Observing the phenological characteristics of winter food crops with spectral indices

Hsuan-Yi Li [1,*], James A. Lawrence [1], Philippa J. Mason [2] and Richard C. Ghail [3]

[1]Department of Civil and Environmental Engineering, Skempton Building, Imperial College London, South Kensington, London SW7 2AZ, UK; hsuan-yi.li22@imperial.ac.uk*; j.lawrence@imperial.ac.uk

[2]Department of Earth Science & Engineering, Imperial College London, Prince Consort Road, London SW7 2AZ, UK; p.j.mason@imperial.ac.uk

[3]Department of Earth Sciences, Queens Building 245, Royal Holloway, University of London Egham, Surrey TW20 0EX, UK; richard.ghail@rhul.ac.uk

Keywords: Winter food crops, Spectral indices, Sentinel-2, Unsupervised classification, Crop phenology.

Abstract

This study is based on the best crop classification result generated by the proposed unsupervised Machine Learning (ML) method in Li *et al*., 2025a, using the spectral indices calculated by the formula with spectral bands from Sentinel-2 image products, Normalized Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), Enhanced Vegetation Index (EVI) and Normalized Difference Moisture Index (NDMI). The patterns and characteristics of these spectral indices, across arable fields with different crop types following the winter growing seasons, have not yet been analyzed in detail. This research aims to provide a comprehensive study of each input spectral index and its impact on the crop classification model. Each spectral index is analyzed across a series of crop fields, using Sentinel-2 images, carefully selected to follow the patterns of winter crop phenology, and the results of unsupervised classification for each crop type in Norfolk, UK are successfully generated and analyzed. The different growing rates between winter barley and wheat have been classified found on a monthly basis using Sentinel-2 RGB images and thus the images during the harvest time, May and June, can support crop classifications. Wild grasses or other plants on the fields led to some crop misclassification from November to March in the Sentinel-2 RGB images. Similarity between winter barley and wheat and the different sowing time among the same type of crop also led to misclassification. In future these misclassifications could be avoided through better understanding of the relation between spectral indices and crop planting cycles.

1. Introduction

Spectral indices have been widely applied in crop and land studies, and Normalized Difference Vegetation Index (NDVI). is the most widely used because of its simplicity and that the necessary spectral bands are available on most multispectral sensors (Tenreiro *et al*., 2021); NDVI has been applied in crop classifications and identifications (Veloso *et al*., 2017, Johnson, 2019, Tenreiro *et al*., 2021, Blickensdörfer *et al*., 2022, Md-Tahir *et al*., 2024), crop yield analysis (Marino *et al*., 2021, Belmahi, *et al*., 2023) and Land Use Land Cover (LULC) studies (KC *et al*., 2021, Ghorbanian *et al*., 2022, Ahmed *et al*., 2023, Md-Tahir *et al*., 2024) over many decades of research. Additionally, long-term LULC mapping has been conducted widely using NDVI patterns over 5-year or decadal periods (Ghorbanian *et al*., 2022, Ahmed *et al*., 2023). To understand the phenological character of crops, the NDVI values should be collected and analyzed by months or at particular date periods throughout the growth cycle. Some studies have provided NDVI analysis per month but they included all crop cover (winter and summer crops) in the same category which was not precise enough for any specific crop classification (KC *et al*., 2021, Tenreiro *et al*., 2021). The phenological NDVI trends of specific crop types have been studied and analyzed and some have included winter barley, wheat and rapeseed (Veloso *et al*., 2017, Johnson, 2019, Blickensdörfer *et al*., 2022, Md-Tahir *et al*., 2024), which were used as benchmarks to identify clusters for unsupervised winter food crop classification. Johnson (2019) produced historical crop maps in the USA, of corn, soybean and winter wheat, from 1984 to 2007, based on Landsat image products. The NDVI trends of different crop types (corn, soybean, winter wheat, cotton, rice, sorghum, canola, barley, sugar beets, potatoes) from March to November, with data values every 16 days, were analyzed. The monthly NDVI time series analysis of crop types within a crop rotation scheme (wheat-fallow, wheat-cotton-rotation, wheat-rice-rotation and wheat-maize-rotation) were provided in an unsupervised LULC classification using MODIS and Landsat 5 TM images in Pakistan (Md-Tahir *et al*., 2024). In these studies, only the NDVI trends were studied but other spectral indices were not analyzed in combination with crop phenology. In this research study therefore, in addition to NDVI trends across winter food crops, three other spectral indices have been analyzed, monthly and in combination with crop phenology. The crop classification results produced by each variable (spectral index) are presented here.

2. Methodology

Our study area is located in Norfolk, UK, where three types of food crops, barley, wheat and rapeseed, are the main varieties grown in the winter. Sentinel-2 atmospherically corrected image products, with cloud cover less than 10%, were downloaded from the Copernicus data space ecosystem (Sentinel-2, 2023). The 5 spectral bands of Sentinel-2’s image products, Red, Green, Blue, Near Infrared (NIR) at 10 m spatial resolution, and Short-Wave Infrared (SWIR), at 20 m spatial resolution, were used in this research. The images were resampled to the most suitable pixel size, 60 x 60 m, to classify the crops using an unsupervised Machine Learning (ML) model, referred to as FastDTW-HC, which was constructed using Fast Dynamic Time Warping (DTW) and Hierarchical Clustering (HC) (Li *et al*., 2025b). Spectral indices were calculated on a pixel-by-pixel basis, using well known formulae to derive NDVI, Soil Adjusted Vegetation Index (SAVI), Enhanced Vegetation Index (EVI) and Normalized Difference Moisture Index (NDMI) images, summarised in Table 1. These were used as inputs to our model to generate classified crop maps in 2020 using FastDTW-HC. To further optimize FastDTW-HC and to better understand the phenological trends of winter barley, wheat and rapeseed using these 4 spectral indices,

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
https://doi.org/10.5194/isprs-annals-XI-3-2026-741-2026

all input variables and their crop classification results have been analyzed following the winter food crop phenology patterns across three main growing seasons: The germination and seedling growth stages occur in November and December (GS00-20); tillering and stem elongation in January, February and March (GS20-29); stem elongation, flowering and grain filling in April, May and June (GS30-89) (AHDB, 2025), as shown in Figure 2. This analysis was conducted across cropped fields identified with the Ground Observation Points (GOPs) collected by the Rural Payments Agency (RPA), UK, and are marked as 1A to 3E in Figures 1b and 1c.

