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Research Paper

Remote Sensing and Sustainable Management of Soil Organic Carbon in the Sahelian Area, Senegal, West Africa

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Abstract
The mapping of soil organic carbon (SOC) variability was carried out in a Sahelian region of Senegal by testing the effectiveness to include the Sentinel 2 remote sensed data in the characterization of the soil properties. Ordinary kriging (OK) applied under ArcGIS is compared with multiple linear regression (MLR) calibrated under R software. The results showed a slight decrease of the root mean square error ranging from 0.18 with kriging to 0.16 for multiple linear regression. Carbon variability was also detailed at a finer scale with multiple linear regression at the pixel scale from 10 to 20 m. Spectral bands situated in the visible wavelength, NDWI and NDVI were the most discriminating explanatory variables in the spatial modeling of organic carbon by multiple linear regression. Specific locations that require inputs of manure or compost were also geo-localized with multiple linear regression in order to ensure sustainable management of soil organic carbon. The use of remote sensed data also puts into perspective the possibility of spatializing the physical and chemical properties of the soil on larger areas and correcting the lack of information on soil mapping in the Sahelian regions of Africa.

Keywords
Organic carbon, Remote sensing, Multiple linear regression, Soil mapping

1. INTRODUCTION

Improving agricultural practices to achieve food security is an issue of sustainable development in the Sahelian area. However, the process of soil degradation tends to reduce the area under cultivation by reducing agricultural productivity. In Senegal, the economic cost of land degradation could reach the equivalent of 4.5 % of GDP for the year 2000 (Mondiale, 2008). Sow et al. (2016) reported the total cost of land degradation at about 8% of the 2007 country's GDP; in this rate soil fertility mining on cropland contributes for 2% following Land Use Cover Change (4%). This degradation process became more pronounced after the 1970s, affecting nearly 2/3 of arable land (Mondiale, 2009). The conditions of access to agricultural land are becoming more and more difficult especially for the local populations even if they continue to develop adaptation strategies to mitigate the risks of degradation of natural resources and ensure the minimum of welfare.

In the Sahelian area, the decrease of carbon content is an indicator of the process of soil degradation. With the work of Pieri (1989) for example, the sustainability of production systems in the Sahelian environment was evaluated on the basis of organic matter contents, pH, fine soil particles (clays and silt) and exchangeable cations. Accurate mapping of the variability of organic carbon offers opportunities for implementing sustainable soil fertility management strategies in the Sahelian agrosystems. Currently, satellite data with medium spatial resolution and denser temporal resolution is available for free access, such as Sentinel 2. The satellite data produced by Europe has 12 bands consisting of visible, near infrared and shortwave infrared bands. This combination of bands has the opportunity to be used to create vegetation indices and soil surface wetness indices which are related to soil characteristic and soil properties such as soil color and soil organic matter content.

The objective of this study was to evaluate the contribution of Sentinel remote sensed data in the accuracy of the soil organic carbon mapping in the Sahelian agrosystems. The availability and accessibility of remote sensing data with high spatial resolution are decisive contributions for mapping the variability of the soil properties. Digital soil mapping methods have shown the interest of using remote sensing data in the spatialization of soil physico-chemical properties both at the landscape and the national scales (Stoorvogel et al., 2009; Viaud et al., 2010; Mulder et al., 2011; Loum et al., 2014; FAO, 2018). The lack of information on the soil mapping in the West Africa countries can be corrected by using the remote sensing data.

2. EXPERIMENTAL SECTION

2.1 The study area

The study area is situated in the village of Bushra which is located in the Sahelian region of Senegal to the west of the Tambacounda region (Figure 1). The rainy season lasts three to four months (June to October) with rainfall ranging between 500 and 850 mm. The dry season lasts from November to May and is marked by high temperatures of about 33.7° C in May. The relief components include lowlands and upland with medium altitude. The vegetation is a wooded savannah with Combretaceae and Mimosaceae. Concerning, the hydrological characteristics, the soil is drained by a hydrographic network composed of temporary streams flowing towards the Gambia river.

