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AN AUTOMATED APPROACH FOR UPDATING LAND COVER CHANGE MAPS USING SATELLITE IMAGERY

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ABSTRACT: Land cover change is a critical aspect of global environmental dynamics, influencing ecosystems, biodiversity, and climate change. This study presents an automated approach for updating land cover maps across Europe, combining Sentinel-1 and Sentinel-2 satellite imagery within the Copernicus framework. The application utilises machine learning algorithms to categorise land cover changes into classes such as no change, retained/reclassified, deurbanisation, afforestation, and urbanisation. Case studies in Poland, Greece, and Italy demonstrate the application's effectiveness, revealing the impact of motorway construction, afforestation efforts, and rapid urbanisation. Overall accuracy rates ranged from 68% to 95%, emphasising the reliability of the methodology. The open-source application, implemented in Python Jupyter and Voila, provides a user-friendly platform for researchers and stakeholders to monitor and analyse land cover changes, supporting informed decision-making for sustainable land management and conservation efforts. This study contributes valuable insights to understanding and addressing the environmental consequences of land cover changes in diverse geographical contexts.

KEYWORDS: application, land use, land cover, machine learning, satellite images

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Introduction

Land cover change, a fundamental component of global environmental dynamics, is crucial for understanding and managing the Earth's ecosystems. It encompasses the transformation of natural and semi-natural land surfaces due to natural processes and human activities. The accurate monitoring of land cover changes is important for numerous reasons, including the assessment of environmental impacts, the preservation of biodiversity, the management of natural resources, and the formulation of effective land use policies (Phiri et al., 2020; Wang et al., 2023). Satellite-based monitoring, particularly through the Copernicus Programme and the use of Sentinel-1 and Sentinel-2 satellites, has emerged as a vital tool for comprehensively analysing and monitoring land cover changes across various spatial scales and temporal resolutions (Chughtai & Karas, 2021). By utilising the capabilities of satellite observations, scientists, policymakers, and land managers can gain valuable insights into the dynamics of land cover changes, allowing for informed decision-making and proactive environmental stewardship. Furthermore, initiatives like the Corine Land Cover program enhance the integration of satellite data, facilitating standardised land cover mapping and contributing to international efforts in preserving our planet's ecological integrity (Bielecka & Jenerowicz, 2019).

Currently, the Copernicus Climate Change Services offer a global land cover classification gridded map based on the United Nations Food and Agriculture Organization's Land Cover Classification System (LCCS). This dataset provides land cover information at a 300 m resolution and covers the period from 1992 to 2020, with annual updates. The global coverage allows for a comprehensive understanding of land cover changes worldwide. The Copernicus Land Monitoring Service provides two land cover change products:

- Copernicus Global Land Service (CGLS) Dynamic Land Cover map offers a 100 m resolution dataset that depicts land cover changes globally. This product covers the period from 2015 to 2019, with yearly updates. The higher spatial resolution, compared to the global land cover classification gridded map, allows for a more detailed analysis of land cover changes.
- CORINE Land Cover (CLC) vector inventory focuses on the pan-European region (Demirkan et al., 2020). Produced in 2000, 2006, 2012, and 2018, this dataset provides comprehensive land cover information for Europe. The spatial resolution of the CLC vector inventory varies by region and offers valuable insights into land use changes in Europe (Balzter et al., 2015).

To enhance the analysis of land cover change, the proposed study aims to implement a web application incorporating Sentinel-1 Synthetic Aperture Radar (SAR) and Sentinel-2 Multispectral Instrument (MSI) Level-1C and Level-2A satellite data. With a spatial resolution of 10 m, these data sources allow for a more detailed analysis of land cover changes (Leinenkugel et al., 2019). The temporal resolution remains annual, covering the period from 2015 to 2021. By utilising these higher-resolution satellite inputs, the application aims to offer a novel approach to evaluating land use change, capturing fine-scale details and enabling more accurate analysis. The Copernicus framework, along with the available land cover change products, provides valuable resources for assessing land use changes. The combination of global and pan-European datasets from the Copernicus Climate Change Services and Copernicus Land Monitoring Service offers comprehensive coverage. Additionally, the proposed application enhances the analysis by incorporating higher-resolution satellite data, allowing for a more detailed evaluation of land use change. This method lays the groundwork for conducting a thorough land use change analysis, which can have significant implications for effectively managing and understanding land resources.

Methods

The following steps were taken to develop a machine-learning-based application for updating land cover changes: (1) selecting areas of interest (AOI) across Poland and Europe, as well as collecting satellite imagery; (2) preprocessing satellite data, including cloud masking and creating median composites; (3) developing a Random Forest (RF) classifier with the CORINE Land Cover 2018 (CLC) database as a reference; (4) generating spatiotemporal land cover/land use classifications across the AOIs for the period 2015-2021; and (5) evaluating classification statistics to produce maps for each year. Brief descriptions are provided for context, and color coding has been used to visually distinguish each step (Figure 1).

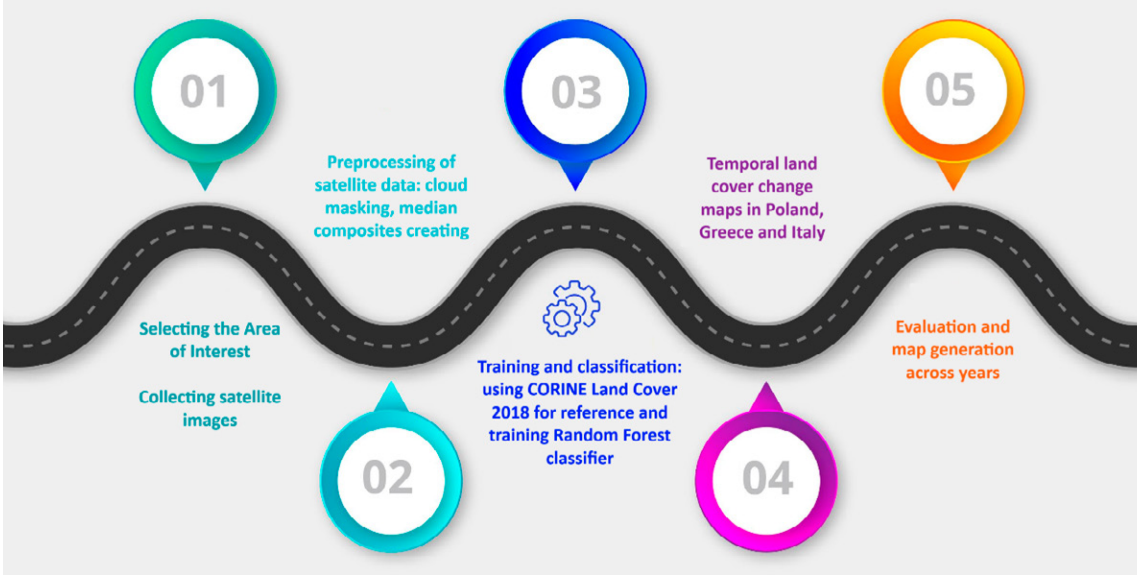


Figure 1. The process of updating land cover maps across Europe based on satellite imagery

An innovative land cover change monitoring application is introduced, focusing on the comprehensive analysis of land cover transformations across diverse geographical regions. The application is designed to passively identify and monitor five distinct types of land cover changes. These include:
1) No change: Areas where the land cover remains stable over time.
2) Retained/reclassified: Regions where land cover experiences minor adjustments, such as reclassifications of land use categories without significant changes.
3) Deurbanisation: Areas where urban developments are reversed, returning to natural or rural landscapes.
4) Afforestation: Regions where tree planting and the establishment of new forests occur.
5) Urbanisation: The expansion and intensification of urban areas, transforming natural or agricultural landscapes into built environments.

