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BALANÇO DE ENERGIA COM BASE NO MODELO S-SEBI SOBRE GRAMÍNEAS EM BARRAX, ESPANHA E NO BIOMA PAMPA DO SUL DO BRASIL.

PORTO ALEGRE
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BALANÇO DE ENERGIA NO BIOMA PAMPA COM BASE NO MODELO S-SEBI APLICADO EM BARRAX, ESPANHA

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Dedico este trabalho a todas as mulheres que são vítimas de um sistema machista e patriarcal, mas que não se cansam de ir à LUTA por uma sociedade mais justa e igualitária.

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“Basta uma crise política, econômica e religiosa
para que os direitos das mulheres sejam
questionados. A vigilância deve ser constante.”

Simone de Beauvoir

RESUMO

No Brasil, existem seis biomas, sendo eles Amazônia, Mata Atlântica, Cerrado, Caatinga, Pantanal e Pampa. Cada bioma possui características únicas e importantes para a manutenção dos seus processos ecossistêmicos. Neste sentido, no bioma Pampa há uma dinâmica socioambiental que influencia a vegetação, o manejo agrícola e o modo de vida da população local. Este bioma é único no mundo porque traz na vegetação rasteira sua fonte de biomassa e energia como em nenhum outro ecossistema, seus campos nativos são os responsáveis pela conservação e preservação dos recursos hídricos, da fauna silvestre e da biodiversidade. A supressão da vegetação nativa deste bioma para a monocultura de grãos compromete a manutenção da biodiversidade e gera impactos nos recursos naturais, alterando as suas condições ambientais, a disponibilidade de água e a temperatura de superfície. Além disso, as mudanças climáticas têm modificado os componentes do Balanço de Energia (BE). Em relação ao balanço energético este bioma tem, no estado do Rio Grande do Sul, a mesma importância climática que as florestas em regiões tropicais, já que cobre 63% do Estado e possui influência nas dinâmicas atmosféricas. Sendo assim, o objetivo deste trabalho é avaliar as particularidades ambientais do BE e do cálculo de evapotranspiração (ET) no bioma Pampa. A ET é a responsável pelas interações da biosfera-atmosfera-hidrosfera. Estas interações se dão por utilizar energia eletromagnética para a formação de vapor d'água a partir da transpiração vegetal e da evaporação da água. O uso do Sensoriamento Remoto tem sido eficaz nas estimativas de fluxo de calor sensível e fluxo de calor latente por diferentes métodos, porém a aplicação de forma operacional, a heterogeneidade da superfície e a influência da temperatura de superfície (Ts) são desafios deste trabalho. O modelo S-SEBI para recuperação de dados de ET foi avaliado no bioma Pampa e em Barrax, um sítio de validação localizado no mediterrâneo espanhol. O modelo demonstrou ser eficaz em vegetação campestre, além de ser menos dependente da Ts em relação a outros modelos reportados na literatura. Os resultados deste trabalho visam contribuir para a geração de melhor qualidade de dados de ET em futuras análises de mudanças de uso do solo, mudanças climáticas e gestão dos recursos hídricos para todo o bioma Pampa.

Palavras-chave: Balanço de Energia, Sensoriamento Remoto, Evapotranspiração, Campos Nativos

ABSTRACT

In Brazil, there are six biomes, namely the Amazon, Atlantic Forest, Cerrado, Caatinga, Pantanal, and Pampa. Each biome has unique and important characteristics for the maintenance of the ecosystemic processes of each environment. In this sense, in the Pampa biome there is a socio-environmental dynamic that influences the vegetation, agricultural management, and the way of life of the local population. This biome is unique in the world because it brings in its undergrowth vegetation its source of biomass and energy like no other ecosystem; its native grasslands are responsible for the conservation and preservation of water resources, wildlife, and biodiversity. The suppression of the native vegetation of this biome for the monoculture of grains compromises the maintenance of biodiversity and generates impacts on natural resources, altering the environmental conditions of the ecosystem, water availability, and surface temperature. In addition, climate change has modified the components of the Energy Balance (EB). In relation to the energy balance, in the state of Rio Grande do Sul, this biome has the same climatic importance as the forests in tropical regions, since it covers 63% of the state and influences the atmospheric dynamics. Therefore, the objective of this work is to evaluate the environmental particularities of BE and the calculation of evapotranspiration (ET) in the Pampa biome. ET is responsible for biosphere-atmosphere-hydrosphere interactions. These interactions occur by using electromagnetic energy for the formation of water vapor from plant transpiration and water evaporation. The use of Remote Sensing has been effective in estimating sensible heat flux and latent heat flux by different methods, but the application in an operational way, the heterogeneity of the surface and the influence of the surface temperature (Ts) are challenges of this work. The S-SEBI model for ET data retrieval was evaluated in the Pampa biome and in Barrax, a validation site located in the Spanish Mediterranean. The model proved to be effective in grassland vegetation, and is less dependent on Ts compared to other models reported in the literature. The results of this work aim to contribute to the generation of better quality ET data in future analyses of land use change, climate change, and water resource management for the entire Pampa biome.

Keywords: Energy Balance, Remote Sensing, Evapotranspiration, native grasslands.

SUMÁRIO

APRESENTAÇÃO

Apresento esta tese em formato de Capítulos, sendo que cada capítulo se refere à um artigo científico publicado ou submetido para publicação durante a realização do doutorado no Programa de Pós-graduação em Sensoriamento Remoto da Universidade Federal do Rio Grande do Sul[1]. Um Resumo Expandido é apresentado no início deste texto, compondo as principais considerações e os principais resultados encontrados, assim como, a relevância deste estudo.

No resumo expandido, apresento ao leitor a problemática do estudo, os objetivos, as metodologias utilizadas e os principais resultados encontrados. É neste resumo que eu busco discutir a tese de que o bioma Pampa é único no Planeta, não apenas por ser um ecossistema endêmico, mas também em relação ao balanço de energia e evapotranspiração.

No Capítulo 1, apresento uma revisão sistemática sobre sensoriamento remoto no Bioma Pampa a partir de artigos científicos publicados disponíveis na *Web of Science Collection*. O primeiro artigo publicado foi em 1995 e, desde lá, 166 artigos foram escritos. No entanto, a partir de 2010 observou-se um aumento do número dos trabalhos publicados e referenciados nesta coleção. Além desta análise quali-quantitativa, apresento uma discussão dos principais assuntos encontrados e os rumos para o futuro desta área de pesquisa. Este capítulo foi submetido para a revista *Geocarto* em novembro de 2021 (ROCHA; ROLIM; VEETTIL, [s.d.]).

No Capítulo 2 apresento o trabalho desenvolvido durante o doutorado sanduíche realizado em 2018 e 2019 na *Unidad de Cambio Climático* da Universidade de Valência, Espanha, ao qual eu fui orientada pelo professor Juan Carlos Jiménez-Muñoz e pelo professor José Antonio Sobrino. Neste trabalho, apresento a validação do modelo S-SEBI (*Simplified Surface Energy Balance Index)* com medidas de lisímetro em diferentes coberturas vegetais. A partir desta análise foi possível operacionalizar a recuperação de evapotranspiração diária e horária. O modelo também se mostrou mais eficaz no cálculo de evapotranspiração em vegetação campestre plantada do que em culturas agrícolas

[1] Esta tese foi desenvolvida em meio à pandemia Covid-19, muitas atividades de campo e de laboratório previstas não foram realizadas para preservar a saúde de todos.

(trigo e cevada). Este artigo foi publicado em Setembro de 2021 na revista *Remote Sensing* (SOBRINO et al., 2021).

No capítulo 3 realizei a validação do modelo S-SEBI no bioma Pampa com dados da torre de fluxo localizada em Santa Maria, Rio Grande do Sul. Além disso, avaliei a influência da temperatura de superfície (Ts) no cálculo de evapotranspiração. Este é o primeiro trabalho desenvolvido no bioma Pampa com esse objetivo. Com este estudo: 1) demonstramos que o S-SEBI é menos dependente da Ts que outros modelos reportados na literatura e, 2) constatamos que os campos nativos do bioma Pampa são tão importantes no balanço de energia, e por consequência no balanço hidrológico, quanto as florestas (verticais) nativas encontradas na região. Este artigo foi publicado na revista *Atmosphere* em 2020 (ROCHA et al., 2020a).

No capítulo 4, apresento o seguinte questionamento: Baseado no consenso que a vegetação do bioma pampa é única no mundo, questiona-se se ela também é distinta nos aspectos ambientais relativos ao balanço de energia da vegetação de suas pastagens cultivadas. Para tanto, duas áreas de teste foram usadas neste estudo. Uma delas no bioma Pampa, em Santa Maria, Brasil; e outra no sítio Barrax, no oeste da província de Albacete, Espanha. Concluímos que o bioma Pampa se distancia de outros ambientes campestres, principalmente em variáveis como Temperatura de Superfície (Ts) e *Normalized Diference Vegetation Index* (NDVI) avaliadas neste estudo, gerando diferenças no balanço de energia. Este trabalho foi publicado em Março de , 2020 nos anais do *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences.*(ROCHA et al., 2020b).

JUSTIFICATIVA

1 Mudanças Climáticas e os impactos no bioma Pampa

Mudanças climáticas são alterações permanentes nas condições meteorológicas e intensificadas por atividades antrópicas, como o uso intensivo de combustíveis fósseis (IPCC, 2013). A mudança climática global é considerada uma das maiores ameaças evolutivas para vários ecossistemas, incluindo as espécies e habitats de 34 ambientes terrestres e marinhos, devido ao aumento da média temperatura do ar e as variações nos eventos de precipitação e seca (MCCARTY, 2001; SCHOLZE et al., 2006). As mudanças climáticas induzidas pelo homem afetam e intensificam os eventos extremos climáticos e meteorológicos em todas as regiões do mundo. O relatório do *Intergovernmental Panel Climate Change* (IPCC) de 2021 relata que, desde o relatório anterior de 2015, ondas de calor, precipitação intensa, secas e ciclones tropicais têm se intensificado, atribuindo-os à influência humana. (IPCC, 2021).

Utilizando os dados do IPCC de 2007, estudos preliminares preveem, ainda para este século, uma grande alteração da vegetação do bioma Pampa e dos ecossistemas da região em função do prognóstico de savanização do clima do sul do Brasil (CRUZ; GUADAGNIN, 2010; SOUZA DA ROCHA et al., 2019). Ou seja, dada a grande velocidade das alterações climáticas (escala de décadas) haveria um período de grande tensão ecológica, que não seria acompanhado imediatamente por processos de deslocamento espacial da vegetação tampouco por processos adaptativos das espécies.

Esta instabilidade cria oportunidades para que uma série de agravantes aumente a vulnerabilidade das populações pampeanas. Uma delas é a facilitação para que espécies exóticas e invasoras aumentem os ritmos de contaminação biológica (OVERBECK; PODGAISKI; MÜLLER, 2015). Outra consequência seria a perda de valor adaptativo dos conhecimentos e práticas das populações tradicionais que co-evoluiram com o bioma Pampa (COSTA, 2012; CRUZ; GUADAGNIN, 2010). Esta perda de valor adaptativo, frente aos cenários mais drásticos de mudança climática, tem o potencial de levar as sociedades tradicionais ao colapso (COSTA, 2012).

A sustentabilidade dos ecossistemas é fundamental para o desenvolvimento socioeconômico da Metade Sul do Rio Grande do Sul e depende da gestão dos seus recursos naturais e da qualidade dos dados utilizados nos diversos cenários estudados, inclusive nas previsões de alteração de clima. Para tanto, variáveis responsáveis pelos fluxos de energia da Terra, obtidas através de técnicas de sensoriamento remoto, demonstram ser eficazes e com alto custo-benefício no planejamento ambiental do território.

Neste sentido, um estudo publicado recentemente concluiu que os efeitos das mudanças climáticas já estão ocorrendo no Bioma Pampa e que, mesmo que o aumento da temperatura do ar cesse antes das previsões do IPCC se tornarem realidade, o déficit hídrico já ocorre e influencia a sociedade (ROCHA et al., 2021). Neste estudo, os autores concluíram que o déficit hídrico tem afetado principalmente os pecuaristas familiares da região, devido à falta de água potável para seu dia a dia e subsistência, colocando este bioma em risco, uma vez que a pecuária mantém as condições ecossistêmicas do local.

A gestão dos recursos hídricos para a mitigação das mudanças climáticas, além de uma estratégia de adaptação, pode minimizar a influência do aquecimento global nas comunidades que dependem do bioma Pampa para a sua sustentabilidade socioambiental.

2 Importância do Bioma Pampa

Bioma é um território geográfico com inúmeros ecossistemas que possuem as mesmas características físicas, biológicas e climáticas, além de variedades de espécies de plantas e animais próprios. O Brasil apresenta seis biomas: Caatinga, Cerrado, Floresta Amazônica, Pantanas, Mata Atlântica e Pampa.

No Rio Grande do Sul predominam dois biomas que compõe os campos sulinos: a Mata Atlântica na Metade Norte do estado e o Pampa na Metade Sul. Este último representa 2,07% do território nacional e se estende para a Argentina e o Uruguai.

Os ecossistemas campestres, com suas diferentes fisionomias, ocupavam originalmente cerca de 152,3 mil km² no bioma Pampa do Rio Grande do Sul (OVERBECK et al., 2009). Em 2002, restavam 41,6% da cobertura original (MMA, 2007) e, em 2007, 35,3% (HASENACK; CORDEIRO; COSTA, 2007). Um estudo mais detalhado desenvolvido pelo *MapBiomas*[2], encontrou apenas 39% de vegetação campestre, incluindo áreas de

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[2] Projeto MapBiomas - é uma iniciativa multi-institucional para gerar mapas anuais de uso e cobertura da terra a partir de processos de classificação automática aplicada a imagens de satélite. A descrição completa do projeto encontra-se em **http://mapbiomas.org**

cultivo de pecuária antropizadas, ano base 2019 (SOUZA et al., 2020). Estes dados são resultados da exploração agrícola e da conversão indiscriminada da vegetação nativa para outros usos do solo, principalmente para a monocultura de grãos. É importante ressaltar que, durante décadas, os campos sulinos não foram considerados importantes para conservação, não se acreditava na importância da biodiversidade dessas espécies e poucos eram os estudos realizados na região (PYLRO; MORAIS; ROESCH, 2015).

A vegetação do bioma Pampa envolve a coexistência entre os tipos fitogeográficos savana gramíneo-lenhosa, floresta estacional semidecidual e alguns pequenos fragmentos de floresta ombrófila mista. Esta variedade caracteriza uma paisagem de tensão ecológica sobre solos rasos e com afloramento de rochas, onde sua manutenção torna-se possível devido à presença da atividade pecuária na região (HASENACK; CORDEIRO; COSTA, 2007; IBGE, 2010).

Em relação ao uso dos recursos hídricos e às atividades agrícolas, a região apresenta alta deficiência hídrica no solo nos meses de verão, além de possuir a menor disponibilidade hídrica superficial do Rio Grande do Sul. A supressão da vegetação nativa para a agricultura de grãos e silvicultura prejudica a segurança hídrica da região, pois interfere diretamente na recarga dos aquíferos (FIGUEIRÓ et al., 2011; ROCHA et al., 2019; ROCHA et al., 2021).

O bioma Pampa possui como principal atividade econômica e sociocultural a pecuária familiar (CRUZ; GUADAGNIN, 2010; NESKE; ANDRADE; BORBA, 2012). São estas famílias as responsáveis pela conservação do bioma através do manejo do campo e do pisoteio do gado. Em contraponto, a vegetação campestre deste bioma serve de fonte forrageira para a pecuária e ajuda a manter estas famílias no campo e na produção primária de alimentos (OVERBECK et al., 2007; OVERBECK; PODGAISKI; MÜLLER, 2015).

RESUMO EXPANDIDO

1 INTRODUÇÃO

O bioma Pampa é considerado pelo Ministério do Meio Ambiente (MMA/Brasil) uma das áreas de campo de clima temperado mais importantes do planeta (BOLDRINI, 2009; OVERBECK et al., 2007; PILLAR; ANDRADE; DADALT, 2015). Na América do Sul, este bioma se estende por uma área de aproximadamente 750.000 km², compartilhada pelo Brasil, Uruguai e Argentina. No Brasil, este bioma está restrito ao Estado do Rio Grande do Sul, ocupando 63% do seu território e 2,07% do território nacional (BOLDRINI, 2009; NIMER, 1990).

No que se refere a biodiversidade e aos serviços ambientais, os campos constituem fonte forrageira para a pecuária, abrigam diversidade de espécies vegetais e animais e garantem a conservação dos recursos hídricos (OVERBECK et al., 2006). Além disso, controlam a erosão do solo e o sequestro de carbono que atenuam as mudanças climáticas (CRUZ; GUADAGNIN, 2010; IPCC, 2013).

A perda da biodiversidade deste bioma compromete o potencial de desenvolvimento sustentável da região. Em relação às áreas naturais protegidas no Brasil, o Pampa é o bioma que tem menor representatividade (3,3%). As pesquisas desenvolvidas, juntamente com o planejamento e a gestão dos recursos naturais deste território, são fatores determinantes para a sua conservação. Apesar disso, apenas nas últimas décadas o Pampa despertou o interesse dos cientistas, somente a partir de 2015 que as pesquisas têm aumentado neste ecossistema (PYLRO; MORAIS; ROESCH, 2015). Para estes autores é necessário maior investimento em pesquisas locais, no que eles chamam de "microbiomas", para garantir a sustentabilidade e a proteção da biodiversidade destes locais.

Uma das ações fundamentais para a estabilidade dos campos é o fomento às atividades econômicas de uso sustentável, a exemplo da pecuária com manejo do campo nativo que mantém as condições ecossistêmicas da região e o desenvolvimento econômico (CRUZ; GUADAGNIN, 2010; GUADAGNIN et al., 2009; OVERBECK et al., 2007). É importante ressaltar que a vegetação campestre nativa difere profundamente de pastagens cultivadas, geralmente formadas por espécies exóticas que resultam da eliminação da vegetação original (OVERBECK; PODGAISKI; MÜLLER, 2015).

As diferenças ecossistêmicas entre a vegetação campestre e as pastagens cultivadas resultam em variabilidade nos balanços de energia e hídrico, pois modificam as variáveis meteorológicas, fisiológicas e biofísicas desses ambientes (ROCHA et al., 2021; FONTANA et al., 2018; SCHIRMBECK; FONTANA; ROBERTI, 2018; ROCHA et al., 2019).

Evapotranspiração (ET) é a relação entre os fluxos de energia solo-vegetação-atmosfera e o conteúdo de água das plantas através do balanço de energia (GOMIS-CEBOLLA et al., 2019). Sendo assim, a quantificação da ET é essencial para a gestão dos recursos naturais e sua medida continua a ser um dos termos mais incertos nos balanços de água e energia. Rubert et al., (2018) avaliaram sazonalmente, por eddy-covariance, a ET em duas áreas de estudo diferentes com a mesma cobertura vegetal nativa do Bioma Pampa. Os autores concluíram que 65% da energia disponível foi utilizada para evapotranspiração, os outros 35% são utilizados para aquecer a superfície e acabam se perdendo no sistema. Os autores constataram ainda que, mesmo com as diferenças de umidade do solo, não houve distinção na partição da energia nas duas áreas de estudo. Medições convencionais de campo desta variável possuem um uso limitado por serem espacialmente não representativas, principalmente em áreas heterogêneas (TANG; LI, 2008) .

Neste sentido, o sensoriamento remoto tem sido uma alternativa para o cálculo de ET, através do uso de produtos de temperatura de superfície (Ts) e emissividade (ε) de superfície, gerados por técnicas de cálculo de radiância (TANG; LI; SUN, 2013). Estes produtos são amplamente utilizados em escala regional no monitoramento agrícola/ambiental de vários ecossistemas (BASTIAANSSEN et al., 1998a; SÁNCHEZ et al., 2008).

Schirmbeck, Fontana e Roberti (2018) realizaram um dos primeiros estudos de fluxos de energia do bioma Pampa no Rio Grande do Sul, utilizando os modelos SEBAL e METRIC em produtos de temperatura de imagens MODIS. Os autores observaram um melhor desempenho nos resultados obtidos nas estações de verão em relação às de inverno, causados, provavelmente, pela baixa variabilidade da Ts nos campos nativos.

2 OBJETIVO

O objetivo desta tese é avaliar as particularidades ambientais do balanço de energia e do cálculo de evapotranspiração no bioma Pampa.

2.1 Objetivos Específicos

- Avaliar quali-quantitavivamente a situação atual do Bioma Pampa Sul-Americano no que diz respeito ao uso e aplicação de dados de sensoriamento remoto.
- Validar o modelo S-SEBI de cálculo de evapotranspiração para diferentes usos e operacionalizar este cálculo de maneira a facilitar seu uso.
- Testar e validar o modelo S-SEBI de cálculo de evapotranspiração para o bioma Pampa.
- Analisar a influência que as incertezas na estimativa da temperatura de superfície podem causar no cálculo de ET pelo modelo S-SEBI.
- Avaliar as particularidades do campo nativo em relação ao balanço de energia comparado com vegetação florestal e solo exposto.

3 ÁREA DE ESTUDO

3.1 Bioma Pampa

As áreas amostrais deste estudo compõem sítios selecionados no projeto NEXUS (Pesquisa e Desenvolvimento em Ações Integradas e Sustentáveis para a Garantia da Segurança Hídrica, Energética e Alimentar nos Biomas Pampa) e no projeto PELD 2016 (Programa Ecológico de Longa Duração).

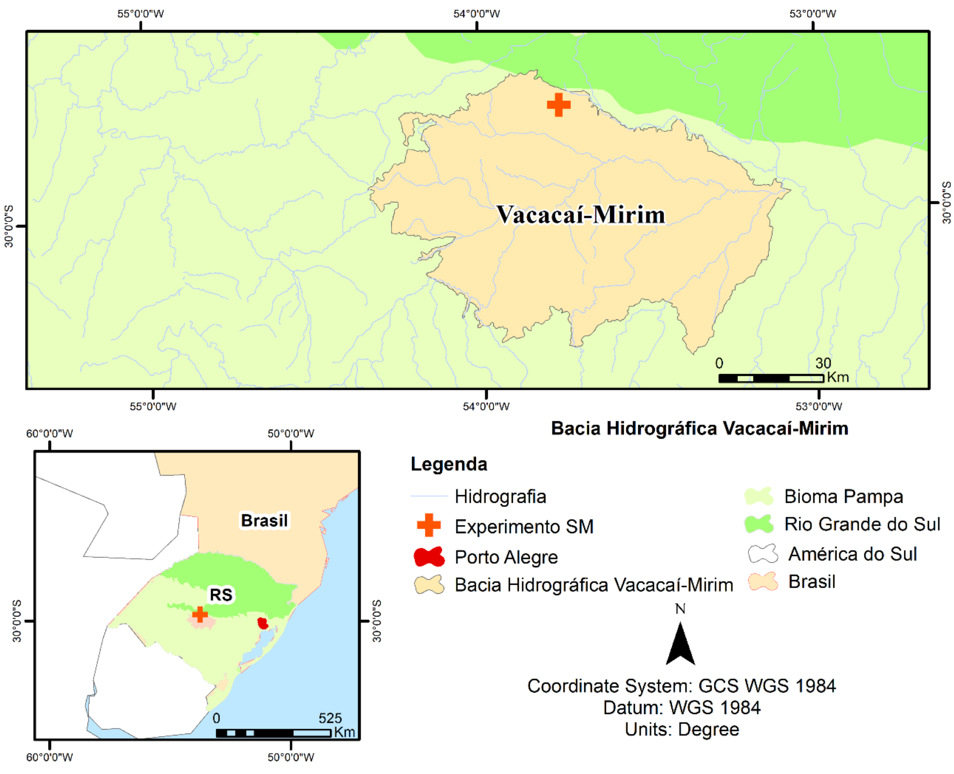
Ambos os projetos são apoiados pelo CNPq e pela FAPERGS e as análises e os resultados do estudo de Balanço de Energia serão utilizados por estes para compor objetivos mais amplos: (1) analisar os cenários de conservação e restauração dos ecossistemas campestres em diferentes dimensões da sustentabilidade das paisagens agrícolas na região do bioma Pampa e (2) contribuir para embasar cientificamente políticas públicas que garantam, de maneira integrada, a segurança hídrica, alimentar e energética nessa região e que atendam a seis dos Objetivos do Desenvolvimento Sustentável da Agenda 2030 da ONU.

As áreas escolhidas para análise local da ET e que serviram para validação foram Santa Maria e Barrax. A primeira é uma área de conservação do bioma Pampa e pertence à Universidade Federal de Santa Maria, com um histórico de dados de manejo e uso do solo disponíveis e uma Torre de Fluxo com dados meteorológicos indispensáveis na validação dos modelos de evapotranspiração testados neste projeto. A segunda fez parte do doutorado sanduíche desenvolvido durante os meses de novembro de 2018 a maio de 2019 e serviu como validação do modelo S-SEBI de evapotranspiração testado em diferentes coberturas vegetais.

3.2 Santa Maria

A área experimental de Santa Maria (SM) possui uma cobertura de campos nativos com características fisiológicas próprias do bioma Pampa de 24 ha e é localizada próxima à cidade de Santa Maria, a 292 km de Porto Alegre (Figura 1). A área é utilizada para experimentos da Universidade Federal de Santa Maria em várias áreas de conhecimento, principalmente direcionados morfologia de espécies nativas para produção pecuária (CONFORTIN et al., 2017; OLIVEIRA et al., 2015).

Figura 1 – Localização Vacacaí-Mirim no Bioma Pampa e experimento Santa Maria (SM).



Fonte: Elaborado pela autora com dados do IBGE (2010).

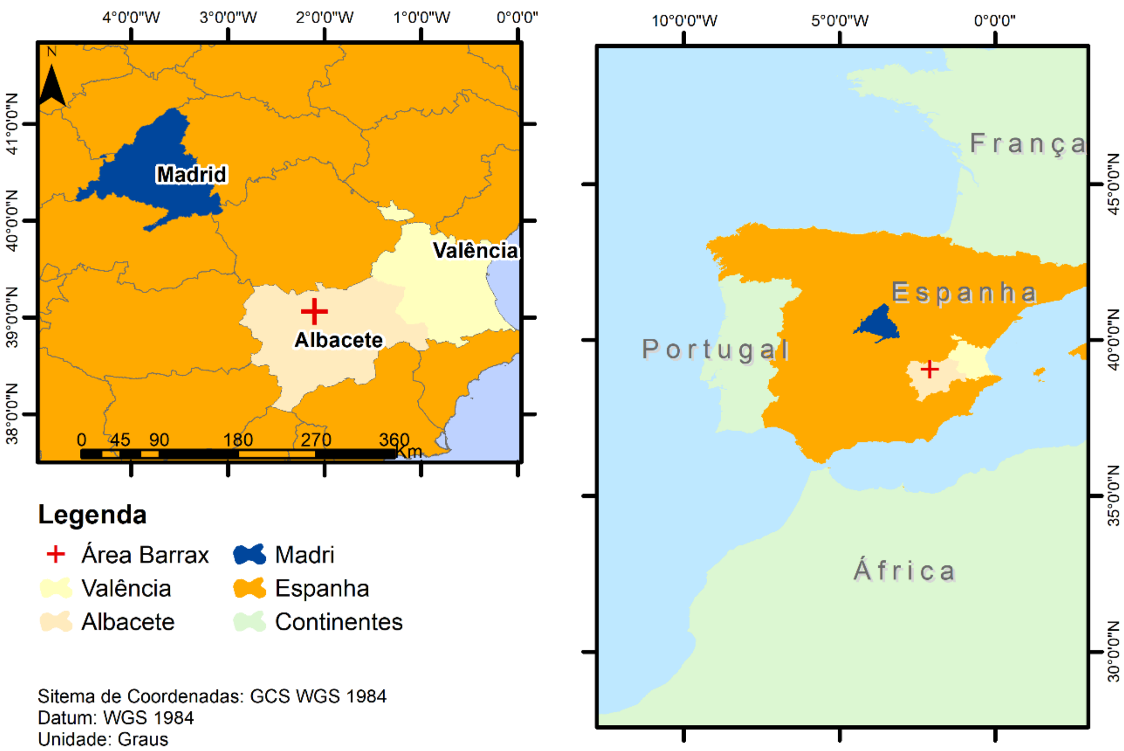
A evapotranspiração desse sítio também está sendo estudada pelo laboratório de Micrometeorologia da Universidade Federal de Santa Maria a partir de dados da torre de fluxo e do método *eddy covariance.* Os primeiros resultados desta pesquisa foram publicados por Rubert et al., (2016) e foram utilizados para a validação do modelo S-SEBI testado neste trabalho.

3.3 Sítio Barrax/Albacete – Espanha

O sítio Barrax vem sendo utilizado como área experimental há muitos anos pelo *Image Processing Lab* (IPL) nos estudos de transferência radiativa na atmosfera e de balanço de energia, considerado um dos mais importantes sítios de calibração/validação da Europa (GÓMEZ et al., 2005; JIMENEZ-MUNOZ et al., 2014a; MATTAR et al., 2014; SKOKOVIC; SOBRINO; JIMENEZ-MUNOZ, 2017; SOBRINO et al., 2007).

Barrax está localizado na província de Albacete a 28 km de Madrid, região de *La Mancha,* Espanha (Figura 2). A área possui agriculturas anuais de grãos e sementes, além de vegetação natural de campo.

Figura 2: Área de Estudo Barrax em Albacete/Espanha.

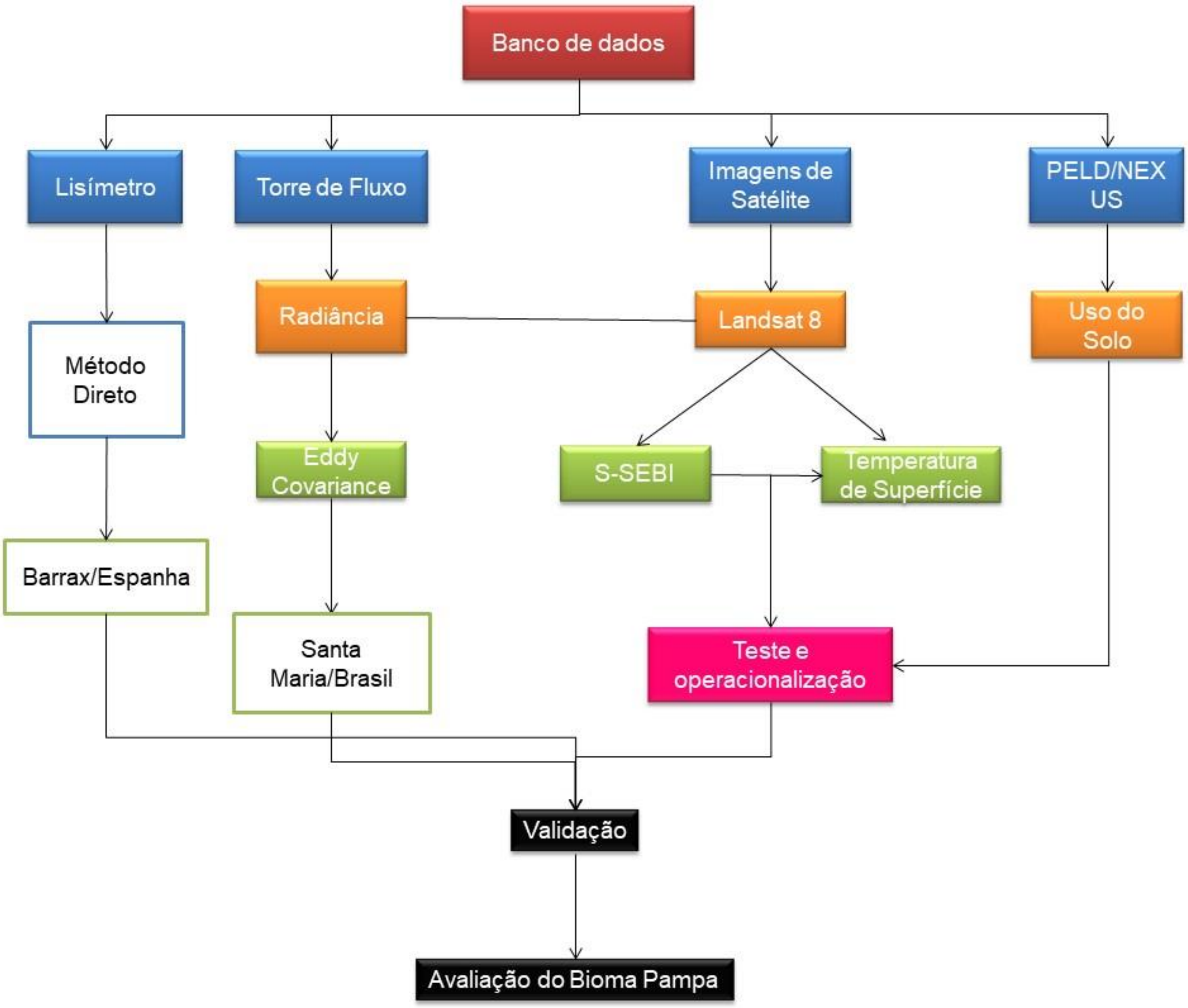


Fonte: elaborado pela autora a partir de dados de campo e da Agência Espacial Europeia (ESA).

4 MÉTODOLOGIA

O estudo foi realizado a partir da coleta de dados de campo, das variáveis de torres de fluxo e imagens de satélite, sendo parte desenvolvida durante o período do Doutorado Sanduíche na Universidade de Valencia, Espanha. A Figura 3 representa o desenvolvimento metodológico realizado.

Figura 3: Fluxograma dos métodos para elaboração da Tese.



4.1 Evapotranspiração e Balanço de Energia

Evapotranspiração (ET) é o processo de transformação da água líquida presente nos corpos d’água (evaporação) e nos tecidos vegetais (transpiração) em vapor d’água para a atmosfera. ET é uma variável fundamental do sistema climático, pois desempenha um papel importante nas interações da biosfera-atmosfera-hidrosfera (RUBERT et al., 2016). Estima-se que 60% da água precipitada retorna à atmosfera através da evapotranspiração (OKI; KANAE, 2006).

