PHUSICOS

According to nature

Deliverable D4.7

Long-term monitoring plans to document effectiveness of NBS

Work Package 4 – Technical Innovation to Design a Comprehensive Framework

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UNINA

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Project information

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1 Introduction

The main aim of PHUSICOS is to assess with a multi-disciplinary comprehensive approach the effectiveness of nature-based or nature-inspired solutions (NBS) in reducing the risk posed by natural hazards induced by extreme weather events in mountainous and rural areas.

In the frame of PHUSICOS project, NBS efficacy in reducing the risk associated with different natural hazards is assessed in different countries, at varying geological, morphological, and hydrological settings and under distinct climate scenarios.

In Task 4.1 of the project, a comprehensive framework for NBS assessment was developed to support governance in the decision-making processes (Autuori et al., 2019; Caroppi et al., 2023). Some key indicators included in the assessment framework tool are linked to the effectiveness of NBS in hazard and risk reduction, in terms of both reduction of areas affected by a natural phenomenon and reduction of its intensity in the examined area.

During Task 4.4 (Modelling changing pattern of hazard and risk and identifying the return period of the extreme events that the NBS could safely withstand), the effectiveness of NBS in reducing risks was assessed at the three Demonstrator cases (DCs) of the project, namely the Serchio River Basin in Italy, the Gudbransdalen Valley in Norway and the Pyrenees sites in France and Spain. This was done by implementing numerical modelling and analyses to generate the hazard maps for threats of interest, with and without NBS implementation, and for different climatic scenarios (Pignalosa et al., 2022). The assessment of the effectiveness of NBS against natural hazards was pursued through the modelling of hazard scenarios before and after NBS' implementation. The comparison of modelling results for different scenarios allowed evaluating the change in hazard patterns as a result of the implementation of mitigation measures, providing further relevant inputs for stakeholders involved in the decision-making processes.

Moreover, in Task 4.6, the NBS effectiveness was further evaluated, through the comparison of the intensity and the spatial distribution of risk at baseline (before implementation of NBS measures) and NBS scenarios, aimed at identifying and estimating the residual risk and eventually defining complementary risk reduction or risk-transfer measures for reducing it further.

To achieve this goal, we adopted a general methodological framework for risk assessment able to evaluate the effects of NBS implementation on different domains of the risk components (i.e. environment, biodiversity, society, economy) and suitable for risk and residual risk assessment according to the scale of analysis and data availability at each case study site. The approach was based on the conceptual framework for vulnerability and risk assessment of socio-ecological systems in the contexts of NBS (VR-NBS framework) (Shah et al., 2020), proposed by OPERANDUM, one of PHUSICOS HydroMet sister projects. VR-NBS framework was adopted since it computes the inherent risk as the product of its components – Hazard, Vulnerability and Exposure – and proposes specific indicators for their calculation, in a flexible indicator library that was substantially commensurate to the PHUSICOS Assessment Framework Tool (AFT) developed in Task 4.1 and included in PHUSICOS deliverable D4.1 (Autuori et al., 2019).

The application of VR-NBS framework to PHUSICOS DCs allowed us to generate hazard, exposure, and vulnerability maps for each case study and, through their proper correlation, risk maps for both baseline and NBS scenario. By comparing the baseline and NBS risk maps, it was possible to identify where the residual risk was located in the study areas and how intense it was. This is a key output that can provide relevant information to site-owners and stakeholders, concerning where to implement complimentary risk reduction measure for dealing with the residual risk.

One of the lessons learnt from Task 4.4 is that risk and residual risk analyses should be performed multiple times during different seasons throughout the designed NBS maturation stages. Indeed, some of the designed NBS at PHUSICOS DCs rely on the growth of organic elements (e.g., trees and plants), which are also influenced by seasonal climatic variability. Clearly, a thorough understanding of NBS effectiveness would only be achieved through the development of a continuous monitoring plan, able to ensure that the risk reduction benefits of the designed NBS are delivered in the long term or to highlight possible loss of effectiveness due to ageing of NBS.

Basically, after the PHUSICOS ending, public authorities who promoted the implementation of NBSs would need to monitor their performances at an ex-post stage. Actually, the development of a shared and effectively feasible monitoring plan is the only reliable approach to check whether the implemented NBSs will be capable to deal with natural hazard, to enhance environmental features, as well as to generate social and economic benefits during their lifetime.

It is worth noting that, in the framework of PHUSICOS Task 4.3, an extensive knowledge about NBS potential monitoring needs had already been built. Actually, the deliverable D4.3 contains a guideline covering conceptual design considerations that could be adopted as a working reference for site-owners planning on implementing NBS monitoring. In D4.3 the monitoring needs have been defined for each ambit, providing for each indicator the methods, sensors, and data that can be used. Each of these are subsequently described, highlighting the advantages and drawbacks of them. Technologies presented include both tried-and-true technologies, as well as state of the art.

