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Aligning citizen science and remote sensing phenology observations to characterize climate change impact on vegetation

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Abstract

Phenology observations are essential indicators to characterize the local effects of climate change. Citizen participation in the collection of phenological observations is a potential approach to provide data at both high temporal scale and fine grain resolution. Traditional observation practices of citizen science (CS), although precise at the species scale, are limited to few observations often closely located to an observer's residence. These limitations hinder coverage of the great variability of vegetation phenology across biomes and improvement of the knowledge of vegetation changes due to climate change impacts. This study presents a new approach to overcome these limitations by improving CS guidance and feedback as well as expanding phenology report sites and observations across different habitats and periods to contribute to monitoring climate change. This approach includes: (a) a new methodology focused on harmonizing remote sensing phenology products with traditional CS phenology observations to direct volunteers to active phenology regions and, (b) a new protocol for citizen scientists providing tools to guide them to specific regions to identify, collect and share species phenological observations and their phenophases. This approach was successfully tested, implemented and evaluated in Catalonia with more than 5000 new phenologically interesting regions identified and more than 200 observations collected and Sentinel-2 derived phenometrics were demonstrated as of good quality.

1. Introduction

In the last decade, public participation in environmental research, understood as any voluntary contribution of citizens engaged in the process of scientific research to generate new science-based knowledge (Shirk *et al* 2012, Fraisl *et al* 2020), has grown rapidly (MacPhail and Colla 2020). Contributions to science and conservation are identified as the most important motivations for participation and often become more significant as project participation progresses (Larson *et al* 2020).

Public participation has also been properly recognized as a potentially useful tool to reduce costs and increase efficiency of traditional research (McKinley *et al* 2017). Indeed, observational data collected by citizen science (CS) is considered a valuable data source in many environmental analyses related to monitoring ecosystem activities (Kirchhoff *et al* 2021, Pucino *et al* 2021), analyses of trends and drivers or nature conservation (García *et al* 2021). Moreover, in the last decades CS projects have grown in number and scope (Burgess *et al* 2017).

Further, scientifically managed CS projects provide the valuable asset of bringing research closer to the general public. This improves society's perception of the value of science by amplifying understanding of the subject matter (Forrester *et al* 2017) and increasing trust between scientists and the general public (Bonney *et al* 2014), a challenge that the scientific community has been historically pursuing.

Ground observations made by the general public are not something new. Traditionally, farmers or naturalists and some scientists have recorded environmental observations for decades in their daily work or as a hobby, ranging from meteorological data to biodiversity sightings, and some of them also recording phenology. Phenology, understood as the phases of the life cycle of living organisms (plants or animals) and how they are affected by seasonal and interannual climate variations, has been a common societal topic (White *et al* 1997, de Beurs and Henebry 2004), and is booming in the context of climate change, as such observations have become an indisputable indicator and regulator of the impacts of climate change (Peñuelas *et al* 2009, Richardson *et al* 2013, Scranton and Amarasekare 2017). In fact, changes in phenology corresponding to specific vegetation physiological processes (leaf unfolding and flowering of plants in spring, fruit ripening, colour changing and leaf fall in autumn, among others) led to adaptation to new environmental resources (Feldman *et al* 2018, Zeng *et al* 2020). Also, changes in historical seasonality of vegetation phenology are recognized as a sensitive indicator of climate change and its local effects in terms of ecosystem response (Ganguly *et al* 2010). However, frequent and repeated observations over time are required to perceive these changes (Feldman *et al* 2018).