The use of five distinct land cover change classes in the application offers several advantages, enabling a more detailed and accurate understanding of land cover dynamics. By categorising land cover changes into specific types, the application allows for a precise analysis of how different areas evolve over time. This classification system enables the detection of subtle changes, such as minor reclassifications or reversals of urban development, which might otherwise be overlooked with broader categories. It also helps track trends in afforestation and urbanisation, which are important for understanding the effects of human activities on natural landscapes. The differentiation between stable areas and those undergoing transformation allows users to monitor land cover with greater accuracy. This approach supports more targeted decision-making in land management, urban planning, and conservation, ultimately fostering more sustainable development and the protection of natural ecosystems.

The primary objective of this advanced land cover monitoring application is to leverage machine learning algorithms to accurately classify land cover for two user-defined years. By utilising advanced machine learning techniques, the application can effectively analyse satellite imagery and remotely sensed data to categorise land cover into various classes based on the specified time frames (Zeferino et al., 2020). Machine learning methods are increasingly being used in land cover classification due to their significant advantages in analysing large datasets, such as satellite imagery and remotely sensed data (Bartold & Kluczek, 2023). Traditional classification methods often require manual rule-setting and parameter determination, which can be time-consuming and inefficient when dealing with large volumes of data (Bartold, 2012; Dąbrowska-Zielińska et al., 2016). In contrast, machine learning algorithms can automatically learn patterns and relationships from input data, enabling fast and accurate classification of different land cover types.

The various steps involved in creating an automatic detection system for land cover changes have been proposed. These steps encompass the utilisation of Sentinel-1 radar data registered with SAR, Sentinel-2 optical data registered with MSI, and advanced machine learning algorithms, allowing for precise and efficient detection of changes in land cover (Figure 2).

First, a user-defined area is selected as the basis for generating randomly distributed points derived from Corine Land Cover data (Dabija et al., 2021; Weinmann & Weidner, 2018). These points form the dataset used for subsequent land cover classification. To ensure accurate classification, a combination of satellite imagery is employed, including Sentinel-1 radar data and Sentinel-2 optical data (Level-2A and Level-1C). Next, for the specified user-defined years, Sentinel-1 and Sentinel-2 satellite imagery is acquired and processed to create multi-temporal compositions. These compositions are generated using the median values of the corresponding satellite images, facilitating a robust analysis of land cover changes over time.

The data is subsequently partitioned into training (80%) and validation (20%) subsets, preparing it for training the Random Forest (RF) algorithm. The RF algorithm is trained using the training subset, and its accuracy is rigorously assessed using the overall accuracy metric. Once the RF algorithm is trained and validated, it is applied to classify Sentinel-1 (S1), Sentinel-2 (S2), or combined Sentinel-1 and Sentinel-2 (S12) data, depending on dataset availability. This classification process is performed for each of the user-defined years. Finally, an automated algorithm is employed to compare the classified maps of land cover for the user-defined years. This algorithm facilitates the creation of detailed land cover change maps and enables the calculation of essential statistics and prediction accuracy measures (Stehman & Foody, 2019).

For the synergistic use of optical and radar satellite images, we matched the spatial resolution of Sentinel-1 to that of Sentinel-2 by applying pixel neighborhood resampling. This method resamples the Sentinel-1 pixels based on the surrounding neighborhood, ensuring compatibility between the datasets and enabling seamless combination for analysis. To generate the Sentinel-2 median mosaic, we processed all available optical satellite acquisitions, including both cloudy and cloud-free images, applying cloud masks where necessary. Similarly, the Sentinel-1 median mosaic was constructed using all available radar satellite acquisitions.

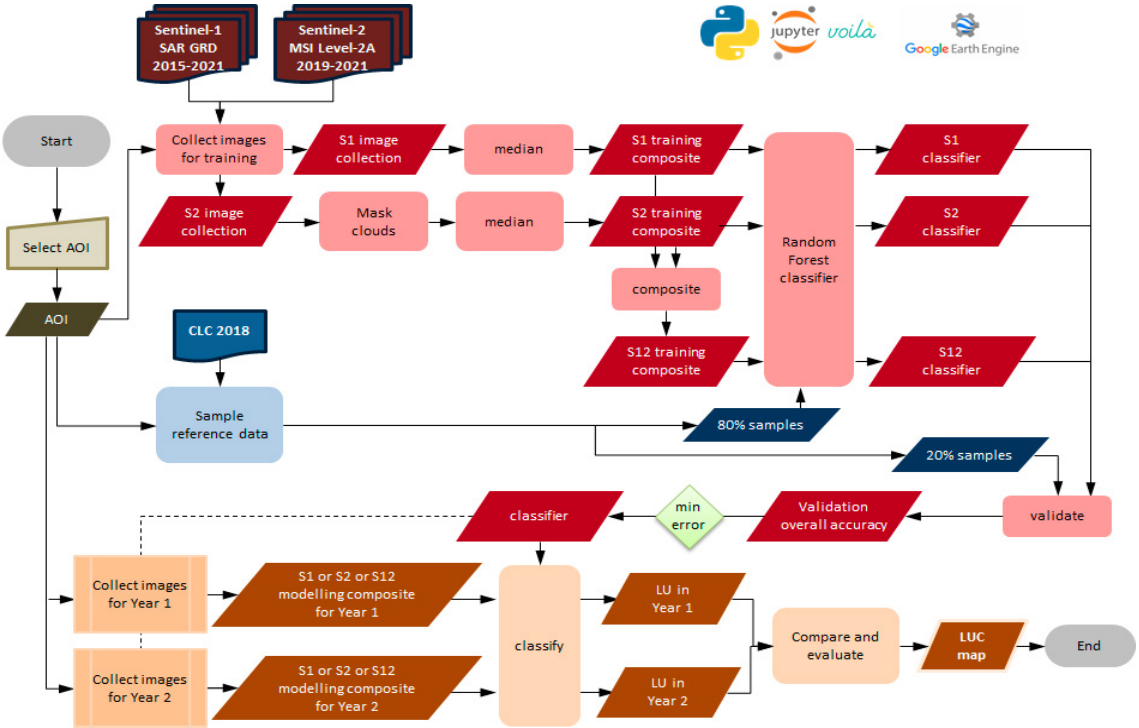
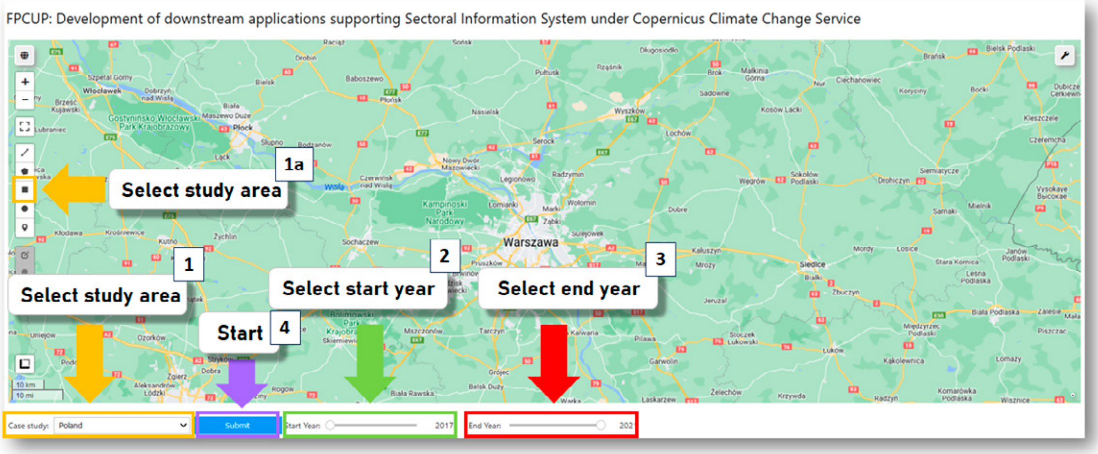


Figure 2. Process diagram of steps undertaken during processing satellite imagery for updating land cover changes across study sites

An application was developed to monitor land cover changes, utilising Google Earth Engine (Gorelick et al., 2017) and the geemap library in Python Jupyter as the coding platform, which was subsequently implemented in Voila. The integration with Voila allows the application to be deployed on various cloud platforms, including open-source options like Heroku, as well as commercial alternatives.