Table 1. The formulae of spectral indices used in this study.

Index	Formula
NDVI	(NIR-Red)/NIR+Red) (Goward *et al.*, 1991)
SAVI	(1+L)*(NIR-Red)/(NIR+Red+L); where L=0.5 (Huete, 1988)
EVI	2.5*(NIR-Red)/(NIR+6*Red-7.5*Blue+1) (Liu and Huete, 1995)
NDMI	(NIR-SWIR)/(NIR+SWIR) (Gao, 1996)

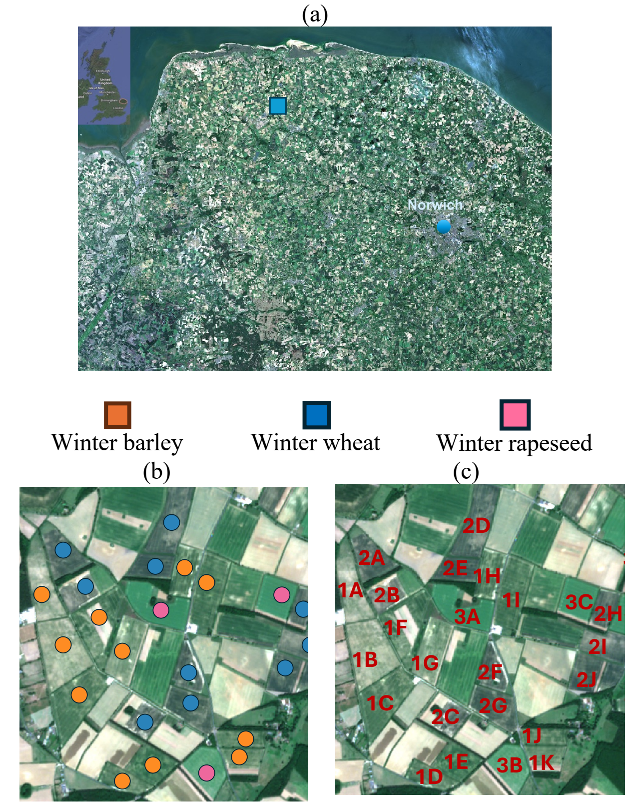


Figure 1. Sentinel-2 true-color composite images of (a) the study area (blue box) in Norfolk, UK; (b) GOPs of winter barley (orange), wheat (blue) and rapeseed (pink) in 2020 (RPA, 2021); (c) Fields of winter barley marked as 1A to 1L, winter wheat as 2A to 2J, and winter rapeseed as 3A to 3E, at the GOP locations shown in (b).

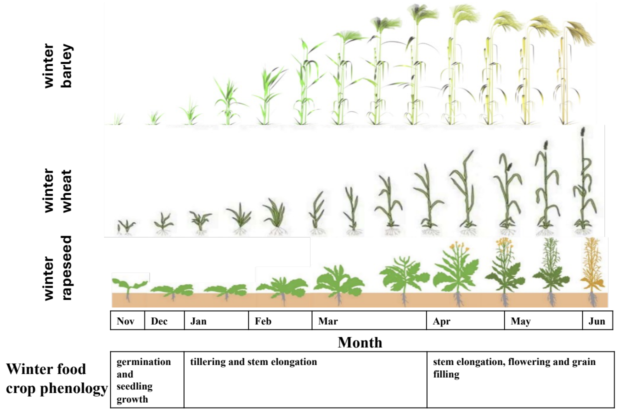


Figure 2. The phenological patterns of winter barley, wheat and rapeseed illustrated by month. (Li *et al*., 2025a)

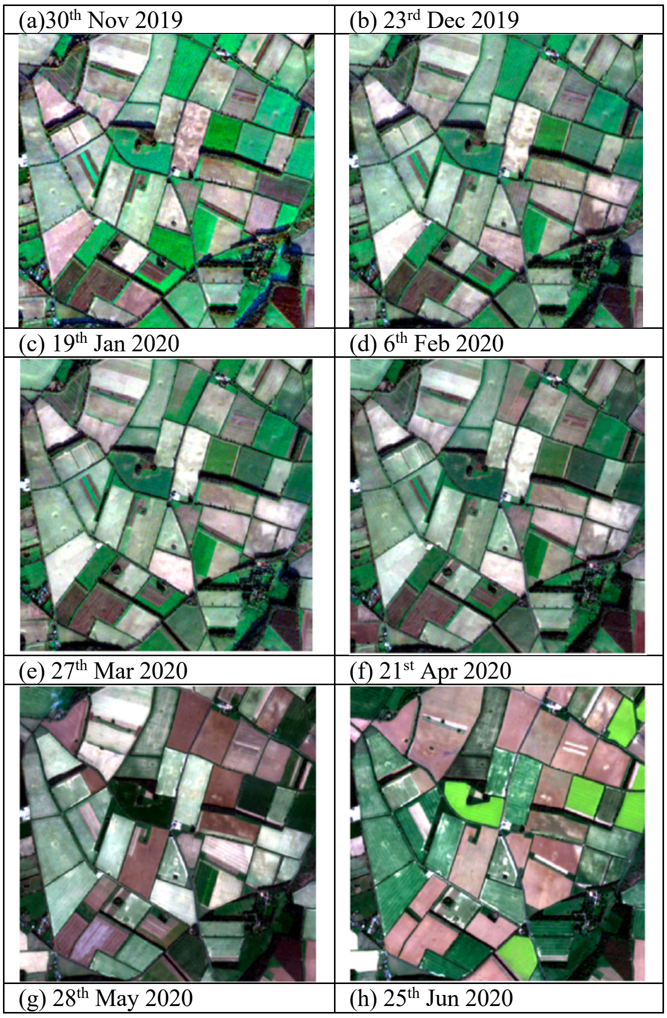
3. Results

Our best unsupervised winter food crop classification result in Norfolk, UK was generated with NDVI, SAVI, EVI and NDMI by FastDTW-HC (Li *et al*., 2025a), as shown in Figure 3. To understand the respective contributions of the selected spectral indices, the phenological trends of NDVI, SAVI, EVI and NDWI of winter barley, wheat and rapeseed have been analysed. However, the results suggested that more detailed investigations were required to optimize FastDTW-HC and thus to fully understand the arable crop phenological changes, which was achieved through the use of monthly Sentinel-2 image products. This analysis allowed the visualisation of growth stages of winter barley, wheat and rapeseed, using Sentinel-2 true-color composite images. It was found that growth stages clustered into three seasons: 1. Germination and seedling; 2. Tillering and stem elongation; 3. Stem elongation, flowering and grain filling stages; these can all be recognised in true-color composite images, shown in Figure 4. Crops were, therefore, analysed only within these three seasons, in the following sections.