Although CS is considered a potential source of data at a high temporal scale and fine grain resolution (Burgess *et al* 2017) so far, ground-observed phenology, although precisely at species scale, is reduced to small traditional elements closely located to an observer's home (White *et al* 2005). Generally speaking, volunteers' efforts may be biased by representing a small demarcated area but in a very precise and systematic way, as they are usually more likely to collect data from accessible locations (close to the roads or urban areas) (Dickinson *et al* 2010, Phillimore *et al* 2013, Crimmins *et al* 2022). Nevertheless, through worldwide observers, this is a modest but not a negligible approximation to cover the great variability of vegetation phenology across biomes or habitats aiming at improving the knowledge of vegetation changes as a consequence of climate change impacts. If the strategy is to be comprehensive and systematic, this ground-based approach faces major gaps. On the one hand, volunteers participating in the CS approach require better guidance in plant identification (Morrison 2016, Knapp 2019, Bonnet *et al* 2020) and reported location of phenologically active regions of interest (ROIs) (McDonough MacKenzie *et al* 2017). They also need protocols to improve CS skills (MacPhail and Colla 2020, Crimmins *et al* 2022), although there are some quite well established programs working in this direction, such as the USA National Phenology Network or the Pan European Phenology Project PEP725. On the other hand, the variability of vegetation phenology across biomes is significantly large (Richardson *et al* 2013), so having more data to improve the knowledge about these changes is a must and a challenge that can hardly be fulfilled by volunteers (Bonney *et al* 2014, Morrison 2016, Chandler *et al* 2017). Unfortunately, currently, there are not many other projects involving CS and phenology monitoring that could guide the volunteers (MacPhail and Colla 2020) and increase the number of participants.

This context raises a new challenge for scientists wishing to improve participation in environmental research, who have to build guidance to volunteers, assess the quality of collected data, and expand the observed sites across different biomes or habitats (McDonough MacKenzie *et al* 2017). Indeed, meeting this challenge will have to involve different methodologies combining citizen-based observations and technological methods to manage limiting factors related to volunteers' participation and large-scale and long-term temporal and spatial coverage.

With regard to the latter constraints, Earth observation from space has become a highly used technology to observe global change phenomena at a large scale, thanks to the amount of satellites in orbit constantly revisiting the Earth (Duchemin *et al* 1999, White *et al* 2009, Nagai *et al* 2010, Isaacson *et al* 2012, Evans *et al* 2014). Thus, remote sensing (RS) provides effective means to observe global change with temporal and spatial precision (Guo 2014). Undoubtedly, long time spatially continuous resolutions of RS data are essential characteristics for phenology monitoring because they capture in detail the monitored seasonal variation in vegetation dynamics. Current, RS products present too coarse a view of phenology dynamics, insensitive to small changes in species and habitat distribution. The lack of focus on individual species or habitats creates two problems. Firstly, since each species has different sensitivity to climate change (Thuiller 2004, Schuetz *et al* 2019), it is difficult to assess the effects of climate change on them with available RS products. Secondly, since the phenology observations by CS look to individual plants in detail, it is not easy to evaluate the medium resolution RS products against *in-situ* measurements. Current medium spatial resolution satellite sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS), present specially suitable spectral and spatial resolutions (13 bands, and pixel size from 250 m to 1000 m) and a long time series (from 2000 to present) to detect spatial variation during the phenological life cycle. Indeed, MODIS distributes a Global Land Cover dynamics product (Ganguly *et al* 2010) that provides 8 d information related to land surface phenology used in many phenology studies over large geographic regions (Zhang *et al* 2003, Ahl *et al* 2006, Fisher and Mustard 2007, Zeng *et al* 2020). However, in many areas of the Earth where fragmented and heterogeneous landscape/vegetation is predominant, MODIS spatial resolution (250 m at best) is still too coarse (Nagai *et al* 2016). Alternatively, Landsat legacy sensors present better spectral and spatial resolution of eight bands and 30 m, respectively, and an image archive spanning almost five decades. However, Landsat 16 d temporal resolution imagery may be hampered by clouds lowering its ability to generate a regular and dense time series to detect rapid phenological changes such as blossoming, which may occur rapidly within a 16 d window.