The user interface has been designed to offer extensive functionality, allowing users to define their research areas based on specific requirements (Figure 3). Additionally, the application provides a selection of pilot areas in Poland, Greece, and Italy, covering a wide range of geographical interests. Within the user interface, users can easily utilise interactive sliders to select the range of years they wish to analyse for land cover changes. This flexibility enables researchers and stakeholders to effectively study long-term trends and patterns in land use transformations. Moreover, the application allows users to individually select layers of interest, customising their analysis to focus on specific aspects of land cover changes, such as vegetation, urbanisation, or deforestation.

One of the key features of the application is its ability to display Sentinel-2 preview images for defined date ranges. These preview images provide valuable visual insights into the land cover conditions at specific time points, facilitating a comprehensive understanding of changes occurring in the selected regions. This image displays functionality enhances the user experience, making the analysis more intuitive and accessible. Overall, the application offers a robust and user-friendly platform for monitoring land cover changes. Its implementation in Voila, along with compatibility with various cloud application platforms, ensures seamless access and usability, regardless of the hosting environment.



FPCUP: Development of downstream applications supporting Sectoral Information System under Copernicus Climate Change Service

Case study: Poland

Start Year: 2017

End Year: 202

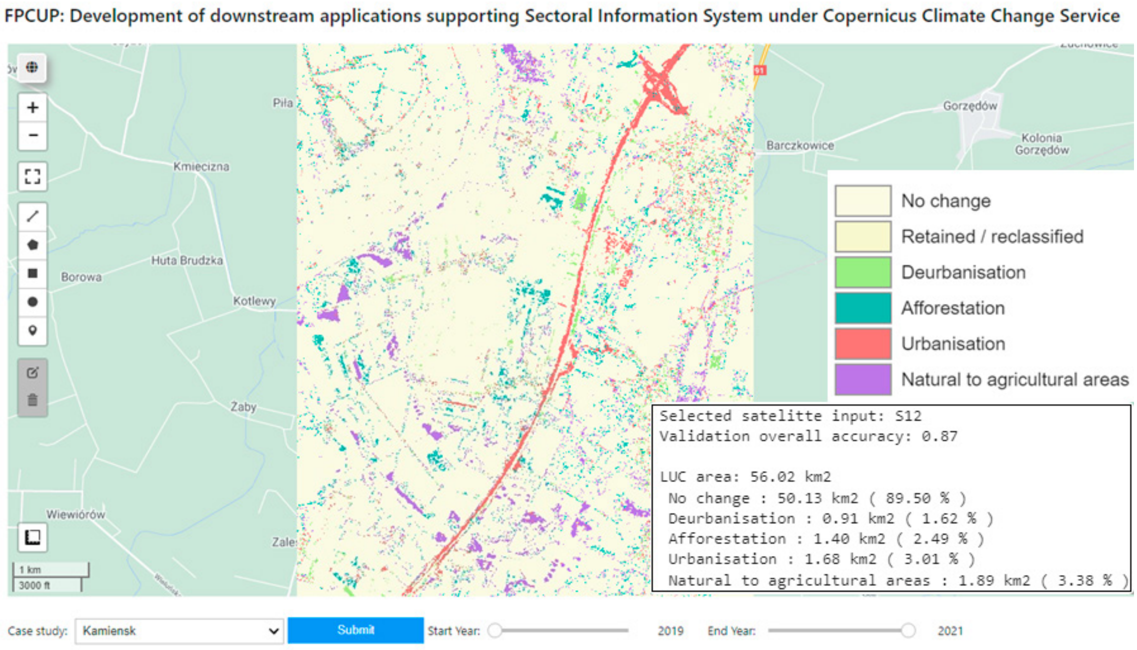
Figure 3. User interface for monitoring land cover changes in the application

The developed application, designed for monitoring land cover changes, follows the principles of open-source software and is readily accessible to the public via GitHub. Interested users, researchers, and developers can easily access the application's source code at the following GitHub repository: https://github.com/Remote-Sensing-Centre/FPCUP-Climate. By hosting the code on GitHub, the developers demonstrate their commitment to transparency, collaboration, and community involvement in the application's ongoing development. GitHub provides an ideal platform for fostering an active and engaged community around the project, allowing users and developers to contribute by suggesting improvements, reporting issues, or submitting pull requests. This collaborative approach promotes innovation and ensures the application continues to evolve through valuable contributions from diverse perspectives.

Results

A comprehensive series of case studies was conducted in Poland, focusing on three distinct regions that experienced varying types of land cover changes. These case studies aimed to provide in-depth insights into the environmental impact and implications associated with these transformations. The selected areas for examination were Kamieńsk, Białowieża, and Karczew, each representing a unique example of land cover alteration in Poland. The first case study focused on Kamieńsk (Figure 4), a region where extensive motorway construction took place. This investigation delved into the effects of such infrastructure development on the surrounding land cover. By analysing the changes in vegetation, soil composition, and ecosystem health, researchers aimed to understand the ecological consequences of motorway construction in this particular area. The second case study centered around Białowieża (Figure 5), an area notorious for changes in forest cover. Here, the research team aimed to examine the ecological repercussions of large-scale tree removal and its subsequent impact on biodiversity, soil fertility, and overall ecosystem stability. This investigation provided valuable insights into the consequences of deforestation on both local and regional levels. The third case study focused on Karczew (Figure 6), a region experiencing rapid urbanisation and intensive land use changes. In addition to the Polish case studies, pilot areas were also identified in Greece (Figure 7) and Italy (Figure 8) to broaden the scope of the research.

The case studies provided valuable insights into the complex relationship between land cover changes and their environmental consequences. The findings of these studies can serve as a foundation for informed decision-making in land management, urban planning, and environmental policy formulation. By understanding the impacts and challenges associated with land cover changes, stakeholders can work towards more sustainable and environmentally responsible practices to preserve ecosystems and ensure a balanced coexistence between human development and nature.



FPCUP: Development of downstream applications supporting Sectoral Information System under Copernicus Climate Change Service

- ☐ No change
- ☐ Retained / reclassified
- 🟩 Deurbanisation
- 🟩 Afforestation
- 🟥 Urbanisation
- 🟪 Natural to agricultural areas

```
Selected satellite input: S12
Validation overall accuracy: 0.87

LUC area: 56.02 km2
 No change : 50.13 km2 ( 89.50 % )
 Deurbanisation : 0.91 km2 ( 1.62 % )
 Afforestation : 1.40 km2 ( 2.49 % )
 Urbanisation : 1.68 km2 ( 3.01 % )
 Natural to agricultural areas : 1.89 km2 ( 3.38 % )
```