A estimativa de ET é uma das grandes dificuldades no cálculo do Balanço Hídrico Climatológico (BHC) em escala regional, porque depende do conhecimento de variáveis climatológicas (temperatura, precipitação, vapor d'água, vento) e, também, de variáveis fisiológicas das plantas. No entanto, a quantificação da ET é essencial para a gestão dos recursos hídricos e para o planejamento ambiental e agrícola. Métodos baseados nas informações obtidas no espectro Infravermelho Termal (*Thermal Infra-Red – TIR*) são usados, por exemplo, no monitoramento da irrigação de plantios agrícolas no mundo todo (BAHIR et al., 2017; BASTIAANSSEN et al., 1998a, 1998b; SÁNCHEZ et al., 2008).

Entre tantas variáveis meteorológicas, a temperatura de superfície (Ts) é uma das mais importantes nas estimativas de ET. Além disso, a ET em ambiente natural é afetada por uma série de fatores, como energia solar e água disponíveis, pressão de vapor d'água, velocidade do vento e atividade vegetativa. Neste sentido, os dados de Ts estabelecem uma forma de estimar a ET independente do conhecimento dos vários componentes do balanço hídrico.

Medições convencionais de ET (i.e., *sap flow, weighing lysimeter, pan measurement, Bowen ratio system, eddy correlation system*, e *scintillometer*) possuem um uso limitado por serem espacialmente não representativas (TANG; LI, 2008), possuírem um alto custo de instalação, além da instrumentação sensível e elaborada (LI; ZHAO, 2010; MONTEITH; UNSWORTH, 1990). Alguns experimentos calculam a ET de forma pontual a partir de dados de superfície (coeficiente de cultura, parâmetros climáticos, umidade do solo, medida dos fluxos de vapor, dentre outros). Contudo, essas estimativas pontuais não permitem a extrapolação espacial da ET em escala regional em função da heterogeneidade da superfície.

No bioma Pampa a estimativa de ET por *eddy-covariance* foi avaliada sazonalmente por Rubert et al., (2018) em duas diferentes áreas de estudo com mesma cobertura vegetal nativa e diferentes tipos de solo. Os autores concluíram que durante o período do estudo, 65% da energia disponível era usada para a evapotranspiração. Além disso, mesmo com as diferenças de umidade do solo, não houve distinção aparente na partição de energia nas duas áreas de estudo e a evapotranspiração diária não variou significativamente entre os sítios avaliados. Os autores também demonstraram a alta variabilidade sazonal da evapotranspiração, com valores mais altos durante o período primavera-verão em relação ao outono-inverno.

Por fim, o uso de diferentes estimativas de precipitação, evapotranspiração e de vazão pode resultar em um desequilíbrio no balanço hídrico regional de até 50% (BASTIAANSSEN et al., 1998b; TUCCI; COLLISCHONN, 2003).

Os avanços científicos na área de sensoriamento remoto e agrometeorologia são responsáveis pelo desenvolvimento de vários métodos para a estimativa da ET. A maioria deles parte de um modelo físico empírico derivado da equação de balanço de energia (*Surface Energy Balance* – SEB), com diferentes graus de complexidade. Como por exemplo, podemos citar os modelos SEBAL (*Surface Energy Balance Algorithm over Land*), METRIC (*Mapping Evapotranspiration with Internalized Calibration*), SEBS (*Surface Energy Balance System*), SAFER (Simple Algorithm for Evapotranspiration Retrieving), TSM (*Two Source Model*), TSTIM (*Two-source time-integrated model*) e S-SEBI (*Simplified Surface Energy Balance Index*).

O modelo S-SEBI foi o trabalhado nesta tese, focando na aplicação operacional e automática, na validação em diferentes coberturas vegetais em escala regional e local e na influência da temperatura de superfície no modelo.

4.1.1 Modelo S-SEBI de Balanço de Energia

O modelo S-SEBI foi desenvolvido por Roerink; Su; Menenti, (2000), e leva em consideração a relação entre o balanço de radiação disponível e o balanço de energia. Este modelo resulta em uma estimativa de fluxo de calor latente (LET) para cada pixel de uma imagem de satélite. Os autores testaram a interação da radiação com os fluxos de energia, utilizando imagens Landsat-TM, e validaram com dados *in-situ*. Basicamente, o modelo determina uma temperatura de superfície máxima para condições secas e uma temperatura mínima para condições úmidas, ambas dependentes da reflectância obtida na imagem de satélite. Por fim, os fluxos de calor sensíveis e latentes são divididos de acordo com a temperatura real da superfície naquele determinado momento da passagem do satélite.

Em 2005, Sobrino et al. apresentaram uma metodologia para estimar a evapotranspiração, conversão de LET em ET, utilizando o modelo S-SEBI e a fração evaporativa desenvolvida por Roerink; Su; Menenti, (2000). A ET foi estimada utilizando um sensor de alta resolução espacial (de 2 a 20m, dependendo da altura do voo) e espectral (79 bandas entre 0.4 a 13 μm), chamado *Digital Airborne Imaging Spectrometer*, (DAIS -

sensor 7915). Os autores chegaram a um erro de 1mm/dia e ressaltaram que outros modelos, como por exemplo o SEBAL obtém resultados de ET diária melhores, porém que dependem de outras variáveis muito mais complexas, como o coeficiente de rugosidade das plantas. Em 2007, Gómez et al. testaram o método utilizando 160 imagens de baixa resolução espacial (1km) do sensor AVHRR (*Advanced Very High Resolution Radiometer*) a bordo da plataforma da Administração Nacional Oceânica e Atmosférica (NOAA) sob a Peninsula ibérica de 1997 a 2002.

Em todos os casos testados partiu-se das suposições de que havia condições atmosféricas constantes e número suficiente de pixels úmidos e secos sobre a imagem. Essa condição é um desafio assumido neste trabalho, visto que o bioma Pampa é caracterizado por sua homogeneidade e por possuir baixa variabilidade de pixels quentes e frios (FONTANA et al., 2018b).

Por outro lado, o modelo necessita apenas de parâmetros de sensoriamento remoto como albedo, MSAVI (Índice de Vegetação Ajustado do Solo Modificado) e imagens de temperatura e emissividade da superfície, para a sua implementação, permitindo a estimativa de ET sem medidas *in situ*.

Matematicamente, a equação simplificada do modelo S-SEBI para obtenção de fluxo de calor latente, é dada na equação 1.

$$LET_i = \Lambda\,(R_{ni} - G_i) \qquad \text{(Eq. 1)}$$

Onde: LET_i é o fluxo de calor latente instantâneo (W m^{-2}); Λ é a fração evaporativa; R_{ni} é o fluxo de radiação instantânea (W m^{-2}); e G_i é o fluxo de calor instantâneo do solo.

O fluxo de radiação instantânea (R_{ni}) é dada pela Equação 2.

$$Rni = (1-\alpha)Rs\downarrow + \varepsilon RL\downarrow - \varepsilon\sigma Ts^4 \qquad \text{(Eq. 2)}$$

Onde: α é o albedo, ε é a emissividade, $Rs\downarrow$ é a radiação de onda curta incidente dado em W/m², $RL\downarrow$ é a radiação de onda longa incidente dado em W/m², Ts é a temperatura de superfície em Kelvin (K) e $\sigma = 5{,}67x10^{-8}W/m^2K^{-4}$ é a constante de Stefan-Boltzman.

O fluxo de calor instantâneo do solo (G) foi obtido a partir da relação entre Ts, NDVI e R_{ni} (Eq. 3), discutida por (BASTIAANSSEN, 2000).

$$G = \left(\left(\frac{Ts}{\alpha}\right)x\,(0{,}0038x\,\alpha) + (0{,}0074\alpha^2)x(1-0{,}98xNDVI^4)\right)xRn \qquad \text{(Eq. 3)}$$

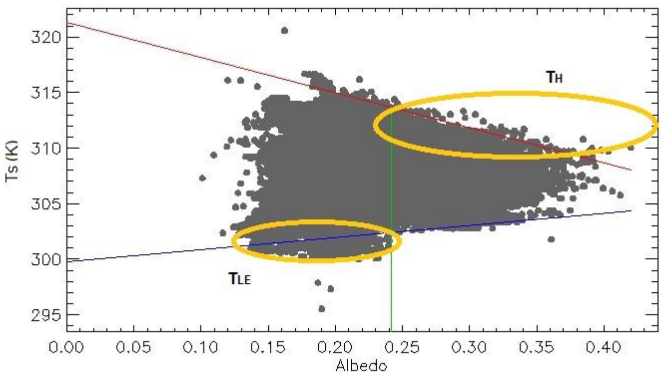
A fração evaporativa é dada pela Equação 4 (ROERINK; SU; MENENTI, 2000; SOBRINO et al., 2005).

$$\Lambda = \frac{T_H - T_S}{T_H - T_{LET}} \quad \text{(Eq. 4)}$$

Onde: T_S é a temperatura de superfície e T_H e T_{LET} são temperaturas obtidas a partir da relação entre albedo e T_S para a identificação de áreas mais úmidas e mais secas na imagem.

As temperaturas (T_H e T_{LET}) são obtidas a partir da imagem de satélite e para selecioná-las, os valores das imagens de albedo e T_S são plotados e relacionados em um gráfico, representado na Figura 4.

Figura 4 – Temperatura de Superfície *versus* Albedo. Linha azul representa o *Latent Heat Flux* (LE); Linha vermelha representa o *Sensible Heat Flux* (H)



Fonte: Acervo da autora.

No gráfico da Figura 4 observa-se que há uma T_S aproximadamente constante para valores de albedo mais baixos (linha azul, até linha verde), estes representam superfícies saturadas como corpos de água e terras irrigadas, neste caso toda a energia disponível é utilizada no processo evaporativo (T_{LE}). Ao contrário, quando há valores altos de albedo com temperaturas também mais altas, há uma diminuição de T_S (linha vermelha, a partir da linha verde), isto ocorre porque a umidade do solo diminuiu a tal ponto que nenhuma evaporação pode ocorrer neste caso, e toda energia disponível é usada para aquecer a superfície (T_H).

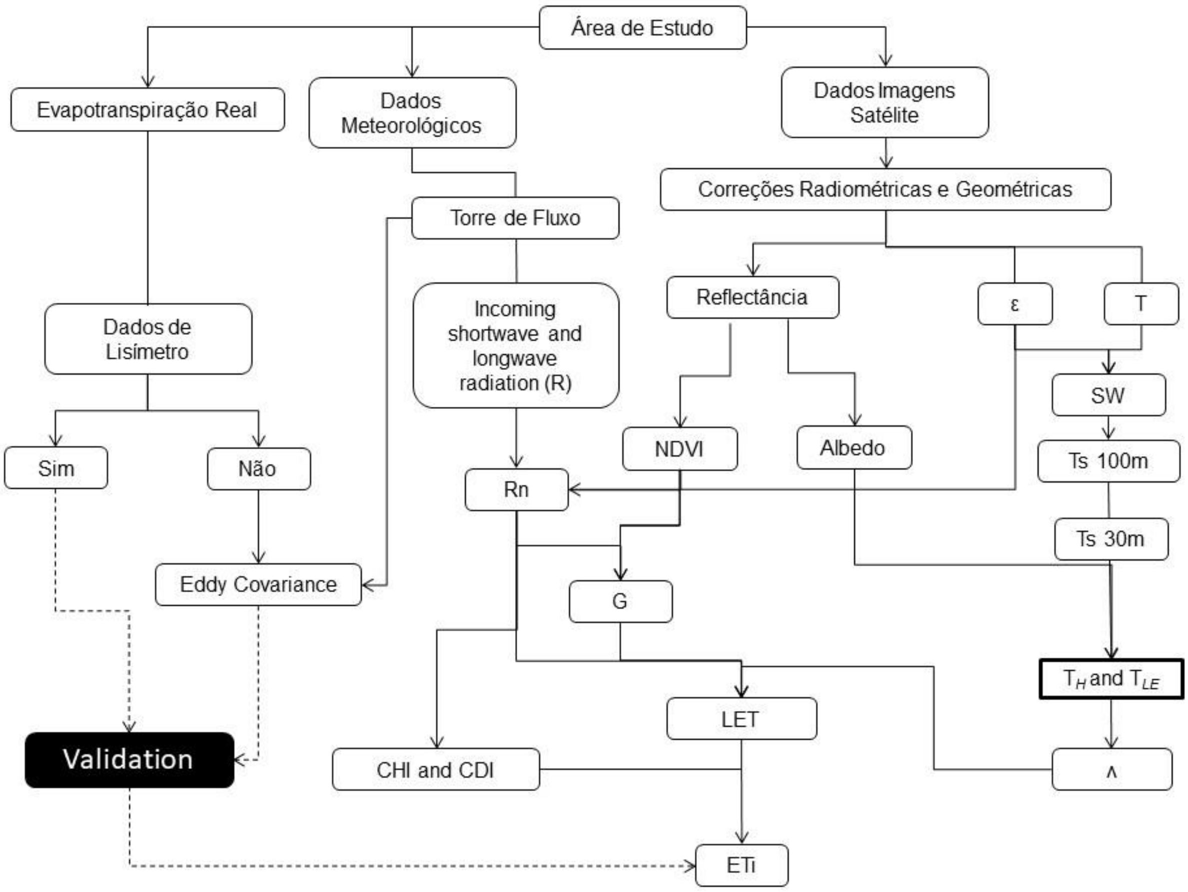
Dito isso, a estimativa de fluxo de calor latente diário (LET_d) necessita da integração matemática do valor instantâneo de fluxo de calor latente (LET_i) para um dia inteiro. A integração da equação matemática resulta então na equação 5.

$$LET_d = LET_i \frac{R_{nd}}{(R_{ni} - G_i)} \quad \text{(Eq. 5)}$$

Onde: LET_i é o fluxo de calor latente instantâneo, dado na Eq. 1; R_{nd} e R_{ni} são o fluxo de radiação diária e instantânea, respectivamente; e G_i é o fluxo de calor do solo instantâneo.

Os pré-processamentos e a dinâmica de aquisição da ET de maneira operacional foram discutidos por Sobrino et al., (2005) e testados por Mattar et al. (2014). A seguir, são apresentadas na Figura 5.

Figura 5: Fluxograma para a obtenção da evapotranspiração pelo modelo S-SEBI.



Fonte: Adaptado de Sobrino et al., (2005).

Essa dinâmica é detalhada no Capítulo 2 e no Capítulo 3 desta tese, em que apresentamos a metodologia de obtenção e validação de evapotranspiração em Barrax e em Santa Maria.

Na Tabela 1 são apresentadas as equações utilizadas no pré-processamento de imagens para a obtenção de Temperatura de superfície (T_s), *Normalized Difference Vegetation Index* (NDVI), Albedo (α) e Emissividade (ε).

Tabela 1 – Equações utilizadas no processamento de imagens.

Variável	Equação	Descrição
NDVI	$(\rho NIR - \rho RED)/(\rho NIR + \rho RED)$	ρNIR é a reflectância do Infravermelho próximo do Landsat 8 (0.86µm) e ρRED se refere refers a reflectância banda do vermelho no Landsat 8 OLI (0.65 µm)(ROUSE et al., 1973a);
α	$0.130\rho 1 + 0.115\rho 2 + 0.143\rho 3 + 0.180\rho 4 + 0.281\rho 5 + 0.108\rho 6 + 0.042\rho 7.$	*ρ* é a reflectância em cada banda do Landsat 8 OLI; (KE et al., 2016)
Ts	$Ti - 0.268(Ti - Tj) + 1.378(Ti - Tj)^2 + 16.4 + (0.183 + 54.3w)(1 - \varepsilon) + (-2.238 - 129.2w)\Delta\varepsilon$;	*Ti* e *Tj* são a temperatura de brilho do sensor das bandas *i* (10) e *j* (11) em Kelvin; *ε* é a media de emissividade, $\varepsilon = 0.5(\varepsilon i + \varepsilon j)$, Δ*ε* é a variação de emissividade, $\Delta\varepsilon = (\varepsilon i - \varepsilon j)$ das bandas *i* (10) and *j* (11); *w* é o conteúdo de vapor de água da atmosfera (in g/cm−2); (JIMENEZ-MUNOZ et al., 2014b; SOBRINO et al., 1996)
ε	$a + b\rho RED$; $(FVC = 0)$ $\varepsilon_s(1 - FVC) + \varepsilon_v FVC$; $(0 < FVC < 1)$ $\varepsilon = 0.99$; $FVC = 1)$	*FVC* é a fração de cobertura vegetal e é dada por $FVC = NDVI - NDVIs/NDVIv - NDVIs$; ε_s and ε_v são a emissividade do solo e da vegetação, respectivamente. (SOBRINO et al., 2008)

4.1.2 Cálculo de Evapotranspiração Diária e Horária

Após a obtenção do fluxo de calor latente (LET) vista no capítulo anterior, faz-se necessária a conversão de valores instantâneos de LET, obtidos a partir de imagens de satélite, em estimativas de Evapotranspiração dadas em milímetros por dois motivos: 1) validar os dados de satélite com dados '*in situ*' de medições convencionais, como por exemplo dados de lisímetro utilizados no Capítulo 2 desta tese; e 2) para que os dados tenham maior aplicabilidade na gestão de recursos hídricos.

A ET diária (ET_{daily} dada em mm/dia) é definida como a integração temporal dos valores de ET instantânea e pode ser obtida usando o conceito de CDI, introduzido e validado por Gómez et al., (2005) e Sobrino et al., (2007), que consiste na relação entre o fluxo de radiação solar diária (R_{nd}) e instântanea (R_{ni}), a ET diária é então dada como segue na Equação 6.

$$ET_{daily} = 24\ x\ 3600\ (\frac{CDI\ x\ \Lambda\ x\ R_{ni}}{\lambda}) \quad \text{(Eq. 6)}$$

Onde: λ é o calor latente de vaporização da água (2.45 MJ/kg); Λ é a fração evaporativa, considerada constante durante o dia. Na ET diária o fluxo de calor latente do solo (G) foi considerado nulo, pois toda a radiação absorvida pelo solo durante o dia retorna para atmosfera durante a noite (SAUER; HORTON, 2015)

Analogamente, nesta tese apresentamos uma forma de conversão de ET instantânea em ET horária (ET_{hourly} dada em mm/h), conforme Equação 7.

$$ET_{hourly} = 24\ x\ 3600\ (\frac{CHI\ x\ \Lambda\ x\ R_{ni} - G_i}{\lambda}) \quad \text{(Eq. 7)}$$

Onde: CHI é a relação entre o fluxo de radiação solar horária (Rnh) e a instântanea (Rni), G_i é o fluxo de calor no solo instantâneo (considerado constante, assumindo erros mínimos) e Λ é a fração evaporativa também considerada constante durante a hora.

Estes conceitos de evapotranspiração diária e horária foram testados e analisados nos Capítulos 2 e 3 desta tese.

4.2 Imagens Landsat 8

O satélite Landsat 8 (L8) foi lançado em 2013 dando sequência a série histórica dos satélites Landsat com resolução temporal de 16 dias e radiométrica de 16 bits. Este possui dois sensores, o Operational Land Imager (OLI) e o Thermal Infrared Sensor (TIRS). O primeiro sensor OLI coleta dados em oito bandas do espectro eletromagnético com 30 metros de resolução espacial, desde o visível, infra-vermelho próximo (NIR) e infravermelho de ondas curtas (SWIR). O segundo sensor TIRS possui uma resolução espacial de 100 metros e coleta dados em duas regiões espectrais do infravermelho termal, a banda 10 (10,60-11,19 μm) e a banda 11 (11,50-12,51 μm).

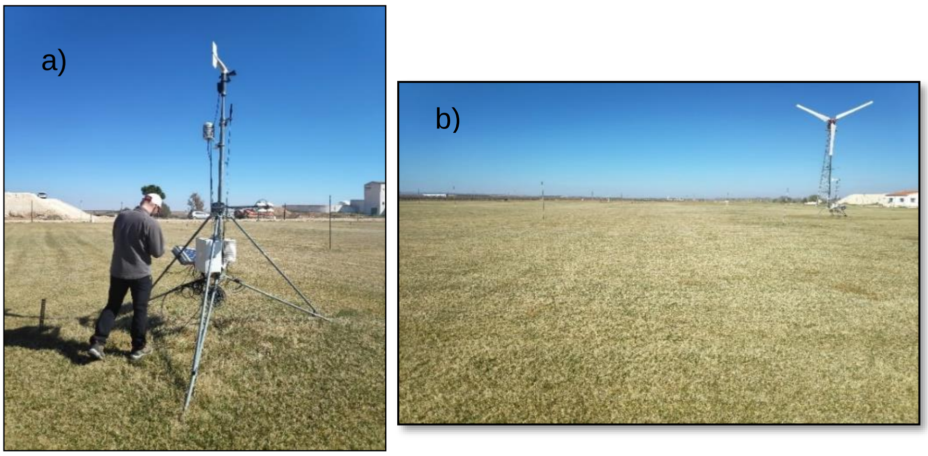
Para o sítio Barrax, foram selecionadas todas as imagens L8 disponíveis de 2014 a 2018 sem presença de nuvens, resultando em 222 cenas processadas para obtenção de dados de temperatura e emissividade de superfície, NDVI e albedo. Para o sítio Santa Maria foram selecionadas todas as imagens disponíveis de janeiro de 2016 a abril de 2019, resultando em 168 imagens também processadas pelo *Image Processing Laboratory* (IPL/Valência) durante o estágio Doutorado Sanduíche. Essas imagens serviram para a análise da evapotranspiração sazonal no sítio e para a validação dos modelos S-SEBI nas regiões do estudo.

4.3 Dados de experimentos do IPL/UV

4.3.1 Torre de Fluxo

A Torre de Fluxo está localizada na área de estudo de Barrax (Figura 6) com medições horárias de radiação solar direta, radiância atmosférica *donwelling*, temperatura do ar a 1 m e a 2 m, temperatura de superfície, umidade relativa do ar e do solo. Estes dados são de responsabilidade do IPL da Universidade de Valência (UV).

Figura 6 – a) Torre de Fluxo na área de estudo Barrax; b) Uso do solo/Vegetação na qual a torre está instalada.



Fonte: Acervo da autora (Março, 2019)[3].

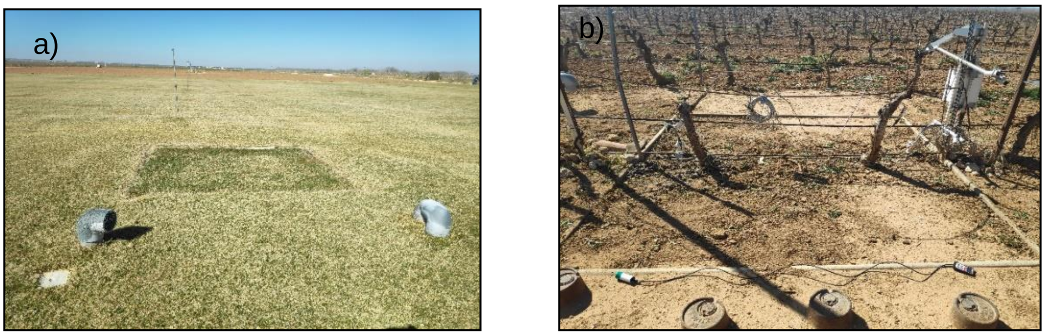
4.3.2 Lisímetros

A área de estudo possui três lisímetros instalados com diferentes culturas, sendo um deles instalado na mesma área da torre de fluxo e os outros dois em áreas de cultivo de vinhas e de grãos (Figura 7 a e b). O primeiro possui medições diárias a cada 15min de

[3] Fotografias tiradas durante o estágio sanduíche na Universidade de Valência/Espanha.

2014 até 2018, porém os outros dois só possuem medidas em épocas de plantio, reduzindo o banco de dados para as culturas de grãos.

Figura 7– a) Lisímetro na área de campo (*Grass*); b) Lisímetro na área de vinha em época de queda de folhas (inverno)



Fonte: Acervo da autora (março, 2019).[4]

4.4 Dados de experimentos do LabSRGeo/UFRGS e parceiros PELD/NEXUS

4.4.1 Torre de Fluxo Santa Maria

A torre de fluxo presente na área de estudo de Santa Maria é de responsabilidade do Laboratório de Meteorologia da UFSM que vem desenvolvendo trabalhos importantes na área de balanço de energia (Figura 8), localizada na latitude 29.725ºS e longitude 53.760ºO. A estação micrometeorológica possui sensores que medem: 1) Intensidade do vento; 2) Concentração de vapor d'água e CO_2; 3) Radiação solar (4 componentes da radiação); 4) Fluxo de calor no solo; 5) Temperatura do solo; 6) Temperatura do ar; 7) Conteúdo de água no solo; 8) Umidade relativa do ar; e 9) Precipitação; (RUBERT et al., 2018).

[4] Fotografias tiradas durante o estágio sanduíche na Universidade de Valência/Espanha

Figura 8 – Torre de Fluxo na área de estudo em Santa Maria e Uso do solo/Vegetação na área.

Fonte: Acervo Laboratório de Meteorologia da UFSM.

4.4.2 Método Eddy-covariance

O método Eddy-covariance (EC) (AUBINET; VESALA; PAPALE, 2012) foi utilizado nesta tese para fins de validação dos componentes do balanço de energia estimados pelo modelo S-SEBI no Capítulo 2 desta tese. As medições de dados para estimar LE e fluxo de calor sensível (H) foram realizadas com um anemômetro sônico 3D (Wind Master Pro; Gill Instruments, Hampshire, UK), medindo temperatura do ar e vento, e um analisador de gás (LI7500, LI-COR Inc., Lincoln, NE, EUA), medindo a concentração de H2O/CO2 a 3-m de altura amostrada em uma freqüência de 10-Hz de janeiro de 2014 a 15 de junho de 2016. Após este período, o analisador de gás e o anemômetro foram substituídos pelo sensor Analisador de gás integrado de CO2 e H2O de percurso aberto e um Anemômetro Sônico 3D (IRGASON, Campbell Scientific Inc., Logan, UT, EUA).

O processamento de dados dos fluxos foi realizado em um período de meia hora utilizando o software EddyPro™, versão 6 (Li-Cor, Lincoln, Nebraska) com as configurações descritas em Rubert et al. (2018).

A radiação líquida (Rn) e o fluxo de calor do solo (G) também foram obtidos na torre de fluxo. O Rn foi medido com um radiômetro líquido (CNR4, Kipp & Zonen, Delft, Holanda) e o G foi medido com placas de calor do solo (HFP01, Hukseflux Thermal Sensors B.V., Delft, Holanda) colocadas a 0,10 m de profundidade.

Avaliamos os dados de fluxo em condições de céu claro entre 2014 e 2019, conforme disponibilidade de dados de sensoriamento remoto descritos no Capítulo 2. A média diária dos fluxos foi usada para fechar o BE ao longo da abordagem da razão Bowen (β = H/LE) (Twine et al. 2000; Wilson, 2002). Nesta metodologia, o resíduo entre a energia disponível

(Rn - G) e a energia usada para processos turbulentos (H + LE) é dividida entre LE e H por β, gerando um LE e H corrigido.

5 RESULTADOS

No Capítulo 1 de revisão bibliográfica, foi realizada uma análise cientificométrica dos dados da Coleção *Web of Science* utilizando a relação entre autores/co-autores, instituições, países e palavras-chave. Apesar do grande número de trabalhos publicados sobre ecossistemas de pastagens, poucos deles foram realizados no bioma Pampa, ou pelo menos poucos deles citam o bioma Pampa como sua área de estudo. Encontramos 166 artigos científicos, dos quais o primeiro publicado em 1995 foi realizado na Argentina, enquanto no resto do mundo a pesquisa vem sendo realizada desde 1985.

É importante ressaltar que muitos trabalhos desenvolvidos neste bioma ficaram de fora da análise inicial porque não apontavam em seu resumo, ou título ou palavras-chave, o termo “bioma Pampa” ou “Pampa”, isso reforça a tese de que este bioma demorou a ser reconhecido pela comunidade científica como um ecossistema tão importante quanto ecossistemas florestais. Durante décadas trabalhos foram desenvolvidos no bioma Pampa, mas os pesquisadores não se importavam em nominá-lo e descrevê-lo corretamente, aumentando assim a invisibilidade dessa região, essa falta de representação nunca foi um fator para biomas como Floresta Amazônica ou Mata Atlântica.

Desde 2015, alguns periódicos demonstraram mais interesse no Sensoriamento Remoto da região do Pampa: a) *IEEE Journal of Selected Topics in Applied Earth*, b) ISPRS *Journal of Photogrammetry and Remote Sensing* c) e *Science of the Total Environment.*

Vários métodos de sensoriamento remoto aplicados em outros lugares ainda não foram aplicados nesta região. Concluímos neste capítulo que o sensoriamento remoto fornece métodos precisos, econômicos e oportunos para o manejo de pastagens, especialmente para compreender a situação atual dos ecossistemas de pastagens e características biofísicas das pastagens, tais como degradação e invasão de espécies exóticas, e para identificar os desafios existentes na manutenção de pastagens naturais.

Entretanto, poucos são os trabalhos desenvolvidos no que se refere ao balanço de energia do bioma Pampa utilizando modelos de Sensoriamento Remoto. Destacamos os trabalhos desenvolvidos no próprio programa de pós-graduação em SR da UFRGS (KÄFER et al., 2020; ROCHA et al., 2020a; SCHIRMBECK; FONTANA; ROBERTI, 2018), sendo um deles o Capítulo 3 desta tese. Uma das questões que discutimos neste capítulo foi como o os fluxos de energia são afetados por diferentes coberturas vegetais, discutimos a importância da vegetação campestre nativa com manejo adequado para o balanço de energia da região pampeana.

O modelo S-SEBI nunca havia sido testado no bioma Pampa, tampouco encontramos trabalhos que validavam esse modelo com imagens do sensor Landsat 8. Desta forma a validação do modelo foi realizada no bioma Pampa em vegetação nativa (Capítulo 3) e em Barrax (Espanha) em diferentes culturas (cevada, trigo, gramínea e vinhedo) durante o doutorado sanduíche em Valência (Capítulo 2). Mesmo com as condições preliminares de que o modelo depende da presença de pixels quentes e frios na imagem, e mesmo considerando que o bioma Pampa possui pouca variabilidade, o modelo demonstrou grande capacidade de resposta para a estimativa de ET nas regiões de estudo com erros de até 1mm/dia.

Discutimos a sazonalidade da evapotranspiração nas duas regiões de estudo, sendo que no bioma Pampa a ET no verão e na primavera atingem valores mais altos. O inverno é um limitante de crescimento de vegetação, e praticamente toda a vegetação campestre passa a ser consumida pela pecuária, diminuindo consideravelmente a ET. O modelo se mostrou muito eficiente tanto no cálculo de ET diária, quanto no cálculo de ET horária, porém os erros encontrados podem estar relacionados com o tamanho do pixel das imagens L8.

Uma das contribuições mais importantes dessa tese é apresentada no Capítulo 2, onde implementamos a conversão de um dado instantâneo de fluxo de calor latente em evapotranspiração horária a partir do cálculo do *CHI*. Já havia na literatura a conversão de valores instantâneos para ET diária, mas pela primeira vez essa conversão se deu para validação de dados horários.

Avaliamos também a influência da temperatura de superfície nas estimativas de ET pelo S-SEBI, no Capítulo 3. Concluímos que a variação gaussiana da Ts (entre 2 K e 2 K) não influencia a média da variável e leva a uma pequena variação da ET, que não excede 0,5 mm/dia em pastagens, com média erro entre ambas as análises (com e sem ruído no Ts) em torno de 0,18 mm/dia. Entendemos a importância de se ter uma certa acurácia na seleção dos pixels quente e frio para o funcionamento do modelo S-SEBI, porém ele é menos dependente da estimativa de Ts, o que difere de outros modelos reportados na literatura.

Por fim, podemos concluir que o bioma Pampa é único no Planeta e se difere de outros ecossistemas em todos os aspectos ambientais, tanto àqueles reportados na literatura, quanto ao balanço de energia e evapotranspiração estudados nesta tese. Ao se comparar algumas variáveis ambientais, como Ts e NDVI, entre o bioma Pampa e outras gramíneas cultivadas na Espanha, encontramos maior variabilidade temporal do NDVI, com uma maior variabilidade espacial e temporal da vegetação que compõe as pastagens naturais do bioma Pampa.

CAPÍTULO 1

WATER-SOIL-PLANT INTERACTIONS OF SOUTH AMERICAN PAMPA BIOME: A SYSTEMATIC REVIEW TO REMOTE SENSING OF GRASSLAND ENVIRONMENTS[5]

Abstract

Remote sensing data contains multiple information (spectral, spatial, radiometric, and temporal) helpful in mapping and monitoring extensive grasslands extent, minimizing the cost of field data collection and laboratory analysis, thereby improving management and conservation of these ecosystems. The South American Pampa Biome is a highly productive ecosystem consisting of evergreen grassland environment in the southern areas of the continent (Brazil, Uruguay and Argentina). In this review paper, we analyzed the current environmental status of South American Pampa Biome regarding the options and functions of remote sensing applications in research. A Scientometrics analyses was perform to Web of Science Collection data using the relationship between authors/co-authors, institutions, countries and keywords. Despite the large number of published works on grassland ecosystems, few of them have been carried out in the Pampa biome. We found out 166 article documents, of which the first one published in 1995 performed in Argentina, while in the rest of the world research has been going on since 1985. Recently, some Journals have demonstrated more interested in Remote Sensing of Pampa region: a)*IEEE Journal of Selected Topics in Applied Earth*, b) *ISPRS Journal of Photogrammetry and Remote Sensing* c) and *Science of the Total Environment*. A number of remote sensing methods applied elsewhere are yet to be applied in this region, including LiDAR applications. Different grassland parameters that have been estimated using remote sensing are discussed in detail. Remote sensing provides accurate, cost-effective and timely methods for grassland management, especially for understanding the current status of grassland ecosystems and grassland biophysical characteristics, such as degradation and invasion of alien species, and also identifying the existing challenges in maintaining natural grasslands.

Keywords: Grassland ecosystems; South American Pampa Biome; grassland remote sensing; grassland biomass; vegetation mapping.

