Universidade do Estado do Pará
Pró-Reitoria de Pesquisa e Pós-Graduação
Centro de Ciências Naturais e Tecnologia
Programa de Pós-Graduação em Ciências Ambientais – Mestrado

Paulo Amador Tavares

# Identificação, Classificação e Mapeamento de Serviços Ecossistêmicos em Áreas Urbanas Utilizando Técnicas de Geoprocessamento

Belém-PA

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Dissertação apresentada como requisito parcial para obtenção do título de mestre em Ciências Ambientais no Programa de Pós-Graduação em Ciências Ambientais.

Universidade do Estado do Pará.

**Orientadora:** Profa. Dra. Norma Ely Santos Beltrão.

**Coorientador:** Dr. Ulisses Silva Guimarães.

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*“Earth provide enough to satisfy every(one’s) need but not every(one’s) greed”* (**Mahatma Gandhi**).

*“It always seems impossible until it’s done”* (**Nelson Mandela**).

## RESUMO

A manutenção de ecossistemas naturais e suas funções em áreas urbanas tem se tornado um tema relevante para a qualidade de vida das populações. Nessa perspectiva, as pesquisas que envolvem o mapeamento de Serviços Ecossistêmicos (SE) através de dados e técnicas de Sensoriamento Remoto (SR) têm recebido grande destaque. Desta forma, a presente dissertação teve por objetivo identificar, classificar e mapear os SE existentes no município de Belém através da aplicação de técnicas de geoprocessamento. A dissertação é composta por três artigos científicos, sendo: i) identificação na literatura, através de revisão sistemática, das principais aplicações de dados e técnicas de SR para pesquisas de SE; ii) integração de dados de radar e ópticos para mapeamento acurado (e com classes de acordo com a prestação de SE) do uso e cobertura do solo no município de Belém; e iii) mapeamento da oferta e demanda de SE no município de Belém através da pós-classificação dos melhores dados produzidos na integração radar-óptico e estimativa por uso e cobertura da terra de SE de regulação, provisão e culturais. A principal técnica identificada na literatura para mapeamento de SE foi a de uso e cobertura da terra, sendo as aplicações com dados gratuitos as mais utilizadas na literatura investigada. O desenvolvimento dessa pesquisa produziu o mapeamento de uso e cobertura da Terra mais acurado para a área de estudo identificado na pesquisa de bibliografia. Em relação aos SE, o terceiro artigo mostrou que, no município de Belém, a demanda ultrapassa a oferta em todos os Distritos Administrativos (DA) densamente povoados, e que o DA de Mosqueiro é o único que apresenta valores de oferta ultrapassando a demanda nas três macroclasses de SE estimadas. A pesquisa mostrou que é possível a inserção dos conceitos e valores dos SE em nível de gestão ambiental local, destacando-se a possibilidade de aprimoramento da qualidade de vida dos habitantes através da adequada gestão dos ambientes naturais urbanos.

**Palavras-chave:** Florestas Urbanas; Planejamento Urbano; Bem-estar Humano; Sentinel-1; Sentinel-2.

## ABSTRACT

The maintenance of natural ecosystems and their functions in urban areas has become an essential issue for the quality of life of the population. Therefore, researches that involve the mapping of Ecosystem Services (ES) through Remote Sensing (RS) data/techniques have received significant attention. Thus, the present dissertation aimed to identify, classify and map the existing ES in the municipality of Belém through the application of RS tools. The thesis is composed of three scientific papers, which are: i) identification in the literature, through a systematic review, of the main SR data/techniques used for ES assessments; ii) integration of radar and optical data for accurate mapping (considering ES provision) of Land Use and Land Cover (LULC) in the town of Belém; and iii) mapping of the supply and demand of ES in the city of Belém through post-classification of the best LULC data produced in the radar-optical integration and estimation for each LULC class for the budget of ES of regulation, provision and cultural. The primary technique identified in the literature for mapping ES was the LULC classification, and the usage of free satellite data was the most recurrent. The development of this research produced the most accurate LULC mapping for the area of study identified in the literature investigated. Regarding the ES supply and demand, the third article showed that, in the municipality of Belém, the demand exceeds the supply in all densely populated administrative districts (DA), and that Mosqueiro DA is the only one that presents supply values exceeding demand in the three estimated macro-classes of ES estimated. The research illustrated the possibility for the insertion of ES concepts and benefits at the level of local environmental management, highlighting the possibility of improving the quality of life of the inhabitants through the proper administration of urban natural environments.

**Keywords:** Urban Forests; Urban Planning; Human Wellbeing; Sentinel-1; Sentinel-2.

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# SUMÁRIO

# 1. INTRODUÇÃO GERAL

Os Serviços Ecossistêmicos (SE) são classificados na literatura como os benefícios que os seres humanos obtêm, de maneira direta ou indireta, da natureza (DAILY, 1997; TEEB, 2010). Esses SE são comumente divididos em 17 classes, sendo elas: regulação de gases, regulação climática, regulação de distúrbios, regulação de recursos hídricos, abastecimento de água, controle de erosão e retenção de sedimentos, formação do solo, ciclagem de nutrientes, tratamento de resíduos, polinização, controle biológico, refúgio, produção de alimentos, matérias primas, recursos genéticos recreação e cultural (COSTANZA et al., 1997, 2017; TEEB, 2010). Esses 17 SE foram posteriormente subdivididos em quatro macroclasses, aceitas na literatura, sendo elas: i) Provisão, ii) Regulação, iii) Suporte ou Habitat, e iv) Culturais (TEEB, 2010).

Nas áreas urbanas, os SE são de particular interesse para as pesquisas científicas, assim como para o desenvolvimento de políticas públicas voltadas para o desenvolvimento sustentável, pois estes influenciam diretamente na vida dos seres humanos (CORTINOVIS; GENELETTI, 2018; MCPHEARSON et al., 2016a; VAN OUDENHOVEN et al., 2018). É relevante ressaltar que as áreas urbanas são as localidades onde a maior parte dos beneficiários dos SE estão localizados (BURKHARD et al., 2012; HAAS; BAN, 2017; HAASE et al., 2014; LOCKE; MCPHEARSON, 2018). A identificação desses SE pode contribuir para o bem-estar social, a partir da identificação de espaços urbanos que necessitam de maior atenção pelo poder público, além de destacar importantes informações como a adaptação da área urbana às mudanças climáticas e questões relacionadas à saúde humana a partir da infraestrutura verde das cidades (ELMQVIST et al., 2015; GÓMEZ-BAGGETHUN; BARTON, 2013; SIRAKAYA; CLIQUET; HARRIS, 2018).

Os estudos de SE em áreas urbanas estão liderando o caminho para que no futuro existam obrigações legais para a manutenção e restauração dos SE nessas áreas (SIRAKAYA; CLIQUET; HARRIS, 2018). Apesar de complexa, a identificação dos SE pode ser obtida através de dados e técnicas de sensoriamento remoto (SR), que permitem o monitoramento continuo das áreas à serem observadas e estimativas condizentes com as especificidades das áreas de estudo (ALAM; DUPRAS; MESSIER, 2016; AYANU et al., 2012; BARÓ et al., 2016; DERKZEN; VAN TEEFFELEN; VERBURG, 2015; HAASE et al., 2014; MCPHEARSON; KREMER;

HAMSTEAD, 2013). Neste aspecto, destaca-se a possibilidade de mapeamento de oferta e demanda de SE para planejamento urbano sustentável, projeto da União Europeia intitulado ESMERALDA (do inglês, “Enhancing ecosystem services mapping for policy and decision-making”) (BURKHARD et al., 2018; NEDKOV et al., 2018).

Na perspectiva do monitoramento de áreas naturais através do SR, têm-se na análise de uso e cobertura da terra a compreensão de como os ambientes estão sendo modificados com o decorrer dos anos (ALMEIDA et al., 2016; KWOK, 2018; PAUL; MASCARENHAS, 1981; SANNIGRAHI et al., 2018). Essas análises representam uma oportunidade para entender como a expansão urbana afeta os ambientes naturais (RIMAL et al., 2017; SAHANI; RAGHAVASWAMY, 2018; WANG et al., 2018), e como é possível a realização do monitoramento de áreas protegidas e da expansão do desmatamento (ADHIKARI; HANSEN, 2018; ALMEIDA et al., 2016; MUKUL et al., 2017; SHAHARUM et al., 2018). Para essa pesquisa, destaca-se o potencial dessa técnica no monitoramento de SE (BURKHARD et al., 2012, 2018; KWOK, 2018; PETTORELLI et al., 2014).

Para a adequada aplicação do SR na perspectiva da análise de variáveis ecológicas, como a identificação e classificação dos SE, deve-se considerar a escolha adequada de imagens de satélite de acordo com as resoluções: i) espacial, ii) espectral, iii) radiométrica, e iv) temporal, condizentes com o tipo de análise que se deseja realizar (AYANU et al., 2012; KWOK, 2018; MULLER-KARGER et al., 2018). Ressalta-se aqui que diversos dados de SR possuem baixa resolução espacial, dificultando a identificação em localidades onde a concentração de tipos de uso do solo é grande, como as cidades, onde dificilmente será possível identificar áreas verdes urbanas com imagens de resolução de 30x30 metros, por exemplo (ALMEIDA et al., 2016; AYANU et al., 2012). Na aplicação de SR para mapeamento de SE outra variável que se deve ter em mente é a incerteza produzida por esses dados (SONG, 2018), sendo que o processamento dos dados deve ser elaborado de maneira transparente e clara, de tal maneira que esses produtos sejam confiáveis para aplicações ambientais (ROSA; AHMED; EWERS, 2014).

Nos últimos anos, Agência Espacial Europeia (ESA) vêm distribuindo imagens de satélites orbitais de boa qualidade de maneira gratuita (TORRES et al., 2012). Dentre esses produtos, destaca-se o Sentinel-1 (S-1) e o Sentinel-2 (S-2), produtos de radar e óptico, respectivamente. Apesar de possuir menor precisão na identificação de feições diversificadas, o S-1 se torna uma excelente ferramenta para o monitoramento do ambiente natural em áreas tropicais, onde a quantidade de nuvens é muito elevada (JOSHI et al., 2016; PEREIRA et al., 2018; REICHE et al., 2016). Além disso, destaca-se que o uso combinado entre radar e o óptico produz produtos de melhor qualidade, levando-se em consideração as classificações supervisionadas (CLERICI; VALBUENA CALDERÓN; POSADA, 2017; ERINJERY; SINGH; KENT, 2018; WHYTE; FERENTINOS; PETROPOULOS, 2018).

Além da adequada escolha dos produtos para o sensoriamento remoto, deve-se levar em consideração a adequada escolha das técnicas a serem implantadas. Dentre as técnicas bem definidas na literatura para a análise de uso e cobertura da Terra, têm-se o aprendizado de máquina, dentre as quais destacam-se o Random Forest (RF), o Support Vector Machine, o K-nearest neighbour e as redes neurais artificiais (CLERICI; VALBUENA CALDERÓN; POSADA, 2017; MAXWELL; WARNER; FANG, 2018; NOI; KAPPAS, 2018; WHYTE; FERENTINOS; PETROPOULOS, 2018; ZHANG; XU, 2018).

Neste contexto, percebe-se a necessidade do desenvolvimento de estudos capazes de auxiliar os gestores locais e regionais na tomada de decisão, incorporando a sustentabilidade dos ecossistemas em áreas urbanas (BARÓ et al., 2015; BURKHARD et al., 2018; GÓMEZ-BAGGETHUN; BARTON, 2013; TEEB, 2011; VAN OUDENHOVEN et al., 2018). Para isso, propõe-se a abordagem dos SE, através dos quais, pode-se compreender a interação dos fatores sociais, ecológicos, econômicos e dos sistemas tecnológicos o que nos permite construir medidas abrangentes e integradas de bem-estar social e sustentável que possam impulsionar o progresso em direção a esse objetivo, alcançando inclusive o indicado pelas metas de desenvolvimento sustentável propostas pela ONU (COSTANZA et al., 2016; ELMQVIST et al., 2015; KUBISZEWSKI et al., 2017; LOCKE; MCPHEARSON, 2018; MCPHEARSON et al., 2016b, 2016a).

No município de Belém, a alteração da paisagem urbana seguiu a lógica fundiária moderna, a qual foi marcada por altos índices de precariedade das moradias e pela expansão e ocupação no entorno de eixos rodoviários (CARDOSO et al., 2016). Por causa disso, o município apresenta crescente perda de área natural (GUTIERREZ et al., 2017) e o aparecimento de "ilhas de calor" urbanas, os quais são microclimas vinculados ao desconforto térmico (SOUZA; NASCIMENTO; ALVALÁ, 2015).

Desta forma, essa pesquisa questiona se é possível a aplicação de dados e técnicas de SR para mapeamento de SE na área urbana de Belém e se esses conceitos podem ser inseridos no planejamento urbano municipal. Com essa pesquisa, foi desenvolvido o mapeamento de SE por distrito administrativo no município de Belém, e foram identificadas as arenas de negociação para planejamento municipal às quais esses conceitos podem ser inseridos.

Assim, a presente pesquisa teve por objetivo geral identificar, classificar e modelar a provisão de SE no município de Belém, Pará, Brasil, através da análise de oferta e demanda de SE por Distrito Administrativo no município. Para tal, três objetivos específicos foram propostos: i) Identificar as principais técnicas de sensoriamento remoto aplicadas na área de serviços ecossistêmicos em áreas urbanas, ii) Investigar a possibilidade de uso combinado de produtos de radar (S-1) e ótico (S-2), e seus derivados, para mapeamento com elevada acurácia temática do município de Belém, e iii) Analisar a oferta e demanda de SE na área urbana do município de Belém e a potencial aplicação desses conceitos a nível de gestão pública municipal.

O primeiro artigo dessa dissertação apresenta uma revisão sistemática de literatura, na qual foram identificadas as principais técnicas de SR aplicada para o mapeamento e identificação de SE. O artigo identificou que as técnicas de uso e cobertura da Terra são as mais utilizadas para esse fim, sendo os SE de regulação os mais comumente mencionados. Foi possível a percepção da crescente inserção do SR na perspectiva de monitoramento de SE.

No segundo trabalho referente aos objetivos dessa pesquisa, foi realizada a fusão de dados do S-1 e do S-2 e de índices derivados desses para a aplicação da técnica de classificação supervisionada do RF. Os resultados de acurácia da classificação mostraram que a melhor interação ocorreu entre o S-1 e o S-2 somente (dentre as seis abordagens feitas). Esse mapeamento obteve uma acurácia de 91,07%, sendo o melhor atualmente identificado na literatura.

Por fim, para o terceiro artigo, foi realizada a pós-classificação dos melhores dados obtidos para o segundo artigo com o intuito de mapear os SE no município de Belém. Os dados foram obtidos por distrito administrativo e identificou-se que as localidades mais densamente povoadas são também as que a demanda por SE é também maior. O plano diretor municipal foi identificado na literatura como o principal instrumento para a inserção dos conhecimentos sobre SE no planejamento urbano de Belém.

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## 2. ARTIGO 1: A Systematic Review of the Remote Sensing Applications and Methodologies for Urban Ecosystem Services Estimation.

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*Review*

# A Systematic Review of the Remote Sensing Applications and Methodologies for Urban Ecosystem Services Estimation

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**Abstract:** Urban Ecosystem Services (UES) is an essential approach to the development of sustainable cities and must be incorporated into urban planning to be able to improve humans' life quality. This paper aimed to identify Remote Sensing (RS) data/techniques used in the literature in the past full five years for UES investigation and to analyse the similarity between them. For this purpose, we used the Scopus database of scientific journals, and a set of appropriate filters were applied. A total of 44 studies were selected being 93.18% of them located in the Northern Hemisphere, mostly in Europe. The most common dataset used was the secondary data, followed by the Landsat family products. Land Use and Land Cover (LULC) was the most common method employed, succeeded by radiometric indexes and band related approaches. All four main classes of Ecosystem Services (ES) were identified in the papers considered, wherein regulating services were the most popular studied. Seven different groups were established as having 100% of similarity between methods and ES results. Therefore, RS are identified in the literature as an important technique to reach this goal. However, we highlight the lack of studies in the southern hemisphere.

**Keywords:** spatial analysis; urban forest; satellite data; human well-being; urbanization.

## 1. Introduction

Ecosystem services (ES) are described as the processes, conditions and benefits provided by nature to maintain and fulfil the human needs and are commonly subdivided into four main classes of services: (i) Provision; (ii) Regulation; (iii) Supporting and; (iv) Cultural [1–3]. These classes incorporate at least 17 different types of ES with a total estimated value of about $ 33 trillion in average [1]. In opposition to the dominant hypothesis that ES are provided only by natural landscapes, literature suggest an important interaction between ES and the daily human life in urban scenarios [4–7]. In addition, most of the applied research in this area has indicated that the development of sustainable cities passes by the understanding and aggregation of ES knowledge to day-to-day life and progress in its social-ecological resilience through increase in quantity, quality and diversity of ES, as well as to public policies development related with improvement in quality of life [8–16].

Highlighting the key challenges and insights for future research regarding Urban Ecosystem Services (UES), Luederitz et al. [17] and Kremer et al. [18] agreed that the current studies about this subject have some lacks when they are analysed under the interdisciplinary context. These authors found that the integration of the indicators analysed must be improved, so has the stakeholder's involvement with the insertion of UES concepts in public policies. In addition, these authors reinforced the need for integrating research efforts and comparing results with similar locations.

As a way of identifying environmental variables that provide ES, several authors suggest the use of Remote Sensing (RS) data/techniques [19–21]. Kwok [21] argues that the possibilities of RS for ecological studies are plentiful and accessible, highlighting the number of open access data and free and open source software available for this purpose. Its potential is still greater when considering data sources with daily images [22], this is relevant because of the cloud coverage, which complicates the use of optical data [23], especially for tropical regions [24].

Environmental studies involving RS data/techniques can relate and link to ecological fields in different areas and applying different methodologies, which can vary greatly from machine learning techniques [25–27] and the mapping and assessment of potential for urban agriculture [28,29] to the use of geospatial data to investigate animals estimates on the red list of threatened species [30]. RS data/techniques are also used to monitor natural resources and the environmental behaviour in relation to anthropogenic actions. Some examples of their applicability are: Land Use and Land Cover (LULC) change detection in Brazilian Legal Amazon [31] and forest disturbance history [32], the evaluation of water quality index with machine learning algorithms [33], the use of ALOS-2 PALSAR-2 and Sentinel-2A imagery in order to estimate aboveground biomass [34] and the application of Synthetic Aperture Radar (SAR) and lidar data to evaluate the flood depth through the application of normalized difference index [35].

In urban areas, the RS data/methods are also broadly employed. The RS techniques stands out as one of the six research priorities for cities sustainability and climate change [36]. Using these techniques, ecological relationships of green areas in anthropised regions are possible to be studied, incorporating a 3D interpretation in these analysis [37]. A well-known example is the interrelation between the land surface temperature (LST) and the existence of heat islands in a metropolitan region [38].