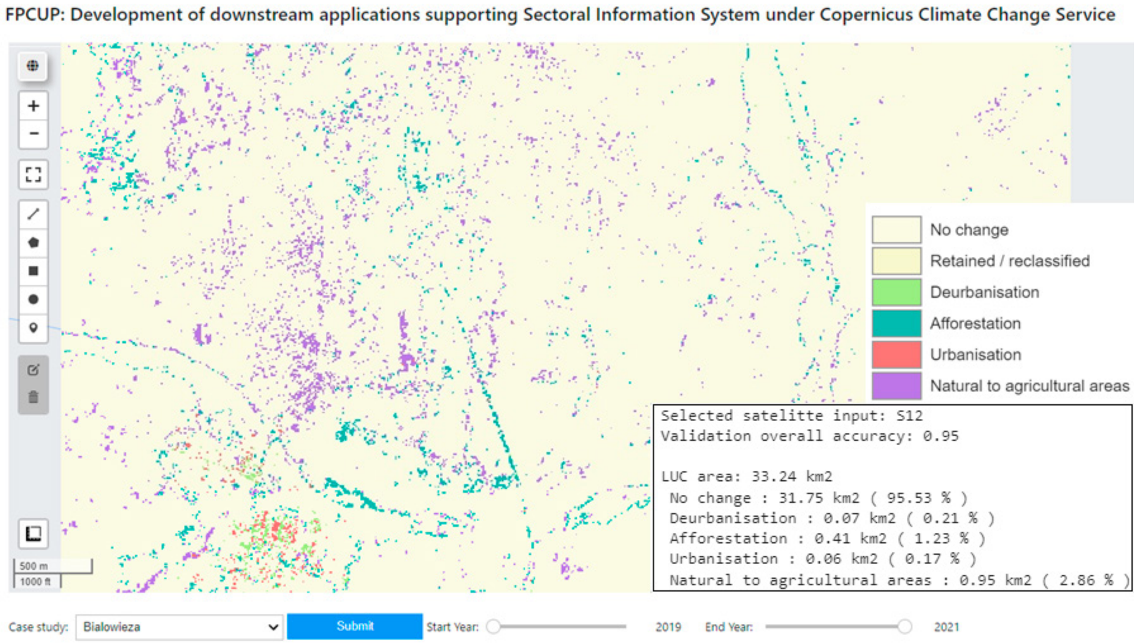
Case study: Kamiensk

Start Year: 2019 End Year: 2021

Figure 4. Polish case studies: Kamieńsk area, land cover changes between 2017-2020

The analysis conducted in the Kamieńsk area (Figure 4) assessed land use and land cover (LUC) changes across a 56.02 km^2 region, utilising Sentinel-1 and Sentinel-2 satellite data (S12) with a validation accuracy of 87%. The predominant category, “No change,” accounted for 50.13 km^2 (89.50% of the area). Notable changes included 0.92 km^2 (1.64%) for deurbanisation, 1.40 km^2 (2.49%) for afforestation, 1.68 km^2 (3.01%) for urbanisation, and 1.89 km^2 (3.38%) transitioning from natural to agricultural areas. The increase in urbanisation reflects the impact of motorway construction on the landscape, highlighting the conversion of natural areas into urban environments. The afforestation rate of approximately 2.5% demonstrates efforts to expand forested areas, potentially contributing to habitat restoration and biodiversity conservation. While the analysis achieved a slightly lower accuracy of 87%, it remains reliable and supports the credibility of these findings.

Figure 5 illustrates the results of the analysis conducted in Białowieża, which examined land use and land cover (LUC) changes across a 33.24 km^2 area using data from Sentinel-1 and Sentinel-2 satellites, with an overall validation accuracy of 95%. The dominant category, “No change,” covered 31.75 km^2 (95.53% of the area). Notable transitions included 0.07 km^2 (0.21%) for deurbanisation, 0.41 km^2 (1.23%) for afforestation, 0.06 km^2 (0.17%) for urbanisation, and 0.95 km^2 (2.86%) transitioning from natural to agricultural areas. A particularly noteworthy finding was the afforestation rate of approximately 1.5%, reflecting a positive trend in reforestation efforts in the region. This increase in forested areas suggests potential for restoring natural habitats and preserving local biodiversity. The high accuracy of the analysis (95%) underscores the reliability and precision of the methodology, reinforcing the credibility of the findings and confidence in their validity.



FPCUP: Development of downstream applications supporting Sectoral Information System under Copernicus Climate Change Service

```
Selected satellite input: S12
Validation overall accuracy: 0.95

LUC area: 33.24 km2
 No change : 31.75 km2 ( 95.53 % )
 Deurbanisation : 0.07 km2 ( 0.21 % )
 Afforestation : 0.41 km2 ( 1.23 % )
 Urbanisation : 0.06 km2 ( 0.17 % )
 Natural to agricultural areas : 0.95 km2 ( 2.86 % )
```

Case study: Bialowieza

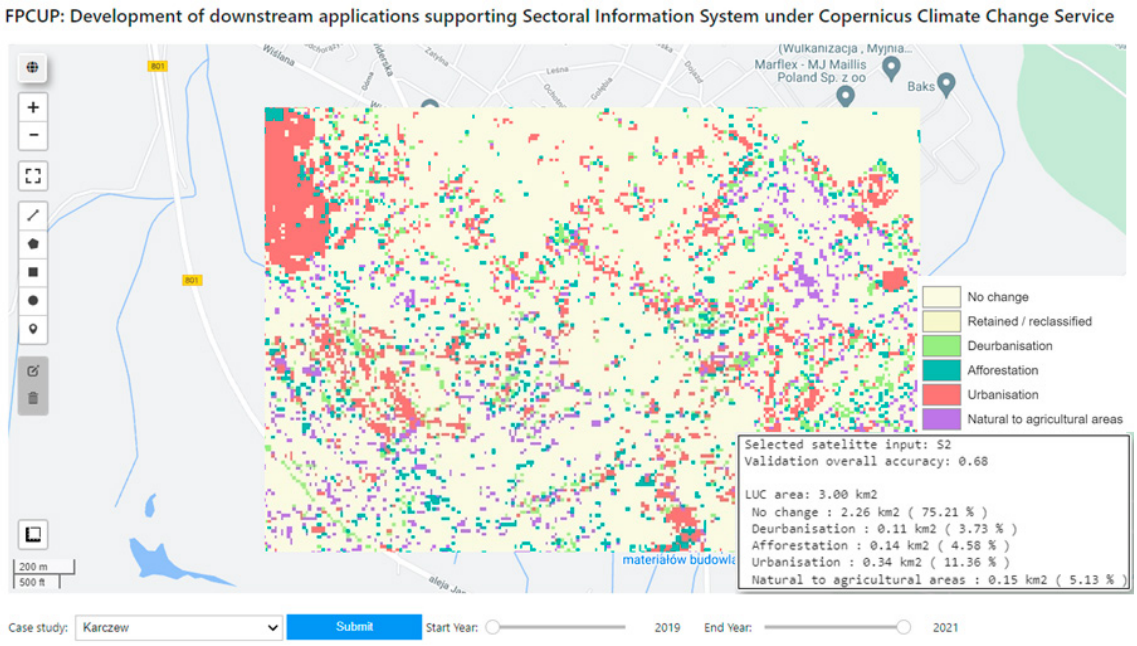
Start Year: 2019

End Year: 2021

Figure 5. Polish case studies: Białowieża area, land cover changes between 2017-2020

The analysis conducted in the Karczew area evaluated land use and land cover (LUC) changes across a 3.08 km^2 region using Sentinel-2 satellite data, achieving a validation accuracy of 68% (Figure 6). The predominant category, “No change,” accounted for 2.26 km^2 (75.21% of the area). Other significant transitions included 0.11 km^2 (3.73%) for deurbanisation, 0.01 km^2 (0.31%) for afforestation, 0.34 km^2 (11.16%) for urbanisation, and 0.35 km^2 (5.13%) transitioning from natural to agricultural areas. The urbanisation rate of over 11% suggests significant land conversion, likely driven by local development pressures, while the afforestation rate remains minimal. Despite the lower validation accuracy of 68%, the analysis provides valuable insights into the region’s land cover dynamics and highlights ongoing changes in the local environment.