Figure 3. The best result of winter food crop classification compared with GOPs (dots) from RPA, UK (modified after Li *et al*., 2025a).

3.1 Sentinel-2 true-color composite images

Two months, November and December (GS00-20), are included in season 1, as shown in Figures 4a and 4b. The germination and seedling stages of winter varieties of crops (barley, wheat and rapeseed) occur in season 1. It can be seen that these fields appear very pale green (low vegetation cover) when compared to the following seasons. Nevertheless, due to the slight difference of the sowing time across multiple fields, which might have multiple owners, some winter barley and wheat fields are shown as bare soil. In season 2, January, February and March, we see the tillering and stem elongation stage (GS20-29) of winter food crops, barley, wheat and rapeseed. The green color of the fields becomes more obvious and darker, since the stems have elongated and leaves sprouted out from the stems in this season, hence the chlorophyll reflectivity is higher, as shown in Figures 4c, 4d and 4e. Season 3, April, May and June, are characterized by stem elongation, flowering and grain filling stages (GS30-89). The fields appear darker green in this season, as shown in Figures 4f, 4g and 4h, since the winter crops, barley, wheat and rapeseed become more mature, with longer stems and denser leaves. The flowering season occurs in late April and this is clearly seen in the intense yellowy-green color of the fields occupied by winter rapeseed with its iconic yellow flowers during the season (Figure 4f). Some other fields sowing seeds of plants in spring trimmed the grass or plants on the fields in April. Due to the untrimmed grass or other plants on the fields before April, these spring plants are misclassified as winter barley or wheat in the classification results with single spectral index input. In this case, it is worth adjusting the date ranges of the input images to the ML model, to avoid this type of misclassification. From late May until mid-June, it is the grain filling stage which is seen in the dark green color of the winter barley, wheat and rapeseed fields, which later became sparse again. June sees harvest time for all these winter crops arrived in Figure 4h, when many of these green fields become bare again.



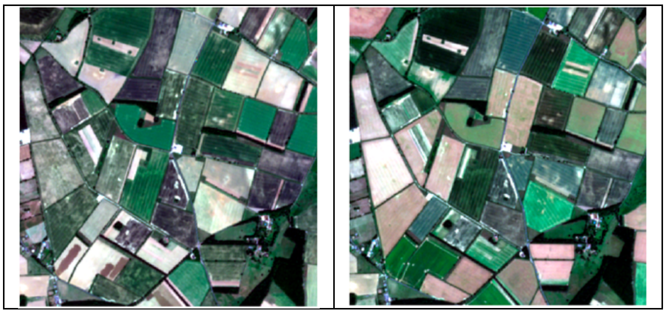


Figure 4. (a to h) Monthly Sentinel-2 true colour composite (RGB) images throughout the growing season of winter crops from Nov 2019 to Dec 2020.

3.2 Normalized Difference Vegetation Index (NDVI)

Images of NDVI values are shown in Figure 5, with each image representing values between 0 and 1 (red to blue) across the crop fields of the study area, allowing analysis of the chlorophyll content of the crops throughout the growing season. It is clear that the NDVI values of winter barley were increasing throughout the growth season until the point of flowering in April, as shown in Figure 5. Analysis of the NDVI values shows that two different germination and seedling periods for winter barley fields (at sites 1A, 1B, 1D, 1F, 1G, 1H, 1J, 1K and 1L; 1E and 1I) can be seen in Figures 5a and 5b. Around 0.1 difference in NDVI values caused by the multiple germination periods on same types of crop fields continued throughout the growth stages from tillering, stem elongation, flowering and grain filling. Winter wheat and winter barley share phenological characteristics and hence class separation is challenging using NDVI alone within the ML method; misclassifications are visible in this result, as shown in Figure 6. From germination until flowering, the NDVI trends are visible in the fields of winter barley and winter wheat, where 2D and 2E are similar to 1A, 1B, 1D, 1F, 1G, 1H, 1J, 1K and 1L and 2A, 2B, 2C, 2F, 2G, 2H, 2I and 2J are similar to 1E and 1I, as shown in Figures 5a to 5f. From the grain filling stage, the NDVI values of winter wheat decrease at a lower rate than those of winter barley; this is evident in the fact that winter wheat fields had yet to be harvested in late June, as shown in Figure 5h. The phenological patterns of winter rapeseed are notably different from both winter barley and winter wheat, and thus it can be separated readily using only NDVI in the ML model, as shown in Figure 6. The NDVI values of winter rapeseed in Figures 5a to 5e are higher and increase more rapidly than both winter barley and winter wheat, between the germination to stem elongation stages, of November to the late March. In the flowering season, winter rapeseed shares the same average NDVI values with winter barley and winter wheat, as shown in Figure 5f. The fields of winter rapeseed have NDVI values close to 1 after the flowering season, as shown in Figure 5g, then NDVI values decrease in the grain filling stage, as shown in Figure 5h. Although the winter rapeseed fields 3A, 3C, 3D and 3E share the same NDVI patterns, 3B appears to be different and therefore has not been classified as winter barley in Figure 6.

