MONITORING PHENOLOGICAL TRAITS OF A COASTAL MEDITERRANEAN MAQUIS AREA THROUGH AUTOMATED SYSTEMS

Carla Cesaraccio, Alessandra Piga, Andrea Ventura, Angelo Arca, Pierpaolo Duce

Abstract: Understanding ecosystem dynamics in an era of global change and declining biodiversity requires monitoring biotic components such as plant behaviors and traits. Innovative integrated systems using high-frequency digital images automate vegetation tracking and record of detailed morphological and phenological data. In this study, a description of prototypal monitoring systems based on repeated digital images for detecting changes in phenological traits of Mediterranean coastal maquis in North-West Sardinia is reported. Developed at CNR Laboratories, the systems use high-resolution cameras on automated robots to perform (1) image acquisition, (2) transmission, and (3) post-processing phase. High-resolution images were analyzed to extract Vegetation indices (ExG, REI) from RGB chromatic coordinates. Vegetation Indices patterns were related with phenological traits. Main results highlighted how these systems can be a valid support for monitoring phenological behaviors of vegetation, even in a rugged environment such as Mediterranean coastal ecosystems. This study advances knowledge of plant responses to environmental changes supporting ecological and environmental studies.

Keywords: Near Surface Monitoring System, Phenological Traits, High-Resolution Digital Images, Vegetation Indices.

Carla Cesaraccio, CNR-IBE, Institute of BioEconomy, Italy, carla.cesaraccio@ibe.cnr.it, 0000-0002-1642-4663
Alessandra Piga, CNR-IBE, Institute of BioEconomy, Italy, alessandra.piga@ibe.cnr.it, 0009-0005-6489-7931
Andrea Ventura, CNR-IBE, Institute of BioEconomy, Italy, andrea.ventura@ibe.cnr.it, 0000-0003-3120-0390
Angelo Arca, CNR-IBE, Institute of BioEconomy, Italy, angelo.arca@cnr.it
Pierpaolo Duce, CNR-IBE, Institute of BioEconomy, Italy, Pierpaolo.duce@ib.cnr.it, 0000-0002-5011-2903

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Introduction

Biodiversity faces increasing threats, with about 25 % of species at risk of extinction [8]. Effective ecosystem monitoring requires biotic data, but conventional surveys are highly skilled and labour-intensive and thus making regular, comprehensive biodiversity assessments challenging [1,11].

Low-resolution, short-term monitoring fails to fully capture ecosystem dynamics [3], while high-resolution methods are costly and invasive, which limit the temporal and spatial range of historical observations [30]. To balance detail, coverage, and frequency, complex and integrated monitoring systems that cover larger areas and gather extensive data are necessary [9,32].

Near-surface integrated systems, based on high-frequency digital image acquisition, provide innovative frameworks for automated vegetation monitoring. They have been used as an ecological monitoring tool for vegetation traits related to phenology, biomass and productivity [7,14,29]. Consumer-grade digital cameras offer a quick, affordable way to increase data volume, both spatially and temporally, and capture species- and site-specific responses. They provide high spatial resolution, robust data collection, and are less weather-dependent compared to airborne and satellite remote sensing [2,18,22].

Phenology significantly impacts ecosystem function, prompting efforts to improve vegetation monitoring networks [16]. The development of the phenocam method has been crucial, linking ground-based phenological observations with global-scale, coarse-resolution satellite data [22]. A phenocam is a digital camera that captures time-lapse images of plant canopies to analyse vegetation seasonal rhythms through colour-based image analysis [21]. They are used in phenocam networks that are globally expanding over Europe, North America, and Asia, such as the EUROPHEN network. Similar networks can also be found in Asia and Australia [6]. These systems enable the recording of standardized, detailed data on plant traits across various ecosystems [23].

The quantitative data derived from phenocam imagery are of high quality, provided that appropriate precautions are taken regarding camera model, settings, and field setup. They exhibit minimal noise and a robust seasonal signal across various ecosystems, including those with evergreen vegetation [24,25,27,28]. Therefore, phenocams offer objective, automated phenological data with high temporal and spatial resolution, often in real-time. They also create permanent visual records, documenting site development, changes, and responses to factors like growth, disturbances, extreme events, and species composition shifts [21].

Vegetation indices extracted by RBG signals can be considered proxies of vegetation properties as they can be defined as spectral data algorithms used for quantitative and qualitative evaluations of vegetation biophysical and biochemical properties, such as growth dynamics, phenology, and abiotic/biotic stress [31].