The statistics and validation results from the case studies in Kamieńsk, Białowieża, and Karczew offer a detailed overview of land cover changes and their associated accuracies. These findings highlight key trends, such as the expansion of artificial impervious surfaces, afforestation efforts, and increasing urbanisation. By understanding the extent and impacts of these changes, policymakers and stakeholders can make informed decisions to promote sustainable land management practices, protect natural habitats, and address potential ecological challenges. Such insights are invaluable for balancing development with environmental preservation and ensuring long-term ecological resilience.



FPCUP: Development of downstream applications supporting Sectoral Information System under Copernicus Climate Change Service

```
Selected satelitte input: S2
Validation overall accuracy: 0.68

LUC area: 3.00 km2
 No change : 2.26 km2 ( 75.21 % )
 Deurbanisation : 0.11 km2 ( 3.73 % )
 Afforestation : 0.14 km2 ( 4.58 % )
 Urbanisation : 0.34 km2 ( 11.36 % )
 Natural to agricultural areas : 0.15 km2 ( 5.13 % )
```

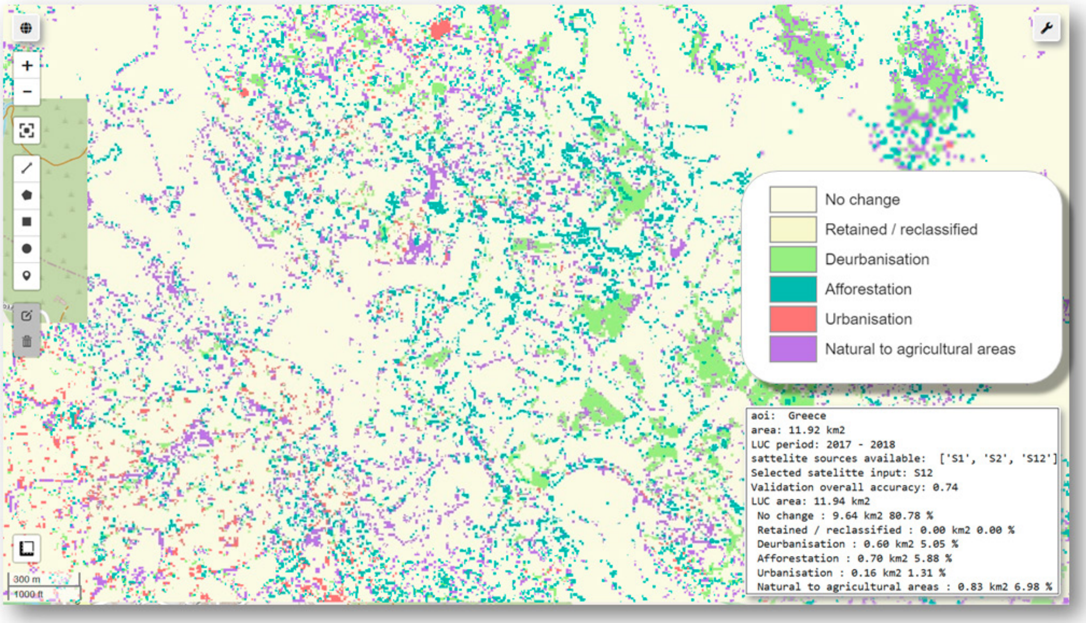
Case study: Karczew

Start Year: 2019

End Year: 2021

Figure 6. Polish case studies: Karczew area, land cover changes between 2017-2020

The pilot study conducted in Greece (Figure 7), focusing on an area near Thessaloniki, aimed to analyse land cover changes between 2017 and 2018. The overall accuracy of the classification process was determined to be 74%, indicating a reliable assessment of land cover changes within the study area. This accuracy reinforces the robustness of the methodology and enhances confidence in the results. Notably, significant changes were observed in two specific land cover classes. Afforestation showed substantial growth, covering approximately 6% of the total study area. This increase highlights the region's positive efforts in reforestation and the establishment of new forested areas, which can benefit biodiversity and ecosystem health.



```
aoi:  Greece
area: 11.92 km2
LUC period: 2017 - 2018
sattelite sources available:  ['S1', 'S2', 'S12']
Selected satelitte input: S12
Validation overall accuracy: 0.74
LUC area: 11.94 km2
 No change : 9.64 km2 80.78 %
 Retained / reclassified : 0.00 km2 0.00 %
 Deurbanisation : 0.60 km2 5.05 %
 Afforestation : 0.70 km2 5.88 %
 Urbanisation : 0.16 km2 1.31 %
 Natural to agricultural areas : 0.83 km2 6.98 %
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Figure 7. Greece pilot study: area near Thessaloniki, land cover changes between 2017-2018

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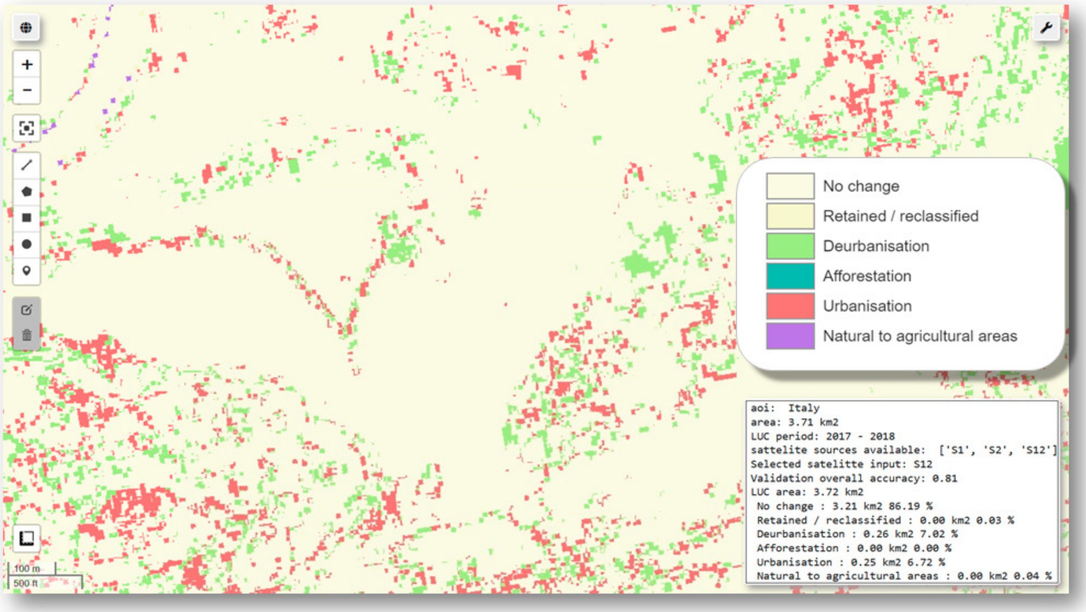
The pilot study conducted in Italy focused on an area near Rome (Figure 8), with the goal of analysing land cover changes between 2017 and 2018. The classification process achieved an overall accuracy of 81%, demonstrating the reliability and precision of the methodology. This accuracy further reinforces the robustness of the approach and instills confidence in the results. Notably, urbanisation emerged as a key focus, with approximately 6% of the study area undergoing urban expansion and intensification during this period. This significant increase in urban areas highlights the region's continued urban development and the challenges associated with managing urban sprawl and its impact on natural ecosystems.