https://doi.org/10.5194/isprs-annals-XI-3-2026-741-2026 |

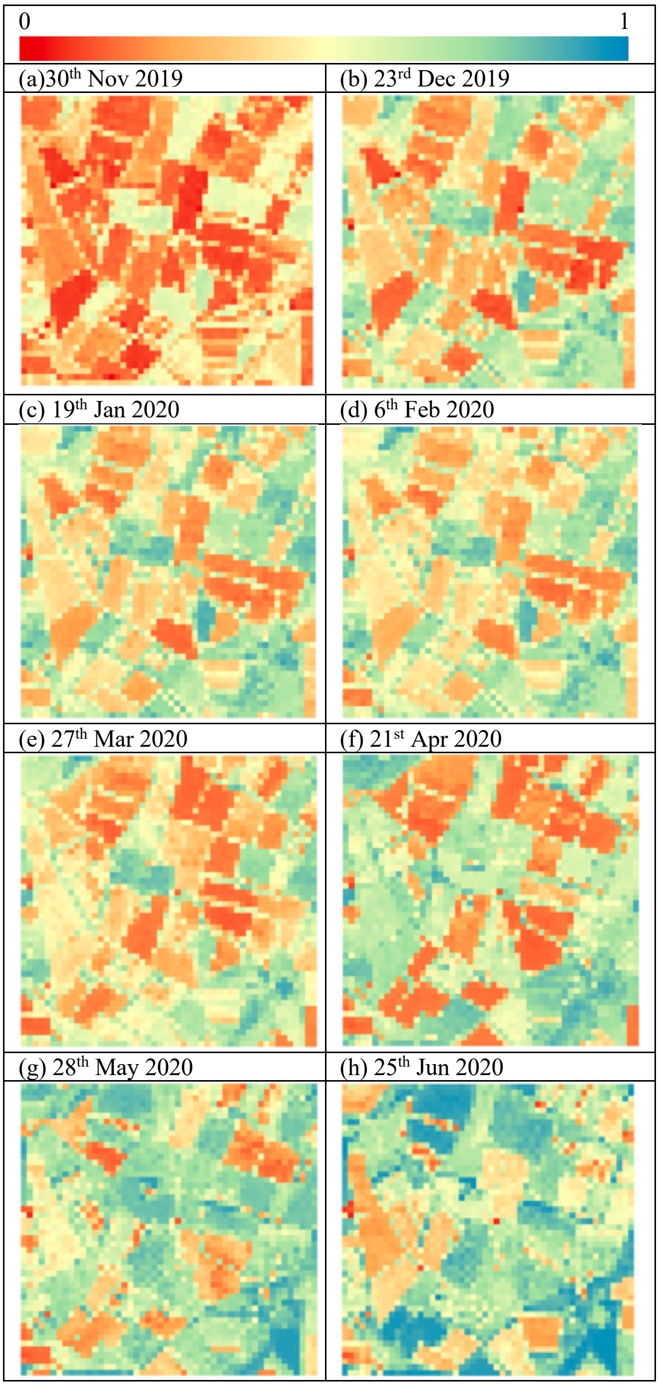


Figure 5. (a - h) NDVI images of the study area derived from Sentinel-2 data acquired from November 2019 to June 2020.

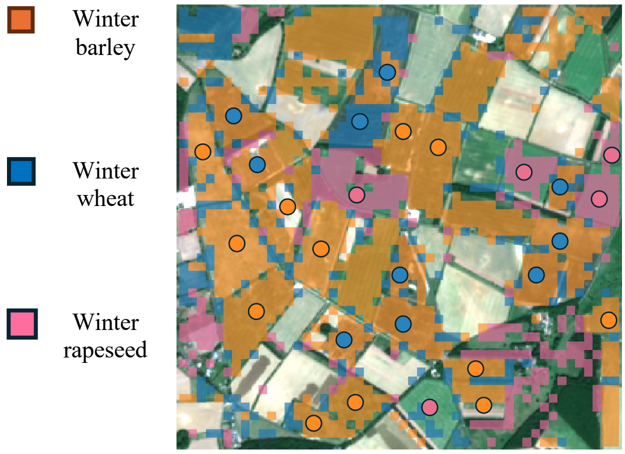


Figure 6. The crop classification result using NDVI only in the FastDTW-HC model comparing with GOPs (dots) from RPA, UK.

3.3 Soil Adjusted Vegetation Index (SAVI)

In general, the SAVI values of crop fields are slightly lower than the corresponding NDVI values throughout the growing season because SAVI is an adjusted spectral index that is less sensitive to soil color and moisture than NDVI, hence it is designed to be more sensitive to the chlorophyll content and so to enhance the presence of vegetation. From the SAVI images, two different germination periods of winter barley fields (1A, 1B, 1D, 1F, 1G, 1H, 1J, 1K and 1L; 1E and 1I) can be identified, in Figure 7a. Thus, throughout the growing season, as shown in Figures 7a to 7h, the SAVI values across the winter barley fields show slightly variations. The SAVI values are highest in the flowering stage and start to decrease from the grain filling stage onwards, which resembles the patterns seen in the NDVI images. From November to April, the germination to flowering stages, the fields of winter wheat share the same SAVI values with winter barley and thus the majority of winter wheat pixels are misclassified as winter barley in Figure 8. Unlike NDVI, SAVI values of winter wheat are slightly lower than those of winter barley in the flowering stage. The situation of winter wheat growing more slowly than the winter barley can be seen in Figures 4a to 4h. After the flowering stage, SAVI values for winter wheat reach their highest in late May, as shown in Figure 7g, and they decrease in the grain filling stage in June, as shown in Figure 7h. SAVI values of winter rapeseed are above 0.5 and are consistently higher than those of winter barley and winter wheat until late May. From November to late May, Figures 7a to 7g, SAVI values for winter rapeseed fields increase until late March and then decrease at the flowering stage in April, then they and increase again after the flowers have withered in May. The grain filling stage of winter rapeseed occurs in June which is reflected in the relatively lower SAVI in Figure 7h. In Figure 8, the winter rapeseed field 3C was not classified at all and 3E was misclassified because the SAVI trends are different from the other winter rapeseed fields, 3A, 3B, 3D and 3E throughout the growth season.