Images acquired throughout the day over target vegetation are used for creating time-lapse sequences from sunrise to sunset. Essentially, digital images consist of three "layers", each corresponding to one of the three colour channels. The colour and brightness of a given pixel are determined by the intensity in each colour layer, stored as a digital number (DN) triplet [21]. From DNs, data on vegetation colour, such as "canopy greenness," is extracted to assess phenological changes. Specific transition dates, like the onset of spring green-up, can be identified from the seasonal trend of canopy greenness [28]. Green chromatic coordinate (Gcc) measures green intensity relative to total RGB intensity, serving as an index of "greenness", reflecting changes in foliage development and senescence [21].

Various techniques for processing digital images of plant canopies are detailed in the literature. Researchers have addressed data quality and filtering to reduce noise in green trends [14], extraction of phenological dates using curve fitting and smoothing [6], and the use of digital signals as proxies for spectral data related to pigment dynamics [2]. Studies also link leaf measures to plant functions, enhancing understanding of greenness in different biomes [13].

The success of automated cameras systems to capture digital images across time as a means to monitor plant changes, in particular phenology, is mainly due to the low cost, high accuracy, and data record capabilities. Camera systems technique has many advantages over the traditional observation-based monitoring, including: (1) tracking vegetation changes over time through continuous and regular monitoring; (2) phenological observation data systematically recorded and permanently stored; (3) reduced labour and costs of field observations; (4) standardized measurement protocol across sites and reduction of bias due to observer variation in identifying the date of phenological stages, which is typical of traditional monitoring; (5) possible quantitative digital post-processing analyses of phenological patterns. Therefore, to track vegetation changes over long periods, the development of more reasonably priced near-surface proximal sensing systems and the application of easier-to-use, open-source software tools for the analysis of large-scale datasets represent potential solutions to monitoring challenges [11].

In this study, a description of prototypal monitoring systems, based on repeated gigapixel panoramic acquisition, for detecting changes in phenological traits of vegetation, is reported. These systems employ near-surface proximal sensing techniques to achieve higher temporal resolution and better spatial coverage than ground-based observations. The performance of two different prototype configurations were tested over mediterranean coastal ecosystems dominated by evergreen and semi-deciduous shrubland. Some main outcomes from experimental campaigns are also presented to show the potential in describing the phenological pattern of different species.

Materials and Methods

Study sites

The monitoring systems were tested over Mediterranean ecosystems. The experimental sites are located in northwestern Sardinia, Italy, within the Porto Conte - Capo Caccia Natural Reserve along coastal areas (40° 37' N, 8° 10' E, 74 m a.s.l.). The main soil type is Terra Rossa (Lithic Xerorthent and Typic Rhodoxeralfs - USDA 1993. Average annual precipitation amount is of 566 mm. The average annual temperature is 16.4 °C.

Four distinct types of vegetation grow in this area: the Mediterranean maquis, the Quercus ilex forest, the recent pine forest and the garrigue and dominated by bushes and tiny herbaceous plants [5]. The Mediterranean maquis includes both semi-deciduous and evergreen shrub species mainly *Juniperus Phoenicia* L., *Pistacia lentiscus* L., *Phyllirea angustifolia* L., and *Cistus monspeliensis* L. [20].

Monitoring Phenological Automated Systems

The monitoring prototype developed at CNR Laboratories used high-resolution cameras on automated robots with power supply devices. Designed as an evolution of common phenocams, the system focused on image acquisition, local and remote storage, and post-processing and data analysis.

The monitoring systems, mounted on trellis, cover large areas using cameras with robotic systems that enable the Pan-Tilt-Zoom (PTZ) technique, allowing movement across multiple pre-set views.

Image acquisition protocol

To determine the camera setting and the optimal visual coverage (angle of view, depth of field and resolution of the image) of the experimental site, a custom software was developed and field tests were conducted. Series of images of the study area, framed from different angles and positioning the camera lens on a 3-meter height platform, were evaluated.

Two different setting were chosen for each monitoring system. The first, named APOS, was set to acquire one panorama of 36 shots x panorama (3 rows x 12 columns) with a 30 % of image overlapping. The second, named PHATOS, was programmed to capture 44 images, with a horizontal viewing angle of 170°, a vertical angle of 25°, with a 20 % overlap. To minimize the shadow influence due to the trellis, the systems were programmed to acquire daily data at noon.