On this matter, the present PHUSICOS deliverable D4.7 is developed with the aim of providing a consistent starting point for the development of the monitoring plan at each case study site, based on both the expertise gained in previous PHUSICOS activities and tasks and the acquired information on the features and the availability of measurement instruments declared by the site owners and the facilitators.

The deliverable aims at defining and structuring several aspects that should be accurately taken into account in the selection and estimation of the parameters to be monitored. In this regard, a detailed survey of any monitoring activity at each DC, in progress or planned by the site owners or other public authorities, was carried out to optimize the cost-benefit ratio from existing data series. Moreover, in parameters selection, needs and resources of DC site owners were carefully evaluated and discussed to build up a feasible monitoring plan. Thus, matching the matrix structure of the AFT developed in D4.1 with the outcomes of D4.2 (on monitoring the ecosystem services), D4.3 (the implemented database and platform for monitoring and early warning), D4.4 (on hazard modelling), and D4.6 (on residual risk assessment), and with several information collected in D2.4 (Nature-based solutions implemented in PHUSICOS), the main goals of the present D4.7 is to answer to the following questions:

a) *Can the site owners allocate resources to install and service new monitoring stations or to develop new monitoring activities?*
b) *How frequently will they be able to carry out monitoring surveys?*
c) *Which parameters are easier to be monitored considering the site features and the cost-benefit analysis?*

The final output is a set of tailored monitoring sheets, customized for each DC as a function of the main features of the site. For each selected monitoring activity, parameters and related measurement procedures and tools are provided, along with the frequency of data collection, and the main approaches and devices to be employed for their consistent monitoring.

2 Demonstrator cases sites

2.1 Serchio River Basin, Italy

2.1.1 Ongoing monitoring activities

Serchio is the PHUSICOS DC where the designed NBS were completed before any others and, therefore, a significant number of monitoring activities is ongoing.

Shortly after the implementation of the NBS was completed, the site owner, Autorità di Bacino del Serchio (ADBS), started to monitor several key parameters through both a periodic and a continuous monitoring.

The regular periodic manual sampling started from October 2020, by using 17 monitoring stations located in the south-east area of Lake Massaciucoli (Figure 1). As the loss of soil and the runoff of nutrients and pesticides are the main issues, much of the monitoring is focused on physical and chemical indicators and turbidity, measured in surface waters (Figure 2). Data acquired from the manual sampling includes:

- pH;
- Temperature;
- Conductivity;
- Redox potential;
- Dissolved O2;
- Turbidity;
- Nitrate;
- Ammonium;
- Trace elements.

In addition, water level in the canals is monitored for flooding purposes. However, as the interventions are also expected to have a flood risk reducing potential, water level is an important indicator to monitor as a function of precipitation. The manual sampling has been repeated every 14 days and calibration probes have been performed every 4 months.

Manual sampling data are available on a web-platform (user- and password controlled), accessible at the following website: http://131.114.22.25/phusicos (username: adb_user; password: mass321) (Figure 3, Figure 4).

The continuous monitoring system started to deliver data from April 2021. A total of 6 stations were installed for monitoring station using HydroLab HL-7 multiparameter probes, 24Ghz Doppler radar rain gauge (Figure 5). Three of them and a rainfall station are located in Studiati area, one is located in a channel between Studiati and the sediment basin (Figure 6). Furthermore, two probes have been inserted in October 2022 for continuous monitoring to obtain information on the main physical and chemical parameters of the incoming and outgoing water in the sedimentation basin (Figure 7). Data acquired from the sampling includes:

- pH;
- Temperature;
- Conductivity;
- Redox potential;
- Hach LDO dissolved oxygen;
- Nitrate ion NO3-;
- NH4+ ammonium ion;
- Turbidity;
- Rainfall classes: rain, snow, sleet, rain, frost, hail;
- Droplet size: from 0.3 to 5 mm with 11 classes of 0.5 mm each;
- Rainfall intensity: 0.01 to 200 mm/h;
- Particle velocity: 0.9 to 15.5 m/s;
- Hydrometric level.

