

Supplement of “Mapping forest canopy height over Europe by integrating Sentinel-1, Sentinel-2, GEDI, and ICESat-2 data”

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S.1 Vegetation indices

Index	Description	Reference
NDVI	Normalized Difference Vegetation Index – NDVI is used to quantify vegetation greenness and is useful in understanding vegetation density and assessing changes in plant health.	(Rouse et al., 1974)
EVI	Enhanced Vegetation Index - EVI is similar to Normalized Difference Vegetation Index (NDVI) and can be used to quantify vegetation greenness. However, EVI corrects for some atmospheric conditions and canopy background noise and is more sensitive in areas with dense vegetation.	(Huete et al., 2002)
NIRV	Near-Infrared Reflectance of Vegetation – represents the proportion of pixel reflectance attributable to vegetation in the pixel	(Badgley et al., 2017)
NDWI	Normalized Difference Water Index– related to water content in water bodies	(McFeeters et al., 1996)
NDGI	Normalized Difference Greenness Index (or more common name is NGRDI or Normalized difference green/red index) – related to greenness	(Tucker, 1979)
NDMI	Normalized Difference Moisture Index – related to the water content of leaves	(Gao et al., 1996)
NBR	Normalized Burn Ratio - NBR is often used to identify burned areas and provide a measure of burn severity	(Garcia et al., 1991)
NBR2	Normalized Burn Ratio2 - NBR2 modifies the Normalized Burn Ratio (NBR) to highlight water sensitivity in vegetation.	(Garcia et al., 1991)
REP	Red Edge Position - sensitive to changes in chlorophyll concentration	(Curran et al., 1995)

ANIR	Angle at Near-Infrared – suited to detect to dry plant matter in the presence of soil and green vegetation cover	(Khanna et al., 2007)
NDRE2	Normalized Difference Red Edge index – based on Sentinel-2 red edge band 6, chlorophyll content	(Gitelson & Merzlyak, 1994)
NDRE3	Normalized Difference Red Edge index – based on Sentinel-2 red edge band 7, chlorophyll content	(Gitelson & Merzlyak, 1994)

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S.2 ALS data collection

ALS data were collected for each of the selected patch locations, provided that freely available LAZ-files were available. Over 18 countries ALS data could be retrieved, with varying means of accessing and downloading the data (Table S1).

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Table S1: Summary of ALS data download for 18 countries.

Country/Region	Description
Belgium	ALS data was provided over Flanders by Digitaal Vlaanderen through the EODaS (Earth Observation Data Science) programme. The data were obtained from the Open LiDAR Vlaanderen portal (https://remotesensing.vlaanderen.be/apps/openlidar/) and are distributed under the Free Open Data License Flanders v1.2: Free Open Data License Flanders v1.2. In Wallonia, ALS data were obtained from the Service public de Wallonie dataset Lidar 2021–2022 – Série (01-03-2023) available through the Walloon geodata portal (https://geodata.wallonie.be/id/3ef17388-54cd-4034-baad-d247243123c2). The dataset is distributed under the Creative Commons Attribution 4.0 International (CC BY 4.0) license: Attribution 4.0 International (CC BY 4.0).
Denmark	ALS data for were obtained through the Danish data portal (https://dataforsyningen.dk). The dataset is provided by the Danish Climate Data Agency and the Danish Agency for Data Supply and Efficiency. It is distributed under the Creative Commons Attribution 4.0 International (CC BY 4.0) license: Attribution 4.0 International (CC BY 4.0).
Estonia	ALS data for Estonia (2012–2017) were obtained from the Estonian Land Board (Maa-amet) geoportal (https://geoportaal.maaamet.ee/eng), provided by the republic of Estonia Land and Spatial Development Board. The dataset is distributed under the Republic of Estonia Land and Spatial Development Board open data license: Republic of Estonia opendata licence.