The recent Sentinel-2 satellite European Spatial Agency constellation, (Sentinel-2A and Sentinel-2B) presents some interesting outstanding characteristics compared to its predecessors. Its high spatial (up to 10 m), high spectral (13 bands from visible and near-infrared to short wave infrared) and high temporal (almost only 5 d at the maximum) resolutions make it an optimal choice for phenology monitoring (European Commission 2018). This fact was recently acknowledged by the Copernicus Land Monitoring Service (CLMS) by launching a High Resolution Vegetation Phenology and Productivity product (HR-VPP) (Copernicus Land Monitoring Service 2021). Its aim is to assess climatic and anthropogenic impacts on ecosystems and increasing support of the implementation of key EU policies such as the Biodiversity Strategy 2030, the Common Agricultural Policy, the Sustainable Development Goals as well as other climate initiatives. The HR-VPP product is generated at high spatial resolution (10 m) since 2017 comprising four different daily Vegetation Indices (Normalized Difference Vegetation Index—NDVI; Fraction of Photosynthetically Active Radiation; Plant Phenology Index and Leaf Area Index), 10 d seasonal trajectories and Vegetation Phenological and Productivity (VPP) parameters of yearly metrics for up to two growing seasons (start or end of the growing season, season length, seasonal productivity, etc).

With this new CLMS product, free and open accessible data through WEkEO Data and Information Access Service (WEkEO 2021), the interactive portal and distributed public cloud infrastructure makes data more available to different users. Unfortunately, neither the processing environment nor access to HR-VPP products through WEkEO are manageable for the amateur phenology community who might be interested in considering RS derived data to help monitor phenology. This limiting factor reinforces the need for a win–win harmonized process between CS and RS phenology. By linking the strengths of both methodologies, the CS and the RS, creating this interoperable approach, the scientific community also ensures the availability of high-quality research data to be correlated with RS data, guarantees value for climate impact studies, supports public participation in science and enhances appreciation and engagement in environmental stewardship (Larson *et al* 2020).

Therefore, the aim of this study is to present an approach to direct *in-situ* traditional phenology volunteers to areas of interest where phenology it can be well characterized by high resolution RS data as well. In this case study, we overcome the crucial limiting factors of both techniques by (a) generating a protocol that harmonizes CS and RS phenological observations, while (b) evaluating its application regionally to finally, (c) qualitatively evaluate its results.

2. Methodology workflow design and application

A methodological approach (figure 1) combining RS, data and CS was co-designed between scientists and CS experts on phenology, and regionally implemented and evaluated in the study area.

To start, a list of species presenting interesting phenological patterns that could be detected with RS data is defined though a co-design session with citizens devoted to monitoring phenology (figure 1(A)). For each species, specific phenophases are detailed (figure 2). In parallel, areas with a minimum 3600 m^2 (60×60 m) presenting homogeneous vegetation cover and stable phenological responses observable from space are identified based on existing vegetation cartography and ancillary data and Sentinel-2 phenometrics, respectively (Domingo-Marimon *et al* 2020) (figure 1(B)). A set of random 1600 areas is then selected and for each area three phenometrics (green-up, maturity and senescence) based on the Sentinel-2 NDVI 2019 curve are computed (figure 1(C)). Now that the Copernicus HR-VPP product is available, these metrics can be easily extracted and so it is recommended. Phenometrics are phenological phases describing specific stages on the seasonal growth curve. Green-up is defined as the date (day of year—DOY) on which the slope of the NDVI curve increases by 20% in reference to the minimum. Maturity is defined as the DOY when the NDVI curve reaches the maximum. Senescence is defined as the DOY when the NDVI curve decreases by 80% in reference to the minimum. From this dataset, homogeneous vegetation cover areas with a clear and detectable phenological pattern (according to clearly differentiated phenophases) that are potentially easier to be differentiated in the field by citizens are selected as ROIs (Domingo-Marimon *et al* 2020) (figure 1(D)).