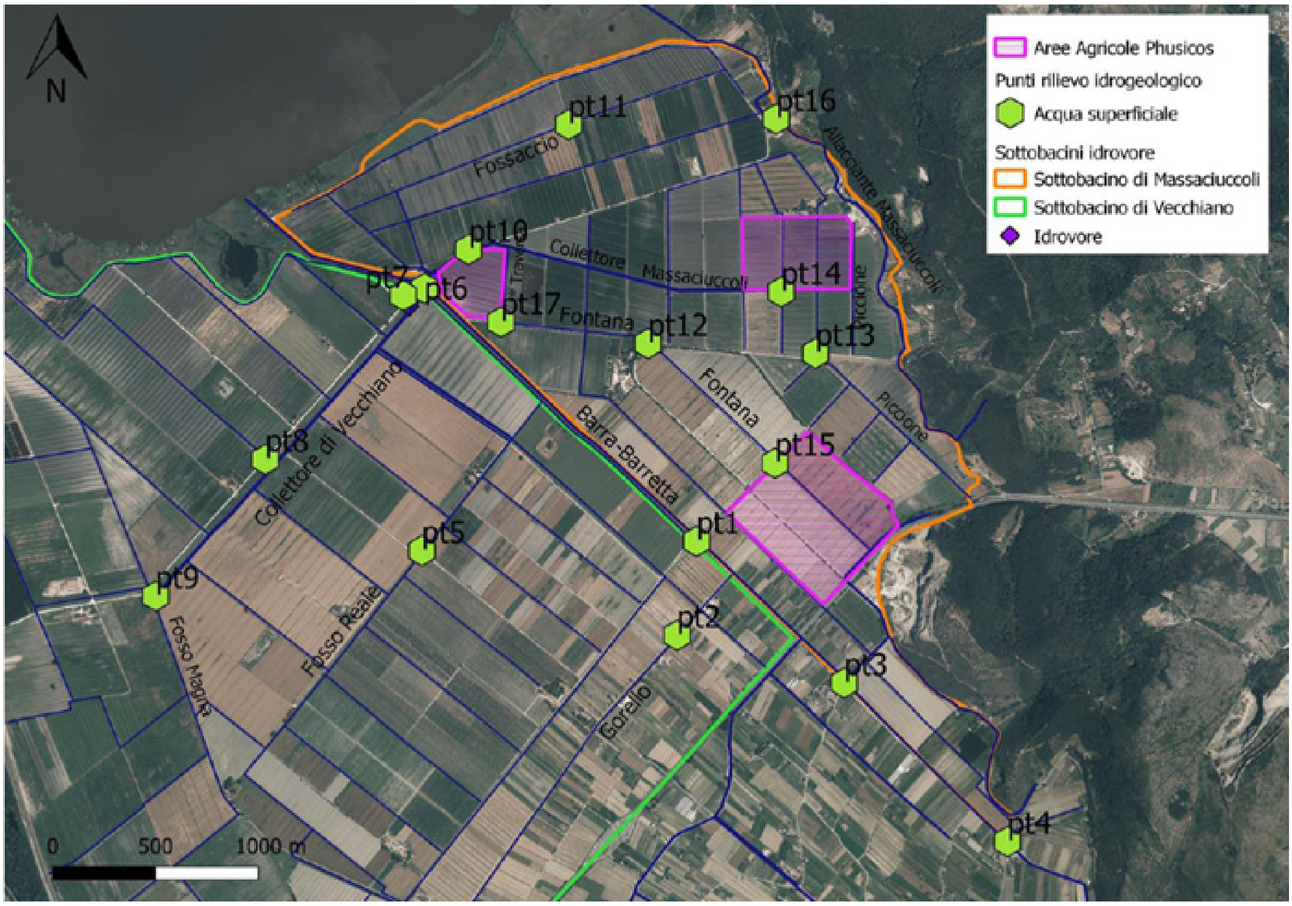


Figure 1. Overview of monitoring stations for surface water periodic sampling.

Figure 2. Manual periodic sampling (Photo credits: ADBS).