https://doi.org/10.5194/isprs-annals-XI-3-2026-741-2026

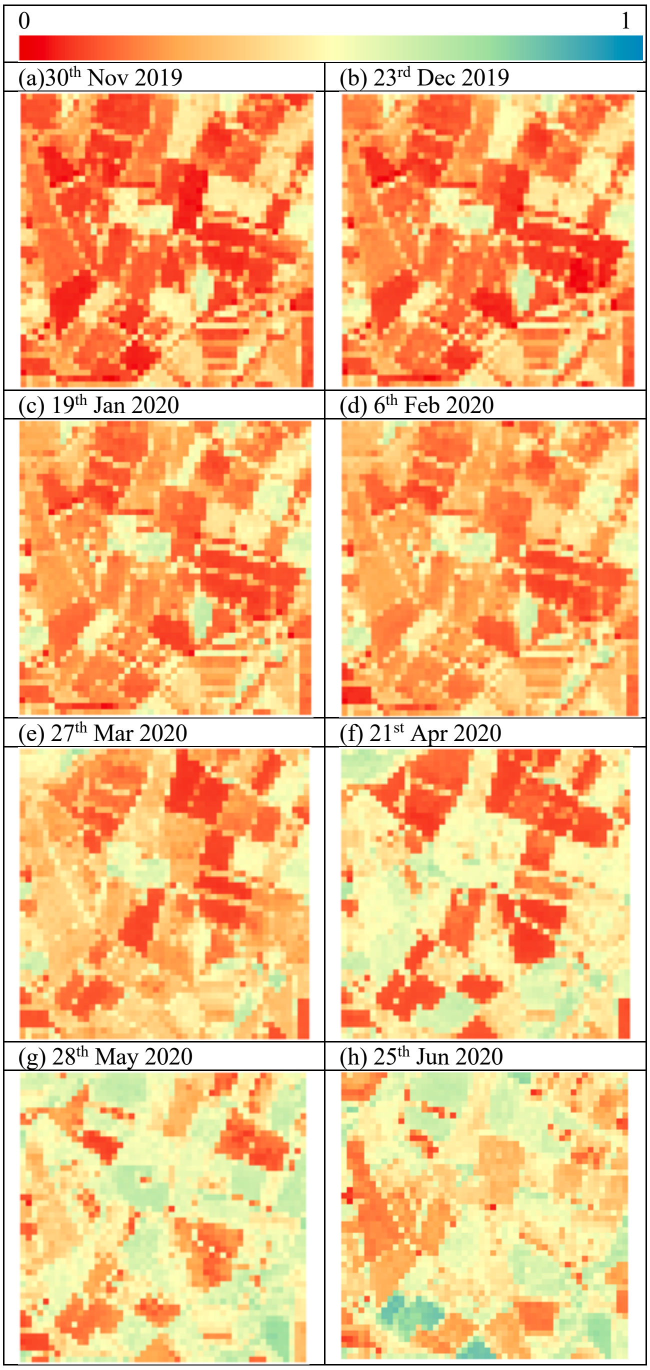


Figure 7. (a - h) SAVI images of the study area derived from Sentinel-2 data acquired in November 2019 to June 2020.

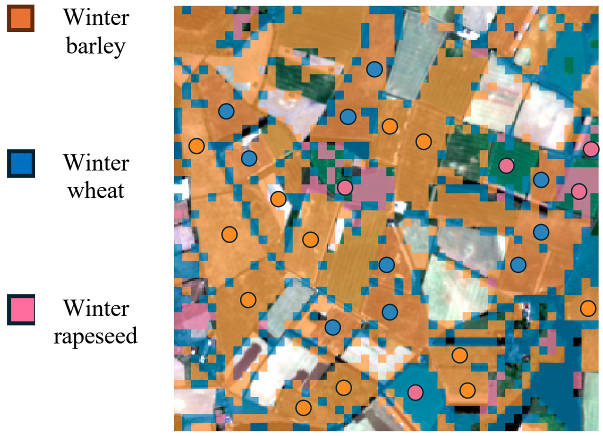


Figure 8. Crop classification result using SAVI only in the FastDTW-HC model comparing with GOPs (dots) from RPA, UK.

3.4 Enhanced Vegetation Index (EVI)

Compared to NDVI and SAVI, EVI values are lower than NDVI but higher than SAVI. EVI is a spectral index which includes the blue band in its calculation, which makes it more sensitive to leaf cover and therefore the density of vegetation. Referring to section 3.1, two different germination periods of winter barley fields (1A, 1B, 1D, 1F, 1G, 1H, 1J, 1K and 1L; 1E and 1I) were still found in Figure 9a. This influence of around 0.1 EVI value difference on same crop types continued throughout the growing season until the harvest time in late June. The germination and seedling period (November and December), in Figures 9a and 9b, have similar EVI values in the fields over this period. The EVI values of winter barley fields increased from January to April (tillering, stem elongation and flowering stages), in Figures 9c to 9f. In May (grain filling stage), the EVI values of winter barley decreased in Figure 9g and returned to around 0.25 in Figure 9h during the harvest time in June. In November, grasses could clearly be seen on two fields of winter wheat, as shown in Figure 4a, where the EVI values of winter wheat fields 2G and a part of 2J are above 0.6, as shown in Figure 9a. In December, these two fields are trimmed to bare soil in December, leading to EVI values of nearly zero, and thus winter wheat on fields 2G and 2J are subsequently sown later in December, as shown in Figure 9b. The influence of sowing may influence the classifications in Figure 10, where most pixels in these two fields have been recognized as winter barley. Though few of the pixels in the other winter wheat fields are correctly clustered, most pixels are classified as winter barley due to the similarity between winter wheat and barley (2D and 2E are similar to 1A, 1B, 1D, 1F, 1G, 1H, 1J, 1K and 1L and 2A, 2B, 2C, 2F, 2G, 2H, 2I and 2J are similar to 1E and 1I, as shown in Figures 9a to 9f) on EVI values. The difference of EVI values can be seen in Figures 9g and 9h, May and June, which improves the classifications of winter wheat.

The EVI trend across winter rapeseed fields are clearly different from those of NDVI throughout the growing season. At the germination stage (November) the winter rapeseed fields had high values above 0.7 in EVI, as shown in Figures 9a and 9b. The EVI values decrease in December and remain very similar from January to March, the tillering and stem elongation stages, in Figures 9c, 9d and 9e. At the flowering stage (April), the EVI values decrease again since the flowers effectively obscure the leaves from satellite observations. Thus, after the flowering, the dense leaves are shown again and the EVI values gain again and reach around 1 in Figure 9g, the highest throughout the phenology. In June, the grain filling stage in Figure 9h, the EVI values reduce to their lowest because the plants senesce (turn yellow) and droop during this period.