A vast literature has pointed out the use of RS to UES identification, classification, and modelling. The RS is highlighted for several authors as an efficient method of investigating urban green spaces [39,40]. For this purpose, the LULC analysis and its changes [41–45] and the analysis of urban heat islands [46–48] are common techniques applied. Aspects related to the temporal dynamics of UES have also been mentioned in the literature, such as the vegetation structural attributes [49] and the change in provision of UES [48,50].

Understanding the nature's benefits and how ES affect both rural and urban environments is challenging for many researchers, but the economic evaluation of ES has emerged as an important tool to achieve such objectives [1,5,18]. In this sense, several methodologies have been proposed in the literature for evaluating nature through RS techniques. Among them, it is highlighted the CORINE LULC classification method which gives a monetary value to land use or cover class [51]. Some other landscape evaluation techniques have also been proposed considering different types of land use and different satellite information [52–54]. To these ideas, Song [52] argues and presents the incorporation of the satellite-based uncertainties coming from the images to the evaluation of such areas.

Conceptually, the outcomes obtained from UES studies are linked to the human well-being and its close relationship with nature [55,56]. From a global point of view, researchers must contribute to the efforts of United Nations (UN) to promote the development of sustainable cities and communities (SDG 11) until 2030 [8,9,57,58]. Thus, RS data/techniques turns the findings of ES studies more relevant [59], more adequate to urban planning and able to guide for sustainable development in these areas [4,10,60–62].

Therefore, considering the importance of identifying, classifying and modelling ES in urban environments, as well as the recent developments achieved by the RS data/techniques, the objectives of this work are: (i) to analyse, through a literature review, how researchers are interpreting results from RS data/techniques under a UES perspective; (ii) to identify the methodologies and databases used and; (iii) to analyse the similarities and differences between the studies.

## 2. Materials and Methods

In order to evaluate and interpret the available and relevant research developed under the topic UES by using RS data/techniques, a systematic literature review was carried out [63,64]. Thus, to present the state of art of the suitability of RS data/techniques to identify, classify and model UES, it was conducted a survey covering the last five full years of research in the area, starting from January 2013 until December 2017.

Scopus bibliographic database was chosen to identify these papers. Scopus has a broad coverage with more than 22,000 titles from over 5,000 international publishers. This indexer has functional tools for acquiring relevant documents, besides providing them in different ways and covering areas of study that are relevant to the keywords chosen [65]. The Scopus platform contains results refinement tabs that offers several types of filtering options, which are i) Access type; ii) Year; iii) Author name; iv) Subject area; v) Document type; vi) Source title; vii) Keyword; viii) Affiliation; ix) Funding sponsor; x) Country/territory; xi) Source type; and xii) Language. These options support the appropriate choice of relevant scientific articles. For these reasons, Scopus is mentioned in the literature as a trustable tool for identifying relevant papers [65–68].

We then chose scientific journals with high impact factor and relevant conference papers were selected using the Scopus database as it is provided by the education institute where this analyse was carried out. We selected three different sets of keywords, which were chosen in previous analysis of relevant articles to the UES study. These sets of keywords were a) "Satellite" and "Ecosystem Service" and "Urban"; b) "Mapping" and "Ecosystem Service" and "Urban"; and c) "Remote Sensing" and "Ecosystem Service" and "Urban". Moreover, this literature survey considered the following subject areas: 1) Environmental science, 2) Agricultural and Biological science, 3) Social science, 4) Earth and Planetary science, 5) Decision science, 6) Engineering, 7) Physics and Astronomy, 8) Economics, Econometrics, and Finance. These subjects were selected as they can be related, in some level, to the scope of this work.

Finally, the types of documents considered included Articles and Conference Papers, as both types are relevant for developing and promoting research in this subject. We have defined some exclusion criteria, which are mentioned, in order, as follows: (i) removal of duplicate results in the identification section; (ii) in the screening segment, by reading the abstracts, we removed studies that did not use RS applications, nor were UES studies, and studies that did not involve only urban areas; (iii) in the eligibility section, we verified, by assessing the full body of the text, the information described in the exclusion criteria number (ii).

The results found were arranged in three main classes: 1) Database; 2) Method; and 3) Types of ES considered. To better understand the similarity between the techniques used and the types of results found in each study, we performed a multivariable statistical analysis, and a dendrogram was produced for visualising this result, as mentioned by Booth et al. [69] as important approach for systematic reviews.

Figure 1 illustrates the flowchart of the processing analyses made. In the identification part, only duplicated data were removed. For screening, we read the abstracts and excluded the ones not related to our scope. Then, the full-text analysis was done, and 44 studies were included in both qualitative and quantitative analysis.

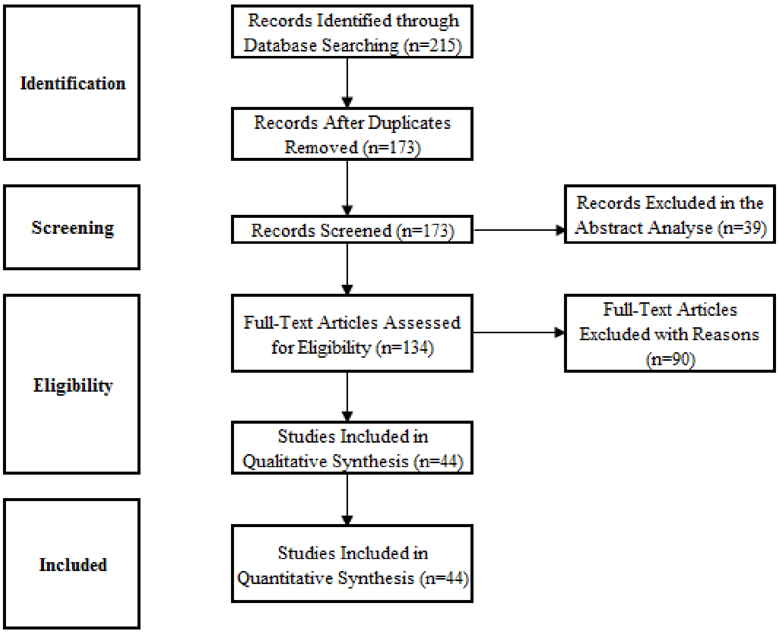


**Figure 1.** Steps adopted for this research purpose.

## 3. Results and Discussion

A total of 44 (20.46% of the total) papers were analysed in both quantitative and qualitative investigation. Hence, we highlight that a small amount of studies relating RS data/techniques with UES approaches were produced during the period analysed. All these articles were manually reviewed in order to address word ambiguity issues and to ensure that they were applications of RS data/technique for UES approaches.

The Earth's Northern Hemisphere accounted most of the studies (93.18%), mainly located in Europe (52.27%), similarly to what was found for Haase et al. [70]. In the America continent (22.72%), the Latin America countries represented the Southern Hemisphere with 6.81% of the total and 30% of the value for America only. The USA represented 60% of America's studies and 13.63% of the total value. In Asia (25%), the biggest contributor was China with 63.63% of Asia's contribution and 15.90% of the total. The results concentrated in the Northern Hemisphere confirms that exists lack of studies in the Southern Hemisphere for sustainable development of cities, when compared with the ones in developed countries [8,36,58].

The studies assessed were distributed along six years according to the following percentage: 2013 (4.55%), 2014 (18.18%), 2015 (9.09%), 2016 (22.73%), and 2017 (45.45%). In this range, it is possible to identify a slight tendency in the increase in the numbers of UES papers published during these years, that removing the year 2015, which achieved results lower than 2014 in published papers. Largely, 2017 was the major contributor, indicating an increasing trend for research involving ES for urban areas sustainable development.

Figure 2 illustrates that the primary data used in the selected studies are costless, in close agreement with the literature concerning the idea that RS facilitates ecological studies given the low-cost investments needed to study natural phenomena [21,71]. The Landsat and Sentinel families are some of the most cited satellite images. These are related to easy access and availability in platforms such as the United States Geological Survey (USGS) and the Copernicus Sci-Hub from the European Space Agency (ESA) [72]. The data aggregation of Landsat and Sentinel constellation provides an Earth observation status with a revisit interval of 2.9 day, which is a perfect scenario for monitoring environments and their ES [73].

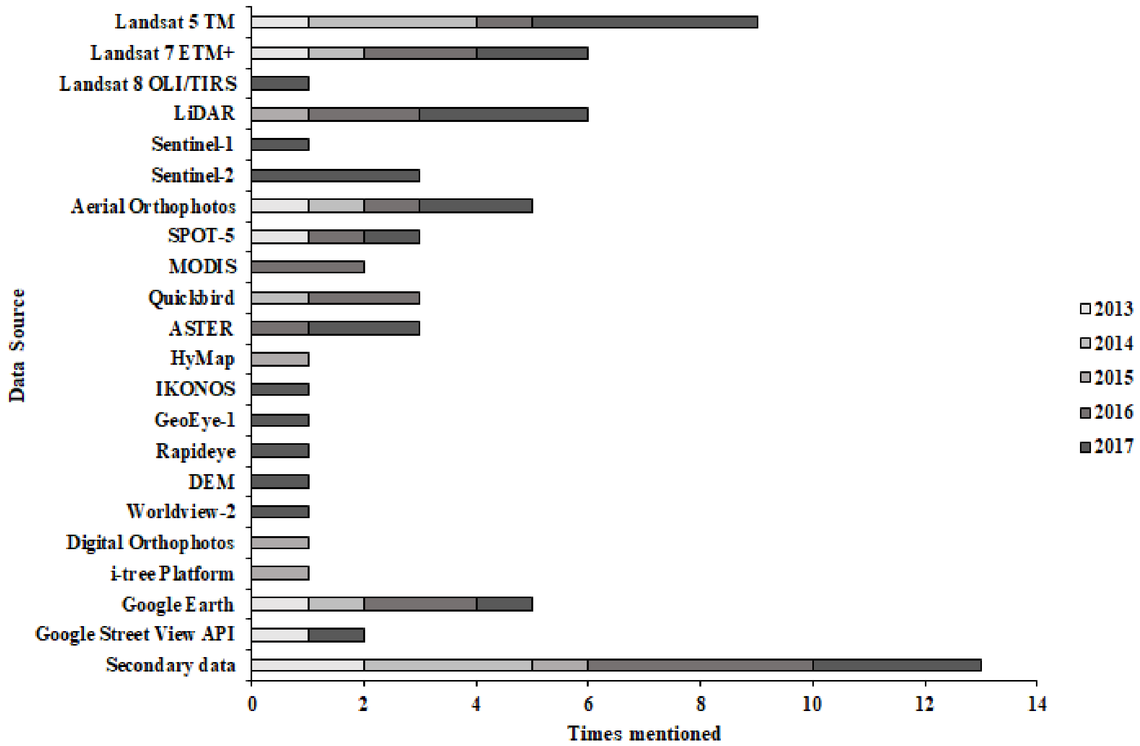


**Figure 2.** Identification of data source used by the authors, separated by year (2013-2017).

Secondary data, mainly related to LULC mapping, was also highly mentioned. The information extracted from these secondary data were related with zoning plans [74], urban atlas [75], soil maps [76], High Ecological Resolution Classification for Urban Landscape and Environmental Systems (HERCULES) [42], Census data [77] and information regarding naturalness and natural protected areas [78].

The Google Earth images, another free and open access data source, have been used by the UES authors for LULC purposes and for validation analysis of supervised and unsupervised classification algorithms [42,79–81]. Similarly, the Google Street View API has been used for understanding the urban green canopy cover, while Google Street View photos, for instance, was used to determine the green canopy cover in different locations of Singapore [82].

High resolution imagery such as SPOT-5 [80,83], aerial and digital orthophotos [84–86] Worldview-2 [87], RapidEye imagery [88], GeoEye, IKONOS [89], Quickbird [80,90,91] and HyMap [92] are considered more trustable and accurate resources for UES evaluation. However, these data are generally related to the researcher level of data access and research funding, since this type of high-quality imagery usually have a high acquisition cost.

Recently, the United States (US) Government started to consider charges introduction to USGS data acquisition, including the Landsat family [93]. This might bring impacts on the LULC studies and deforestation monitoring in critical ecosystems in the world and consequent effects on UES studies, since mostly have been used free source data up to now. The combination of different datasets is also an important alternative to the monitoring difficult areas, such as the rainforest where the cloud coverage is commonly elevated [94,95].

In the methodological analyses, the most cited methodology was the LULC (75%), followed by the Normalized Difference Vegetation Index (NDVI) with 15.91%, Leaf Area Index (LAI) (11.36%) and LST (9.09%). Some methods were mentioned only once (2.27%): Normalized Difference Green-Building Volume (NDGB), Green Canopy Cover, ES Index, Modified Normalised Difference Water Index (MNDWI) and Visible Red and NIR-based Built-up Index (VrNIR-BI). The biomass estimation in urban areas, the species mapping and the Modelling of Carbon Assessment (MOCA) flux model were cited in 4.55% of the papers assessed.

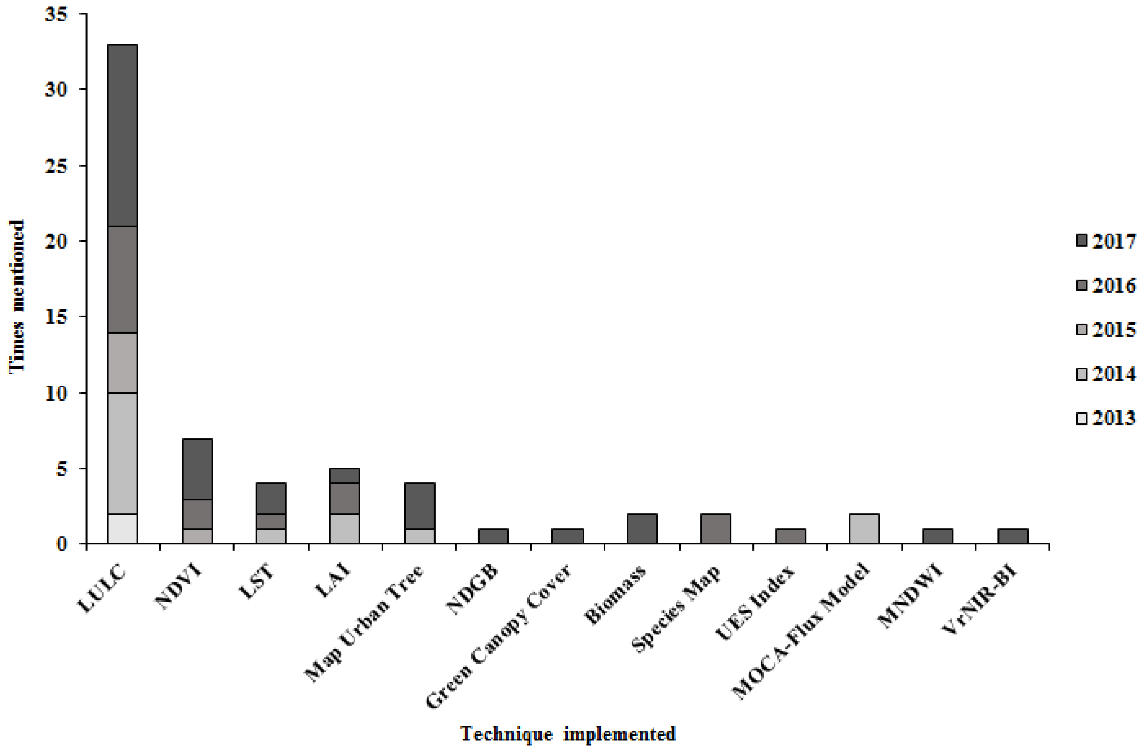


**Figure 3.** Methods implemented by the authors to infer UES results, separated by year (2013-2017).

Among several methodologies surveyed, LULC was the only cited in all years. As mentioned, LULC is obtained from several types of techniques and different data sources, including data extracted directly from secondary data. Machine learning techniques, such as random forest (RF), support vector machine (SVM) and artificial neural networks (ANN) are tendencies for the LULC classification and identification of ecological variables. The accuracy of the methods is increasing along with the diversity in its modes of application, this because of the popularisation of the techniques [26,27,96–98], even for UES studies [79,89,99,100].

One factor that stimulates researchers from using LULC techniques to UES identification and classification purposes is that some authors describe the evaluation of each land use type. For instance, the work of Burkhard et al. [51] is highly mentioned since it comprehends a description of how to evaluate ES from the CORINE land cover classification, which by itself consider 44 different types of land use and cover. From the interpretation of this paper, it is possible to perform the evaluation and modelling of other classifications simpler or derivate from CORINE [75,85,89,99,101,102].

Radiometric indexes calculation (NDVI, LAI, NDGB and MNDWI) and methodologies directly related with interpretation of sensor's data, produces more accurate and well-defined results strictly based on band math, irrespective of human interpretation [47,103,104]. These indexes have been used in some papers to increase the LULC accuracy from machine learning techniques [26,98].

Urban trees mapping methodology was mentioned as one useful approach for understanding and regulating services [85,86,88,105] and supporting services [105]. Such mapping usually uses high-quality images as Aerial Orthophotos [85,86] and LiDAR [88] since its accuracy is essential to identify the tree coverage in urban areas.

The UES index methodology was mentioned only once in the assessed papers [41]. However, it is important to highlight that results found in that study delivered a more consistent approach on UES importance as well as ES supply and demand in the urban scenario. Such finding seems to be a robust tool to instantly propose suggestions for urban planning and development of sustainable cities.

The figure 4 summarises the four main ES groups (Provisioning, Regulating, Supporting and Cultural) identified in the literature review and their ES subtypes. It is also highlighted in a separated category the Urban Green Spaces.

