NIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
FACULDADE DE AGRONOMIA
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIA DO SOLO

ROTAÇÃO DE CULTURAS EM LATOSSOLO SUBTROPICAL EM PLANTIO DIRETO: CARBONO ORGÂNICO E PRODUTIVIDADE DAS CULTURAS

Guilherme Rosa da Silva

(Dissertação de Mestrado)

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GUILHERME ROSA DA SILVA
Engenheiro Agrônomo (UFRGS)

Dissertação apresentada como um
dos requisitos à obtenção do Grau
de Mestre em Ciência do Solo

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GUILHERME ROSA DA SILVA
Engenheiro Agrônomo - UFRGS

DISSERTAÇÃO

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Por

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Data: 12/03/2024 10:50:31-0300
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CIMÉLIO BAYER
Orientador-PPG Ciência do Solo

ALBERTO VASCONCELLOS INDA JUNIOR
Coordenador do
Programa de Pós-Graduação em
Ciência do Solo

PAULO CÉSAR DO NASCIMENTO
PPG Ciência do Solo/UFRGS
(Microsoft Teams)

JONATAS THIAGO PIVA
PPG Agronomia/UTFPR Pato Branco
(Microsoft Teams)

Documento assinado digitalmente
gov.br CARLOS ALBERTO BISSANI
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YARA Fertilizantes Brasil S.A.
(Microsoft Teams)

CARLOS ALBERTO BISSANI
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de Agronomia

"I have a dream that my four little children will one day live in a nation where they will not be judged by the color of their skin but by the content of their character."

Martin Luther King Jr

Dedico à minha mãe e ao meu pai, às minhas avós, e aos meus antepassados e conterrâneos do quilombo. Neuza e Rogério, Maria Alzira e Maria Ieda, Quilombo de Casca.

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ROTAÇÃO DE CULTURAS EM LATOSSOLO SUBTROPICAL EM PLANTIO DIRETO: CARBONO ORGÂNICO E PRODUTIVIDADE DAS CULTURAS [1]

Autor: Eng. Agr. Guilherme Rosa da Silva
Orientador: Prof. Dr. Cimélio Bayer

RESUMO

O impacto do manejo do solo na matéria orgânica e no sequestro de carbono (C) no solo é crucial no desenvolvimento de sistemas de produção agrícola com características de elevada produtividade. O objetivo deste estudo foi avaliar o potencial de sequestro de C em um Latossolo subtropical em plantio direto com sistemas de rotação de culturas e o impacto destes na produtividade da soja, milho e cevada em comparação a sistemas de monocultura na região Centro-Sul do Paraná. O estudo foi baseado em experimento de longa duração (20 anos) com sistemas de monocultura de soja ou milho no verão com cevada no inverno, e de rotação de soja e milho no verão, e de cevada com trigo, aveia branca, canola ou nabo forrageiro no inverno. Foi amostrado o solo até a profundidade de 40 cm em 5 camadas para determinar o C pelo método de combustão a seco. Os sistemas de culturas apresentaram impacto expressivo no conteúdo de C orgânico do solo (COS) na maioria das camadas até 40 cm no solo, mas seu efeito mais expressivo foi na camada superficial do solo (0-5 cm). O estoque de COS na camada de 0-40 cm variou de 114,0 a 131,8 Mg ha^{-1} (CS-1 a CS-5), resultando em taxas anuais de sequestro de C variando de 0,36 a 0,89 Mg ha^{-1}ano^{-1} (CS-2 a CS-5) em comparação ao solo sob monocultura de soja, com taxa média de 0,44 Mg ha^{-1} por ano. Na média, a cada unidade (1 Mg ha^{-1}) de C adicionado anualmente pelos resíduos vegetais a mais na rotação de culturas, 0,2 Mg ha^{-1} de C foi acumulada adicionalmente no solo. Em geral, a soja (3.352 a 3.517 kg ha^{-1}), milho (8.441 a 12.185 kg ha^{-1}) e cevada (3.132 a 4.020 kg ha^{-1}) apresentaram maiores produtividades quando cultivadas em rotação de culturas do que em monocultura, e o impacto na produtividade foi relacionado à diversidade de espécie na rotação. A estabilidade da produtividade do milho e da cevada foi maior também com a maior diversidade de espécies, mas a soja não foi influenciada pelo arranjo cultural. Os maiores benefícios das rotações de culturas sobre o rendimento de grãos das culturas foram observados em safras com ocorrência de déficit hídrico (baixo índice de satisfação da necessidade de água, ISNA) do que nas safras com adequado suprimento de água (alto ISNA), e a diferença na produtividade das culturas em rotação em relação à monocultura aumentou ao longo do período de 20 anos. Além de ampliar o sequestro de C em solos em plantio direto, a diversidade de espécies em sistemas de rotação contribui para a maior produtividade das culturas, principalmente em anos secos.

Palavras-chave: manejo do solo, plantio direto, sequestro de carbono, agricultura de conservação.

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[1]Dissertação de Mestrado em Ciência do Solo. Programa de Pós-Graduação em Ciência do Solo, Faculdade de Agronomia, Universidade Federal do Rio Grande do Sul. Porto Alegre. (70p.) abril, 2021. Trabalho realizado com apoio financeiro do CNPq, Fapergs e Yara Brasil Fertilizantes S.A.

CROP ROTATION IN A SUBTROPICAL OXISOL IN NO-TILLAGE: ORGANIC CARBON AND CROP YIElD[2]

Author: Eng. Agr. Guilherme Rosa da Silva
Adviser: Prof. Cimélio Bayer

ABSTRACT

The influence of soil management on organic matter dynamics and carbon (C) sequestration is a crucial topic for the development of high-yield and climate-smart agriculture systems. We assessed the potential of crop rotations on increasing soybean, maize, and barley yield, and to increment soil organic C (SOC) stocks and annual C sequestration rates in a subtropical clayey Hapludox under no-till in comparison to soybean-barley monocropping. The study was based on a long-term experiment with monocropping of soybean and maize in summer and barley in winter, and crop rotations of maize and soybean in summer and barley with oat, wheat and canola or folder radish in winter in the Center-south region of Paraná State. The soil was sampled to a depth of 40 cm for five layers; the C was determined by the dry combustion method in a Thermo CN Flash 2000 analyzer. Cropping systems had an expressive impact on SOC content in most layers until 40 cm, but its main effect was in the topsoil layer (0-5 cm). The SOC stock of 0-40 cm layer ranged from 114.0 to 131.8 Mg ha^{-1} (CS-1 to CS-5), resulting in annual C sequestration rates ranging from 0.36 to 0.89 Mg ha^{-1}yr^{-1} (CS-2 to CS-5) in comparison to soybean monocropping, with an average rate of 0.44 Mg ha^{-1}. In average, for each unit (1 Mg ha^{-1}) of C added per year by plant residues more than in monocropping, an additional rate of 0.2 Mg ha^{-1} yr^{-1} of C was accumulated in the soil. In general, the yield of soybean (from 3,352 to 3,517 kg ha^{-1}), maize (8,441 to 12,185 kg ha^{-1}), and barley (3132 to 4020 kg ha^{-1}) was higher when grown in crop rotation than in monocropping, and the impact on grain yield had a close relationship with crop diversity. The yield stability of maize and barley increased with crop diversity, but soybean had similar stability of yield grown in crop rotation or monocropping. The higher benefits of crop rotation on grain yield of crops were observed in drought growing seasons (low water requirement satisfaction index, WRSI) than moist growing seasons (high WRSI), and the difference of crop rotation related to monocropping increased over the 20 years. Thus, in addition to increase the potential of C sequestration in no-till soils from subtropical regions, the increase of crop diversity in crop rotation systems brings several benefits to crop yield and can reduce the impact of climate change on crop yields and improve food security.

Keywords: soil management, no-tillage, carbon sequestration, conservation agriculture.

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RELAÇÃO DE ABREVIATURAS

PORTUGUÊS:

C – carbono

N – nitrogênio

SPD – sistema plantio direto

GEE – gases de efeito estufa

AC – agricultura de conservação

COS – carbono orgânico do solo

MOS – matéria orgânica do solo

CTC – capacidade de troca de cátions

ISNA – índice de satisfação das necessidades de água

IDC – índice de diversidade de culturas

INGLÊS:

C – Carbon

N – Nitrogen

NT – no-till or no-tillage

GHG – greenhouse gases

CA – conservation agriculture

CS – cropping system

SOC – soil organic carbon

SOM – soil organic matter

BD – bulk density

WRSI – water requirement satisfaction index

CDI – crop diversity index

CAPÍTULO I – INTRODUÇÃO

A mudança no uso da terra causou, no último século, um aumento nas emissões de CO_2 devido às atividades humanas. Estima-se que a conversão de áreas de vegetação nativa para agrícolas anterior a 1900 pode ter contribuído com 25% do aumento observado na concentração de CO_2 na atmosfera (ROBERTSON, 2014). Em grande parte, isso se deveu à redução dos estoques de C orgânico contido no solo por causa do intenso revolvimento e baixo aporte de resíduos vegetais ao solo (ASSUNÇÃO *et al.*, 2019a; BAYER *et al.*, 2006a, 2006b, 2000b; HUANG *et al.*, 2015). Associado às perdas de matéria orgânica do solo (MOS), ocorre uma redução da capacidade produtiva dos solos agrícolas devido à erosão e degradação de suas condições físicas, químicas e biológicas, processo o qual é bastante intensificado em ambientes tropicais e subtropicais (LAL, 2019a, 2019b).

A reversão desse processo de degradação do solo e o alcance da sustentabilidade da produção agrícola em regiões tropicais e subtropicais podem ser alcançados pela adoção da agricultura conservacionista, a qual tem nos princípios do sistema plantio direto (SPD) o seu alicerce: (1) não revolvimento do solo, (2) cobertura permanente do solo, e (3) diversificação de culturas (LAL, 2015, 2019a). O não revolvimento é um aspecto essencial em sistemas agrícolas tropicais e subtropicais pois, através da cobertura de solo pelos resíduos vegetais, tem forte impacto no controle da erosão hídrica, além dos seus efeitos na melhoria da qualidade do solo devido à redução das taxas dos processos de natureza biológica, os quais são muito intensos nesses ecossistemas (BAYER *et al.*, 2000a, 2000b; ROBERTSON, 2014; SANTOS; BAYER; MELNICZUK, 2008).

Além do não revolvimento do solo, o qual tem um efeito essencial na redução das taxas de decomposição microbiana da matéria orgânica do solo, a recuperação dos estoques de C orgânico do solo é muito dependente dos sistemas de cultura em plantio direto devido à sua influência no aporte anual de C fotossintetizado ao solo (BAYER *et al.*, 2006b; PAUSTIAN, 2014a). A recuperação dos teores de C orgânico no solo determinam uma melhoria da qualidade do solo, e esse efeito também pode ter uma expressiva influência na produtividade das culturas. Nesse sentido, o SPD tem um papel fundamental na sustentabilidade da agricultura em nível mundial, e em grande expressão, no subtrópico (região Sul) e trópico (Amazônica e Cerrado) brasileiros, tanto no que se refere ao controle da erosão hídrica e melhoria da qualidade do solo, quanto na produtividade das culturas devido destacadamente à maior disponibilidade de nutrientes (BAYER *et al.*, 2006a; LIU *et al.*, 2006; TURMEL *et al.*, 2015) e maior disponibilidade de água (FERREIRA *et al.*, 2020; JENSEN *et al.*, 2020; TURMEL *et al.*, 2015).

O SPD, que foi iniciado e conduzido baseado no não revolvimento, cobertura permanente do solo e diversidade cultural, com o passar do tempo passou a ter introduzidas técnicas como o pousio e a monocultura, os quais ferem os preceitos originais de cobertura permanente e de diversificação cultural, comprometendo a eficiência deste sistema de manejo conservacionista quanto ao seu potencial impacto na qualidade do solo e produtividade das culturas. As estimativas de área de adoção dessas práticas são escassas principalmente no que se refere ao pousio, mas estima-se que mais que 50% da área cultivada no verão esteja em sucessão a áreas sob pousio invernal (VELOSO *et al.*, 2018). Por sua vez, a diminuição temporal da área de milho, tendo reduzido nas últimas décadas de uma proporção de 33% na rotação com a soja para um valor aproximado de 10%, configurando o cultivo de milho um ano intercalado a nove cultivos de soja na mesma lavoura (CONAB, 2021).

O baixo aporte de biomassa vegetal e, portanto, uma pouco expressiva cobertura de solo, é um dos problemas relacionados à práticas comuns atualmente como o pousio invernal e a monocultura da soja no verão, as quais, além da erosão hídrica e da menor ciclagem de nutrientes, se reflete no menor aporte de C fotossintetizado e no comprometimento dos benefícios do SPD no que se refere ao aumento dos estoques de matéria orgânica no solo (BAYER *et al.*, 2006b, 2000a; OGLE; BREIDT; PAUSTIAN, 2005; WEST; POST, 2002), com reflexos na qualidade do solo. Além dos aspectos relacionados ao solo, a rotação de culturas também traz benefícios relativos à produtividade das culturas devido a menor incidência de pragas e doenças (DANG *et al.*, 2020; WALL; NIELSEN; SIX, 2015), incidência e manejo de ervas daninhas (BANA *et al.*, 2020; CATES *et al.*, 2016; MAILLARD *et al.*, 2018), além da redução dos custos pela otimização do uso da mão de obra e do maquinário no âmbito da propriedade rural (GAUDIN *et al.*, 2015).

Do ponto de vista ambiental, o potencial do SPD em promover o sequestro de C no solo é comprometido parcialmente pela adoção da monocultura e da prática de pousio invernal. Taxas anuais de sequestro de C em solos em SPD com sistemas de cultura intenso são estimadas em aproximadamente 0,5 Mg ha^{-1} ano^{-1}, enquanto que em sistemas de monocultura ou sistemas com culturas com baixo aporte de biomassa, essas taxas de acúmulo de C no solo são praticamente nulas ou muito baixas, segundo Bayer et al.(2006a) inferiores a 0,10 Mg ha^{-1} ano^{-1}. O uso de rotação de culturas pode favorecer o acúmulo de C orgânico no solo porque pode regular a disponibilidade da entrada de C e taxas de decomposição através do controle da quantidade, qualidade e periodicidade do C aportado via resíduos vegetais da parte aérea e raízes, modificando as condições ambientais do solo e de como os recursos são utilizados (HUGGINS *et al.*, 2007). Nesse sentido, quando em longo prazo sob monocultura de soja, a qualidade do solo pode ser menor do que sob rotações de culturas mais complexas com cultivo duplo com cereais e leguminosas (NOVELLI; CAVIGLIA; PIÑEIRO, 2017). Por sua vez, a inserção do milho em rotação com a soja tem potencial de aumento dos estoques de C orgânico do solo em relação à monocultura da soja (HUGGINS et al., 2007).

Aumentar os estoques de C orgânico em solos agrícolas como uma a alternativa para mitigar as emissões de CO_2 é altamente reconhecido em nível internacional. Na COP21, em Paris, o Brasil se comprometeu em reduzir as emissões de gases de efeito estufa (GEE) em 37% até 2025 (UNFCCC; INDC, 2015), e dentro desse planejamento estabeleceu estratégias para o desenvolvimento de uma agricultura de baixa emissão de carbono, as quais envolvem diferentes atividades/ações, com destaque para o plantio direto, cuja contribuição (fator aditividade) pode ser decorrente da ampliação da área de adoção, bem como da melhoria da sua qualidade. O termo “qualidade” do SPD está relacionado à implantação de boas práticas como cobertura de solo permanente e diversificação de culturas.