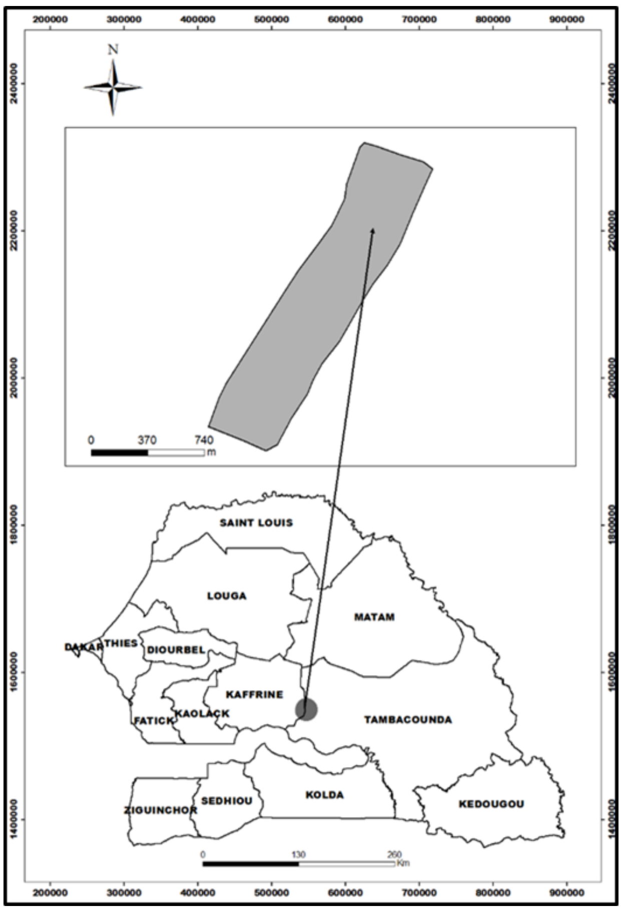

Figure 1. Localisation of the study area

Rainfed agriculture is the main socio-economic activity in the study area. Groundnuts (*Arachis hypogaea*), millet (*Pennisetum typhoides*), maize (*Zea mays*) and cowpea (*Vigna unguiculata*) are the main crops cultivated by the local populations. Animal production ranks second with an extensive breeding system marked by frequent movements of livestock to grazing areas. Sedentary livestock are mainly goats and sheep. The harvest is mostly done during the lean season for consumption and/or sale through small businesses. The collection of energy wood is also an activity of interest to local populations, especially women.

2.2 Organic carbon of the Sahelian soils

Organic carbon influences plant production as well as the physical, chemical and biological properties of soils. It can help reduce greenhouse gas emissions or increase soil fertility through its storage in the soil (Lal et al., 2007; Francaviglia et al., a,b). In the Sahelian environment, organic carbon from surface horizons has been recognized as a potential indicator of sustainability of cropping systems (Feller and Beare., 1997). However, inappropriate farming practices often cause loss of the soil carbon and deplete the physico-chemical properties (Manlay et al., 2007). The continuous practice of groundnut and millet crops were described as a factor of deterioration of the quality of Sahelian soils (Charreau, 1972). Carbon stocks, for example, have been measured or estimated to assess the potential for carbon storage in the soil. In cropped areas, measured carbon stocks vary between 8.9 and 11.3 in the first 25 cm (Tschakert et al., 2004; Loum et al., 2014). Thus, exhaustive characterization of soil carbon variability using digital mapping methods can help to better implement protocols for monitoring the dynamics of soil organic carbon in the Sahelian agrosystem.

2.3 The remote sensed data

The use of remote sensed data in this study aims to improve the accuracy of the result of the mapping of the soil organic carbon. The possibility to acquire free Sentinel 2 images (10 to 20 m resolution) facilitates the implementation of digital soil mapping techniques. The corrected spectral bands or land-use maps derived from remote sensed data serve as auxiliary variables for a characterization of the variability of soil properties in space. In this case we use Blue band, Red band, NIR band, and SWIR band to create indices such as Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI). We also use 11 bands for integrating multiple linear regression (MLR) as shown in Table 1. With the validation of automated methods for geographical or radiometric corrections of satellite images with free software (QGIS or R Statistical Computing), the use of remote sensed data becomes easier for the monitoring of agricultural land exploitation.