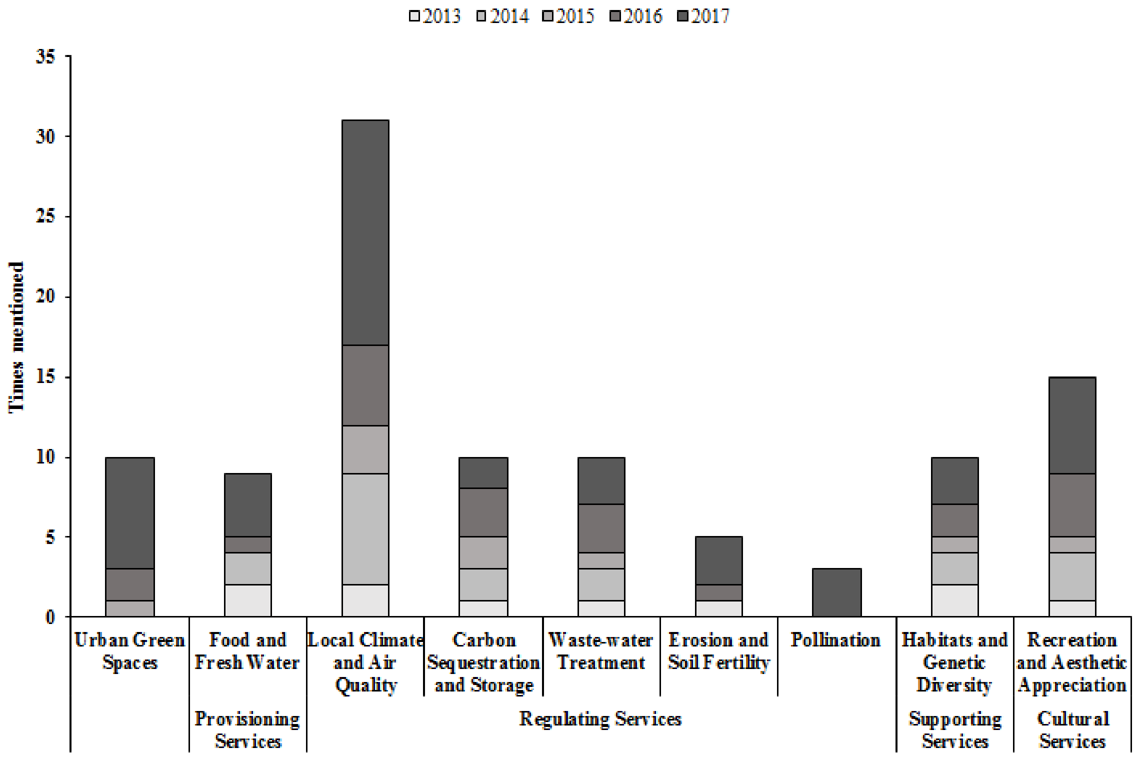


**Figure 4.** UES identified in the literature reviewed, separated by year (2013-2017).

All the four main classes of ES described by Costanza et al. [1,3] and TEEB [2] were found in the studies assessed. The ES types mentioned in all five years assessed were: Local Climate and Air Quality (70.45%), Carbon Sequestration and Storage and Wastewater Treatment (22.73%) for regulating types of services Habitats and Genetic Diversity (22.73%) for Supporting Services and Recreation and Aesthetic Contemplation (34.09%) representing cultural services.

The most mentioned regulating services identified were, generally, extracted by the direct interpretation of RS results and indexes for ecological purposes [106]. In contrast, other regulating services such as erosion and soil fertility and pollination would only be estimated using factors and coefficients throughout data interpretation [77,81].

Supporting services (habitats and genetic diversity) and cultural services (recreation and aesthetic contemplation) were generally obtained by interpreting urban green coverage and identifying significant localities for maintenance of local species of fauna and flora, as well as social interactions and social life, respectively [87,103,105].

The provision services were only related to fresh water and food supply which were identified through water bodies and urban agriculture in urban and peri-urban localities and mainly related to urban green coverage [42,74,75,77,83,87,89,99,100].

Urban green spaces were considered in a different column, because its presence (natural or human-made) can be related to the provision of bundles of ES, having positive effects on people living and buildings monetary values situated in the neighbourhood [49,79,80,84,91,99,107–110].

Another parameter considered in this literature review was the similarity of methodologies and results found in the assessed papers. The dendrogram shown in Figure 5 illustrates the findings of cluster analysis.

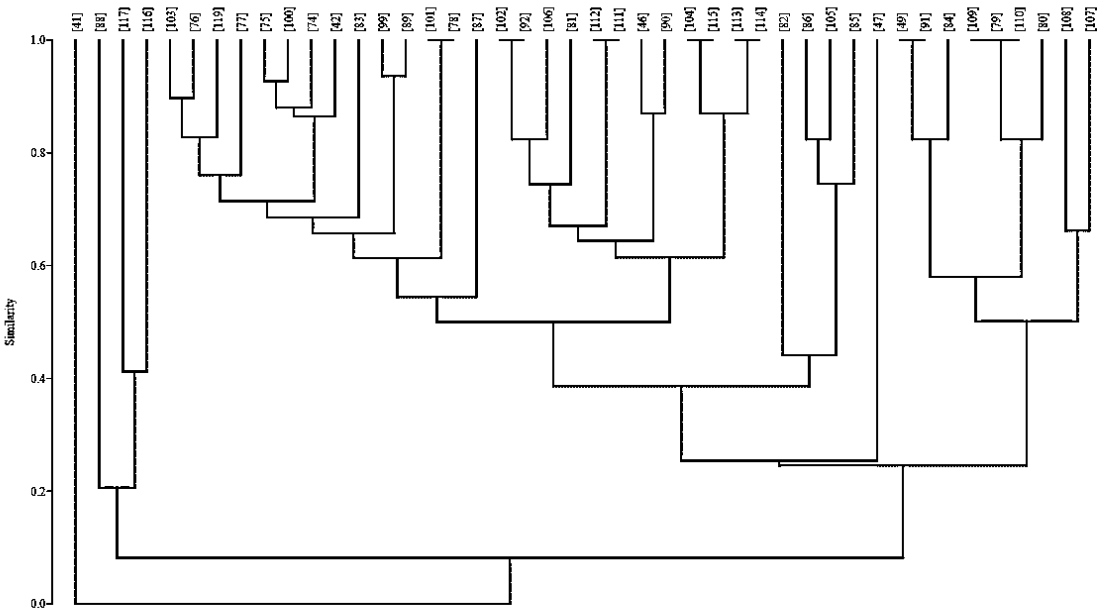


**Figure 5.** Cluster analysis of the similarity between the methodologies used and the UES identified, the full body papers investigated are expressed according to the order of appearance in the body of the text.

Larondelle et al. [111] and Kim et al. [112] studied the same type of UES by using the same method, as noticed in Figure 5. These authors chose the LULC method and had their results based on regulating services – local climate and air quality, and carbon sequestration and storage. Similarly, Behling et al. [92] and Goldenberg et al. [102] also chose the same type of methodology to identify the same range of UES. In their method, regulating services were the focus of the study, but LULC was also selected. Nonetheless, the services considered were local climate, air quality and wastewater treatment.

Manes et al. [113,114] used the same types of methods LULC, LST, MOCA and Flux-Model to identify local climate and air quality regulating services. The only difference between the work of Manes et al. [115] and Fusaro et al. [104] was that this author did not use the MOCA flux model methodology.

LULC was also the methodology chosen by Ala-Hulkko et al. [101] and Casado-Arzuaga [78]. These papers found the cultural services of recreation and aesthetic opportunities as results. The data source selected by these authors was the secondary data, since for recreation and aesthetic purposes to understand the local objectives and concerns is important as the features identification.

De Mola et al. [79], Peng et al. [109] and Richards et al. [110], developed a LULC methodology for mapping urban green spaces. It is noteworthy the different approaches of obtaining LULC information since all authors used different data sources in their studies: Google Earth data [79], ASTER, Landsat 7 ETM+ and Landsat 5 TM imagery [109], and only Landsat 7 ETM+ imagery [110].

The last group with 100% similarity was from the papers published by Van de Voorde [91] and Ren et al. [49], which used NDVI to identify urban green spaces. The first seems to present results that are more accurate in his study developed in Belgium using Quickbird high-quality satellite imagery. In contrast, Ren et al. [49] used a 30m resolution free data source Landsat 5 TM.

Tigges et al. [88], Alonzo et al. [116] and Sasaki et al. [117] produced results from their employed methodologies that were not very similar to the other papers assessed, but all of them produced satisfactory results in their analysis. Tigges et al. [88] suggested the use of urban trees mapping methodology to identify carbon sequestration and storage services. To this end, Alonzo et al. [116] used LAI and species map, whereas Sasaki et al. [117] used species maps to assess carbon sequestration and storage, and habitats and genetic diversity results, respectively.

The UES index provided by Kremer et al. [41] was the only study to present no similarity with others. An explanation would be that their study incorporates a vast range of ES to produce a result reasoned in one value per pixel. Despite its unique methodology, this paper suggests an impressive simulation for urban scenarios by identifying precisely what city areas have more supply or demand for ES. An UES index was also proposed for Alam et al. [118] where several ES were selected as indicators and weighted through a SWOT analysis, however, this paper was not found in the scope made for this systematic literature review. Baró et al. [119] also considered several indicators of ecosystem services to have a greater understanding of the UES capacity, flow and demand, however, they do not developed an index to include all these results in one value.

## 4. Conclusions

In this paper was studied the range of RS applications from the UES perspective. Most of the UES studies are concentrated in Northern Hemisphere sites, drawing attention to the need for additional UES studies and scenarios analysis in developing countries. In such regions, science investments are scarce, and therefore the use of RS methods with free and open data sources is an option, since the data source most mentioned in the surveyed studies are available for free. This paper tries to highlight the importance of free data access for RS purposes under the perspective of developing countries.

The benefits of using secondary data for UES studies include more access and a cheaper alternative to estimate ES per area unit using trustable data. For instance, most of the studies, which considered cultural services, were able to estimate the provision of ES with a high degree of quality. In addition, official data previously validated can reduce costs related to ground truth observations and measurements.

LULC was the most mentioned methodology from those surveyed. Vegetation indexes and data able to be extracted directly from band math, such as NDVI and LST, were also mentioned a few times. These methods usually have a smaller percentage of errors when the imagery is adequately pre-processed.

All core classes of ES, described in the classic literature of ES, were mentioned for urban environments in the sample assessed. Regulating services showed a vast range of methodologies used to identify the benefits that urban green areas have to regulate local climate, as well as to estimate the amount of carbon captured and stored in the urban forest.

The similarity test for the studies assessed demonstrated that there is no standard procedure of producing or reproducing RS techniques for UES. The methods can vary, such as the dataset used, and the type of ES evaluated. Some results are more accurate than others are, but they depend on the quality of the data and the researcher's experience.

In summary, it is possible to identify a vast range of data sources, techniques employed and ES classification. There is plenty of opportunities for reproducing methodologies for UES, and the RS methods give the opportunity for people in all countries to work with them. UES Identification through RS data/techniques provides opportunities for scientists to conduct an array of environmental studies able to help countries to achieve, by 2030, the SDG 11 related to the development of sustainable cities. Countries, states, and municipalities in the development of more environmentally friendly public policies could discuss results from these studies.

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editing, P.A.T., N.E.S.B., U.S.G. and A.C.T.; supervision, N.E.S.B., U.S.G. and A.C.T.; project administration, P.A.T. and N.E.S.B.; funding acquisition, N.E.S.B.

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## 3. ARTIGO 2: Integration of Sentinel-1 and Sentinel-2 for Classification and LULC Mapping in the urban area of Belém, eastern Brazilian Amazon.

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*Article*

# Integration of Sentinel-1 and Sentinel-2 for Classification and LULC Mapping in the urban area of Belém, eastern Brazilian Amazon

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**Abstract:** In tropical regions, such in Amazon, the use of optical sensors is limited by high cloud coverage throughout the year. As an alternative, Synthetic Aperture Radar (SAR) products could be used, alone or in combination with optical images, to monitor tropical areas. In this sense, we aimed to select the best Land Use and Land Cover (LULC) classification approach for tropical regions using Sentinel family products. We choose the city of Belém, Brazil, as the study area. Images of close dates from Sentinel-1 (S-1) and Sentinel-2 (S-2) were selected, pre-processed, segmented and integrated to develop a machine learning LULC classification, through a Random Forest (RF) classifier. We also combined textural image analysis (S-1) and vegetation indexes (S-2). A total of six LULC classifications were made. Results showed that the best Overall Accuracy (OA) was found for the integration of S-1 and S-2 (91.07%) data, followed by S-2 only (89.53%) and S-2 with radiometric indexes (89.45%). The worse result was for S-1 data only (56.01). For our analysis the integration of optical products in the stacking increased de OA in all classifications. However, we suggest the development of more investigations with S-1 products due to its importance for tropical regions.

**Keywords:** machine learning; random forest; spatial analysis; optical data; radar data; urban land cover.

## 1. Introduction

Land Use and Land Cover (LULC) data are important inputs for countries to monitor how their soil and land use are being modified over time [1,2]. It is also possible to identify the impacts of increasing urban environments in different ecosystems [3–6], monitoring protected areas and the expansion of deforested areas in tropical forests [1,7–9].

The application of remote sensing data/techniques are used as a tool for monitoring changes in environmental protection projects reducing the prices of surveillance. An example is the LULC approach for monitoring Reduced Emissions from Deforestation and Forest Degradation (REDD+) [10,11] and for ecosystem services (ES) modelling and valuation [12–14]. For this latter purpose, the LULC mapping has been used to enhance the results found for Costanza et al. [15] that provided global ES values. In that research, the values have been rectified since its first publication [16,17] and the LULC approach provides land classes which allow to estimate ES by unit area, making it possible to extrapolate ES estimates and values for greater areas and biomes around the world by using the benefit transfer method [1,17,18]. Nonetheless, Song [19] highlights the limitation of these values estimations, since LULC satellite-based products have uncertainties related to the data.

From an Earth Observation (EO) perspective, it is useful to have provided for free and open data access, e.g. Landsat and Sentinel families [20]. These are orbital sensors that when used in combination (Landsat-5-8 and the optical sensor of the Sentinel family, the Sentinel-2, hereafter S-2) they have 3 days revisit time on the same point on the Earth surface [21,22]. In contrast, these sensors have a medium-quality spatial resolution (30m for the Landsat and 10m for the S-2) when compared with other data, such as the Quickbird (0.6m) and Worldview (0.5m), but can deliver satisfactory results when the correct methodology is applied [23–25].

More recently, the United States (US) started to consider reintroduce prices for the Landsat products acquisition [26]. That is a step backwards when we consider that more than 100.000 published articles were produced since 2008 when US made Landsat products available for free. In contrast, S-2 products are becoming more popular, and despite not having enough data to produce temporal analysis yet, they have a better spatial resolution to develop more precise results [22,27–29].

In the perspective of monitoring areas with high cloud coverage, such as tropical regions and estuarine areas, some developments have been reported in using Synthetic Aperture Radar (SAR) products [30–32]. To increase SAR usage products for environmental monitoring and security, the European Spatial Agency (ESA) launch the Sentinel-1 (hereafter S-1) in 2014 [33]. Similar to the S-2 products, the S-1 is available for free in the Copernicus platform and covers the entire Earth [34,35].

Recently, processes as stacking, co-registration and data fusion of optical with radar products have been applied to improve classification quality and its accuracy. Although radar polarisation may be a barrier to identify some features, this product does not have the presence of atmospheric obstacles, such as clouds [11,27,36].

The synergetic use between optical and radar data is a recognised alternative for urban areas studies [37–39]. The literature indicates that although the limitations of the microdots in detecting the variety of spectral signatures over the urban environment, such data aggregation contributes to improve the classification accuracy. Also, the importance of radar data has been emphasised in tropical environmental studies [31,40–42], once the cloud coverage in these areas are high throughout the year hindering the use of optical images [43,44], making radar data an alternative to acquiring imagery during all months of the year in these locations.

Another alternative described in the literature for accuracy enhancement of final classification results is the inclusion of optical indexes of vegetation, soil, water, among others [45–48]. Indexes included in the data sets allow to increase the training data range and class statistical possibilities of classification algorithms, thereby raising their efficacy.

Besides choosing suitable products and deciding how to combine different imagery types, the developer of LULC classifications must test different methodologies to select the most accurate for each landscape analysed [27,36,49]. In this sense, the Machine Learning (ML) algorithms are presented as an optimal solution to supervised classification, where there is no need of ground information measurements of the entire landscape to determine the different classes of LULC for the whole area. Some ML algorithms have been used to classify images with low, medium or high spatial resolutions [50,51], among them are the Random Forest (RF) [52], Support Vector Machine (SVM) [53], Artificial Neural Networks (ANN) [54], and the k-nearest neighbour (k-NN) [55]. In addition, to the proper selection of satellite imagery, application or not of data fusion and choosing the fittest classification algorithm method, we should also select computer programs that are robust enough to run each of those LULC ML classifications [50].

In this perspective, this study aims to investigate the synergy use between S-1 and S-2 products to identify the suitability for LULC based on ML classification approach. In addition, derivate products such as vegetation and water indexes and SAR textural analysis were applied in the RF classification, to finally test all data sets and select the most thematic accurate product for tropical urban environments at regional spatial scale.

## 2. Materials and Methods

### *2.1. Study Area*

The selected study area is the city of Belém in the eastern Amazon, Brazil. The city has a total territorial area of 1,059.46km², subdivided into eight administrative districts, all included in this study [56]. The estimated population in 2017 was 1,452,275 residents. According to the Köppen classification, the climate is tropical Afi, with average annual rainfall reaching 2,834 mm [57]. The forest fragments of the locality are classified as Terra Firme and Várzea forests, being subtypes of dense Ombrophilous forests [58]. The humid tropical environments in coastal Amazon is described as a complex environment which involves the relationship of flowing rivers with the ocean, different types of natural and anthropised vegetations, and further the impervious surfaces [59]. Figure 1 shows the study area considered and the coverage of the selected satellite scenes.

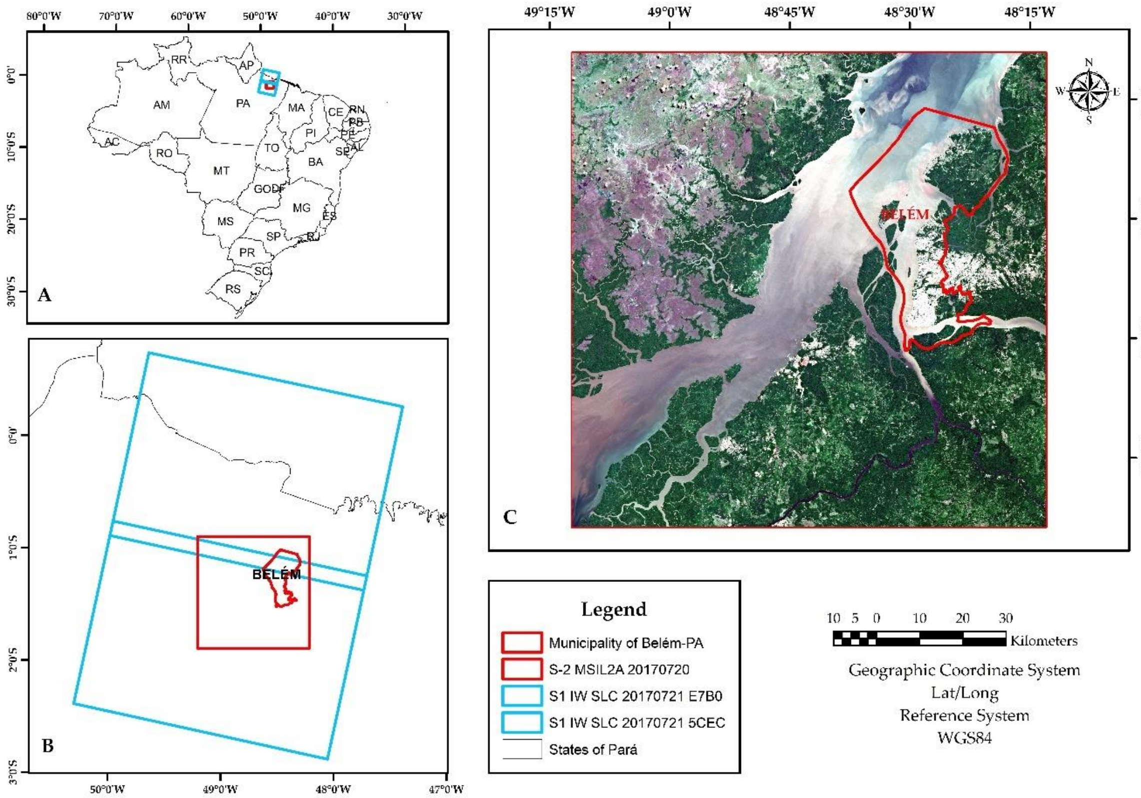



**Figure 1.** Study area in the municipality of Belém, state of Pará, Brazil.

*Where A is the location in the Brazilian territory of the S-1 and S-2 scenes used; B shows the relative tracks of the S-1 scenes and S-2 tile used; and C is an RGB composition of the S-2 scene where it is illustrated the complexity of the tropical coastal environment chosen (water bodies, different types of vegetation (dense, lowlands, and mangrove), impervious areas, among other ecosystems).