O uso de rotações de culturas mais complexas aumenta a produtividade de grãos em comparação ao uso de monoculturas (NOVELLI; CAVIGLIA; PIÑEIRO, 2017). Além disso, influencia na variabilidade e estabilidade do rendimento das culturas, onde sistemas de rotação de culturas são mais eficazes na redução da variabilidade da produção a longo prazo do que sistemas de monocultura (LIU *et al.*, 2006).

O objetivo geral foi avaliar o efeito dos sistemas de rotação de culturas entre as duas principais culturas de grãos do Brasil no contexto ambiental e produtivo de sistemas agrícolas. Primeiramente, objetivou-se avaliar o efeito de longo prazo do aumento da proporção de milho participando da rotação com a soja nos estoques de C orgânico em solo sob plantio direto. O segundo objetivo foi analisar a resposta da produtividade das culturas da soja, milho e cevada em relação ao seu cultivo em rotação de culturas comparativamente ao seu cultivo em monocultura. Para estes fins, um experimento de 20 anos de rotação de culturas em plantio direto sobre um Latossolo Bruno (600 g kg^{-1} argila) foi acessado quanto ao efeito sobre os estoques de C orgânico do solo, produtividade e estabilidade do rendimento ao longo do tempo.

CAPÍTULO II – REVISÃO BIBLIOGRÁFICA

1. Matéria orgânica e qualidade do solo

A matéria orgânica do solo (MOS) é o principal indicador de qualidade dos solos, sendo afetada pelo manejo dos solos agrícolas, e responsável por interferir nas suas características químicas, físicas e biológicas(BOT , A.; BENITES, 2005). Assim, quando ocorre o aumento do teor de MOS, ocorre aumento da estabilidade de agregados, retenção de água e da disponibilidade de nutrientes (LIU *et al.*, 2006; TURMEL *et al.*, 2015). A quantidade e a qualidade da MOS influencia a formação e estabilidade dos agregados do solo por seus agentes de ligação (JENSEN *et al.*, 2020). Com a estabilização dos agregados pela matéria orgânica do solo se tem um maior espaço poroso no solo, ocorrendo maior infiltração de água pelos macroporos e o armazenamento nos microporos (FERREIRA *et al.*, 2020).

Também o fornecimento de nutrientes é influenciado pelo conteúdo de MOS, o qual se divide em compartimento lábil e o húmus (TURMEL *et al.*, 2015). O compartimento lábil é decomposto mais rapidamente pelos microrganismos, sendo responsável pelos nutrientes de fácil mineralização e disponibilidade para as plantas, já o compartimento húmus é de mais difícil degradação e é responsável pelas características físico-químicas do solo (TURMEL *et al.*, 2015). Nota-se que em solos com maiores conteúdos de MOS há maiores valores de capacidade de troca de cátions (CTC), sendo observado uma CTC maior na camada superficial do solo de 0-5 cm (DUIKER; BEEGLE, 2006). Alves et al. (2019) observaram que em solos sob pastejo onde há uma maior quantidade de resíduos na superfície do solo a CTC foi 11 a 15% maior, onde teve um aumento nos teores de MOS. O aumento da CTC é maior em solos com baixa atividade de argila, pois estes dependem das cargas negativas dos grupos funcionais da MOS (ALVES *et al.*, 2019; CIOTTA *et al.*, 2003).

A característica física mais importante que a MOS afeta é a agregação do solo, que, por sua vez, influencia a estrutura do solo, com impactos na densidade do solo, porosidade, aeração, capacidade de retenção e infiltração de água(FERREIRA *et al.*, 2020; KIANI *et al.*, 2017). O aporte de biomassa vegetal sobre o solo protege os agregados do solo pelo impacto da gota de chuva protegendo da compactação que a gota da chuva causa (BLANCO-CANQUI; LAL, 2009; JORDÁN; ZAVALA; GIL, 2010; SIX *et al.*, 2004; TURMEL *et al.*, 2015). Esse aporte de resíduos vegetais pode melhorar a estrutura do solo pelo incremento da MOS aumentando a agregação do solo pelos seus agentes ligantes (ASSUNÇÃO *et al.*, 2019b; SIX *et al.*, 2002; TURMEL *et al.*, 2015). Como a MOS favorece a formação de agregados, os mesmos contribuem na proteção da MOS à decomposição dos microrganismos, através da interação organomineral com a oclusão desta em seu interior (SIX *et al.*, 2004, 2002; TURMEL *et al.*, 2015).

O solo em si é um ecossistema complexo que possui a maior diversidade de vida; essa biota do solo pode ser classificada de diversas maneiras mas sendo a mais comumente usada a por tamanhos de organismos sendo: microflora correspondente a bactérias, fungos, algas verdes; microfauna constituída por protozoários e nematoides habitando o espaço poroso com água; mesofauna que inclui os microartrópodes, enchytraeidae; e a macrofauna com indivíduos maiores do 2 mm, tais como minhocas, cupins e artrópodes (ROGER-ESTRADE *et al.*, 2010). A biodiversidade do solo deve ser considerada na hora do planejamento de práticas de manejo de agroecossistemas por terem funções importantes que influenciaram nos rendimentos das culturas, para se ter uma riqueza da biota do solo em números de espécies e evitar o domínio de algumas espécies que podem causar prejuízos para os agroecossistemas (BRUSSAARD; RUITER; BROWN, 2007). Os microrganismos tem um papel importante no ecossistema do solo, eles participam na dinâmica do C no solo, realizando ciclagem de nutrientes com a decomposição da MO das plantas para que as mesmas o absorvam novamente(MAILLARD *et al.*, 2019), secretam uma série de enzimas extracelulares que decompõem os compósitos orgânicos complexos (ZHENG *et al.*, 2018).

A diminuição no teor de matéria orgânica no solo pode gerar uma diminuição na abundância de comunidades macrofaunais nos solos a curto prazo, influenciado na dinâmica da matéria orgânica (ELIE *et al.*, 2018). KAMAU *et al.* (2017) sugerem que a abundância de macrofauna do solo se deve ao insumos orgânicos como decomposição da serapilheira e renovação da raízes, observando relação da presença de minhocas com o P advindo da serapilheira e N e P das raízes, já para cupins foram encontrados onde as árvores que predominavam forneciam uma matéria orgânica de baixa qualidade, devido a eles utilizarem enzimas produzidas pela sua microflora intestinal. A preferência da microbiota pelas frações de matéria orgânica recém adicionada ao solo promove a proliferação de microrganismo e aumenta a taxa de mineralização do C (KAMAU *et al.*, 2020). BANFIELD *et al.* (2018) observaram uma presença de 50% de C a mais em bioporos de origem de minhocas do que nos bioporos das raízes, porém os bioporos de raízes são quarenta vezes mais frequentes do que os das minhocas. Em estudo realizado no País de Gales junto programa de Monitoramento e Avaliação Glastir (GMEP) GEORGE et al. (2017) relataram a correlação positiva entre ácaros oribatídeos e a matéria orgânica do solo, já que os oribatídeos são sensíveis as práticas agrícolas.

2. Dinâmica do C orgânico em solos agrícolas

A dinâmica dos teores de C orgânico no solo é função da quantidade e do tipo de resíduo vegetal que é adicionado ao solo, se é proveniente da parte aérea ou de raízes das plantas, e também da taxa de decomposição microbiana da matéria orgânica do solo (BIELUCZYK *et al.*, 2020; DESJARDINS *et al.*, 2006;

ERNST *et al.*, 2014; LAL, 2002). O balanço das entradas e saídas de C orgânico no solo pode ser negativo ou positivo, resultando em declínio e aumento, respectivamente, dos estoques de C orgânico no solo ao longo dos anos de adoção das práticas de manejo (PAUSTIAN, 2014a).

A variação temporal dos estoques de C no solo (*dC/dt*) é expressa na equação [1]:

$$[1] \frac{dC}{dt} = K_1.A - K_2.C$$

Na equação, a taxa de variação do estoque de C no solo (dC/dt) é dada com a diferença entre a taxa de adição de C ($K_1.A$) e a taxa de perda de C ($K_2.C$), onde *A* é o carbono fotossintetizado adicionado ao solo em forma de resíduos, exsudatos radiculares e raízes (Mg ha^{-1} ano^{-1}); *C* é o estoque de C orgânico no solo (Mg ha^{-1}); K_1 é o coeficiente isohúmico, o qual corresponde a fração do carbono adicionado que é efetivamente retido na MOS após o período de um ano; e K_2 é a taxa anual de decomposição da MOS (BAYER *et al.*, 2006b; BAYER; MIELNICZUK; MARTIN-NETO, 2000; PAUSTIAN, 2014a; SANTOS; BAYER; MELNICZUK, 2008). BAYER *et. al.*(2006b) encontraram valores de K_1 e K_2 de 0,146 e 0,019 ano^{-1} para o SPD em clima subtropical e tropical, enquanto LOVATO *et al.* (2004) encontraram valores menores para os coeficientes K_1 e K_2 *de* 0,129 e 0,0166 ano^{-1} em SPD. São relatados valores de K_1 entre 0,077 ano^{-1} a 0,230 ano^{-1} (BOLINDER *et al.*, 1999). Para o coeficiente K_2 foram encontrados valores entre 0,012 a 0,029 ano^{-1} para SPD em clima subtropical e tropical (BAYER *et al.*, 2006b, 2000a; BAYER; MIELNICZUK, 2000; LOVATO *et al.*, 2004; LOVATO, 2001).

Em climas tropicais e subtropicais a decomposição da matéria orgânica é mais acelerada do que em clima temperado, porém pode ser contrabalanceada por uma maior adição de resíduos favorecida pela maior produção de biomassa vegetal (SANTOS; BAYER; MELNICZUK, 2008). Em regiões tropicais e subtropicais, os solos apresentam em sua maior parte um grau de intemperismo elevado, com predomínio de óxidos de ferro e alumínio e caulinita na fração argila, minerais estes que apresentam grupos funcionais na superfície que são altamente reativos com a matéria orgânica, contribuindo para uma maior estabilidade do carbono nesses solos de carga variável (MARTIN *et al.*, 1982; PARFITT *et al.*, 1997; SANTOS; BAYER; MELNICZUK, 2008).

3. Efeito do plantio direto nos estoques de C orgânico dos solos

O não revolvimento do solo no SPD é um fator essencial no balanço de C pois promove uma desaceleração da decomposição da MOS, fortalecendo a agregação do solo e evitando a ruptura dos agregados anteriormente verificada nos sistemas de preparo convencional (BAYER *et al.*, 2000b; DESJARDINS *et al.*, 2006), com reflexos também na redução do fracionamento e incorporação dos resíduos vegetais que são mantidos na superfície do solo e evitam a ocorrência de elevadas temperaturas (COSTA *et al.*, 2008; TURMEL *et al.*, 2015).

Como no sistema de preparo convencional a estrutura do solo é degradada, pois é lavrado diversas vezes, causando a desestruturação e a aeração do solo e ocorrendo uma maior oxidação da C orgânico do solo (JAT *et al.*, 2019). SANTANA et al. (2019) observaram no bioma Caatinga no Brasil a redução nos estoques de carbono de 63 para 47 Mg ha^{-1} com a conversão da vegetação natural para agricultura. Então sistemas de manejos conservacionistas tendem a manter estoques de C orgânico mais elevados em relação aos sistemas tradicionais. Com a adoção de SPD há uma maior estabilização da MOS, pois a preservação dos agregados de solo evita a exposição do C orgânico aos microrganismos e suas enzimas (PAUSTIAN, 2014a). Estima-se que a conversão de sistema de preparo convencional para o SPD possa aumentar os estoques de carbono em 10% em clima temperado, 16% clima temperado e úmido, 17% clima tropical seco e 23% para tropical úmido (OGLE; BREIDT; PAUSTIAN, 2005). Em metanálise global, estimou-se um aumento médio de 0,48 Mg ha^{-1} ano^{-1} com a conversão de preparo convencional para o plantio direto (WEST e POST, 2002). Esta estimativa é similar ao levantamento de Bayer et. al. (2006b) em solos brasileiros, segundo o qual as taxas médias de acumulo anual de C orgânico no solo são de 0,48 Mg ha^{-1} no Sul do Brasil e de 0,35 Mg ha^{-1} na região do Cerrado, ambas superiores à taxa de 0,24 Mg ha^{-1} estimada em solos temperados dos Estados Unidos (LAL *et al.*, 1999).

4. Efeito da rotação de culturas nos estoques de C orgânico de solos em plantio direto

No solo SPD que apresenta uma maior estabilização do C orgânico, as taxas de acúmulo de C também são totalmente dependentes da quantidade aportada anualmente de resíduos vegetais, o que é altamente dependente dos sistemas de cultura adotados (COSTA *et al.*, 2008; LOVATO *et al.*, 2004; PAUSTIAN, 2014a). Nesse sentido, para que o SPD obtenha sucesso como prática de manejo conservacionista em aumentar a MOS, sistemas de cultura com alto aporte de resíduos terão que ser adotados (BAYER *et al.*, 2009). Então, é altamente desejável a adoção de sistemas de culturas com alta produtividade vegetal, envolvendo a rotação de culturas e a inserção de plantas de cobertura em rotação com culturas comerciais (PAUSTIAN, 2014a).

Mas esta não é a realidade atual do SPD. O que apresenta uma grande proporção da área cultivada atualmente é a monocultura de soja e o pousio invernal como uma prática utilizada com grande frequência nas lavouras no Sul do Brasil. Essas duas práticas, isoladamente ou associadas, comprometem o potencial de aporte de C fotossintetizado ao solo e, portanto, o balanço de entradas e saídas de C no sistema solo-planta em SPD. Nesse sentido, taxas anuais de acúmulo de C estimadas em 0,48 Mg ha^{-1} ano^{-1} para solos em SPD com sistemas de cultura intensos, quando da adoção da monocultura de soja e alta frequência de pousio invernal as taxas anuais de acúmulo de C são muito baixas ($<0,10$ Mg ha^{-1} ano^{-1}) ou praticamente nulas (BAYER *et al.*, 2006a).

O balanço positivo de entradas e saídas de C no solo em SPD pode ser alcançado quando da adoção de sistemas de rotação de culturas, principalmente com a inserção do milho em rotação com a soja (HUGGINS et al., 2007), e com o uso de plantas de cobertura em rotação com os cereais no inverno (NOVELLI; CAVIGLIA; PIÑEIRO, 2017). Na mesma linha de raciocínio, verificou-se que o aumento da frequência de soja na rotação com milho tem reflexo negativo nos estoques de C orgânico do solo a longo prazo (NOVELLI; CAVIGLIA; MELCHIORI, 2011). Como avaliado em uma meta-análise realizada por JIAN et al. (2020), rotações e sucessões de culturas onde o foco era somente produção de culturas comerciais, tais como milho-soja e milho-trigo-soja, não aumentaram significativamente os estoques de C orgânico no solo em SPD, indicando a necessidade da utilização de plantas de coberturas no sistemas para que haja aumento nos estoque de C orgânico do solo.

Com o aumento da complexidade do sistema pela inserção de plantas de cobertura, principalmente leguminosas, há um incremento gradual nos estoques de carbono no solo (VELOSO; CECAGNO; BAYER, 2019). Segundo BAYER et al.(2000b), o maior acúmulo de C orgânico ao solo por plantas de cobertura ocorre devido ao maior aporte de resíduos ao solo. O aumento dos estoques de C orgânico no solo a longo prazo pode variar de 15,5% a 30,0% representando taxas anuais de sequestro de C orgânico de 0,56 a 1,05 Mg ha^{-1} (JIAN *et al.*, 2020).