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[5] Artigo submetido para a revista Science of The Total Environment em Agosto 2021

1. Introduction

Almost 25% of the earth's terrestrial area is covered by grasslands, and these stores 20% of global pedologic carbon (LIU et al., 2019). Permanent grasslands (as opposed to semi-natural grasslands or recent shifts from potential forest to grassland occurs due to climate change or land use practices) are one of the most productive ecosystems on the earth (LEMAIRE; HODGSON; CHABBI, 2011). Grasslands are widely distributed throughout the world along tropical, subtropical and temperate regions; Llanos of South America are examples of tropical/subtropical grasslands whereas Prairies of North America and Pampas of South America are examples of temperate grasslands (COUPLAND, 1979). Grassland vegetation plays a major role in the world's food security as it is an essential resource for diary and meat production (SCURLOCK; HALL, 1998).

One of the fundamental actions for the stability of the grasslands is the promotion of economic activities of sustainable use. Among them, cattle ranching with the management of the native grassland, that maintains the ecosystem conditions of the region and economic development. It is important to emphasize that native grassland vegetation differs profoundly from cultivated pastures, usually formed by exotic species that result from the elimination of the original vegetation (OVERBECK et al., 2009).

Anthropogenic activities that modify water-soil-plant interactions (as land use changes) combined with extreme climate phenomena have resulted in the ecological deterioration of grassland ecosystems (LIU et al., 2019; ZHANG et al., 2016). Climate change driven changes in the seasonality and intensity of rainfall influence grassland ecosystems and associated species interactions, and these in turn are likely to influence their ability to mitigate climate change (SUTTLE; THOMSEN; POWER, 2007). Livestock activities in many developing countries are highly dependent on grassland ecosystems and, hence, negative impacts on climate change on grasslands can affect livestock-dependent economies in such regions (THORNTON et al., 2009). In many regions of the world, a reduction in grasslands due to agricultural intensification and climate-driven changes have been observed since the last few decades (DUSSEUX et al., 2015), which includes changes in regional and global carbon balance, grassland productivity, food production, and habitat changes (LIU et al., 2019).

The integration of information from remote sensing, global and regional climate and land use databases can improve our understanding of the resilience and resistance of ecologically vulnerable grassland ecosystems (STANIMIROVA et al., 2019). In this systematic review article, we aim to contribute toward a better understanding of the current status of South American Pampa Biome regarding the use and application of remotely sensed data for the study of biosphere-atmosphere-hydrosphere interactions grassland ecosystems and their sustainability.

2. The South American Pampa Biome

The South American Pampa Biome (Figure 1) is a permanent grassland ecosystem distributed in Uruguay (51,000 km^2), Argentina (550,000 to 600,000 km^2) and Southern Brazil (176,496 km^2). The Pampas in Argentina include the provinces of Buenos Aires, La Pampa, Santa Fe, Entre Rios and Cordoba. The whole of Uruguay is considered as a part of the Pampas and in Brazil, southern regions of the State of Rio Grande do Sul are included. The whole area is located within the Southern Temperate Zone, comprising a natural grassland ecosystem with high species diversity with both direct and indirect interrelationships between humans and biodiversity (OVERBECK et al., 2006; OVERBECK; PODGAISKI; MÜLLER, 2015; ROESCH et al., 2009).

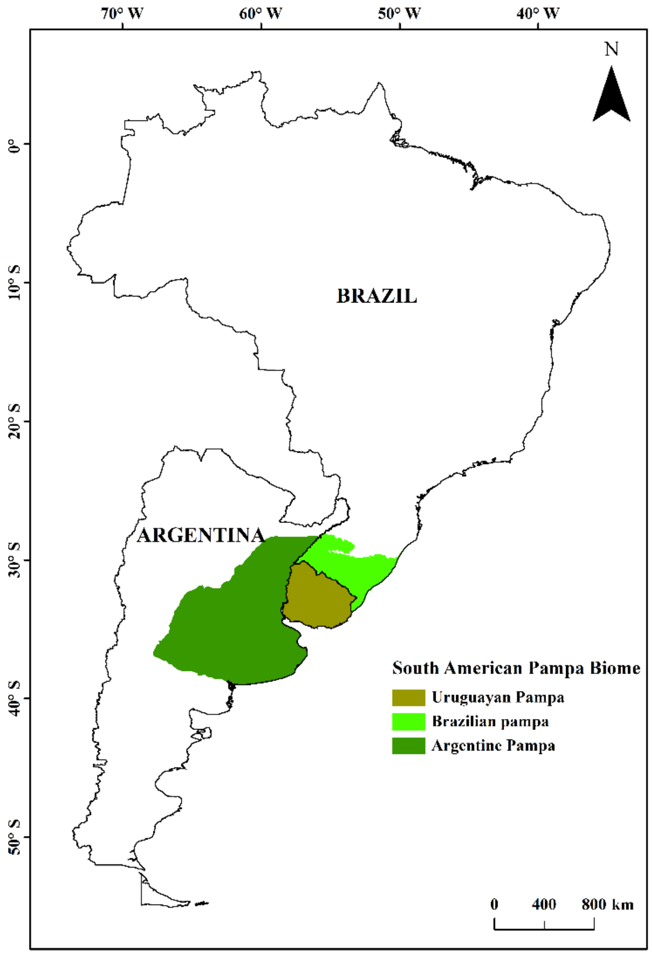

Figure 1. The South American Pampa Biome

The grassland plant community is mainly composed of *Stipa* spp., *Briza* spp., *Bromus* spp., and *Poa* spp. (CABRERA, 1971). It has been reported that 356 alien plant species have been identified in Pampa grasslands (natural as well as semi-natural) and it is a challenge to tackle these biological invasions at a regional scale (FONSECA et al., 2013). *Eragrostis plana* Nees is one of the most invasive species in Pampa Biome, introduced in the 1950s from South Africa and currently present in nearly 10% of the total area of the Pampas (GONZÁLEZ, 2017). Key factors influencing grassland ecosystems in the South American Pampa biome are climate change, overgrazing, afforestation and alien plant species invasion and expansion of croplands.

Since the 16th century, the main economic activity in this region is livestock production, mainly cattle and sheep, due to the presence of evergreen grasslands (CARVALHO; BATELLO, 2009; MODERNEL et al., 2016). Between 2000 and 2010 soy cultivation increased by 210%, and approximately 43 million cattle graze pastures in the grasslands (natural and planted) (MODERNEL et al., 2016). The Pampas is one of the largest temperate regions in the southern hemisphere dedicated to cereal and oil crops (RIMSKI-KORSAKOV; ALVAREZ; LAVADO, 2015). Due to its extremely sandy texture, soil in this region is fragile and is prone to erosion (water and wind). Furthermore, climate change and anthropogenic factors may lead to the loss of biodiversity and socioeconomic opportunities (ROESCH et al., 2009). Even though this region has tremendous agricultural potential, there is a need for aggressive action and changes in crop production to save Pampas soils from degradation (WINGEYER et al., 2015).

Modernel et al. (2016) studied beef production farms in Pampas and Campos across Rio de la Plata. Analyzing 280 farms, the authors estimated that, on average, meat production (but not income) tended to decline with native grassland area on farms. However, they also highlight the multi-functionality of the agro-ecosystems and raise questions on the dominant focus on green-house gas emissions as the sole indicator of sustainability.

2.1 Argentine Pampas

The Pampa Biome in Argentina was originally entirely covered by temperate grasslands (the climate is humid in the east and semiarid in the west) (RIMSKI-KORSAKOV; ALVAREZ; LAVADO, 2015). The most fertile soil in Argentina is located in the Pampean region (SÁ; PEREIRA; SILVA, 2005). More than 370 different species of grasses, about 400 species of birds and ~100 land mammals were found in Argentine pastures (WIZNIEWSKY; FOLETO, 2017). The climate in the Argentine Pampas is highly regionalized with at least eight climatic sub-regions based on the frequency, periodicity, duration and intensity of precipitation (ALIAGA; FERRELLI; PICCOLO, 2017). Land cover can be classified into two: The Flooding Pampa, which is extremely flat; and the Southern Pampas, which includes hills and coastal plains (GUERSCHMAN et al., 2003). Main threats for the Flooding Pampas are invasive plant and animal species and the expansion of crops and ley, and the Southern Pampas is also threatened by overgrazing (MODERNEL et al., 2016). High cultivation rates have increased the severity of floods in the Argentine Pampas and the ecological catastrophes of the region during the 20th century are considered as a result of the geological configuration, climate variability and human intervention (VIGLIZZO; FRANK, 2006).

Agricultural expansion and intensification are the main causes of grassland reduction in the Argentinean Pampas and Chaco regions (BALDI; PARUELO., 2008; PIQUER-RODRÍGUEZ et al., 2018). Cropland expansion is likely to increase in the Argentine Pampas as the profit (cropland profit was reported to have increased by 20% between 2000 and

2010) from agriculture continues to increase due to demand (PIQUER-RODRÍGUEZ et al., 2018). A few invasive shrubs (e.g. *Gleditsia triacanthos* L., *Morus alba* L., and *Melia azedarach* L.) are currently naturalized in the Argentine Pampas and the presence of these shrubs is irreversible (GHERSA et al., 2002).

Introduction of afforestation programs in the Argentine Pampas (e.g. *Eucalyptus grandis*) has resulted in poorly quantified effects on the hydrological cycle in the area (ENGEL et al., 2005). Nosetto; Jobbagy; Paruelo, (2005) highlighted the increase in evapotranspiration from afforested areas compared to grasslands, which can result in higher water losses.

2.2 Brazilian Pampas

The Pampa Biome occupies 2.1% of the Brazilian territory (63% of the territory of Rio Grande do Sul State, southern Brazil) 750,000 km^2. This region is being rapidly converted by crops and exotic plants (e.g. Eucalyptus) (REICHERT et al., 2017). The Brazilian Pampa was officially named as a biome in 2004; previously it was included as a subregion of the *Campos Sulinos*, considered part of Atlantic Forest Biome. This distinction was important for the Pampa to be included as a subject on the national environmental agenda, contributing to its conservation.

Despite the Pampa Biome occupying only 2.1% of the national territory, it is one of the richest areas from a geo-ecological perspective, mainly because it includes several micro-ecosystems. In addition to the natural grasslands, it has a large variety of species (flora and fauna), which compose a peculiar landscape. It has been reported that the natural grassland area in the Brazilian Pampa has decreased by 32.9% between 1975 and 2005 (OVERBECK et al., 2018). According to Oliveira et al., (2017), almost 3 million hectares of the Pampa grasslands had been converted into other agricultural activities by 2005. It is to be noted that some of the grassland areas in Brazil are included in the Atlantic Forest Biome (these two grassland types are known as the South Brazilian *Campos*) and neither have gained much attention by the authorities compared to forest ecosystems (OVERBECK et al., 2007). Two key factors shaping the grasslands in this region are grazing and fire and these grasslands are also under threat from degradation as a result of invasive species, monoculture planting and excessive cattle production (GUERINI FILHO; KUPLICH; QUADROS, 2020; OVERBECK et al., 2007). In this sense, the forestry monocultures have grown in the region not only because of the optimal adaptation conditions, but mainly because of high and rapid financial return (OLIVEIRA et al., 2017). Eucalyptus grown in the Pampa biome, in comparison to natural grassland, significantly changes the components of water balance by decreasing streamflow, and increasing interception, soil deep drainage and soil water storage (REICHERT et al., 2017).

Livestock production (Figure 2) is one of the main economic activities in this region and the meat produced in this region is considered as of high quality in terms of odour and flavour (LOBATO et al., 2014). Grazing is also considered as the principal factor maintaining the ecological properties and physiognomic characteristics of the Pampa grassland ecosystem (OVERBECK et al., 2007; PILLAR; QUADROS, 1997). Exhaustive grazing can result in decreased soil cover and increase the risk of erosion, whereas too low grazing pressure can result in the excessive growth of tall grasses with low nutritional value or shrubs of low forage quality (OVERBECK et al., 2007). In other words, grazing is a major factor in maintaining the grassland ecosystems in the Pampa Biome in Brazil. The low productivity of pastures in Brazilian Pampa grasslands is due to the unsustainable management of resources, including overgrazing (OVERBECK et al., 2007).

Figure 2: Livestock production in Brazilian Pampas

Many exotic species (Figure 3), such as those having high invasive capacity (e.g. *Melinis minutiflora* and *Eragrostis plana* Nees) have been deliberately introduced to the Brazilian Pampa Biome for forage use (Focht and Medeiros 2012; Fonseca et al. 2013). Invasion of *Eragrostis plana* Nees is favoured by lower grassland sward heights, dependent on grazing intensity (FOCHT; MEDEIROS, 2012). In addition, monocultures of exotic tree species, as *Eucalyptus spp*., have been cultivated in the Brazilian pampa biome since the 2000s. The replacement of grassland by trees may improve rainwater interception, even though the harvesting of such trees may have negative impacts later (REICHERT et al., 2017). Furthermore, family cattle raisers in this region resist bringing exotic species (forestry for cellulose production) because of the impact of these exotic species on water sources, destruction of natural pastures and natural landscape, and decreases in beef cattle and sheep production (AZEVEDO; VERARDI FIALHO, 2015).

Figure 3: Invasive and cultivated exotic species in Brazilian Pampa Biome (**a**. Eucalyptus, **b**. invasive shrubs, **c**. Soybean, **d**. Rice paddy). Photographs taken from Alegrete, Brazil.

2.3. Uruguay Pampas

Uruguay is entirely composed of grassland biome (Campos and Pampas) and the agro-ecosystem in the country is composed of two main subsystems known as natural grasslands and croplands (SANCHEZ, 2017). Pampa grasslands in Uruguay are similar to those in Brazil and Argentina, and sustain livestock, one of the major economic activities in the region. Even though intensive grazing can result in the loss of above-ground biomass, a recent study by López-Mársico et al., (2015) showed that grazed areas in Uruguay grasslands were associated with higher below-ground biomass, NPP and turnover than ungrazed areas. In fact, more than 65% of the land territory in Uruguay is grassland (DOMÍNGUEZ; PRIETO; ACHKAR, 2002). In addition to economic services, natural grasslands in Uruguay are of great relevance in providing ecosystem services (PIERRI; FOLADORI, 2001). Large areas of grasslands in the country were converted to planted forest in Uruguay even though the grassland use changes and its influence on grassland ecosystems were not yet evaluated in detail. However, the above-ground Net Primary Productivity (ANPP) of grasslands in this region is observed to be highly dependent on rainfall patterns and hence it is difficult to evaluate the influence of land use changes on ANPP as extreme weather events are common in the region (DIAZ et al., 2019).

Between 1990 and 2009, nearly 23% of the natural grasslands in Uruguay were replaced by agriculture, particularly soybean cultivation (TISCORNIA; ACHKAR; BRAZEIRO, 2014). The conversion of grasslands to croplands has resulted in the decline of associated fauna, such as grassland birds (SILVA; DOTTA; FONTANA, 2015). Furthermore, increased use of phosphorus fertilizers was observed to be associated with low species diversity in Uruguay grassland-cropland system (JAURENA et al., 2016).

The replacement of natural grasslands by tree plantations in Uruguay has also resulted in the loss of biodiversity (LATERRA; RIVAS, 2005). A few studies (e.g. VASSALLO et al., 2013; VIHERVAARA et al., 2012) advocate that properly managed tree plantations (e.g. eucalyptus, pines) can improve ecosystem services (high and stable ANPP and higher interception of solar radiation by trees than grass species). However, the motives behind afforestation by eucalyptus in grassland areas were merely profit from cellulose industry rather than addressing environmental issues (PAYRET et al., 2009). Gazzano; Achkar; Díaz, (2019) discussed the impacts of the territorial transformations in Uruguay; the results confirmed not only the decrease of natural grasslands and their systemic use, but also with its linkage to social and economic transformations affecting traditional livestock systems, which have also been occurring in Brazilian Pampa Biome since 2000s.

3 Data and Methods

3.1 Literature Search Strategy

In this paper we have used the Web of Science core Collection database assigned by Clarivate Analytics and used to identify the most important articles published in the World regarding the Pampa biome and Remote Sensing (RSPampa). The search formula of the method selected according to the RSPampa research subject were: (‘Pampa biome’ or ‘pampa’) AND (‘Remote Sensing’ or ‘Normalized Difference Vegetation Index (NDVI)’ or ‘Thermal Infra-red’ or ‘Landsat’ or ‘Sentinel’ or ‘MODIS’ or ‘big data’ or ‘Google Earth

Enginee’). The database was refined to the period from 1995 to 2021 (update July, 22), the document type was Article written in English.

3.2 Scientometrics Analysis Method

We analyzed our data in VOSviewer and Microsoft Excel to mine, analyze, process, and visualize the literature data. VOSviewer is free software used to graph and show the relationship between authors/co-authors, institutions, countries and keywords, which can reveal the research topic of the literature and also reflect the researcher hotspot in the field (LI et al., 2021).

3.3 Discussion and analyses of the results

In a second moment, after we draw scientific knowledge of the RSPampa field, we indicated the most popular papers regarding Water-soil-plant interactions of South American Pampa Biome and discussed with others grassland ecosystems status around the World. Finally, we provide future topics for RSPampa research and some strategies to improve scientific knowledge in the field.

4 Scientometrics Analysis Results

A total of 166 documents were obtained from 1995 – 2021 using the keywords related before on Web of Science Collection, the earliest (1995) document of RSPampa was citated 79 times and it used NDVI method and NOAA-AVHRR data to classification on Argentina Pampas (KERDILES; GRONDONA, 1995). There are an important lack publication in the field from 1995 to 2000, when the second paper was published. However, the RSPampa only became an important field in 2016 with 19 published papers and riches its importance in 2020 with 31 published papers (Figure 4). These results demonstrate the slowly development of RSPampa research studies, while in the rest of the world research related to grasslands ecosystems has been going on since 1985 and has grown exponentially since 1990 (LI et al., 2021).

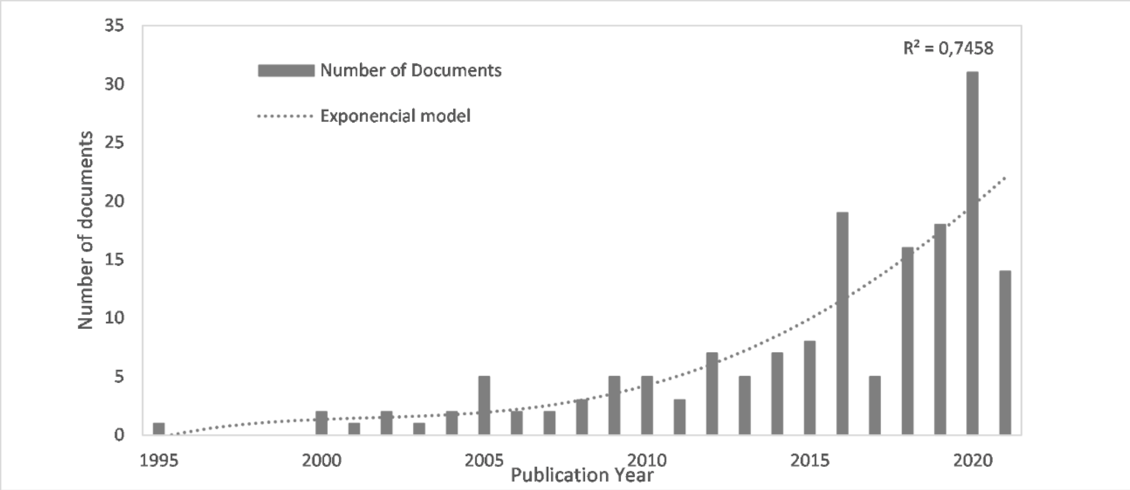

Figure 4. Temporal evolution of documents on Remote Sensing Pampa (RSPampa) research from 1995 to 2021.

The first research in the field occurs in Argentina, and around 2015 we found some articles developed in Brazil (Figure 5). In Figure 7 we can observe the low interest the international scientific community has in research on the Pampa Biome. In 2015, Pylro; Morais; Roesch, (2015) related a lack on the research in microbiomes including Pampa biome, the authors also indicated that these studies needed some leaders to improve the knowledge.

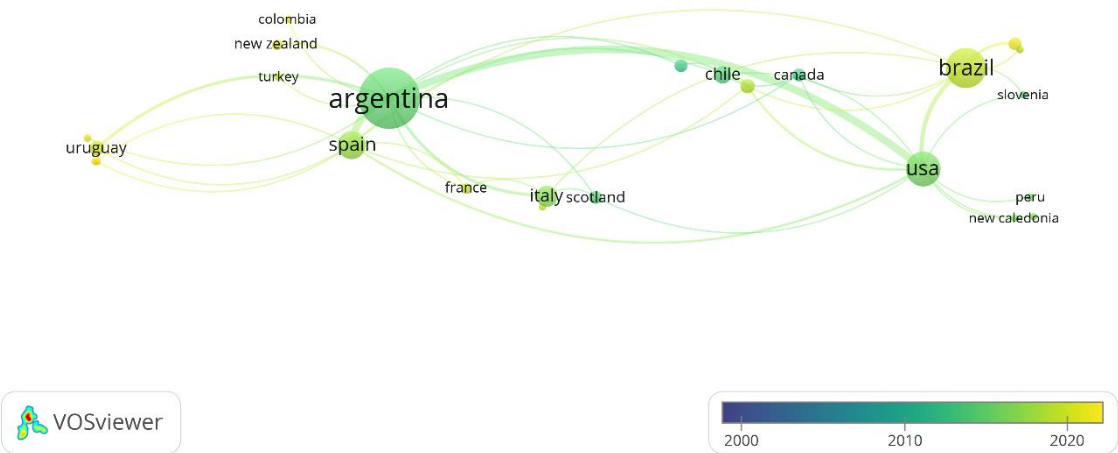

Figure 5. Documents per country and their cooperation density visualization in RSPampa research field.

According to Li et al (2021), Remote Sensing of grassland ecosystems increased from nine fields concentrated mainly in Remote Sensing, Environmental Science, Ecology and Imaging Science Photographic. When RSPampa research is analyzed, we noted the same categories field in the top 5 discipline distribution (Figure 6). However, while in the rest of world Forestry and Meteorology Atmospheric Sciences have appeared as an important issue, in RSPampa these disciplines are not in the top 10 main research fields.

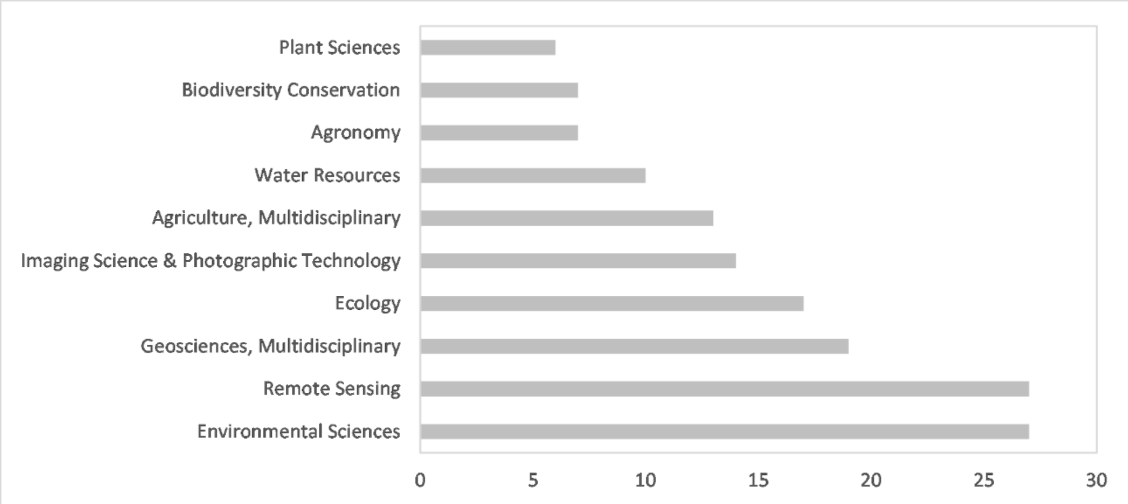

Figure 6. Top 10 main research fields in Web of Science on RSPampa research studies from 1995 to 2021.

Influential Journals

The RSPampa subject has appeared in 106 Journals since 1995, but in 76 (71%) of them this subject appears only once. Most of the publications on this topic are concentrated in only 15 (14%) Journals, which are also the most cited in the scientific community (Appendix 1). The top 15 Journals have published 56 (33%) of the total number of documents.

Table 1. Top 15 journals ranked by the number of documents in Remote Sensing Pampa research from 1995 to 2021.

Journal	ND	TLCS	AC	Year	IF
International Journal of Remote Sensing	8	307	38.38	1995	3.266
Remote Sensing	8	138	17.25	2012	5.353
Agriculture Ecosystems & Environment	6	377	62.83	2006	6.064
IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing	5	43	8.6	2015	3.784
Ecosystems	4	235	58.75	2001	4.776
Applied Vegetation Science	4	99	24.75	2000	3.252
International Journal of Applied Earth Observation and Geoinformation	3	142	47.33	2014	5.933
Agricultural Systems	3	57	19	2007	5.622

Geomorphology	3	50	16.67	2011	4.623
ISPRS Journal of Photogrammetry and Remote Sensing	3	41	13.67	2018	9.948
Rangeland Ecology & Management	3	41	13.67	2005	2.019
Remote Sensing of Environment	3	39	13	2014	11.057
Science of the Total Environment	3	39	13	2018	7.842

Abbreviations: ND, the number of documents; TLCS, the total local citation score; AC, average citation; Year, published year started; IF, impact factor in the last 5 years.

As shown in Table 1 the top three journals with the largest number are *International Journal of Remote Sensing* (8), *Remote Sensing* (8) and *Agriculture Ecosystems & Environment* (6). The first two are also considered to be the leading Journals in the publication of Grassland Remote Sensing subject (Li et al. 2021).

However, recently, since 2015, 3 other Journals have shown interest in the topic research: a) *IEEE Journal of Selected Topics in Applied Earth* (5), b) *ISPRS Journal of Photogrammetry and Remote Sensing* (3) c) and *Science of the Total Environment* (3). Whereas (a) and (c) do not appear as top 20 when we are looking at Grassland Remote Sensing subject (Li et al. 2021).

4.1 Discussion: The role of remote sensing in monitoring the Pampa Biome

A number of studies on grassland ecosystems around the world have been conducted using remote sensing data (KIM et al., 2020; LARA, 2019; ULLAH et al., 2012; VILLOSLADA et al., 2020; WARD et al., 2013). Some of the methods applied in these studies have been used for mapping, monitoring and evaluating the grasslands of South American Pampa Biome, as a whole or on a site basis (e.g.BALDI; GUERSCHMAN; PARUELO, 2006). A summary of recent grassland studies in the South American Pampa Biome using remote sensing datasets is given in **Appendix 1**.

4.2 Grassland ecosystem parameters in derived from remote sensing

Even though remote sensing is effective in mapping various plant communities, mapping grassland with a range of vegetative classes over large areas is challenging due to the coarse resolution of the data and the high costs of acquiring high resolution data (LAN; XIE, 2013). One of the difficulties in using remote sensing for land use and land cover analysis in the Pampa biome is precisely the delimitation of the native grassland when compared to pastures or other annual crops. Shimabukuro et al., (2020) analyzed the land use and land cover based on PROBA-V sensor and compared it with databases used in Brazil (FROM-GLC project and Mapbiomas). The authors found that Pastureland showed a difference of 27% (-52.05 million hectares ±16.76), followed by grassland with 74% (-40.60 million hectares ±11.14), when those databases were compared.

However, a large number of grassland ecosystem parameters have been derived, so far, from a wide variety of remote sensing data. Grassland area, plant diversity and species richness, aboveground biomass and productivity, grassland use intensity and soil degradation patterns, age and population structure of invasive species, biochemical, structural and functional traits and heat fluxes are among these parameters. For example, Baldi; Paruelo, (2008) estimated that the overall grassland coverage in the South American Pampa Biome has been changed from 67.4% to 61.4% during the period between 1985-1189 to 2002-2004, based on a study using Landsat data. Similarly, Vega et al., (2009) observed an overall 6% reduction of grasslands, 60% increase of afforestation, and 3% increase of croplands in the South American Pampa Biome using Landsat data between 1986 and 2005.

Regarding the analysis of climate data, Scottá; Fonseca, (2015) had validated the aboveground net primary production data at the local scale, from 1970 and 2011, and the NDVI data, from 1998 and 2011. The authors concluded that data collected at the local scale and its relationships with climate can be expanded at the regional scale in the Pampa biome by using remote sensing techniques.

4.2.1 Grassland coverage/area, growth and plant diversity/species richness

Area of grassland habitat, ecosystems and plant diversity are two parameters widely estimated using airborne multispectral/hyperspectral (GAMON et al., 1993) and spaceborne optical data (GRIFFITHS et al., 2020) or a combination of optical and microwave data (SCHUSTER et al., 2015). For studies of carbon dynamics, biodiversity conservation and land use management, accurate grassland inventories are important. For cloud-free regions, optical data can be useful in creating grassland inventories. However, for regions with persistent cloud cover, multitemporal radar data, such as those from ALOS-2 or Sentinel-1 missions, can be helpful for grassland inventories by applying different image processing algorithms such as machine learning methods (BARRETT et al., 2014). Green; Cawkwell; Dwyer (2018) used MODIS NDVI products for grassland growth measurement for the period between 2002 and 2013 in Ireland. Tarantino et al., (2016) applied a cross correlation analysis with high resolution WorldView-2 images with Landsat 8 data for change detection in semi-natural grasslands (the authors also used a semi-natural grasslands layer extracted from an existing validated LULC map). Fauvel et al. (2020) used Sentinel-1 spaceborne radar data and Sentinel-2 optical satellite data for the prediction of grassland plant diversity by applying machine learning algorithms. Phenological characteristics of the South American Pampa Biome have been well studied using MODIS products (NDVI, EVI and GPP) and a combination of vegetation indices and meteorological data has been proved to be effective in these studies (MOREIRA, 2018). Kuplich; Moreira; Fontana (2013) by using EVI (MODIS MOD13Q1), observed that the growth of grassland species in the Pampa Biome is higher in the spring and summer compared to that in autumn and winter. Fontana et al. (2018) used NDVI and meteorological data as indicators of natural grassland growth in Brazilian Pampas.

For detailed information on plant species richness in grassland ecosystems, hyperspectral data can be useful. For example, Carter et al. (2005) used Airborne Visible and Infrared Spectrometer (AVIRIS) data with 224 channels (400nm – 2500nm) for understanding species richness in mesic grassland in northeastern Kansas by evaluating upwelling spectral radiance, prairie spectral reflectance and band ratios. The above-mentioned study suggested the remote sensing of soil exposure as a useful indicator of species richness in grazed grasslands (which is valid for the Pampa Biome)(CARTER et al., 2005).

4.2.2 Biomass and primary productivity

Biomass estimation in grassland ecosystems has been done using a wide variety of remote sensing data including aerial photography/videography (EVERITT et al., 1986), UAV multispectral (VILLOSLADA PECIÑA et al., 2021), spaceborne multispectral data such as Landsat TM (EVERITT et al., 1986), Landsat 8 (QUAN et al., 2017), or SPOT-VGT (LIU et al., 2015), SPOT 4 (DUSSEUX et al., 2015), and hyperspectral data (PSOMAS et al., 2011). It was observed to be robust and reproducible an estimation aboveground biomass of grassland communities by applying a radiative transfer model (RTM) method to Landsat 8 data, which was (QUAN et al., 2017). A number of vegetation indices (NDVI, SAVI, TSAVI, REIP, MTCI, band depth analysis parameters, etc.) have been applied to quantify biomass and nitrogen content of seagrasses from spaceborne multispectral data (LIANG et al., 2016; ULLAH et al., 2012). Ullah et al. (2012) obtained higher accuracy in biomass estimation by the application of band depth analysis parameters compared to vegetation indices using MERIS data. Spaceborne optical data with lower resolution (e.g. MODIS) have also proved to be effective in estimating aboveground biomass using vegetation indices in combination with long-term climate and in situ data (Liang et al., 2016).

It should be noted that most vegetation indices measure vigour of green vegetation only and not senescent matter, which is an important part of natural grassland vegetation (GUERINI FILHO; KUPLICH; QUADROS, 2020). A few studies (e.g. Manso et al. 2016; Ren et al. 2016) used an index called Plant Senescence Reflectance Index (PSRI), which is sensitive to senescent matter, for this purpose. Guerini Filho (2018) used a combination of Sentinel-2 and hyperspectral data (from a field spectrometer) for estimating grassland biomass in the Brazilian Pampa Biome whereas Guerini Filho; Kuplich; Quadros (2020) estimated the biomass in the same region using Sentinel-2 data and field measurement of biomass (the authors applied NDVI, EVI, PSRI and the normalized difference red edge index – NDREI).

It has been reported that Brazilian Pampa grassland contains important stocks of soil organic carbon, whose conservation is relevant for mitigating climate change (PILLAR; TORNQUIST; BAYER, 2012). In a recent study, Trentin; Trentin (2019) applied statistical model to remote sensing data for estimating biomass and carbon stock from grassland spectral data in the Brazilian Pampa Biome. The South American Pampa Biome grasslands have a unique coexistence of several C3 and C4 plants (WAGNER et al., 2018). Aboveground biomass varies with species composition; C3 and C4 grass species with different physiological morphological and phenological characteristics influence aboveground biomass and ecosystem service provision (SHOKO et al., 2018). Shoko et al. (2018) used Sentinel-2 and in situ data for characterizing the spatiotemporal variations in aboveground biomass of C3 (*Festuca*) and C4 (*Themeda*) dominated grasslands in South Africa by applying Partial Least Squares Regression (SPLSR) to differentiate the phenological characteristics (between C3 and C4 species). Wagner et al. (2018) successfully characterized the annual and seasonal variability of NDVI and EVI over grassland types (C3 and C4) to identify the differences among the ecological regions in the Pampa Biome in Brazil and Uruguay between 2000 and 2011.

Net primary productivity (NPP), which is the rate of biomass accumulation per unit area, can be estimated from Land Use Land Cover (LULC) data derived from optical satellite imagery. Baeza; Paruelo (2018) calculated aboveground NPP and human appropriation of

NPP in the Rio de la Plata grasslands (which includes South American Pampas and Campos) using LULC data derived from MODIS satellite data. The authors mentioned that factors, such as spatial biases, artefacts from downscaling information and the influence of particular years, can contribute to errors in estimating NPP from optical satellite data (BAEZA; PARUELO, 2018). Wang et al. (2005) showed that NDVI time-series can be used as an excellent measure of the prevailing patterns of NPP that can be measured as biomass production in local-scale native grasslands. Sun; Du (2017) estimated the effects of precipitation and temperature on NPP and precipitation use efficiency of grasslands in China using MODIS data, and the study showed that NPP varies greatly with annual precipitation changes. The MODIS-based NPP product is useful for the assessment of grassland carrying capacity and this method can be implemented where traditional carrying capacity assessments are difficult to conduct due to geomorphological factors (DE LEEUW et al., 2019). The combination of multi-source optical data has been proven to be effective in estimating grassland productivity. For example, Gu; Wylie (2015) developed a 30m resolution grassland productivity estimation map for central Nebraska by integrating a 250m MODIS and 30m Landsat 8 data based on NDVI.