### *2.2. Data source and collection*

The products acquisition of both S-1 and S-2 were performed in the Copernicus open access hub platform (https://scihub.copernicus.eu/dhus/#/home) considering the cloudy coverage of less than 5% for the S-2 product and the date proximity of the S-1 product in relation to the S-2 (one day of difference). The Planet Labs scenes were acquired through a contract of the Environment and Sustainability Secretariat of the state of Pará, Brazil.

### 2.2.1. Sentinel-1 Images

In order to cover the whole study area, two S-1 images were collected: S-1 C-band SAR Interferometric Wide Swath (IW) in dual polarisation mode (VV+VH) from 2017-07-21. Data characteristics and the main characteristics of S-1 are described in Table 1.

**Table 1.** Main attributes from the SAR dataset.

| | | | | | |
|---|---|---|---|---|---|
| **S-1 System** | **Operation** | Since 03/04/2014-current | **S-1 data** | **Imaging date** | 21/07/2017 |
| | **Orbit height** | 693 km | | **Swath width** | 250 km |
| | **Inclination** | 98.18° | | **Sub-swaths** | 3 |
| | **Wavelength** | C-band (3.75-7.5 cm) | | **Incidence angle range** | 29.1° - 46.0° |
| | **Polarization** | Dual (VV+VH) | | **Spatial resolution** | 5x20 m (single look) |
| | **Temporal resolution** | Six days | | **Pixel Spacing** | 2.3x17.4 m |

### 2.2.2. Sentinel-2 Images

One scene of S-2A Level-1C (hereafter, L1C), with radiometric and geometric corrections, was acquired for this study. The S-2A L1C provides the top of atmosphere (TOP) reflectance. The image selected has 0% of cloud cover and dates from 2017-07-20. Disregarding the SWIR/Cirrus band, which was used for the atmospheric correction, all bands were used for the classification. The Table 2 illustrate the technical characteristics of the S-2A product collected.

**Table 2.** Main attributes of S-2A products and the scene selected.

| | | |
|---|---|---|
| **Temporal resolution** | Ten days for S-2A and five days for S-2A and S-2B | |
| **Swath width (km)** | 290 | |
| **Cloud cover of the scene** | 0% | |
| **Radiometric resolution** | 12 bits | |
| **Operation** | Since 23/06/2015-current | |
| **Imaging date** | 20/07/2017 | |
| **Spectral Bands** | **Central Wavelength (nm)** | **Spatial Resolution (m)** |
| Band 1 - Coastal Aerosol | 443 | 60 |
| Band 2 - Blue | 490 | 10 |
| Band 3 - Green | 560 | 10 |
| Band 4 - Red | 665 | 10 |
| Band 5 - Vegetation Red Edge | 705 | 20 |
| Band 6 - Vegetation Red Edge | 740 | 20 |
| Band 7 - Vegetation Red Edge | 783 | 20 |
| Band 8b - NIR | 842 | 10 |
| Band 8a - Vegetation Red Edge | 865 | 20 |
| Band 9 - Water Vapour | 945 | 60 |
| Band 10 - SWIR/Cirrus | 1375 | 60 |
| Band 11 - SWIR | 1610 | 20 |
| Band 12 - SWIR | 2190 | 20 |

### 2.2.3. Planet Imagery

Seventeen high-resolution Planet scenes acquiring in 2017-07-28 were used to validate the RF classification. Since early 2017, the sun-synchronous orbit of this satellite has the temporal resolution of one day, making it an excellent instrument for monitoring and data validation [60,61]. The specifications of the Planet mission for the images acquired are described in Table 3.

**Table 3.** Main attributes of Planet Labs imagery and the scene selected.

| **Temporal resolution** | Daily | |
|---|---|---|
| **Swath width** | 24.6km x 16.4km | |
| **Orbit Altitude (km)** | 475 (~98° inclination) | |
| **Cloud cover of the scenes** | 0% | |
| **Radiometric resolution** | 12 bits | |
| **Operation** | Daily imagery since 14/02/2017-current | |
| **Imaging date** | 28/07/2017 | |
| **Spectral Bands** | **Wavelength (nm)** | **Spatial Resolution (m)** |
| Blue | 455-515 | 3 |
| Green | 500-590 | 3 |
| Red | 590-670 | 3 |
| NIR | 780-860 | 3 |

## *2.3. Data analysis*

The data processing is presented in the flowchart illustrated in Figure 2 and involves: (i) pre-processing and data integration; (ii) product segmentation and RF classification; and (iii) accuracy assessment and validation.

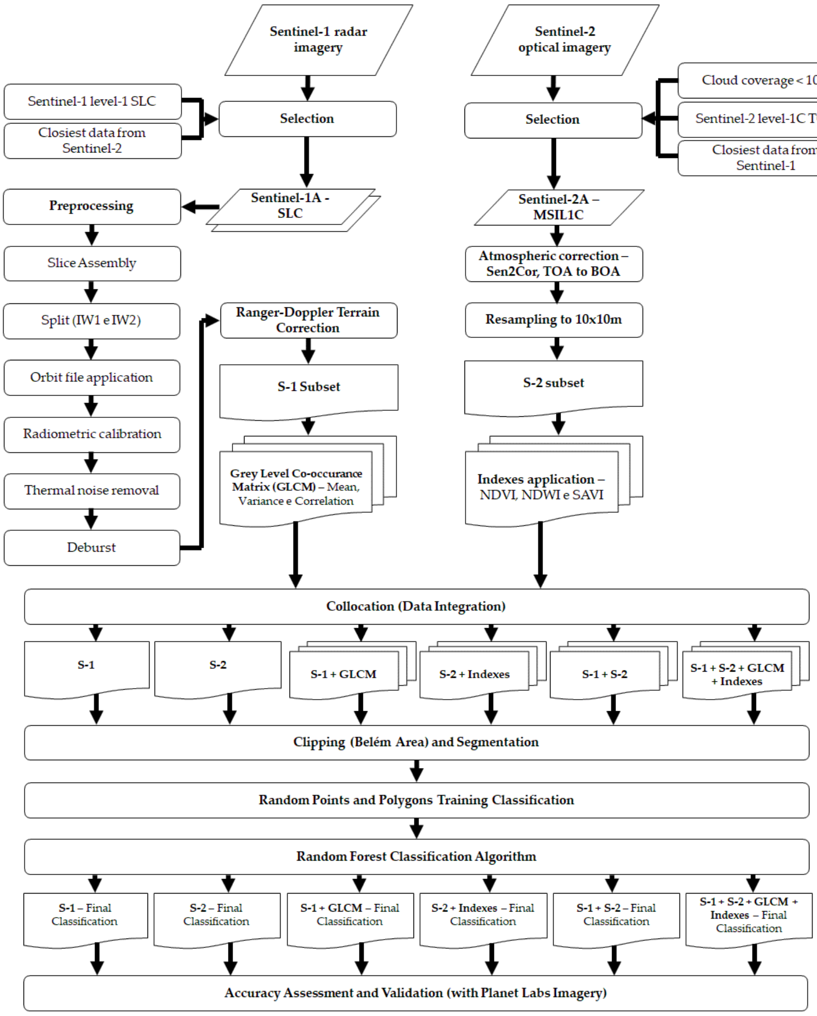



**Figure 2.** Process flowchart for RF classification of LULC classes using S-1 and S-2 integration and validation with Planet Labs imagery.

### 2.3.1. Pre-processing data

The pre-processing of the S-2 consisted in the atmospheric correction of the data, made by Sen2Cor algorithm [36,62,63] to obtain surface reflectance. All the S-2 spectral bands were resampled to 10m spectral resolution using the bilinear upsampling method and a mean downsampling method.

As already indicated, two S-1 images were also used, and a slice assemble technique was required to join them. A split of the sub swots IW1 and IW2 was applied to reduce the scene size, hence improving the processing time. The application of the orbit file, radiometric correction, thermal noise removal, and deburst was applied as it is a well-consolidated methodology. We opt to do not apply a Speckle filter, using the Multilooking with a single look (5m Range looks and 20m Azimuth looks). Finally, a range-Doppler terrain correction was applied, using the UTM WGS84 projection and the 30m SRTM, where a 10m resampling was made to fit the integration requirements [27,36,37,64].

### 2.3.2. Radar textures and Multispectral indexes

Metric textures were generated from S-1 data and vegetation and water indexes from S-2 images. Three grey-level co-occurrence matrix (GLCM) texture metrics were applied to both S-1 polarisations (VV and VH) with a window size of 5x5 in all directions based on the variogram method [65]. In order to test the application effectiveness of these indexes and metrics in the RF classification, they were tested together and separately [40,46,66]. The indexes employed, and their correspondent equations are described in Table 4. The SNAP 6.0 software was used for this task.

**Table 4.** Textural analysis and radiometric indexes employed in this research.

| S-2 Indexes | | References |
|---|---|---|
| **Index applied** | **Equation*** | |
| NDVI | $\frac{NIR - Red}{NIR + Red}$ | [67] |
| NDWI | $\frac{NIR - MIR}{NIR + MIR}$ | [68] |
| SAVI | $\frac{L * (NIR - Red)}{NIR + Red + 0.5}$ | [69] |
| **S-1 GLCM Textural Measures** | | |
| Mean | $\sum_{i,j=0}^{N-1} iP_{i,j}$ | |
| Variance | $\sum_{i,j=0}^{N-1} iP_{i,j}(i-\mu)^2$ | [70] |
| Correlation | $\frac{\sum_{i,j=0}^{N-1} iP_{i,j} - \mu_x\mu_y}{\sigma_x\sigma_y}$ | |

*Where NIR is the near infrared band, 842nm for S-2, for NDVI, NDWI and SAVI; Red is 665nm for S-2 for NDVI and SAVI; MIR is 2,190nm for S-2, for NDWI; P(i,j) is a normalized grey-tone spatial dependence matrix such that SUM(i,j=0, N-1) (P(i,j))=1; i and j represent row and column respectively, for Mean, Variace and Correlation measures; μ is the mean, for the Variance textural measure; and N is the number of distinct grey levels in the quantised image; μx. μy, σx and σy are the means and standard deviations of px and py respectively, for the Correlation textural measure.

### 2.3.3. Image stacking and image segmentation

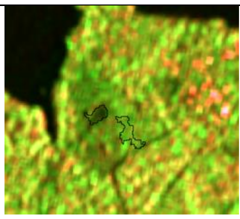
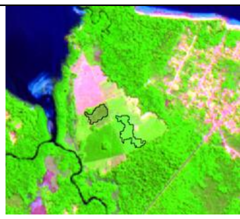
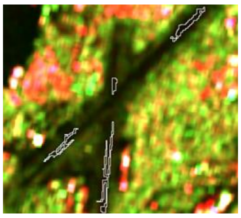
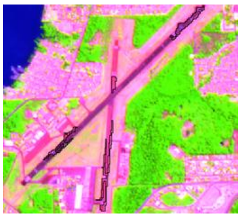
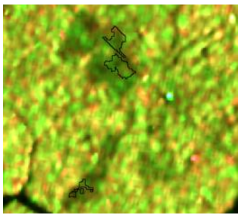
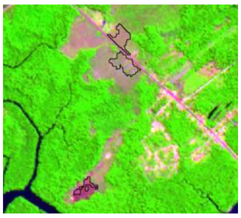
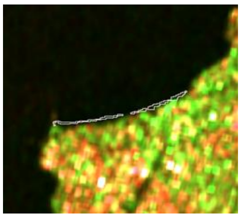
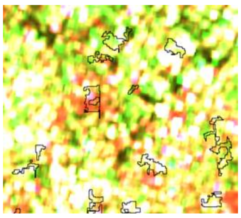
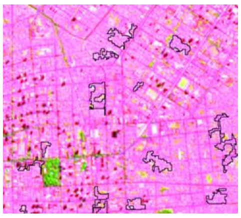
For the image stacking of the S-1 and S-2 products it was used the nearest neighbour resampling method. In the tool selected two products were used, where the pixel values of one product (the slave) were resampled into the geographical raster of the other (the master) [71]. We used the S-1 product as the master and S-2 data as the slave [27,32,37,63,72]. Subsequently and similarly, the integration was made with S-2 and vegetation and water indexes; S-1 and GLCM textural measures, and the combination of all products generated [46].

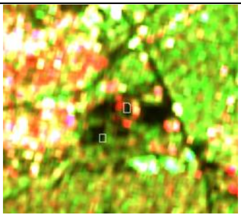
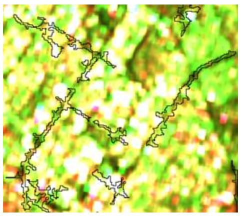
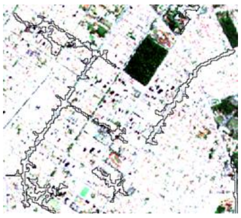
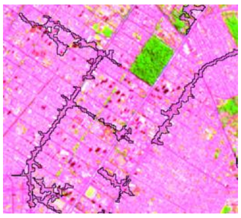
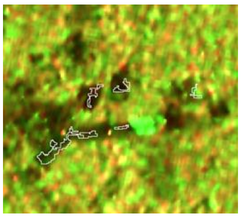
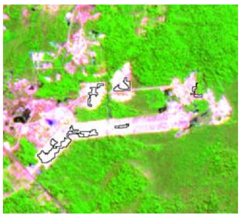
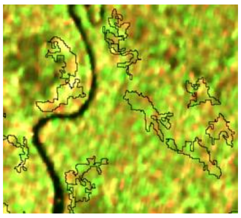
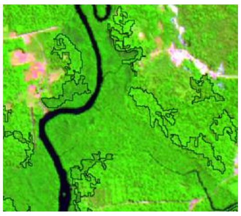
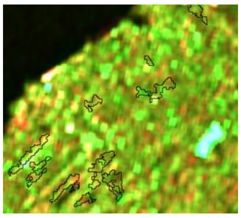
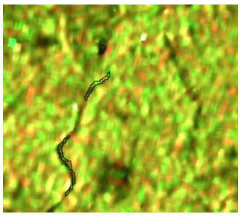
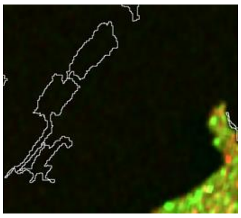
To better aggregate pixels with similar values, a segmentation procedure was performed in SNAP [32,73,74]. This procedure was made using only the collocation of S-1 and S-2 products. For that, a local mutual best fitting region merging criteria was performed and a Baatz & Schape merging cost criteria selected [75,76]. A total of 82.246 segments were produced.

#### 2.3.4. Random points' classification and RF image classification

After the segmentation process, all the other steps were developed in a GIS software. Basically, 1.600 random points were defined to be overlapped by the segmentation polygons, and these were visually interpreted as one of the twelve selected classes. The twelve classes were defined considering the potential attributed by the literature to RF classification algorithm and the S-1 and S-2 synergy, and the particularities of the study area [27,37]. In Table 5 it is possible to identify how the classes were interpreted with coloured compositions for S-1 and S-2.

**Table 5.** Keys of Interpretation to recognise the different LULC with S-1 and S-2 coloured compositions.

| **Classes** | **Class code** | **S-1 (R:** VV; **G:** VH; **B:** VV/VH)* | **S-2 (R:** B4; **G:** B3; **B:** B2)* | **S-2 (R:** B12; **G:** B8; **B:** B4)* |
|---|---|---|---|---|
| Agriculture | C1 |  |  |  |
| Airport | C2 |  |  |  |
| Bare Soil | C3 |  |  |  |
| Beach | C4 |  |  |  |
| Built-up | C5 |  |  |  |

| | | | | |
|---|---|---|---|---|
| Grassland | C6 |  |  |  |
| Highway | C7 |  |  |  |
| Mining | C8 |  |  |  |
| Primary Vegetation | C9 |  |  |  |
| Urban Vegetation | C10 |  |  |  |
| Water without Sediments | C11 |  |  |  |
| Water with Sediments | C12 |  |  |  |

*The drawn polygons were the ones produced in the segmentation and classified for each class to perform the LULC classification.

We applied the RF based on user-defined parameters using ArcGIS 10.4. The RF classifier is based on tree-structure classifiers [47,52]. The users must define two parameters in RF, being the number of trees to grow in the forest (N) and the number of variables used to split each node [40,47]. In order to select the number of variables that provides sufficiently low correlation with adequate predictive power, we developed some tests to perform analysis with the best accuracy. All tests were chose proportionally with the default values proposed by Forkuor et al. [22]. The best possible scenario in the software chosen was with 700 max number of trees, and 1,000 max number of samples per class, values that we applied for all the six classifications made. These numbers were the most significant possible, once the literature suggests that there is no standard value for the number of trees (N) and the number of variables randomly sampled as candidates at each split (n) [50,52].

### 2.3.5. Accuracy Assessment

It was identified the contribution of each band to the classification and to the accuracy. These were essential information for decision making when choosing the bands for the classification and those which can be removed intending to decrease the processing time. For accuracy assessment, 1,232 randomly points were used. These points were visually classified using the high-resolution Planet satellite imagery. The Producer's and User's accuracy (PA and UA) were estimated from each of the six RF classifications performed. Finally, the Overall Accuracy (OA) and kappa coefficient were calculated and ranked to highlight the most effective product.

## 3. Results

In Figure 3 it is illustrated the six LULC classification produced.