Com a utilização de sucessões, rotações e consórcios com culturas de cobertura ocorre a mudança nas frações da matéria orgânica do solo, influenciando o fornecimento de nutrientes disponíveis às plantas. Nos estudos normalmente se avaliam três frações principais da matéria orgânica: fração leve livre, considerada um reservatório de carbono não protegido; a fração leve oclusa, localizada no interior de agregados do solo, conferindo uma proteção à ação de degradação dos microrganismos do solos; e a fração pesada, associada aos minerais (VELOSO; CECAGNO; BAYER, 2019). Em um experimento utilizando gramíneas como plantas de coberturas, NASCENTE *et al.* (2013) observaram maior concentração das frações da matéria orgânica leve-livre e leve-oclusa na camada superficial do solo (0-5 cm) do que nas camada mais profundas. VELOSO *et. al.* (2019) observaram que a fração leve livre continha 9% do C orgânico do solo, enquanto a fração leve-oclusa variou de 9 a 27% do C orgânico do solo de acordo com o sistema de culturas adotado, ilustrando o impacto da utilização de plantas de cobertura do solo na estabilização da MOS.

5. Rotação de culturas e seu impacto na produtividade e na sua estabilidade ao longo dos anos

Os sistemas de culturas possuem suas particularidades em relação ao seu arranjo, se as espécies comerciais são cultivadas em monocultura ou em rotação, e na frequência de cada espécie na rotação, bem como se plantas de cobertura são cultivadas em rotação com cereais no inverno ou não. Esses arranjos podem serem entendidos como a complexidade do sistemas de culturas, e este pode ser quantificado através do índice de diversidade de culturas (IDC), conforme sugerido por TIEMANN *et al.*(2015) ou por um indicador de diversidade de espécies na rotação de culturas (IRC), sugerido por BOWLES *et al.*(2020).

Segundo estudo conduzido por Bowles et al. (2020), a diversidade da rotação de culturas aumentou a produtividade do milho em nove de um total de 11 locais avaliados, além de ser observado um aumento mais expressivo da produtividade a longo prazo. A diversificação do sistema de rotação milho-soja com trigo aumentou o rendimento médio da soja em 13% (GAUDIN *et al.*, 2015). Nesses sistemas de rotação, a produtividade de milho e soja desviaram das linhas de tendência em anos desfavoráveis em até ~41% para milho e ~16% para soja. A rotação de culturas têm proporcionado produtividade de milho, em média, 5% a 10% mais elevadas do que quando cultivado em monocultura, mesmo em uma rotação de apenas duas culturas - milho e soja (BOWLES *et al.*, 2020; KARLEN *et al.*, 1994). Entretanto, uma maior diversidade de culturas pode ser benéfica nas rotações de soja e milho. Um dos motivos para isso é que as rotações mais complexas possibilitam diminuir os atrasos no plantio de milho e soja (GAUDIN *et al.*, 2015) devido ao melhor aproveitamento do período de melhores condições climáticas para o plantio e desenvolvimento da cultura, escapando de possíveis estresses que poderia resultar em menores produtividades.

A sequência do cultivo em rotação gera um grande impacto na produtividade das culturas principalmente para as culturas da soja e do milho. Para o primeiro ano de soja pós-milho, há registros de aumento de produtividade entre 7,2% e 8% maiores do que na soja em monocultura (MEYER-AURICH *et al.*, 2006; PEDERSEN; LAUER, 2003). A diversificação promove uma menor flutuação na produtividade de soja devido a melhores condições no cultivo, levando ao aumento na estabilidade temporal, principalmente em anos quentes e secos (GAUDIN *et al.*, 2015; LI *et al.*, 2019).

O rendimento de grãos de milho no primeiro ano pós-soja aumenta também consideravelmente comparado à monocultura (STANGER; LAUER, 2008). De forma similar ao que ocorre com a soja, na cultura do milho observou-se que nos anos mais secos os rendimentos de milho foram entre até 89% mais elevados em rotações mais diversas do que em rotações simplificadas ou monocultura (BOWLES *et al.*, 2020). GAUDIN *et al.* (2015) observaram que sequências mais simples de soja e milho tiveram maiores coeficientes de variação, rendimentos cumulativos e médios menores, maiores probabilidade de alcançar baixos rendimentos em condições desfavoráveis do que rotações mais diversas. Sistemas mais diversos possuem uma gama mais ampla de características e funções, capazes de melhorar a resiliência dos sistemas agrícolas às mudanças ambientais (LIN, 2011).

CAPÍTULO III – DO CROPPING SYSTEMS IMPACT CARBON STOCK IN SUBTROPICAL OXISOL UNDER NO-TILLAGE?

1. Introduction

Agriculture is responsible for 25% of the total greenhouse gases (GHG) emissions at global level (HANDMER *et al.*, 2012), and soils subjected to traditional soil managements with intensive soil disturbance and low C input resulting from fallow and monocropping that experienced a fast decline of soil organic C (SOC) and act as a net source of carbon dioxide (CO_2) to atmosphere (CORSI *et al.*, 2012; PAUSTIAN, 2014b). Aiming to decrease the agriculture contribution to GHG emissions, Brazil assumed the compromise to decrease GHG by 37 % up to 2025 (UNFCCC; INDC, 2015), and due to high contribution of agriculture 4sto GHG emissions, the country stablished a Program of Low Carbon Agriculture, where five strategies were proposed, highlighting the conversion of soil management to no-tillage (AMARAL, D. D.; CORDEIRO, L. A. M.; GALERANI, 2011).

No-tillage system is the main component of conservation agriculture, which area reached ~32 Mha in Brazil (FEBRAPDP, 2012). However, the no-tillage system carried out in Brazil accomplish only partially the three principles of conservation agriculture or no-tillage system that are no soil disturbance, permanent soil cover, and crop diversity (DIDONÉ; MINELLA; EVRARD, 2017; FRIEDRICH; DERPSCH; KASSAM, 2017; REICOSKY, 2015). In fact, the main area of no-tillage system in Brazil is comprised by a high frequency of winter fallow and a predominance of soybean monocropping in summer.

The main impact of no-tillage on soil organic matter dynamics is related to no soil disturbance, which promote a decrease on microbial decomposition of soil organic matter (SOM) and, consequently, promoted an increase of SOC stocks in soil (BAYER *et al.*, 2000b; DESJARDINS *et al.*, 2006; TURMEL *et al.*, 2015) . However, the C input by crop to no-tillage soil is also very important to reach a positive C balance in the soil-plant-atmosphere system, that will occur only when C input is higher than C output in the no-tillage soil. The tropical and subtropical climate conditions are very favorable to a high microbial activity that consume the SOC in soil and release CO_2 to atmosphere. Thus, in the environment the C balance will be positive only if the cropping system determine a high annual C input (PAUSTIAN, 2014a). BAYER & DIECKOW (2020) suggest that positive C balance in no-tillage soil under sub(tropical) climate will be attained only with more than 10 Mg ha^{-1} yr^{-1} of dry matter crop residues. Above this amount, there is a predominance of ordinate soil processes, than dissipative ones, the SOC accumulates in soil and there is an improvement of soil quality (BAYER; DIECKOW, 2020).

Thus, the low C input in no-tillage soil resulting from winter fallow and soybean monocropping in summer impacts negatively the potential of C sequestration and of amelioration of soil quality in no-tillage in Brazil (NOVELLI; CAVIGLIA; MELCHIORI, 2011; NOVELLI; CAVIGLIA; PIÑEIRO, 2017). These management gaps can compromise the conservation agriculture (CA) potential in increasing soil carbon storage. For no-till to be successful as a conservation management practice in increasing SOM, cropping systems with high C input must be adopted simultaneously, considering the cover crops growing as cover crops in winter and cash crops in rotation in summer (BAYER *et al.*, 2009; PAUSTIAN, 2014a).

The positive effect of winter cover crops in relation to fallow is very recognized and several studies demonstrated C sequestration ranging from 0,11 to 0,68 Mg ha^{-1} yr^{-1} (BAYER *et al.*, 2006a, 2009; VELOSO *et al.*, 2018; VELOSO; CECAGNO; BAYER, 2019). However, scarce results are available on cash crop rotations in relation to monocropping on SOC stocks, mainly for tropical and subtropical regions. A recent meta-analysis showed that crop rotation is presented in SOC storage between 0.56 and 1.05 Mg ha^{-1} $year^{-1}$ compared to the cultivation of cash crops such as maize-soybean, maize-wheat-soybean (JIAN *et al.*, 2020). When looking for conservation agriculture systems for tropical and subtropical soils, in general studies reported a variation in C sequestration rates ranging from 0.11 to 0.68 Mg ha^{-1} $year^{-1}$ for the soil layer of 0-20 cm (BAYER *et* *al.*, 2006a; VELOSO *et al.*, 2019). The introduction of maize in the crop rotation can bring benefits to the SOC storage. Maize C input was 58% greater for the continuous maize system than for the maize-soybean system to the relationship between SOC change and C input (POFFENBARGER *et al.*, 2017).

Our focus in this study was to evaluate the impact of increasing the proportion of maize in crop rotation with soybean in summer on SOC stocks of a clayey Oxisol under no-tillage in comparison to the traditional soybean monocropping. We hypothesized that increasing the proportion of maize in rotation with soybean contributes to the accumulation of SOC under no-tillage in long-term. This study was based on a 19-year experiment with crop rotations under no-tillage with different arrangement of crops and the proportion of maize in crop rotation with soybean in summer ranging from 0 (soybean monocropping) to 100% (maize monocropping).

2. Material and methods

2.1. Site description

This study was based on a long-term field experiment (19 years) located at the Agrarian Foundation for Agricultural Research (Guarapuava, PR, 25º 33` S, and 51º 29` W, 1.105 m EASL), in southern Brazil. The climate is subtropical humid, with a moderately hot summer, Cfb according to Köppen classification (APARECIDO *et al.*, 2016). Annual rainfall ranges from 1550 to 1800 mm, and annual mean temperature ranges from 16.5 to 18.5°C, according to regional weather data of 25 years (from 1989 to 2014) (APARECIDO *et al.*, 2016). According to US taxonomy (Soil Survey Staff 2014), the soil at the experimental area is a Rhodic Hapludox, with 524, 356, and 120 g kg^{-1} of clay, silt, and sand in the 0-0.20 m layer, respectively.

Before the experiment, the area was occupied by a mixed ombrophilous forest, where araucaria [*Araucaria angustifolia* (Bertol.) Kuntze] predominated. Then, in 1970s, the area was subjected for small grain production with soybean (Glycine max L.) and maize (*Zea mays* L.) in summer and mainly wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) in winter summer, based on conventional tillage practices with plowing and disking two times per year. This soil management with intensive soil disturbance was conducted for about 20 years. 15 years before the experiment had begun; soil management was converted to no-tillage. During this period, liming was carried out at least four times. However, the amount of lime and fertilizers applied in this previous period is unknown.

At the beginning of the experiment (winter 2000), the soil had the following chemical properties at the 0-0.20 m layer: SOM of 5.5%; soil pH-H_2O of 5.5; exchangeable Al, Ca, and Mg (extracted by 1.0 mol L^{-1} KCl) of 0.0, 6.9, and 2.0 $cmol_c$ dm^{-3}, respectively; potential cation exchange capacity at pH 7.0 of 16.2 $cmol_c$ dm^{-3}; base saturation of 57%; available P and K (extracted by Mehlich-1) of 13.7 and 150 mg kg^{-1}, respectively.

2.2. Long-term experiment: design and conduction

The experiment was installed in 2000 and follows a complete randomized block design, with three replicates of each plot had a total area of 90 m² (9 x 10 m). The experiment comprises five no-till cropping systems (CS) with a variable proportion of maize and soybean in summer, and barley, wheat, oat (*Avena sativa* L.), and radish (*Raphanus sativus* L.) or canola (*Brassica napus* L.) in the winter season (Figure 1).

The CS-1 and CS-5 consist of soybean and maize monocropping, respectively, and only barley was grown in the winter season. In the other treatments, maize was cultivated in rotation with soybean. In CS-2, CS-3, and CS-4, maize was grown every four, three, and two years (25, 33, and 50% of maize, respectively) in rotation with soybean (75%, 67%, and 50%, respectively). In these treatments (CS-2, CS-3, and CS-4), barley, wheat, canola (*Brassica napus* L.), oat, or fodder radish were grown in the winter season (Figure 1, Apendices 1).

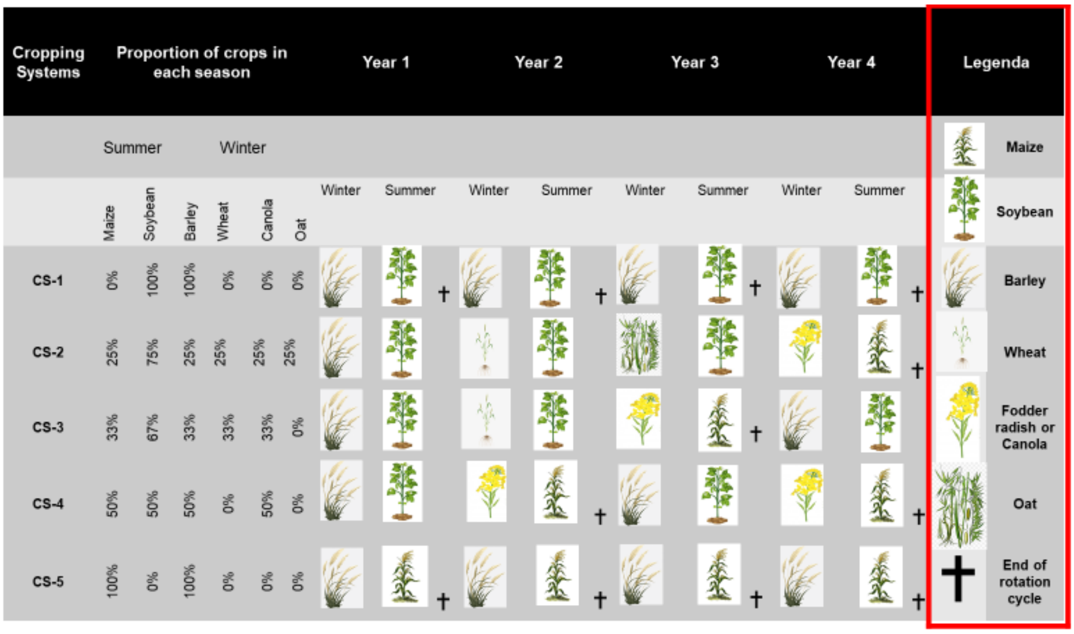


Figure 1. Schematic representation of the no-till cropping systems (CS) with a variable proportion of maize and soybean in the summer season and of winter cereals (barley, wheat, or oat) and canola (from 2000 to 2008) or fodder radish (since 2009) in winter season in a long-term (19-yrs) field experiment in southern Brazil. *Radish was grown as a cover crop in the CS-2, CS-3, and CS-4 until 2008 when canola was substituted.

According to the regional technical recommendation, all crops were sowed at recommended period and subjected to phytosanitary treatments and NPK fertilization (FONTOURA *et al.*, 2015). While maize, barley, wheat, canola, and oat received an average of 104, 37, 38, 64, and 36 kg ha^{-1} of N per season, soybean was inoculated *Bradyrhizobium* strains and not received nitrogen fertilization. All crops received, on average, 37 kg ha^{-1} (from 36 to 38 kg ha^{-1}) of P per season. Fodder radish managed as a cover crop and, thus, was not fertilized. The K input per season ranged from 22.8 to 72.6 kg ha^{-1} for summer crops and from 0 (cover crop fodder radish) to 75.7 kg ha^{-1} for winter crops. Liming was not performed during the 19 years of the experiment.

2.3. Soil sampling, and bulk soil density and organic C analysis

The soil sampling was carried out in May 2019. Trenches were manually opened between the crop lines of the harvested summer crop. On two sides of each trench, undisturbed soil samples were collected for soil bulk density and disturbed soil samples for organic C analysis in the 0-5, 5-10, 10-20, 20-30, and 30-40 cm layers. Steel rings of 5 cm diameter and height were inserted in the center of soil layers (BLAKE; HARTGE, 1986). The soil was oven-dried at 105 ^{o}C and calculated bulk density (BD) as the ratio of soil mass and ring volume (Apendices 2).