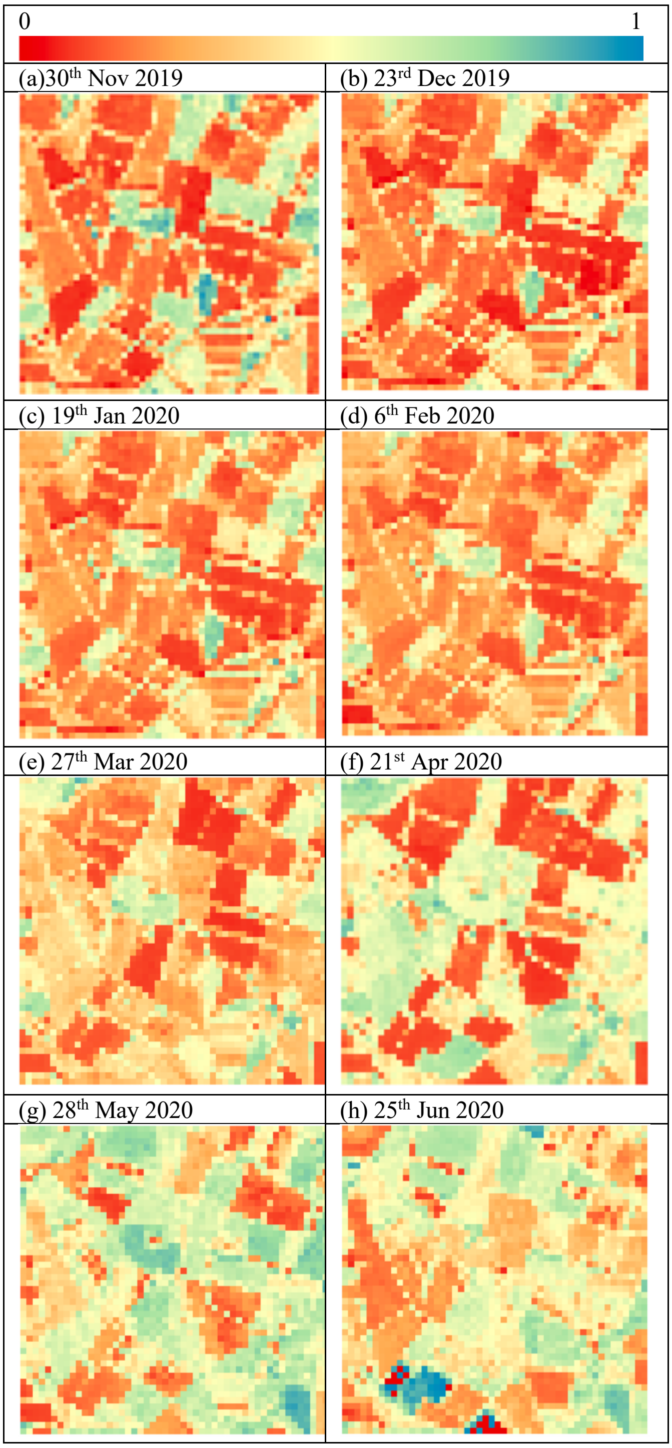


Figure 9. (a - h) EVI images of the study area from Sentine-2 data acquired in November 2019 to June 2020.

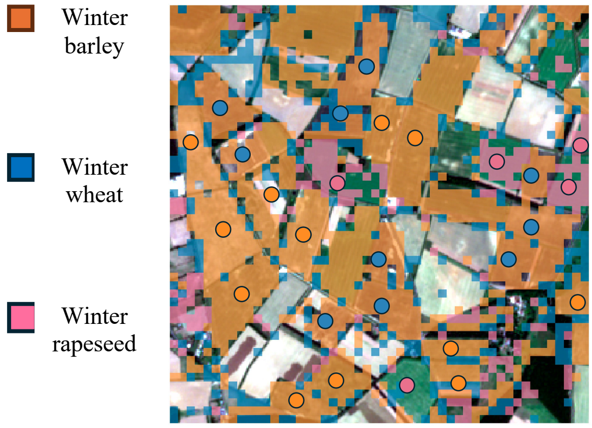


Figure 10. Crop classification result using EVI only in the FastDTW-HC model comparing with GOPs (dots) from RPA, UK.

3.5 Normalized Difference Moisture Index (NDMI)

The calculation of NDMI includes SWIR band reflectance which is sensitive to Water Content (WC) within the plants i.e. canopy moisture (not soil moisture). Plant WC varies throughout the growing season, and it therefore enables crop phenology to be analyzed and classified. However, WC can be influenced by either irrigation or rainfall or both. The monthly cumulative rainfall at Norfolk is shown in Figure 11; careful analysis of NDMI patterns and trends (Figure 12) over the period of a year reveals that there is no clear or direct relationship between rainfall and NDMI. The hypothesis of the link between irrigation and WC of crops could not be confirmed. At the early stage of winter food crop growth, minimal irrigation is needed and excess moisture can lead to damaged crops (Reuß et al., 2025). In March, the values of NDMI are at the lowest of the year, which may be a result of the lack of both irrigation and rainfall. After stem elongation, in flowering and grain filling stages, adequate soil moisture is required to ensure the yields of winter food crops (NeSmith and Ritchie, 1992, Svobodová and Míša, 2004).

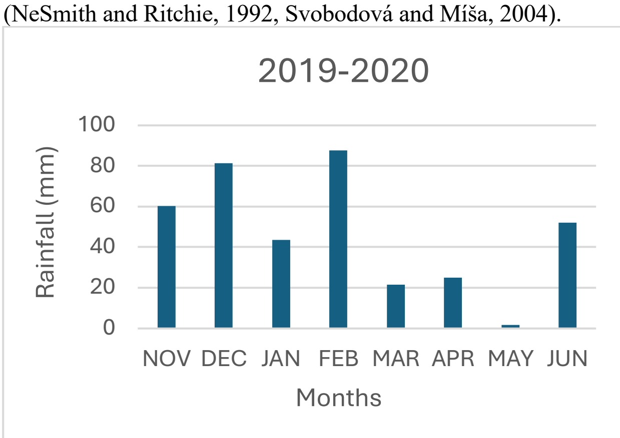


Figure 11. Monthly accumulative rainfall from November 2019 to June 2020.

The NDMI trends of winter barley and wheat are similar from November to April, from Figures 12a to 12f. Thus, as shown in previous sections, most pixels of winter wheat are recognized as winter barley. However, in May and June, the NDMI values of winter barley and wheat have significantly difference, so the pixels of winter wheat are better extracted, as compared to the results of SAVI and EVI, as shown in Figure 13. Winter barley reaches the grain filling stage in May and harvest time in June but winter wheat matures more slowly after the flowering stage and is still at the grain filling stage in June, whereas the NDMI values of winter wheat remains higher than winter barley in May and June, as shown in Figures 12g and 12h. Compared to winter barley and wheat, winter rapeseed has a higher requirement for water (Miyasaka *et al*., 2021) and it can be seen that its NDMI values are higher than winter barley and wheat throughout the growing season, as shown from Figures 12a to 12h. From November to April, in germination to flowering stages, there is no obvious variation in the NDMI values for winter rapeseed. Until the grain filling stage, the NDMI values of winter rapeseed increase around 0.1 to 0.15 in Figure 12g and the NDMI values decrease in June since the winter rapeseed grain matures and dries at this time, in Figure 12h.