```
aoi:  Italy
area: 3.71 km2
LUC period: 2017 - 2018
sattelite sources available:  ['S1', 'S2', 'S12']
Selected satelitte input: S12
Validation overall accuracy: 0.81
LUC area: 3.72 km2
 No change : 3.21 km2 86.19 %
 Retained / reclassified : 0.00 km2 0.03 %
 Deurbanisation : 0.26 km2 7.02 %
 Afforestation : 0.00 km2 0.00 %
 Urbanisation : 0.25 km2 6.72 %
 Natural to agricultural areas : 0.00 km2 0.04 %
```

Figure 8. Italy pilot study: area near Rome, land cover changes between 2017-2018

Discussion

Our study is aimed at delivering a user-friendly application for do-it-yourself (DIY) projects which are significant for several compelling reasons. Firstly, they enhance accessibility by catering to a broad audience, accommodating individuals with varying levels of expertise on LULC maps and identifying LULC changes. This inclusivity is pivotal in encouraging people from diverse backgrounds and skill sets to engage in DIY activities. A reduction in the learning curve is another key advantage of user-friendly interfaces, making it easier for users to comprehend project steps, particularly for those lacking prior experience (Tsou et al., 2003). Efficiency is a notable benefit, with well-designed applications streamlining the project process, ultimately saving users time and effort. Clear navigation, concise instructions, and interactive features contribute to a more seamless workflow, particularly beneficial for individuals with limited time to dedicate to their projects. Moreover, the boost in user confidence is substantial. When interfaces are intuitive, users are more likely to feel capable and empowered to successfully complete their projects (Buettig et al., 2022; Tsou et al., 2003). The widespread adoption of DIY culture is facilitated by user-friendly applications. Accessible via GitHub repository tools and resources contribute to the growth of a more engaged and collaborative community, fostering the sharing of skills and knowledge (Mikulak et al., 2021). Additionally, the adaptability of such applications to a diverse range of projects is a key advantage. Whether the focus is on home improvement, crafting, or technology-related endeavors, versatile and intuitive applications can cater to a variety of interests and needs. Digital collaboration and sharing are also promoted through user-friendly applications, featuring functionalities that enable users to share project progress, seek advice, and collaborate with others remotely (Dawid & Bielecka, 2022). This social aspect enhances the sense of community among DIY enthusiasts. Furthermore, as DIY projects increasingly integrate technology, user-friendly applications become essential. They enable users to seamlessly leverage modern tools such as augmented reality, virtual reality, and the Internet of Things (IoT), aligning with evolving trends and meeting user expectations (Koala et al., 2021; Ullo & Sinha, 2021). In summary, the importance of user-friendly applications for DIY projects lies in their ability to enhance accessibility, reduce learning barriers, save time, boost user confidence, foster collaboration, cater to diverse interests, and align with technological trends.

Land Use Land Cover (LULC) maps offer valuable insights into the prevailing landscape conditions of a given area. These maps serve as crucial resources for users seeking a comprehensive understanding of the current land features (Aleksandrowicz et al., 2014; Dawid & Bielecka, 2022). When incorporated into national spatial databases, annual LULC data facilitates the systematic monitoring of temporal changes in various elements such as agricultural ecosystems, forest conversions, and surface water bodies. This periodic information proves instrumental in tracking the dynamic shifts within the landscape on an annual basis (Chaves et al., 2020). Our distinctive advantage in applications lies in our ability to precisely and up-to-date map changes in land use and land cover utilising real-time Sentinel satellite data. This capability sets us apart by providing accurate and up-to-date insights into the evolving dynamics of landscapes. By harnessing actual satellite data, our applications ensure a level of precision and reliability that is indispensable for monitoring and analysing shifts in land features, making them an invaluable resource for informed decision-making and comprehensive understanding of environmental changes over time (Close et al., 2018). A key and highly significant aspect of our applications is that users no longer need to wait for annual updates of land cover products. Our system empowers users to promptly access and utilise the latest satellite data to map the current status and changes in land cover. This real-time capability eliminates the necessity for prolonged waiting periods associated with traditional annual updates, providing users with instantaneous and up-to-date information to better respond to dynamic environmental conditions and make informed decisions promptly.

However, proposed automated updates on land cover status and changes are not without limitations. The complexity of certain land cover types, particularly those with spectral similarities or dynamic characteristics, poses a challenge to accurate classification. Successful implementation relies heavily on the availability of high-quality training data (Thinh et al., 2019), and issues such as change detection (Häme et al., 2020), subtle environmental alterations (Gudmann et al., 2020), and the interpretation of spectral information can impact accuracy (Verhoeven & Dedoussi, 2022; Gómez et al., 2016). Automated methods may struggle to incorporate contextual understanding, overlooking factors like regional policies or local knowledge (Karra et al., 2021). Additionally, the potential for overfitting in machine learning models (Mishra et al., 2020) and the limited ability to detect gradual changes in land cover highlight the need for a balanced approach that combines automated processes with human validation (Aleksandrowicz et al., 2014; Malinowski et al., 2020). Striking this balance ensures the optimal utilisation of technology while addressing the nuanced challenges presented by diverse landscapes and conditions (Lu et al., 2019).

The advantages and limitations are listed in Table 1 concerning the basic specifications offered through various products on the automated approach for land cover land use maps production. Our approach offers full automation for end-user and application is available at GitHub. While ESRI land cover product (Karra et al., 2021) is easily accessed via Google Earth Engine GEE cloud computing platform, however, the data is current from the year 2020. Malinowski et al. (2020) deliver through S2GLC land cover map for 2017 only, that have been fully automated but not offering up-to-date maps. While ESA WorldCover offers the maps with identified 13 classes of land cover with years 2020-2021 only (Zanaga et al., 2022). Both of them are now available through the CREODIAS cloud computing platform. Last but not least, Copernicus Land Monitoring Service offers CORINE LC maps, which are updated and delivered at intervals of every six years.

Table 1. Specifications of automated land cover/use maps using Sentinel satellite imagery

Name of product / Authors	Automatization	Area of coverage	Algorithms	Do It Yourself project	User-friendly access	Up-to-date
Bartold et al. (2025)	YES	Europe	Machine learning	YES Jupyter Notebook	GitHub	2024
ArcGIS Online	YES	Global	Deep learning	NO	GEE snippet esri_lulc2020	2020
S2GLC	YES	Europe	Machine learning	NO	CREODIAS	2017
ESA WorldCover	YES	Global	Machine learning	NO	CREODIAS	2021
Corine Land Cover	Semi-automated	Europe	Visual interpretation	NO	Copernicus LMS Dataset catalogue	2018