Remote sensing methods for estimating grassland biomass in the Pampa Biome have been applied in a number of recent studies (BAEZA et al., 2010; FONTANA et al., 2018a; GUIDO et al., 2014). Fontana et al. (2018) used NDVI (MODIS product) and meteorological data for subsidizing growth modelling by relating two variables (NDVI and meteorological data) to the annual dynamics of biomass accumulation. The authors observed that winter is the critical season for livestock production due to lower forage accumulation rate and NDVI values together with reduction in the air temperature and solar radiation (FONTANA et al., 2018b). Guido et al. (2014) were able to estimate above-ground net primary productivity (ANPP) of grasslands in Uruguay based on EVI derived from MODIS imagery. Baeza et al. (2010) used both Landsat and MODIS data for estimating above-ground NPP in grasslands in Uruguay. Baeza and Paruelo (2018) estimated the Human Approximation of NPP (HANPP), which is the difference between NPP in the absence of human influence and the NPP of actual vegetation remaining after the harvest, in Uruguay (Pampas and Campos) using MODIS data by applying NDVI and statistical analysis. HANPP is an important ecosystem parameter in Pampa grasslands as these areas are impacted by a number of anthropogenic activities.

4.2.3 Grassland use intensity and soil degradation patterns

Grassland use intensity is typically assessed by means of mowing frequency, grazing intensity and fertilization input and these three indicators can be monitored using remote sensing data. For example, Gómez Giménez et al. (2017) estimated the grazing intensity of grassland in Switzerland using RapidEye image series by applying different automatic image processing algorithms (e.g. vegetation indices). Spatial dependence measurement of optical satellite data (e.g. Landsat TM) can also provide information on grassland changes (HENEBRY, 1993). Yu; Evans; Malleson, (2018) used MODIS LAI data for the quantification of grazing patterns to successfully provide precise and nearly real-time grassland grazing monitoring information.

Pampa grasslands were used for extensive agriculture expansion in recent years (OVERBECK et al., 2018; PIQUER-RODRÍGUEZ et al., 2018; REICHERT et al., 2017; TISCORNIA et al., 2019). Nobrega (2016) used MODIS vegetation indices (NDVI and EVI) for monitoring the expansion of soybean cultivation in the Brazilian Pampa Biome between 2000 and 2015 and the study observed a significant increase in soybean expansion in this region (some areas were planted with rice as well). Similar changes in grassland areas due to soybean expansion (23% decreases in grassland areas between 1990 and 2009) using Landsat TM data have been reported from Uruguayan grasslands as well (TISCORNIA; ACHKAR; BRAZEIRO, 2014). MODIS NDVI data during the 2000-2017 periods in Uruguay showed that the ANPP as lower in areas on higher land use intensity, particularly where cropland expansion took place (GAZZANO; ACHKAR; DÍAZ, 2019).

Integration of multi-source optical data, such as Sentinel-2 and Landsat series, can overcome the limitations of conventional classification-based mapping approaches for characterising grassland use intensity (GRIFFITHS et al., 2020). Dusseux et al. (2015) estimated grazing capacity Q (in number of days) from biomass measurements from remote sensing data, considering the needs of animals and available grass resources for grazing as:

$$Q = (b\_mas * Surface)/(LSU * animal\_needs) \quad (1)$$

Where *b_mas* is the biomass in tonnes of Dry Matter (DM)/ha, *Surface* is the area in hectares, LSU corresponds to the livestock unit used and *animal_needs* is a constant value indicating the food requirements of animals expressed in Kg of DM/LSU/day. The estimation of Q is important in grassland areas such as South American Pampa Biome, where the population is economically dependent on livestock for sustaining their daily lives.

In a study using multitemporal Landsat 8 data, it was observed that grassland degradation occurs at higher altitudes (>4300 m a.s.l.) and colder and drier climatic zones, which will have a spatially differential impact on the Pampa by sub-region (FASSNACHT; LI; FRITZ, 2015).

It is also possible to estimate cattle stocking rates in temperate grasslands using NDVI products (e.g. MODIS NDVI). For example, Green; Cawkwell; Dwyer (2016) presented a 250m scale characterization of early spring vegetation growth from 2003 to 2012 in European grassland systems based on MODIS NDVI, which is available for the Pampa Biome grasslands as well. Junges et al. (2016) analysed the potential use of vegetation indices (NDVI and EVI) from MODIS data for discriminating grazing intensities on natural grasslands in the Brazilian Pampa Biome. Interestingly, it was observed that areas of moderate grazing intensity exhibited a higher vegetation index compared to areas with low and high grazing intensities (JUNGES et al., 2016). EVI can be used to discriminate between moderate grazing intensity and low/high grazing intensities in any season, whereas NDVI is more suitable for spring and winter, based on the above-mentioned study conducted in the Brazilian Pampa Biome (JUNGES et al., 2016).

Soil degradation in grassland ecosystems caused by extreme topography, climate conditions and land use practices can be assessed using a number of remotely sensed data, including aerial photographs, satellite or UAV-based data. A number of image processing methods are available for the assessment of soil degradation in grassland ecosystems. For example, Zweifel; Meusburger; Alewell (2019) applied an Object-Based Image Analysis (OBIA) method for mapping the spatio-temporal pattern of soil degradation in Switzerland. Land degradation in the transition zone between grassland and cropland is more complex and few studies (CHEN; RAO, 2008) have used spaceborne optical data for monitoring such changes.

Scottá (2013) studied the influence of climate on grasslands in the Brazilian Pampa Biome using field, remote sensing (NDVI from SPOT data) and meteorological data between 1998 and 2011. Wagner (2013) undertook a similar work in Brazil and Uruguay using MODIS data, where the temporal dynamics of vegetation indices (NDVI and EVI) and their relationship with regional meteorological data were analysed. Wagner (2013) observed that the interannual variability in meteorological data due to ENSO was reflected in the patterns of vegetation indices, which shows that vegetation indices have the potential for describing the relation between spatiotemporal variations in grassland vegetation and climate in South

American Pampas. Cunha (2016) used Landsat data for evaluating the erosion susceptibility in the Alto Camaquã Basin in the Brazilian Pampa Biome and showed that the eastern region of the Brazilian Pampa Biome is highly susceptible to erosion, not suitable for intensive agricultural activities. Soil and grassland degradation in Pampa Biome grasslands can be caused by a number of factors such as intense use of grassland pastures, construction of settlements, water deficit and rainfall anomalies. Mengue et al. (2018) used Landsat series, MODIS and DMSP-OLS (Defence Meteorological Satellite Program - Operational Linescan System) data for monitoring land use changes in Brazilian Pampa Biome and observed that the degradation of grasslands in this region is primarily caused by the expansion of silviculture.

Dubinin et al. (2010) used AVHRR data (validated using RESURS, Landsat and MODIS data) for reconstructing a time series (1985-2007) of burned areas in arid grasslands in Russia. Iire-induced spectral reflectance changes ban be used for estimating combustion completeness in *dambo* grassland in Zambia. Wildfire propagation susceptibility in grasslands from MODIS data can be evaluated using multivariate logistic approach (CAO et al., 2013); the input parameters for this type of wildfire propagation susceptibility were NDVI, optimized soil-adjusted vegetation index (OSAVI), moisture stress index (MSI), global vegetation moisture index (GVMI), dead fuel index (DFI), elevation, slope, and aspect.

Grazing changes the species composition of grassland ecosystems and alters physical and biogeochemical properties of soil that can change hydrological processes that impact water budgets and quality (PETERSON; PRICE; MARTINKO, 2002). Multispectral data, such as Landsat TM, can be used to investigate grazing intensity, range condition and desertification of grasslands, which are of high economic importance in South American Pampa Biome, by applying the spectral reflection characteristics using NDVI (PETERSON; PRICE; MARTINKO, 2002) or spectral mixture analysis and decision-tree methods (LI et al., 2013). Lara (2019) studied the fragmentation of grasslands in Argentine Pampas using Landsat data and observed that 12.6% of the natural grasslands in this region have been replaced by grass species more adapted to grazing cattle during the period 1974-2011.

The presence of invasive grass species or changes in plant species composition can be used as an indicator for grassland degradation (MANSOUR; MUTANGA, 2012), which can be evaluated using multispectral remote sensing data. (MANSOUR et al., 2016) used SPOT 5 data for producing grassland degradation maps in South Africa based on the spatial distribution of *Themeda triandra* and *Hyparrhenia hirta*. There are a range of environmental factors that can influence the distribution of plant communities in grasslands (WARD et al., 2016), these can be used to produce correlative models derived from remotely sensed data to map the extent and location of different plant communities (WARD et al., 2013), as well as evaluate the impacts of climate change particularly where this alters the water regime (WARD et al., 2016).

Biomass burning from grassland fires is a source of greenhouse gas emissions and the quantification of biomass emissions from grasslands can be done using optical satellite data. Badarinath; Kiran Chand; Krishna Prasad (2009) used IRS-P6 AWiFS data to quantify emissions (CO_2, CO, NO_x, CH_4, non-methane hydrocarbons, particulate matter, organic carbon and black carbon) from grassland burning in Kaziranga National Park in India. In fact, monitoring grassland dryness and fire potential has been assessed using spaceborne data (e.g. NOAA AVHRR) even in the 1980s (PALTRIDGE; BARBER, 1988).

Unlike green vegetation, the dead component of grassland vegetation is hard to estimate using remote sensing applications as the spectral response of dead plant materials is similar to that of bare soil (XU et al., 2014). The authors used Landsat data for measuring the dead component of mixed grasslands based on NDVI by investigating the correlation between NDVI and dead cover.

Grasslands in the Pampa Biome have been widely used for livestock production, which in turn results in the production of greenhouse gases (e.g. Methane, N_2O) and the quantity of greenhouse gas emission depends on the animal performance on natural grassland and seasonality (higher in the winter due to low herbage accumulation) (CEZIMBA, 2015). Studies on greenhouse gas emission as a result of grazing activities in Pampa Biome have been conducted in Brazil (CEZIMBA, 2015; VASCONCELOS et al., 2018), Argentina (HUARTE et al., 2010; NIETO et al., 2018), and Uruguay (DINI et al., 2012). A number of studies have successfully estimated the emission of greenhouse gases over grassland areas in other regions using remote sensing methods (RO et al., 2009; TRATT et al., 2014). Pampa grasslands are vast in area and the application of remote sensing for monitoring changes in methane emissions from livestock areas can be useful from an ecosystem management perspective. More research is needed in this direction, particularly including different climate change scenarios due to greenhouse gas emissions.

4.2.4 Age and population structure of invasive shrubs

Shrub encroachment or invasion in arid and semiarid grassland ecosystems threatens the sustainability of grassland resources and livestock production in different parts of the world, including South America (CABRAL et al., 2003; CAO et al., 2018). High spatial resolution optical imagery, such as spaceborne, airborne or UAV-borne platforms and LiDAR data can be used to estimate the age and population structure of invasive species, such as shrubs. Medium or low resolution images, such as Landsat series and MODIS data, can be used for estimating the shrub coverage, whereas individual shrub identification requires high resolution data such WorldView-2 and QuickBird or aerial photographs. Cao et al. (2018) used the crown area of each shrub from high resolution data and regional precipitation data for developing shrub age estimation model to estimate the age of individual shrubs in semiarid grasslands. Two factors that influence the accuracy of age estimation are precipitation error and errors in shrub crown area measurement, of which the latter strongly influences the accuracy of age measurement (CAO et al., 2018). Hong et al. (2014) used an integration of optical (MODIS) and SAR (RADARSAT-2 SAR) data for differentiating grassland and alfalfa areas successfully.

In the Pampa Biome, González (2017) used Landsat and MODIS data for the analysis of invasive species (*Eragrostis plana* Nees) by applying Genetic Algorithm for Rule Set Production (GARP) and Maximum Entropy Modeling (MAXENT). Gomes (2017) used Sentinel-2 data with 10m spatial resolution for monitoring this invasive species (2015-2015) in Brazilian Pampa grasslands. In a recent study high spatial resolution RapidEye, IKONOS and KOMPSAT data have been used for mapping the areas invaded by *Eragrostis plana* Nees in the Brazilian Pampa grasslands(CICCONET, 2017).

LiDAR data have already been used for discriminating natural grassland from cultivated grassland in Canada, a method that can also be used to distinguish natural grassland from invasive species (FISHER; SAWA; PRIETO, 2018).

4.2.5 Biochemical, structural and functional traits

The two main approaches for estimating grassland canopy characteristics from remotely sensing data are statistical approaches and physically-based radiative transfer models (BARET; BUIS, 2008; RIVERA et al., 2014). Remotely sensed vegetation indices (NDVI, MSAVI, difference vegetation index-DVI, ratio vegetation index-RVI and simple vegetation index-VI) can be used to estimate grassland canopy parameters (e.g. LAI) (HE et al., 2016; WYLIE et al., 1996). Biochemical (e.g. chlorophyll concentration, leaf water content, phosphorus content, dry matter content), structural (e.g. LAI, specific leaf area – SLA, leaf angle, canopy height) and functional (e.g. maximum carboxylation rate - V_{cmax}, Ball-Berry sensitivity parameter) parameters of grasslands have been measured in a few studies using field spectroradiometers and field data (e.g. chamber-based CO_2 flux, evapotranspiration) using multiple-constraint inversion approaches (OLLINGER, 2011; PACHECO-LABRADOR et al., 2019; USTIN et al., 2009). These studies utilize various optical and thermal properties in relation to photosynthesis and other physiological processes. For example, photosynthetic pigments have multiple roles in plant physiology, varying from capturing solar energy for photosynthesis to protective functions, and it is possible to identify and quantify individual pigments *in vivo* using high resolution spectroscopy (USTIN et al., 2009).

Structural characteristic information for grasslands is important in supporting management decisions at national and regional levels (TISCORNIA et al., 2019). For grassland ecosystems in mountainous regions, such as those in the Pampa grasslands in Cordoba, Argentina (Figure 7), specific LAI retrieval algorithms (e.g. based on inversion of radiative transfer models) from optical satellite data (e.g. MODIS), for alpine grasslands have been developed (PASOLLI et al., 2015). Many such regions have undergone afforestation by shrub-like trees in recent years, which make it complex to apply unique algorithms for mapping vegetation. Di Bella; RebellA; Paruelo, (2000) used NOAA AVHRR imagery for estimating evapotranspiration in the Pampa region of Argentina. Structural parameters of Pampa grasslands, such as LAI and canopy height, in Pampa Biome have been estimated using spaceborne optical data products (e.g. MODIS-derived vegetation indices). For example, Tiscornia et al., (2019) used MODIS vegetation indices and Landsat OLI data for estimating the sward height of natural grasslands in Uruguay.

Figure 7: Grassland environment in Parque Nacional Quebrada del Condorito, Cordoba Hills, Argentina.

Pacheco-Labrador et al., (2019) mentioned that this method can be applied to diverse grassland ecosystems and instead of a spectroradiometer, other hyperspectral data (e.g. spaceborne platform) can be used, where simultaneous eddy covariance flux measurements are available. Specific Leaf Area (SLA) derived from optical satellite data, such as Landsat or Sentinel-2, has been observed to be useful as a proxy of functional diversity (ROSSI et al., 2020). Land surface temperature (LST) from medium resolution spaceborne optical data with a thermal channel (e.g. MODIS, Landsat) combined with soil moisture measurements using microwave data can be used for evapotranspiration measurements in grassland ecosystems, even though the use of optical data is limited by cloud cover or spatial resolution (CASTELLI et al., 2018). A few studies (e.g.DARVISHZADEH et al., 2008) have used inversion of a radiative transfer model for estimating both LAI and leaf chlorophyll content and canopy chlorophyll content using a spectroradiometer. Inversion of a radiative transfer model and statistical approaches for estimating LAI can also be applied to airborne hyperspectral data, such as HyMap data (e.g. DARVISHZADEH et al., 2011). In a study using SPOT05 and CASI-550 data, Tong; He,

(2017) observed that vegetation indices that utilize reflectance data from one or more wavelengths in the red-edge region (690-750 nm) perform better in retrieving chlorophyll content in heterogeneous grasslands. Water yield in afforested areas in the Argentine Pampas was 48% less than in grassland watersheds. Whereas NDVI from MODIS data indicated higher transpiration and primary productivity under plantations compared to grasslands (JOBBÁGY; ACOSTA; NOSETTO, 2013).

Vegetation water content (absolute and relative) in grasslands can be estimated from remotely sensed data in the shortwave optical domain by applying linear band combinations or indices (DAVIDSON; WANG; WILMSHURST, 2006), either using field spectroradiometers, airborne or satellite data. Gao et al., (2019) estimated forage phosphorus levels, which can provide significant information for pastoral agriculture and livestock management, using hyperspectral data by applying multi-factor (topography, soil, vegetation and meteorology) machine learning algorithm. Biswas et al., (2014) applied a different type of index, called the normalized difference dry index (NDDI = [SWIR – NIR]/[SWIR + NIR]), in combination with NDVI for monitoring and identifying moist grasslands and discriminating grassland types, which can be applied to evaluate the influence of an altered flooding regime on grassland distribution.

Influences of increased CO_2 on grasslands are traditionally investigated via destructive sampling methods whereas hyperspectral approaches are rapid, non-destructive and cost-effective (OBERMEIER et al., 2019). Grassland ecosystems play key roles in carbon sequestration (LIU et al., 2019). Based on studies in the Pampa grasslands of Uruguay, Paruelo et al., (2016) developed an index, known as Ecosystem Services Provision Index ([ESPI = $NDVI_{Mean}$ * (1-$NDVI_{CV}$)]; CV denotes the coefficient of variation and $NDVI_{CV}$ is highly sensitive to land use changes), for estimating different grassland ecosystem services including soil carbon sequestration, evapotranspiration, groundwater recharge as well as bird diversity.

4.2.6 Heat and energy fluxes

Latent heat fluxes (LET), which are essential components of water and energy cycles as well as key variables in agronomy and forestry resource management, can be estimated using land surface temperature (LST) from remotely sensed data as a key input (Jimenez et al. 2017) associated with variables such as albedo, NDVI, Leaf Area Index (LAI), and meteorological data as water vapour, air temperature and wind. A number of satellite data (e.g. AATSR, MODIS, SEVIRI, AMSR-E, and SSMIS) have been used to derive LST and in many cases, it is necessary to compare LST from satellite data with *in situ* data. Infrared estimates of LST are limited in terms of temporal coverage as the quality is dependent of the presence of cloud cover while microwave estimates (all-sky coverage) are limited in terms of spatial resolution SKOKOVIC; SOBRINO; JIMENEZ-MUNOZ, 2017). In a nutshell, an accurate land heat flux measurement from satellite data requires an accurate satellite-derived LST product. ‘

Biophysical parameters, such as LAI, have been used as key variables for vegetation monitoring and for modelling energy and matter fluxes in the biosphere. Asam et al., (2013) utilized RapidEye data for estimating LAI using the ratio vegetation index and red edge indices.

The estimation of LET in Pampa Biome by eddy-covariance has been seasonally assessed by Rubert et al., (2018) in two different study areas with the same native vegetation cover, but with different soil types. The authors concluded that 65% of the available energy was used for evapotranspiration and, even with the differences in soil moisture; there was no apparent distinction in energy partition in the two study areas. Schirmbeck; Fontana; Roberti, (2018) studied the Pampa Biome fluxes in Rio Grande do Sul by SEBAL model using MODIS images; the authors obtained better results during summer seasons than winter caused, which could be caused by the low variability of LST.

Some studies are aimed to understand how the energy balance is affected by different agricultural management (DIAZ et al., 2019; FONTANA et al., 2018a; MONTEIRO et al., 2014; ROCHA et al., 2020a, 2020b; RUBERT et al., 2018; SCHIRMBECK; FONTANA; ROBERTI, 2018). Those studies have proved that the weather station affects and modifies the accumulation of forage in the natural grasslands of the Pampa biome, which is typical of the subtropical climate prevailing in the region. In this sense, winter is the critical season for livestock production, which corroborates with the results of this work that demonstrates the decrease of evapotranspiration in winter indicating less forage production.

ROCHA et al., (2020a) developed the first study in the Brazilian Pampa biome that seeks to understand the influence of the Ts on energy balance fluxes and daily ET evaluating S-SEBI model, but also discuss the importance of native grassland not only to the biodiversity conservation but also to the environment process.

5 Future of grassland remote sensing with reference to the Pampa Biome

Even though a large number of remotely sensed data types and methods have been used all over the world for grassland research, it is deduced from the available literature that only a few have been applied in the South American Pampa Biome.

The main interest field have been changing in the last years. If in the 2000s, scientists were interested in researching more about agriculture, land uses and fragmentation, in recent years the main issues of interest are: urbanization, change detection, circular economy, climate variability (Figure 8). Besides, if before the Argentinean Pampas were more studied, nowadays there are an increase in studies regarding the Brazilian Pampas.

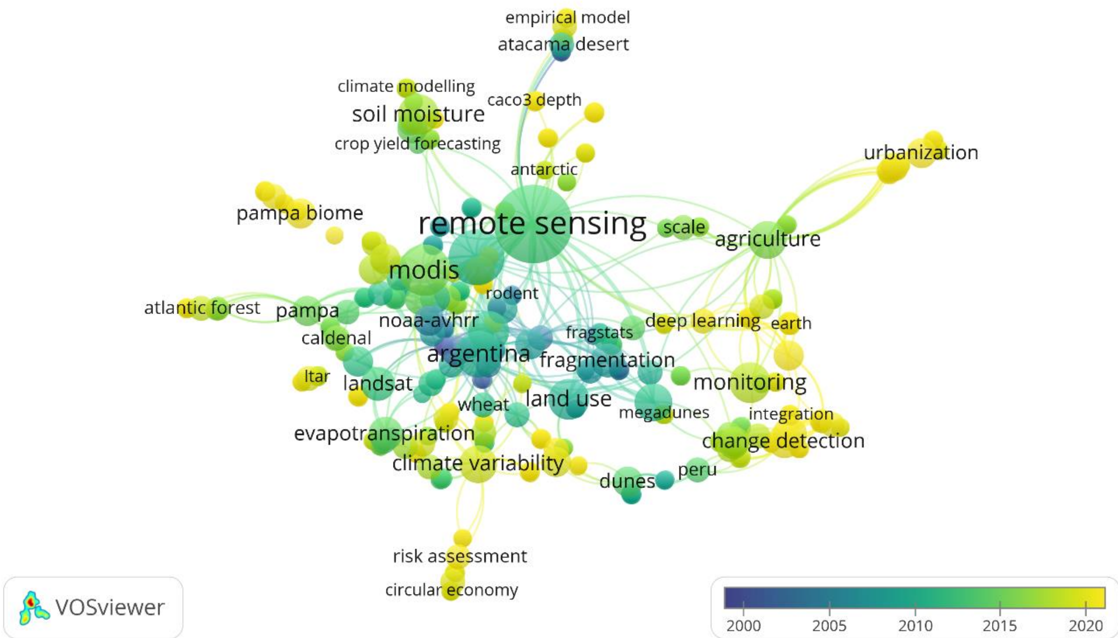

Figure 8. Network of keywords based on the co-occurrence method on RSPampa research from 1995-2021.

The South American Pampas are composed of areas with different geomorphological conditions (mountains, coasts, and plains). This requires multi-source remote sensing data and specific methods can be used for effective mapping and monitoring of grasslands in the region.

Most studies developed in the last years have used MODIS, Landsat and NOAA-AVHRR data. The potential of LiDAR data to monitor the Pampa biome grasslands still remains unexplored, even though such data provide high spatial resolution and carry information about the vegetation that spans their optical properties. The use of UAV platforms can substantially reduce the cost of LiDAR for data acquisition.

5.1 The need for a ‘multi’ approach

A combination of multiple data types is suggested by many researchers for accurate mapping of grassland ecosystems (ESCH et al., 2014; PITKÄNEN; KÄYHKÖ, 2017; PROPASTIN; KAPPAS, 2009; VILLOSLADA et al., 2020), which can be applied in Pampa Biome. For example, a combination of low-density LiDAR data and optical remote sensing data (e.g. aerial photographs, Landsat imagery) can be used for reducing the classification error while detecting grassland overgrowth, particularly in heterogeneous (e.g. where encroachment of woody plants into grasslands occurs or pastured and non-pastured grasslands) environments (PITKÄNEN; KÄYHKÖ, 2017). The use of high-density LiDAR instead of low-density is believed to further enhance the classification accuracy (PITKÄNEN; KÄYHKÖ, 2017), although medium density LiDAR has been shown to work well (WARD et al., 2013).

For area-wide, spatially detailed and up-to-date information of grassland distribution and land use intensity, Esch et al., (2014) suggested using a combination of multi-seasonal high and medium resolution satellite imagery (e.g. LISS3 and AWiFS). Integration of optical satellite data (e.g. Landsat series) with field measurements also can improve accuracy of mapping LAI of grasslands (PROPASTIN; KAPPAS, 2009). Lehnert et al., (2015) obtained the best accuracy for mapping grasslands by the application of a multi-scale, multi-sensor and multi-method approach, where spaceborne optical data with varying special resolution have been used (WorldView-2m, Landsat-30m, Modis-500m) and SVM methods in particular. Integrated optical and radar data can be applied to differentiate natural grassland from invasive species effectively (HONG et al., 2014). Biomass estimation using multisource remote sensing data has been used effectively in Pampa Biome. For example, Guerini Filho; Kuplich; Quadros, (2020) used a combination of multispectral (Sentinel-2) and hyperspectral (field spectrometer) data for successful biomass estimation in the Brazilian Pampa Biome.

Evapotranspiration measurements have been shown to be effective when combining LST measurements from optical sensors and soil moisture measurements from microwave sensors (CASTELLI et al., 2018) or optical data such as AVIRIS and MODIS (LIU et al., 2012). For an accurate satellite-derived land heat flux measurement, a combination if infrared and microwave data is suggested by some researchers (e.g. SKOKOVIC; SOBRINO; JIMENEZ-MUNOZ, 2017).

6 Conclusions

Currently, a large number of remotely sensed data from different platforms (terrestrial and aerial photographs, airborne, spaceborne and UAV-borne) with varying resolutions (spatial, spectral, temporal, radiometric) are available for grassland research at global and regional scales. The application of remote sensing methods can substantially reduce the cost of field surveys and data collection, minimize laboratory analysis (e.g. for biomass estimation) and help to improve the implementation of ecosystem management and conservation, particularly in extensive areas of interest.

The South American Pampa Biome, covering the southern areas of the continent (Brazil, Uruguay and Argentina), is one of the most highly productive ecosystems in the world. Despite this, this biome has only aroused the interest of the scientific community in the last 10 years and, while many studies are developed in grasslands ecosystems using remote sensing methods, on opposite there are a slowly development of RSPampa research studies.

Pampa grasslands in South America are facing a number of problems, such as invasive species, reforestation by exotic species, expansion of agriculture (e.g. soybean), climate change, and grazing. It is important to have a time-series analysis of grassland cover change in the region in order to conserve the indigenous ecosystem. Remote sensing, with its vast variety of data, including terrestrial photography/videography and field spectrometer, airborne multispectral/hyperspectral data, spaceborne multispectral/hyperspectral data, LiDAR and Radar, and different types of data taken from UAV platform, have been used by researchers for grassland studies around the world and the vast majority of these would be appropriate to apply in Pampas studies.

For detailed monitoring of grasslands in the South American Pampas, a multi-source approach is necessary, particularly due to the varying geomorphology of the region and a single type of data may not be effective. Pampean grassland parameters that can be estimated using remotely sensed data are grassland cover/area, growth and plant diversity/species richness, biomass and primary productivity, grassland use intensity and soil degradation patterns, age and population structure of invasive shrubs, biochemical, structural and functional traits, and heat and energy fluxes. Future studies may provide more conclusions about the influences of different native grasslands managements.

One of the remote sensing data types, which have not been utilized in the South American Pampas for grassland research, is LiDAR. It is suggested that multi-source and multi-type remote sensing data can be used for detailed study of different grassland parameters in the Pampas. Recent development in UAV technologies would be helpful in mapping and monitoring grassland ecosystems in this region in cost-effective and spatially accurate ways, particularly were used in conjunction with data having a greater spatial coverage.

Appendix 1.

Table 1: Summary of studies using remote sensing data for grassland research in the South American Pampa Biome (2000-2020)

Reference	Country/region	Data used	Study period	Methodology used	Key findings/ notes
Filho et al. (2020)	Brazil	Sentinel-2A	2017	Vegetation indices (NDVI, EVI, PSRI, NDREI), field sampling, statistical analysis.	Combination of multispectral data and field sampling for grassland biomass estimation in Brazilian Pampa Biome.
Acuna et al. (2019)	Argentina	SARAT SAR, COSMO-SKYMED	2010-2016	Discrete scattering model	Growth cycle of wheat over Argentine Pampas using SAR data.
Altesor et al. (2019)	Uruguay	MODIS imagery	2014	NDVI, statistical analysis	State-and-transition model for Uruguayan grasslands derived from satellite data.
Garcia et al. (2019)	Argentina	Sentinel-1 SAR and MODIS data	2014-2016	Water balance model, regression models and Artificial Neural Networks (ANN)	Soil moisture estimation over Argentinean Pampas using SAR data
Gazzano et al. (2019)	Uruguay	MODIS NDVI	2000-2017	Land Use Intensity Index (LUII)	ANPP values in Uruguay were observed to be lower in the areas of agricultural intensification.
Mengue et al. (2019)	Brazil	MODIS EVI, Landsat	2014	Decision Tree classification	LULC maps of Brazilian Pampa Biome using MODIS data.
Tiscornia et al. (2019)	Uruguay	MODIS data products, Landsat OLI	2012-2015	Vegetation indices and statistical analysis	Height of native grasslands in Uruguay using satellite data.
Trentin et al. (2019)	Brazil	MODIS	2012-2014	Vegetation indices and NIR reflectance	This study tried to correlate the above-ground biomass of Pampean grassland with spectral reflectance using MODIS data.

Baeza and Paruelo (2018)	Uruguay	MODIS	2001-2002 2012-2013	NDVI, statistical analysis	HANPP in Rio de la Plata grasslands using MODIS imagery.
Filho (2018)	Brazil	Sentinel-2, hyperspectral data	2017	Vegetation indices	Combination of multispectral and hyperspectral data for biomass estimation in Brazilian Pampa Biome.
Fontana et al. (2018)	Brazil	MODIS, meteorological data	2000-2013	NDVI	Grassland growth measurements and influence of ENSO on grassland growth rate using optical satellite and meteorological data..
Mengue (2018); Mengue et al. (2018)	Brazil	Landsat, MODIS, DMSP-OLS, and SRTM DEM	1985-2015	Decision Tree classification	Degradation of grassland due to anthropic activity (silviculture) using remote sensing.
Moreira (2018)	Brazil	MODIS (NDVI, EVI, and GPP)	2002-2012	NDVI, EVI, GPP	Phonological characteristics of grasslands using vegetation indices from MODIS data.
Wagner et al. (2018)	Brazil and Uruguay	MODIS/Terra MOD13Q1	2000-2011	NDVI and EVI	Characterization of annual and seasonal variability of NDVI and EVI over grassland types. EVI shows more potential to detect vegetation vigor.
Cicconet (2017)	Brazil	RapidEye, IKONOS, KOMPSAT	2011-2017	SVM classification	Mapping the invasion of *Eragrostis plana* Nees in Brazilian Pampa grasslands.
Gomes (2017)	Brazil	Sentinel-2	2015-2016	Extraction and Classification of Homogeneous Objects (ECHO)	Use of Sentinel-2 data for the identification of the invasion of *Eragrostis plana* Nees in Brazilian Pampa grasslands.
Gonzalez (2017)	Brazil	Landsat 8, MODIS/Terra	2006-2015	GARP, MAXENT	Analysis of invasive species using spaceborne optical data.
Demaria et al. (2016)	Argentina	MODIS/Terra, Landsat	2000-2010	Non-supervised classification, visual interpretation	Remote sensing approach for revised Pampa grassland inventory in Argentina.

Lara (2016)	Argentina	Landsat series	1974-2011	Digital Number statistics	Fragmentation of natural grassland and its replacement by different species in Argentine Pampas.
Nobrega (2016)	Brazil	MODIS	2000-2015	Object-oriented classification using NDVI and EVI	This study used vegetation indices for monitoring the expansion of soybean cultivation in Pampa Grasslands (Brazil).
Paruelo et al. (2016)	Uruguay	MODIS MOD13Q1	2000-2014	NDVI, ESPI	Estimated ecosystems services provisions of grasslands in Uruguay using spaceborne data.
Grings et al. (2015)	Argentina	ASCAT and SMOS data	2010-2014	Land-surface model (GLDAS)	Validation of satellite-based soil moisture in Argentine Pampas
Roglich et al. (2015)	Argentina	Historical maps, aerial photographs, forest inventory map, CBERS	1880s–2000s	Visual inspection,	Multitemporal land cover changes in Argentine Pampas between 1880s and 2000s using multisource land cover data.
Scotta and Fonseca (2015)	Brazil	SPOT-4, SPOT-5, Landsat TM	1998-2011	NDVI method	Above-ground NPP of Brazilian Pampa grasslands using remote sensing and ground data.
Trentin (2015)	Brazil	MODIS	2012-2014	Statistical methods, NDVI	Grassland biomass and carbon stock in Brazilian Pampa Biome using MODIS data.
Guido et al. (2014)	Uruguay	MODIS/Terra	2000-2010	EVI method	Above-ground Net Primary Productivity (ANPP) of Pampa grasslands in Uruguay using MODIS data.
Lara and Gandini (2014)	Argentina	Aerial photographs, Landsat series	1974-2011	Maximum likelihood classification and visual interpretation	Fragmentation of Argentine Pampa grasslands using time-series analysis of Landsat data and visual interpretation of aerial photographs.
Tiscornia et al. 2014	Uruguay	Landsat TM	1990-2009	Supervised and unsupervised classification	Changes in grassland ecosystem in Uruguay due to the expansion of soybean cultivation.
Jobbagy et al. (2013)	Uruguay	MODIS	2004-2007	NDVI	Comparative water yield under grasslands and afforested areas in Argentine Pampas using MODIS data.