Image managing and processing

An application routine for semi-automated image management with a Graphical User Interface (GUI), named Vegetation Index Calculator Interface (VINCI), was developed. This modular routine performs the following automated functions: (1) converting files from raw to hr-jpg format with normalized lighting and sharpness, (2) renaming converted files, and (3) organizing files by frame folders. High-resolution panoramas were created daily using advanced stitching algorithms (AutopanoGiga and Roundshot VR Driving software). A semi-automated MATLAB routine (ANNOT_GUI), with a Graphical User Interface, was developed for calculating RGB Chromatic Coordinates and Vegetation Indices (VIs) [7]. Seasonal trends of VIs for species and growing seasons were analyzed to detect phenological traits and vegetation status, highlighting main phenological transition dates.

Results

Monitoring System Architecture: hardware and camera setup

The installation and configuration of system components inside a previously selected experimental area was carried out through the following steps: a) equipment setup in the field; b) deployment of the power supply system; c) sensor positioning; d) data collection and transmission testing.

We refer to the first configuration as APOS (Automated Phenological Observation System), and to the second one as PHATOS (Phenological Automated Tower Observation System) which is an evolution of the first one. The general architecture of APOS and PHATOS includes several components, designed specifically to perform major functions: 1) Image acquisition, made through the use of a camera connected to a robot, so as to frame and pan an area in accordance with the visual coverage of the site of study; 2) Image transmission, permitted by a modem-router for broadband access to the Internet; 3) Image processing: image stitching and elaboration made by remote computer. Following a description of main hardware for each of the system is separately reported.

APOS - Automated Phenological Observation System: the image acquisition is made using a Canon EOS 7D digital camera (18 MPx) with 18-135 mm zoom lens. The acquired images are transmitted from the camera using a specific accessory (wireless file transmitter, WFT) directly connected to the camera body by its proprietary interface. The transmitter allows performing a high-speed wireless file transfer process. WFT Server mode allows a web browser to manually view images stored on the memory card as well as control the camera from a web browser. WFT can connect a hard disk drive for local image storage in addition to a camera memory card. The GigaPan hardware/software system was implemented in APOS (fig.1). For taking numerous photos by panning/tilting the robotic camera mount GigaPan EPIC was used. The acquired images, once transmitted to the remote computer server, are stitched by software (Autopano Giga) to obtain a high-resolution panorama (fig.2).

Figure 1 – Different view of APOS installed in the experimental site Capo Caccia, Italy: system mounted on the trellis with camera/robot inside the protection case (left), camera coupled to GigaPan robot (centre) and power supply system (right).

Figure 2 – One day high-resolution panorama obtained by stitching technics from 36 combined images shooted by APOS in the Capo Caccia experimental site, Italy.

PHATOS - PHenological Automated Tower Observation System: PHATOS is an evolution of the APOS system (fig.3). The design scheme was improved including (1) a pan-and-tilt-head with high-performance robotic arm to capture 360-degree panoramas, (2) a very high-resolution camera (36 Mpx), (3) a protection structure equipped with automatic opening and closing control system integrated with a remote management software system. The images were acquired by using a Nikon D800 camera with AF-S VR Zoom-Nikkor 70-300 mm f/4.5-5.6G IF-ED lens. This camera is directly connected to the Robotic panoramic shooting support Clauss Rodeon VR Head CL. The RODEON modular is an automatic pan-and-tilt-head for segmented panoramic photography, wide-angle shots, 360° and multirow sphere panoramic photography (fig.4). The pan-and-tilt-head can work with horizontal or vertical drive, and comes with a transceiver module, battery adapter, and a camera bar with quick release plate.

Figure 3 – Different view of PHATOS installed in the experimental site Capo Caccia, Italy: system mounted on the trellis with camera/robot inside the protection case (left), camera coupled to Rodeon robotic arm (centre) and power supply system (right).

Sharpness and resolution levels have been set to recognize morphological elements needed to detect phenology at individual level. To obtain a good stitching result from the pictures, the use of a fixed focus has proven to give the best results, along with the use of the same focal length and the same aperture for all the shooting. The system is connected to a Getac S400 semi-rugged notebook which functions as a command centre for the execution of a routine of actions that are repeated on a daily basis. This routine is controlled by the Rodeon Preview 2.4 PRO software, which was set up to automatically starts, controls acquisition parameters, stores parameters, stores raw images on the hard disk, and allows remote control via a remote server. The power system with photovoltaic system is composed of four panels, four batteries, charge regulator, inverter.

A protective structure was added to protect the hardware systems against the negative effects of marine aerosol, and to prevent atmospheric water vapor from condensing on the surfaces. The structure is equipped with a marine plywood box covered with spaced protection panels, to reduce solar radiation and heat conduction of the external surface. All surfaces are covered with white surfaces to reduce the absorption of radiant energy. The box, fixed to a stainless-steel structure and two telescopic guides, is lifted by 45 cm using two electromechanical actuators, that allow opening only during image acquisition each day, operated by a programmable logic control (PLC) system.