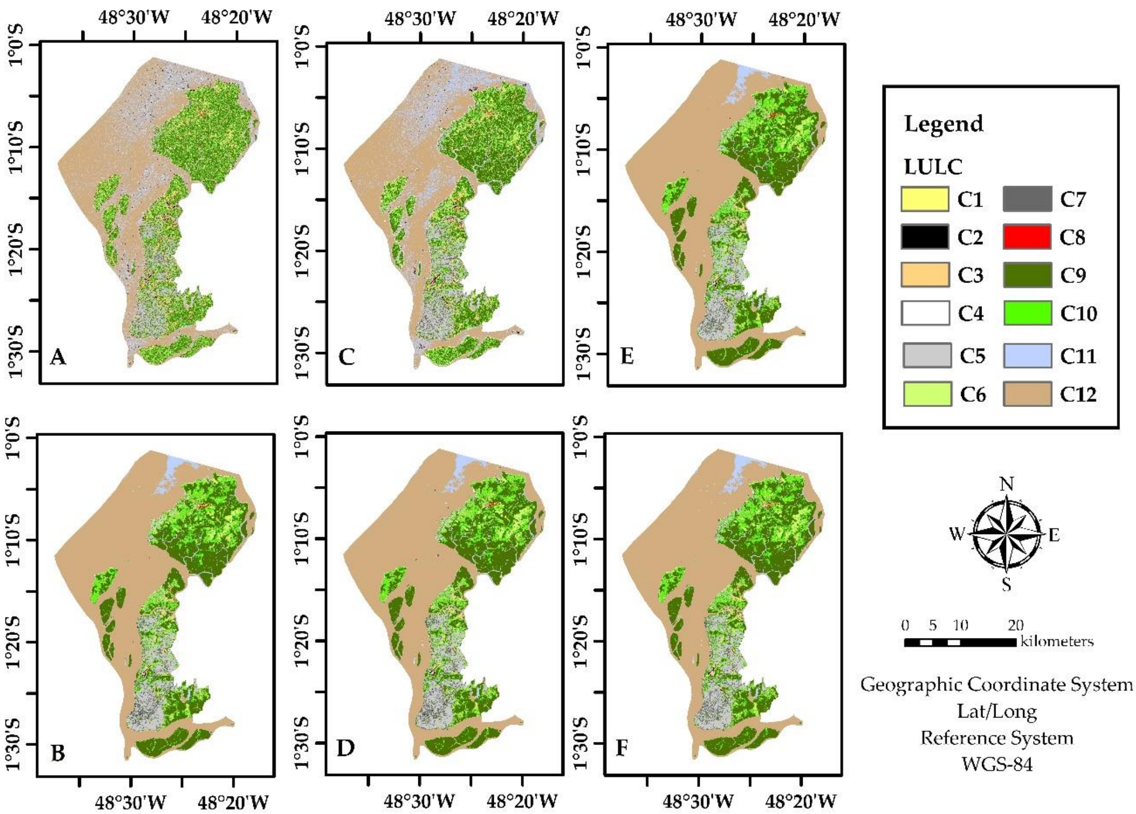



**Figure 3.** LULC classification maps produced by RFs*#.

*Where A is for S-1 only; B is for S-2 only; C is for S-1 and GLCM textures; D is for S-2 and radiometric indexes; E is for S-1 and S-2; and F is for All bands jointed together.

#The classes are represented as follows: C1 = Agriculture; C2 = Airport; C3 = Bare Soil; C4 = Beach area; C5 = Built-up; C6 = Grassland; C7 = Highway; C8 = Mining; C9 = Primary vegetation; C10 = Urban vegetation; C11 = Water without sediments; and C12 = Water with sediments.

The contribution of each band for the six RF classifications produced are described in Figures 4A, 4B, 4C, 4D, 4E, and 4F. The band 12 of the S-2 product (SWIR band) was the only that repeats as the most significant contributor for the RF classification made, Figures 4B and 4E, classifications with only the S-2 and for the classification of S-1 and S-2. Thus, in all the classification that contains the S-2, some of its bands were identified as one of the most significant contributors to the classification. Therefore, for the classification with all products, the red band of the S-2 had the highest contribution (0.0641), for S-1 together with S-2 and for the S-2 only, it was the SWIR band 12 of the S-2 (0.1 and 0.1067, respectively), and for S-2 and indexes it was the SWIR band 11 (0.084). On the other hand, for the classifications that only consider the SAR products, it was shown that the largest contribution was from the S-1 VV (0.6307) and for S-1 and its textures, it was the S-1 VH GLCM Mean (0.1434).

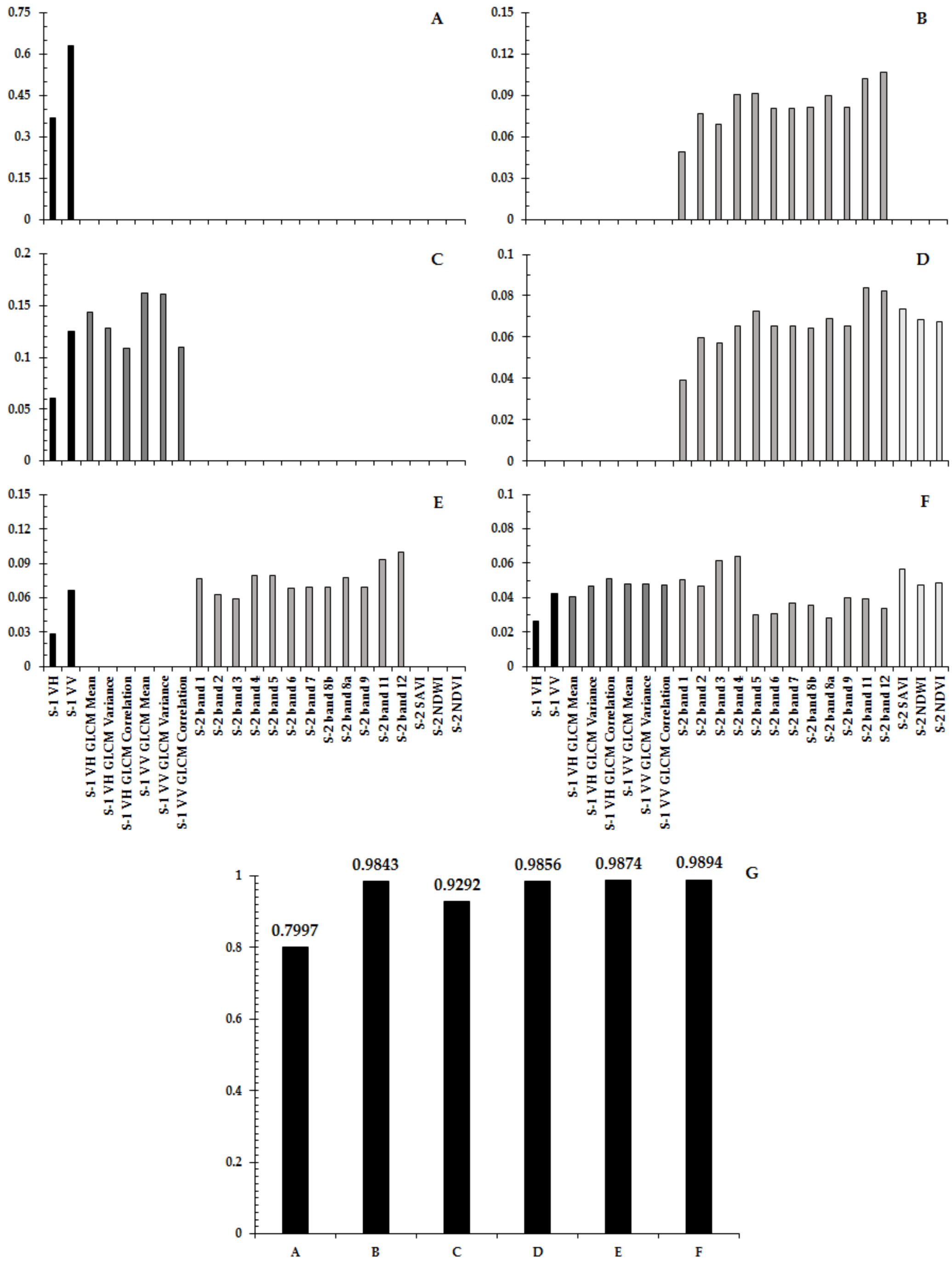



**Figure 4.** Bands contribution for classification and the training accuracy of each classification made*.

*Where A is the bands contribution for the S-1 only, B is for S-2 only, C is for the collocation of radar and its textures, D represents S-2 and its indexes, E is for the integration of S-1 and S-2, F is for the bands contributions where all the bands selected and produced were used, and G is the train accuracy for the classifications made in figures A, B, C, D, E and F.

The train accuracy of all classifications is also described in Figure 4G. The train accuracy found was similar for four of the classifications produced: 0.9894 (for all variables), 0.9874 (for integration of S-1 and S-2), 0.9856 (for S-2 with its radiometric indexes), and 0.9843 (S-2 only). The train accuracy for the integration of S-1 and its textural analysis was a slightly worse (0.9292). Hence, the S-1 along with their textures presented better results than only the S-1 product (0.7997).

The PA and UA results are presented in Figure 5. The optical integration with radar and the optical only classifiers stands out with generally better results of PA. The worst results were found for classifiers without the S-2, being them the S-1 only and the S-1 with the GLCM secondary products. The UA followed a similar trend. The worst result by class was found for the agriculture and mining classes in the classifier that used radar and its textures, where the results for both PA and UA were equal to 0%. However, the mining class achieved 100% in PA for all classifiers that had S-2 bands. S-2 only, S-2 with its indexes and the integration of S-1 with S-2 had more than one PA equals to 100%, Agriculture (C1) and mining (C8) were repeated in all these classifications, for the integration of S-1 and S-2, the Airport (C2) class also had PA equals to 100%. The only UA with 100% accuracy was for the identification of beaches in the classification S-2 with indexes.

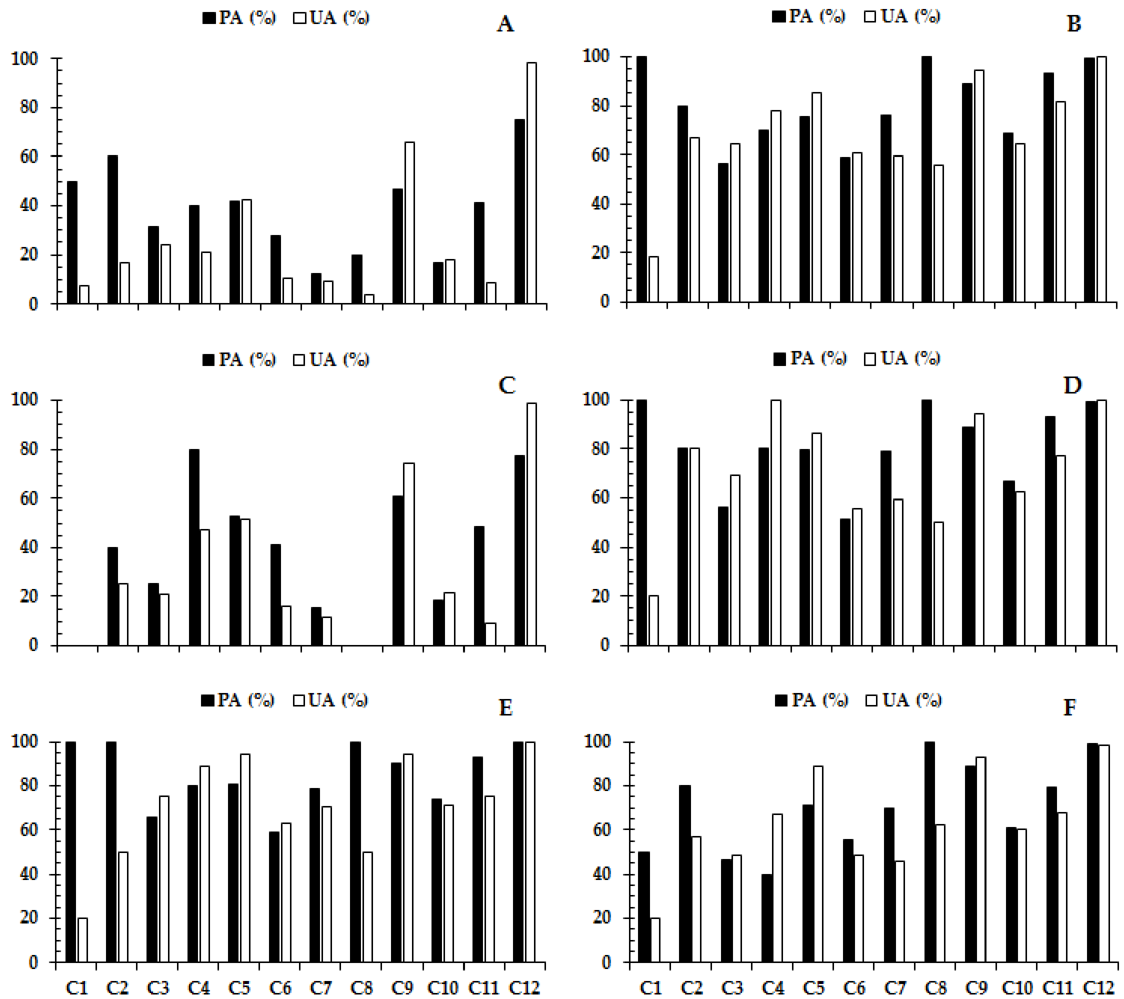



**Figure 5.** PA and UA for each class in the different types of RF classifications produced*#.

*Where the image A is the PA and UA for the S-1 only, B is for S-2 only, C is for the integration of S-1 and its textures, D represents S-2 and its radiometric indexes, E is for the integration of S-1 and S-2, and F is for the UA and PA all the bands selected and produced were used.

#The classes are represented as follows: C1 = Agriculture; C2 = Airport; C3 = Bare Soil; C4 = Beach area; C5 = Built-up; C6 = Grassland; C7 = Highway; C8 = Mining; C9 = Primary vegetation; C10 = Urban vegetation; C11 = Water without sediments; and C12 = Water with sediments.

Table 6 illustrate the OA and the Kappa coefficient found in this research. It is possible to understand that the integration of the S-1 and the S-2 products resulted in a more precise product (91.07% of OA and 0.8709 of Kappa), and as expected, the S-1 product alone had the worst result of all the analyses (56.01% of OA and 0.4194 of Kappa). The inclusion of textures in the S-1 products increased the results of the RF classification (61.61% OA and 0.4870 of Kappa), on the other hand the inclusion of vegetation and water indexes in the S-2 product reduced its OA (89.45%) and Kappa coefficient (0.8476), when compared with the S-2 alone (89.53% of OA and 0.8487 for the Kappa coefficient). The integration of all the products analysed produced the worst result among all the data combination that have S-2 products involved (87.09% OA and 0.8132 of Kappa coefficient). However, the results of OA and Kappa coefficient for the four best classifications were similar.

**Table 6.** OA and Kappa coefficient for each classifier. They have been ranked in order of accuracy.

| Data combination | Overall Accuracy (%) | Kappa Coefficient | Rank |
|---|---|---|---|
| S-1 with S-2 | 91.07 | 0.8709 | 1 |
| S-2 Only | 89.53 | 0.8487 | 2 |
| S-2 with Indexes | 89.45 | 0.8476 | 3 |
| All | 87.09 | 0.8132 | 4 |
| S-1 with Textures | 61.61 | 0.4870 | 5 |
| S-1 Only | 56.01 | 0.4194 | 6 |

## 4. Discussion

Among the ML methods described in the literature [50], SVM and RF stand out for their good classification final accuracy. These methods usually have good results when compared with similar methods, such as k-NN or more sophisticated ones such ANN and Object Based Image Analysis (OBIA) methods [27,36,49]. It is also verified that the application of radiometric indexes and radar textures is widely accepted as mean to improve ML classification [11,27,36,46,63,77].

Among the authors who applied several ML methods (RF, SVM and k-NN), Clerici et al. [36] consider the data fusion of S-1 and S-2 products. They also applied radiometric vegetation indexes (NDVI, Sentinel-2 Red-Edge Position index (S2REP), Green Normalized Difference Vegetation Index (GNDVI), and Modified SAVI) and textural analysis of the S-1, in order to interpret their contributions to the supervised classification accuracy. Six classes were tested after segmentation to have similar pixel values. Their results were considerably worse than ours. In their image stacking, they found an OA of 55.50% and a Kappa coefficient of 0.49. The isolated results of S-1 and S-2 were also worse than our integration. They suggest SVM for their study area because it presents better accuracy results. One important step that we adopted for improving our classification was the segmentation, the implementation of this action can explain the difference between their and our results.

Whyte et al. [27] applied RF and SVM algorithms for LULC classification in the synergy of S-1 and S-2. They applied derivatives from both S-1 and S-2 to test the data combination for LULC. They selected 15 classes and found better results when using all products (S-1, S-2 and their derivatives) using the RF algorithm. The OA was 83.3% and the Kappa coefficient was 0.72. However, all the scenarios of synergy appeared to have higher results than using optical data only. This study contrast to what we found, once our results with derivatives were worse in almost all circumstances, except in S-1 and GLCM stacking.

Zhang & Xu [49] also applied the fusion test of optical images and radar for multiple classifiers (RF, SVM, ANN and Maximum Likelihood). Optical images of Landsat TM and SPOT 5 were used, while SAR images of ENVISAT ASAR/TSX. The authors could interpret that the best values were found for the RF and SVM classifications, while the fusion of optical and SAR data contributed to the improvement of the classification, increasing the accuracy by 10%.

Deus [46] used the synergy of ALOS/PALSAR L band and Landsat 5 TM and applied several vegetation indexes and SAR textural analysis. The author applied the SVM algorithm in order to obtain five LULC classes. Their highest OA was 95% when only the features with the best performance in the classification were combined, that including both PALSAR and TM bands and their derivatives.

Jhonnerie et al. [78] and Pavanelli et al. [40] also used ALOS/PALSAR and the Landsat family. They considered 8 and 17 LULC classes, respectively. Both studies applied the RF algorithm. They applied vegetation indexes and GLCM textural analysis. For the RF classification, both authors found their highest OA and Kappa coefficient results for the hybrid model, 81.1% and 0.760 [78], and 82.96% and 0.81 [40].

Erinjery et al. [11] also used the synergy between S-1 and S-2, and their derivatives to compare results from two ML, including Maximum Likelihood and RF. The total number of classes was seven. For the RF classification, an OA of 83.5% and a Kappa coefficient of 0.79 were found. They state the inclusion of SAR data and textural features for RF classification as a tool to improve the classification accuracy. Similarly, to our study, they found OA lower than 50% when using only the S-1 product.

Braun & Hochschild [64], by investigating environmental assessment around refugee camps combined S-1, RapidEye and SRTM products, consider the RF technique to classify 10 LULC classes and found an OA of 84% in their best classification. These authors found their best result in the stacking of the most significant number of bands, which contrasts with our results since that integration of all variables did not increase the classification accuracy.

Shao et al. [77] integrated the S-1 SAR imagery with the GaoFan optical data to apply a RF classification algorithm in six different LULC classes. They also produce SAR GLCM textures and vegetation indexes. Their best result was obtained considering all the features stacked. An OA of 95.33% and a Kappa coefficient of 0.91 was obtained. The use of S-1 only had the worst result, with an OA of 68.80% and a Kappa coefficient of 0.35.

Srestasathiern & Sukawattanavijit [79] compared results of the nearest neighbour object-based classification with the SVM algorithm. They used an optical image with similar spectral resolution with S-2, the THAICHOTE (15m) and SAR imagery with better resolution than S-1, COSMO-SkyMed (9m). A segmentation algorithm was employed to define classes. For the SVM they found an OA of 77% and a Kappa coefficient of 0.667. However, they considered only four classes. They also suggest that object-based methods obtain better accuracy results than ML algorithms for classification purposes.