Scotta (2013)	Brazil	SPOT-3 and SPOT-4	1998-2011	NDVI, statistical analysis	Influence of climate on grasslands in Pampa Biome using remote sensing and meteorological data.
Wagner (2013)	Brazil and Uruguay	MODIS/Terra MOD13Q1	2000-2011	NDVI and EVI	This study analysed the temporal dynamics of vegetation indices and their relation with regional meteorological data.
Holzman et al. (2012)	Argentina and Uruguay	MODIS/Terra	2007-2010	Temperature Vegetation Dryness Index (TVDI), EVI	LST and EVI from satellite data for understanding the effects of ENSO on Pampa region.
Baeza et al. (2010)	Uruguay	Landsat, MODIS	1999-2000	NDVI, supervised classification	Landsat and MODIS data for estimating above-ground NPP in Uruguayan grasslands.
Kurtz et al. (2010)	Argentina	Landsat series	2000-2006	Maximum Likelihood Classification, NDVI	Assessment of grassland management in Argentine Pampas using satellite and field data.
Vega et al. (2009)	Argentina, Brazil, Uruguay	Landsat series	1985-1990 2002-2005	Markovian models of land use change (statistical analysis)	Overall 6% reduction of grasslands, 60% increase of afforestation, and 3% increase of croplands in the South American Pampa Biome.
Baldi and Paruelo (2008)	Argentina, Brazil, Uruguay	Landsat series	1985-1989 2002-2004	NDVI, unsupervised ISODATA classification	Grassland area decreased from 67.4% to 61.4% of the total land area during the study period.
Zalba et al. (2008)	Argentina	Aerial photographs	1967-2003	Photogrammetry, linear regression analysis	Invasion of pines in Argentine Pampa grasslands using aerial photographs.
Baldi et a. (2006)	Argentina, Brazil, Uruguay	Landsat TM	1996-1997	NDVI, Supervised classification	Grassland fragmentation in South American Pampas using Landsat data
Debelis et al. (2005)	Argentina	Aerial photographs	1989	Photogrammetry, laboratory analysis of soil	Used aerial photographs in understanding the relationship between soil characteristics and vegetation as a function of landform position.
Guerschman et al. (2003)	Argentina	Landsat TM	1996-1997	Supervised (maximum likelihood) classification	Land cover classification in Argentine Pampas using Landsat TM imagery.

Zalba and Villamil (2002)	Argentina	Aerial photographs	1967-1994	Photogrammetry, Area Index (AI)	Woody plant invasion in Argentine Pampa grasslands using aerial photographs.
Bella et al. (2000)	Argentina	NOAA AVHRR	1982-1983	NDVI, multiple regression analysis	Evapotranspiration measurements in Argentine Pampas using NOAA AVHRR data

CAPÍTULO 2

Article

Evapotranspiration estimation with s-sebi method from landsat-8 data against lysimeter measurements in barrax site, spain

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Abstract. Evapotranspiration (ET) is a variable of the climatic system and hydrological cycle that plays an important role in the biosphere-atmosphere-hydrosphere interactions. In this paper remote sensing-based ET estimates with the simplified-surface energy balance index (S-SEBI) model using Landsat 8 data were compared with in-situ lysimeter measurements for different land covers (Grass, Wheat, Barley and Vineyard) in Barrax site, Spain for the period 2014-2018. Daily estimates produced superior performance than hourly in all the land covers, with an average difference of 12% and 15% for daily and hourly ET estimates, respectively. Grass and Vineyard showed the best performance, with RMSE of 0.10 and 0.09 mm/hour and 1.11 and 0.63 mm/day, respectively. Thus, the S-SEBI model is able to retrieve ET from Landsat 8 data with an average RMSE for daily ET of 0.86 mm/day. Some model uncertainties were also analyzed, and we concluded that the overpass of the Landsat missions does not represent neither the maximum daily ET nor the average daily ET, which contributes to increase errors in the estimated ET. However, S-SEBI model can be used to operationally retrieve ET from agriculture sites with good accuracy and sufficient variation between pixels, thus being a suitable option to be adopted into operational ET remote sensing programs for irrigation scheduling or other purposes.

Keywords: Energy balance; Evapotranspiration; Remote Sensing; Lysimeter

1. Introduction

Evapotranspiration (ET) represents the loss of water from the Earth's surface to the atmosphere through the combined process of evaporation and transpiration. In general terms, the evaporation process occurs via open water bodies, bare soil and plant surface, whereas the transpiration occurs through vegetation or any other moisture-containing living surface (BASTIAANSSEN et al., 1998b). Within the land-atmosphere interface, the ET regulates the Earth's energy and water cycles (BASTIAANSSEN et al., 1998b; COURAULT; SEGUIN; OLIOSO, 2005; ROERINK;

SU; MENENTI, 2000; RUBERT et al., 2018; SOBRINO et al., 2005; SU, 2002). As a result, its estimation is critical to the ideal design and management of irrigation systems, efficient irrigation scheduling, and a wide variety of water resources management efforts (MOHAMMADI; MEHDIZADEH, 2020). Although the ET represents an essential component of the hydrological cycle, it is one of the least understood. It is estimated that 60% of the precipitated water returns to the atmosphere through ET (OKI; KANAE, 2006). Nonetheless, because of the complex physical and biological controls on evaporation and transpiration in addition to different land cover properties, the ET estimates may diverge substantially (CHEN; LIU, 2020).

Conventional measurements of ET (i.e., sap flow, weighing lysimeter, pan measurement, bowen ratio system, eddy covariance system) have a limited use because they are not spatially representative and due to the dynamics nature of heat transfer processes (TANG; LI, 2008; TANG; LI; SUN, 2013; WANG et al., 2007). Additionally, its employment is often expensive, time-consuming, laborious and sometimes subject to instrument failure (LIOU; KAR, 2014) . Satellite remote sensing allows obtaining large-scale ET, which can accordingly characterize the surface heterogeneity, ranging from individual pixels to an entire raster image. Hence, the combination of process-based models with remote sensing observations is a valuable strategy to quantify the spatio-temporal variations of ET. Accurate estimates of ET depend on the land surface temperature (Ts), solar radiation, albedo (α), and atmospheric conditions (e.g. transmissivity, downward radiation, cloud presence, etc.). In this context, various algorithms have been developed utilizing information from various types of remote sensing sensors. These approaches generally vary from purely empirical to physically-based techniques derived from the surface energy balance (SEB) equation with different degrees of complexity, such as the Surface Energy Balance Algorithm over Land (SEBAL), the Mapping Evapotranspiration with Internalized Calibration (METRIC), the Surface Energy Balance System (SEBS), the Simple Algorithm for Evapotranspiration Retrieving (SAFER), the Simplified Surface Energy Balance Index (S-SEBI), the Two Source Model (TSM) and the two-source time-integrated model (TSTIM) (COURAULT; SEGUIN; OLIOSO, 2005; LIOU; KAR, 2014; LIU et al., 2019).

Although many advances have been achieved in recent decades to accurately retrieve ET from satellite data, the validation of the final ET remains a troublesome issue, mainly due to both scaling effects (i.e., comparisons between remote sensing ET and ground-based ET measurements), and advection effects (LI; ZHAO, 2010). Discrepancies between modelled and observed components of ET indicate that the models may not be estimating the right values of total ET for the right physical reasons (TALSMA et al., 2018). In addition, the conversion from instantaneous values (in watts) to daily or hourly values (in millimeters) is challenging as it adds possible estimation errors. The S-SEBI method was originally proposed by Roerink et al. (ROERINK; SU; MENENTI, 2000) to solve the SEB and retrieve ET from remote sensing. Afterwards, Gómez et al. (GÓMEZ et al., 2005) and Sobrino et al. (SOBRINO et al., 2005) extended the concept to map the daily ET so that the sensible and latent heat flux (H and LE) are not calculated separately, but through the evaporative fraction (FAN et al., 2007; GÓMEZ et al., 2005). Unlike other methods that try to fix temperature for wet and dry conditions for the whole image and/or for each land use class, the S-SEBI can estimate the SEB considering wet and dry conditions of land surface. Furthermore, no additional meteorological inputs are required to run the model. Therefore, the S-SEBI is considered relatively simple to be applied, which makes it appropriate for regions that lack in situ data and may guide the operational generation of continuous products for monitoring ET over agricultural areas.

The increasing pressure on water use is globally well-known, at the same time irrigation intensification is required to be increased for food production for a growing population (CALERA et al., 2017). Improving efficiency in techniques for monitoring water use, as well as regarding the validation of remote sensing-based models, is an immediate and current issue to be solved. It is fundamental to keep in mind that any empirical models should not be used indiscriminately without any modification or improvement to estimate ET from satellite data (LI; ZHAO, 2010). The S-SEBI has been already tested in different sites around the world by several researchers (ALLIES et al., 2020; FAN et al., 2007; GALLEGUILLOS et al., 2011; GÓMEZ et al., 2005; KÄFER et al., 2020; ROCHA et al., 2020a; VERSTRAETEN; VEROUSTRAETE; FEYEN, 2005; ZAHIRA et al., 2009a) being reported as a simple and moderately accurate method to partition the SEB terms (ROERINK; SU; MENENTI, 2000; SOBRINO et al., 2005). However, in most cases the method has been evaluated with in situ flux data, such as eddy covariance (EC) measurements, which have energy balance closure errors that may reach 30%(GOWDA et al., 2013; WILSON et al., 2001). Therefore, differently from other in situ measurements that have known discrepancies, lysimeters are considered the ultimate standard for measurement of ET, considering they are properly installed and managed (MOORHEAD et al., 2017). In this paper, we explored the application of the S-SEBI model with Landsat-8 imagery against three different in situ lysimeters for the period of 2014-2018 in Barrax site, Spain. We assessed the performance of the model under different land covers (Grass, Wheat, Barley and Vineyard) and established a trustable validation for the proper comprehension of the method potentialities in generating novel ET products for future satellite missions.

2. Methodology

In this section the application and validation to the S-SEBI model using Lansat 8 images to an agricultural region in Spain (Barrax) is presented. Figure 1 shows the flowchart of the methodology applied.

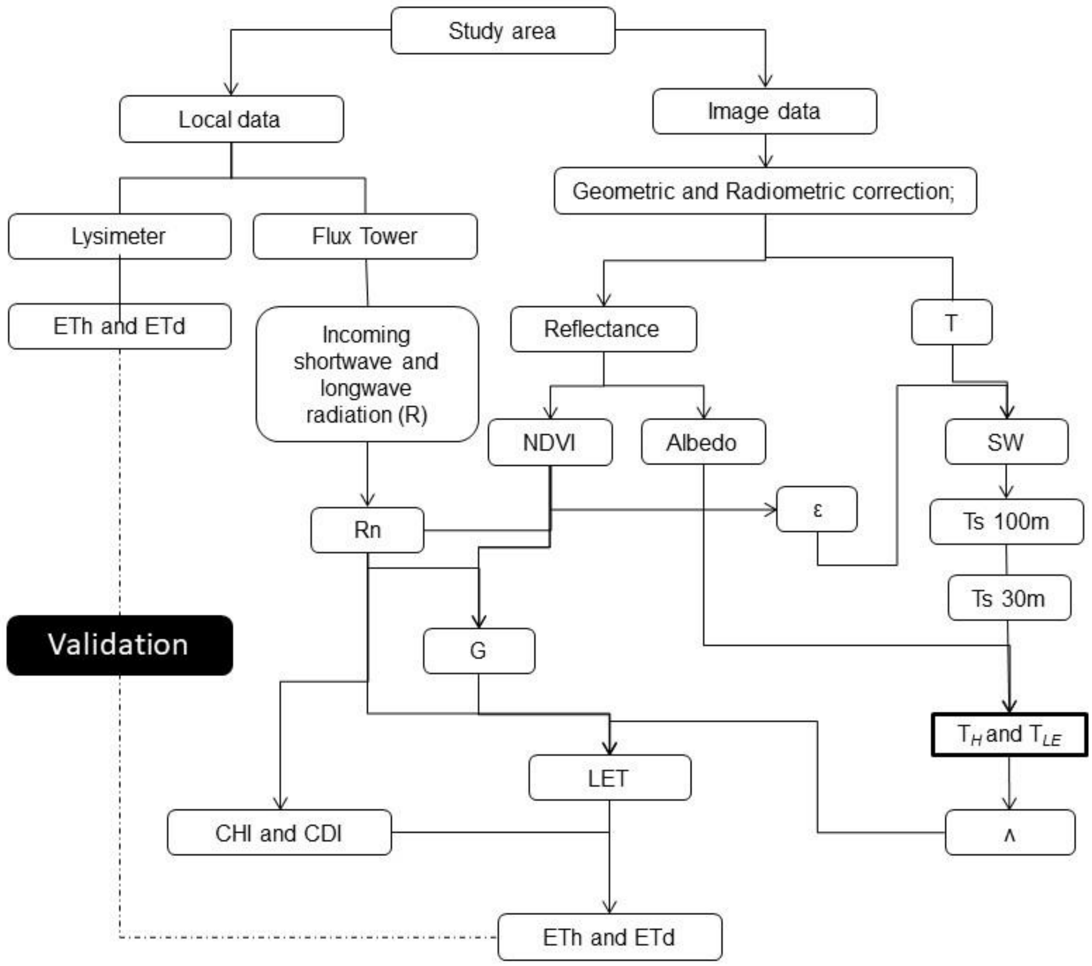

Figure 1. Flowchart of the main steps of the proposed methodology for ET retrieval and validation from Landsat-8 data.

The variables of the flowchart will be presented in the next sections. In the Figure 1, NDVI is the Normalized Difference Vegetation Index; T is the brightness temperature; SW is the Split-Window method, Ts is the land Surface Temperature; ε is the emissivity; Rn is the surface net radiation, G is the soil heat flux; T_H and T_{LE} are the temperatures corresponding to dry and wet conditions; LET is the latent heat flux; Λ is the evaporative fraction; C_{di} is the ratio between daily (R_d) and instantaneous (R_{ni}) net radiation flux respectively; C_{hi} is the ratio between hourly (R_{hd}) and instantaneous (R_{ni}) net radiation flux respectively.

A disaggregation algorithm for Ts data was included because of a high spatial variability of Barrax agricultural area and because we consider that pixels of 100 m are not representative of some small plots, as vineyard or barley and wheat, which areas are below to 100 × 100 meters. Disaggregation is recommended in order to retrieve finer Ts pixel, more plot representative than a coarse Ts pixel, which can contain a mixture of different plots.

As the spatial resolution of thermal infrared pixels (100 meters) is lower than Visible Near InfraRed (VNIR) data (30 meters), a disaggregation method was applied to TS in order to meet the spatial resolutions of albedo and NDVI variables. To do so, a linear relationship between TS and NDVI in a sliding 5×5 pixels window was performed to retrieve the TS pixel at 30m, following the methodology proposed by Jeganathan et al.(JEGANATHAN et al., 2011) .

2.1. Study Area description

This study was performed in Barrax site located in the west of Albacete province, Spain. The site is a Mediterranean climate test area with heaviest rainfalls in Spring and Autumn and lowest in Summer (Figure 2). The rainfall statistics show that the average annual rainfall is little more than 400 mm in most of the area, making La Mancha one of the driest regions in Europe (BASTIAANSSEN et al., 1998a; FAN et al., 2007; GÓMEZ et al., 2005; ROERINK; SU; MENENTI, 2000; ROUSE et al., 1973a; SOBRINO et al., 2005, 2007; SOBRINO; SKOKOVIĆ, 2016). The Barrax area has been selected in many field campaigns for calibration/validation activities because of its flat terrain and the presence of large, uniform land-use units (approximately 100 ha), suitable for validating moderate-resolution satellite image products.

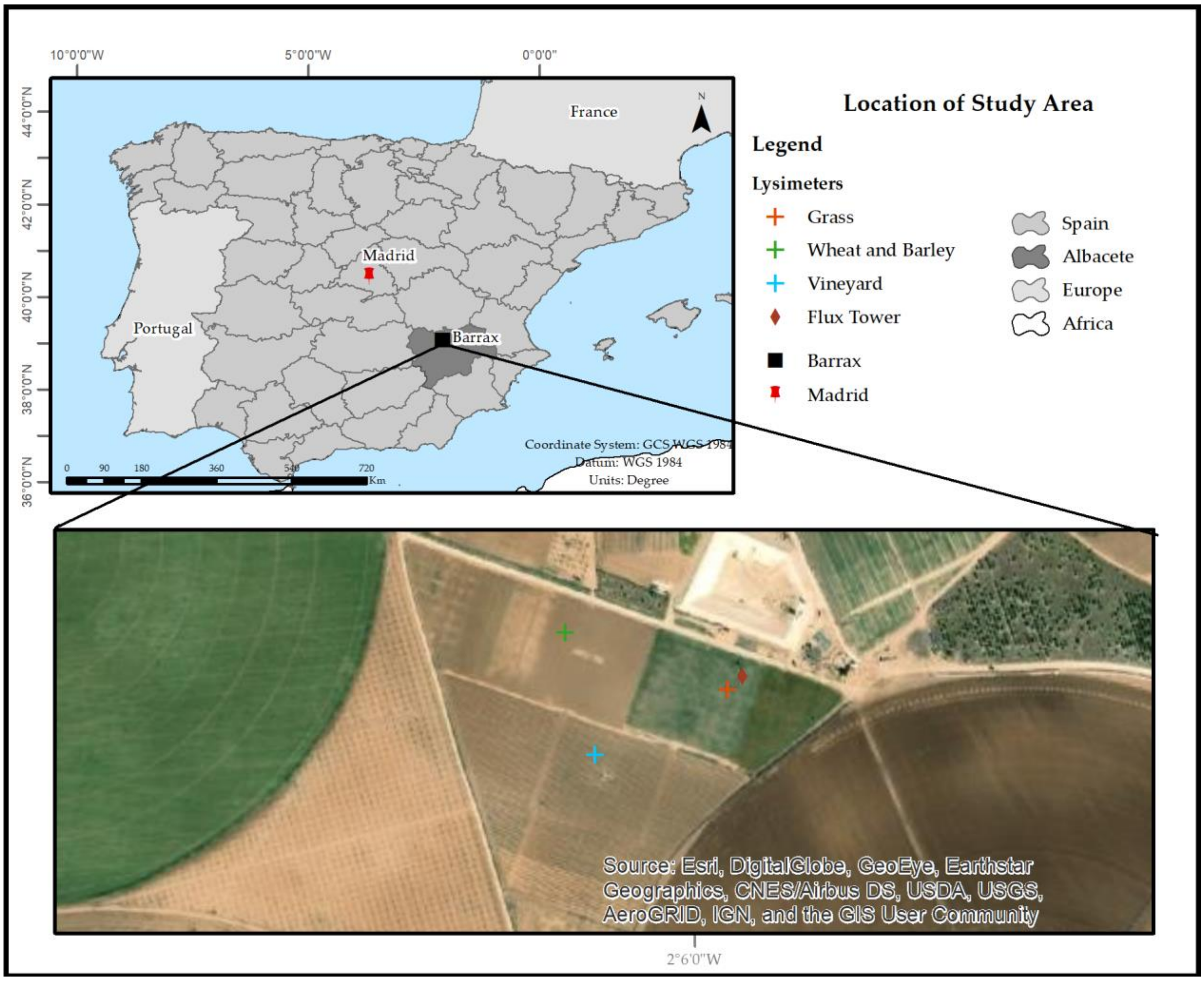

Figure 2. Barrax area location in Albacete, Spain and Europe. Lysimeters and tower flux points are shown on the map.

2.2. In situ data

Barrax has a fixed station over grass field with continuous Ts (Land Surface Temperature) measurements taken by a radiometer that covers a footprint of 3 m² (SKOKOVIC; SOBRINO; JIMENEZ-MUNOZ, 2017). Besides Ts, this station provides other variables as wind direction and speed, soil flux, moisture and temperature, air temperature and humidity, as well as net radiation. The net radiometer (model NR01) carries out separate measurements of solar (direct and reflected) and far infra-red (direct and reflected) radiations. A pyranometer measures the solar radiation flux from a field of view of 180º and has a spectral response from 0.3 to 2.8 μm. A pyrgeometer measure the far infra-red radiation flux from a field of view of 180º and has a spectral response from 4.5 to 50 μm.

The study area also has three continuous weighing lysimeters (see Figure 2) with electronic data reading: one lysimeter for Grass crop, one for rotating herbaceous crops (Wheat and Barley) and a permanent one for Vineyard. Each lysimeter is surrounded by a square protection plot of one hectare, the dimensions of the Grass and Herbaceous crops lysimeters recipient are 2.3 m 2.7 m to a side and 1.7 m depth with approximately 14.5 t total mass, Vineyard lysimeter recipient is 3m x 3m to a side and 1.7m depth with 18.5 t total mass. The lysimeters have the necessary equipment to make a complete and acccurate hydric balance and precisely, as explained and tested by many authors (LÓPEZ-URREA; MONTORO; TROUT, 2014; ROUSE et al., 1973a). The data are available in hourly measurements which were used to validate the estimated ET calculated by S-SEBI model between March 2014 and April 2018.

2.3. Satellite data

We selected 62 Landsat 8 OLI/TIRS images to assess the efficiency of the S-SEBI model in estimating ET over different crops. Table 1 shows the days of years (DOYs) of the scenes used for each land cover and year evaluated. Grass has the largest amount of available in situ data for validation, thus being the land cover with more images selected.

Table 1. Days of the year of the images used in this work for each land use.

Land Use	Day of the Year (DOY)				
	2014	2015	2016	2017	2018
Grass	66; 75; 82; 98; 107; 123; 130; 146; 155; 162; 178; 194; 203; 219; 235; 251; 299; 306; 322;	5; 14; 37; 69; 110; 126; 133; 158; 190; 213; 238; 270; 318; 334; 341; 357;	8; 17; 24; 33; 65; 72; 273; 312; 337	83; 99; 122; 147; 163; 179; 218; 250; 282; 298; 314; 323; 330	22; 29; 54; 86; 109
Wheat	66; 75; 82; 98; 107; 123; 130; 146; 155; 162; 178;				
Barley				99; 122; 163; 170; 179	
Vineyard	123; 130; 146; 155; 162; 178; 194; 203; 219; 226; 235; 251;	126; 133; 158; 190; 197; 222; 238; 245; 254; 270;	248; 273;	122; 163; 170; 179; 218; 250;	

2.4. Operational equations

In order to apply the S-SEBI from remote sensing-based models, some variables are required. Table 2 exhibits the mathematical expressions used to estimate Normalized Difference Vegetation Index (NDVI), Albedo (α), Land Surface Temperature (*Ts*) and Land Surface Emissivity (ε). The equations were employed for all the Landsat scenes (Table 1) to obtain instantaneous *LE* in Watts, which was subsequently converted to ET.

Table 2. Equations applied to Landsat-8 data.

Variable	Equation	Description
NDVI	$(\rho NIR - \rho RED)/(\rho NIR + \rho RED)$	ρNIR is the Near Infrared reflectance of Landsat 8 (0.86µm) and ρRED refers to the Red band reflectance of Landsat 8 OLI and (0.65 µm) (ROUSE et al., 1973a);
α	$0.130\rho1 + 0.115\rho2 + 0.143\rho3 + 0.180\rho4 + 0.281\rho5 + 0.108\rho6 + 0.042\rho7$.	ρ is the reflectance at each Landsat 8 OLI channel; (KE et al., 2016)
Ts	$Ti - 0.268(Ti - Tj) + 1.378(Ti - Tj)^2 + 16.4 + (0.183 + 54.3w)(1 - \varepsilon) + (-2.238 - 129.2w)\Delta\varepsilon$;	*Ti* and *Tj* are the at-sensor brightness temperatures at the bands *i* (10) and *j* (11) in Kelvins; εi *and* εj are the emissivities for bands 10 and 11, respectively; ε is the mean emissivity, $\varepsilon = 0.5(\varepsilon i + \varepsilon j)$; $\Delta\varepsilon$ is the emissivity difference, $\Delta\varepsilon = (\varepsilon i - \varepsilon j)$; *w* is the total atmospheric water vapor content (in g/cm−2)(JIMENEZ-MUNOZ et al., 2014b; SOBRINO et al., 1996)
ε	$a + b\rho RED;\ (FVC = 0)$ $\varepsilon_s(1 - FVC) + \varepsilon_v FVC;\ (0 < FVC < 1)$ $\varepsilon = 0.99;\ FVC = 1)$	*FVC* is the Fractional Vegetation Cover and is given by = $NDVI - NDVIs/NDVIv - NDVIs$; ε_s and ε_v are the soil and vegetation emissivity values respectively. (SOBRINO et al., 2008)

2.5. Evapotranspiration estimation by the S-SEBI model

The estimation of ET from remote sensing data is based on assessing the SEB through several surface properties such as albedo, vegetation cover and *Ts* (COURAULT; SEGUIN; OLIOSO, 2005). When considering instantaneous conditions, the SEB is written as:

$$LET = Rn - G - H \quad (1)$$

where *Rn, H* and *G* are the surface net radiation, the sensible heat flux, and the soil heat flux, respectively, all are expressed in energy units (W/m^2), and *LET* is the latent heat flux and can be obtained according to:

$$LET = \Lambda\ (Rn - G) \quad (2)$$

where (Λ) is the evaporative fraction (ROERINK; SU; MENENTI, 2000), adapted and tested (SOBRINO et al., 2005, 2007), and it is described by:

$$\Lambda = \frac{T_H - Ts}{T_H - T_{LE}} \quad (3)$$

where, *Ts* is the land surface temperature, and T_H and T_{LE} are the temperatures corresponding to dry and wet conditions, all in Kelvin. Dry and wet temperatures are retrieved in function of the albedo value by plotting a scatterplot between surface temperature and albedo (ROERINK; SU; MENENTI, 2000).

Once Λ is obtained, *LET* (see Eq. 2) requires the knowledge of *Rn* and *G*, which can be obtained according to:

$$Rn = (1-\alpha)\ Rg + \varepsilon\ Ra - \varepsilon\ \sigma\ Ts^4, \quad (4)$$

Rg and *Ra* being the incident solar radiation and the longwave radiation both measures in $W\,m^{-2}$, respectively, α is the surface albedo , ε the surface emissivity, *Ts* is the land surface temperature and σ the Stefan–Boltzmann constant (= 5.67 × 10^{-8} $W\,m^{-2}\,K^{-4}$).

To obtain G we have considered the approach given by the authors (BASTIAANSSEN et al., 1998a; LI; ZHAO, 2010), i.e.:

$$G = 0.3\ x\ (1 - 0.98\ x\ NDVI^4)\ x\ Rn \quad (5)$$

where NDVI is the Normalized Difference Vegetation Index (ROUSE et al., 1973a).

2.6. Daily and Hourly ET

The comparison between ET obtained by the S-SEBI model on different crops against in situ lysimeter data was carried out considering both hourly (in mm/hour) and daily (in mm/day). While lysimeter data are given in hourly and daily, S-SEBI values are only instantaneous at the moment of the satellite overpass and are given in W/m^2. Therefore, in order to match the time scales, it was necessary to convert instantaneous values acquired through the images to hourly and daily values. The daily ET (ET_{daily}) is defined as the temporal integration of ET instantaneous values during a day and can be obtained using the C_{di} (GÓMEZ et al., 2005; SOBRINO et al., 2007) , which consists of the ratio between daily net radiation flux (R_{nd}) and instantaneous (R_{ni}), respectively according to:

$$ET_{daily} = 24 \ x \ 3600 \ \frac{C_{di} \ x \ \Lambda \ x \ Rni}{\lambda} \tag{6}$$

where λ is the latent heat of vaporization (2.45 MJ/kg); the soil heat flux (G) was considered equal to zero and not included in the equation (SAUER; HORTON, 2015) assuming that much of the energy that enters that reaches the soil during the day returns to the atmosphere at night through terrestrial longwave radiation, Λ is the evaporative fraction and can be considered constant during the day.

Analogously, hourly ET (ET_{hourly}) in mm/h is obtained as

$$ET_{hourly} = 3600 \frac{(C_{hi} x \ Rni - G_i) x \ \Lambda}{\lambda} \tag{7}$$

where C_{hi} is the ratio between hourly (R_{hd}) and instantaneous (R_{ni}) net radiation flux respectively, G_i is the instantaneous soil heat flux (considering it constant and assuming that the impact on results is minimal) and that Λ during the hour is also constant. For both conversions R_n, R_{nh} and R_{nd} have been retrieved from a tower flux located in the study area (Figure 2) in order to reduce the uncertainties on hourly and daily estimations.

2.7. Statistical metrics

The development of the algorithms and image processing was carried out in interactive data language (IDL). The operational application of the S-SEBI model requires the identification of the percentile boundary limits to be automatized. These limits are used to obtain the evaporative fraction, which is the basis of the method. We tested different percentile values (0.01; 0.1; 0.2) and selected 0.1% for the entire dataset because it demonstrated the best estimates all over the land cover types. Finally, to assess the performance of the S-SEBI, we used the root mean square error (RMSE), which allows to quantify the difference between simulated and observed data. In addition, the mean standard deviation (MSD) and Bias were also used to complement the statistical analyzes.

3. Results and discussion

3.1. Comparison of S-SEBI estimated and measured ET

The comparison of the S-SEBI hourly and daily ET against lysimeter data for each land cover type is shown in Figures 3a and b, respectively. Generally, the daily estimates had moderately superior performance relative to the hourly in all the land covers assessed. Grass produced the best linear relationship with the in situ ET data. It can indicate that the relation is better when the land cover is more homogeneous. The Biases of the hourly and daily ET estimated by the S-SEBI in comparison to the lysimeter data were also plotted and are exhibited in Figures 3c and d. When the Bias is positive the model overestimates the ET, which was observed mostly for dates with low values of ET. The hourly Bias of the S-SEBI varied between -0.4 mm/hour and 0.4 mm/hour (Figure 3c) and the ET overestimation of the in situ values occurred essentially between 0.05 mm/hour and 0.6 mm/hour. On the other hand, when the in situ ET is higher (between 0.6 mm/hour and 0.9 mm/hour), the model tends to underestimate the ET. A similar random pattern was seen in the daily Bias, which varied between -3.2 mm/day and 5.3 mm/day, producing values closer to zero (Figure 3d).

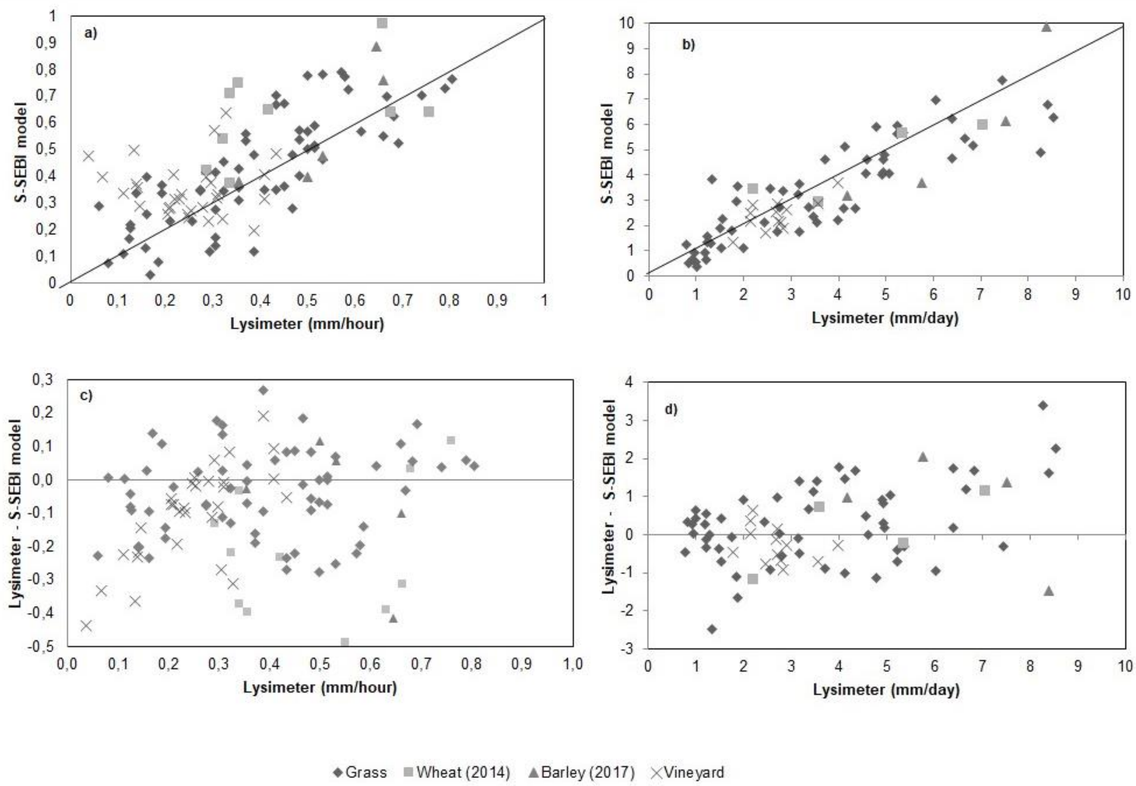

Figure 3. a) Hourly ET correlation analyzes, b) Daily ET correlation analyzes between S-SEBI model and Lysimeter data; c) Relationship between Hourly ET Bias and Lysimeter data and d) Daily ET Bias and Lysimeter data measurements. Line 1:1 is included.

A difference of 12% (0.45 mm/day) was found between the S-SEBI model and the lysimeters, with average daily ET for all the land covers of 3.55 mm/day and 4.01 mm/day, respectively. In contrast, the average hourly ET is 0.44 mm/hour for the S-SEBI and 0.36 mm/hour for the lysimeters, with a difference of 15% (-0.07mm/hour). Different accuracy situations have been reported in the literature for remote sensing-based ET models in comparison to lysimeter data. Using METRIC model Chavez et al. (CHÁVEZ et al., 2012) found similar but slightly larger errors for hourly ET in comparison to the daily values. An evaluation carried out in Tanjung Karang, China, used SEBAL model, meteorological and lysimeter data over cultivated rice and found that the determination of ET by satellite data overestimates the values obtained from lysimeters by 10% (HASSAN; SHARIFF; AMIN, 2008). In a semiarid climate in Las Tiesas, Spain, different models overestimated the lysimeter measurements between 3% and 70% depending on method applied (LÓPEZ-URREA et al., 2006). Mkhwanazi et al. (MKHWANAZI; CHAVEZ; ANDALES, 2015) developed a modified SEBAL that requires daily averages of limited weather data and validated against lysimeter data over an Alfalfa field. The authors reported average underestimates with values up to 24% for the modified model and up to 38% for the original SEBAL algorithm.