Finland	<p>ALS data were obtained from the National Land Survey of Finland (Maanmittauslaitos) through the Karttapaikka geoportal (https://asiointi.maanmittauslaitos.fi/karttapaikka). The dataset originates from the National Land Survey's laser scanning data (0.5 points m⁻²; acquisition years 2008–2019) and is distributed under the Creative Commons Attribution 4.0 International (CC BY 4.0) license: Attribution 4.0 International (CC BY 4.0).</p>
France	<p>ALS data over France were obtained from the LiDAR HD dataset provided by the Institut national de l'information géographique et forestière (IGN) through the Géoplateforme portal (https://geoservices.ign.fr/lidarhd). The dataset is distributed under the Open Licence 2.0 (Etalab): France open licence 2.0.</p>
Germany	<p>Data for several German federal states were obtained from publicly available geospatial portals. These include datasets provided by the Bayerische Vermessungsverwaltung (Bavaria), the Landesvermessung und Geobasisinformation Brandenburg through the OpenGeodata Brandenburg portal, the Geschäftsstelle IMA GDI.NRW (North Rhine-Westphalia), the Landesamt für Geobasisinformation Sachsen (Saxony), and the Thüringer Landesamt für Bodenmanagement und Geoinformation (Thuringia). The datasets were accessed through the respective state geodata portals (https://geodaten.bayern.de/opengeodata/, https://data.geobasis-bb.de, https://www.geoportal.nrw, https://www.geodaten.sachsen.de, https://geoportal.thueringen.de) and are distributed under either the Creative Commons Attribution 4.0 International (CC BY 4.0) licence (Bavaria), the Data licence Germany – attribution – Version 2.0 (dl-de/by-2-0) (Brandenburg, Saxony, Thuringia), and the licence Germany – Zero – Version 2.0 (North Rhine-Westphalia): Attribution 4.0 International (CC BY 4.0), Data license Germany Attribution 2.0, and Data Licence Germany - Zero - Version 2.0.</p>
Italy	<p>ALS data for the Autonomous Province of Trento were obtained from the geospatial portal of the Provincia Autonoma di Trento (https://siat.provincia.tn.it/stem/). The data are distributed under the Creative Commons Attribution 4.0 International: Attribution 4.0 International (CC BY 4.0).</p>
Latvia	<p>Airborne laser scanning (ALS) LiDAR data for Latvia were obtained from the Latvian Geospatial Information Agency (LGIA) geospatial data portal (https://www.lgia.gov.lv/en/Digit%C4%81lais%20virsmas%20modelis). The dataset is distributed under the Creative Commons Attribution 4.0 International: Attribution 4.0 International (CC BY 4.0).</p>
Luxembourg	<p>ALS data were obtained from the geospatial portal of the Administration du Cadastre et de la Topographie (https://map.geoportail.lu). The data are distributed under the Creative Commons Zero licence: Deed - CC0 1.0 Universal - Creative Commons.</p>

Netherlands	ALS data were obtained from the Actueel Hoogtebestand Nederland (AHN) portal provided by Rijkswaterstaat via the PDOK platform (https://www.pdok.nl/) under licence CC-0: Deed - CC0 1.0 Universal - Creative Commons.
Norway	ALS data were obtained from the Høydedata.no portal provided by the Norwegian Mapping Authority (Kartverket). The dataset is distributed under the Creative Commons Attribution 4.0 International: Attribution 4.0 International (CC BY 4.0).
Poland	ALS were obtained from the national geospatial portal Geoport.al.gov.pl, operated by the Head Office of Geodesy and Cartography (GUGiK). The dataset was openly distributed: https://www.gov.pl/web/gugik-en/data .
Slovakia	ALS data were obtained from the geospatial portal of the Geodesy, Cartography and Cadastre Authority of the Slovak Republic (ÚGKK SR). The dataset is distributed under the Creative Commons Attribution 4.0 International: Attribution 4.0 International (CC BY 4.0).
Slovenia	ALS data were obtained from the geospatial data portal of the Slovenian Environment Agency (ARSO) (https://gis.arso.gov.si/evode/). The data were distributed by the Ministry of Environment and Spatial Planning and Slovenian Environment Agency under the Creative Commons Attribution 4.0 International: Attribution 4.0 International (CC BY 4.0)
Spain	ALS data were obtained from the download portal of the Centro Nacional de Información Geográfica (CNIG) (https://centrodedescargas.cnig.es). The dataset is distributed under the Creative Commons Attribution 4.0 International (Attribution 4.0 International (CC BY 4.0)) and forms part of the Plan Nacional de Observación del Territorio coordinated by the Instituto Geográfico Nacional.
Sweden	ALS data were obtained from the geospatial data portal of the Lantmäteriet (the Swedish Mapping, Cadastral and Land Registration Authority). It is distributed under licence CC-0: Deed - CC0 1.0 Universal - Creative Commons.
Switzerland	Airborne laser scanning (ALS) LiDAR data for Switzerland were obtained from the swissSURFACE3D dataset provided by the Federal Office of Topography swisstopo. The data were provided under the following terms of use: Terms of use for free geodata and geoservices (OGD) from swisstopo.
United Kingdom	Data from England were obtained from the data portal of Environment Agency (https://environment.data.gov.uk/survey). LiDAR data for Scotland were obtained from the Scottish Remote Sensing Portal (https://remotesensingdata.gov.scot/), maintained by the National Library of Scotland. The datasets are distributed under the Open Government Licence v3.0.

S.3 Availability of ALS data over Europe

20 ALS data could be collected and processed over a total of 3695 patches across 18 countries in Europe (Table S2). The patches cover a gradient from the north of Europe (Scandinavia) to the south of Europe (Spain) but show a gap in the Balkan countries and Italy. It is notable that ALS data could not be obtained for every sampled patch across all countries. For example, out of the 564 patches delineated for Italy, ALS data was retrievable only for 10 patches; data for the remaining patches either could not be located, were unavailable, or required payment.