2.4 Methodological Approach

The exploitation of Sentinel 2 images contributed to the definition of the perimeter of the study area and to the validation of the strategy of soil sampling. In summary, the methodology includes, among others, the digitization of the limits of the study area, the adoption of a sampling strategy and the application of the tools for the processing and the analysis of the soil information.

2.5 Digitization of the limit

Firstly, the Bushra area was explored using the Google Earth portal, the remote sensed images of Sentinel 2 and the morpho pedological map at the scale of 1:500,000. This pre-field phase was complemented by a prospecting visit which allowed to generate the shapefile of the limits of the study area followed by the positioning of soil pits on the basis of the homogeneity of the soil environmental variables (relief, land cover and land use).

2.6 The sampling strategy

In the area of 100.58 ha of the study zone, a sampling strategy using a systematic grid at 200 m intervals allowed to establish 36 sampling points with an auger (Figure 2a). Depths of 0-20 cm and 20-40 cm were collected, giving 72 soil samples for all. The 0-20 cm depth were retained in this study for evaluation of the contribution of the Sentinel 2 imagery for the mapping of the soil organic carbon. The digital terrain model of 10 m of resolution (Figure 2b) generated in the study area also facilitated the identification of the main soil types. In addition to the auger, pedological equipment mobilized in the field included GPS, Munsell Code, shovels, picks, grabs and other accessories for a description of the soil profiles.

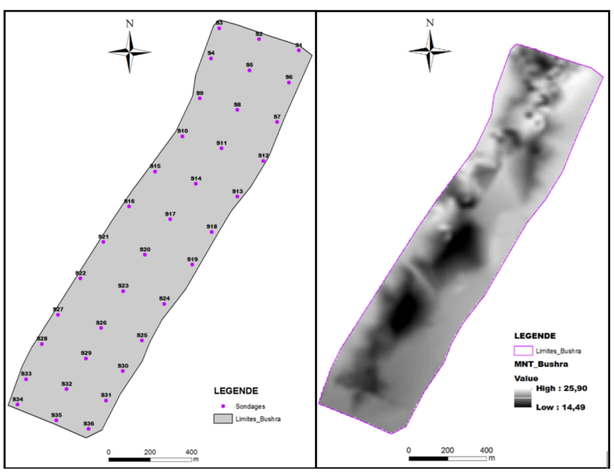

Figure 2. (2a) Soil sampling, (2b) Digital terrain model;

2.7 The processing of the data

The Sentinel 2 image of April 2017 was downloaded directly from the portal `https://earthexplorer.usgs.gov/`. Of the 13 spectral bands acquired in the raw state, 11 bands (Table 1) were radiometrically processed and integrated into the carbon variability mapping methodology. The semi-automatic classification extension available on QGIS software was applied to the Sentinel image to convert digital counts to spectral reflectance. The multiple linear regression was then parameterized under R software using the reflectance values of the spectral bands of the Sentinel image as an auxiliary variable for spatializing organic carbon. The

Table 1. Characteristic of the spectral bands

Spectral Band	Resolution (m)	Wave Length
Band 1	60	Visible
Band 2	10	Visible
Band 3	10	Visible
Band 4	10	Visible
Band 5	20	Visible
Band 6	20	Near infrared
Band 7	20	Near infrared
Band 8	10	Near infrared
Band 8a	20	Near infrared
Band 11	20	Short Wave Infrared (SWIR)
Band 12	20	Short Wave Infrared (SWIR)

regression model also included the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) calculated for Sentinel imagery by Zhang et al. (2017). Ordinary kriging mapping with ArcGIS 10 considering only organic carbon was compared with multiple linear regression to evaluate the contribution of remote sensing data in the accuracy of soil mapping methods.

Regarding the soil analytical parameters, organic carbon was determined by back-dosing after dichromate oxidation or calcination by an auto-analyzer CN-encoder that simultaneously measures carbon and nitrogen. Particle size analysis determination included the three main classes: clay, silt and sand. The sand was obtained by sieving the clay and the silt by densimetry with the Robinson pipette method. The texture triangle (Moeys, 2016) applied to clay, silt and sand allowed to plot the classification of soil texture.