For organic C analysis, the soil was collected manually in the same soil layers, air-dried, ground, and passed through a 2 mm mesh sieve and then ground with mortar until pass through a 0.25 mesh sieve. The organic C analysis was performed by dry combustion in a Thermo CN analyzer Flash 2000 (Thermo Electron Corporation, Milan, Italy). The SOC stocks were calculated using the equivalent mass approach (ELLERT; BETTANY, 1995), taking the soil mass of CS-1 (soybean monocropping) as reference.

Eq.[1] $M_{element} = conc \times \rho_b \times T \times 10000 m^2 ha^{-1} \times 0.001 Mg\ Kg^{-1}$

Where:

$M_{element}$= element mass per unit area (Mg ha^{-1})

$conc$= elment concentration (kg Mg^{-1})

ρ_b= field bulk density (Mg m^{-3})

T= thickeness of soil layer (m)

Eq.[2] $M_{soil} = \rho_b \times T \times 10000 m^2 ha^{-1}$Where:

M_{soil}= soil mass per unit area (Mg ha^{-1})

Eq.[3] $T_{add} = \frac{(M_{soil,\ equiv} - M_{soil,\ surf}) \times 0.0001\ ha\ m^{-2}}{\rho_{b\ subsurface}}$

Where:

T_{add}= additional thickness of subsurface layer required to attain the equivalent soil mass (m)

$M_{soil,\ equiv}$= equivalent soil mass= mass of heaviest horizon (Mg ha^{-1})

$M_{soil,\ surf}$= sum of soil mass in surface layer(s) or genetic horizon(s) (Mg ha^{-1})

$\rho_{b\ subsurface}$= bulk density of subsurface layer (Mg m^{-3})

Eq.[4] $M_{element,equiv} = M_{element,\ surf} + M_{element,T\ add}$

Where:

$M_{element,equiv}$=element mass per unit area in an equivalent soil mass (Mg ha^{-1})

$M_{element,\ surf}$= sum of element mass in surface layer(s) (Mg ha^{-1})

$M_{element,T\ add}$= element mass in the additional subsurface layer (Mg ha^{-1})

The annual SOC accumulation rate was calculated as the difference of the SOC stocks of the CS-2 to CS-5 concerning CS-1 (soybean monocropping) used as a reference, divided by the time elapsed (years) since the implementation of the experiment, i.e., 19 years.

2.4. Annual C input by cropping systems

For the cash crops, the shoot biomass input was calculated using the apparent harvest index (HI) of crops that consist of the grain mass and grain mass + shoot biomass ratio. A mean HI for each cash crop was calculated taking considering a HI determined for winter crops in 2019 and summer crops in 2019/20, plus the HI of same crops grown in southern Brazil reported in literature (BECHE *et al.*, 2014; MAROLLI *et al.*, 2017; UMBURANAS *et al.*, 2019; UNKOVICH; BALDOCK; FORBES, 2010).

The mean HI used for the annual C input estimative was 0.5 for soybean, 0.5 for maize, 0.62 for barley, 0.62 for wheat, 0.53 for oat, and 0.69 for canola. For fodder radish was considered a mean shoot biomass per season of 12.73 Mg ha^{-1} (SANCHEZ *et al.*, 2012), which agrees with data obtained on-farm regionally. To the data of shoot biomass of crops, a proportion of 30% was added for the root system(BALESDENT; BALABANE, 1992; BOLINDER; ANGERS; DUBUC, 1997; BUYANOVSKY; WAGNER, 1986; CROZIER; KING, 1993; FEHRENBACHER; ALEXANDER, 1955; KISSELLE *et al.*, 2001; VELOSO *et al.*, 2018; ZANATTA *et al.*, 2007).

Based on shoot + root biomass input, an average of 40% was considered aiming to the calculation of annual C input by crops in the CS-1 to CS-5 (BAYER *et al.*, 2000b; BURLE; MIELNICZUK; FOCCHI, 1997; VELOSO *et al.*, 2018). For details of the annual C input calculation, please see Apendices 3.

2.5. Statistical analysis

Data normality and variance homogeneity were checked by Shapiro-Wilk and Levene tests, respectively, and the adequate transformation was performed when necessary. The results were subjected to analysis of variance (ANOVA) and, when significant ($p < 0.05$), the difference between treatment means were evaluated by Tukey's test at the significant level of 0.05. Presumptions of analysis of variance and Tukey test were performed using the package SAS® v.9.4 (Statistical Analysis System Institute Cary, North Carolina).

3. Results

3.1. Annual C input by cropping systems

The soil C input ranged from 2.66 to 6.02 Mg C ha^{-1} yr^{-1} (Figure 2). The increment of maize proportion of crop rotation, in general, increased the C input as observed in the CS-1 to CS-4. From CS-2 to CS-4, the increment of maize proportion increased of 32% to 52% (1,6 to 3,1 Mg C ha^{-1} yr^{-1}) the contribution of this crop for total C input by cropping system. In the CS-5, maize monocropping, the C input was slight lower than CS-4 (75% of maize in rotation with soybean). Thus, when maize was cultivated, this crop represented the major C input in the cropping system even when its proportion in summer was only 25% (CS-2) or 33% (CS-3) (Figure 2).

Cropping system also consisted of a winter rotation of grain and cover crops (barley, canola, and fodder radish). In soybean monocropping (CS-1), the winter cereal (barley) is more important in C input than when grown with maize in monocropping (CS-5), barley contribution was only 19% of total annual C input. Canola in rotation with barley was substituted by fodder radish in the CS-2, CS-3, and CS-4. This cover crop added from 7% to 21% total C input which was added to the soil in these cropping systems.

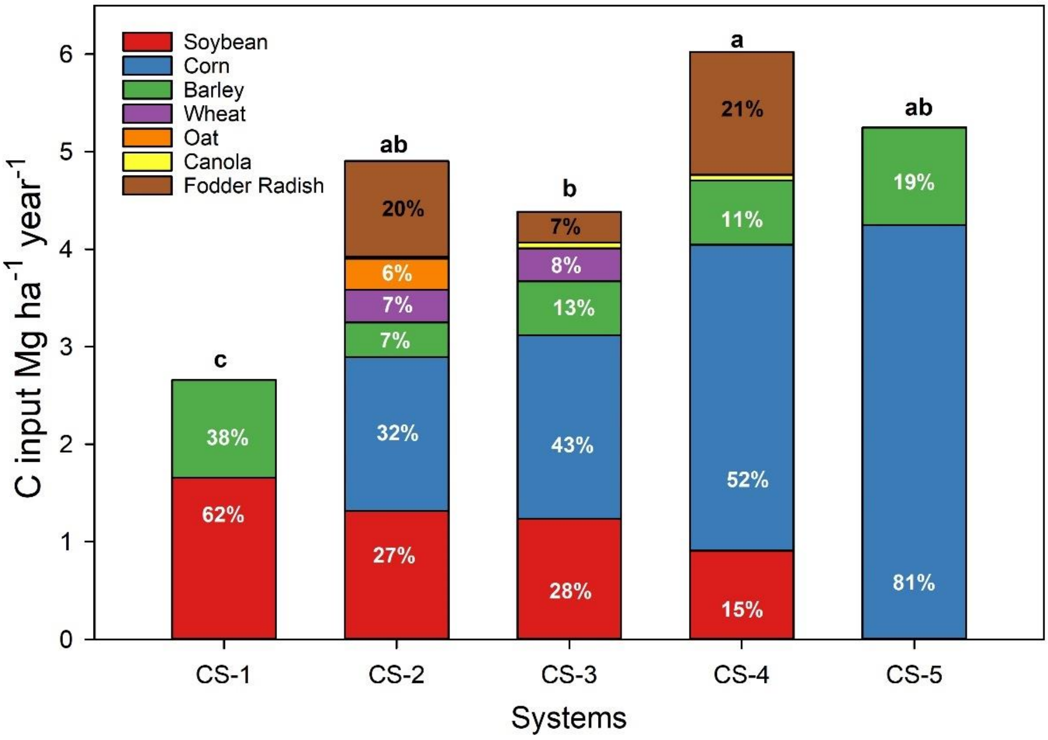
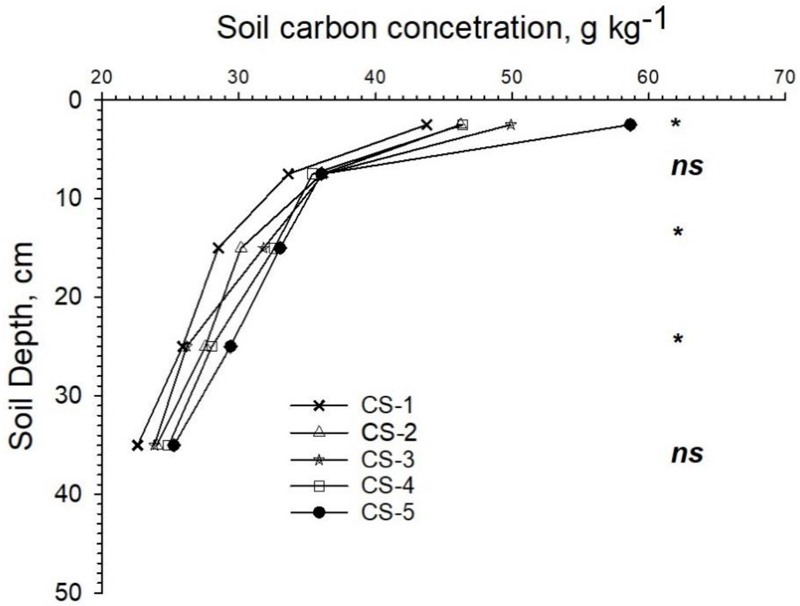


Figure 2. Average annual C inputs for cropping systems in the whole experimental period of 19-yrs. Values in the bars represent the proportional contribution of each crop for the total C input in the cropping system. CS-1 and CS-5 comprised barley monocropping in winter in sucession to soybean or maize monocropping in summer, respectively; CS-2, CS-3, and CS-4 comprised soybean-maize crop rotations in the proportion of 75%-25%, 67%-33% and 50-50% in summer season, respectively, while barley, wheat, oat, and canola grown in rotation in winter season (for more detais, please see Figure 1). Letters above bars compare cropping systems according to Tukey's Test ($P < 0.10$).

3.2. Soil organic carbon content and stocks

Long-term cropping systems significantly affected the SOC content in layers up to 30 cm depth of no-till soil profile, but the most expressive impact was observed in the surface soil layer (0-5 cm) (Figure 3). Maize in monocropping (CS-5) promoted the highest SOC content (Figure 3). Cropping systems affected subsurface soil layers (10-20 and 20-30), in general, following the increase proportion of maize in the crop rotation. The changes in SOC contents in the soil profile resulted in SOC stocks ranging from 114.0 to 131.8 Mg ha^{-1} in the 0-40 cm depth of soil among cropping systems.



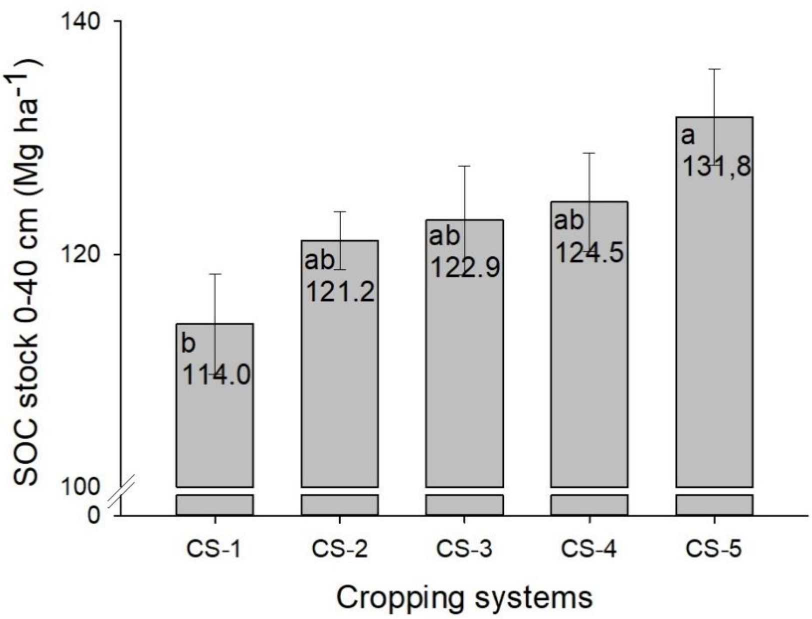


Figure 3. Soil organic C (SOC) contents (a) and stocks (b) in the 0-40 cm profile of a subtropical clayey Hapludox subjected to different cropping systems under no-tillage for 19 years. CS-1 and CS-5 comprised barley monocropping in winter in sucession to soybean or maize monocropping in summer, respectively; CS-2, CS-3 and CS-4 comprised soybean-maize crop rotations in the proportion of 75%-25%, 67%-33% and 50-50% in summer season, respectively, while barley, wheat, oat, and canola grown in rotation in winter season (for more detais, please

see Figure 1). Simbol (*) to significant, and not significant (ns) compare cropping systems (within the same layer) according to Tukey's Test ($P < 0.10$).Letters above bars compare cropping systems according to Tukey's Test ($P < 0.10$).

The relationship between the annual C input, affected by cropping systems, and the SOC content of different soil layers is presented in the Figure 4. Except for the 5-10 cm layer, all soil layers presented a linear increase of SOC content with the increment of annual C input, with a higher increment observed in the top 0-5 cm layer (Figure 4). These regressions showed that the increased C input had significant on SOC concentration increments in deep soil layers.

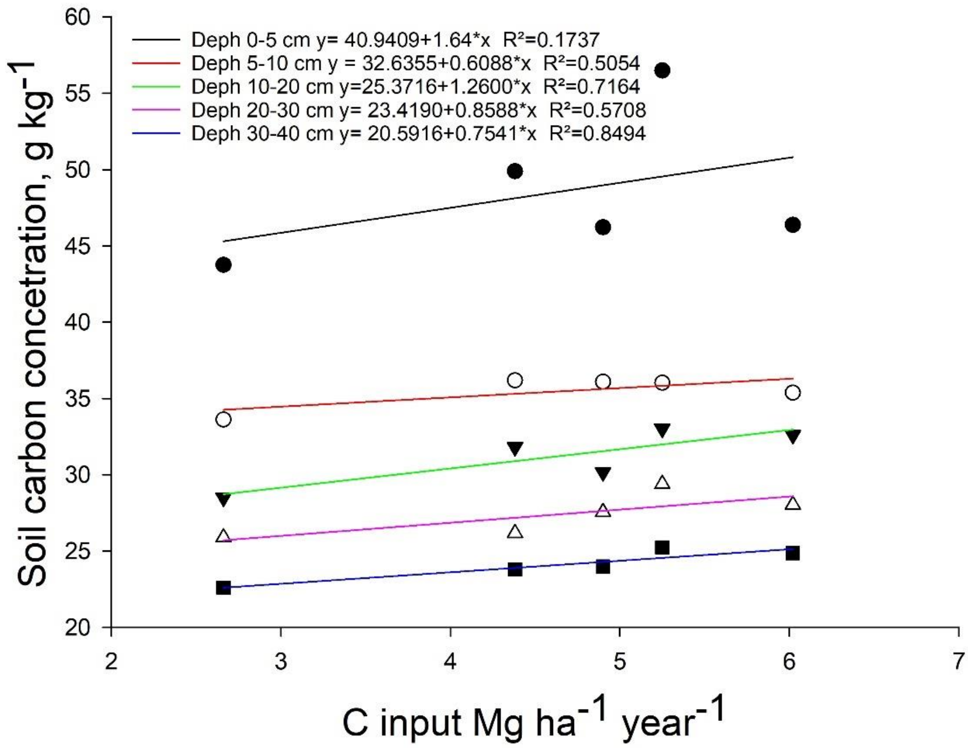


Figure 4. Relationship between mean annual C inputs with SOC concentration in surface and subsurface layers of soil by cropping systems.