Figure 4 – One day high-resolution panorama obtained by stitching technics from 44 combined images shooted by PHATOS in the experimental site Capo Caccia, Italy.

Vegetation indices and phenophase transition dates

Digital numbers (DNs), representing RGB colour channel information, are transformed into chromatic coordinates through ANNOT_GUI. The graphic interface consists of two main sections: (1) File "List", used for the selection of image files; (2) "Image", for the definition of the Region of Interest (ROI), by clicking on the image and draw a polygonal perimeter. ROI is drawn for including as much of the vegetation as possible. As a result, the ROI varied depending on the vegetation available in the field of view that was different for each system with irregular shape and variable size. The GUI is optimized to handle sequences of images representing temporal change of panoramas or single shoot. The output CSV file will include a header containing coordinates of the vertices of the polygon that defines the selected ROI, and results for each processed image. The CSV file can be easily imported into other applications, such as R and Microsoft Excel, for further processing.

Vegetation index patterns during growing seasons are analysed to identify changes in vegetation status through green/red signal variations. Inflection points indicate significant changes, with the Excess Green Index (ExG) highlighting the green-up phenological phase. In fig.5, an example of pattern retrieved from colour signal is shown, as mean daily values of the Vegetation Indices (VIs) ExG and REI (Red Excess Index), calculated for *Cistus monspeliensis* L. and *Pistacia lentiscus* L. The pattern of VIs clearly follows the phenological development of species. *Cistus monspeliensis* is a drought semi-deciduous species, characterised by seasonal leaf dimorphism, producing brachyblasts with small leaves at the end of spring–beginning of summer, and dolichoblasts in autumn–winter, with larger and thinner leaves [20]. The peaks in ExG curve show clearly the seasonal leafing events in spring and autumn whereas the higher values of REI are related to drought periods when Cistus loose most of the spring leaves. *Pistacia lentiscus* is a dioecious sclerophyllous evergreen shrub, well-adapted to harsh growing conditions and drought tolerant. The leaves are leathery and bright green and their senescence occur during summer. The globular fruit start ripening in August and colour change with maturity from red to brown [17]. The ExG signal amplitude growth more than 40 % in late spring when leafing flushing occurs. The increased value of REI, starting in late summer, clearly reveal the ripening of the drupes.