3. RESULTS AND DISCUSSION

3.1 Remote sensing and sustainable management of the SOC

The soil types

Descriptions of soil pits (Table 2) and field observations allowed to identify Arenosols (photo 1), Colluviosols (photo 2) and Lithosols (photo 3) in the Bushra Study Area (Figure 3). Arenosols have very sandy profiles with a thickness of at least 120 cm. The structure is massive and marked by the absence of the BT horizon. The colors vary from 10YR5/3, 10YR6/4 and 10YR6/6. Colluviosols most often occupy slope positions along the landscapes. Colluviation leads to a gradual accumulation of soil materials, alterites or loose rocks uprooted higher up in the landscape, leading to superficial formations in the depressions. Colors vary from 10YR5/3, 10YR5/4, 10YR5/6, 10YR5/4 and 10YR5/3. The structure is particular and very fine in the surface horizon and massive in deep horizons. Lithosols have solums limited in depth by a coherent, hard and continuous material marked by a weak root system. The colors vary from 7.5YR7/6, 7.5YR7/8 and 5YR7/6. The structure is massive with a sandy-loamy texture.

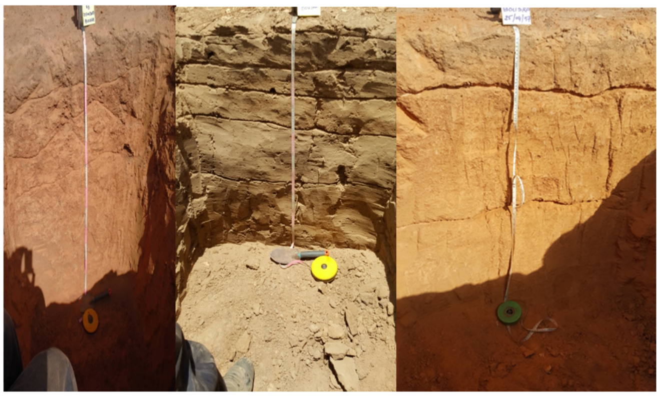

Photo 1: Arénosol   Photo 2: Colluviosol   Photo 3: Lithosol

Figure 3. Some soils found in study area

The classification of soil units was established on the basis of the French Pedological Reference (2008). The correspondence of soil units according to the French Pedological Reference and the World Reference Soil Base FAO (2018) is given in Table 3. The silty-sandy texture samples are located in colluviosols while arenosol and lithosols are mostly sandy soil (Figure 4).

Table 2. Geographical coordinates (UTM) of The Soil Pits

Soil type	X	Y
Colluviosol	546288	1549615
Lithosol	545938	1548624
Arenosol	545683	1548713

Table 3. The soil units of the study area

Soil type	Référentiel pédologique français (2008)	WRB (2014)	FAO
1	Arenosols	Arenosols	Arenosols
2	Colluviosols	Fluvisols	Fluvisols
3	Lithosols	Leptosols	Leptosols

3.2 The Mapping of Soil Organic Carbon

The ordinary kriging (OK) of organic carbon realized under ArcGIS showed a variability between 0.18 and 0.90% (Figure 4a) with a root mean square of 0.18. The nugget effect of the variogram is 0.02 with a range of 0.62 from 150 m (Figure 5). With multiple linear regression (MLR) integrating 11 spectral Sentinel bands, NDVI and NDWI (Figure 6 and 7), the root mean square error of carbon mapping was 0.16. The spatialized carbon variability ranged between 0.11 and 0.90%.