The SOC stocks in the 0-40 cm soil layer presented a close relationship with annual C input in the cropping systems and, thus the annual SOC accumulation rate (Figure 5). Taking the CS-1 (soybean monocropping) as reference, for each 1 Mg C ha^{-1} of C input per year in cropping systems, a increase of SOC stock of 0.2 Mg C ha^{-1} yr^{-1} was observed in this no-tillage soil. Thus, in comparison to the soybean monocropping, the soil in crop rotations had annual SOC accumulation rates ranging from 0.36 to 0.89 Mg ha^{-1}, which presented a close relationship with annual C input by cropping systems (Figure 5).

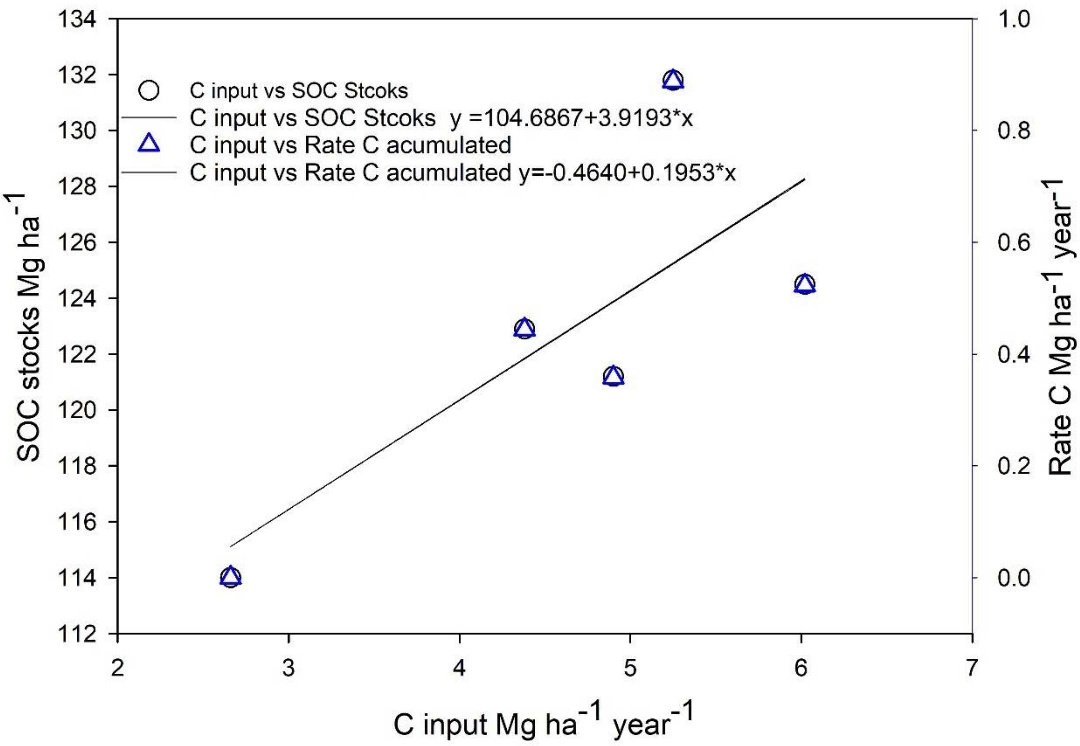


Figure 5. Relationship between C input with soil organic C (SOC) stocks (left axle) and with annual SOC accumulation rate in relation to CS-1 (soybean monocropping) in the 0–40 cm layer of a subtropical clayey Hapludox under no-tillage.

4. Discussion

The evaluated cropping systems had an average C addition between 2.66 and 6.02 Mg C ha^{-1} year^{-1}, and the maize had a significant contribution to C input, ranging from 32% to 81% of the total C input. As expected, maize was the major crop related to annual C input to the soil and, thus, the annual C input increased with the proportion of maize in the crop rotation. Maize is recognized as the cash crop with highest biomass production of global agriculture (CHEN *et al.*, 2018; LOCATELLI *et al.*, 2020; PIVA *et al.*, 2020; WANG *et al.*, 2015). We observed C input ~2 times larger than soybean, and this result was similar than 1.8 times larger than soybean reported by Huggins et al. (2007).

Thus, maize has a high importance regarding crop residues input and soil cover, contributing to the erosion control and to the quality of soil. When in monocropping (CS-5), annual C input was lower than in CS-4 where maize grown one each two growing seasons in rotation with soybean (50% maize-50% soybean). The result of the lower annual C input by maize in monocropping than in rotation with soybean is due to lower performance of maize that show grain yield 40% lower in monocropping than in crop rotation system in this same field experiment.

The increase of C input by cropping systems had a sensible effect on increasing SOC stocks in long-term. Despite this effect, it was more expressive in the top soil layer (0-5 cm), it was observed in the whole soil profile (0-40 cm) of the clayey Hapludox under no-tillage. The SOC stocks ranging from 114.0 to 131.8 Mg ha^{-1} among the cropping systems in 19 years. Thus, the improvement of crop rotations in no-tillage soil had a strong impact on SOC stocks, with potential benefits also on soil quality and crop yield.

These results are very interesting because usually the no-tillage effect is observed only in the surface soil (BAYER *et al.*, 2000a, 2000b; TURMEL *et al.*, 2015), what is attributed to the addition of crop residues on soil surface (BAYER *et al.*, 2000a; DIEKOW *et al.*, 2005; PAUSTIAN, 2014a; TURMEL *et al.*, 2015; ZANATTA *et al.*, 2007). In this clayey Hapludox the C input was also on soil surface, but the increase of SOC stocks was also observed in deeper soil layers. Small and significant increases may be evident in the subsoil due to C deposited by the growth roots (CARTER; GREGORICH, 2010). However, a migration of C compounds in soil profile in the long-term no-tillage soil can also contribute to the increase of cropping systems on SOC stocks in deeper soil layers, although the mechanisms involved are unknown.

For each increment of 1 Mg ha^{-1} of C added annually by cropping systems, approximately 0.2 Mg C ha^{-1} of C is stabilized in no-tillage soil. This resulted in annual C sequestration rates varying from 0.36 to 0.89 Mg ha^{-1} in soil under crop rotations in comparison to the no-tillage soil with soybean monocropping. The crop rotation effect on C sequestration in no-tillage soil highlights the importance of the improvement of cropping systems for the no-tillage soils can act as a stronger C sink (BEHNKE *et al.*, 2018; GONZALEZ-SANCHEZ *et al.*, 2019; VELOSO *et al.*, 2018; VELOSO; CECAGNO; BAYER, 2019). This is mainly important in Brazil, where the no-tillage systems predominantly have high frequency of winter fallow and soybean monocropping in summer (BATLLE-BAYER; BATJES; BINDRABAN, 2010; BOLLIGER *et al.*, 2006; NOURI *et al.*, 2019; TELLES *et al.*, 2019; VIZIOLI *et al.*, 2021). When combined with these practices that determine a low C input to the soil, the no-tillage system likely present low or null C sequestration rates (AGUILERA *et al.*, 2013; BAYER *et al.*, 2000b, 2009; HADDAWAY *et al.*, 2017; OGLE; SWAN; PAUSTIAN, 2012; SÁ *et al.*, 2017; VELOSO *et al.*, 2018). Thus, these data highlight that increase of quality of no-tillage system with the improvement of crop rotations in summer, plus cover crops instead of fallow in winter, have an additive effect on C sequestration in relation to the low quality no-tillage system, widely adopted by Brazilian farmers.

Previous studies evidenced that low diversified cropping systems did not increase SOC stocks significantly (HALL; RUSSELL; MOORE, 2019; JIAN *et al.*, 2020; POFFENBARGER *et al.*, 2017; RUSSELL *et al.*, 2009; WEST; POST, 2002). Our carbon stock results showed similar results found by Albuquerque et al. (2015) in a Ferralsol under no-tillage with crop rotation; where the lowest and largest C stock were to soybean and maize monocropping, respectively, which were probably related to the C input.

The use of crop diversification, soybean, and maize crop rotation can provide additional C storage of 0.523 Mg C $ha^{-1}year^{-1}$ (difference in SOC storage rate between CS-1 and CS-4). Consequently, increasing soil organic matter, which is a crucial indicator of soil quality and an essential driver of agricultural sustainability, promotes better soil quality (LAL, 2015).

It supports that Brazilian farms using no-till with crop rotations will have enough SOC storage to help mitigate greenhouse gas emissions by agriculture activities. We estimated growth for soybeans with 16 Mha in 2021 (IBGE, 2021), potentially being cultivated with monocropping soybean. This estimate provides for the possibility of capturing 8.4 Tg C year^{-1} or 31 Tg CO_2 year^{-1} equivalent to mitigating 7% of emissions total of 466 Tg CO_2 year^{-1} that release from Brazilian agricultural activities (LAPOLA *et al.*, 2014).

5. Conclusions

Annual C input by cropping systems increased with proportion of maize in rotation with soybean in summer. The increase of annual C input increased linearly soil organic C stocks at 0-40 cm layer of the subtropical clayey Hapludox. Annual accumulation rates of soil organic C in soil under crop rotation systems varied from 0.36 to 0.89 Mg ha^{-1} in comparison to the soybean monocropping, highlighting the influence of crop rotations to the potential of C sequestration in no-tillage soils. The data suggest that the C sequestration rates were positively influenced by the impact of cropping systems in sub-surface soil layers of this soil. These results evidence the role of deep soil layers to C sequestration in tropical soils, which is very interesting, and it is becoming more and more common in literature. This role of deep soil layers for C sequestration highlight the importance of strategies to input C by roots, and that new efforts are needed by aiming to understand the mechanisms accomplished in the migration and stabilization of C added in soil surface inside the soil profile.

CAPÍTULO IV – GRAIN YIELD AND ITS STABILITY INFLUENCED BY CROP ROTATIONS IN A NO-TILL SUBTROPICAL OXISOL

1. Introduction

Brazilian agricultural systems today focus on optimizing yields and profits. It is the reason an expressive number of Brazilian farms choose to use monocropping, coming to the areas under no-till in which if estimate that half of the area under no-till (~16 Mha) are using monocropping (FEBRAPDP, 2012; VELOSO *et al.*, 2018). We are concerned with the sustainability of agriculture systems to crops yield and stability yield due to the unpredictable increase of climate changes (KNAPP; VAN DER HEIJDEN, 2018; SCHMIDHUBER; TUBIELLO, 2007). Thus, agriculture is in an era of competing land use for food, fuel, and biomaterial, amidst a trend toward environmental conservation and climate resilience (MANNS; MARTIN, 2018). Then, we must provide better use of land management practice to enable higher gains in crop yield and stability in cropping systems under no-till.

With the recurrent agricultural expansion in Brazil to new areas of native vegetation, there has been a concern about the agricultural practices used mainly on soil preparation. Thus, an alternatuve is the use of conservation agriculture wich has been fostered not only in Brazil but throughout the world, consisting of three basic principles: (I) no-till of crops with minimal soil disturbance, (II) permanent soil cover by crop residues or cover crops, and (III) crop rotation (KNAPP; VAN DER HEIJDEN, 2018; LAL, 2015, 2019a). In Brazil, since the use of no-till has been encouraged, it has been an exponential growth exceeding 32 million hectares (FEBRAPDP, 2012), thus, being the Latin American country with the largest area of land under conservation agriculture (~35Mha) (LAL, 2019a). This amount of area under conservation agriculture can also be mistaken, considering that, in Brazil mainly in the South, farmers have often reduced conservation agriculture to the use of no-till alone, using soybean monocropping combined with winter fallow (DIDONÉ; MINELLA; EVRARD, 2017; FRIEDRICH; DERPSCH; KASSAM, 2017).

The use of no-tillage associated with crop rotation and succession practices can bring additional benefits to the crop's yield, mainly in rainfed agriculture under dry climates (FRIEDRICH; DERPSCH; KASSAM, 2017; PITTELKOW *et al.*, 2015). For allowing an intensification of the cultivation sequence and better use of the crop season window by early field entry and planting (BROUDER; GOMEZ-MACPHERSON, 2014). This helps to increase the diversity of crops used in the agricultural production system with a higher frequency of crop rotation and cover crops.

The crop diversity increase in agricultural systems brings several benefits to crop yield, due to the regeneration of soil health (TIEMANN *et al.*, 2015)*,* which provide related effects to extreme weather events, reducing the risk of issues such as climate change, droughts and the reduction of impact by the effect portfolio where different cultures responde in different ways stress (BOWLES *et al.*, 2020). Gaudin *et al.*(2015) observed a 13% increase in soybean yield by increasing diversity crops in a maize-soybean system with wheat. In addition to the increase in average income, the diversity influences the resilience of agricultural production mainly in intensive systems (BOWLES *et al.*, 2020).

The ability of an agricultural system to be resilient is extremely important if we are to provide food for the people of the planet. One way of assessing whether we know the resilience of systems is through the yield and temporal stability, as a way of simplifying the different indices of assessment of resilience, which are the attributes of the entire system, cycles, and associations between interconnected scales (PETERSON; EVINER; GAUDIN, 2018). In this case, it is necessary to analyze the harvest yields of long-term studies for the analysis of yield stability (GROVER; KARSTEN; ROTH, 2009), which helps understanding the year-to-year variability, and the year-x-cropping system interactions. The integration of grain legumes with crop consortium or in rotation with maize can improve yield stability (CHIMONYO; SNAPP; CHIKOWO, 2019), satisfying economic and food security. According to Renard & Tilman (2019), the hypothesis of diversity stability is based on the portfolio effect, which is a mathematical theory that predicts the conditions for which the average (or sum) of random and independent variables would be progressively more stable as more variables were calculated (or added).

The analysis of temporal stability can be performed in several ways, which can be measured by a standard deviation over the years that is called absolute stability (KNAPP; VAN DER HEIJDEN, 2018), or by the variation coefficient which divides the variability over the years (expressed as standard deviation) by the average yield of the same period, which is called relative stability (KNAPP; VAN DER HEIJDEN, 2018). The use of standard deviation as stability temporal can be a problem because does not account for the differences in yield, while the use of variation coefficient as stability temporal accounts for the differences in yield, resulting in a stability temporal (stability relative) scaled per unit yield produced (KNAPP; VAN DER HEIJDEN, 2018). This averages that both the variability across years and the average yield level influence relative yield stability. To explain this, one example described was adapted by KNAPP & VAN DER HEIJDEN (KNAPP; VAN DER HEIJDEN, 2018), a cropping system with a lower yield, but equal in absolute stability (standard deviation) the reference cropping system used has lower relative yield stability (greater coefficient of variation) than the reference cropping system used because the amount of variation per unit yield is higher. Many factors can cause the yield of crop species to change across years consequently varying standard deviation as well. Factors can be differences in precipitation, temperature, pest outbreaks, weed pressure, soil fertility, soil structure, and agricultural management, with each cropping system, responded differently.

The main goal of this study was to evaluate long-term yields and stability of crop yields to cropping systems under a range of environmental conditions and test their potential as a strategy for sustainable intensification. We hypothesized that increased crop diversities created by cropping systems under no-till improve yields while decreasing the vulnerability of crop yields to weather variation. We tested this hypothesis using a 20-year dataset yield of three main crops, soybean, maize, and barley, in five cropping systems from an experiment long-term under no-till in southern Brazil and measure the impacts of cropping systems on the stability yield of crops and yield response to the water requirements satisfaction index (WRSI) throughout the experiment and the effect of the intensity of crop rotation. Our results provide insight into the long-term stability of subtropical cropping systems' performance and the potential of crop rotation to build up sustainability and resilience in agriculture, mainly in the Brazilian farms that use cash crops as soybean-based.