ROIs are used to guide and motivate citizen scientists to collect *in-situ* phenological observations at

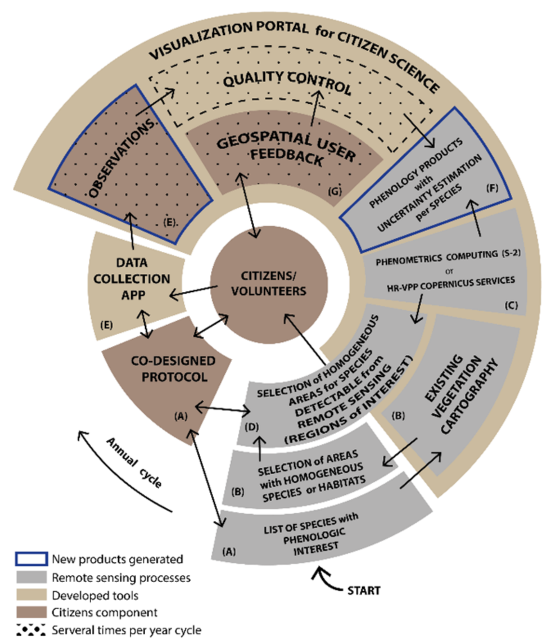

Figure 1. Workflow of the developed new approach combining RS and developed tools to facilitate and foster phenology CS.

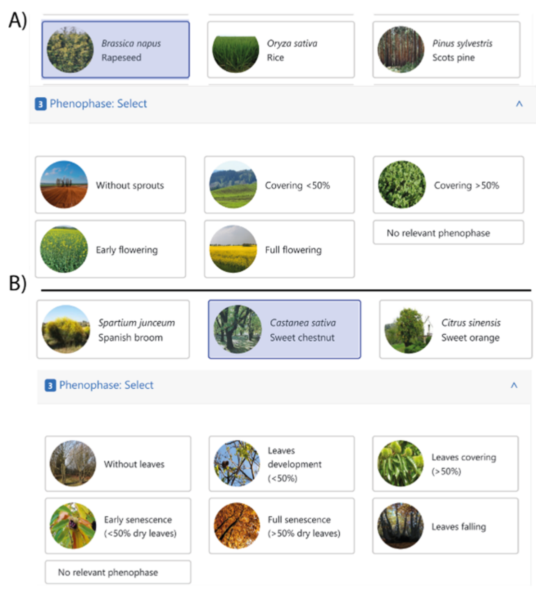

Figure 2. App phenophase selection options provide specific phenological information per each species. (A) Phenophases observed for Rapeseed, (B) phenophases observed for Sweet Chestnut.

these particular areas through a data collection app (figure 1(E)).

Finally, once the phenological season ends, the CS date of observations of a specific event of a given ROI can then be compared with the same events extracted by RS (figure 1(F)). The number of times the two observations coincide will give an indication of the quality of the RS product (uncertainty) that can be used for product evaluation. If the quality is acceptable, then the RS phenometrics can be considered useful to extrapolate phenological observations for all ROIs, dramatically increasing the area initially covered only by CS observations. Workflow in figure 1 can be repeated several times per year coinciding with the annual phenological changes resulting in quality assessed RS maps representing the spatial distribution of phenological parameters of individual species or habitats.

This workflow was applied in Catalonia, a Mediterranean region covering 32 000 km^2 located on the north–east of the Iberian Peninsula (SW Europe) for two main reasons. First, this area has a wide altitudinal range (from 0 to more than 3000 m) conferring a heterogeneous landscape with high biodiversity, composed of agriculture land (herbaceous and orchards) mixed with natural and semi-natural vegetation areas, including coniferous, sclerophyllous, and deciduous forest.

Second, and most importantly, Catalonia stands out for having a wide and strong community of CS observers thanks to the FenoCat network-Phenological Network of Catalonia (Servei Meteorològic de Catalunya 2020) and the RitmeNatura CS Observatory (Ritme Natura Observatory 2015) initiatives, thus facilitating the engagement of volunteers to participate and evaluate the proposed methodology. Thus, due to these aspects, the study area is a unique spot for evaluating an interoperable approach between CS and RS phenology monitoring.