Our an automated approach for updating land cover maps across Europe might support the LULUCF initiative, referring to land use, land use change, and forestry, that encompasses the management of soil, trees, plants, biomass, and wood, all of which play a crucial role in the European Union's efforts to combat climate change. Regarding European Commission report (2018) LULUCF are highly significant due to being among the few opportunities not only to reduce emissions but also to remove CO2 from the atmosphere. It's essential to highlight the role of forests and identified within the application afforestation areas in the EU, which annually absorb nearly 10% of the total greenhouse gas emissions in the European Union. Providing actual land cover changes at agriculture and forestry areas for administrative units and NGOs, end-users are able to investigate land cover changes for sustainable development under the European Union programs.

Conclusions

We have developed and implemented a user-friendly and an innovative land cover change monitoring application, leveraging the power of advanced machine learning algorithms and high-resolution satellite data within the Copernicus framework. Our approach focused on providing DIY a detailed analysis of land cover changes, categorising them into distinct classes, and conducting case studies in diverse geographical regions. The significance of mapping land cover lies in its crucial role in global environmental dynamics and its profound impact on climate change. Land cover changes, as demonstrated in our case studies, have far-reaching consequences on ecosystems, biodiversity, and socio-economic aspects. The ability to accurately monitor and analyse these changes is paramount for informed decision-making in environmental stewardship. Our application successfully categorised land cover changes into five classes: no change, retained/reclassified, deurbanisation, afforestation, and urbanisation. This passive categorisation facilitated a comprehensive understanding of land cover dynamics, empowering researchers and policymakers with valuable insights. The integration of machine learning algorithms with Sentinel-1 and Sentinel-2 satellite data enabled us to achieve a high level of accuracy in classifying land cover changes. The case studies conducted in Poland, Greece, and Italy provided detailed insights into specific regional changes, such as the impact of motorway construction, afforestation efforts, and rapid urbanisation. The results from these case studies demonstrated the effectiveness of our approach, with overall accuracy rates ranging from 68% to 95%. These findings not only highlight the reliability of our methodology but also provide valuable data for stakeholders to address the environmental consequences of land cover changes. In Poland, the study in Kamieńsk revealed the transformation of natural areas into built environments due to motorway construction. In Białowieża, afforestation efforts positively impacted biodiversity and ecosystem stability. However, in Karczew, intensive urbanisation processes were observed, indicating the challenges of balancing urban development with environmental conservation. The pilot studies in Greece and Italy showcased the applicability of our methodology in different geographical contexts. Afforestation efforts in Greece and urban expansion in Italy were accurately detected, emphasising the versatility of our approach in capturing diverse land cover changes. Our application, implemented in Python Jupyter and Voila, offers a user-friendly platform for researchers and stakeholders. The open-source nature of the project on GitHub encourages collaboration, transparency, and continuous improvement. In conclusion, our study contributes to the field of land cover change monitoring by providing a robust and efficient methodology. The insights gained from the case studies emphasise the importance of informed decision-making for sustainable land management, conservation efforts, and addressing the challenges posed by global environmental changes. As we move forward, the integration of advanced technologies and collaborative efforts will further enhance our understanding of land cover dynamics and support the development of effective strategies for a balanced coexistence between human development and the environment.

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The contribution of the authors

Conceptualization, M.B., M.K. and K.D.-Z.; literature review, M.B and M.K.; methodology, M.B. and M.K.; formal analysis, M.B. and M.K.; writing, M.B., M.K. and K.D.-Z.; conclusions and discussion, M.B. and M.K.

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References

Aleksandrowicz, S., Turlej, K., Lewiński, S., & Bochenek, Z. (2014). Change detection algorithm for the production of land cover change maps over the European Union countries. Remote Sensing, 6(7), 5976-5994. https://doi.org/10.3390/rs6075976

Balzter, H., Cole, B., Thiel, C., & Schmullius, C. (2015). Mapping CORINE land cover from Sentinel-1A SAR and SRTM digital elevation model data using random forests. Remote Sensing, 7(11), 14876-14898. https://doi.org/10.3390/rs71114876

Bartold, M. (2012). Monitoring of forest damages in Poland and Slovakia based on Terra. MODIS satellite images. Geoinformation Issues, 4(1(4)), 23-31. https://doi.org/10.34867/gi.2012.3

Bartold, M., & Kluczek, M. (2023). A machine learning approach for mapping chlorophyll fluorescence at inland wetlands. Remote Sensing, 15(9), 2392. https://doi.org/10.3390/rs15092392

Bielecka, E., & Jenerowicz, A. (2019). Intellectual structure of CORINE land cover research applications in Web of Science: A Europe-wide review. Remote Sensing, 11(17), 2017. https://doi.org/10.3390/rs11172017

Buettig, S., Lins, M., & Goihl, S. (2022). WaterMaskAnalyzer (WMA) – A user-friendly tool to analyze and visualize temporal dynamics of inland water body extents. Remote Sensing, 14(18), 4485. https://doi.org/10.3390/rs14184485

Chaves, E. D. M., Picoli, C. A. M., & Sanches, D. (2020). Recent applications of Landsat 8/OLI and Sentinel-2/MSI for land use and land cover mapping: A systematic review. Remote Sensing, 12(18), 3062. https://doi.org/10.3390/rs12183062

Chughtai, H. A., & Karas, I. R. (2021). A review on change detection method and accuracy assessment for land use land cover. Remote Sensing Applications: Society and Environment, 22, 100482. https://doi.org/10.1016/j.rsase.2021.100482

Close, O., Benjamin, B., Petit, S., Fripiat, X., & Hallot, E. (2018). Use of Sentinel-2 and LUCAS database for the inventory of land use, land use change, and forestry in Wallonia, Belgium. Land, 7(4), 154. https://doi.org/10.3390/land7040154

Dabija, A., Kluczek, M., Zagajewski, B., Raczko, E., Kycko, M., Al-Sulttani, A. H., Tardà, A., Pineda, L., & Corbera, J. (2021). Comparison of support vector machines and random forests for CORINE land cover mapping. Remote Sensing, 13(4), 777. https://doi.org/10.3390/rs13040777

Dawid, W., & Bielecka, E. (2022). GIS-based land cover analysis and prediction based on open-source software and data. Quaestiones Geographicae, 41(3), 75-86. https://doi.org/10.2478/quageo-2022-0026

Dąbrowska-Zielinska, K., Bartold, M., & Gurdak, R. (2016). POLWET – System for new space-based products for wetlands under RAMSAR Convention. Geoinformation Issues, 8(1(8)), 25-35. https://doi.org/10.34867/gi.2016.3

De Fioravante, P., Luti, T., Cavalli, A., Giuliani, C., Dichicco, P., Marchetti, M., Chirici, G., Congedo, L., & Munafò, M. (2021). Multispectral Sentinel-2 and SAR Sentinel-1 integration for automatic land cover classification. Land, 10(6), 611. https://doi.org/10.3390/land10060611

Demirkan, D., Koz, A., & Duzgun, S. (2020). Hierarchical classification of Sentinel-2A images for land use and land cover mapping and its use for the CORINE system. Journal of Applied Remote Sensing, 14(2), 1-21. https://doi.org/10.1117/1.JRS.14.026524

Du, L., Dong, C., Kang, X., Qian, X., & Gu, L. (2023). Spatiotemporal evolution of land cover changes and landscape ecological risk assessment in the Yellow River Basin, 2015–2020. Journal of Environmental Management, 332, 117149. https://doi.org/10.1016/j.jenvman.2022.117149

European Commission. (2018). *Analysis of LULUCF actions in EU Member States as reported under Art. 10 of the LULUCF Decision – Final report.* https://data.europa.eu/doi/10.2834/571578