2. Material and methods

2.1. Site description

The study was carried out in the southern Brazil and it was based on a long-term field experiment conducted for 20-years at the experimental area of the Agrarian Foundation for Agricultural Research (Guarapuava, PR, 25º 33` S, and 51º 29` W, 1.105 m a.s.l).The climate is subtropical humid, with a summer moderately hot, being classified as Cfb according to Köppen, with rainfall average of 1956 mm year^{-1}, and an average temperature of 16,9°C (APARECIDO *et al.*, 2016). Despite to be usual in southern Brazil, at this region specifically is not common the occurrence of drought periods in summer season. In some winter seasons, a short period of drought occur in august in the beginning of the winter cereals crop cycle. The soil is classified as typical clayey Hapludox according to US taxonomy (SOIL SURVEY STAFF, 2014).

2.2. Long-term experiment and crops conduction

The on-going experiment began in the winter season of 2000 and cromprised five main cropping systems (CS) under no-tillage and comprising different proportions of summer and winter crops in 4-years crop rotation cycles. Two are monocroppings of soybean (*Glycine max* L.) (CS-1) or maize (*Zea mays* L.) (CS-5) growing in summer and barley (*Hordeum vulgare* L.) in winter. The CS-2, CS-3, and CS-4 comprised crop rotations with decreased proportion of soybean (75%, 67% and 50%, respectively) and increased proportion of maize in summer (25%, 33% and 50%, respectively) (Table 1). In winter season, barley (until 2008) and fodder radish (*Raphanus sativus* L, until 2008) or canola (*Brassica napus* L., since 2009) comprised each 25% of crop rotation in CS-2, 33% in CS-3, and 50% in CS-4. In the CS-2 and CS-3 the crop rotation in winter was completed with wheat (*Triticum aestivum* L.) and oat (*Avena sativa* L.) (25% in CS-2, and 33% in CS-3). The crop composition of a 4-years crop rotation cycle was summarized in the Table 1. Additonally, the CS-2, CS-3, and CS-4 are replicated in the time, being subdividided respectively in 4, 3 and 2 subsystems. This arrangement allowed that all winter and summer crops grown every growing season.

Table 1. Different proportions of summer and winter crops comprising monocropping systems (CS-1 and CS-2) and crop rotations (CS-2, CS-3, and CS-4) in a single 4-year crop rotation cycle in the long-term field experiment in southern Brazil.

Cropping Systems	Sub-systems	4-years Crop Rotation Cycle							
		1st year		2nd year		3nd year		4nd year	
		winter	summer	winter	summer	winter	summer	Winter	summer
CS-1	1	Barley	Soybean†	Barley	Soybean	Barley	Soybean	Barley	Soybean
	2	Barley	Soybean	Wheat	Soybean	Oat	Soybean	Radish/Canola	Maize†
CS-2	3	Radish/Canola	Maize	Barley	Soybean	Wheat	Soybean	Oat	Soybean†
	4	Oat	Soybean	Radish/Canola	Maize	Barley	Soybean	Wheat	Soybean†
	5	Wheat	Soybean	Oat	Soybean	Radish/Canola	Maize	Barley	Soybean†

	6	Barley	Soybean	Wheat	Soybean	Radish/Canola	Maize†	Barley	Soybean
CS-3	7	Radish/Canola	Maize	Barley	Soybean	Wheat	Soybean†	Radish/Canola	Maize
	8	Wheat	Soybean	Radish/Canola	Maize	Barley	Soybean†	Wheat	Soybean
CS-4	9	Barley	Soybean	Radish/Canola	Maize†	Barley	Soybean	Radish/Canola	Maize
	10	Radish/Canola	Maize	Barley	Soybean†	Radish/Canola	Maize	Barley	Soybean
CS-5	11	Barley	Maize†	Barley	Maize	Barley	Maize	Barley	Maize

† end of rotation cycle.

The experiment followed a complete randomized block design, with three replicates, in plots with 9 x 10 m. The 11 treatments are distribuited at field according to a factorial arrangement. In the experimental period of 20 years, the crops conduction followed all technical recommendation regarding soil and crop management. For soybean, the sowing recommendation period was becoming early along of the experimental period (first fortnight of December from 2000 to 2006 and between the second fortnight of October to second fortnight of November from 2007 to 2020. Maize was sowed in the recommended period between the second fortnight of September to the first fortnight of November. Barley was sowed between the first to the second fortnight of June. Wheat was sowed between the second fortnight of June to the second fortnight of July. Oat was sowed between the first fortnight of June to the first fortnight of July. Fodder radish was sowed between the first fortnight of May to the second fortnight of June. Canola was sowed between the first fortnight of April to the second fortnight of June. According to the regional technical recommendation, all crops were subjected to phytosanitary treatments and fertilization (FONTOURA et al., 2015). N fertilization used to maize, barley, wheat, canola, and oat were an average of 104, 37, 38, 64, and 36 kg ha^{-1} of N per season, while seeds of soybean were inoculated with *Bradyrhizobium* strains and not received nitrogen fertilization. All crops received, on average, 37 kg ha^{-1} (from 36 to 38 kg ha-1) of P per season. Fodder radish managed as a cover crop, thus, was not fertilized. The K input per season was to soybean, maize, and canola in an average rate of 45, 62, and 33 kg ha^{-1} for the season; and barley, wheat, and oat were on average of 50 kg ha^{-1} for the season. Liming was not applied during the 20 years of the experiment.

2.3. Grain yield evaluation of summer and winter crops

Graind yield was evaluated in all summer and winter seasons during the 20 years. As the cropping systems (CS) were replicated in time, data of 20 harvests were collected for each winter and summer crop, allowing to evaluate the impact of crop arrangements on the grain yield and its stability on the time.

The harvest was conducted with a plot harvester for summer and winter crops. The useful area harvested was of 60 m^2 (6 m in front and 10 m in length, leaving 1.5 m on each side as "border-rows"). During the experiment's conduction, all operations were carried out with commercial machinery seeking to simulate the conduction of cash crops at regional farms. Grain crop yield was expressed in 130 g kg^{-1} seed moisture.

2.4. Yield-stability analysis

The descriptive analysis using the lme4 package for mixed linear models to metrics average yield (μ), standard deviation (σ), and the coefficient of variation (CV) was conducted, with cropping systems as fixed effects and years, and blocks as random effects (y ~ factor(year) * system + (1|block/plot)). Grain yield trends over the 20 years were analyzed using linear mixed-effects models with cropping systems and years as fixed effects and blocks and plots within blocks as random effects (y ~ year * systems + (1|block/plot)). We assessed stability of crop production (soybean, maize, and barley yield) using coefficient of variation (relative stability) calculated usig detrended data. Detrending removed long-term linear trends potentially generated by cropping systems in order to only consider variability of the residuals around the average of each cropping systems due to transient environmental conditions (NUNES *et al.*, 2021). Data were not detrended by removing cropping system effects and cropping system-specific linear temporal trends using the residuals of the linear model y ~ year * cropping systems (NUNES *et al.*, 2021). Hence, the coefficient of variation is an important indicator for the analysis of yield stability because divides the variability across years (expressed as standard deviation) by the average grain yield over the same period (KNAPP; VAN DER HEIJDEN, 2018; RASEDUZZAMAN; JENSEN, 2017; TILMAN; REICH; KNOPS, 2006).

The coefficient of variation (CV) of cropping systems as an indicator of yield variability, was standardized by unit yield (HEDGES; GUREVITCH; CURTIS, 1999; KNAPP; VAN DER HEIJDEN, 2018; NAKAGAWA *et al.*, 2015) for each cropping system. The CV was calculated for each block as the standard deviation of yield (over the 20 yr period)/average yield (over the 20 yrs period). The plot-level CV was considered the unit of replication. Higher values for CV indicate greater variability (reduced stability) 9 (Please see Apendices 4) (KNAPP; VAN DER HEIJDEN, 2018). The equation for the respective response was:

$$[2] CV = \left(\frac{\sigma}{\mu}\right) \times 100$$

Water requirement satisfaction index (WRSI) of the soybean, maize, and barley grown in cropping systems with different arrangement of crops

The WRSI refers to the ratio between the real and potential evapotranspiration by crops (ETr/ETp). When the crop water requirements is fully met, the WRSI is equal to 1 (ETr = ETm). When ETr < ETm (0 < WRSI < 1), the crop water requirement are not being fully met, and below a given value of WRSI, the yield may be limited by water stress (FRANCHINI *et al.*, 2012). The WRSI was determined from the calculation of the water balance using an electronic excel spreadsheet adaptated from Rolin and Sentelhas (1998) with daily time step. WRSI data were calculated for the critical period of soybean (R1-R6), maize and barley (both flowering).

2.5. Diversity of cropping systems

For assessing the complexity of the cropping systems, the crop diversity index (CDI) proposed by Bowles et al.(2020) was used, which is defined as the square root of the number of species in the system multiplied by the length of the crop rotation cycle.

[3] $CDI = \sqrt{nº\ crops\ \times length\ of\ the\ crop\ rotation}\ cycle$ [6]

-

2.6. Statistical analysis

Data normality and variance homogeneity were checked by Shapiro-Wilk and Bartlett tests, respectively, and the adequate transformation was performed when necessary. The results were subjected to analysis of variance (ANOVA) and, when significant ($p < 0.05$), the difference between treatment means was evaluated by Tukey's test at the significant level of 0.05. Presumptions of analysis of variance and Tukey test were performed using the package R software.

3. Results

3.1. Grain yield of summer and winter crops

Along of the 20-yrs, average grain yield ranged from 3,339 to 3,528 kg ha^{-1} for soybean and from 8,580 to 12,287 kg ha^{-1} for maize in summer season (Table 2). When soybean was grown in rotation with maize in summer, and composed up to 67% and 50% of crop rotation (CS-3 and CS-4, two soybean growing each three summer seasons and one soybean growing each two seasons, respectively) its grain yield was 5.6% higher than in monocropping (CS-1; 3,339 kg ha^{-1}). However, when the proportion of soybean in crop rotation was

75% (CS-2; three soybean growing each four summer seasons), the grain yield was similar to under monocropping (Table 2).

Table 2. Average grain yield of summer and winter crops grown in monocropping (CS-1 and CS-2) and crop rotation (CS-2, CS-3 and CS-4) in a no-till subtropical farming system in southern Brazil. Data average of the 20-yrs experimental period.

Cropping system	Summer crops		Winter crops			
	Soybean	Maize	Barley	Wheat	Oat	Canola
	---------------------------------- kg ha^{-1} -------------------------------------					
CS-1	3,339 b		3,153 b			
CS-2	3,451 ab	12,287 a	3,972 a	3,622ns	3,562	1,333ns
CS-3	3,528 a	12,078 a	4,021 a	3,696ns		1,357ns
CS-4	3,522 a	12,144 a	3,756 ab			1,365ns
CS-5		8,580 b	3,132 b			

*Means following the same letter in colunm denotes significant difference by Tukey test at 0.05 significance level; ns = no significant ; CS-1 and CS-5 comprised barley monocropping in winter in sucession to soybean or maize monocropping in summer, respectively; CS-2, CS-3 and CS-4 comprised soybean-maize crop rotations in the proportion of 75%-25%, 67%-33% and 50-50% in summer season, respectively, while barley, wheat, oat, and canola grown in rotation in winter season (for more detais, please see Table 1).

The positive effect of maize growing in rotation on grain yield of soybean was observed in the two first seasons after maize cultivation, while in the third year of sucessive soybean cultivation in crop rotation the grain yield was similar than those observed for soybean grown in monocropping (Figure 6). In the two first seasons when soybean was grown in sucession to maize in summer, the grain yield was, in average, 8% higher than in monocropping (270 kg ha^{-1} in the 1st year and 251 kg ha^{-1} in the 2nd growing season, respectively).

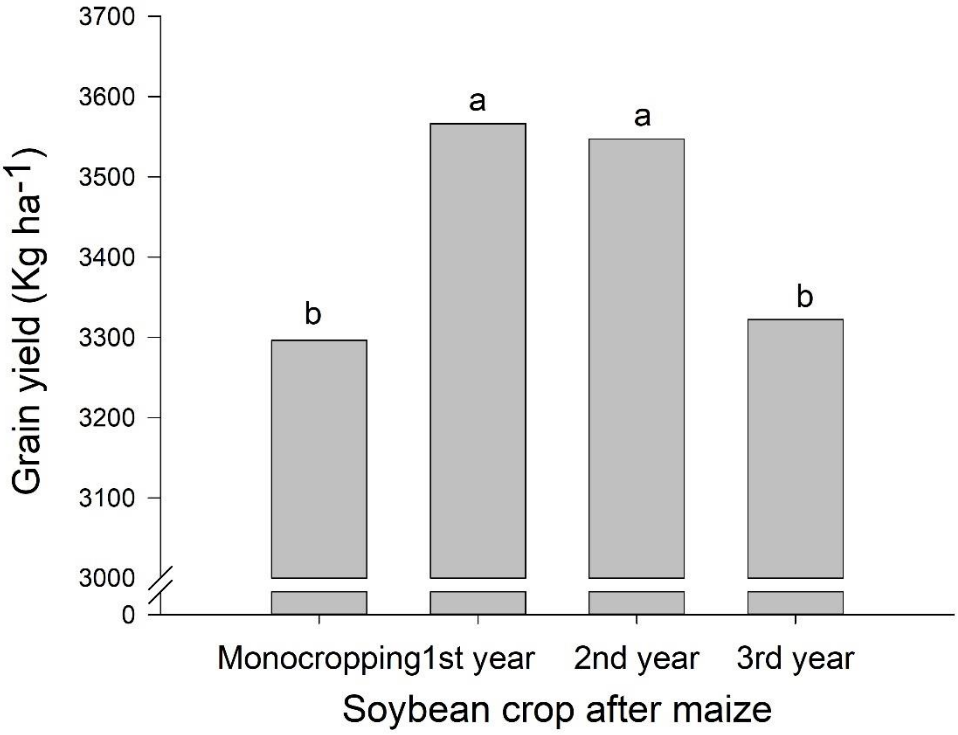


Figure 6. Grain yield of soybean grown in the 1st, 2nd, and 3rd year in sucession of maize in crop rotation and in monocropping in a no-till subtropical farming system in southern Brazil. Letters above bars compare cropping systems according to Tukey's Test ($P < 0.10$).

Grain yield of maize was higher than 12,000 kg ha^{-1} when grown in rotation with soybean (CS-2, CS-3, and CS-4), about 40% higher than 8,580 kg ha^{-1} of grain yield when grown in monocropping (CS-5) (Table 2). Maize was more impacted in the 1st growing season after soybean in crop rotation when its grain yield was 44% higher than monocropping (Figure 7). In the 2nd growing season after soybean, the maize yield was 22% higher than monocropping.