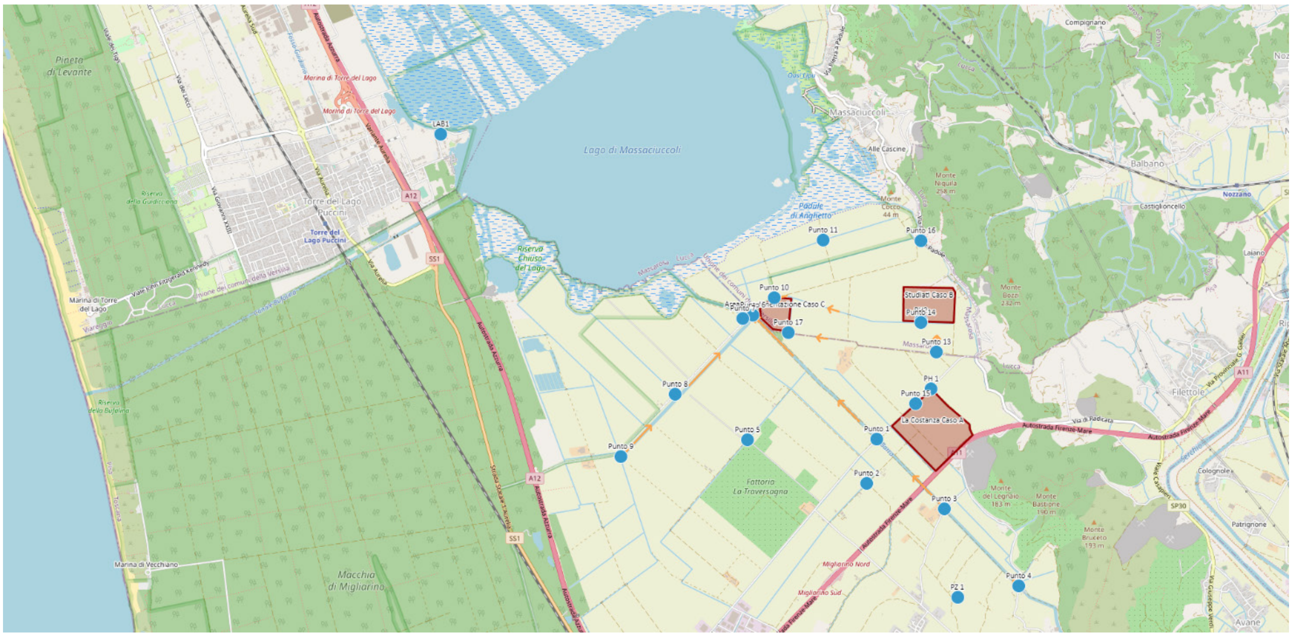


Figure 3. Graphical user interface of the web platform hosting data achieved from manual sampling monitoring.

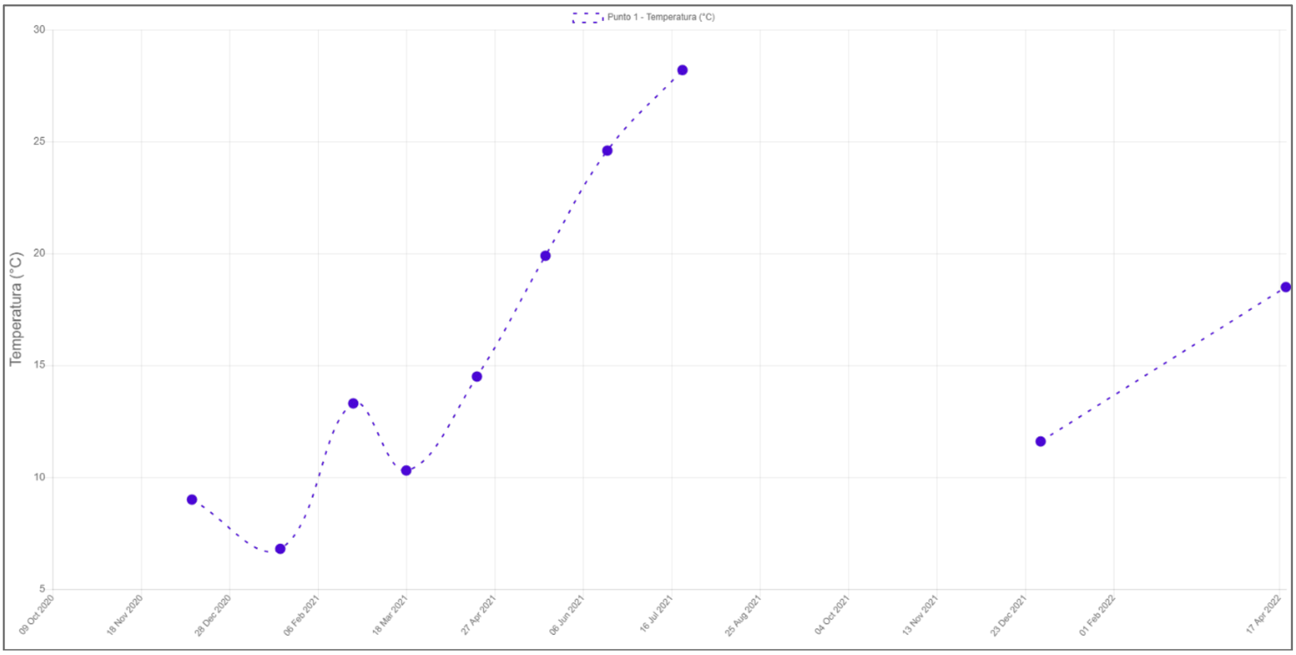


Figure 4. Arbitrary example of data on Temperature at monitoring sampling station 1 exported from the web platform hosting data achieved from manual sampling monitoring.