Chatziantoniou et al. [63] fused S-1 and S-2 imagery with SRTM to apply a SVM classification. The authors calculated the NDVI and NDWI in aggregation with GLCM textural analysis. They also applied a segmentation algorithm to identify regions of interest with similar values. They found an OA of 94.82% and a Kappa coefficient of 0.9362, slightly better than our better result. These authors also suggest the manual post classification to improve the accuracy in the results, depending on the final objective.

Haas & Ban [37] in a data fusion analysis of S-1 and S-2 applied the SVM classification method. Considering 14 classes, they found an OA of 79.81% and a Kappa coefficient of 0.78. The authors suggested the post-classification analysis to improve its accuracy once they final objective was to have area values to apply the benefits transfer method of Burkhard et al. [17] to environmentally evaluate the urban ecosystem services of an area. The number of classes was similar to our study, and it was possible to check that the accuracy was superior.

In regional studies [2] and for global applications [80,81] of RF classification the results found of OA were below of ours. Their OA results were: 75.17% [81], 63% for South America using RF [80], and 76.64% for Amazon LULC classification [2]. All these studies used satellite data with a temporal resolution of 16 days and a spatial resolution of 30m. In contrast, we found results with a revisit time of 5 days for optical and six days for SAR, and with a greater spatial resolution (10m). Also, we produced a dataset with more classes (12) against six [80] and seven [81] classes found for global studies, which makes the separation of features more complex.

## 5. Conclusions

In this work, the best result found was in the integration of S-1 and S-2 products. In general, integrating the vegetation and water indexes and SAR textural features made the OA and kappa coefficient decrease. The worse result was found for the S-1 the only classification. The results encountered agreed in its most part with the literature. For our better classifications, the OA results were significantly greater than what is found in the literature for global and Amazon applications of RF classification.

Both in the PA and UA scenarios and the Kappa statistic scenario, it can be stated that the integration of S-1 and S-2 presented better results in the implemented ML technique. However, if in one hand the GLCM increased the SAR product accuracy, on the other hand, the inclusion of vegetation and water indexes decreased the optical accuracy, when compared with the single use of S-1 and S-2, respectively. Lastly, the results found for the integration of all products were worse than the ones observed for the combination of S-1 and S-2 only.

Depending on the final aim of the LULC classification, it could be relevant to make a post-classification analysis because many spectral responses resemble each other and can confuse the learning of the machine. However, in the best scenario produced, the accuracy found was satisfactory for several types of analysis. Furthermore, it is possible to use the data integration of S-1 and S-2 to LULC cover classification in tropical regions. It is noteworthy that few studies with similar methodology were found in the literature for the southern hemisphere.

In this sense we contribute in state of the art by producing a more accurate data locally, with better revisit opportunities and with more classes than global studies, which considered our study area. Future work must be done with S-1 and its variables; once in tropical regions, it is difficult to have long terms of optical data available. Finally, we encourage the synergetic use of S-1 and S-2 for LULC classification, considering the availability on near date.

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## 4. ARTIGO 3: Mapping urban ecosystem services supply and demand for local management in a coastal Amazon city.

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**Mapping urban ecosystem services supply and demand for local management in a coastal Amazon city**

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**ABSTRACT**

The supply and demand analysis of Urban Ecosystem Service (UES) are a rising concept from the perspective of developing sustainable cities. The environmental challenges of cities, such as high urbanisation, is also found in Amazon towns, such as the Municipality of Belém, second largest city in Brazilian Amazon. In this sense, in this paper we aimed at mapping and comprehending the supply and demand UES dynamic in Belém, so that it is coherent and pliable to integration at the local public policy level. For this purpose, we carried out a Random Forest (RF) Land Use and Land Cover (LULC) classification, including a post-classification to reduce the uncertainty of the data. We ranked the supply and demand of UES (regulating, provision and cultural), from -5 to 5, for each LULC class and give total results for each administrative district (DA) in town. The DAs located in the continental part of Belém, densely populated, were the ones with worst results in the provision of UES. Periurban areas, islands and water bodies were the responsible for the most part UES provision in Belém. We also found opportunities to increase urban and secondary vegetation areas in all DAs. The strategically development plan for the Municipality of Belém was the public arena found in which the actors for sustainable development in town can incorporate UES budget into environmental and social local development. We highlight that the local sustainable development actors should seek chiefly to maintain and restore protected areas that are at risk and, subsequently, to increase urban forests areas.

**Keywords:** Urban Planning, Urban Green Spaces, Benefit Transfer, Remote Sensing, Optical and Radar Data Integration, Random Forest.

## 1. Introduction

The conservation and restoration of terrestrial and aquatic ecosystems are fundamental for maintaining the biodiversity and resilience of natural areas, as well as providing Ecosystem Service (ES) of provision, regulation, habitat (support) and cultural (TEEB, 2010). Thus, natural areas are expressed with high economic values, when studied from the perspective of the ES (Costanza et al., 2017, 1997; de Groot et al., 2012; Kubiszewski et al., 2017).

The use of the concepts of ES has become of great value for management, preservation or restoration of natural environments, reconciled with the progress of human well-being (Burkhard et al., 2018; Oudenhoven et al., 2018; TEEB, 2010). Conciliatory models of development that encompass economic, environmental and social development are considered as ideal in an ES perspective (de Groot et al., 2010; Kubiszewski et al., 2017). Based on this approach, public policies are also promoted and go beyond a rationale in the process of carbon sequestration and stock, which tends to fail to preserve local and global biodiversity (Ferreira et al., 2018).

Cities are the places where the most significant part of ES beneficiaries resides and is also an ecosystem by itself (McPhearson et al., 2016b). Therefore, it must be considered as essential study areas for urban ES (UES) analysis (Kremer et al., 2016a; Locke and McPhearson, 2018; McPhearson et al., 2016a, 2016b) and integration for local management (Burkhard et al., 2018; Cortinovis and Geneletti, 2018; Nedkov et al., 2018; Schubert et al., 2018). In this context, research must not only discriminate which each area provides ES, but also illustrate and implicate how these ES concepts and values can be incorporated into the urban plan perspective (Burkhard et al., 2018; Olander et al., 2017), so scientist must stand up for the future of the cities (McPhearson et al., 2016a). However, knowledge production in UES is still concentrated in the developed countries, especially Europe (Alavipanah et al., 2017; Haase et al., 2014).

The application of remote sensing (RS) data and techniques for ecological applications have grown (Burgess et al., 2016; Kwok, 2018; Paul and Mascarenhas, 1981). RS is widely used for UES identification, and the most used technique in the scientific literature is the land use and land cover (LULC) (Alavipanah et al., 2017; Goldenberg et al., 2017; Haas and Ban, 2017; Kopecká et al., 2017; Kremer et al., 2016b; McPhearson et al., 2013). However, the use of satellite imagery generally has an aggregate acquisition cost, being Landsat and Sentinel families the more famous free data with satisfactory spatial, spectral, radiometric and temporal resolution (Ayanu et al., 2012; Muller-Karger et al., 2018; Poursanidis and Chrysoulakis, 2017).

These imagery characteristics are fundamental to produce reliable results considering biodiversity variables and reducing the uncertainties related to RS (Muller-Karger et al., 2018; Song, 2018). When used together Landsat-8 and Sentinel-2 Multispectral Instrument (hereafter, S-2 MSI) have a temporal resolution of fewer than three days, being adequate for environmental monitoring (Forkuor et al., 2018).

The LULC application is generally used to analyse the anthropisation of natural areas and are related to significant changes in ecosystems functionality and the provision of ES (Wolff et al., 2017). LULC techniques are usually linked to an Overall Accuracy (OA), which relates to how reliable the model of representation of the earth's surface can represent the use or coverage of the Earth that it presents (Jensen, 2014). The OA can be identified as an uncertainty in the analysis of the Earth's coverage, leading to a modification of the understanding from the perspective of the ES (Song, 2018). Therefore, data and techniques in RS should be processed in a way that reduces the uncertainty generated by these data (Rosa et al., 2014).

In what refers to the LULC models, considerable effort has been made concerning the improvement of the machine learning algorithms, since these algorithms allow the interpretation of complex spectral signatures and accurate identification of classes of LULC from the earth (Maxwell et al., 2018). Among these methods, we highlight the Random Forest (RF) (Breiman, 2001), which we used for processing our data. In the RF classification, the user selects the number of "number of trees" and "number of variables that will be randomly selected as candidates for each tree" so that in the end the candidates with the highest number of votes are defined as a class.

A highly used ES approach is the spatially explicit benefit transfer technique, which is based on deriving ES values or budget through a mathematic function that is derived from a case of study (Masiero et al., 2018). The benefits transfer approach works well with LULC variables since the literature uses different LULC classes for different regions with this technique (Burkhard et al., 2012; Goldenberg et al., 2017; Haas and Ban, 2017; Nedkov et al., 2018). In some cases, where previously ES valuation studies were carried out in the area, the economic valuation of each LULC is also an alternative to be assessed (Liu et al., 2010; Nedkov et al., 2018; Sannigrahi et al., 2018).

In the European Union, where understanding and application of ES values and concepts are more advanced regarding acting, there is the ESMERALDA (Enhancing ecosystem services mapping for policy and decision-making) project (Burkhard et al., 2018). This project aims at developing scientific knowledge, through ES mapping and assessment strategies, to mobilise relevant actors, so that they can improve local environmental management concerning ES (Burkhard et al., 2018; Nedkov et al., 2018). The ES assessment and incorporation in public policy is also an alternative regarding catch up with the United Nations Sustainable Development Goals, implemented in 2015 (Costanza et al., 2016).

The Brazilian states of the Amazon region have some experiences in the identification, classification and valuation of ES, considering spatial information from RS (Barbosa et al., 2016; Le Clec'h et al., 2018; Strand et al., 2018). However, such studies do not consider the peculiarities of each region and, when analysed at municipal or microregion scale, they tend to decrease their accuracy in estimating ES when compared to more local studies involving better spatial data and the interpretation of the local realities (Carvalho and Szlafsztein, 2018; Le Clec'h et al., 2016; Rosa et al., 2014; Song, 2018).

In Brazil, public action is increasingly being treated regarding the territory, an approach that is considered the most adequate to manage public problems resulting from the effects of globalisation and environmental demands (Teisserenc and Teisserenc, 2014). In order to support such local collective action, public policies may foresee "generic technical devices" that create "relatively stable frameworks or contexts of action and negotiation," however the technical effectiveness of these devices is dependent on their relationship to values and principles of action on the territory (Teisserenc et al., 2016). In this perspective, the Brazilian legal system has foreseen the strategically development plans as instruments of municipal planning, which allows the popular participation in the land use decision making, aiming to guarantee the well-being of its inhabitants (Oliveira et al., 2018).

The regulation of this instrument of municipal planning is contained in Law No. 10.257/2001, also known as the “City Statute”, being obligatory to Municipalities with more than twenty thousand inhabitants (Brasil, 2001). The “City Statute highlights the municipal competence for the planning of its territory, according to article 182 of the Brazilian Federal Constitution (Brasil, 1988). However, social participation in these plans only arose from urban social movements. These movements suggested three primary directives: i) the democratic management of the city, concretized in the active participation of the government and other actors, i.e., producers, users and occupants of the territory in negotiation forums, aiming the creation of agreements; ii) the promotion of the social function of the city through the use of instruments that inhibit the speculative use of the soil and promote social equity through land and urban regularization; and iii) the right to the city that consists of the perception of social justice and quality of life (intangible aspects of both individual and collective well-being within the city) (Souza and Silva, 2010).

Natural attributes of the Municipality of Belém's, played an essential role in the formation of the town, since rivers and forests were barriers that made occupation difficult, requiring transformations in the physical structure of the territory for expansion purposes, directly affecting the socioeconomic variables, territorial and cultural characteristics that characterize the territory of Belém (Cardoso and Ventura Neto, 2013). Belém has several infrastructural problems and many areas naturally prone to flooding (Mansur et al., 2018), this together with the fact that less than 10% of all the sewage produced in the city is treated (ITB, 2017) make it relevant to assess ES demand and supply in this area. As part of the Amazon coastal zone, and also biggest city in eastern Amazon, the city also faces the challenge of incorporating into its public policy the management of these natural areas related to the coast region (Szlafsztein, 2012).

In this context, we consider the urban planning of green spaces as a problem for Brazilian Amazon large cities. Hence, we suggest that the incorporation of UES concepts and the supply and demand analysis are a reliable approach for urban planning and can be incorporated into the strategically development plan for these cities. Thus, in this paper, we conceived a derived approach from the European ESMERALDA project, aiming at mapping the supply and demand of UES for each management unit in the Municipality of Belém, Brasil, using an RS data and technique analysis. We also identify the possibilities for incorporating these concepts into the local strategic management plan, and the role that the actors for sustainable development must play in this perspective.

## 2. Material and Methods

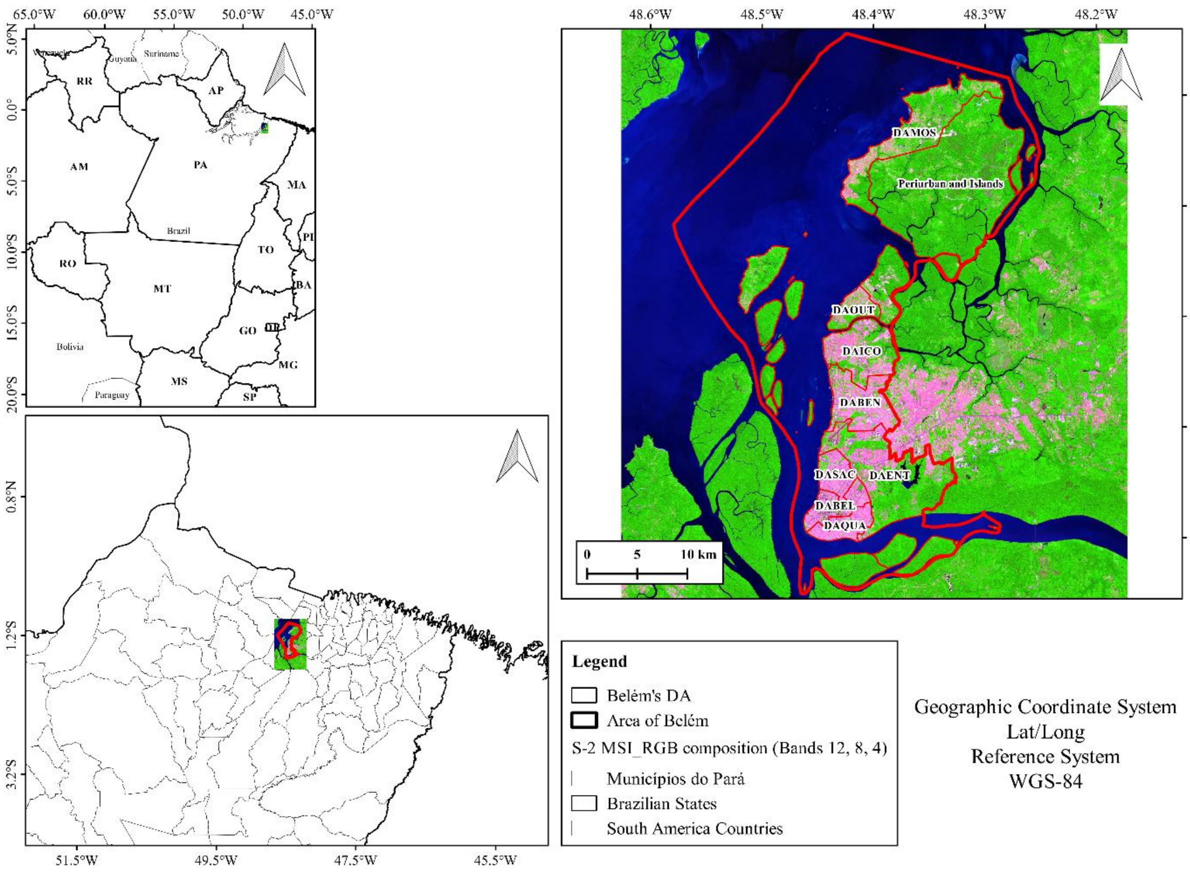
The following subsections describe how we collect, process and understand the data for UES classes and values estimation and its possible incorporation into the local management for the study area.

### *2.1. Study area*

Our study was developed in the Municipality of Belém, Brazil. Belém is the second largest city in Amazon (1,393,399 in 2010 and 1,452,275 residents estimated for 2017), which is subdivided into eight Administrative Districts (DA, an acronym of original Portuguese expression), and rural areas, which are mainly periurban and islands regions (IBGE, 2010). The DAs are named as follows: Belém (DABEL), Guamá (DAGUA), Sacramenta (DASAC), Bengui (DABEN), Entroncamento (DAENT), Mosqueiro (DAMOS), Icoaraci (DAICO), Outeiro (DAOUT). The climate for the area is classified as tropical Afi, in the Köppen, with an average rainfall of 2,834mm per year (Pará, 2017). Belém's fragments of natural vegetation are characterised as Terra Firme and Várzea forests, both incorporated in the dense Ombrophilous types of vegetation (Amaral et al., 2009).

Figure 1 illustrates the location of the city of Belém and the geographical area of each DA in the municipality (a map with an S-2 MSI RBG composition is given in the Supplementary material, to help readers to visualise better the location of the city of Belém and the area covered by each remote sensor scene used).

**Figure 1.** Localisation map of the city of Belém, where it is also illustrated the localisation of each DAs and periurban area existing in the town. *(This is a two-column Figure)*




As the Brazilian demographic census is released every ten years, we considered the populations per DA considering the data from 2010 (IBGE, 2010). The Belém's statistical yearbook, last issued in 2012, shows a survey on the existing green areas per DA (Belém, 2012). Both information, population and green areas, are shown in Table 1.