Table 3 summarizes the statistical metrics of the hourly and daily ET between the S-SEBI and lysimeter data. Good agreements were obtained from the satellite-based estimates, with RMSE varying from 0.1 to 0.19 mm/hour for hourly, and from 0.63 to 1.71 for daily ET, respectively. These results are in accordance with other validation exercises reported for the S-SEBI model worldwide (GALLEGUILLOS et al., 2011; KÄFER et al., 2020; KUMAR et al., 2020; ROERINK; SU; MENENTI, 2000; SOBRINO et al., 2005, 2007; VERSTRAETEN; VEROUSTRAETE; FEYEN, 2005).

Table 3. Statistical analyzes of the S-SEBI model performance with daily (mm/day) and hourly (mm/h) lysimetric data.

	Grass	Wheat (2014)	Barley (2016)	Vineyard

	Hour	Daily	Hour	Daily	Hour	Daily	Hour	Daily
Bias [a]	-0.04	0.52	-0.10	-0.50	0.08	1.24	-0.00	-0.43
MSD [b]	±0.09	±0.98	±0.16	±1.45	±0.09	±1.18	±0.09	±0.46
RMSE[c]	0.10	1.11	0.19	1.53	0.16	1.71	0.09	0.63

[a] [c]Bias = Σ (Oi – Pi)/n; where O_i is the observed ET and P_i is the ET modeled. [b] Mean standard deviation [c] Root mean square error;

The performance of the hourly ET produced superior estimates for Grass and Vineyard, with RMSE and MSD of 0.10 and ±0.09 for Grass and 0.09 and ±0.09 for Vineyard, respectively. Wheat and Barley had the worst hourly ET estimates, with RMSE and MSD of 0.19 and ±0.16 for Wheat and 0.16 and ±0.09 for Barley, respectively. The knowledge of the hourly ET has several advantages and its accuracy evaluation plays an important role in quantifying estimation errors with irrigation water management practices. However, the hourly satellite calibration is a typical source of uncertainties in satellite SEB models. Hashem et al. (HASHEM et al., 2020) compared the hourly ET with lysimeter data in Texas. By using METRIC model, the authors found average RMSEs of 0.14 and 0.16 mm/hour for dry and irrigated agriculture lands, respectively. Despite METRIC model was developed with focus on agriculture areas and is proven to perform very well for these land covers, its computation requires to determine roughness length which is a complicated variable to be retrieved with enough accuracy from classic remote sensing methods (GÓMEZ et al., 2005). Also, over crops in Texas, Gowda et al. (GOWDA et al., 2013) compared the performance of the hourly ET from the SEBS model with data from four lysimeters using a dataset of 16 Landsat 5 images. The authors reported high accuracy with an average RMSE of 0.11 mm/hour. Nevertheless, they pointed out that a locally derived surface albedo-based *G* model improved the *G* component estimates. The limitations of the empirical formulation used to derive *G* from remote sensing have already been emphasized in other works (ALLIES et al., 2020; KÄFER et al., 2020). Furthermore, roughness length is also required in SEBS model computation, in addition to other meteorological inputs such as air temperature, humidity and wind speed measured at a reference height, which sustains the superiority hypothesis of S-SEBI in terms of simplicity. The hourly Bias of the land covers assessed were mostly negatives, except for Barley that produced 0.08. It indicates that the hourly ET was predominantly underestimated.

The performance of the daily ET estimates, such as the hourly, produced the best metrics for Grass and Vineyard, with RMSE and MSD of 1.11 and ±0.98 for Grass, and ±0.46 and 0.63 for Vineyard, respectively. The daily Bias exhibited negative results for Wheat and Vineyard, with values of -0.50 and -0.43, respectively. Unlike the hourly metrics, the daily ET results of Wheat are notably better in comparison to Barley. However, it is worth mentioning that the amount of available data for Barley is reduced relative to the other land cover types, consequently it may not have included properly the annual and pluriannual variability of ET. In order to evaluate the influence of the weather conditions (particularly cloud-cover impacts), in the S-SEBI model accuracy, we calculated the statistical metrics excluding the days with clouds, which will be discussed in the next section.

3.2. Uncertainties in the S-SEBI estimates

The concept of evaporative fraction is the basis of the S-SEBI model. However, its diurnal constancy may not be satisfied under cloudy circumstances (FARAH; BASTIAANSSEN; FEDDES, 2004). Therefore, we selected 55 entirely cloud-free scenes to evaluate the performance of the algorithm under ideal conditions. Table 4 shows the statistical metrics obtained in the daily analysis. Results found demonstrate a considerable improvement in the ET estimates when the atmospheric conditions do not vary much during the day. In general, the average RMSE decreases from 1.25 to 0.86 mm/day when only ideal scenes are used. The low errors suggest that the model works very well for the estimation of ET in all the land covers. The RMSE was found to be 0.85 mm/day for Grass, 0.81 mm/day in Wheat, 1.32 mm/day for Barley and 0.46 mm/day for Vineyard. The MSD indicates that the differences between model results and lysimeter data are less than 1mm/day, which is in agreement with Sobrino et al. (SOBRINO et al., 2007).

Table 4. Statistical analyzes of the S-SEBI model performance with daily (mm/day) lysimetric data, excluding partial cloudy days (n=55).

	Grass	Wheat (2014)	Barley (2016)	Vineyard
Bias	0.28	0.09	0.73	-0.27
MSD	±0.80	±0.8	±1.10	±0.37
RMSE	0.85	0.81	1.32	0.46

Typically, in S-SEBI model errors in the determination of T_H and T_{LET} lines (and consequently in the evaporative fraction) impact the obtention of the instantaneous LET, which directly affects the ET estimates. Afterwards, the daily ET is extrapolated from instantaneous to daily by using the C_{di} (Eq. 6). According to Singh and Senay (SINGH; SENAY, 2015) different methods of upscaling have its own bias. Yang et al. (YANG et al., 2014) demonstrated that in most of their dataset, the variation of evaporative fraction during the daylight tended to be stable within the time window of 10:00 and 15:00 UTC. However, after this window it is not constant and can affect the C_{di}. According to some authors (LIU et al., 2019; ZHANG; LEMEUR, 1995), there are many difficulties to convert instantaneous ET into daily ET, mostly due to the non-stable conditions of the evaporative fraction during a daylight period, which vary with the available energy, surface resistance and other environmental variables. However, because in the S-SEBI model the daily ET is calculated using the available net flux radiation during the day, the daily ET estimates produced are reliable (SOBRINO et al., 2007; ZAHIRA et al., 2009a) which can be considered a strength of the methodology applied. Figure 4 illustrates the behavior of the solar radiation during different DOYs. The solar radiation data from the flux tower were analyzed on the DOY of greatest errors (06/11/2014 - DOY 162 and 06/27/2014 - DOY 178) and compared with a DOY with good linear relationship (04/17/2014 - DOY 107).

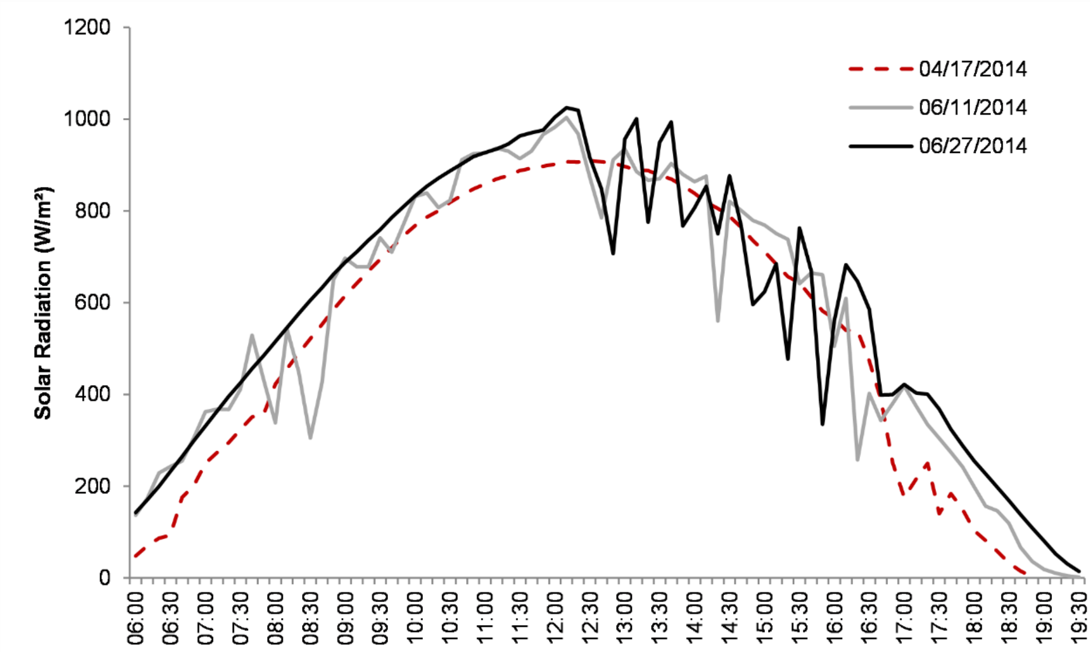

Figure 4. Example of daily solar radiation data from in situ meteorological flux tower.

The "noises" observed in the solar radiation curve clearly reflect the differences between the observed and estimated daily ET. In a clear-sky day when the solar radiation does not show noises caused by clouds or large amounts of water vapor, the S-SEBI-based estimates exhibit an accuracy much lower than 1 mm/day. In April 17th, 2014 (DOY 107) the difference between the in situ ET and calculated is 0.23 mm/day. In contrast, when the daily solar radiation curve presents some noises and the weather conditions vary widely during the day, the difference between the in situ ET and the model estimates is 2.92 mm/day for 6th November, 2014

(DOY 162) and 1.89 mm/day for 27th November, 2014 (DOY 178). In addition to the solar radiation, seasonal drivers from the land surface can strongly affect the ET, making the estimates differ substantially. Yang et al. (YANG et al., 2014) examined remote sensing-based ET estimates from high-resolution data over Wheat in different months and reported an overall RMSE of 0.67 mm/day. The authors pointed out that in months with low coverage and row pattern at the turning green stage, the satellite-based ET accuracy is impacted. In contrast, when the crop is at the harvest stage, better estimates are produced. It occurs particularly because at the time that the normal crop physiological and ecological process gradually are ending, the soil evaporation is over again the main contributor to ET.

3.3. Variation of ET during the daytime

In Barrax site, the lysimeters are located in the center of 100 x 100 m plots and the data are available hourly. As for Vineyard some in situ ET data were missing, they were not included. The average daily ET measured for the entire period was 5.4 mm/day for Wheat, 4.6 mm/day for Barley and 3.7 mm/day for Grass. Given that differences in the thermal, wind, weather conditions and radiation regime between a lysimeter device and its surroundings can affect the measurements (GEBLER et al., 2015), we investigated the hourly average for each land cover type. Figure 5 displays the hourly averages of ET and the maximum values obtained from the lysimeters.

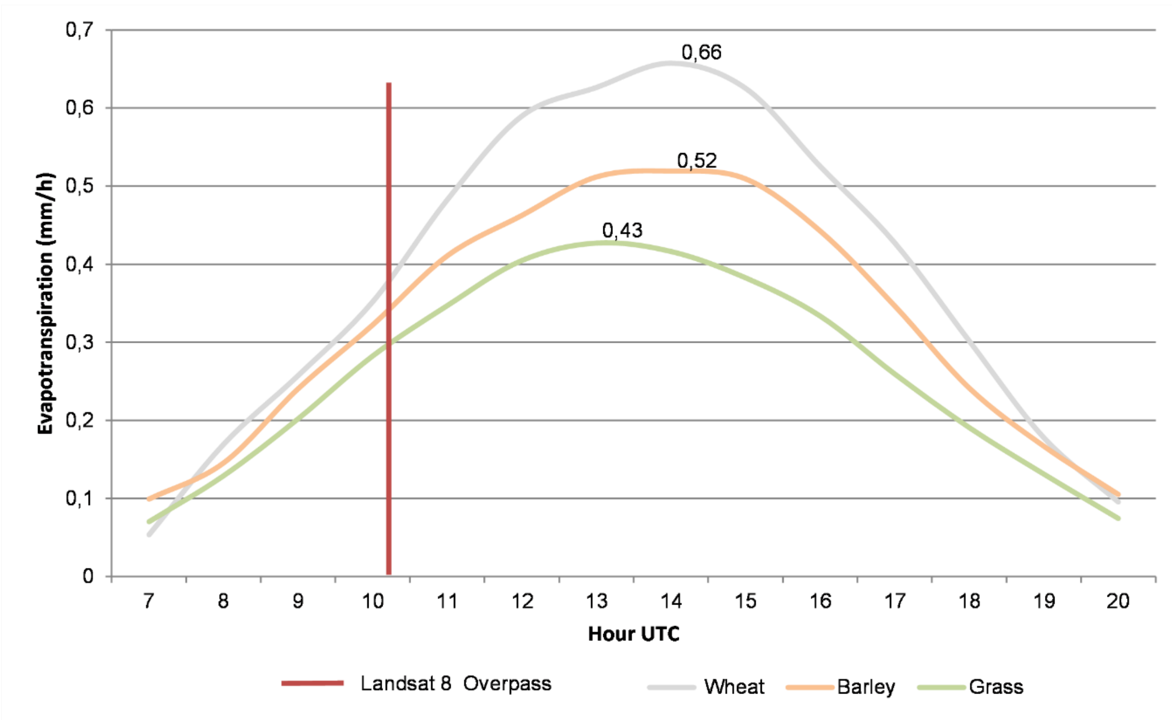

Figure 5. Hourly ET (mm/h) obtained from in situ lysimeter data for Grass, Wheat, and Barley. The red line indicates the overpass time of Landsat-8 at 10:42 UTC.

Overall, the ET exhibits typical fluctuations shape during the day, varying between 7:00 and 20:00 UTC. The hourly ET for Grass ranged from 0.03 to 0.43 mm/hour, with an hourly average of 0.24 mm/hour and with its maximum value at 13:00 UTC. For Wheat, the hourly ET ranged from 0.04 to 0.66 mm/hour, with hourly average of 0.36 mm/hour and its maximum value at 14:00 UTC. Finally, for Barley the hourly ET ranged from 0.05 to 0.52 mm/hour, with hourly average of 0.30 mm/hour and its maximum value at 14:00 UTC. Yang et al. (YANG et al., 2017) reported daytime noticeable ET variations between 7:00 and 18:00, with a peak typically occurring at approximately 14:00 UTC.

Although between 13:00 and 15:00 UTC the ET measurements for each land cover are relatively constant, the maximum differences between curves are more significant in this period. On the other hand, at time of Landsat 8 overpass (10:42 UTC) the in situ ET values are notably increasing quicker. This behavior was observed for all the land cover types. In the S-SEBI model application, the conversion from instantaneous to daily ET through the C_{di} assumes that at the time of the satellite overpass the highest value of ET is being measured, nevertheless, the maximum ET values are seen after the Landsat 8 overpass, around 13:00-14:00 UTC. Consequently, the discrepancy between the hourly ET in situ and the instantaneous from Landsat 8 can be a potential source of uncertainties for the ET validation.

3.4. Seasonally distributed ET

Figure 6 shows the distribution of the hourly and daily ET from the S-SEBI compared to lysimeter ET in situ values for the whole period. Similar patterns were found in daily ET for Grass, Wheat and Barley fields between seasons, which demonstrates a clear seasonal pattern, with higher values in summer and lower in winter due to the cold weather condition (LIU; ZHANG; ZHANG, 2002). Figure 6a and c illustrate the hourly and daily ET in Grass field, respectively. The hourly ET ranged between 0.06 mm/hour during the Winter season and 0.8 mm/hour in Summer and Spring seasons. In most cases, the modeled ET underestimates the values measured by the lysimeter, while the average lysimeter ET is 0.39 mm/hour, the predicted is 0.34 mm/hour. The largest differences between predicted and observed daily ET were noted also in Summer season (DOY 170/2017), in which the lysimeter ET was 8.94 mm/day and the predicted ET was 5.3 mm/day. These results are in agreement with López-Urrea et al. (LÓPEZ-URREA et al., 2006), where FAO Penman–Monteith is applied and compared with lysimeter data. The authors pointed out that the model underestimated ET values mainly during periods of greater evaporative demand.

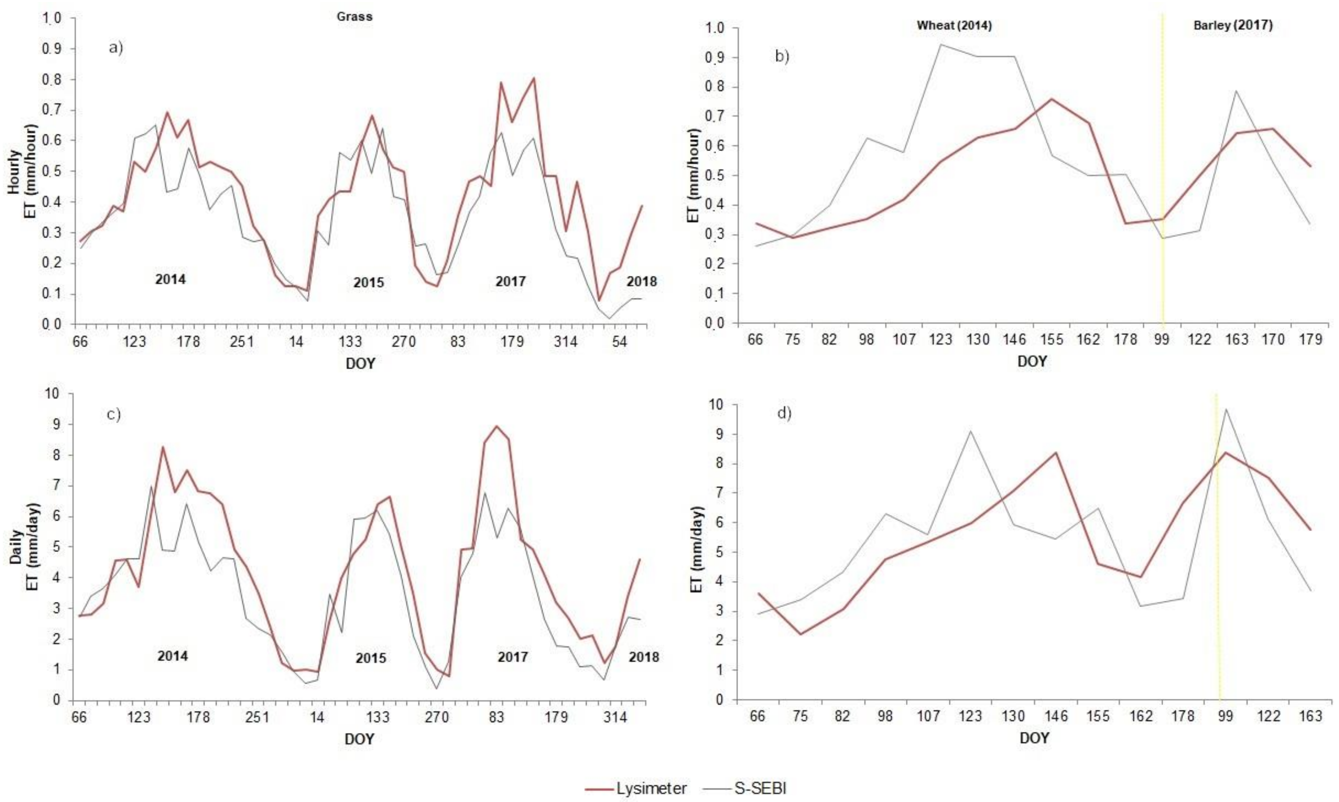

Figure 6. a) Grass hourly evapotranspiration; b) Crops hourly evapotranspiration (mm/hour) ET; c) Grass daily evapotranspiration; d) Crops daily evapotranspiration (mm/day). The yellow line indicates the date when the lysimeter begins to measure Barley instead Wheat ET.

In Figure 6b and d we depict the hourly and daily ET results in Wheat and Barley field. When the satellite-based hourly ET exceeds the lysimeters observations, the daily ET tends to have this behavior likewise. As crop field is irrigated according to its water need, not letting them to be stressed, the only important factor that affects the ET results is the growing and harvesting season. As was pointed at the end of section 3.2, when low crop coverage is present (DOYs 82 to 123) the model show more uncertainties in comparison to the late stages of the crop. S-SEBI model also outperforms when very high and low ET values are achieved. This overtaking was already reported in other studies for the S-SEBI model. Käfer et al. (KÄFER et al., 2020) compared ET estimates derived from S-SEBI with a neural networks-based model in Southern Brazil, which suggested that the S-SEBI values tend to decrease accuracy in estimating extreme ET values, commonly in the transition seasons between Winter and Summer.

The overestimates from the S-SEBI, which were more pronounced in Summer-Spring season, were already reported (WANG et al., 2007). The authors claimed that particularly during severe drought conditions, the parameterization will overestimate ET. The biggest difference between hourly ET occurred on Spring season (DOY 123/2014), in which the standard deviation was of 0.39 mm/hour and the highest rate of water loss occurred. These findings are in accordance with Liu et al. (LIU; ZHANG; ZHANG, 2002), which observed the highest ET in May over-wintering period. The differences between estimated ET and lysimeter data can be explained by the evaporative fraction calculation in the S-SEBI model. Summarily in DOY 123, for higher albedo values the *Ts* does not increase significantly as expected, consequently it generates a greater error in the *Ts* determination to dry and wet conditions. In DOY 163/2017 over the Barley field a similar behavior was seen. It evidences the limitation of the S-SEBI model when operationally applied. The relationship between higher albedos and *Ts* is well-documented in the literature. Sobrino et al. (SOBRINO et al., 2007) and Gómez et al. (GÓMEZ et al., 2005) demonstrated that identifying the boundary limits to obtain evaporative fraction is the critical point of this method and reported that in some cases it reached 1.4 mm/day. In addition, differences between in situ and estimated ET can be related to the extension of the area evaluated, especially given the contrast influence in the landscape that may result in pixel mixing in the albedo and *Ts* determination. The fact that the cultivated area is smaller than the 30 meters pixel size present scale issue to *Ts* estimated and therefore the validation results. In this study, although we used a fixed percentile value for the whole dataset, the ET estimates produced a very high accuracy, and the cloudy effect clearly compromises the albedo-*Ts* relationship more significantly than the other factors mentioned.

3.5. Spatially distributed ET

Remote sensing techniques have been provided an efficient way to retrieve multi-year, spatially consistent, and temporally continuous ET products on the regional to global scale (COURAULT; SEGUIN; OLIOSO, 2005; KÄFER et al., 2020; KHAN; BAIK; CHOI, 2020; ROCHA et al., 2020a; SOBRINO et al., 2007). One of its main advantages is to provide estimates from the whole territory, capturing small spatial variations between pixels that allow to assess the efficiency of the water use and irrigation and groundwater recharge projects or return flows (CHÁVEZ et al., 2012). Figure 7 exhibits the spatial pattern of daily and hourly ET obtained from the S-SEBI method by using a Landsat 8 image over Barrax in Spring season, April 17th, 2014 (DOY 107). Overall, the S-SEBI model can capture the spatial variability of evaporative demand of the atmosphere over the whole study area. Specifically in the daily ET map (Figure 7a), the bare areas with lower ET (blue color) and crop areas with higher ET (red color) can be well distinguished. There were no differences between in situ measurement (lysimeter data) and from S-SEBI model in Grass land cover. In contrast, over the Wheat field it was found a difference of 0.24 mm/day. In the hourly ET map (Figure 7b), the bare areas with lower ET are less prominent and discriminated from the other fields and irrigated areas. The hourly ET average was of 0.6 mm/hour, which is close to the hourly average ET of April (0.64 mm/hour). The difference between in situ data and S-SEBI model was of 0.16 mm/hour in Grass and 0.23 mm/hour in the Wheat area.

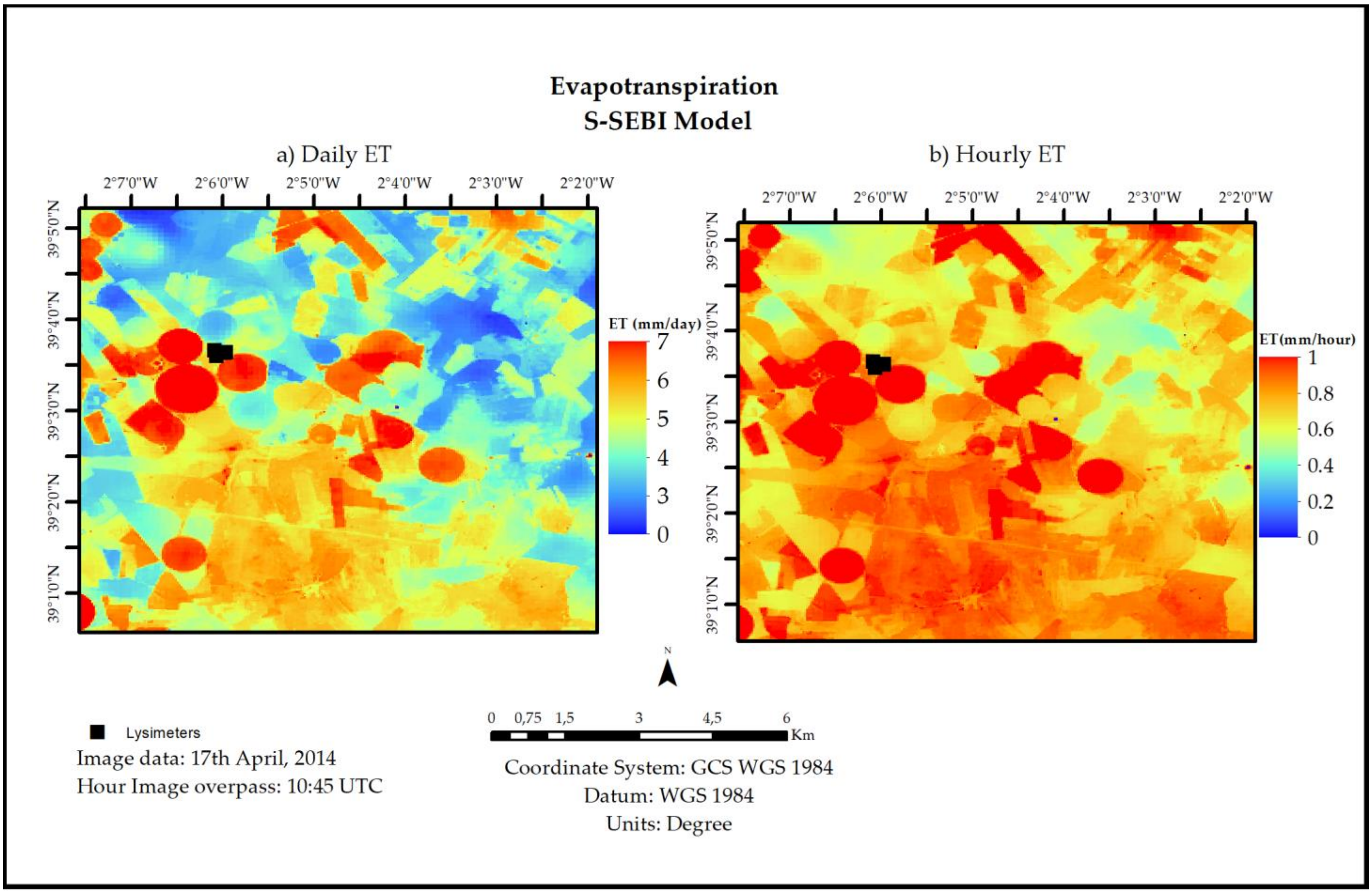

Figure 7. Spatial distribution of a) Daily (mm/day) and b) Hourly (mm/h) ET obtained by the S-SEBI model over Barrax site on 17th April 2014.

In addition to the smaller error obtained in the daily analysis discussed at section 4.2.3, also spatially the daily analysis have more contrast in areas with higher ET and potential water deficit. These findings are important with regard to the water planning of agricultural area, considering that effective water resources management requires an accurate estimation for the water uses and availability to face the water scarcity's challenges (ELNMER et al., 2019).

4. Conclusions

The ET is a key component of the water balance and despite the significant advances in the last decades, remote sensing-based models are not free from uncertainties, especially when applied over different conditions for which they have not been originally developed or calibrated. Therefore, assessing efficiency in techniques for monitoring water use is constantly a research topic. In this paper, we investigated the ET obtained operationally by the S-SEBI model from Landsat 8 data between 2014-2018 in Barrax Site, Spain. Four different land cover types were evaluated (Grass, Wheat and Barley, Vineyard) and validated against lysimeter observations.

In general, the daily estimates produced slightly superior performance relative to the hourly in all the land covers, with an average difference of 12% and 15% for daily and hourly ET estimates, respectively. Grass and Vineyard showed the best performance, with RMSE of 0.10 and 0.09 mm/hour and 1.11 and 0.63 mm/day, respectively. Nonetheless, when only ideal scenes (without any cloud-cover) are considered, the accuracy expressly improves, indicating that the model works very well for all the land covers in suitable conditions. Thus, the S-SEBI model is able to retrieve ET from Landsat 8 data with an average RMSE for daily ET of 0.86 mm/day.

In the operational application of the S-SEBI, identifying operationally the boundary limits of percentiles to obtain the evaporative fraction is challenging. Our findings have shown that assuming a fixed percentile value (0.1%) for different crops can produce enough ET accuracy. In addition, although the conversion from instantaneous to daily ET is frequently cited as a limitation of the remote sensing-based ET models, the mechanism used to extrapolate instantaneous ET to daily values resulted in improved ET estimates, therefore we strongly encourage the application of the C_{di} concept. In fact, the high accuracy of the in situ flux data used contributed for the good performance of the daily estimates. However, it is important to highlight that this is not a restriction, because radiation hourly data are available for the whole globe and can be easily obtained from several reanalysis products and used to generate trustable and continuous daily ET series (LAIPELT et al., 2020).

The hourly ET obtained from the lysimeters provided a detailed analysis of the ET pattern during the day. Between 13:00-15:00 UTC the ET measurements for all the land covers are relatively constant and the maximum values occurred at 13:00-14:00 UTC. At the time of Landsat 8 overpass (10:42 UTC) the in situ ET values showed a rapid increase. Because the C_{di} assumes that at the time of the satellite overpass the highest value of ET is being measured, which is clearly not, the discrepancy between the hourly ET in situ and the instantaneous from Landsat 8 can be a source of uncertainties. The overpass of the Landsat missions does not represent neither the maximum daily ET nor the average daily ET. Differently, more significant variations are seen 10:00 to 11:00 UTC, which contributes to increase errors in the estimated ET. In addition, it is worthy mention that the Landsat pixel size also does not represent appropriately the test sites to validate ET, i.e. the spatial resolution of the TIR sensor of the Landsat satellite is not fully adequate for ET estimates. However, it is expected that with the new Sentinel projects and the improved resolution these issues will be minimized.

The S-SEBI is a model of simple application and low dependence of complex inputs that can well capture the spatial variability of evaporative demand and produce robust daily ET maps over different crops without much effort. Hence, it can be used to operationally retrieve ET from agriculture sites with good accuracy and sufficient variation between pixels, thus being a suitable option to be adopted into operational ET remote sensing programs for irrigation scheduling or other purposes.

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CAPÍTULO 3

Article

The influence of land surface temperature in evapotranspiration estimated by s-sebi model

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Abstract: Evapotranspiration (ET) is one of the least understood components of the hydrological cycle. Its application is varied, from agricultural, ecological and hydrological monitoring, to control of the evolution of climate change. The goal of this work was to analyze the influence that uncertainties in the estimate of Land Surface Temperature (*Ts*) can cause on ET estimates by S-SEBI model in Pampa Biome area. The results indicate that the daily evapotranspiration is higher when the pixel *Ts* is lower, which also shows the influence of land use on the variability of ET. The results demonstrated that the S-SEBI is less dependent on *Ts* estimation than other models reported in the literature, such as the SEBS, which not exceed 0.5 mm/day in grasslands. The evapotranspiration variability between Forest and Grassland were lower than expected, demonstrating that the Pampa biome have in Rio Grande do Sul the same importance that forests regarding to the processes of the hydrological cycle, since it covers 63% of the State.

Keywords: pampa biome, latent heat flux, thermal infra-red

1. Introduction

The physical, chemical and biological processes responsible for life on Earth depend practically on solar energy. Monitoring energy and soil-vegetation-atmosphere mass transfers is a key step in the management of water and agricultural resources. It is also useful for a better understanding and prediction of climate evolution (OLIOSO et al., 1999).

Physically, the energy balance is obtained by determining the magnitude of radioactive and non-radiative fluxes. The radiation balance represents the energy available by the system to non-radiative process, such as evaporate of water or evapotranspiration on vegetated surfaces, by the latent heat flux (LE), heat the atmosphere by the sensible heat flux (H) and heat the subsoil by soil heat flux (G).

Land surface temperature (*Ts*) is one of the sources of input data for modelling land surface processes, such as actual and potential evapotranspiration (ET) that is a critical component of many agricultural and ecological studies (COURAULT; SEGUIN; OLIOSO, 2005; CRISTÓBAL et al., 2018; RUBERT et al., 2018; SOBRINO et al., 2005). The identification of the uncertainties resulting from the different input variables in the estimation of ET remains a challenge due to the complexity of the parameterization of the models (ABID; MANNAERTS; BARGAOUI, 2019; GIBSON; MÜNCH; ENGELBRECHT, 2011).