In this study, ROIs selection was carried out combining the Map of Habitats (Generalitat de Catalunya 2018), the Land Parcel Identification System of Catalunya (Departament d'Agricultura, Ramaderia, Pesca i Alimentació, LPIS 2019), the Land use and Land cover Map of Catalunya (Ibáñez and Burriel 2010), the 4th National Forestry Inventory (Ministerio para la Transición Ecológica y el Reto Demográfico 2008) and the Forest Map of Spain (1:50 000) (Ministerio de la Transición Ecológica y el Reto demográfico 2006).

The resulting dataset was stored into a data visualization portal developed using MiraMon Map Browser technology that fulfils the most common Open Geospatial Consortium (OGC) standards (FenoTwin-PhenoTandem 2020).

3. Results, outcomes and discussion

The methodology presented here is extensible to any location with similar vegetation phenological behaviour. By repeating this approach in subsequent years, it is possible to assess the impact of climate change on each species over time. Also, under the assumptions that the methodology has a stable degree of quality and that species distribution has not changed significantly in different periods, this methodology is applicable to archived high resolution RS data, thus extending the time series.

3.1. Map of regions of interest (ROIs)

As a result of the co-design session, a list of 41 species presenting discernible phenological patterns that can be both detected *in-situ* and with RS data was obtained. Combining this list with a map of homogeneous and pure habitat or species (60 × 60 m areas) resulted in ROIs dataset indicating where *in-situ* observations were comparable with RS observations and when and which phenophase was detectable and active for a given species and when this event took place in the near past (Domingo-Marimon *et al* 2020).

3.2. Visualization portal for CS

A single interface was developed to integrate all resulting products to facilitate CS accessibility to data (Masó 2022). The Visualization Portal for CS observations resulted in a user-friendly interface showing a ROI distribution map enabling citizens to find specific areas for a homogeneous species closer to their location (FenoTwin-PhenoTandem 2020). In addition to this functionality, it also provided an integrated digital compass supporting users' orientation and positioning, when the global positioning system (GPS) of the device (smartphone or PC) is activated (Domingo-Marimon *et al* 2020). Therefore, users are guided to ROIs rather than those typically monitored (e.g. areas close to CS homes, close to pathways or easy accessible areas), endowing their observations with a new dimension. The map browser also shows a high-resolution phenometrics maps displaying when a particular phenological phase occurred in a previous year for a given species. This feature allows users to generate custom data visualization, to perform some direct analytical operations and can be extended with an animation functionality providing temporal data profiles (e.g. NDVI profiles) that can be correlated with CS observations. Also, direct clicking on a particular ROI returns the geographic coordinates, the dominant species and a link redirecting users to the data collection website application. In addition, the visualization of the map browser can be layer-enriched by activating any type of environmental data, such as topographic maps or digital elevation models. The resulting *in-situ* observations collected by citizens are also included in the portal and are later used to evaluate Sentinel-2 derived phenometric products.

3.3. Data collection app

A freely available Data Capture Web App to facilitate field data collection from volunteers was developed (Masó 2020). This tool transforms *in-situ* data acquisition into an easy and attractive task. The app's user-friendly online interface is fully connected to the Visualization Portal, giving the user a seamless experience in the harmonization of RS data and CS observations. Since the observations are done in homogeneous ROIs, the species or habitat identification is automated by position. Unlike other successful applications such as iNaturalist (the global CS platform for biodiversity monitoring) listing only the most common phenophases, the data collection app developed in this study offers the unique phenological phases relevant to the species observed, thus minimising likely identification errors made by observers and reducing the uncertainty of CS data. The data collection app is displayed as a simple form based on six steps: (a) uploading a picture, (b) selecting a species from a list (automatically detected from the ROI layer), (c) selecting a particular phenophase, (d) reporting an observation location (auto filled if the device GPS is activated), (e) providing an observation date (auto filled with 'today') and, (f) advanced options for phenophase species identification (figure 2). Each step includes illustrative pictures and understandable semantics as well as user field protocols describing the species and phenophases available to guide citizens during identification in field campaigns. In the 2020 autumn campaign, more than 200 *in-situ* observations for selected species in specific ROIs were collected.