FPCUP Climate. (2022). *FPCUP – Development of Downstream Applications Supporting Sectoral Information System under Copernicus Climate Change Service* [Application]. GitHub. https://github.com/Remote-Sensing-Centre/FPCUP-Climate

Ghamisi, P., Rasti, B., Yokoya, N., Wang, Q., Höfle, B., Bruzzone, L., Bovolo, F., Chi, M., Anders, K., Gloaguen, R., Atkinson, P. M., & Benediktsson, J. A. (2019). Multisource and multitemporal data fusion in remote sensing: A comprehensive review of the state of the art. IEEE Geoscience and Remote Sensing Magazine, 7(1), 6-39. https://doi.org/10.1109/MGRS.2018.2890023

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment, 202, 18-27. https://doi.org/10.1016/j.rse.2017.06.031

Gómez, C., White, J. C., & Wulder, M. C. (2016). Optical remotely sensed time series data for land cover classification: A review. ISPRS Journal of Photogrammetry and Remote Sensing, 116, 55-72. https://doi.org/10.1016/j.isprsjprs.2016.03.008

Gudmann, A., Csikós, N., Szilassi, P., & Mucsi, L. (2020). Improvement in satellite image-based land cover classification with landscape metrics. Remote Sensing, 12(21), 3580. https://doi.org/10.3390/rs12213580

Häme, T., Sirro, L., Kilpi, J., Seitsonen, L., Andersson, K., & Melkas, T. (2020). A hierarchical clustering method for land cover change detection and identification. Remote Sensing, 12(11), 1751. https://doi.org/10.3390/rs12111751

Karra, K., Kontgis, C., Statman-Weil, Z., Mazzariello, J. C., Mathis, M., & Brumby, S. P. (2021). Global land use/land cover with Sentinel-2 and deep learning. *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium IGARSS*, Brussels, Belgium, 4704-4707. https://doi.org/10.1109/IGARSS47720.2021.9553499

Koala, H., Georgakopoulos, D., Jayaraman, P. P., & Yavari, A. (2021). Managing time-sensitive IoT applications via dynamic application task distribution and adaptation. Remote Sensing, 13(20), 4148. https://doi.org/10.3390/rs13204148

Leinenkugel, P., Deck, R., Huth, J., Ottinger, M., & Mack, B. (2019). The potential of open geodata for automated large-scale land use and land cover classification. Remote Sensing, 11(19), 2249. https://doi.org/10.3390/rs11192249

Lu, Y., Wu, P., Ma, X., & Li, X. (2019). Detection and prediction of land use/land cover change using spatiotemporal data fusion and the Cellular Automata–Markov model. Environmental Monitoring and Assessment, 191, 68. https://doi.org/10.1007/s10661-019-7200-2

Malinowski, R., Lewiński, S., Rybicki, M., Gromny, E., Jenerowicz, M., Krupiński, M., Nowakowski, A., Wojtkowski, C., Krupiński, M., Krätzschmar, E., & Schauer, P. (2020). Automated production of a land cover/use map of Europe based on Sentinel-2 imagery. Remote Sensing, 12(21), 3523. https://doi.org/10.3390/rs12213523

Mikula, K., Šibíková, M., Ambroz, M., Kollár, M., Ožvat, A. A., Urbán, J., Jarolímek, I., & Šibík, J. (2021). NaturaSat – A software tool for identification, monitoring and evaluation of habitats by remote sensing techniques. Remote Sensing, 13(17), 3381. https://doi.org/10.3390/rs13173381

Mishra, P. K., Rai, A., & Rai, S. Ch. (2020). Land use and land cover change detection using geospatial techniques in the Sikkim Himalaya, India. The Egyptian Journal of Remote Sensing and Space Science, 23(2), 133-143. https://doi.org/10.1016/j.ejrs.2019.02.001

Phiri, D., Simwanda, M., Salekin, S., Nyirenda, V. R., Murayama, Y., & Ranagalage, M. (2020). Sentinel-2 data for land cover/use mapping: A review. Remote Sensing, 12(14), 2291. https://doi.org/10.3390/rs12142291

Stehman, S. V., & Foody, G. M. (2019). Key issues in rigorous accuracy assessment of land cover products. Remote Sensing of Environment, 231, 111199. https://doi.org/10.1016/j.rse.2019.05.018

Thinh, T. V., Duong, P., Kenlo, N., & Takeo, T. (2019). How does land use/land cover map's accuracy depend on number of classification classes? SOLA, 15, 28-31. https://doi.org/10.2151/sola.2019-006

Topaloglu, R., Sertel, E., & Musaoglu, N. (2016). Assessment of classification accuracies of Sentinel-2 and Landsat-8 data for land cover/use mapping. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLI-B8, 1055-1059. https://doi.org/10.5194/isprs-archives-XLI-B8-1055-2016

Tsou, M. H., Guo, L., & Stow, D. (2003). Web-based remote sensing applications and Java tools for environmental monitoring. Online Journal of Space Communication, 2(3), 20. https://ohioopen.library.ohio.edu/spacejournal/vol2/iss3/20

Ullo, S. L., & Sinha, G. R. (2021). Advances in IoT and smart sensors for remote sensing and agriculture applications. Remote Sensing, 13(13), 2585. https://doi.org/10.3390/rs13132585

Verhoeven, V. B., & Dedoussi, I. C. (2022). Annual satellite-based NDVI-derived land cover of Europe for 2001–2019. Journal of Environmental Management, 302(Part A), 113917. https://doi.org/10.1016/j.jenvman.2021.113917

Viana, C. M., Oliveira, S., Oliveira, S. C., & Rocha, J. (2019). Land use/land cover change detection and urban sprawl analysis. In H.R. Pourghasemi & C. Gokceoglu (Eds.), *Spatial modeling in GIS and R for Earth and environmental sciences* (pp. 621-651). Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-815226-3.00029-6

Wang, Q., Guan, Q., Sun, Y., Du, Q., Xiao, X., Luo, H., Zhang, J., & Mi, J. (2023). Simulation of future land use/cover change (LUCC) in typical watersheds of arid regions under multiple scenarios. Journal of Environmental Management, 335, 117543. https://doi.org/10.1016/j.jenvman.2023.117543

Weinmann, M., & Weidner, U. (2018). Land-cover and land-use classification based on multitemporal Sentinel-2 data. *Proceedings of the International Geoscience and Remote Sensing Symposium*, Valencia, Spain, 4946-4949. https://doi.org/10.1109/IGARSS.2018.8519301

Zanaga, D., Van De Kerchove, R., Daems, D., De Keersmaecker, W., Brockmann, C., Kirches, G., Wevers, J., Cartus, O., Santoro, M., Fritz, S., Lesiv, M., Herold, M., Tsendbazar, N. E., Xu, P., Ramoino, F., & Arino, O. (2022). *ESA WorldCover 10 m 2021 v200 [Data set].* https://doi.org/10.5281/zenodo.7254221

Zeferino, B. L., Tavares de Souza, L. F., Hummel do Amaral, C., Filho, E. I. F., & Senna de Oliveira, T. (2020). Does environmental data increase the accuracy of land use and land cover classification? International Journal of Applied Earth Observation and Geoinformation, 91, 102128. https://doi.org/10.1016/j.jag.2020.102128

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ZAUTOMATYZOWANA METODA AKTUALIZACJI MAP ZMIAN POKRYCIA TERENU NA PODSTAWIE ZOBRAZOWAŃ SATELITARNYCH

STRESZCZENIE: Zmiany w pokryciu terenu stanowią istotne zagadnienie w badaniach globalnych procesów środowiskowych, wpływając na ekosystemy, bioróżnorodność oraz zmiany klimatu. W niniejszej pracy przedstawiono zautomatyzowaną metodę aktualizacji map pokrycia terenu w Europie, wykorzystującą zobrazowania z misji satelitów Sentinel-1 oraz Sentinel-2 w ramach programu Copernicus. Algorytmy uczenia maszynowego posłużyły do klasyfikacji zmian pokrycia terenu w kategoriach takich jak brak zmiany, zachowane-przeklasyfikowane, dezurbanizacja, zalesianie oraz urbanizacja. Skuteczność rozwiązania została potwierdzona w studiach przypadków przeprowadzonych w Polsce, Grecji i Włoszech, gdzie zidentyfikowano wpływ budowy autostrad, działań zalesieniowych oraz intensywnej urbanizacji. Dokładność klasyfikacji wynosiła od 68% do 95%, co świadczy o wysokiej jakości zastosowanej metodyki. Aplikacja, opracowana w otwartym środowisku Python Jupyter i Voila, zapewnia intuicyjną platformę dla naukowców i decydentów, umożliwiającą monitorowanie oraz analizę zmian pokrycia terenu. Narzędzie to wspiera podejmowanie świadomych decyzji dotyczących zrównoważonego zarządzania gruntami i ochrony środowiska. Niniejsze badanie dostarcza cennych informacji na temat konsekwencji zmian pokrycia terenu w różnych kontekstach geograficznych, przyczyniając się do lepszego zrozumienia i skuteczniejszego zarządzania tymi procesami.

SŁOWA KLUCZOWE: aplikacja, pokrycie terenu, użytkowanie ziemi, uczenie maszynowe, obrazy satelitarne