Many studies estimate that 60% of the precipitated water returns to the atmosphere through evapotranspiration (COURAULT; SEGUIN; OLIOSO, 2005; OKI; KANAE, 2006; OLIOSO et al., 1999; RUBERT et al., 2018). However, the ET is one of the least understood components of the hydrological cycle (COURAULT; SEGUIN; OLIOSO, 2005; OLIOSO et al., 1999). Conventional measurements of ET (lysimeter data, eddy covariance, bowen ratio) have limited application because they are not spatially representative and because of the dynamic's nature of heat transfer processes, also its accuracy is significantly degraded when attempts are made to interpolate or extrapolate spatially sparse measurement networks to landscape and regional scales (CHENG; KUSTAS, 2019). Therefore, remote sensing analyses could be an alternative to solve these problems by different methods.

The S-SEBI (Simplified Surface Energy Balance Index) model estimates evapotranspiration from the relationship between *Ts* and albedo, since it calculates the evaporative fraction by defining the temperatures in drier and wetter regions (GÓMEZ et al., 2005; ROERINK; SU; MENENTI, 2000; SOBRINO et al., 2005, 2007). Hence, the estimation of *Ts* is an important step for the proper functioning of this model. Abid et al. (2019) (ABID; MANNAERTS; BARGAOUI, 2019) have tested the sensitivity of SEBS model to the uncertainties of various input data and their results showed that the changes of ET reach 2 mm/day for changes in *Ts*.

Gibson et al. (2011) (GIBSON; MÜNCH; ENGELBRECHT, 2011) discussed the complexities associated with derivation of ET and the uncertainties related to data and models that have implied potential errors at various stages of ET estimation. These errors are related to two situations: (1) error production and (2) error propagation. Error production refers to a situation where errors in the output products are mainly assigned to the specific operations applied to the data, thus producing errors in the ETs while there were no errors in the original data used as input. Error propagation refers to the process where potentially incorrect input data is passed through certain processing sequences and errors accumulate in ET output.

In this work, we used the S-SEBI model to evaluate the sensitivity of the model output ET to the variation of input *Ts* in a natural vegetation (grassland) in Pampa Biome in southern Brazil. Thus, the main objective of this work was to analyze the influence that the uncertainties in the estimate of *Ts* can cause on ET estimates.

2. Study Area

The Pampa biome is considered by the *Ministério do Meio Ambiente* (*MMA*/Brazil) as one of the most important temperate field areas on the planet. In South America, this biome extends over an area of approximately 750,000 km², shared by Brazil, Uruguay and Argentina. In Brazil, this biome is restricted to 63% of the State of Rio Grande do Sul (RS) and represents 2.07% of the national territory.

From the point of view of biodiversity and environmental services, the fields are a fodder source for cattle ranching, shelter diversity of plant and animal species, and ensure the conservation of water resources (OVERBECK et al., 2006)

The experimental site is located in the Federal University of Santa Maria (UFSM), covering 24 ha of natural vegetation (native grassland) belong to Pampa biome (Figure 1). This study area is part of the International Long Term Ecological Research (ILTER) network and is used for experiments in several areas of knowledge, mainly focused on the morphology of native species for livestock production (CONFORTIN et al., 2017; OLIVEIRA et al., 2015).

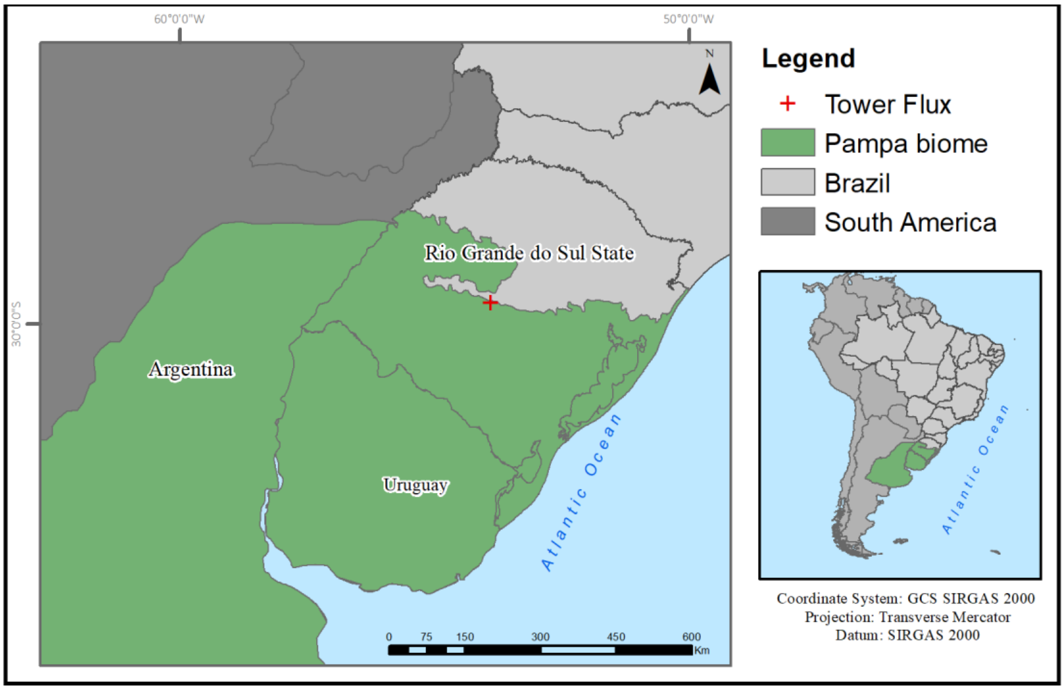

Figure 1. American Pampa Biome and Tower Flux location

The experimental surface fluxes data were obtained with a flux towers installed in the experimental site at (29.725ºS; 53.760ºW). For turbulent fluxes, the sensor set included a 3D sonic anemometer (Wind Master Pro; Gill Instruments, Hampshire, UK), measuring wind and air temperature components, and a gas analyzer (LI7500, LI-COR Inc., Lincoln, NE, USA), measuring theH2O/CO2 concentration at 3-m height sampled at a 10-Hz frequency, from 1 September 2014 to 15 June 2016. After this period, the gas analyzer and the anemometer were replaced by the sensor Integrated CO2 and H2O Open-Path Gas Analyzer and a 3D Sonic Anemometer (IRGASON, Campbell Scientific Inc., Logan, UT, USA). The net radiation was measured at 3-m height with a net radiation sensor (CNR4, Kipp & Zonen, Delft, The Netherlands) and the soil heat flux was measured with soil heat plates (HFP01, Hukseflux Thermal Sensors B.V., Delft, The Netherlands) placed at 0.10-m depth.

The eddy covariance, EC, Aubinet et al. (2002) method (AUBINET; VESALA; PAPALE, 2012) was used in the high-frequency data (10 Hz) for the determination of latent heat flux (LE) and sensible heat flux, both turbulent fluxes, over 30-min block average using EddyPro® software version 6.1 (Li-Cor, Lincoln, NE, USA).) with the configurations described in (RUBERT et al., 2018). The footprint analyses of the EC data by Kljun et al. (2004) (KLJUN et al., 2004) indicates that about 90% of the flux originated within a circle with a radius of 115 m centered in the flux tower.

The daily mean of the fluxes was used to close the energy balance throughout the Bowen ratio approach (TWINE et al., 2000), generating a corrected LE. More details about the experimental site and flux data processing are described in Rubert et al. (2018) (RUBERT et al., 2018). We have evaluated experimental flux data in days with clear sky conditions between 2014 and 2019 and only in dates with less than 2 hours missing data

3. Material and Methods

3.1. Simplify Surface Energy Balance Index (S-SEBI)

The estimation of evapotranspiration from remote sensing data uses thermal infrared (TIR) sensors on satellite, which is based on assessing the energy balance through several surface properties such as albedo, vegetation cover and surface temperature (COURAULT; SEGUIN; OLIOSO, 2005). When considering instantaneous conditions, the surface energy balance is obtained by determining the magnitude of the radiative and non-radiative fluxes the energy balance is written as:

$$LE = Rn - G - H \qquad (1)$$

where LE is the latent heat flux of evaporation or evapotranspiration due to ET; Rn is the surface net radiation; H is the sensible heat flux; and G is the soil heat flux. The variables are expressed in energy units (W/m^2). ET in volume units (e.g., liters m^{-2} d^{-1}, usually simplified to mm d^{-1} to express ET as a depth of water over an indefinite area) can be calculated from LE by the amount of energy needed to evaporate water at a specific temperature and pressure[62].

Once the surface energy balance equation is discriminated, the Rn is calculated as the rest term of all incoming and outgoing shortwave (sw) and longwave (lw) radiation, as describing below:

$$Rn = (1-\alpha)\, Rg + \varepsilon\, Ra - \varepsilon\, \sigma\, Ts \qquad (2)$$

Where:
Rg (W/m^2) is the global incident solar radiation;
Ra (W/m^2) is the incident atmospheric radiation over the thermal spectral domain;
α is the surface albedo;
ε is the surface emissivity;
Ts (K) is the land surface temperature;
σ is the Steffan–Boltzmann constant (5.67 × 10− 8 W m^{-2} K^{-4}).

The latent heat flux (LET) depends on the evaporative fraction (Λ) and is given as follow.

$$LET = \Lambda\, (Rn - G) \qquad (3)$$

The evaporative fraction concept (Λ) was proposed by (ROERINK; SU; MENENTI, 2000), adapted and tested by (SOBRINO et al., 2005, 2007), and it is described by the equation below.

$$\Lambda = (T_H - Ts) / (T_H - T_{LE}) \qquad (4)$$

Where:
T_H (K) is the temperature corresponding to dry condition.
T_{LE} (K) is the temperature corresponding to wet condition.

This method can be only applied when the atmospheric conditions are constants over the image and the study site includes simultaneously wet and dry areas (ROERINK; SU; MENENTI, 2000; SOBRINO et al., 2005, 2007). Besides of that, this method works better in a homogeneous vegetated area - with higher variance between dry and wet pixels.

3.2. Daily Evapotranspiration

Remote sensing data provides instantaneous radiation measurements. However, for agriculture and environment applications the evapotranspiration values are more useful. So, daily ET is defined as the temporal integration of ET instantaneous values in a day. The daily ET can be obtained using the Cdi, which consists of the ratio between the daily net radiation flux (Rnd) and instantaneous radiation flux (Rni), both from the tower flux. This concept was also adopted by Gómez et al. (2005) and Sobrino et al. (2007). Thus, Cdi was calculated through the integration of the radiation for the whole day

$$Cdi = Rnd/Rni \qquad (5)$$

Afterwards, the daily ET (mm/day) can be written as follows

$$ET = (\Lambda\, Rn\, Cdi)\, 0.035265 \qquad (6)$$

Where the soil heat flux (G) was not included according to (SAUER; HORTON, 2015) assuming that much of the energy that enters the soil during the day returns to the atmosphere at night through terrestrial longwave radiation.

3.2. Variables input of S-SEBI

To estimate the balance energy by remote sensing models some pre-processing of image data are needed and some surface properties had to be calculated. Table 2 shows the algorithms used to calculate Normalized Difference Vegetation Index (NDVI), Albedo (α), Soil Heat Flux (G), Land Surface Temperature (Ts) and Land Surface Emissivity (ε).

Table 1. Equations applied to Landsat-8 data.

Variable	Equation	Description
NDVI	$(\rho NIR - \rho RED)/(\rho NIR + \rho RED)$	ρNIR is the Near Infrared reflectance of Landsat 8 (0.86μm) and ρRED refers to the Red band reflectance of Landsat 8 OLI and (0.65 μm) (ROUSE et al., 1973a);
α	$0.13\rho 1 + 0.115\rho 2 + 0.143\rho 3 + 0.180\rho 4 + 0.281\rho 5 + 0.108\rho 6 + 0.042\rho 7$	ϱ is the reflectance at each Landsat 8 OLI channel; (KE et al., 2016).
Ts	Ti+1.378(Ti-Tj)+0.183(Ti-Tj)2-0.268+(54.3-2.238w)(1-ε)+(-129.2+16.4w);	Ti and Tj are the at-sensor brightness temperatures at the bands i (10) and j (11) in Kelvins; ε is the mean emissivity, ε = 0.5 (εi + εj), Δε is the emissivity difference, Δε = (εi − εj); w is the total atmospheric water vapor content (in g/cm−2); (JIMENEZ-MUNOZ et al., 2014b; SOBRINO et al., 1996)
ε	$a + b\rho RED;\ (FVC = 0)$ $\varepsilon_s(1 - FVC) + \varepsilon_v FVC\ ; (0 < FVC < 1)$ $\varepsilon = 0.99; FVC = 1)$	FVC is the Fractional Vegetation Cover and is given by *FVC = NDVI – NDVIs/NDVIv - NDVIs* ; ε_{s} and ε_{v} are the soil and vegetation emissivity values respectively.(SOBRINO et al., 2008)
Soil Heat Flux (G)	((Ts/ α) * (0.0038* α) + (0.0074* α^2) * (1-0.98*NDVI^4)) * Rn;	(BASTIAANSSEN, 2000)

3.3. Satellite data

Landsat 8 has two sensors which operated simultaneously and independently: (1) the Operational Land Imager (OLI) and (2) the Thermal Infrared Sensor (TIRS). The OLI images from visible to short-wave infrared and TIRS has thermal images of two-channels (JIMENEZ-MUNOZ et al., 2014b). We acquired 22 cloud free Landsat 8 OLI and TIRS images, from 2015 and 2019, for the temporal and comparative analysis. All images were cut to a mask covering the study area, where the flux tower is the *in situ* data in native vegetation of the Pampa biome with controlled cattle management. Table 2 shows all days of the years and the season of the images used in this study.

Table 2. Information of the Landsat 8 OLI/TIRS scenes used in this study, Path/Row (222/81).

Acquisition date	DOY	Season	Cloud cover (%)
20 March, 2015	78	Summer	7.56
07 May, 2015	126	Autumn	0.02
27 August, 2015	238	Winter	20.58
12 September, 2015	254	Winter	0.03
28 September, 2015	270	Spring	4.22
15 November, 2015	318	Spring	6.08
18 January, 2016	17	Summer	0.00
28 July, 2016	209	Winter	28.58
13 August, 2016	225	Winter	19.8
03 October, 2017	275	Spring	0.76
20 November, 2017	323	Spring	0.49
22 December, 2017	355	Summer	6.38
29 April, 2018	118	Autumn	27.9
16 June, 2018	166	Autumn	7.12
18 July, 2018	198	Winter	12.53
25 December, 2018	358	Summer	7.85
26 January, 2019	25	Summer	4.14
18 May, 2019	137	Autumn	0.89
19 June, 2019	169	Autumn	1.13
21 July, 2019	201	Winter	0.01
06 August, 2019	217	Winter	0.01
09 October, 2019	281	Spring	0.49

The Landsat data cover 185 km × 180 km Level 1 terrain-corrected products, in which the spatial resolution of TIRS bands are 100 m and resampled by cubic convolution to 30 m to be co-registered with the 30 m OLI spectral bands (KILIC et al., 2016). Also, Landsat 8 OLI surface reflectance Level-2 products are generated at the Earth Resources Observation and Science (EROS). The EROS Science Processing Architecture (ESPA) on-demand interface corrects satellite images for atmospheric effects to create Level-2 data products. These Level 2 products were used in this research to obtain the normalized difference vegetation index (NDVI) and surface albedo.

3.4. Meteorological data

Two meteorological databases were used to produce Rn and *Ts* of this study: (1) The Brazilian Meteorological Institute (*Instituto Nacional de Meteorologia* - INMET) has provided: air temperature (Ta), atmospheric pressure (P) relative humid (RH); (2) The National Centers for Environmental Prediction Climate (NCEP) Forecast System Version 2 (CFSv2)[60] has provided reanalysis data, including the shortwave downward radiation (R_S) and longwave downward radiation (R_L).

We extracted the reanalysis data from the CFSv2 hourly product. The parameters were obtained with 0.205º horizontal resolution for an average between 13-14h UTC on selected dates. From INMET the data were acquired at 12 UTC on the same selected dates in order to coincide with the satellite overpass.

3.5. Land Surface Temperature of S-SEBI model

To analyze the influence that possible uncertainties in the estimation of *Ts* may have on the estimates of LET, a noise was applied to the *Ts* images, with a Gaussian variation of -2 K and + 2 K. Many authors believe that *Ts* retrieval precision varies around 1 - 2 K depending on the heterogeneity atmospheric conditions and the resolution of the sensor used in the process (JIMENEZ-MUNOZ et al., 2014b; SKOKOVIC; SOBRINO; JIMENEZ-MUNOZ, 2017; SOBRINO; SKOKOVIĆ, 2016).

It is important to emphasize that, with this noise, the average *Ts* of the images does not vary, but the minimum and maximum temperatures do, as we can see in Table 3.

Table 3. Land Surface Temperature stats of the images, without noise and with noise (*)

DOY	Average	Min	Min*	Max	Max*
78	306.68	302.88	300.28	315.66	317.63
126	292.18	289.41	287.27	295.89	298.33
238	295.16	293.35	290.84	297.85	300.04
254	292.82	288.85	287.34	295.97	298.27
270	300.09	295.25	293.67	305.98	306.79
318	303.27	298.64	297.31	308.68	310.52
17	310.67	298.67	297.23	323.209	325.068
209	287.41	284.77	282.97	290.48	293.037
225	294.04	290.46	288.57	298.381	300.38
275	298.41	294.98	293.03	301.437	303.466
323	310.17	302.73	300.62	320.88	321.847
355	311.41	303.47	302.15	320.889	321.532
118	301.04	296.82	295.25	305.507	307.662
166	284.88	281.68	279.92	288.066	290.438
198	296.68	294.71	292.3	298.152	301.019
358	305.54	301.55	299.52	311.657	313.422
137	295.52	292.28	290.41	297.604	299.857
169	291.57	288.96	286.92	293.546	296.418
201	297.32	295.28	292.42	300.20	302.042
217	294.43	292.37	289.95	296.84	299.462
281	303.99	299.38	298.12	309.80	311.864

4. Results and Discussin

4.1. S-SEBI validantion

The energy balance components estimated with SSEBI and *in situ* measurements are showed in Fig. 2 considering all scenes available.

The net radiation (Rn) measurements are the most accurate measurements of all the components in the surface energy budget, and they represent the largest part of the global radiation (TWINE et al., 2000). We have found a strong coefficient of correlation (0.81), but the RMSE and Bias produced the worst estimates, with 138.7 (W/m^2) and 132.12 (W/m^2), respectively. Those results may be influencing the results of LE, because when Rn reaches more than 350 W/m^2 the latent heat flux tend to deviate. Besides of that, some authors have discussed that in days with no clouds and Rn less than 200 W/m^2 (mostly during the winter season) the model represents better all the fluxes (RUBERT et al., 2018). Schirmbeck et al. (2018) obtained a RMSE of 50 (W/m^2), and Silva Oliveira et al. (2018) testing METRIC model in Brazilian Cerrado biome obtained a RMSE of 59.8 (W/m^2) with an overestimation of 9%.

The soil heat flux is responsible for lower energy consumption, Schirmbeck et al. (2018) found out less than 8% for all crops studied in pampa biome. The model used in our study overestimate all the flux tower measurement, and the RMSE and Bias produced the worst estimates, with 43.45 (W/m^2) and 40.4 (W/m^2), respectively. Gomis-Cebolla et al. (2019) have validated four ET models, including SEBS in tropical forests of the Amazonian region, and they have concluded that their results serve to emphasize the need to improve the accuracy of reanalysis estimates in order to improve the accuracy in ET estimates. So, the reanalysis data may be inserting minimums errors in our model as well.

According to Twine et al., (2000) and Silva Oliveira et al., (2018) LE tends to be underestimated by EC method due to sources of errors such as non-homogeneous surface coverage, soil characteristics, instrumental errors, topography, divergence or flux dispersion, among others. Besides of that we have obtained mean errors (RMSE) around 92 (W/m^2) and Bias 7.09 (W/m^2), which agree with previous studies in Pampa biome of Schirmbeck et al. (2018) that have obtained an overestimation of 94 (W/m^2) testing OSEB and SEBAL models for 84 MODIS images between 2009-2011. Those uncertainties associated with derived LE could be caused especially because of the evaporative fraction component which is limited by the selection of dry and wet pixels (ZAHIRA et al., 2009b). A physically based two-source energy balance (TSEB) model was tested in an irrigated agricultural area in China applied to high resolution WiDAS data and ASTER data and compared with EC measurements, to LE the authors found Bias and RMSE as 113 W/m^2 and 140 W/m^2, respectively (CHENG; KUSTAS, 2019).

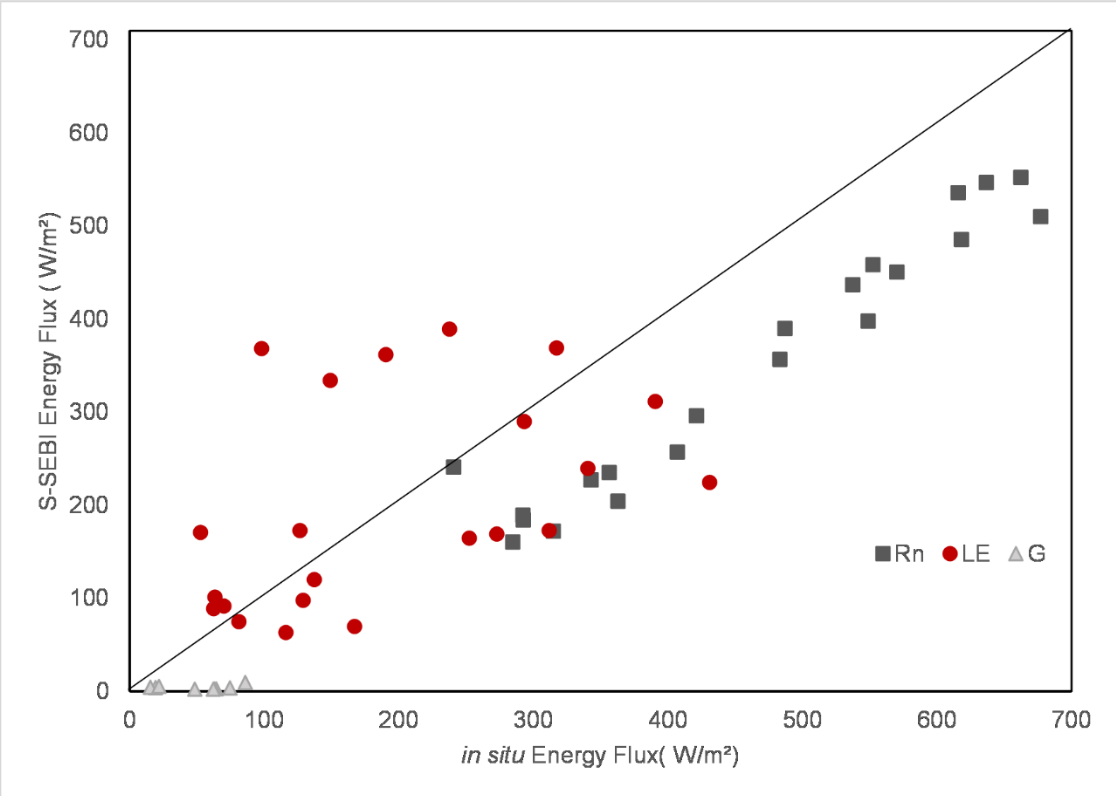

Figure 2. Energy balance components estimated with S-SEBI against *in-situ* data. The black line represents the 1:1 relation.

4.2. Heterogeneity of the study area

The performance of applying remote sensing data to ET calculation is related to the concept of spatial variability of the landscape, especially in selecting the spatial resolution of the sensor. Low spatial resolution sensors, in more heterogeneous landscapes, generate less reliable ET results since intra-pixel spatial heterogeneity is lost due to radiometric signal integration (CHEN et al., 2014; GARRIGUES et al., 2006; GIBSON; MÜNCH; ENGELBRECHT, 2011; KUSTAS; NORMAN, 1996; MCCABE; WOOD, 2006). Besides the importance of the choice of the satellite sensor, Gibson et al (2011) (GIBSON; MÜNCH; ENGELBRECHT, 2011) studied the variability of ET influenced by heterogeneity of landcover, analyzing topography, fractional vegetation cover, NDVI and albedo, the authors found uncertainties which are translated to the estimation of actual evapotranspiration.

In order to understand the heterogeneity of the study area in our site, Figure 3 shows an example of NDVI distribution for each season. It is possible to see the differences between summer/spring and winter/autumn, the most homogeneity in the area occurred in winter season. This behavior can be responsible for the high seasonal variability of evapotranspiration, with higher values during the spring-summer period when compared to autumn-winter observed in Pampa biome by (RUBERT et al., 2018).

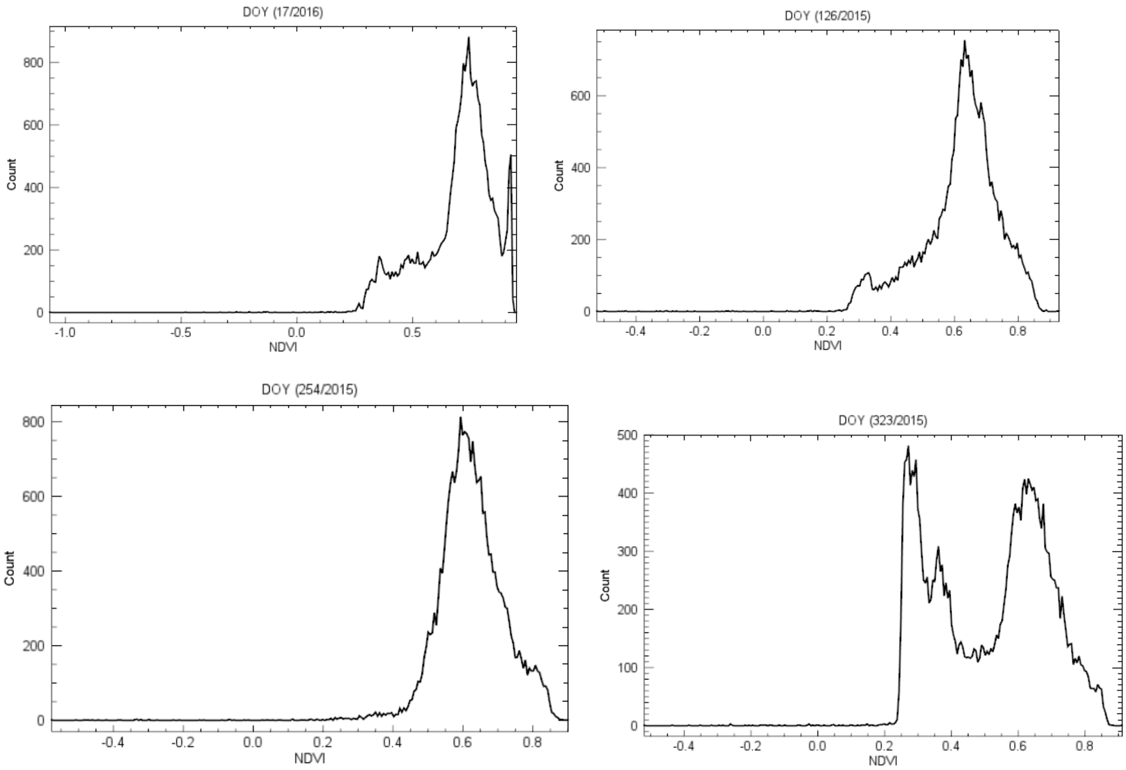

Figure 3. NDVI distribution for the study area for a summer season scene (DOY 17); autumn season scene (DOY 126); winter season scene (DOY 254) and a spring season scene (DOY 323).

To understand the ET variability by the landcover heterogeneity, a pixel from each land use was selected in the study area and the results are shown in Figure 4. We have compared the differences between Native Grassland, Exposed Soil and Forest with the daily ET average for each day. The daily ET seasonality in summer is twice as high as in winter, which was already expected because of the high temperature variability at different times of year characteristic of the study region.

Gibson et al. (2011) (GIBSON; MÜNCH; ENGELBRECHT, 2011) have discussed that in addition to the direct effect of landscape heterogeneity and spatial resolution of input data on remote sensing variables, landscape heterogeneity can also indirectly affect spatial modelling efforts, including the energy fluxes. The ET variability between Forest and Grassland were lower than expected, demonstrating the importance of native grasslands in the Pampa biome regarding to the processes of the hydrological cycle, since it covers 63% of Rio Grande do Sul, with the greatest differences occurring randomly during the warmer and colder seasons.

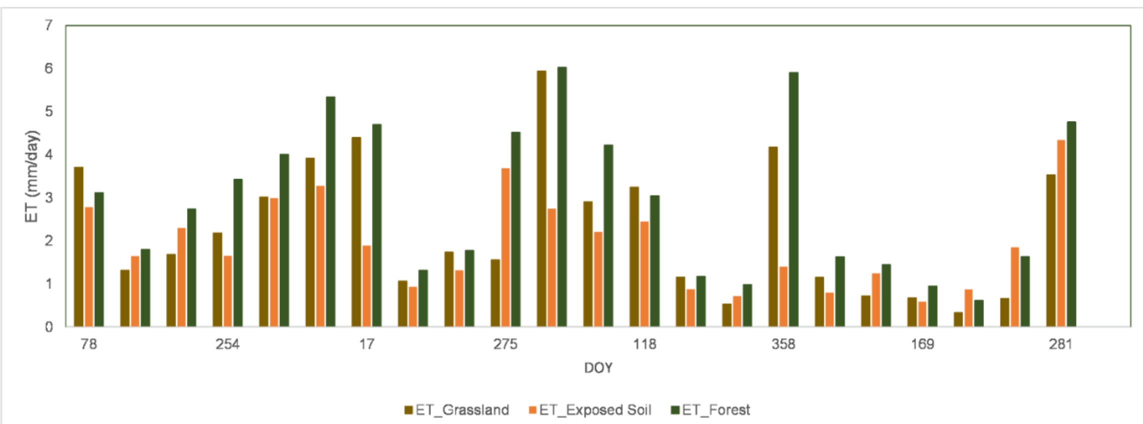

Figure 4. Daily evapotranspiration (mm/day) for different land surface uses in Pampa biome.

It is important to emphasize that the native grassland area of this study has an adequate livestock management controlled by the Federal University of Santa Maria. Studies conducted in field areas with high exploitation management have obtained greater differences in water balance results when compared with forested areas (CRUZ et al., 2016).

4.3. The Ts influence on S-SEBI model

The errors or uncertainty in analysis of remote sensing and GIS products can be associated with several sources. According to Gibson et al. (2011), mostly of these errors or uncertainties are: (1) associated with the specific remote sensing data obtained; (2) introduced with the processing and analysis of image and field data; (3) associated with positional aspects (including image resolution); and (4) associated with the specific model. In this regard, the uncertainties in the derivation of ET for this study were identified in the relationship between *Ts* and albedo for the S-SEBI model performance. In addition, there is an influence of Rn on LE results, discussed in section 4.1, and consequently on evapotranspiration

Table 4 shows the comparison of energy partitioning between S-SEBI results with and without noise in the *Ts*. The biggest difference occurs in LE estimations with 19.36 W/m², this result is lower than other models reported in the literature which are more dependents of meteorological data. Su (SU, 2002) found out a sensitivity of SEBS model around 40 W/m² when the various terms are assumed independent of each other.

The differences in the other fluxes when the noise in *Ts* is applied are not significant, with extremely low errors and variances as RMSE (1.98 and 0.27) and Bias (1.97 and 0.24) to Rn and G, respectively. Those results

Table 4 Comparison between energy fluxes with and without noise: r^2 is the coefficient of determination (–), MSD is the mean standard deviation, RMSE refers to the Root Mean Square Error (W/m²); and Bias is the tendency of the model (W/m²).

Variable	Min-Max	Min- Max (*)	r^2	MSD	RMSE	Bias
LE (W/m²)	52.88 - 431.22	74.51 - 408.95	0.98	±21.13	19.36	11.48
Rn (W/m²)	142.44 - 536.05	140.33 - 533.95	1	±0.14	1.98	1.97
G (W/m²)	7.41 - 86.07	7.55 - 86.48	1	±19.28	0.27	-0.24

4.3. The Ts influence on Daily Evapotranspiration

The natural grassland daily ET mean error between both analyses (with and without noise in *Ts*) is 0.18 mm/day for the whole period of study, those variance to each day at tower flux point are shown in Figure 5. Gibson et al (GIBSON; MÜNCH; ENGELBRECHT, 2011) have analyzed the SEBS model, and conclude that daily ET differences by up to 0.7 mm/day when modifying *Ts* and air temperature. We concluded that the gaussian variation of *Ts* (between -2 K and 2 K) leads to a small variation of ET, it does not exceed 0.5 mm/day in grasslands. Abid et al. (ABID; MANNAERTS; BARGAOUI, 2019) have agreed with this result finding similar value (0.5 mm/day) when comparing de uncertainties of SEBS model in Northern Tunisia.

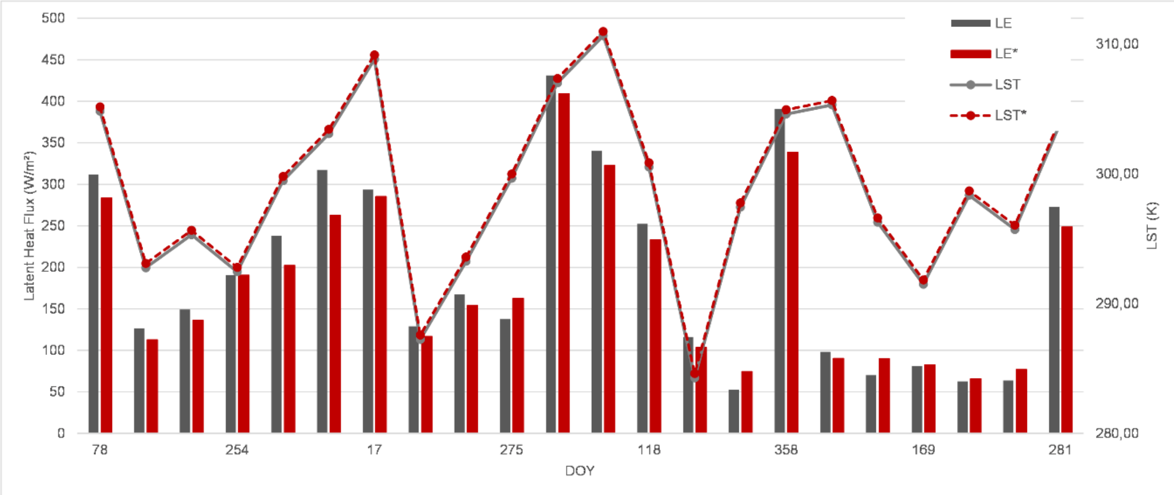

Figure 5. Grassland (in situ) daily evapotranspiration (mm/day) and Land Surface Temperature (K) with and without noise (*).