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Table S2 The number of patches defined per country and the corresponding number of patches with available and processed ALS data

Country	Number of patches	
	Selected	Processed
Belgium	43	43
Denmark	94	94
Estonia	94	94
Finland	476	474
France	663	346
Germany	380	142
Italy	564	10
Latvia	114	114
Luxembourg	2	2
Netherlands	60	60
Norway	501	501
Poland	385	385
Slovakia	56	45
Slovenia	21	21
Spain	676	676
Sweden	586	463
Switzerland	34	29
United Kingdom	456	196
Total	5205	3695

S.4 Flight dates

Information on the flight date of the ALS data could be retrieved over the entire patch for about 98% of the patches (Figure S1). Most of the patches (92%) were covered by a single flight date, while only 5, 1, and 0.1% of the patches were covered by two, three, or four flight dates, respectively. The flight dates varied across Europe: the year of observation ranged between 2011 (e.g., in parts of Poland) to 2023 (e.g., in parts of France). The day of the year (DOY) of the flight also varied across Europe. The data in northern Scandinavia was mostly acquired around summer, whereas most of the data in the United Kingdom, Netherlands, Belgium, and northern France were acquired in the winter period.

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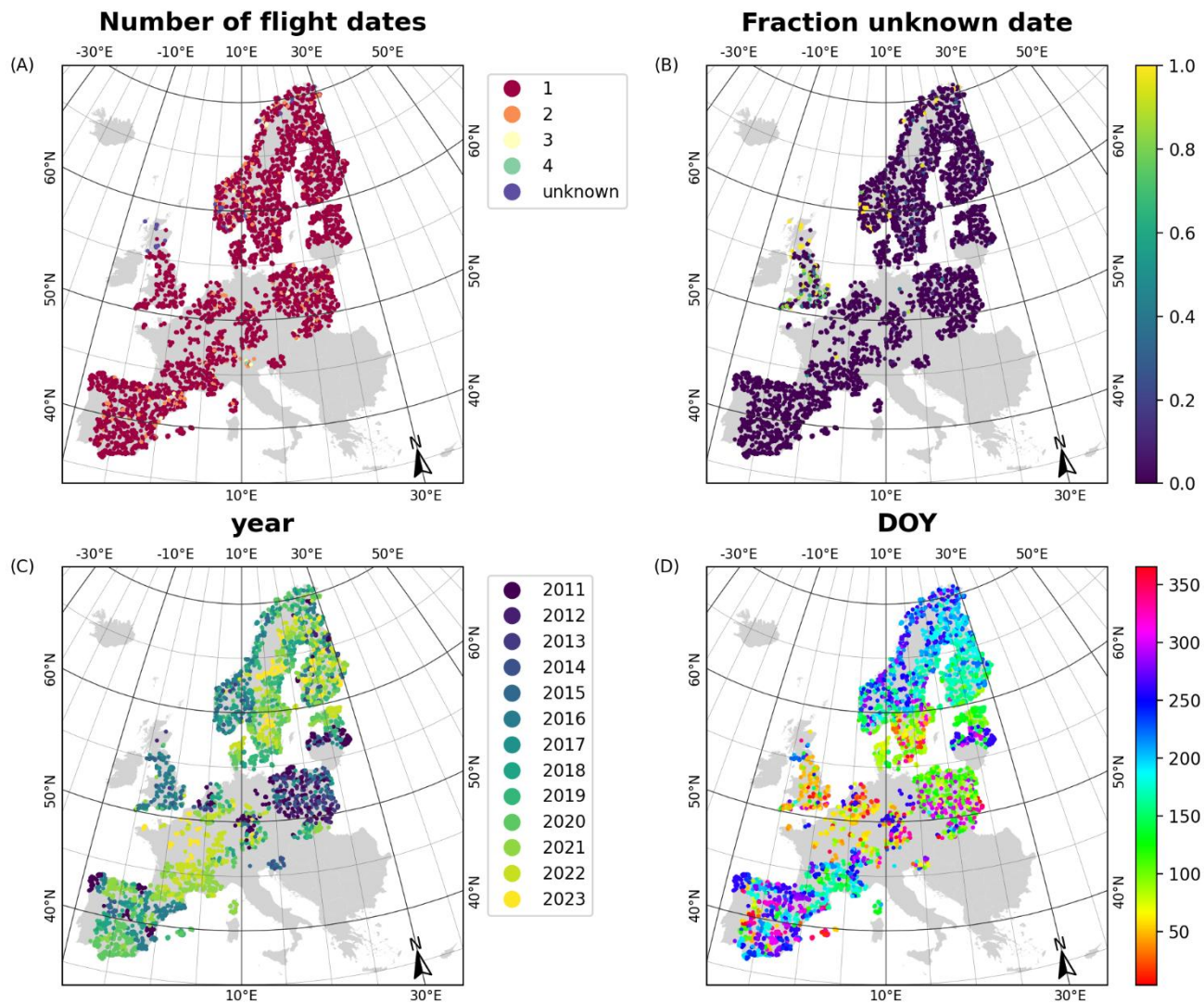


Figure S1: Flight days for the ALS patches. The number of flight days within each patch (A), the fraction of pixels within each patch with an unknown date (B), the flight year for patches with a single flight date (C), and the DOY for patches with a single flight date (D).

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