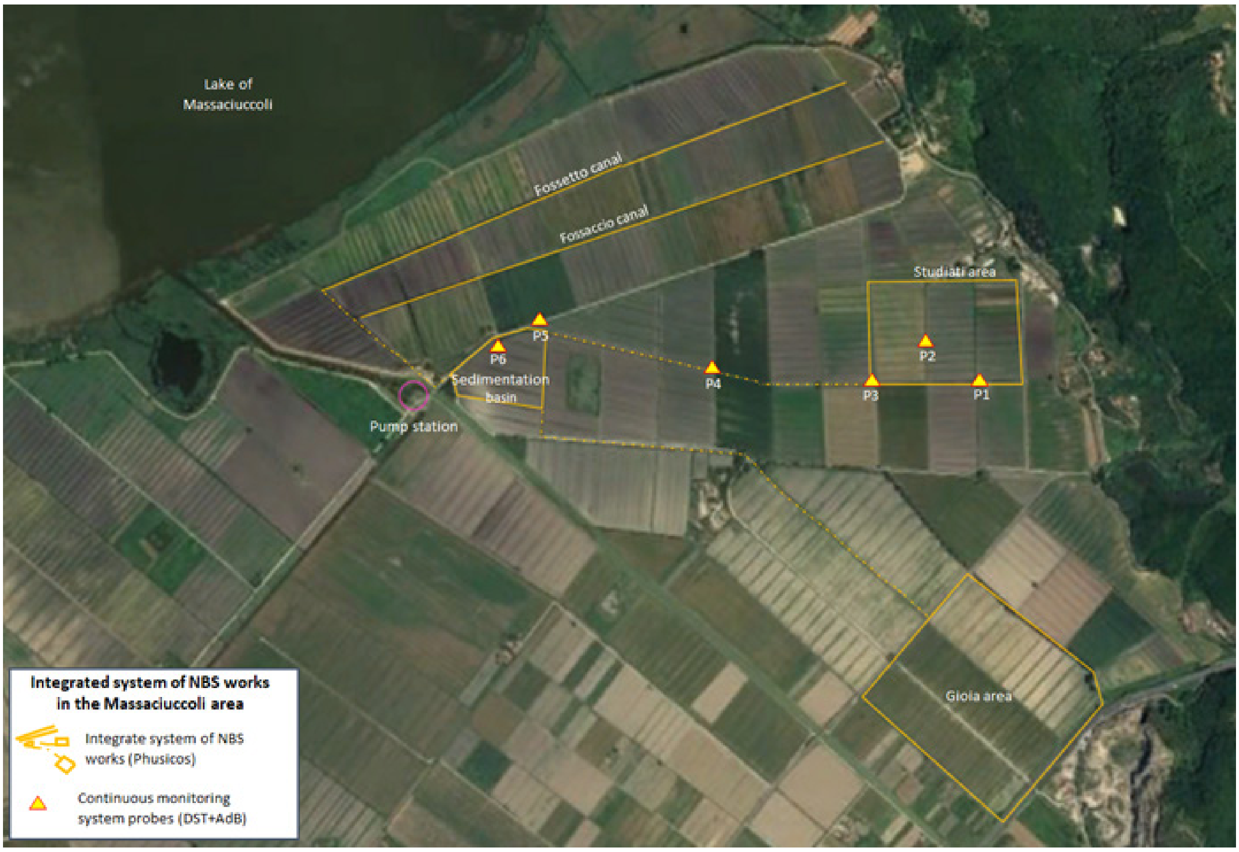


Figure 5. Overview of probes for automatic, continuous monitoring surface water parameters.

Figure 6. Continuous, automatic monitoring system (right) (Photo credits: ADBS).

Figure 7. Photos of the two monitoring probes in the sedimentation basin (Photo credits: ADBS).

The frequency of sampling is every 15-30 minutes and calibration probes have been performed every 3 months.

The monitoring is done partly in collaboration with the University of Pisa (Department of Earth Sciences – DST). All acquired continuous monitoring data are available on a web-platform (user- and password controlled) accessible from the Microsoft® Power BI (username: phusicos@nexman.it; password: Phus1c0s1!) (Figure 8).