3.4. Quality of CS observations—user feedback

In addition to the iNaturalist independent validation system based on its community of contributing experts, a third quality component was included into the data capture system: a feedback mechanism. NiMMbus (Masó and Zabala 2019) is a widget to provide user feedback items following the OGC geospatial user feedback standard such as, comments, ratings, discovered issues, quality reports among others. Citizens participating in data collection campaigns are able to comment on any of the geospatial features in the system. This includes a ROI, phenometrics products, another citizen observation or even suggest new relevant ROIs that have not been initially included by the RS algorithms (figure 1(G)).

All feedback is made available to everyone and linked to a relevant geospatial feature.

3.5. CS engaging campaigns

Since phenology is a topic directly related to nature, the profile of a citizen who can potentially become engaged might be someone who is environmentally concerned. That is the reason the monitoring protocol was co-designed with local nature, hiking and meteorology associations. By making them directly involved in the research process (by deciding species and phenophases to be observed), their participation in the engaging campaigns was ensured. Three sessions took place at the beginning, middle and end of the implementation process. Two information campaigns to recruit volunteers

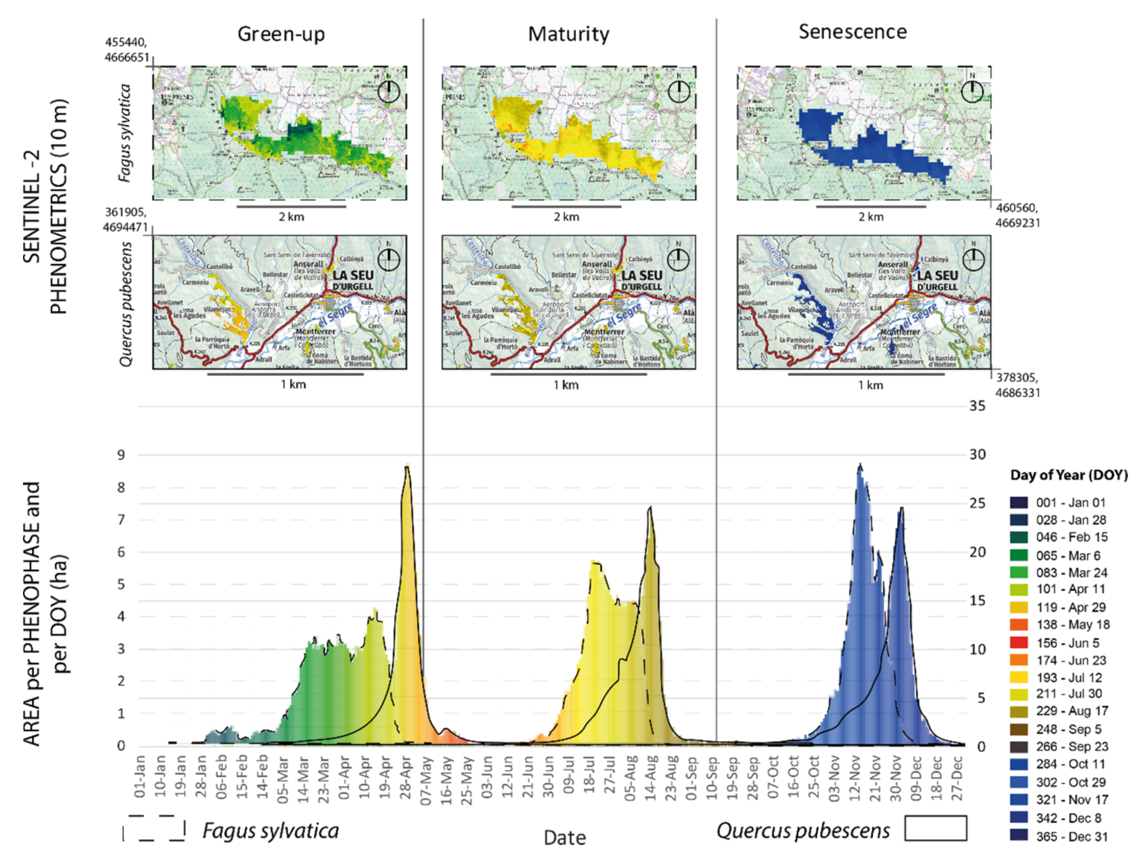

Figure 3. Top maps: Sentinel-2 derived phenometrics of green-up, maturity and senescence for a region with *F. sylvatica* (dashed line) and a region with *Q. pubescens* (black line). Bottom graph: area (in ha) per phenophase and DOY of *F. sylvatica* (dashed line) and *Q. pubescens* (black line). These distributions are essential to guide volunteers to precise locations at the precise time of the year.