Figure 6 shows the resulting changes in Mean, Maximum and Minimum ET against *Ts* considering all scene. The gaussian noise applied is a random noise, so it is probable that the maximum *Ts* pixel value of an image is not the same as in the noisy image, so the maximum and minimum are modified in more than a 2K noise applied. The differences in maximum and minimum *Ts* caused by the noise applied affect ET values, but the mean ET are less affected by these differences on mean *Ts* of the scenes. The biggest differences on mean ET occurred on summer in 2015 with 0.44 mm/day, but the minimum and maximus ET have generated the biggest changes, those values occurred in forest or in exposed soil areas. Those changes in maximum and minimum ET were expected because S-SEBI model has difficulty in reaching extremely high values. (GOMIS-CEBOLLA et al., 2019; SOBRINO et al., 2007)

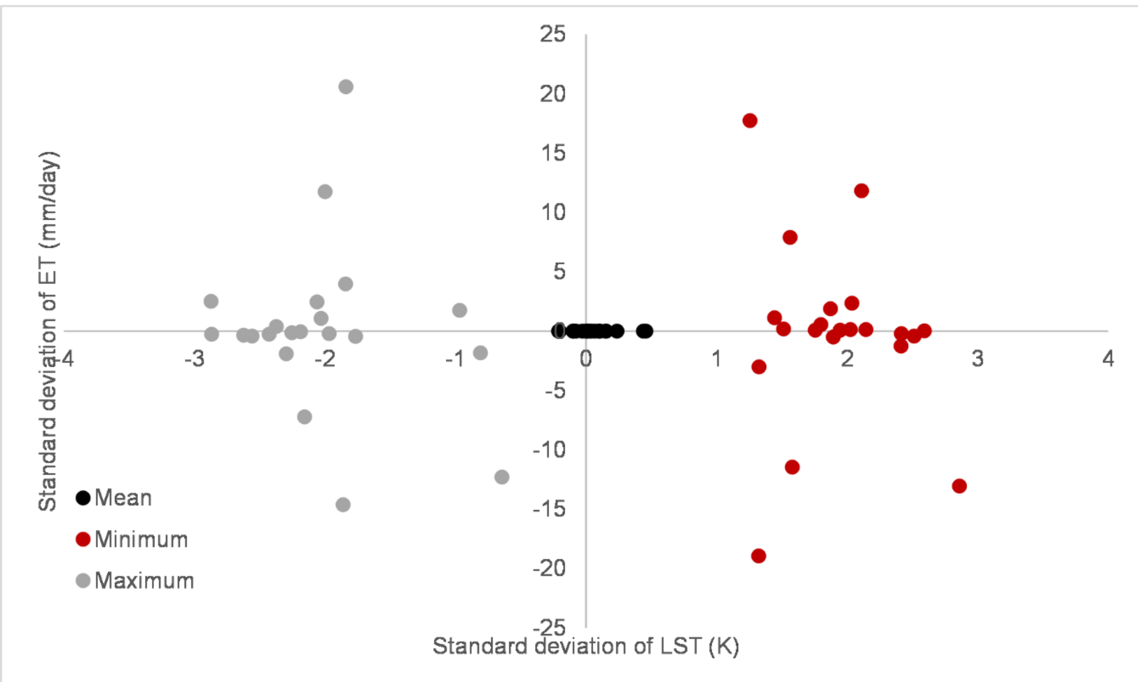

Figure 6. Changes of daily evapotranspiration (ET mm/day) against the changes of land surface temperature (Ts) input by gaussian variation of 2K.

When there are uncertainties in estimates of *Ts*, the errors in the estimates of the daily evapotranspiration multiply for the entire study area, as shown in Figure 7, the maximum and minimum values of *Ts* are responsible for the variation in the ET estimated, even with the same mean *Ts* for the images. In the same figure we can see that *Ts* have biggest range during summer seasons and on winter seasons de maximum and minimum *Ts* are closer, but that differences do not influence the changes in daily ET. These results demonstrate the importance of *Ts'* accuracy in the selection of the driest and wettest pixels, this being the greatest challenge in applying S-SEBI to estimate ET season-independent even though the seasonal variability of ET.

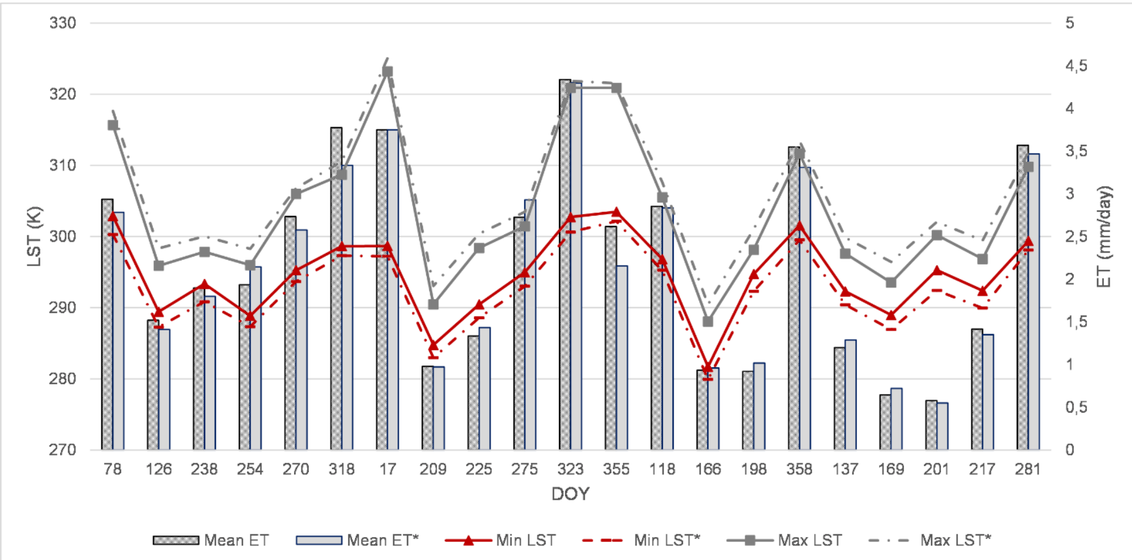

Figure 7. Minimum and Maximum Land Surface Temperature (Kelvin) and Mean daily evapotranspiration (mm/day) of the entire study area.

5. Conclusions

In order to estimate daily evapotranspiration (ET) using S-SEBI model and remote sensing technologies from Landsat 8, a sensitivity study of output ET was performed with a Gaussian noise variability in LST images. The S-SEBI model estimates evapotranspiration from the relationship between LST and albedo, so this study allowed to understand the influence that the uncertainties in LST estimation may have on the ET.

The accuracy of the Rn validation has aggregated some uncertainties in the model, more than 100 W/m² in errors, these may be caused by the use of reanalysis data and we recommend the study of the sensibility of this data on energy balance models for future works.

The lower ET variability between Forest and Native Grassland can demonstrated the importance of native grasslands in the Pampa biome regarding to the processes of the hydrological cycle, since it covers 63% of Rio Grande do Sul, it also indicate that in Pampa biome the native grassland is not only important to the biodiversity conservation but also to the environment process. Future studies may provide more conclusions about the influences of different native grasslands managements.

The gaussian variation of LST (between -2 K and 2 K) do not vary the average of the variable and leads to a small variation of ET, it does not exceed 0.5 mm/day in grasslands, with mean error between both analyses (with and without noise in LST) around 0.18 mm/day for the whole period of study.

We concluded that the S-SEBI is less dependent on LST estimation than other models reported in the literature, such as the SEBS studied by many authors (Abid et al. 2019; Gibson et al. 2011). However, the importance of LST's accuracy in the selection of driest and wettest pixels was proved.

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Rocha and Pâmela S. Käfer; Funding acquisition, Rafael Cabral Cruz, Debora Roberti and Silvia Beatriz Alves Rolim; Investigation, Nájila S. da Rocha, Pâmela S. Käfer, Drazen Skokovic and Lucas Ribeiro Diaz ; Methodology, Nájila S. da Rocha, Pâmela S. Käfer, Drazen Skokovic, Gustavo Veeck , Lucas Ribeiro Diaz , Eduardo André Kaiser , Cibelle Machado Carvalho and Debora Roberti; Project administration, Silvia Beatriz Alves Rolim; Resources, Nájila S. da Rocha, Pâmela S. Käfer, Lucas Ribeiro Diaz , Eduardo André Kaiser , Cibelle Machado Carvalho, Debora Roberti and Silvia Beatriz Alves Rolim; Software, Nájila S. da Rocha and Pâmela S. Käfer; Validation, Nájila S. da Rocha, Pâmela S. Käfer, Drazen Skokovic, Gustavo Veeck , Eduardo André Kaiser and Debora Roberti; Writing – original draft, Nájila S. da Rocha, Pâmela S. Käfer, Lucas Ribeiro Diaz and Cibelle Machado Carvalho; Writing – review & editing, Nájila S. da Rocha, Drazen Skokovic, Rafael Cabral Cruz, Debora Roberti and Silvia Beatriz Alves Rolim.

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CAPÍTULO 4

PAMPA BIOME ENVIRONMENTAL PARTICULARITIES REGARDING TO ENERGY BALANCE

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KEY WORDS: Native grassland, Evapotranspiration, LST, NDVI, Thermal Infra-red, Remote Sensing

ABSTRACT:

Ecosystem evapotranspiration (ET) has been quantified around the world by different methodologies to understand the energy balance, especially to control the evolution of climate change. It is known that the vegetation of the pampa biome is natural grasslands, it has a large variety of species (flora and fauna), however is it different in the environmental aspects related to the energy balance when compared to the grassland cultivated? In this study the objective was to analyze the environmental differences of the Pampa Biome related to the energy balance in comparison with the pastures cultivated in Barrax, Spain. In the first one the minimum daily ET is 0.99 mm/day, while in the second is 1.57 mm/day. However, the highest differences between the sites occur during the summer period, in the maximum daily ET, the maximum is 16.25 mm/day in Pampa and in Barrax is 7.31 mm/day. The results of this study have indicated that the characteristics of the Pampa biome, both in terms of soil and climatic issues and land use, generate differences in the energy balance when compared to similar vegetation in other regions of the world.

1. INTRODUCTION

Pampa biome is the only large natural area restricted to a single Brazilian state and it is considered a peculiar ecosystem. This biome advances to Uruguay and Argentina, thus being unique to southern South America (CRUZ; GUADAGNIN, 2010; SANTOS; TREVISAN, 2009).

In Brazil, the Pampa occupies more than 178 thousand Km², which corresponds to more than 60% of the Rio Grande do Sul State territory and around 2% of the whole country. The region is frequently known as an ecologically poor region. Nevertheless, this is information disseminated and propagated by the “common sense”. In fact, Pampa is rich in vegetation and fauna, with varied ecosystems, such as capoeiras, “pampa” forests and riparian forests.

According to the Map of Brazilian Biomes, it is one of the richest in geoecological configuration, mainly because it includes several microecosystems. In addition to the natural grasslands, it has a large variety of species (flora and fauna), which compose a peculiar landscape, said as “a sea of living green” (Overbeck et al., 2015; Santos and Trevisan, 2009).

Cruz and Guadagnin (2010) mention that the most important Pampa microecosystems are the watersheds, fundamental for the life reproduction and water cycles regulation and the riparian or gallery forests, which serve as refuge for a diverse fauna. In this context, Overbeck et al. (2015) point out that once Pampa ecosystems have their own characteristics, the simple quantification of being larger or smaller than a tropical forest biodiversity, becomes meaningless. For biodiversity purposes, what matters is the unique and irreplaceable biodiversity of each biome. The Pampa biome suffers from economic and social demands that modify its ecosystem, in addition the climate changes have modified the behavior of environmental variables and may also be causing a huge impact on this biome.

Ecosystems evapotranspiration (ET) has been quantified around the world by different methodologies to understand the energy balance and hydrological cycle and its variation, mostly to control of the evolution of climate change. In this way, the Pampa biome has been characterized by the quantification of ET and its relationship with environmental variables, especially when it comes to the validation of ET by remote sensing (FONTANA et al., 2018a; MONTEIRO et al., 2014; RUBERT et al., 2018).

It is already known that the vegetation of the pampa biome is unique in the world, but is it distinct in the environmental aspects concerning the energy balance when compared to grassland cultivated vegetation around the world? To understand that in this preliminary study the objective was to analyze the Pampa Biome environmental differences related to the energy balance in comparison to the grasslands cultivated in Barrax, Spain.

1.1 Study area

Two different test areas have been used in this study. One of them in Brazilian Pampa Biome and another one in Barrax site located in the west of Albacete province, Spain (Figure 1). They were select because, firstly, they have the same kind of vegetation and, secondly, they have a continuous meteorological monitoring. Beside of that it was in Barrax that the ET model test in this work was performed and validated.

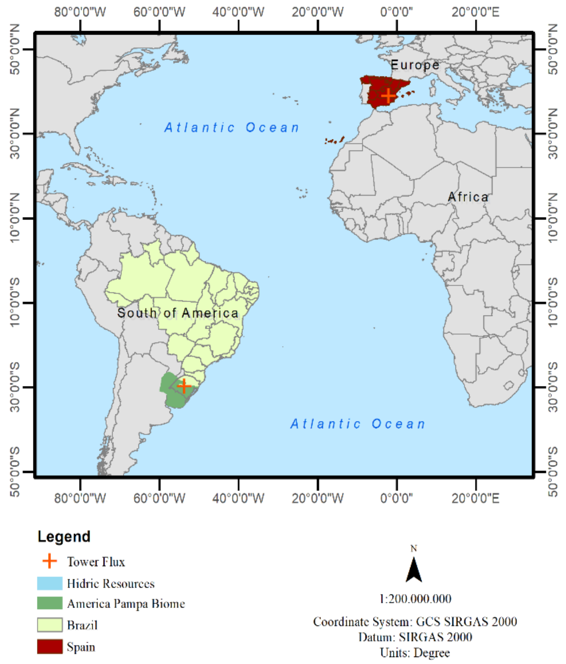

Figure 1. Experimental site locations in Pampa Biome (Brazil) and Barrax (Spain) site

The analyses in the Pampa Biome were performed in the experimental area of the Federal University of Santa Maria (UFSM) with native grassland (Figure 2a). In this area there is a Tower Flux under the responsibility of the Micrometeorology Laboratory of UFSM, which provided some important variables used in this work. This study area is part of the International Long Term Ecological Research (ILTER) network and is used for experiments of the UFSM in several areas of knowledge, mainly focused on the morphology of native species for livestock production (CONFORTIN et al., 2017; OLIVEIRA et al., 2015).

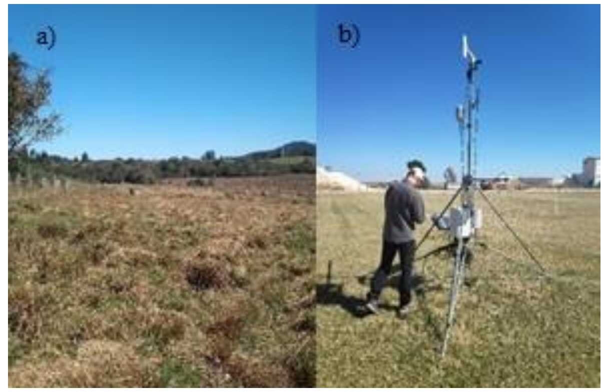

Figure 2. a) Santa Maria experimental site with native grassland; b) Barrax experimental site with cultivated grassland.

In Spain, this study was performed in Barrax site which is an experimental area selected in many field campaigns for calibration/validation activities because of its flat terrain and the presence of large, uniform land-use units (approximately 100 ha), suitable for validating moderate-resolution satellite image products. Figure 2b shows a fixed station over grassland cultivated field with continuous LST measurements taken by a radiometer that covers a footprint of 3 m² (SOBRINO; SKOKOVIĆ, 2016).

In addition to differences in land use and land cover, there are some climatic differences between those two study areas: 1) The annual average temperature of the Pampa Biome varies between 16 ºC and 18 °C and the precipitation between 1,500 mm and 1,600 mm (NESKE; ANDRADE; BORBA, 2012). The climate of the study region is characterized by great homogeneity and is controlled by various factors such as latitude, geomorphology, South Atlantic subtropical anticyclone and ocean currents (HOFFMANN et al., 1997). Furthermore, this region is constantly subject to sudden changes in weather caused by the passage of the polar front (NIMER, 1990). Due to its position between the mid-latitudes of the subtropics, the climate is of temperate type, which gives an important thermal oscillation throughout the year with a cold winter and a hot summer (NIMER, 1990). 2) In Barrax area there is a Mediterranean climate with heaviest rainfalls in Spring and Autumn and lowest in Summer. The rainfall statistics show that the mean annual rainfall is little more than 400 mm in most of the area, making La Mancha one of the driest regions in Europe (GÓMEZ et al., 2005; SOBRINO et al., 2005).

2. METHODOLOGY

2.1 Data Acquisition

Ten images from Landsat 8 were acquired, five for each site, to the year 2018, and treated with geometric rectification and clipped using a study area border. Radiometric calibration and atmospheric correction procedures were conducted to ensure that the change detection analyzes truly detected changes at the Earth's surface rather than at the sensor level, solar illumination differences, and potential differences in atmospheric conditions.

From the tower flux we have been acquired the global incident solar radiation (*Rg)* and the incident atmospheric radiation over the spectral domain (*Ra)*, obtained with the satellite overpass (Table 1).

Acquisition Date	**Season**	**DOY**	**Site**
16 Dec 2018	Summer	349	Pampa
29 Nov 2018	Winter	332	Barrax
25 Aug 2018	Summer	236	Barrax
26 Aug 2018	Winter	237	Pampa
15 Jun 2018	Summer	165	Barrax
06 Jul 2018	Winter	186	Pampa
19 Apr 2018	Spring	108	Barrax
04 Apr 2018	Autumn	93	Pampa
23 Feb 2018	Winter	53	Barrax
15 Feb 2018	Summer	45	Pampa

Table 2. Satellite Landsat 8 OLI/TIRS data by each day of year (DOY) to Pampa Biome

2.2 Data Processing

shows the algorithms used to calculate Normalized Difference Vegetation Index (NDVI), Albedo (α), Soil Heat Flux (G), Land Surface Temperature (LST) and Land Surface Emissivity (LSE). Those indices have been used to estimate the balance energy by remote sensing.

Where:

Table 3

Variable	**Equation**
NDVI	$(\rho NIR - \rho RED)/(\rho NIR+\rho RED)$; [(1)] (ROUSE et al., 1973b)
Albedo (α)	$0.365b2 + 0.130b4 + 0.373b5 + 0.085b6 + 0.072b7 - 0.0018$; (LIANG, 2000; LIANG; STRAHLER; WALTHALL, 1998).
LSE and LST	$Ti - 0.268(Ti - Tj) + 1.378(Ti - Tj)^2 + 16.4 + (0.183 + 54.3w)(1 - \varepsilon) + (-2.238 - 129.2w)\,\Delta\varepsilon$; [(2)] (JIMENEZ-MUNOZ et al., 2014b; SOBRINO et al., 1996)
Soil Heat Flux (*G*)	$((Ts/\alpha) * (0.0038*\alpha) + (0.0074*\alpha^2)*(1-0.98*NDVI^4)) *Rn$; (BASTIAANSSEN, 2000)

Table 3. Equations used to the pre-processing image data

[(1)] ρNIR and ρRED are calculated using Landsat 8 channel 5 (0.86) and channel 4 (0.65);

[(2)] *Ti* and *Tj* are the at-sensor brightness temperatures at the SW bands *i* and *j* (in kelvins), ε is the mean emissivity, $\varepsilon = 0.5(\varepsilon i + \varepsilon j)$, $\Delta\varepsilon$ is the emissivity difference, $\Delta\varepsilon = (\varepsilon i - \varepsilon j)$, *w* is the total atmospheric water vapor content (in g/cm^{-2}), and *c*0 to *c*6 are the Split Window (SW) coefficients to be determined from simulated data.

2.3 METHOD

We used S-SEBI model to obtain instantaneous latent heat flux (LET) for all acquired images (ROERINK; SU;

MENENTI, 2000). The surface energy balance is obtained by determining the magnitude of the radiative and non-radiative fluxes. It is written as follow, when considering instantaneous condition.

$$Rn = LET + G, \qquad (1)$$

Where:

Rn ($W\ m^{-2}$) is the available net radiation flux,

G ($W\ m^{-2}$) is the soil heat flux (see Table 2),

LET ($W\ m^{-2}$) is the latent heat flux (both atmospheric convective fluxes: sensible heat flux and latent energy exchanges).

Once the surface energy balance equation is discriminated, the Rn is calculated as the rest term of all incoming and outgoing shortwave (sw) and longwave (lw) radiation, as describing below:

$$Rn = (1-\alpha)\, Rg + \varepsilon\, Ra - \varepsilon\, \sigma\, LST^4, \qquad (2)$$

Where:

Rg ($W\ m^{-2}$) is the global incident solar radiation;

Ra ($W\ m^{-2}$) is the incident atmospheric radiation over the thermal spectral domain;

α is the surface albedo;

ε is the surface emissivity;

LST (Kelvin) is the land surface temperature;

σ is the Steffan–Boltzmann constant (5.67 × 10− 8 $W\ m^{-2}\ K^{-4}$).

The latent heat flux (LET) depends on the evaporative fraction (Λ) and is given as follow.

$$LET = \Lambda\ (Rn - G) \qquad (3)$$

The evaporative fraction concept (Λ) was proposed by (ROERINK; SU; MENENTI, 2000), adapted and tested by (SOBRINO et al., 2005, 2007), and it is described by the equation below.

$$\Lambda = \frac{T_H - LST}{T_H - T_{LE}} \qquad (4)$$

Where:

T_H (K) is the temperature corresponding to dry conditions;

T_{LE} (K) is the temperature corresponding to wet condition.

The S-SEBI model should be only applied when the atmospheric conditions are constants over the image and the study site includes simultaneously wet and dry areas (ROERINK; SU; MENENTI, 2000; SOBRINO et al., 2005, 2007). Besides of that, this method works better in a homogeneous vegetated area - with higher variance between dry and wet pixels.

2.4 Daily Evapotranspiration

Daily evapotranspiration is defined as the temporal integration of ET instantaneous values in a day. It was performed using the relationship between the daily net radiation flux (R_{nd}) and instantaneous radiation flux (R_{ni}). This concept was tested by the authors and it is called C_{di} (GÓMEZ et al., 2005; SOBRINO et al., 2007). In this context the authors have created an expression to calculate the C_{di} from each image DOY and in this study, to make the process more operational and reapplied, we have used the same expression as described below.

$$C_{di} = -7e^{-6} * (\mathrm{DOY}^2) + (0.0026 * \mathrm{DOY} + 0.0756) \qquad (5)$$

Where:

C_{di} is the relationship between the daily net radiation flux (R_{nd}) and instantaneous radiation flux (R_{ni});

DOY is Day of the Year (see Table 1).

3. RESULTS AND DISCUSSION

In Figure 3 we can observe the temporal variation of daily evapotranspiration throughout the year 2018 for both areas of study. In the Pampa Biome the minimum daily ET is 0.99 mm/day, while in Barrax is 1.57 mm/day. However, the highest differences between the sites occur in the maximum daily ET, in Pampa Biome the maximum is 16.25 mm/day in December (summer season) and in Barrax is 7.31 mm/day in August (summer season). Also, in Pampa Biome the difference between the minimum and maximum ET is greater than in Barrax. According to Fontana et al., (2018) this variability influences all types of vegetation growth and, in the Pampa biome, causes variations in the forage availability to the animals throughout the seasons and also years.

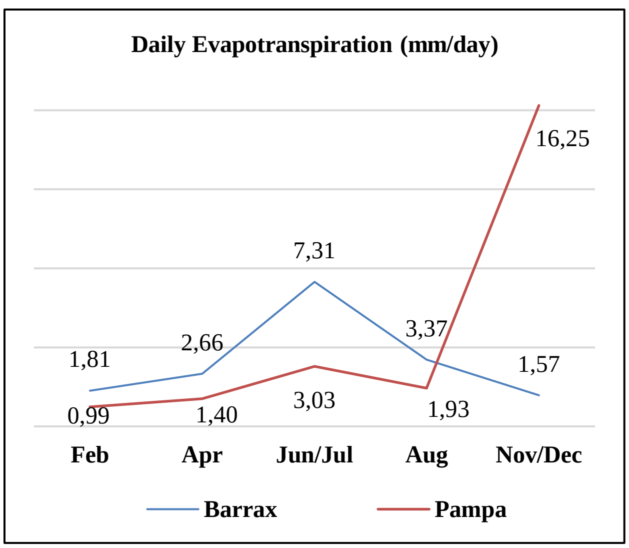

Figure 3. Daily Evapotranspiration for both Pampa Biome and Barrax site

Rubert et al., (2018) have also analyzed the Pampa biome ET by eddy co-variance and have concluded that this biome presented strong seasonality of evapotranspiration, with the highest evapotranspiration rates in the summer season, where the vegetation was in active growth and, therefore, had higher biomass production. The results of this study agree with the authors and indicate that the characteristics of the Pampa biome, both in terms of soil and climatic issues and land use, generate differences in the energy balance when compared to similar vegetation in other regions of the world.

The environmental differences between Pampa and Barrax can be observed in Table 4, the table shows the variables values in the tower flux point for both areas. It can be observed that in a cultivated grassland area (Barrax) there is a higher seasonal difference in LST (24 K) compared to the native grassland (Pampa) LST (13.92 K). This can be explained by the temporal distribution of rainfall throughout the year in Rio Grande do Sul State. According to IPCC (2013) these distribution will change in South of America and precipitation tends to be more concentrated in rainy months. So, it is possible infer that LST behaviour in this area will also change significantly.

Variable	**Daily ET (mm/day)**		**NDVI**	
Season	Pampa	Barrax	Pampa	Barrax
Winter	2,48	1,69	0,54	0,59
Summer	8,62	5,34	0,74	0,65
Variable	**Albedo**		**LST (K)**	
Season	Pampa	Barrax	Pampa	Barrax
Winter	0,17	0,19	288,31	285,81
Summer	0,18	0,19	302,28	310,75

Table 4. Environmental variables differences between Pampa Biome site and Barrax site.

A higher temporal variability of NDVI in Pampa is consistent with a higher spatial and temporal variability of the vegetation that composes the Pampa biome natural grasslands discussed by Overbeck et al., (2007). That is why NDVI can be used as indicators of the vegetation growth and development and are associated with the subtropical climate prevailing in the region. (FONTANA et al., 2018a).

3.1 Analyses for entire image

In Figure 4 is possible to compare the spatial variability of daily ET to Barrax site and in Figure 5 we can see the daily ET to Pampa, both in winter season. In the first one, most of the pixels (area) have around 3 mm/day of ET. In the second one, most of the area have between 5 mm/day and 7 mm/day of evapotranspiration.

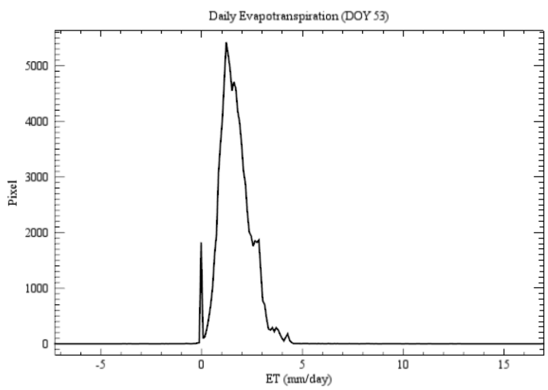

Figure 4. Daily Evapotranspiration (mm/day) graphic distribution for Barrax in winter season (DOY 53)

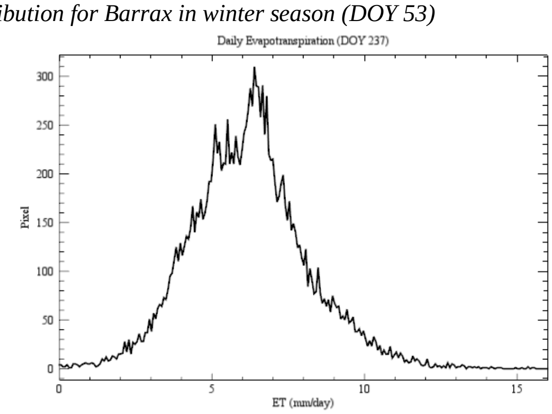

Figure 5. Daily Evapotranspiration (mm/day) graphic distribution for Pampa Biome in winter season (DOY 237)

In summer period this spatial heterogeneity of ET to Pampa is higher than in winter season. In order to understand better the behaviour of evapotranspiration in the Santa Maria site compared to Barrax, Figure 6 presents the graph of mean, minimum and maximum values extracted from the clipping of the image. It is possible to say that although it is known that there is a difference in daily evapotranspiration during the year for the different types of vegetation cover for both sites, mainly in the summer months, the landscape of the Pampa biome in this study is more heterogeneous in terms of energy when compared to the Barrax study site.

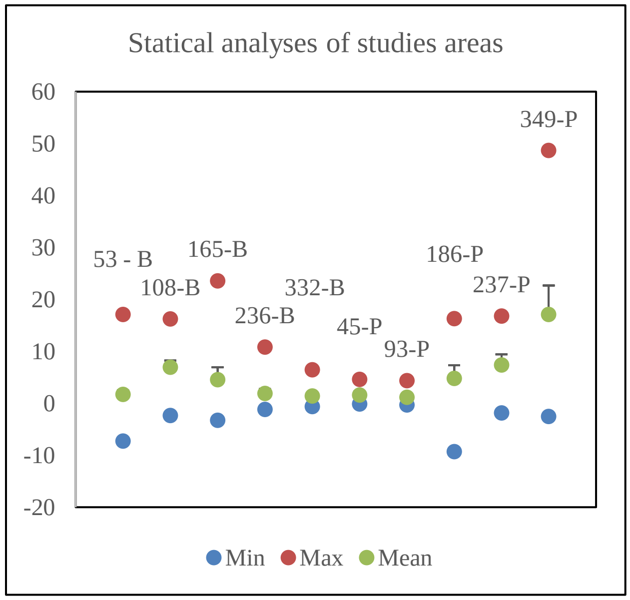

Figure 6. Statistical analyses of the images studied for each Day of the Year (DOY). Where "P" is Pampa Biome and "B" is Barrax

Obviously, we know that the differences between the two validation sites are not only in the type of vegetation, but the meteorological and environmental conditions also influence the available amount of energy for evapotranspiration.

4. CONCLUSIONS

The Pampa Biome is unique in the world, distancing itself in all known environmental aspects. This work sought to understand how these particularities influence the evapotranspiration of the native grassland vegetation of the pampa biome and what the differences are when compared to the grassland cultivated in Spain.

The results indicate differences in two variables studied: LST and NDVI. In a cultivated grassland area, there is a higher seasonal difference in LST compared to the native grassland. Moreover, a higher temporal variability of NDVI in Pampa is consistent with a higher spatial and temporal variability of the vegetation that composes the Pampa biome natural grasslands.

The results presented in this preliminary study indicate that the properties of the Pampa biome generate differences in the energy balance when compared to similar vegetation in other regions of the world. For further studies we have recommended that other variables are included in the analyses, such as: precipitation, air temperature and soil heat flow.

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CONCLUSÕES

A partir da análise do Balanço de Energia e da Evapotranspiração do bioma Pampa, através da aplicação do modelo S-SEBI em diferentes coberturas vegetais e da comparação com resultados obtidos em pesquisas realizadas na área de Barrax na Espanha, confirma-se que é verdadeira a hipótese de que o bioma Pampa e sua vegetação campestre são únicos no Planeta pelas questões ecossistêmicas e também por questões de fluxo de energia.

Os estudos realizados nesta tese puderam discutir as dinâmicas ambientais deste bioma e concluímos que, no Rio Grande do Sul, este bioma tem a mesma importância que áreas nativas de vegetação vertical, como por exemplo florestas encontradas na Mata Atlântica ou silviculturas encontradas no próprio bioma, no que se refere a influência do bioma nas trocas energéticas com a atmosfera.

Uma das grandes preocupações na aplicação de qualquer modelo empírico de estimativa de ET são os possíveis erros acumulados no processamento de imagens e/ou nas limitações dos equipamentos utilizados. Neste sentido, a temperatura de superfície é uma das variáveis que mais causa preocupação, pois sua estimativa depende de muitas outras variáveis e de modelos empírico-físicos que também necessitam de validação. Outra preocupação constante nos cálculos de BE por sensoriamento remoto é a resolução espacial. Neste sentido, o sensor TIRS do Landsat 8 (L8) possui uma resolução espacial de 100m, que pode comprometer a validação dos resultados. Essas duas principais questões foram estudadas e analisadas nesta tese.

Concluímos que os erros obtidos na variação da Ts de até 2K não causam grandes prejuízos nas estimativas de ET, apesar de sua acurácia ser importante na seleção dos pixels seco e úmido para o cálculo da fração evaporativa. Sendo assim, o modelo S-SEBI é menos dependente desta variável que outros modelos citados na literatura, tornando mais eficiente a sua aplicabilidade.

Uma das limitações de estimar ET por sensoriamento remoto está relacionado à disponibilidade de imagens. No caso do L8, pois o horário de passagem (10:42 UTC) não representa a ET máximo diária, tampouco a ET média diária. Ao contrário, as variações mais significativas são observadas das 10:00 às 11:00 UTC, o que contribui para aumentar os erros no ET estimado. Além disso, o tamanho do pixel do L8 não representa adequadamente os locais de testes de para validação da ET. Entretanto, as novas missões do satélite Sentinel, com resoluções espaciais mais altas, podem minimizar as diferenças entre as estimativas de ET.

A resolução espacial do satélite e a presença de nuvens são fatores limitantes na redução de erros nas estimativas de ET. Por outro lado, as metodologias de conversão de calor latente para ET diária e para ET horária se mostraram eficientes (12% e 15% de erro, respectivamente). Esses resultados demonstram a eficácia do modelo para estimar ET no bioma Pampa de forma automática e especializada.

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