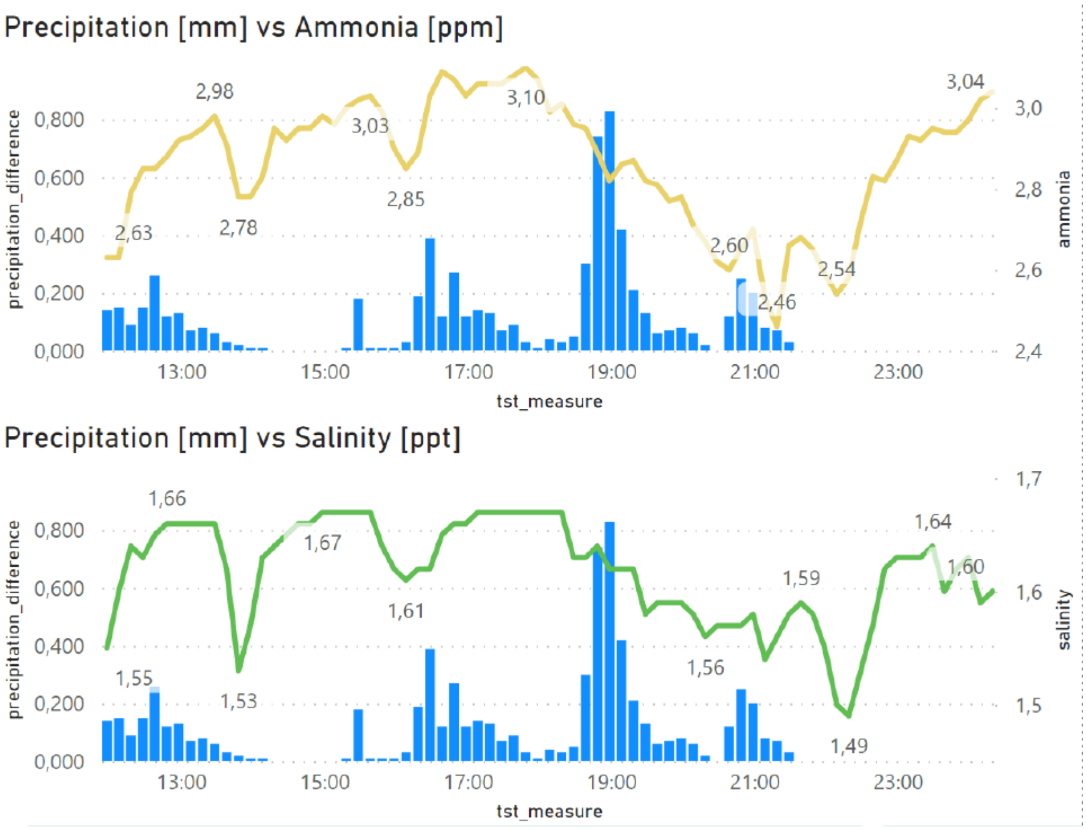


Figure 8. Arbitrary example of data on Ammonia and Salinity vs. precipitation at probe 1, during a 6,5-hour period on 16.11.2021.

In addition, project partner University of Siena, Centre of GeoTechnologies (CGT), has carried out detailed geomorphological and geophysical measurements from the ground, from the air with a 'gyroplane', and by using satellite data. An autogyro/gyroplane survey was conducted in 2018 for mapping the terrain with LIDAR and orthophoto before the “buffer strips” installation. The photogrammetric cameras allow constructing very high-resolution 3D digital models.

Furthermore, CGT has been monitoring land subsidence in the Massaciuccoli area since 2021 through differential surface elevation measurements by using high precision topographic levelling technique. Measurements have been carried out every three months through fieldwork activities by using GNSS and digital level along loops of benchmarks.

Relative and absolute subsidence have also been monitored through Persistent Scatterers radar Interferometry (PSI) from December 2019 to October 2022. The analysis has been carried out through a powerful desktop PC, with Ubuntu operating system installed, and the following software: SNAP, Matlab and the Snap2stamps package. 4 Copernicus-Sentinel satellite imagery per months have been processed and stored in a geodatabase.

Finally, to monitor vegetations and crops conditions, suspension in water along canals Unmanned aerial vehicle (UAV) surveys were conducted periodically (with several sensors, such as RGB, multispectral and hyperspectral) in order to create not only multitemporal DEMs and orthophotos but also with the purpose of evaluating the vegetation/crops conditions, the SMI-Soil Moisture Index and the suspended content in water canals nearby farms. The data processing was carried out using multiple software, such as Metashape, Parge and ENVI (Windows systems).

Beyond the above-mentioned activities, mainly belonging to risk reduction and environment & ecosystem ambits, several monitoring activities of socio-economical co-benefits have been carried out since May 2018, when first Living Labs where activated involving main stakeholders, freelancers, technicians from public authorities, students.

In March 2023, several interviews were conducted with operators and farmers to investigate about new jobs created during and after NBS implementation, sale harvest from buffer strips and cover crops. Finally, in the same period, Tourist Info Point operators were interviewed to get information about increase in tourism.

Further details on the ongoing monitoring activities are provided in Annex 2.

2.1.2 New monitoring activities

The monitoring activities concerning physical and chemical indicators, turbidity and water level through the existing sampling and continuous monitoring stations, each 15 days and 15 minutes, respectively, will be carried forward by ADBS, as long as necessary. No movement of stations currently serviceable is foreseen. The main purpose for the future is improving data organization through the implementation of a single infrastructure for data collection from all monitoring stations and ground surveys.

Increasing the length of the time series will certainly result in a better understanding of the critical issues and medium-term effectiveness of NBS. Moreover, the creation of a single repository of all monitoring data will allow easier and more effective analyses, aimed at assessing trends and correlations.

CGT, in cooperation with ADBD will keep measuring differential surface elevation through high precision topographic levelling technique and PSI. Measurements could be carried out through fieldwork activities by using GNSS and digital level along loops of benchmarks. The high precision levelling survey can be carried out to monitor specific areas that require a deeper analysis for land subsidence conditions (e.g., anomalies from the normal seasonal and artificial trends). On the other hand, the PSI analysis allows to monitor the subsidence remotely (in lab), for a large area, and can be compared with results provided by the high precision topographic levelling. UAV surveys could be carried out periodically (with several sensors, such as RGB, multispectral and hyperspectral) in order to create not only multitemporal DEMs and orthophotos but also with the purpose of evaluating the vegetation/crops conditions, the SMI-Soil Moisture Index, and the suspended content in water canals nearby farms.