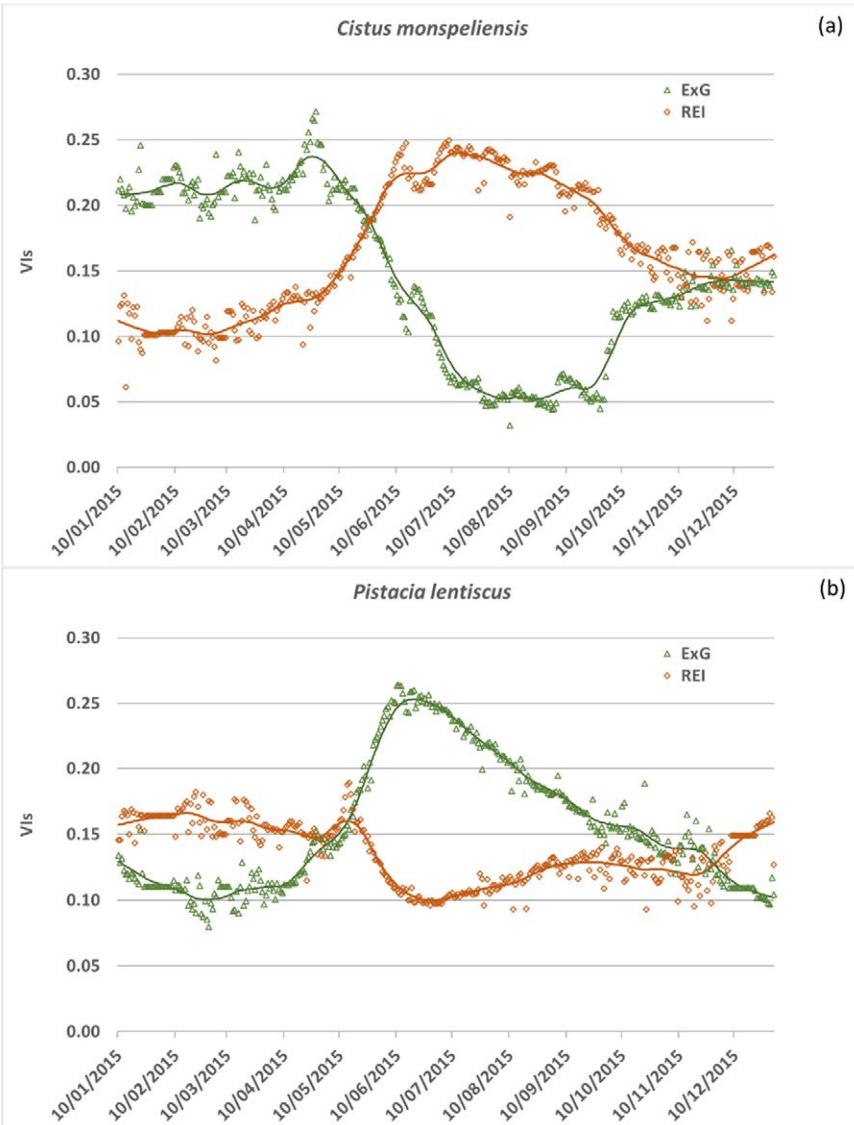

Figure 5 – Mean daily values of the vegetation indices ExG and REI for the semi-deciduous *Cistus monspeliensis* (a) and the evergreen *Pistacia lentiscus* (b) species. Time series Loess smoothing method was applied.

Discussion

Digital cameras can provide objective, automated phenological data with high temporal and spatial resolution, often in real-time. Standard RGB cameras are effective for identifying temporal and spatial patterns in vegetation productivity and composition on different scales [19]. Unlike satellites, these systems can cover the entire growing season with minimal gaps. However, automated, weatherproof systems for capturing time-lapse gigapixel images are rare due to their technical complexity and data management challenges [4]. Such systems, like the GigaPan and Rodeon Clauss Rodeon VR Head CL, implemented in our systems, can stitch overlapping images into high-resolution panoramas, allowing for detailed monitoring of thousands of individual plants across large areas (fig. 2-4). The application of our time-lapse gigapixel image systems gave promising results also for the analysis of a coastal Mediterranean maquis.

Vegetation indices from RGB images such as GCC shows a similar temporal pattern as those from multispectral data (e.g. NDVI). An additional advantage of camera-derived images is that they serve as a permanent visual record of the observed area, providing a unique historical account of site changes over time, including growth, mortality, disturbances, and species composition changes [21,26]. As expected, our system allowed the collection of very high-resolution monitoring datasets, permanently stored, available for additional processing and analysis.

Existing ecosystem monitoring networks lack coordination in the application of sampling protocols and in the choice of camera types and settings [5]. However, significant issues need consideration, such as variations in phenology estimates due to the camera setting (cardinal direction and inclination angle), which affect the estimation of spring budburst [11]. Standardizing sensor direction is essential, but addressing inclination angle impacts is more challenging due to species composition variability. Camera exposure settings, especially during autumn leaf colour changes, also pose challenges [15]. For these reasons, particularly attention was paid to the development of custom software for setting all variables related to camera set-up and field overview parameter acquisition.

RGB-derived indices can vary significantly across different areas, complicating their use for scaling values to larger regions. It remains uncertain if any single color-based index can reliably track seasonal changes in photosynthetic activity across diverse evergreen species and ecosystems [12]. Additionally, mechanistic studies on the physiological basis for seasonal canopy color variations are lacking, adding to uncertainties about the best index to use. In our research several different VIs were calculated and analyzed to verify whether their pattern reveal phenological timing. The phenological traits retrieved by colour VIs are in line with direct phenological observations, confirming the great reliability of the applied methodologies. The proposed approach might represent a real methodological improvement for monitoring ecosystem phenology over natural vegetation.

Conclusions

The use of near-surface proximal sensing methods based on digital images seemed promising for several reasons, including increased data collection rates, standardized datasets permanently stored, and automatic data processing. The implementation of the systems developed in our study have further advantages, including: (1) automation of image management from field acquisition to data processing; (2) advanced calculation of vegetation indices; (3) system interoperability with the most widespread software.

Some main outcomes from this study indicate that the use of digital images seems to be well-suited to identify phenological traits and behaviour in the case of Mediterranean species observed in a coastal area.

Overall, results retrieved from digital images analysis can be a valuable support for ecologists, environmental scientists, and land managers providing information useful to interpret phenological responses of plants to climate change, to improve our understanding on the relationships between phenology and ecosystem processes, and to validate satellite-based data. This approach offers potential to improve data processing but also data modeling, upscaling and extrapolation, opening to further research also in deep learning and cutting-edge machine learning.

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