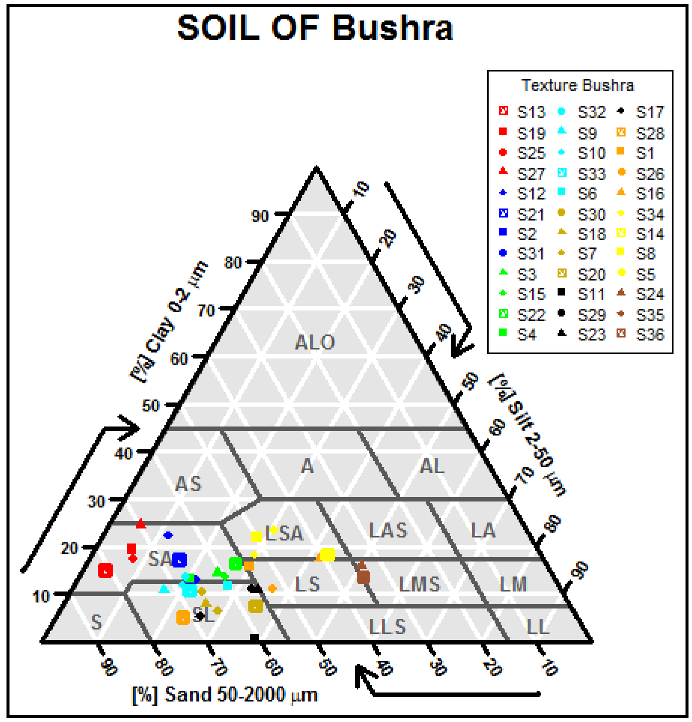

Figure 4. The Soil Textural Triangle of Bushra

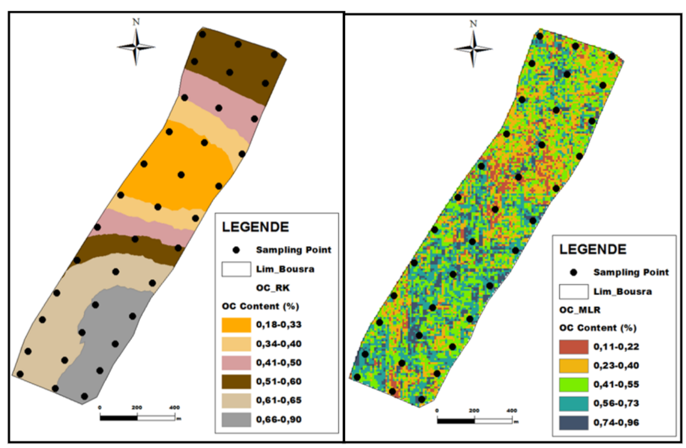

Figure 5. (4a) Map of SOC with OK; (4b) Map of SOC with MLR

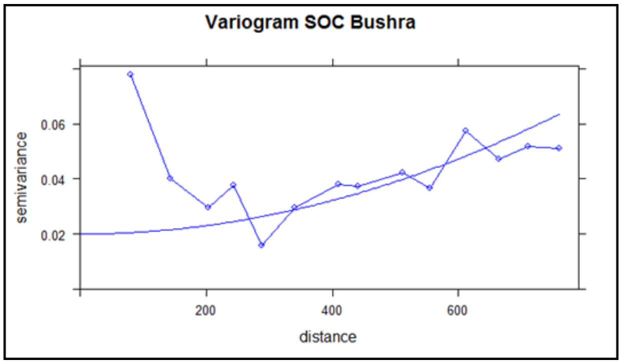

Figure 6. Variogram of ordinary kriging

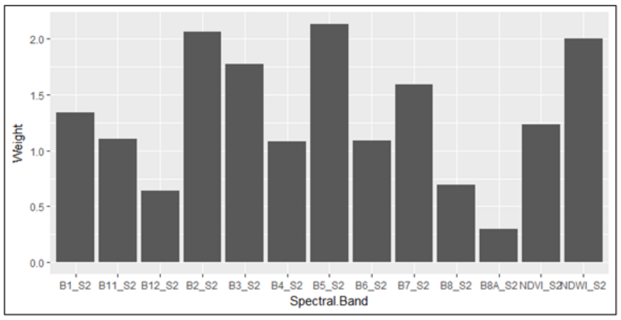

Figure 7. Variables importance of multiple linear regression model

4. CONCLUSION

With ordinary kriging (OK), mapping of carbon variability was less detailed, while multiple linear regression showed variability at the pixel scale of 10-20 m. For example, in the south of the study area, carbon mapping by kriging showed a range of variability between 0.61 and 0.90%, whereas multiple linear regression (MLR) showed pixels with low organic carbon content (0.11 and 0.22%). The results also showed that spectral bands in the visible wavelength (2, 3 and 5) were more important in the mapping of carbon variability than those situated in the wavelength of near and short wave infrared (6, 8, 8a, 11 and 12). Thus, the spectral resolution of the image influences the accuracy of the mapping of the variability of the carbon.