were defined in 2020, one in spring and another in autumn. The campaigns included nature associations newsletters, hikers' magazine, meteorological associations, and related channels on social networks (mainly Twitter, TV and digital newsletters). Around 50 000 citizens received direct information through these media channels. The call also included an initial press release published in several specialized media and blog sites, and regular notices explaining the progress of phenological events to guide citizens to phenological attractive spots pre-detected through RS. Campaigns addressed to specific individuals were more effective than mass media approaches. The objective of the campaigns was clearly described to increase the chances of success. A short, clear, and concise monitoring protocol (including relevant species fact sheets) was also distributed to ensure good quality of data generated. A web page and contact email were set up to support volunteers in the field. Unfortunately, the spring campaign was completely affected by the COVID-19 pandemic. Citizens were confined with no possibility of taking observations. Although the autumn campaign was still affected by COVID-19 restrictions, it recruited 12 direct volunteers and 244 occasional observers.

3.6. Harmonization and validation of CS and RS phenology data

Results of the analysis of Sentinel-2 phenometrics for 2019 (figure 3) showed clear and different phenological patterns for several species, especially for deciduous species, such as *Fagus sylvatica* or *Quercus pubescens.* Results showed when and where each species were leafing out (green-up), when it was at the peak of its foliage (maturity) and when it started to lose leaves (senescence), confirming Sentinel-2 phenometrics as of good quality. The information associated with these distributions is essential to guide citizens to precise locations at the precise time of year to be able to collect *in-situ* data. By assuming the quality of the computed phenometrics as acceptable, the number of ROIs was extrapolated to more than 5000. Although more *in-situ* observations are needed to perform a complete and solid integration of RS and *in-situ* data, a first qualitative correspondence analysis between RS observations and CS observations yielded a good visual agreement between both types of data (figure 4). In case of several observations for a given species and therefore, several DOY indicating observed phenophases, the DOY was used to analyse within species phenophase variability.

