financial support for educational programs
- Employment or consultation
- Support from a project sponsor
- Position on advisory board or board of directors or other type of management relationships
- Multiple affiliations
- Financial relationships, for example equity ownership or investment interest
- Intellectual property rights (e.g. patents, copyrights and royalties from such rights)
- Holdings of spouse and/or children that may have financial interest in the work

In addition, interests that go beyond financial interests and compensation (non-financial interests) that may be important to readers should be disclosed. These may include but are not limited to personal relationships or competing interests directly or indirectly tied to this research, or professional interests or personal beliefs that may influence your research.
The corresponding author collects the conflict of interest disclosure forms from all authors. In author collaborations where formal agreements for representation allow it, it is sufficient for the corresponding author to sign the disclosure form on behalf of all authors. Examples of forms can be found here:
The corresponding author will include a summary statement in the text of the manuscript in a separate section before the reference list, that reflects what is recorded in the potential conflict of interest disclosure form(s).

See below examples of disclosures:
Funding: This study was funded by X (grant number X).
Conflict of Interest: Author A has received research grants from Company A. Author B has received a speaker honorarium from Company X and owns stock in Company Y. Author C is a member of committee Z.
If no conflict exists, the authors should state:
Conflict of Interest: The authors declare that they have no conflict of interest.

AFTER ACCEPTANCE

Upon acceptance of your article you will receive a link to the special Author Query Application at Springer’s web page where you can sign the Copyright Transfer Statement online and indicate whether you wish to order OpenChoice, offprints, or printing of figures in color.
Once the Author Query Application has been completed, your article will be processed and you will receive the proofs.

Open Choice

In addition to the normal publication process (whereby an article is submitted to the journal and access to that article is granted to customers who have purchased a subscription), Springer provides an alternative publishing option: Springer Open Choice. A Springer Open Choice article receives all the benefits of a regular subscription-based article, but in addition is made available publicly through Springer’s online platform SpringerLink.
Springer Open Choice

Copyright transfer

Authors will be asked to transfer copyright of the article to the Publisher (or grant the Publisher exclusive publication and dissemination rights). This will ensure the widest possible protection and dissemination of information under copyright laws.
Open Choice articles do not require transfer of copyright as the copyright remains with the author. In opting for open access, the author(s) agree to publish the article under the Creative Commons Attribution License.

Offprints

Offprints can be ordered by the corresponding author.

Color illustrations

Online publication of color illustrations is free of charge. For color in the print version, authors will be expected to make a contribution towards the extra costs.

Proof reading

The purpose of the proof is to check for typesetting or conversion errors and the completeness and accuracy of the text, tables and figures. Substantial changes in content, e.g., new results, corrected values, title and authorship, are not allowed without the approval of the Editor.
After online publication, further changes can only be made in the form of an Erratum, which will be hyperlinked to the article.

Online First

The article will be published online after receipt of the corrected proofs. This is the official first publication citable with the DOI. After release of the printed version, the paper can also be cited by issue and page numbers.

Springer

http://www.springer.com/journal/10113

Regional Environmental Change
Editor-in-Chief: Cramer, W.; Ford, J.D.
ISSN: 1436-3798 (print version)
ISSN: 1436-378X (electronic version)
Journal no. 10113