CGT is also interested in carrying out analyses on soil geochemical and physical characteristics. In detail, laboratory analyses can be performed on soils of areas of interest. Few examples of analyses that could be carried out are:

a) Physical analyses, such as:
- Textural and granulometric analysis;
- Analysis of soil water content;
- Determination of Atterberg Limits;
- Calculation of the Activity Index, Consistency Index and determination of the land workability and trafficability.

b) Geochemical analyses, such as:
- Determination of soil pH;
- Electrical conductivity;
- Nitrogen and phosphorus content and Organic Matter.

The soil of areas to be analyzed can be sampled with a frequency depending on the study objectives. The main evaluations that could be carried out through these analyses are the relationships between subsidence and soil types.

Finally, ADBS is willing to increase and strengthen knowledge and awareness of the implementation and use of NBS, through new workshops and interviews.

Additional information on new monitoring activities is included in Annex 2.

2.2 Pyrenees, France-Spain

In addition to the Monitoring sheet templates, a special Appendix was developed for the Pyrenees DC, with specific reference to Santa Elena and Capet Forest case studies, concerning soil and plant indicators for NBS monitoring (Appendix A).

Appendix A contains necessary concepts to understand the importance of plants and soil in NBS, both as tools and as indicators of the performance of NBS in enhancing environmental services. Moreover, it contains a proposal for soil and plant monitoring plans for Santa Elena and Capet Forest case studies, including:

a) a set of indicators selected for their responsiveness to the operations, based on the results of intense sampling campaigns;
b) sampling design and monitoring calendar;
c) field and laboratory methods;
d) expected post-operational evolution of the indicators.

2.2.1 Santa Elena

2.2.1.1 Ongoing monitoring activities

At Santa Elena the main issue to mitigate with the NBS intervention is rockfall from the released blocks in the till surface, and rocks lying in the road cause the highest damage. The site is already covered by a web-camera. This is probably the most important monitoring of the risk reducing effect. The webcam was mounted to follow the construction of the measures. It is mounted on a pole on the opposite side of the road and covers the slope and the road below. The camera will be kept and operated for at least 5 years after the implementation. Through the saved photos, the growth of the planted vegetation on the terraces will also be monitored. This is important, as eventually, after approximately 20-30 years, the wooden gabions will be no longer the main protective agent, and the vegetation itself is expected to maintain stability in the slope.

Furthermore, some monitoring activities concerning socio-economical co-benefits have been recently carried out:

1) In September 2022 local company workers contracted for the implementation of the measures were interviewed and it allowed to confirm that 6 jobs were created for 7 months (construction phase)
2) In March 2023, commuters and other drivers were interviewed regarding their sense of safety.

2.2.1.2 New monitoring activities

Further monitoring plans will consist of establishing a calendar of revisions with regular, quarterly visits and corresponding reports. Additional visits will take place after heavy precipitation (rain and/or snow) and/or after any adverse natural events (earthquakes, extreme temperatures, freeze/thaw, etc.). Furthermore, as the vegetation is rooting the stability will be monitored, particularly the first three years after full implementation of the NBS. Clearing of weeds will be carried out in favor of bushes and trees with deeper the root system. The currently operational webcam will be maintained to ensure its adequate working.

Finally, drone flights for detailed topographic mapping will be carried out annually and check if significant changes are observed on the webcam or by physical inspection.

Many of the co-benefits, such as effects for the society and local economy will also be monitored, mainly by interview surveys with various stakeholders, such as commuters and other users of the road, road maintenance personnel, local authorities, private businesses, and the local company contracted to carry out the construction work at Santa Elena. Public and private actors involved in road maintenance, natural hazards mitigation and landscape restoration will be invited once a year to visit the site for discussions of replicability.

Cost of the planned monitoring has been estimated to be ca. 6000 €/year.

Additional information on both ongoing and new monitoring activities are included in Annex 3.

2.2.2 Artouste

2.2.2.1 Ongoing monitoring activities

No relevant monitoring activities were activated before or shortly after NBS implementation in Artouste, except for some monitoring activities concerning socio-economical co-benefits. More specifically, in March 2023, commuters and other drivers were interviewed regarding their sense of safety.

2.2.2.2 New monitoring activities

NBS implemented by PHUSICOS are aimed to reduce the probability of rockfall hitting the road and to improve the protective role of the forest. Monitoring will mostly consist in regular visual inspections and corresponding reports on the state of the solutions and on the adequate management of the forest, ensuring its healthy state and degree of regeneration.

The EGTC Pirineos – Pyrénées is engaged for 10 years of maintenance and close monitoring of the solutions installed in the slopes at Artouste. They are currently (before the end of PHUSICOS) also establishing a protocol and calendar for ordinary and extraordinary visits and reports to ensure the status of the solutions, follow-up and control of the state of the protective forest and other vegetation, in particular its health and degree of regeneration. The monitoring, especially on the road, will be shared with the unit in charge of road maintenance and management from the Departmental Government (CD64).