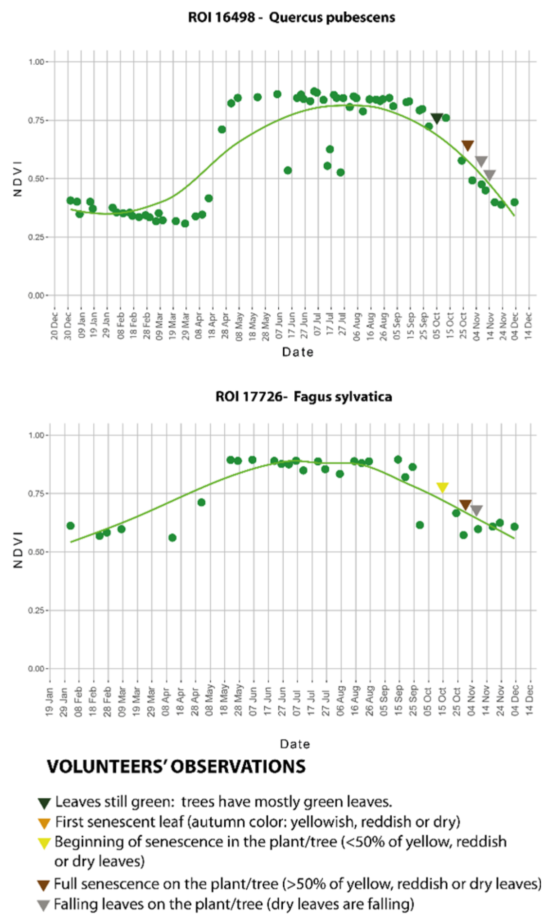

Figure 4. Qualitative correspondence between the phenological observations extracted from RS NDVI time series images (green dots) and interpolated trend (green line) and the *in-situ* observations collected during autumn 2020 (coloured triangles, their vertical position is arbitrary).

4. Conclusions

Phenology monitoring has become one of the main indicators of climate change impacts on vegetation. Is essential to keep track of *in-situ* vegetation changes, especially by citizen scientists around the world. This paper describes a co-designed observation protocol between scientists and potential volunteers to improve citizen engagement and the quality of data collected, by providing simple and clear instructions and tools. This protocol can be applied to any region, biome or habitat several times per year and can be adjusted annually according to new ROIs, species of interest or changes to phenology events. This protocol provides an innovative approach, making CS observations interoperable with RS products and confirms RS as a promising partnership for public participation in environmental research activities. A lesson learned from this situation is that targeted dissemination to interest groups was more effective than mass media campaigns. Therefore, relying on individual commitment rather than an organizational or institutional one is recommended. In addition, the feedback collected indicated that a user-friendly data acquisition interface is desirable to make observations easier for citizen scientists.

The methodological strategy based on Sentinel-2 and the newly developed tools were effective and showed that a harmonized approach between phenological high resolution optical RS and CS observations is operative, functional and practicable.

It was also shown that satellite RS observations, especially those presenting high spatial and temporal resolutions such as Sentinel-2, have the capability to spatiotemporally characterize vegetation phenology in selected ROIs. This overcomes traditional limitations of citizens' observations, such as reduced extension or temporal continuity. The presented approach uses a combination of existing cartography and Sentinel-2 data to spatiotemporally spot phenological ROIs and their phenophases to guide CS volunteers.

In return, the improvement in quantity and quality of data collected by CS ensures its usefulness in scientific RS studies, as the validation data increases significantly. Such information is displayed through a newly developed Phenometrics Visualization Portal.

Due to COVID-19 pandemics, a limited CS observations dataset was collected. Although this allowed for a visual comparison of both RS data and CS observations yielding a visual consistent phenological curves, a more extended CS dataset is needed to evaluate RS phenology products quantitatively. Thus, future work will be developed to quantitatively evaluate the new methodology.

Temporal profiles of RS vegetation indices related to greening, maturity and senescence were coherent with the same events observed at ground phenologically active ROIs. As a result of this methodology, around 5000 new areas presenting phenological changes were identified, significantly increasing ROIs to be visited by CS, as well as the number of observed species. Accuracy of greening-related events from RS is higher, although less engaging for citizens who are usually more attracted to blossoming related events. This has turned into future work, since improving the detection accuracy of blossoming from space would integrate RS more into the citizen's perspective and classical phenology. In summary, the implemented methodology was successfully applied, increasing the quality and number of phenological observations recorded, establishing RS as the new travel companion of CS chasing phenology around the world.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: www.inaturalist.org/projects/ritmenatura.

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