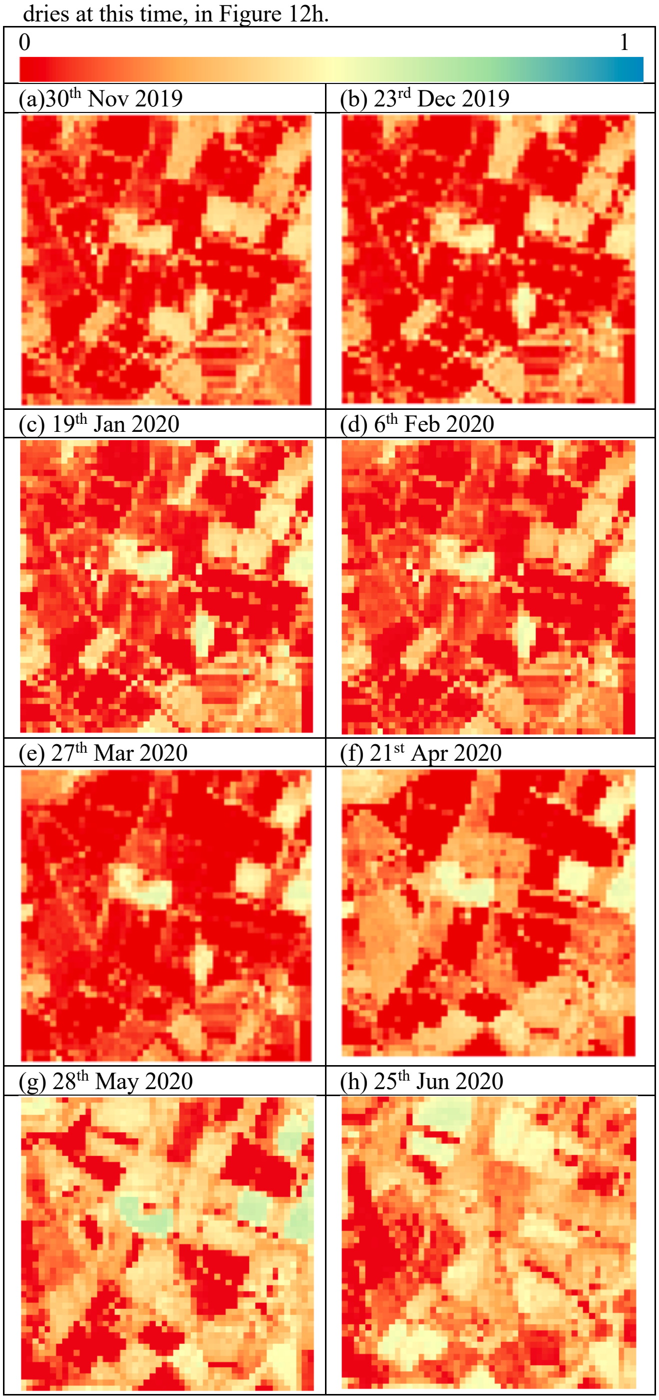


Figure 12. (a - h) NDMI images of the study area from Sentinel-2 data acquired in November 2019 to June 2020.

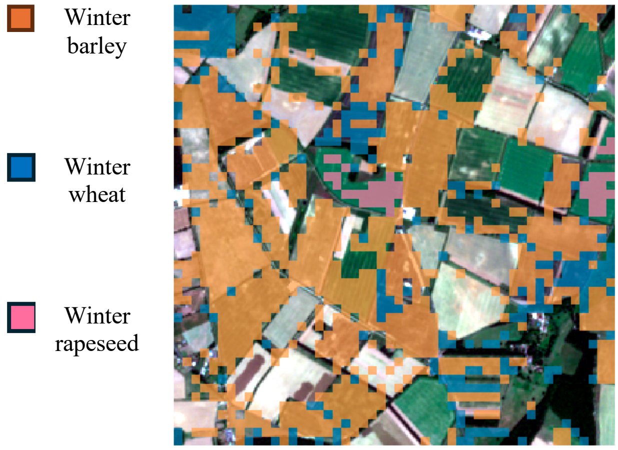


Figure 13. Crop classification result using NDMI only in the FastDTW-HC model.

4. Conclusions

The most successful result from our unsupervised winter food crop classification was generated using the combination of NDVI, SAVI, EVI and NDMI indices by the FastDTW-HC method. Despite the success of the method, there are still some misclassifications, and these can be analyzed, from the variable contributions of each spectral index, to improve the method for the future application. Detailed analysis, using Earth Observation data, to understand the conditions of crops throughout growing season becomes vital and has been the focus of this research study. Following the patterns of winter food crop phenology, across the three main growing seasons, winter crop types, barley, wheat and rapeseed have been analyzed using spectral indices and color composite (RGB) images derived from Sentinel-2 imagery. There are several key findings:

(1) Misclassifications caused by spring plants were identified in the monthly Sentinel-2 RGB images as untrimmed grass or other plants growing across the fields from November to March.

(2) Misclassifications are also caused by similarities in the chlorophyll content, and leaf and plant structures shared by winter barley and wheat. These similarities lead to misclassifications when using a single parameter for crop classification. However, NDMI which detects the water content of plants, is considered to be a spectral index that could better classify winter barley and wheat.

(3) Different sowing times in fields with the same crop type was identified using the Sentinel-2 RGB images acquired in November and December of each year. This caused variations in spectral index values among the fields throughout the whole growing season and caused further misclassifications while grouping pixels with the same crop types to the same cluster.

(4) The different growing rates between winter barley and wheat were helpful in crop classification because of clear differences in the values of spectral indices were observed in May and June, during the grain filling stage and harvest time.

With the detailed analysis of growing conditions across the arable crop fields throughout the year, it is suggested image acquisition dates should be carefully selected to help avoid the misclassifications causing by the growth of spring plants. It is also recommended that NDMI should be used in crop studies, capitalizing on its sensitivity to water content in plant cells, to assist in discriminating crops that share physical and chemical characteristics in the same growing season.