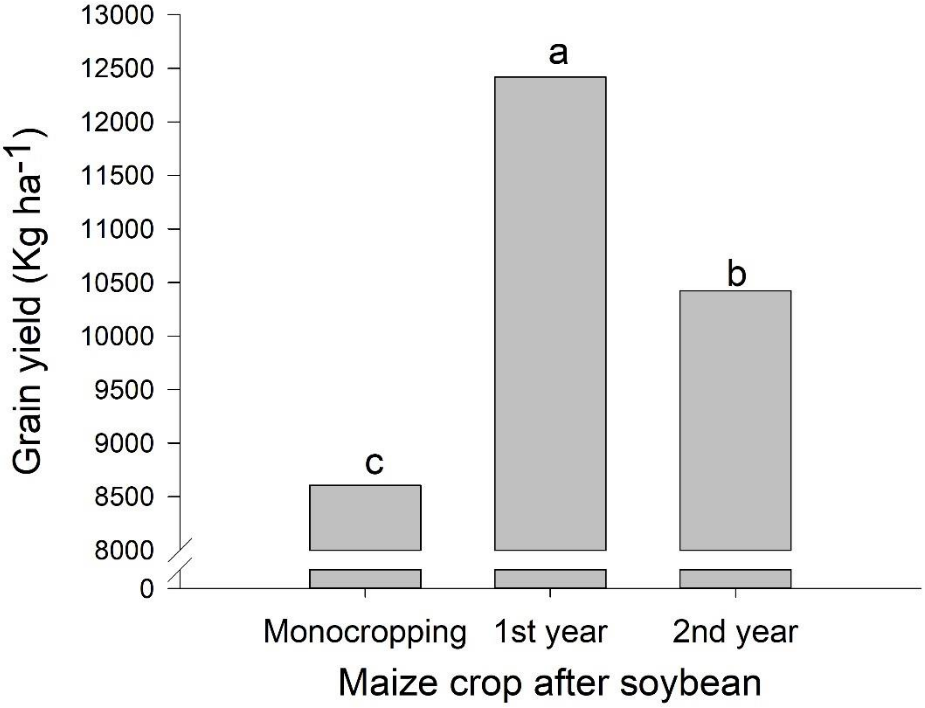


Figure 7. Grain yield of maize grown in the 1st and 2nd year in sucession of soybean in crop rotation and in monocropping in a no-till subtropical farming system in southern Brazil. Letters above bars compare cropping systems according to Tukey's Test ($P < 0.10$).

In winter season, the average barley grain yield ranged from 3,132 to 4,021 kg ha^{-1} (Table 2), and it went from 20 to 28% higher when barley grown in crop rotation with winter cereals (CS-2, CS-3 and CS-4) than in monocropping (CS-1 and CS-5). There was no difference observed upon barley grown in monocropping in winter, whether it was in sucession to soybean or maize in summer (Table 2).

Across the whole experimental period, wheat grain yield averaged 3,622 and 3,696 kg ha^{-1} in CS-2 and CS-3, respectively. Canola grown went from 7th yr to 20th yr of the experiment, also in rotation with winter cereals (CS-2, CS-3, and CS-4), yielded from 1,333 to 1,365 kg ha^{-1} (Table 2). Oat was grown only in the CS-2 and presented an average yield of 3652 kg ha^{-1}.

3.3. Temporal evolution of crop yields and response to crop rotations

Soybean, maize, and barley crops showed a sensible increase of grain yield through the 20 years of the experimental period lapse. While soybean had similar annual increase of grain yield ranging from 81 to 95 kg ha^{-1} in different cropping systems, maize shows higher annual incremments in grain yield, varying from 223 to 250 kg ha^{-1} grown in rotation with soybean, in comparison to inccrement of 94 kg ha^{-1} grown in monocropping. Along with the 20-yrs period, the differences in maize grain yield increased from 2,000 kg ha^{-1} in the first years to more than 5,000 kg ha^{-1} higher when grow in rotation than in monocropping in the last years (figure 8b).

For barley, the effect of crop rotation was more pronounced. While grain yield of barley increased from 53 to 86 kg ha^{-1} per season when grown in rotation with other winter cereals, when grown in monocropping barley showed a decrease of 10 kg ha^{-1} per season when in sucession to maize (CS-5) and of 51 kg ha^{-1} when in sucession to soybean (Figure 8c). This difference in barley yield behavior when grown in rotation or monocropping impacted strongly in the grain yield of this crop in the 20-year period. The grain yield of barley was similar between the cropping systems in the first years, but was more than 2,000 kg ha^{-1} higher when grown in rotation with other winter cereals than in monocropping (Figure 8c).

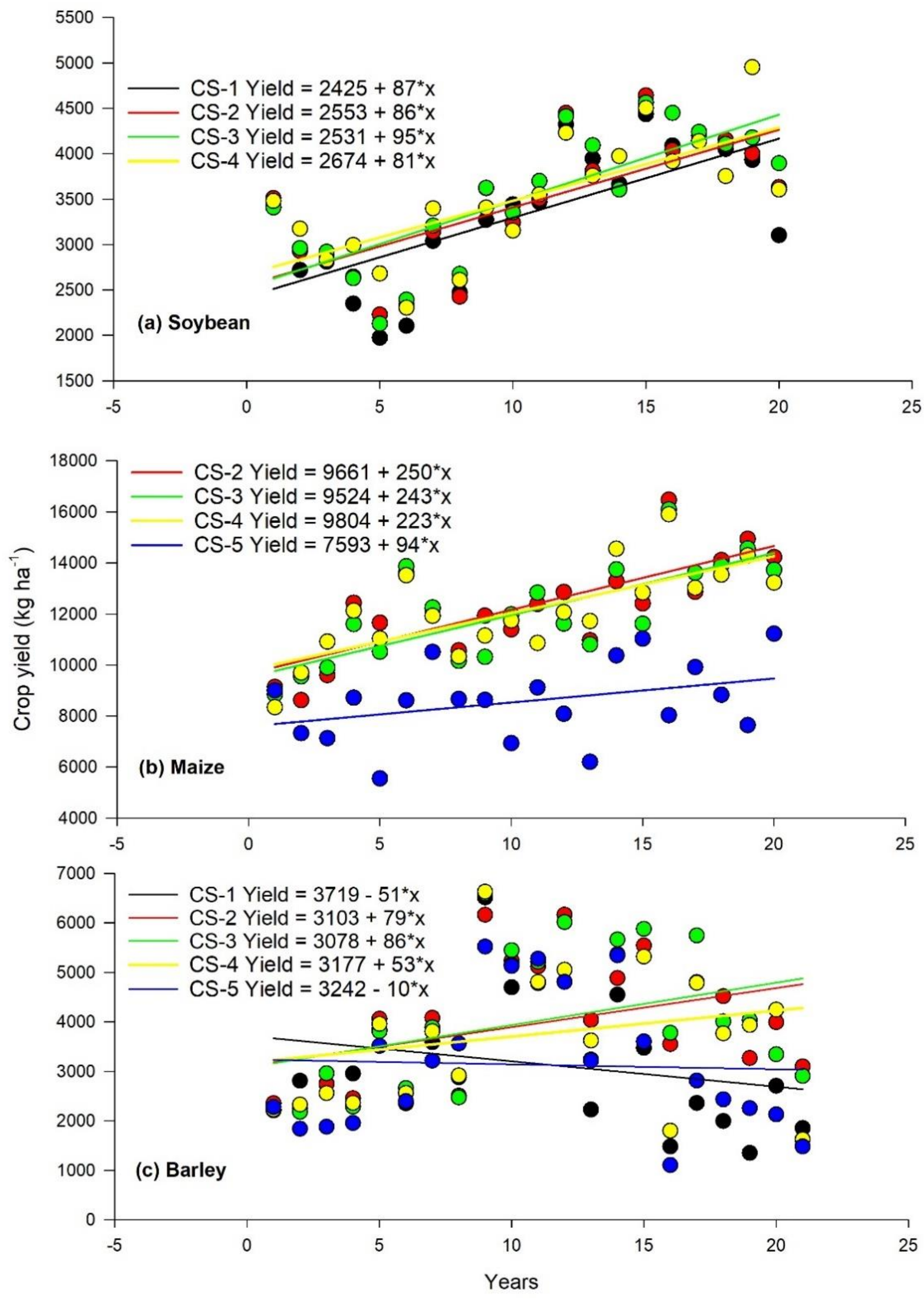


Figure 8. Evolution of grain yield of soybean, maize, and barley grown in different cropping systems in a subtropical no-till farming system in southern Brazil. CS-1 and CS-5 comprised barley monocropping in winter in sucession to soybean or maize monocropping in summer, respectively; CS-2, CS-3, and CS-4 comprised soybean-maize crop rotations in the proportion of 75%-25%, 67%-33% and 50-50% in summer season, respectively, while barley, wheat, oat, and canola grown in rotation in winter season (for more detais, please see Table 1). Lines are linear regression, and the simbols are the data points each cropping systems.

3.4. Crop diversity and its relationship with yield and temporal stability

The crop diversity index (CDI), that is proportional to the number of crops grown in the 4-years rotational cycle, varied from 27 for CS-1 and CS-5 to 50 for CS-2. The CS-3 and CS-4 presented CDI of 42 and 45, respectively.

The mean grain yield of the soybean, maize and barley increase linearly with the increase of the crop diversity (higher CDI) (Figure 9). With exception of soybean, the increase of grain yield stability (lower coefficient of variation) was also higher for cropping systems with higher diversity (Figure 9).

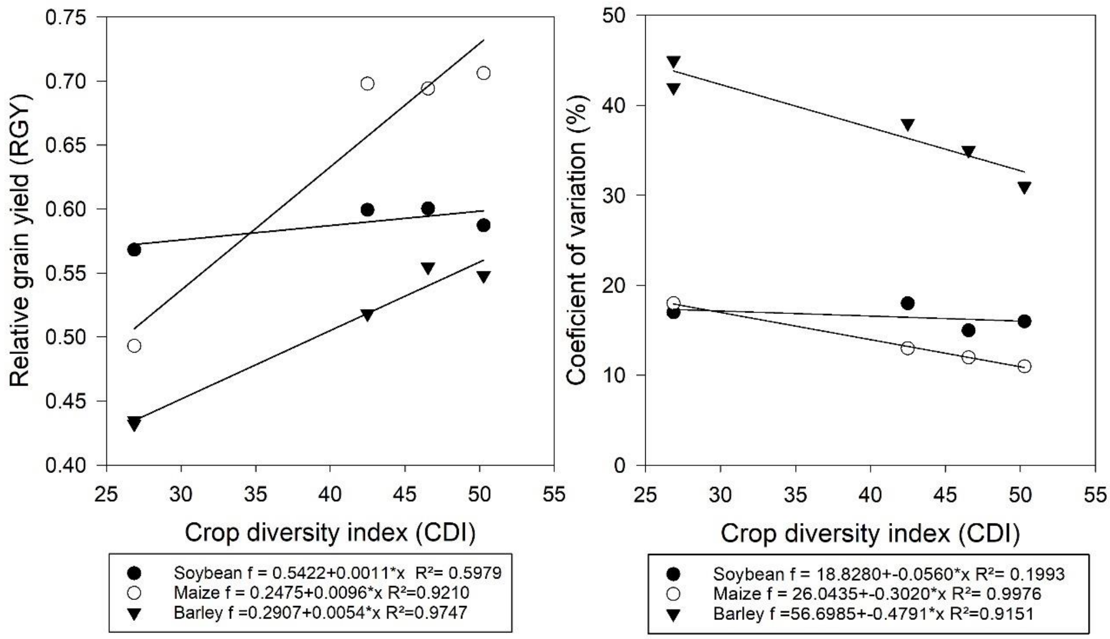


Figure 9. Relationship between Average yield ratio and Relative Stability Ratio of soybean, maize, and barley with crop diversity index (CDI) of cropping systems in a subtropical no-till farming system in southern Brazil. CS-1 and CS-5 comprised barley monocropping in winter in succession to soybean or maize

monocropping in summer, respectively; CS-2, CS-3, and CS-4 comprised soybean-maize crop rotations in the proportion of 75%-25%, 67%-33% and 50-50% in summer season, respectively, while barley, wheat, oat, and canola grown in rotation in winter season (for more details, please see Table 1).

3.5. Relationship between crop yields and water availability

Across cropping systems, the yield ratio of soybean increased with the water availability along of the 20-yrs period, expressed by the Water Requirements Satisfaction Index (WRSI) (Figure 10a). In dry summer seasons with 64% of water requirement satisfied, the soybean grown in monocropping presented a grain yield equivalent of 66% of maximum grain yield. On the other hand, soybean grown in crop rotation (CS-2, CS-3, and CS-4) in same dry growing seasons presented higher grain yields, varying from 71 to 90% of maximum grain yield. In moist growing seasons (90% WRSI), the soybean grown in monocropping had a yield ratio of 0.86, very similar compared to those obtained in crop rotation that varied from 0.86 to 0.91 (Figure 10a).

The maize grown in monocropping (CS-5) shows a lower yield ratio than when grown in crop rotation, independent of WRSI (Figure 10b). The yield ratio in dry (42% WRSI) and moist (90% WRSI) growing seasons varied from 60% to 68% in relation to the maximum grain yield. In contrast, maize grown in crop rotation (CS-2, CS-3, and CS-4) presented grain yield closest to the maximum yield (yield ratio=1) and was also little affected by the water availability varying from 42% to 90% of WRSI among growing seasons (Figure 10b).

Barley yield ratio, in general, was higher when grown in crop rotation than in monocropping independent of water availability. However, the higher difference of yield ratio was observed in dry growing seasons, when barley reached yield rates of 0.50 when grown in monocropping (CS-1 and CS-5, respectively), in comparison to yield ratios varying from 0.71 to 0.80 when grown in crop rotation (CS-2, CS-3 and CS-4). In moist growing seasons (90% WRSI), barley yield ratio varied from 0.77-0.90 when grown in monocropping to 0.86-0.95 when grown in crop rotation.

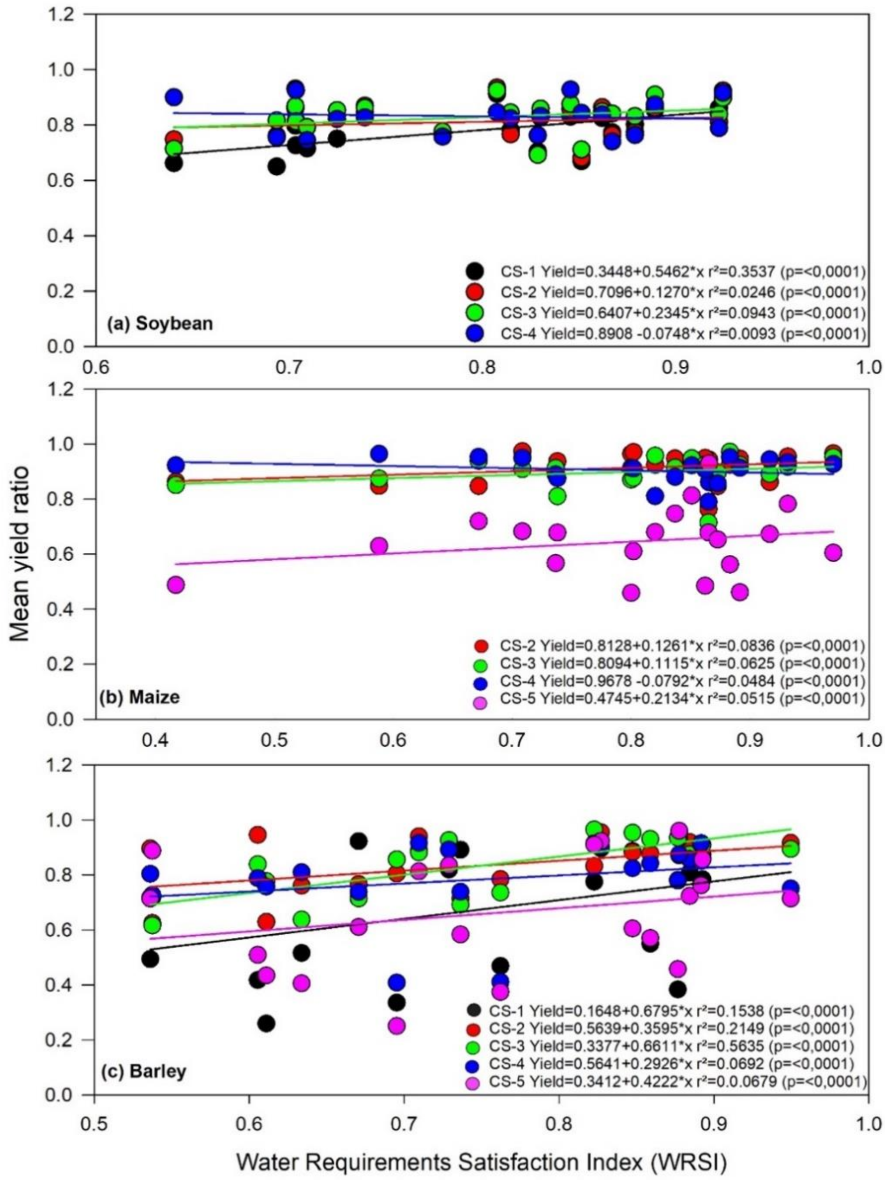


Figure 10. Relationship between grain yield ratio, in relation to the maximum yield of the year, for soybean, maize, and barley grown in different cropping systems and the water availability, expressed as Water Requirements Satisfaction Index (WRSI, %), in a no-till farming system in southern Brazil. CS-1 and CS-5 comprised barley monocropping in winter in sucession to soybean or maize monocropping in summer, respectively; CS-2, CS-3, and CS-4 comprised

soybean-maize crop rotations in the proportion of 75%-25%, 67%-33%, and 50-50% in summer season, respectively, while barley, wheat, oat, and canola grown in rotation in winter season (for more detais, please see Table 1).