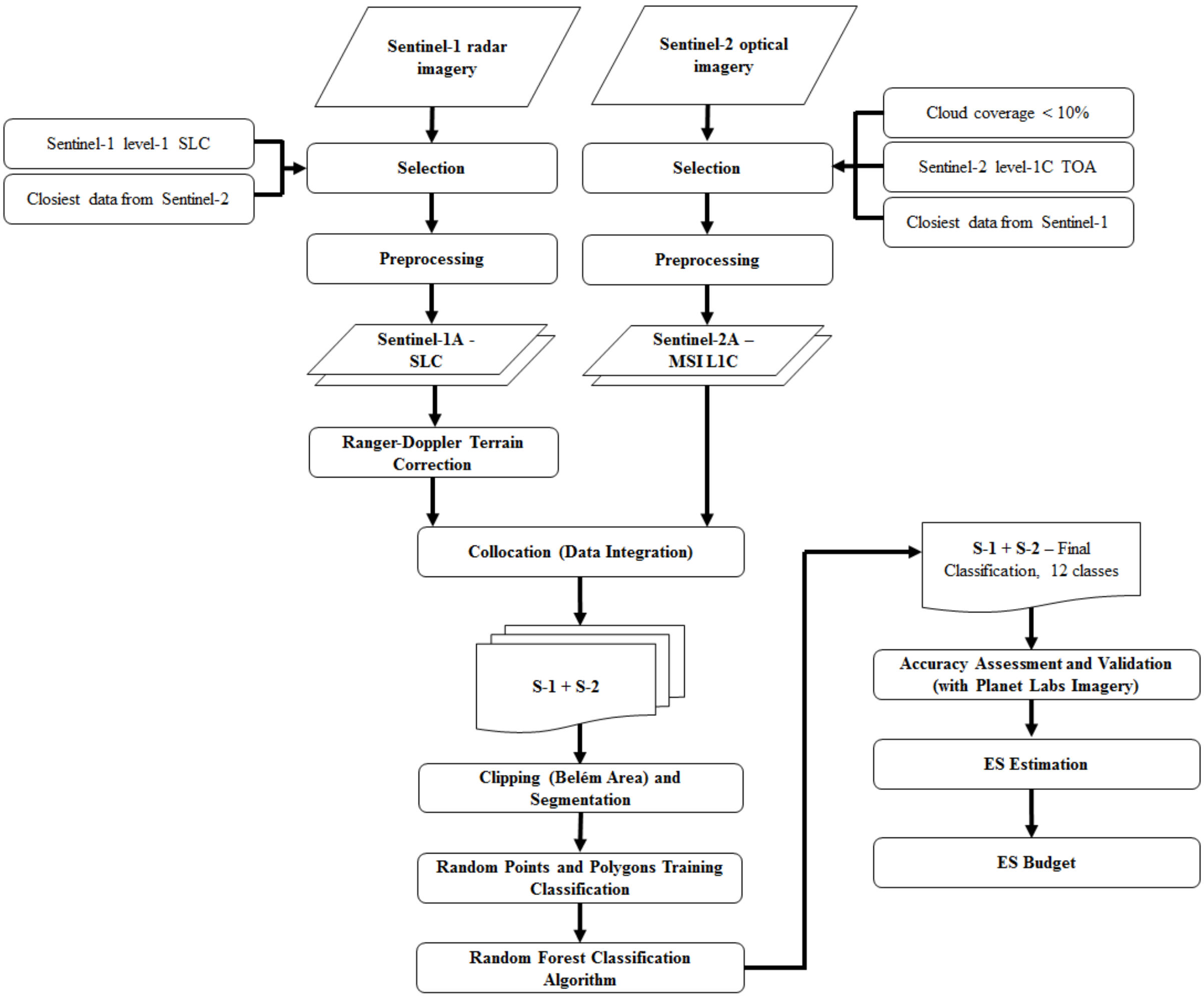
**Table 1.** Total population and the amount of registered green areas for each DA in Belém. (T*his is a one column Table*)

| DA | Total Population (nº of inhabitants) | Total number of green areas |
|---|---|---|
| DABEL | 144,948 | 89 |
| DABEN | 284,670 | 66 |
| DAENT | 125,400 | 93 |
| DAICO | 167,035 | 13 |
| DAMOS | 33,232 | 35 |
| DAOUT | 38,731 (urban) and 10,086 (rural) | 5 |
| DAGUA | 342,742 | 46 |
| DASAC | 256,641 | 47 |

*2.2. LULC data processing*

We collected Sentinel-1 Single Look Complex (hereafter, S-1 SLC) and S-2 MSI, which were processed as illustrated in Figure 2.

**Figure 2.** Flowchart of the random forest classification with the integration of S-1 and S-2 images to estimate and budget ES. *(This is a two-column Figure)*



#### 2.2.1. S-1 SLC and S-2 MSI data pre-processing, integration and segmentation

For the S-1 SLC products, we selected two scenes dating from 21 July 2017, which were pre-processed in the Sentinel Application Platform 6.0 (hereafter, SNAP 6.0). The Slice Assemble was used to join the two scenes, and the split was used to separate only the IW1 and IW2 sub swots, to reduce processing time. The application of the orbit file, radiometric correction, thermal noise removal, and deburst were applied as recommended in SNAP 6.0. We used the Multilooking with a single look (5m Range looks and 20m Azimuth looks) to decrease the product size and processing time. Lastly, we applied the Range-Doppler Terrain Correction, projecting the scenes in UTM WGS84 and they were resampled in 10 meters to meet the image integration requirements (Haas and Ban, 2017; Whyte et al., 2018).

One scene of S-2 MSI dating from 20 July 2017 was used. We used the SNAP 6.0 software for S-2 MSI data pre-processing. For which we applied the Sen2Cor atmospheric correction (Doxani et al., 2018) for all bands, converting into an S-2 MSI level 2A, a surface reflectance product. All bands of S-2 MSI were resampled into 10 meters using the bilinear upsampling method and a mean downsampling method.

To integrate the S-1 SLC and S-2 MSI images we used a nearest neighbour resampling method. The pixel values of the S-2 MSI product was resampled into the geographical raster of the S-1 scenes, a process which is called collocation in the SNAP 6.0 toolbox (ESA, 2014).

We carried out a segmentation in the integrated data of S-1 SLC and S-2 MSI. The segmentation method chosen was the Baatz & Schape, which uses a local mutual best fitting region merging criteria to joint together neighbouring pixels with similar values (Baatz and Schäpe, 2000; Lassalle et al., 2015). We produced 82.246 segments, from which we visually classified 2,800 segments, 1,600 for RF classification and 1,200 for validation purposes.

#### 2.2.2. Image classification, accuracy assessment and area calculation

These three steps were developed in the ArcGIS 10.4 GIS software. For image classification, we selected the RF LULC classification algorithm (Breiman, 2001). We defined 700 as the maximum number of trees and 1,000 as the max number of samples per class. We then analysed the OA and the Kappa Coefficient to illustrate the precision of the product that we produced. We also post classified the image, in order the reduce ambiguity and uncertainties, by having a more accurate data (Chatziantoniou et al., 2017; Haas and Ban, 2017; Song, 2018). The areas for each class were calculated using the GIS software mentioned.

## *2.3. ES supply and demand analysis*

Due to the lack of local studies in UES provision, we applied a benefit transfer technique derived from existing estimative in the scientific literature to obtain the UES provision in the Municipality of Belém. We produced a matrix analysis of the ES supply and demand, ranking the demand from -5 (the ES demand exceeds the supply) to 0 (neutral value), and the supply from 0 to 5 (the supply of ES exceeds the demand) (Burkhard et al., 2012; Goldenberg et al., 2017; Haas and Ban, 2017; Nedkov et al., 2018). We developed the matrix, by investigating the literature and considering authors knowledge about the location and role of each LULC plays in the study area, producing an estimative of supply or demand for each LULC class in a UES approach. In our analysis, we used the same ES considered in Burkhard et al. (2012) study. Figure 3 illustrates the way we analysed the provision of ES in each LULC class.

**Figure 3.** Describes the supply or demand of ES related to each type of LULC. *(This is a two column Figure)*

| LULC class | Average Regulating services | Local climate regulation | Global climate regulation | Flood protection | Groundwater recharge | Air quality regulation | Erosion regulation | Nutrient regulation | Water purification | Polination | Avergae Provision services | Crops | Livestock | Fodder | Capture fisheries | Acquaculture | Wild foods | Timber | Wood fuel | Energy | Biochemicals/Medicine | Freshwater | Average Cultural services | Recreation & aesthetic values | Intrinsic value of biodiversity | Average All services |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Croplands | **-1.1** | 0 | -1 | -1 | 1 | -1 | -2 | -3 | 0 | -3 | **1.4** | 4 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | **0.5** | 1 | 0 | **0.3** |
| Airport | **-1.9** | -2 | -5 | -1 | -1 | -4 | -1 | -1 | -2 | 0 | **-1.5** | -2 | -2 | 1 | -1 | -1 | -1 | -1 | 0 | -5 | -1 | -3 | **-0.5** | -1 | 0 | **-1.3** |
| Bare Soil | **-1.7** | 0 | 0 | -5 | -2 | 0 | -5 | 0 | -3 | 0 | **0.0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.0** | 0 | 0 | **-0.6** |
| Beaches | **0.7** | 0 | 0 | 5 | 1 | 0 | 0 | 0 | 0 | 0 | **0.1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | **2.5** | 4 | 1 | **1.1** |
| Built-up Area | **-3.1** | -5 | -3 | -4 | -5 | -5 | -1 | -1 | -1 | -3 | **-4.1** | -5 | -5 | -1 | -5 | -5 | -5 | -3 | -2 | -4 | -5 | -5 | **-3.0** | -4 | -2 | **-3.4** |
| Grassland | **2.4** | 2 | 3 | 1 | 1 | 0 | 5 | 5 | 5 | 0 | **0.5** | 0 | 3 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | **3.0** | 3 | 3 | **2.0** |
| Highways | **-2.1** | -2 | -4 | -4 | -1 | -4 | -3 | 0 | 0 | -1 | **-0.6** | 0 | 0 | 0 | 0 | 0 | 0 | -2 | 0 | -4 | 0 | -1 | **-1.0** | -2 | 0 | **-1.2** |
| Mining | **-1.1** | 0 | 0 | -2 | -4 | 0 | -4 | 0 | 0 | 0 | **-0.2** | 0 | 0 | 0 | 0 | 0 | 0 | -2 | 0 | 2 | 0 | -2 | **0.0** | 0 | 0 | **-0.4** |
| Primary Vegetation | **4.3** | 5 | 4 | 3 | 2 | 5 | 5 | 5 | 5 | 5 | **1.7** | 0 | 0 | 1 | 0 | 0 | 4 | 4 | 4 | 1 | 5 | 0 | **5.0** | 5 | 5 | **3.7** |
| Urban/Secondary Vegetation | **0.9** | 3 | 1 | 0 | 1 | 0 | 2 | 1 | 1 | -1 | **-0.3** | -1 | -1 | 0 | 0 | 0 | 1 | 0 | 1 | -1 | 0 | -2 | **-1.0** | -1 | -1 | **-0.1** |
| Water without Sediments | **2.9** | 5 | 0 | 5 | 5 | 0 | 0 | 3 | 5 | 3 | **1.8** | 0 | 0 | 0 | 5 | 0 | 5 | 0 | 0 | 5 | 0 | 5 | **5.0** | 5 | 5 | **3.2** |
| Water with Sediments | **2.9** | 5 | 0 | 5 | 5 | 0 | 0 | 3 | 5 | 3 | **1.8** | 0 | 0 | 0 | 5 | 0 | 5 | 0 | 0 | 5 | 0 | 5 | **5.0** | 5 | 5 | **3.2** |

## *2.4. Local management of urban green spaces*

We carried out documental research in the strategically development plan of Belém established by the local Law nº 8,655 of 30 July 2008 (Belém, 2008). Concerning this document, we investigate its contents to understand how and where the contribution of our study could be incorporated in the context of the actor's involvement in local sustainable development. We propose how the ES supply and demand analysis can be added as an instrument for improving local urban management and improving local quality of life.

## 3. Results

### *3.1. LULC classification*

The LULC classification produced using the S-1 SLC and S-2 MSI data integration had an OA of 91.07% and a Kappa Coefficient of 0.8709. In Figure 4, we illustrate the map produced after the post classification assessment.

**Figure 4.** LULC classification produced for the city of Belém. *(This is a two column Figure)*

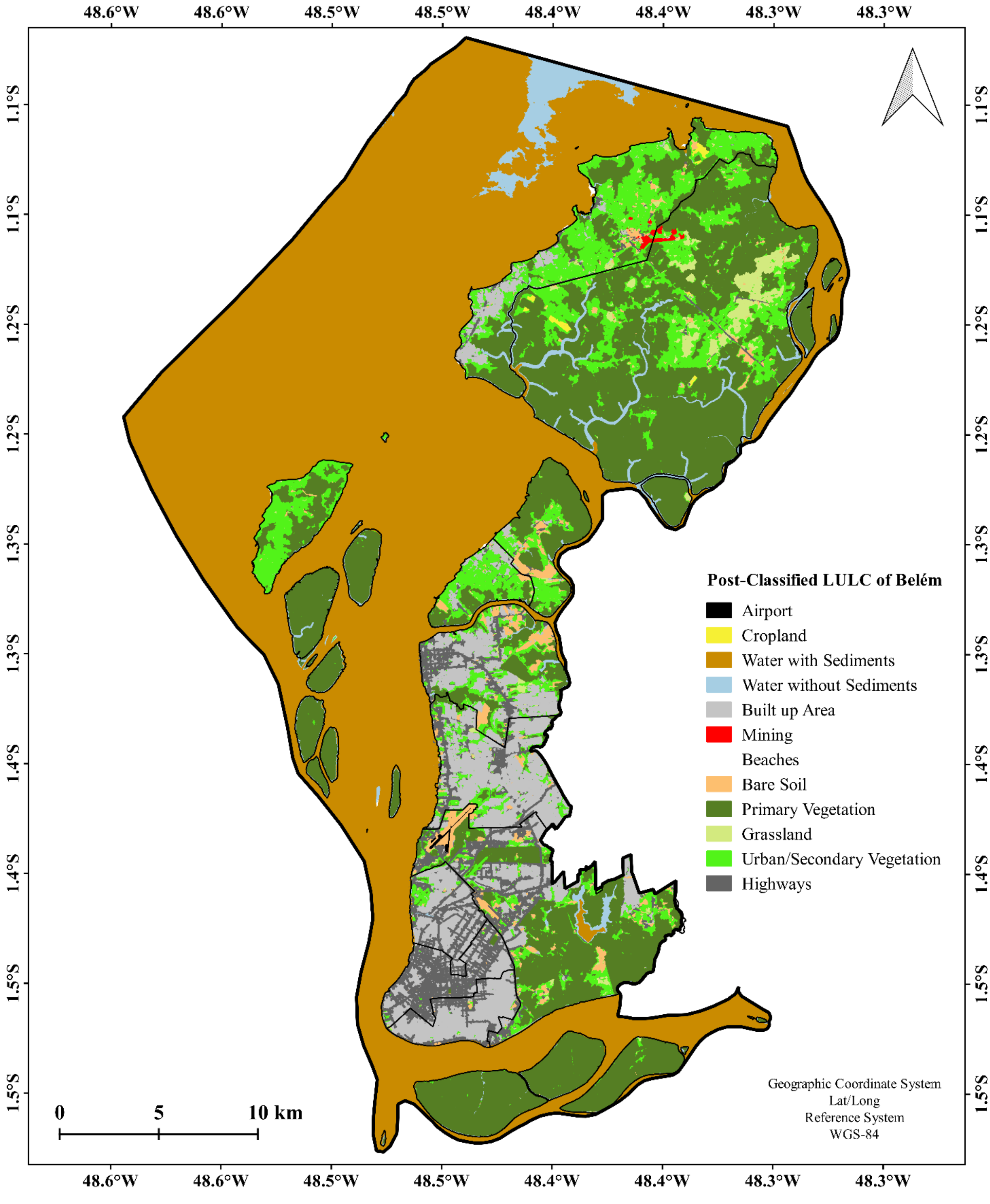


Table 2 shows the area of each LULC class for each DA and the islands and periurban area. In this table, we can see that the primary vegetation area exists mainly in the islands and periurban region. DAENT and DAMOS are the urbanised DAs with a higher amount of natural area preserved. DAENT is where it is located the Utinga conservation unit, thus, it should not be deforested or urbanised. Moreover, the DA of Mosqueiro is a leisure area in the Municipality of Belém, thereby is where we should find most of the Cultural ES in the town.

**Table 2.** Area of each LULC class (in hectare) per DA and in the periurban and islands areas of the municipality of Belém. *(This is a two column Table)*

| LULC | DABEL (ha) | DABEN (ha) | DAENT (ha) | DAICO (ha) | DAMOS (ha) | DAOUT (ha) | DAGUA (ha) | DASAC (ha) | Islands & Periurban (ha) |
|---|---|---|---|---|---|---|---|---|---|
| Airport | 0 | 0 | 54.97 | 0 | 0 | 0 | 0 | 0.16 | 0 |
| Croplands | 0 | 0 | 0 | 0.06 | 41.99 | 0 | 0 | 0 | 72.86 |
| Water with Sediments | 0 | 0 | 113.6 | 0.75 | 0.84 | 0 | 0 | 0.01 | 225.69 |
| Water without Sediments | 2.5 | 44 | 197.35 | 57.39 | 490.06 | 21.89 | 4.03 | 14.42 | 1,300.5 |
| Built-up Area | 1,998.06 | 2,040.4 | 3,372.43 | 1,658.62 | 546.46 | 167.14 | 1,214.17 | 952.7 | 203.7 |
| Mining | 0 | 0 | 0 | 0 | 62.46 | 0 | 0 | 0 | 60.72 |
| Beaches | 0 | 0 | 0 | 1.4 | 107.2 | 16.94 | 0 | 0 | 68.59 |
| Bare Soil | 51.72 | 262.4 | 612.8 | 367.71 | 306.58 | 133.64 | 38.76 | 34.09 | 747.95 |
| Primary Vegetation | 18.08 | 342.16 | 2,903.63 | 684.27 | 4,676.26 | 280.7 | 0 | 47.56 | 18,264.71 |
| Grassland | 16.78 | 91.93 | 281.47 | 142 | 459.19 | 63.5 | 11.16 | 17.91 | 1450.5 |
| Urban/Secondary Vegetation | 60.92 | 602.05 | 1,238.06 | 666.41 | 2,595.58 | 561.67 | 47.2 | 109.46 | 5,296.23 |
| Highways | 1,260.05 | 1,954.16 | 1,669.01 | 694.27 | 324.43 | 138.9 | 1,341.37 | 1,455.6 | 274.7 |
| **Total Area** | 3,408.11 | 5,337.1 | 10,443.32 | 4,272.88 | 9,611.05 | 1,384.38 | 2,656.69 | 2,631.91 | 27,966.15 |

Still considering the Table 2, we can visualise that DAMOS and DAOUT are the only DAs that have higher amounts of green spaces (grassland, primary and secondary vegetation) than urbanised areas (built up and highways). DAENT, DABEN and DABEL are the most urbanised areas in the city, among which DABEN has the second highest population in town. DAGUA, which is the most inhabited district, is also the DA with the lowest rates of green area, which may be a problem regarding social well-being.

*3.2. Supply and Demand of UES for the DAs of Belém*

In Table 3, we listed the UES balance for each of the urban, periurban and islands analysed. For the total area of Belém, we found that the supply of ES exceeds the demand in all four categories investigated (provision, regulating, supporting and cultural). Islands and the periurban regions are primarily responsible for the supply of ES in the land surface area considered. However, when we considered only the land surface area (DAs, periurban and island areas), we have identified a sharp drop in the provision of UES, reaching the point of demand exceeds supply in all scenarios analysed.