References

Agriculture and Horticulture Development Board (AHDB), Key Development Phases and Growth Stages in Barley, 2025. Available online: https://ahdb.org.uk/knowledge-library/key-development-phases-and-growth-stages-in-barley (accessed on 3 September 2025).

Ahmed, Z., Nalley, L., Brye, K., Green, S.V., Popp, M., Shew, A. M., *et al*., 2023. Winter-time cover crop identification: A remote sensing-based methodological framework for new and rapid data generation, *International Journal of Applied Earth Observation and Geoinformation*, 125, 103564. doi.org/10.1016/j.jag.2023.103564.

Belmahi, M., Hanchane, M., Krakauer, N.Y., Kessabi, R., Bouayad, H., Mahjoub, A., et al., 2023. Analysis of Relationship between Grain Yield and NDVI from MODIS in the Fez-Meknes Region, Morocco. *Remote Sens.*, 15, 2707. doi.org/10.3390/rs15112707.

Blickensdörfer, L., Schwieder, M., Pflugmacher, D., Nendel, C., Erasmi, S., & Hostert, P., 2022. Mapping of crop types and crop sequences with combined time series of Sentinel-1, Sentinel-2 and Landsat 8 data for Germany. *Remote Sensing of Environment*, 269, 112831. doi.org/10.1016/j.rse.2021.112831.

Gao, B., 1996. NDWI—A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sens. Environ.*, 58, 257–266. doi.org/10.1016/S0034-4257(96)00067-3.

Ghorbanian, A., Mohammadzadeh, A., Jamali, S., 2022. Linear and Non-Linear Vegetation Trend Analysis throughout Iran Using Two Decades of MODIS NDVI Imagery. *Remote Sens.*, 14, 3683. doi.org/10.3390/rs14153683.

Goward, S.N., Markham, B., Dye, D.G., Dulaney, W., Yang, J., 1991. Normalized difference vegetation index measurements from the advanced very high resolution radiometer. *Remote Sens. Environ*., 35, 257–277. doi.org/10.1016/0034-4257(91)90017-Z.

Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). *Remote Sens. Environ*., 25, 295–309. doi.org/10.1016/0034-4257(88)90106-X.

Johnson, D.M., 2019. Using the Landsat archive to map crop cover history across the United States, *Remote Sensing of Environment*, 232, 111286. doi.org/10.1016/j.rse.2019.111286.

KC, K., Zhao, K., Romanko, M., Khanal, S., 2021. Assessment of the Spatial and Temporal Patterns of Cover Crops Using Remote Sensing. *Remote Sens.*, 13, 2689. doi.org/10.3390/rs13142689.

Li, H.-Y., Lawrence, J.A., Mason, P.J., Ghail, R.C., 2025a. Fast Dynamic Time Warping and Hierarchical Clustering with Multispectral and Synthetic Aperture Radar Temporal Analysis for Unsupervised Winter Food Crop Mapping. Agriculture, 15, 82. doi.org/10.3390/agriculture15010082.

Li, H.-Y., Lawrence, J.A., Mason, P.J., Ghail, R.C., 2025b. Assessing the Effect of Spatial Resolution on Crop Classification Success. IGARSS 2025 - 2025 IEEE International Geoscience and Remote Sensing Symposium, Brisbane, Australia, 2025. (Processing).

Liu, H.Q., Huete, A., 1995. A feedback based modification of the NDVI to minimize canopy background and atmospheric noise. *IEEE Trans. Geosci. Remote Sens*., 33, 457–465. doi.org/10.1109/TGRS.1995.8746027.

Marino, S., Alvino, A., 2021. Vegetation Indices Data Clustering for Dynamic Monitoring and Classification of Wheat Yield Crop Traits. *Remote Sens*., 2021, 13, 541. doi.org/10.3390/rs13040541.

Md-Tahir, H., Mahmood, H.S., Husain, M., Khalil, A., Shoaib, M., Ali, M., et al., 2024. Localized Crop Classification by NDVI Time Series Analysis of Remote Sensing Satellite Data; Applications for Mechanization Strategy and Integrated Resource Management. *AgriEngineering*, 6, 2429-2444. doi.org/10.3390/agriengineering6030142.

Miyasaka, K., Miyasaka, T., Ota, J., Batsukh, S., Jamsran, U., 2021. Effects of Wheat and Rapeseed Production on Soil Water Storage in Mongolian Rangeland. *Agriculture*, 11, 888. doi.org/10.3390/agriculture11090888.

NeSmith, D.S., Ritchie, J.T., Maize (Zea mays L.) response to a severe soil water-deficit during grain-filling, Field Crops Research, 29 (1), 1992, 23-35, doi.org/10.1016/0378-4290(92)90073-I.

Reuß, F., Vreugdenhil, M., Bueechi, E., Wagner, W., 2025. Comparing Satellite-Derived and Model-Based Surface Soil Moisture for Spring Barley Yield Prediction in Central Europe. *Remote Sens.*, 17, 1394. doi.org/10.3390/rs17081394.

Rural Payments Agency (RPA), 2021. Crop Map of England (CROME) 2020. Available online: https://www.data.gov.uk/dataset/be5d88c9-acfb-4052 bf6b-ee9a416cfe60/crop-map-of-england-crome-2020#licence info. (accessed on 9 April 2023).

Sentinel-2—Missions—Sentinel Online—Sentinel Online. (n.d.) Available online: https://dataspace.copernicus.eu/data-collections/copernicus-sentinel-missions/sentinel-2 (accessed on 9 April 2023).

Svobodová, I., Míša, P., 2004. Effect of drought stress on the formation of yield elements in spring barley and the potential of stress expression reduction by foliar application of fertilizers and growth stimulator. *Plant Soil Environ.*, 50(10), 439-446. doi.org/10.17221/4056-PSE.

Tenreiro, T.R., García-Vila, M., Gómez, J.A., Jiménez-Berni, J.A., Fereres E., 2021. Using NDVI for the assessment of canopy cover in agricultural crops within modelling research, *Computers and Electronics in Agriculture*, 182, 106038. doi.org/10.1016/j.compag.2021.106038.

Veloso, A., Mermoz, S., Bouvet, A., Toan, T. L., Planells, M., Dejoux, J., Ceschia, E., 2017. Understanding the temporal behavior of crops using Sentinel-1 and Sentinel-2-like data for agricultural applications. *Remote Sensing of Environment*, 199, 415–426. doi.org/10.1016/j.rse.2017.07.015.