Concerning the agricultural productions, the soil types identified, and the spatialized soil properties showed the possibility to cultivate rainfed crops such as groundnuts, cowpeas, millet and maize which are less sensitive to the sandy soil. Carbon mapping including remote sensing data indicated specific locations where inputs of compost or manure are necessary to improve the organic carbon content. The local population would also like to cultivate the rice crops in the study area of Bushra, which may be considered a dry tropical micro-watershed. However, the results showed the difficulties of the soil types to support the rice crops because of the sandy texture of the soil. Even the colluviosols located in the lowlands are not suitable for rice cultivation since deep horizons can contain up to 60% of sands. The processing of remote sensed images also highlighted bush fires which are visible traces of human degradation on the field during the dry season. In this regard, sustainable management strategies for soil organic matter must take into account the involvement and awareness of local population for the preservation of the environment to promote sustainable agricultural use of the soils.

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REFERENCES

Charreau, C. (1972). Problèmes posés par l'utilisation agricole des sols tropicaux par les cultures annuelles. *L'Agriculture Tropicale*, **27**; 905–929

FAO (2018). *Soil Organic Carbon Mapping Cookbook*. 2nd edition edition

Feller, C. and M. H. Beare. (1997). Physical control of soil organic matter dynamics in the tropic. *Geoderma*, **79**; 69–116

Francaviglia, R., K. P. Coleman, A. P. Whitmore, L. Doro, G. Urracci, M. Rubino, and L. Ledda. (a). Changes in soil organic carbon and climate change - Application of the Roth C model in agro-silvo-pastoral Mediterranean systems. *Agricultural Systems*

Francaviglia, R., G. Renzi, L. Ledda, and A. Benedetti (b). Organic carbon pools and soil biological fertility are affected by land use intensity in Mediterranean ecosystems of Sardinia, Italy. *Science of the Total Environment*

Lal, R., R. Follett, B. Stewart, and J. Kimble (2007). Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science*; 943–956

Loum, M., V. Viaud, Y. Fouad, H. Nicolas, and C. Walter (2014). Retrospective and prospective dynamics of soil carbon sequestration in Sahelian agrosystems in Senegal. *Journal of Arid Environments*, **100-101**; 100–105

Manlay, R., C. Feller, and M. Swift (2007). Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. *Agriculture Ecosystems Environment*, **119**; 217–233

Moeys, J. (2016). *The soil texture wizard: R functions for plotting, classifying, transforming and exploring soil texture data*. 100 pages

Mondiale, B. (2008). *Analyse Environnementale Pays, Sénégal*

Mondiale, B. (2009). *Analyse Environnementale Pays, Sénégal*

Mulder, V., S. Bruin, M. Schaepman, and T. Mayr (2011). The use of remote sensing in soil and terrain mapping - A review. *Geoderma*, **62**(1-2); 1–19

Pieri, C. (1989). *Fertilité des terres : bilan de trente ans de recherche et de développement agricole au sud du Sahara*. Ministère de la coopération française, CIRAD-IRAT

Sow, S., E. Nkonya, S. Meyer, and E. Kato. (2016). Cost, Drivers and Action Against Land Degradation in Senegal. In E. Nkonya, A. Mirzabaev, and J. von Braun, editors, *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development*. Springer. Doi.org/10.1007/978-3-319-19168-3$_1$9

Stoorvogel, J., B. Kempen, G. Heuvelink, and d. S. Bruin (2009). Implementation and evaluation of existing knowledge for digital soil mapping in Senegal. *Geoderma*, **149**; 161–170

Tschakert, P., M. Khouma, and M. Sène (2004). Biophysical potential for soil carbon sequestration in agricultural systems of the Old Peanut Basin of Senegal. *Journal of Arid Environments*, **59**; 511–533

Viaud, V., D. Anger, and C. Walter (2010). Toward Landscape-Scale Modeling of Soil Organic Matter Dynamics Agroecosystems. *Soil Science Society of America Journal*, **74**; 1847–1860

Zhang, T., J. Su, C. Liu, and W. Chen (2017). Band Selection in Sentinel-2 Satellite for Agriculture Applications. In *Proceedings of the 23rd International Conference on Automation Computing*. University of Huddersfield, pages 2–7