**Table 3.** UES budget for each DA, islands and periurban area and the total area of Belém. *(this is a one column Table)*

| DA | Regulating Services | Provision Services | Cultural Services | All Services |
|---|---|---|---|---|
| DABEL | -2.58 | -2.63 | -2.10 | -2.43 |
| DABEN | -1.60 | -1.69 | -1.21 | -1.50 |
| DAENT | 0.01 | -0.92 | 0.37 | -0.18 |
| DAICO | -0.74 | -1.42 | -0.51 | -0.89 |
| DAMOS | 2.31 | 0.63 | 2.39 | 1.78 |
| DAOUT | 0.66 | -0.27 | 0.39 | 0.26 |
| DAGUA | -2.48 | -2.19 | -1.87 | -2.18 |
| DASAC | -2.17 | -1.80 | -1.54 | -1.84 |
| Islands and Periurban | 3.19 | 1.17 | 3.48 | 2.61 |
| **Land surface area only** | **-0.38** | **-1.01** | **-0.07** | **-0.49** |
| **The total area of Belém** | **2.32** | **1.04** | **3.54** | **2.30** |

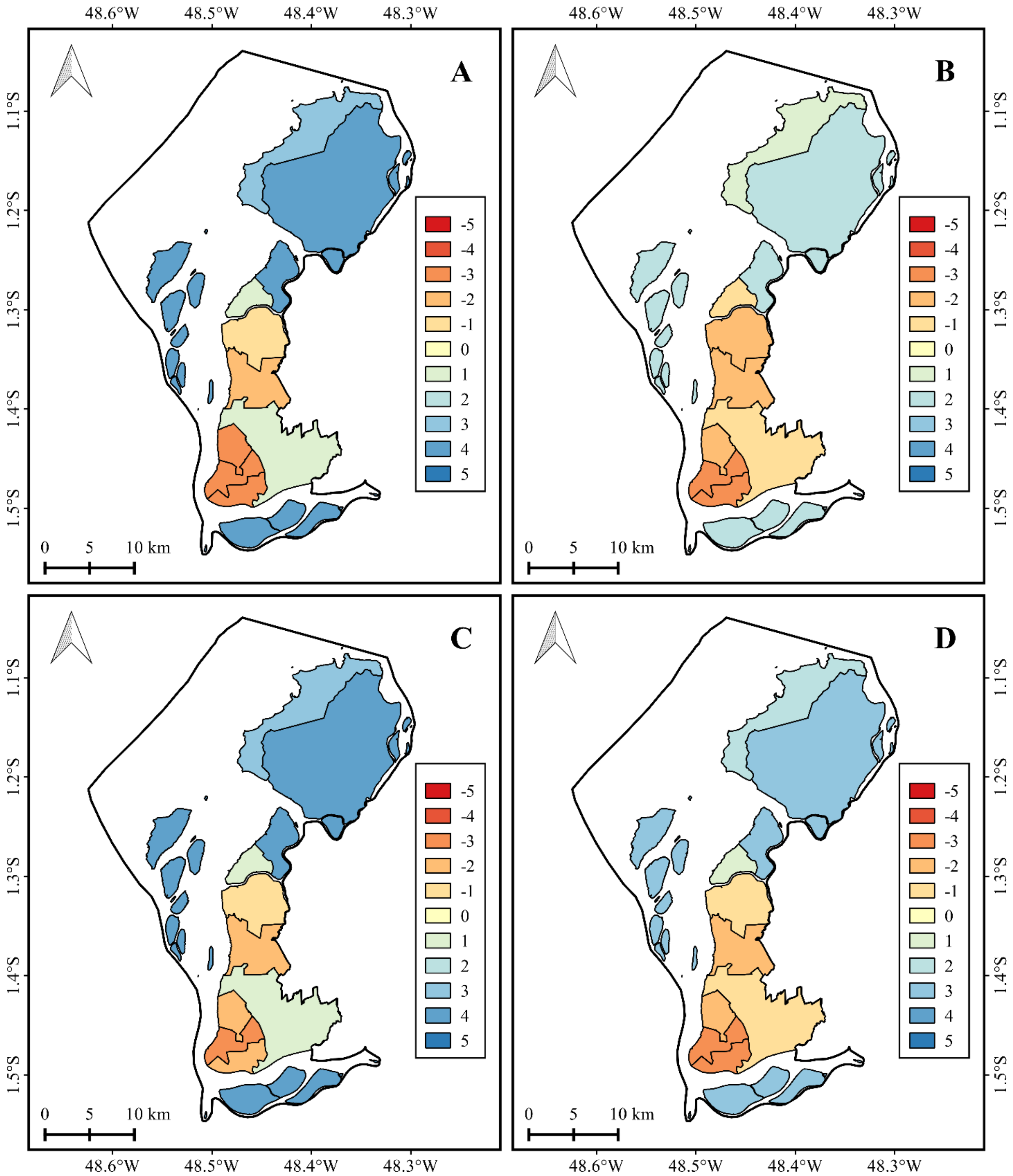
In one hand, DAMOS and DAOUT are the positive highlight, because they are the only urban areas where the supply exceeds the demand when all services are considered, being DAMOS the only one to offer more UES than the demanded in all categories. On the other hand, DABEL has the negative highlight, since in all three categories the demand exceeds the -2 value. DABEN, DAICO, DAGUA and DASAC also obtained negative values of supplying ES in all categories analysed. The UES analysis for DAENT showed positive values for two of the categories (regulating and cultural services). However, we emphasise that this only occur due to the existence of the Utinga conservation unit in the area, which is responsible for most of its UES provision.

For the three main categories of UES analysed, DAGUA is the DA area where the demand far exceeds the supplying of UES, while DAMOS and had better results, considering only the urban areas. Interestingly, DAGUA is the DA with the most significant population rates in Belém, whereas DAMOS has the smallest. In this way, we point out that in Belém the loss of ES is inextricably linked with the expansion of urbanisation to human habitation and urban mobility, due to through the ease of transportation.

Another worth noting point is the dependency of ES-derived from water areas. We can notice that comparing the ES budget for only land surface areas and the total municipal area of Belém (Table 3). Considering the water class area, we found high positive values in the supply of regulating (+2.32), provision (+1.04), cultural (+3.54), whereas when we disregard the rivers, the values fall to -0.38, -1.01 and -0.07, respectively.

In Figure 5, we illustrate the supply and demand analysis of UES (regulating, provision, and cultural services) for each of the DAs of the Municipality of Belém. In Figures 4 and 5 we noticed that most of the urbanisation in Belém occurred in the continental area of the town (DABEL, DABEN, DAENT, DAICO, DAGUA e DASAC). Therefore, demand for UES is higher in these areas, being the supply generally offered only by conservation units.

**Figure 5.** Ranking of Supply and Demand of the four classes of ES per DA of the city of Belém, where: A) Regulating Services; B) Provision Services; C) Cultural Services; and D) Average for All Services. *(this is a two column Figure)*



DAMOS and DAOUT LULC classification (Figure 4) shows that these are the urbanised areas with the most diversified classes (including water bodies and croplands) and are also the only urban areas where the supply of UES exceeds the demand. Both areas are commonly used for leisure, including beaches and bucolical places.

**4. Discussion**

Our LULC classification result was higher than other studies that used data integration from optical and radar products from the Sentinel family, for ES purposes or not (Clerici et al., 2017; Haas and Ban, 2017; Whyte et al., 2018). Our OA and kappa coefficient results were also higher than the accuracy of the Brazilian Amazon official LULC data (Almeida et al., 2016). Therefore, the use of our LULC map would be recommended to reduce the uncertainties related to the processing of RS data (Song, 2018) and for the same reason the post-classification was necessary and applied (Chatziantoniou et al., 2017; Haas and Ban, 2017).

As seen in the studies from ITB (2017) and Mansur et al. (2018), Belém faces challenges related to the provision of essential public services, one of the is the not treatment of the city's sewage. Thus, it is noted the importance of the provision of UES related to the water bodies in the town. For this reason, the water purification has high values regarding the supply of ES, and that is why the value of UES provision highly increases if we include the role played by the rivers in the account.

Carvalho and Szlafsztein (2018), in a regulation services approach for the years of 1986 and 2009 in the districts of DABEL, DASAC and DAGUA, found as the districts that absorb more pollutant in the following order (2009): DAGUA, DASAC and DABEL. These data are different than what we found for regulation services since we found better results for DASAC, followed for DAGUA and in the last position DABEL. This difference may only be for this to be a different approach on ES provision or may indicate that the green area loss was higher in DAGUA than in DASAC, once DABEL has remained in the same colocation and DASAC overtake DAGUAs position in 2017.

The green area loss is also a risk found for DAENT, due to the urbanisation process that it is occurring inside the area of the Utinga conservation unit, wherein the vegetation area decreased from 83% in 1984 to 72% in 2015 (Gutierrez et al., 2017). In the analysis of the LULC distribution inside each study area (Figure 4), the supply of regulating and cultural services is mostly dependent on the existence of this conservation unit.

Endreny (2018) explores the possibility of increasing ES provision in urban areas through the strategic growth of urban forests. The amount of urban/secondary vegetation areas is still low in all densely populated districts (DABEL, DABEN, DAGUA e DASAC). This low values of urban/secondary vegetation should be considered as an opportunity for the city of Belém, since many areas that have no occupation or human use (i.e. bare soil and grassland) were found in all DAs assessed, so this is an alternative for the development of urban forest areas.

In Latin America, de Mola et al. (2017), highlights the uncontrolled urbanisation process that exists in the area. For the authors, the urbanisation is the biggest threat to the urban green spaces, once in these areas, the rural exodus is continuing to happen. Similarly, we see in the comparison of our assessment with Carvalho and Szlafsztein (2018), and Gutierrez et al. (2017) result that the Belém’s landscape is continually changing, due to urban expansion and, consequently, increasing in built-up areas and streets.

Is also important to elucidate that high demand and low supply for UES is not only a problem for developing countries, Baró et al. (2015), in a UES involving five European cities (Stockholm, Salzburg, Barcelona, Rotterdam and Berlin), found the need to expand green areas for urban sustainability. Ins this sense, the urban sustainability depends on a joint effort of scientists from several countries, developed and in developing countries, to be reached, agreeing with what is proposed by McPhearson et al. (2016).

*4.1. Can we integrate these concepts in a local management perspective?*

Cardoso et al. (2016) describes that within its transformation into a metropolitan region, the urban landscape of Belém followed a modern land tenure. This expansion was marked by high indices of precariousness of dwellings and by the expansion and occupation around highways. In this perspective, there was the appreciation of the real estate capital and this reflected upon the preparation of the strategical development plan of Belém of 2008 (Belém, 2008). Therefore, despite having significant participation of community entities, in some points there was a softening of the social function of the city in favour of the real estate sector (Souza and Silva, 2010).

These strategic decisions on land use allocations during the planning process affect the availability and spatial distribution of green areas, which consequently influence the provision of UES in the territory of the Municipality (Cortinovis and Geneletti, 2018; Schubert et al., 2018). Therefore, Cortinovis and Geneletti (2018) argue that it is from the incorporation of ES concepts into the strategical development plans that their quality and ability to contribute to the promotion of strategic actions can be verified in order to structure sustainable and resilient cities (McPhearson et al., 2015).

This popular participation in the management of Brazilian cities by means of strategically development plans can occur through four instruments: i) collegiate bodies present at the national, state and municipal levels of urban management; ii) debates, hearings and public consultations; iii) national, state and municipal conferences on urban management; and iv) popular bill initiative in plans, programs and projects on urban development (Brasil, 2001; Oliveira et al., 2018).

For that reason, considering that the strategically development plan is an instrument that materialises local action, it is inferred that it is the way in which the ES approach can be incorporated as an innovation to address the environmental urban problems in the Municipality of Belém. It is also a way of inserting this new perspective to face the conflicts in the territory under analysis, through the intervention of the actors in the debates of its elaboration, revision or alteration, as a claims Burkhard et al. (2018) in the ESMERALDA project.

## 5. Final Considerations

Our study contributes to the construction of knowledge about the integration of optical and radar data with the perspective of UES mapping. Our classification OA was about 90%, and the post-classification contributed to reducing uncertainties related to RS data and technique applications. This LULC classification offered us better results than the Amazon project of LULC. Thus we recommend the use of this data for further studies in Belém, which uses LULC data.

In this study, we derived the ESMERALDA approach and introduced it in an Amazon urban area. We derived the concept of UES budget from Burkhard et al. (2012) study for the account of UES in our study area. We found that the Municipality of Belém is highly dependent on forest remnants and large river when considering an UES method. DAMOS was the only DA with supplying exceeding demand in all categories of ES analysed. All other urban DAs investigated obtained at least one negative (demand exceeds the supply) category for UES provision.

Our results elucidated that densely populated areas are also the ones with the lowest UES provision. A similar situation was found in the literature for developed countries. We also identified the opportunity to expand the urban and secondary vegetation in all DAs analysed. Such a procedure would mainly help on the local climate regulation, bringing greater thermal comfort and consequently a better quality of life for the population, which resides in the area.

Finally, by analysing the local and national legislation in cities, we found an excellent opportunity to insert UES concepts and budget in the strategical development plan. This instrument of public policy would allow the UES knowledge to be inserted through the actors of local sustainable development in order to reduce the urban environmental problems of the Belém. In this sense, actors should seek primarily to maintain and restore protected areas (conservation units) that are at risk and, secondarily, the development of urban forests in areas not (yet) occupied by human's population.

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## 5. CONSIDERAÇÕES FINAIS

Como contribuições do primeiro artigo desenvolvido nessa dissertação, foi identificado que a maior parte das pesquisas científicas voltadas para a identificação, classificação e modelagem de SE em áreas urbanas estão localizadas no hemisfério norte (93,18%). As principais formas de aquisição de dados de SR, para fins de SE urbanos, foram os dados secundários e os da família Landsat, sendo importante destacar que grande parte dos dados utilizados são gratuitos. A principal técnica de SR apresentada nos artigos integrantes da revisão de literatura foi o uso e cobertura da Terra, de onde os autores puderam derivar diversos tipos de SE. Os SE de regulação foram os que mais se repetiram nos estudos investigados.

A integração de dados do S-1 e do S-2, realizada no segundo artigo, nos possibilitou a aquisição de dados com acurácia geral variando entre 56,01% até 91,07%. Os quatro melhores resultados foram superiores aos encontrados nos principais mapeamentos já existentes para a região. Desta forma, percebe-se a importância do uso combinado de dados de radar e ópticos para fins de uso e cobertura da Terra, sendo encorajada a possibilidade de investigação futura com os dados de radar, uma vez que os mesmos não possuem interferências das nuvens, as quais tem grande influência na aquisição de dados ópticos na região Amazônica

No terceiro artigo desenvolvido, a pós-classificação, realizada nos melhores dados produzidos (advindos da fusão de dados do S-1 e dos S-2), possibilitou a aquisição de dados com menor possibilidades de incerteza, isso considerando o uso e cobertura da Terra. Nesse artigo, notou-se que uma grande parte dos SE existentes no município de Belém são derivados das grandes massas d'água que circundam a cidade. Apenas um distrito administrativo (Mosqueiro) obteve oferta maior que a demanda de SE, o mesmo possui uma diversidade maior de usos e coberturas da Terra, sendo também uma das principais áreas de lazer da região. As áreas mais densamente povoadas também foram as que obtiveram valores de demanda ultrapassando a oferta de SE.

Nessa dissertação, foi possível identificar também o plano diretor municipal de Belém como o principal instrumento para inserção de conceitos e valores de SE na governança pública para o desenvolvimento sustentável na região. Por fim, destaca-se a possibilidade e necessidade de investimentos futuros no aprimoramento das funções dos ecossistemas urbanos (por exemplo, criação e preservação de florestas urbanas e vias vegetadas), uma vez que as áreas urbanas são as localidades onde a maior parte da população vive, as mesmas devem fornecer qualidade de vida e bem-estar social para os cidadãos.

## ANEXO 1 – Diretrizes de Submissão Revista Land/MDPI e Sensors/MDPI

**Manuscript Preparation**
**General Considerations**
**Research manuscripts should comprise:**

Front matter: Title, Author list, Affiliations, Abstract, Keywords

Research manuscript sections: Introduction, Materials and Methods, Results, Discussion, Conclusions (optional).

Back matter: Supplementary Materials, Acknowledgments, Author Contributions, Conflicts of Interest, References.

Review manuscripts should comprise the front matter, literature review sections and the back matter. The template file can also be used to prepare the front and back matter of your review manuscript. It is not necessary to follow the remaining structure. Structured reviews and meta-analyses should use the same structure as research articles and ensure they conform to the PRISMA guidelines.

Graphical abstract: Authors are encouraged to provide a graphical abstract as a self-explanatory image to appear alongside with the text abstract in the Table of Contents. Figures should be a high quality image in any common image format. Note that images displayed online will be up to 11 by 9 cm on screen and the figure should be clear at this size.

Abbreviations should be defined in parentheses the first time they appear in the abstract, main text, and in figure or table captions and used consistently thereafter.

SI Units (International System of Units) should be used. Imperial, US customary and other units should be converted to SI units whenever possible

Equations: If you are using Word, please use either the Microsoft Equation Editor or the MathType add-on. Equations should be editable by the editorial office and not appear in a picture format.

Research Data and supplementary materials: Note that publication of your manuscript implies that you must make all materials, data, and protocols associated with the publication available to readers. Disclose at the submission stage any restrictions on the availability of materials or information. Read the information about Supplementary Materials and Data Deposit for additional guidelines.

Preregistration: Where authors have preregistered studies or analysis plans, links to the preregistration must be provided in the manuscript.

Guidelines and standards: MDPI follows standards and guidelines for certain types of research. See https://www.mdpi.com/editorial_process for further information.

**Front Matter**

These sections should appear in all manuscript types

Title: The title of your manuscript should be concise, specific and relevant. It should identify if the study reports (human or animal) trial data, or is a systematic review, meta-analysis or replication study.

Author List and Affiliations: Authors' full first and last names must be provided. The initials of any middle names can be added. The PubMed/MEDLINE standard format is used for affiliations: complete address information including city, zip code, state/province, country, and all email addresses. At least one author should be designated as corresponding author, and his or her email address and other details should be included at the end of the affiliation section. Please read the criteria to qualify for authorship.

Abstract: The abstract should be a total of about 200 words maximum. The abstract should be a single paragraph and should follow the style of structured abstracts, but without headings: 1) Background: Place the question addressed in a broad context and highlight the purpose of the study; 2) Methods: Describe briefly the main methods or treatments applied. Include any relevant preregistration numbers, and species and strains of any animals used. 3) Results: Summarize the article's main findings; and 4) Conclusion: Indicate the main conclusions or interpretations. The abstract should be an objective representation of the article: it must not contain results which are not presented and substantiated in the main text and should not exaggerate the main conclusions.

Keywords: Three to ten pertinent keywords need to be added after the abstract. We recommend that the keywords are specific to the article, yet reasonably common within the subject discipline.

**Research Manuscript Sections**

Introduction: The introduction should briefly place the study in a broad context and highlight why it is important. It should define the purpose of the work and its significance, including specific hypotheses being tested. The current state of the research field should be reviewed carefully and key publications cited. Please highlight controversial and diverging hypotheses when necessary. Finally, briefly mention the main aim of the work and highlight the main conclusions. Keep the introduction comprehensible to scientists working outside the topic of the paper.

Materials and Methods: They should be described with sufficient detail to allow others to replicate and build on published results. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited. Give the name and version of any software used and make clear whether computer code used is available. Include any pre-registration codes.

Results: Provide a concise and precise description of the experimental results, their interpretation as well as the experimental conclusions that can be drawn.

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