4. Discussion

Soybean yield was little influenced (increase of 5.6% in average) by higher crop rotations than grown in monocropping, and the increment in the yield was higher in the first (8.2%) than the second (7.6%) growing season after maize cultivation in summer. Several studies have reported positive impact of crop rotation on soybean yield ranging from 7 to 13% in comparison to monocropping in no-tillage soils (BEHNKE *et al.*, 2018; COULTER *et al.*, 2011; EDWARDS; THURLOW; EASON, 1988; GAUDIN *et al.*, 2015). PEDERSEN; LAUER, (2003, 2004) found for the first year of soybeans, after 5 (five) years of maize crops a increase of 14% concerning soybean monocropping, and a increased 8% to second year of soybeans after maize.

Crop rotation had much higher impact on maize in summer and on barley in winter than on soybean. Maize yield was 40% higher in average and across crop rotations than in monocropping, and the increase of yield was higher in the first (44%) than in the second (22%) growing season after soybean cultivation. Most literature present lower impact of crop rotation on maize yield ranging from 4 to 23% (CHIMONYO; SNAPP; CHIKOWO, 2019; GAUDIN *et al.*, 2015) higher than maize yield grown in monocropping, but in few cases the impact can reach up 100% (SMITH; GROSS; ROBERTSON, 2008).

Barley yield had the best performance grown in rotation with other cereals in winter than in monocropping succeding maize (CS-5) or soybean (CS-1). Most studies in literature present higher yields of barley in crop rotation than grown in monocropping with increases varying from 6 to 101% (JANOVICEK *et al.*, 2021; RYAN; SINGH; CHRISTIANSEN, 2012; WOZŃIAK *et al.*, 2019; YAU; RYAN, 2012), although large increases in yield are unlikely.

The incremment of yield of the crops along of the 20 years period was a result related to the adoption of new cultivars, better management of weeds and soil and crop management for all monocropping and crop rotation systems.

However, mainly for maize and barley the behaviour of crop yield over the 20 years was more pronounced when grown in crop rotation than in monocropping. As consequence, the difference of maize and barley yields in crop rotation in relation to monocropping were higher in long-term than in short-term, suggesting a cumulative effect on the plant development conditions under crop rotations.

The same positive and significant trends for crop rotations were observed by GROVER et. al. (2009). Crop rotation significantly increased maize grain yield over time (STANGER; LAUER, 2008). Although the genetic potential of maize has greatly improved, however, the negative effect of monocropping nullifies any improvement in yield (TOLLENAAR; WU, 1999). Another study developed in a long-term experiment found that maize yield increased steadily grown in crop rotation, while the monocropping decreased yield slightly (BORRELLI *et al.*, 2014). In our study, the same slope of the regressions for crop rotations CS-2, CS-3, and CS-4, suggest all crop arrangements had similar efficiency, similar to observed by STANGER & LAUER (STANGER; LAUER, 2008).

Along of the 20 years, barley yield was strongly hampered by repeated cultivation of barley in successive years, with a significant decrease of yield over this period. The behavior of barley yield over the 20 years indicated that barley responds better to advances in crop and soil management and genetic improvements when growing in rotation to other cereals than in monocropping, similar to observed by KLIMA et al. (2020).

The crop yields in average had a close relationship with crop diversity in cropping systems. Higher diversity also resulted in higher yield stability for maize and barley, but not for soybean. Thus, maize and barley had more stable grain yields when grown in crop rotation than in monocropping. Similarly, KNAPP et al. (2018) did not verify impact of conservation management systems on the stability of soybean yield, while maize grown in rotation had lower coefficients of variation than grown in monocropping (CHIMONYIO et al., 2019; GROVER et al., 2009). GAUDIN *et al.* (2015) reported that production stability increased significantly when maize and soybeans were integrated into a more diverse crop rotation, mainly when there were the addition legumes. Similar results were reported regarding winter cereals, where yield stability of barley is usually higher growing in rotation with other crops, resulting in a higher crop diversity. According to meta-analysis the crop-rotational diversity increase maize yields in most sites (BOWLES *et al.*, 2020), and this positive relationship between crop diversity and yield may involve the complementarity of using soil resources between plants with different nutricional demands and shoot plus roots characteristics resulting in distint nutrient cycling and physical soil conditions for plant development (TRACY; SANDERSON, 2004;).

We observed WRSI values below 0.5, which is a high drought condition according to MASUPHA and MOELETSI, 2018; MOELETSI and WALKER, 2012) and growing seasons with WRSI higher than 0.8 that are considered normal or rainy growing seasons (MOELETSI and WALKER, 2012).

In general, the higher benefits of crop rotation on grain yield of soybean, maize and barley was observed in drought than moist growing seasons. The low influence of WRSI on maize yield was a unexpected result considering the high demand of water for maize development, in comparison to soybean and barley. Thus, maize usually is much more dependent of water availabity in rainfed conditions than the other crops (references). The low response of maize to WRSI varying from 0.49 to 0.90 can be observed by the smaller slope of the linear regressions than for soybean and barley. An plausible explanation is that rainy growing seasons sometimes present often cloudy days that influence negatively the photossintesis rate of the plants in summer season (references).

5. Conclusions

Yields of soybean, maize, and barley were higher when grown in crop rotation than in monocropping, which effect had a close relationship with the crop diversity and was more pronounced in drought than moist growing seasons. The impact of crop rotation on grain yield increased in long-term for maize and barley, but was similar along of the 20 years for soybean. The stability of maize and barley was higher when grown in crop rotation than in monocropping, but for soybean was the same.

CAPÍTULO IV – CONSIDERAÇÕES FINAIS

Esse estudo mostrou que o aumento da proporção de milho na rotação com a soja aumentou os estoques de C orgânico no solo na camada de 0-40 cm evidenciando o papel da rotação de culturas como pratica eficaz para sequestro de C da atmosfera. A entrada anual de C pelos sistemas de cultivo aumentou com a proporção do milho em rotação com a soja no verão. O aumento da entrada anual de C aumentou linearmente os estoques de C orgânico do solo na camada de 0-40 cm. As taxas anuais de acúmulo de C orgânico no solo em sistemas de rotação de culturas variaram de 0,36 a 0,89 Mg ha^{-1} em comparação com a monocultura da soja, evidenciando a influência das rotações de culturas no potencial de sequestro de C em solos de plantio direto.

Os dados sugerem que as taxas de sequestro de C foram positivamente influenciadas pelo impacto dos sistemas de cultivo nas camadas subsuperficiais deste solo altamente intemperizado. O que de fato evidencia o papel das camadas profundas do solo para o sequestro de C em solos tropicais. Este papel das camadas profundas do solo para o sequestro de C ressalta a importância de estratégias de entrada de C pelas raízes, e mecanismos que realiza a migração e estabilização do C adicionado na superfície do solo para camadas profundas do perfil do solo.

Complementar aos benefícios da captura de C pelos sistemas de rotação, foi o efeito na produtividade culturas de soja, milho e cevada foram maiores quando cultivadas em rotação de culturas do que em monocultura, cujo efeito teve estreita relação com a diversidade de culturas, sendo mais pronunciado em estações secas do que nas estações úmidas de cultivo. O impacto da rotação de culturas na produtividade de grãos aumentou no longo prazo para milho e cevada, mas foi semelhante ao longo dos 20 anos para soja. A estabilidade do milho e da cevada foi maior quando cultivada em rotação de cultura do que em monocultura, mas para a soja foi a mesma.

Esses resultados permitem inferir que a rotação de milho e soja com o uso de plantas de cobertura permite o sequestro de C no solo com potencial de ajudar na mitigação de GEE no aquecimento global em condições tropicais. Portanto mostrando a possibilidade de com as principais culturas de grãos do Brasil de se contribuir para mitigação das emissões de GEE das atividades agrícolas e se obter maior rendimento de grãos nos sistemas agrícolas.

Os sistemas de rotação de culturas são uma excelente alternativa para adoção nas fazendas brasileiras, melhorando a produtividade e estabilidade de rendimento das culturas e do sistema de produção, devido a um maior aporte de C ao solo que proporciona uma melhor qualidade do solo. No contexto nacional essa dissertação fornece evidências científicas para que políticas públicas de incentivo do uso de lavouras com rotações de culturas mais diversificadas sejam implementadas no Brasil, já que o alto custo e falta de bonificação para os agricultores resulta em uma baixa adoção dessa pratica. Assim como pontos importantes a serem respondidas por futuros trabalhos científicos para aporte de C no solo por culturas comercias em rotações de culturas, sobre a dinâmica do sequestro de C no solo nas camadas mais profundas do solo para entender como ocorre a migração e estabilização desse C adicionado na superfície do solo e pelas raízes nas camadas profundas e em quais compartimentos o C está sendo adicionado.

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Apendices

Apendice 1Winter and summer crops grown over years (from 2000 to 9) in no-till cropping systems with increasing proportion of maize in summer season in Southern Brazil.

Year	Season	Cropping system				
		-1	-2	-3	-4	-5
	Winter	Barley	Barley	Barley	Barley	Barley
	Summer	Soybean	Soybean	Soybean	Soybean	Maize
	Winter	Barley	Wheat	Wheat	Fodder radish	Barley
	Summer	Soybean	Soybean	Soybean	Maize	Maize
	Winter	Barley	Oat	Fodder radish	Barley	Barley
	Summer	Soybean	Soybean	Maize	Soybean	Maize
	Winter	Barley	Fodder radish	Barley	Fodder radish	Barley
	Summer	Soybean	Maize	Soybean	Maize	Maize
	Winter	Barley	Barley	Barley	Barley	Barley
	Summer	Soybean	Soybean	Soybean	Soybean	Maize
	Winter	Barley	Wheat	Wheat	Fodder radish	Barley
	Summer	Soybean	Soybean	Soybean	Maize	Maize
	Winter	Barley	Oat	Fodder radish	Barley	Barley
	Summer	Soybean	Soybean	Maize	Soybean	Maize
	Winter	Barley	Fodder radish	Barley	Fodder radish	Barley
	Summer	Soybean	Maize	Soybean	Maize	Maize
	Winter	Barley	Barley	Barley	Barley	Barley
	Summer	Soybean	Soybean	Soybean	Soybean	Maize
	Winter	Barley	Wheat	Wheat	Canola	Barley
	Summer	Soybean	Soybean	Soybean	Maize	Maize
	Winter	Barley	Oat	Canola	Barley	Barley
	Summer	Soybean	Soybean	Maize	Soybean	Maize
	Winter	Barley	Canola	Barley	Canola	Barley
	Summer	Soybean	Maize	Soybean	Maize	Maize
	Winter	Barley	Barley	Wheat	Barley	Barley
	Summer	Soybean	Soybean	Soybean	Soybean	Maize
	Winter	Barley	Wheat	Canola	Canola	Barley
	Summer	Soybean	Soybean	Maize	Maize	Maize
	Winter	Barley	Oat	Barley	Barley	Barley
	Summer	Soybean	Soybean	Soybean	Soybean	Maize
	Winter	Barley	Canola	Wheat	Canola	Barley
	Summer	Soybean	Maize	Soybean	Maize	Maize
	Winter	Barley	Barley	Canola	Barley	Barley
	Summer	Soybean	Soybean	Maize	Soybean	Maize
	Winter	Barley	Wheat	Barley	Canola	Barley
	Summer	Soybean	Soybean	Soybean	Maize	Maize
	Winter	Barley	Oat	Wheat	Barley	Barley
	Summer	Soybean	Soybean	Soybean	Soybean	Maize

Apendice2 Mean values (n= 3 replicates) of soil bulk density values of a subtropical clayey Hapludox under no-tillage subjected for long term to different cropping systems.

Cropping system	Depth cm	Soil bulk density Mg/m³
	0-5	0.89
	5-	1.10
-1	-	1.04
	-	0.95
	-	0.97
	0-5	1.03
	5-	1.12
-2	-	1.07
	-	0.94
	-	0.94
	0-5	0.92
	5-	1.14
-3	-	1.07
	-	0.98
	-	0.93
	0-5	0.96
	5-	1.05
-4	-	1.10
	-	0.89
	-	0.96
	0-5	0.85
	5-	1.05
-5	-	1.06
	-	0.98
	-	0.94

-1 and CS-5 comprised barley monocropping in winter in sucession to soybean or maize monocropping in summer, respectively; CS-2, CS-3, and CS-4 comprised soybean-maize crop rotations in the proportion of 75%-25%, 67%-33% and 50-50% in summer season, respectively, while barley, wheat, oat, and canola grown in rotation in winter season (for more details, please see Table 1).

Apendice 3. Mean C input by different crops composing five cropping systems conducted for long term (20-years) in a no-till clayey Hapludox.

	Mean C input Mg $ha^{-1}year^{-1}$ by crops' biomass							
Systems	Soybean	Corn	Barley	Wheat	Oat	Canola	Radish	Total
-1	1.7	-	1.0	-	-	-	-	2.7
-2	1.3	1.6	0.4	0.3	0.3	-	1.0	4.9
-3	1.2	1.9	0.6	0.3	-	0.1	0.3	4.4
-4	0.9	3.1	0.7	-	-	0.1	1.3	6.0
-5	-	4.2	1.0	-	-	-	-	5.2

-1 and CS-5 comprised barley monocropping in winter in sucession to soybean or maize monocropping in summer, respectively; CS-2, CS-3, and CS-4 comprised soybean-maize crop rotations in the proportion of 75%-25%, 67%-33% and 50-50% in summer season, respectively, while barley, wheat, oat, and canola grown in rotation in winter season (for more details, please see Table 1).

Apendice4 Coefficient of variation (%) for soybean, maize, and barley grown in different cropping systems in a subtropical no-till farming system in southern Brazil

	Cropping systems	Soybean	Maize	Barley
(%)	-1	17 ns		42 ab
	-2	16 ns	11 b	31 c
	-3	15 ns	12 b	35 bc
	-4	18 ns	13 b	38 abc
	-5		18 a	45 a

For soybean and barley, the CS-1 was taken as reference, and CS-5 for maize; Means following the same letter in colunm denotes significant difference by Tukey test at 0.05 significance level; ns = no significant ; CS-1 and CS-5 comprised barley monocropping in winter in sucession to soybean or maize monocropping in summer, respectively; CS-2, CS-3, and CS-4 comprised soybean-maize crop rotations in the proportion of 75%-25%, 67%-33% and 50-50% in summer season, respectively, while barley, wheat, oat, and canola grown in rotation in winter season (for more details, please see Table 1).