As part of the visual inspections of the site, the Hazard Control Index (Indice de Maîtrise de l'Aléa, IMA in French) developed by the French Forest Office (ONF) in "Guide de Gestion des Forêts Pyrénéennes à rôle de protection"(Villiers, 2016) will be used to assess the level of protection provided by the forest, compared to the baseline (before the interventions). The aim is to increase the IMA from the current low to medium (IMA = 2/5 – 3/5). The cost of monitoring and reporting is estimated to be 3000 €/year.

Environment and ecosystems monitoring will be also part of the regular visits, with inspection of tree health and the general state of the vegetation in the slope. Furthermore, co-benefits related to society and local economics will, as for Santa Elena, be monitored through interview surveys with various stakeholder groups. Quarterly (plus after extreme events) interviews with workers in charge of road management and maintenance about the status of the solutions. Furthermore, public and private actors involved in the road maintenance, natural hazards mitigation and landscape restoration will be invited once a year to visit the site for possible replicability.

Assessing the maintenance needs of the installed measures will be part of the regular inspection visits and will be included in the protocol and calendar for visits, as the 10-year engagement of EGTC Pireneos-Pyrénées also covers maintenance.

The cost of monitoring and reporting is estimated to be 3000 €/year. This covers also routine maintenance during the first years. Potential increase of this with time, is not yet accounted for.

Further details about ongoing and new monitoring activities in Artouste can be found in Annex 4.

2.2.3 Capet Forest

2.2.3.1 Ongoing monitoring activities

At Capet, hazard monitoring is based on detailed monitoring of the avalanches that occur. Currently in France, avalanches are recorded by Institutional avalanche monitoring program supported by the Ministry of the Environment through three different systems:

- the map of avalanche phenomena map (*Carte de Localisation des Phénomènes d'Avalanche* - CLPA), which describes the areas where avalanches have occurred in the past and are represented by their known extreme limits;
- the Permanent Avalanche Survey (PAS), which is a historical record of events at selected sites;
- the Avalanche Sensitive Populated Sites (ASPS), which is an inventory of sites inhabited in winter and accessible by an avalanche safe route, classified into 3 groups according to their sensitivity to avalanche risk.

These data can be investigated through the web-portal https://www.avalanches.fr/.

2.2.3.2 New monitoring activities

Automatic instrumentation to monitor snow height will be installed in 2023. A snow LIDAR flight was carried out with the support of PHUSICOS at the end of February 2023. Regular follow-up of the state of the structures and plantations will be carried out. Furthermore, pressure will be monitored by an instrument mounted on one of the avalanche fences. Despite this being on a 'grey' structure, it will record all avalanches hitting the structure.

In addition, a collaboration with the CNRS in the 'Envirosciences-Pyrénées' project aims to create catalogues of hydro-gravitational and tectonic events in two specific territories of the Pyrenees: Pays Toy and Béarn. Lack of detailed information on the location and date of occurrence of these phenomena in the Pyrenees has raised the need to deploy dense networks of multi-parameter measurement stations. By the end of 2022, about fifty autonomous real-time stations will be deployed for 10 years in both territories, with locations in both valleys and upper slopes. The intention is that also Capet Forest is included in this network of stations, which is important, as seismicity may also trigger avalanches. Each station will consist of a seismological, meteorological and GNSS antenna. The School and Observatory of Earth Sciences (EOST, Strasbourg) and GéoAzur (Nice) have designed and built a prototype of a modular and low-cost integrated station, associating several types of sensors (4.5 Hz geophone, GNSS receiver and meteorological station), a high-frequency digitization module, a communication module and a power supply module (mainly by solar energy), planned also for installation in the Capet Forest.

According to ONF, the French public forest administration, avalanche hazard monitoring in Capet should pursue three main targets:

1) Documenting the climatic parameters that have a role on the departure of snow avalanches;
2) Monitoring the evolution of the snowpack;
3) Monitoring real-time conditions in the departure zones of the Capet couloirs.

These targets could be achieved by using at least the following instrumentation:

- A weather station (Campbell Scientific Station);
- Automated snow probes (SR50A Campbell Scientific);
- One or several sensor(s) for snow transport/movement (FlowCapt Fc4);
- Photo cameras to document the evolution of the snowpack;
- Webcam to follow the evolution of the weather conditions in real time (Campbell Scientific).

In a first phase, a weather station/tower and the devices measuring should be installed to monitor the following parameters:

- Average temperature (°C);
- Maximum temperature (°C);
- Minimum temperature (°C);
- Wind force (km/h);
- Wind direction (0 to 360 degrees);
- Solar radiation (W);
- Liquid precipitation (mm);
- Solid precipitation (mmEE);
- Atmospheric pressure (kPa);
- Relative humidity (%).

The station should be installed on or slightly below the ridge and at least 30 meters away from obstacles (Figure 9). The precipitation measuring device should also be located on a ridge so as not to be affected by windy snow. The real-time webcam can be attached to the weather tower provided that the field of view allows the observation of the snowpack in the corridors and structures.

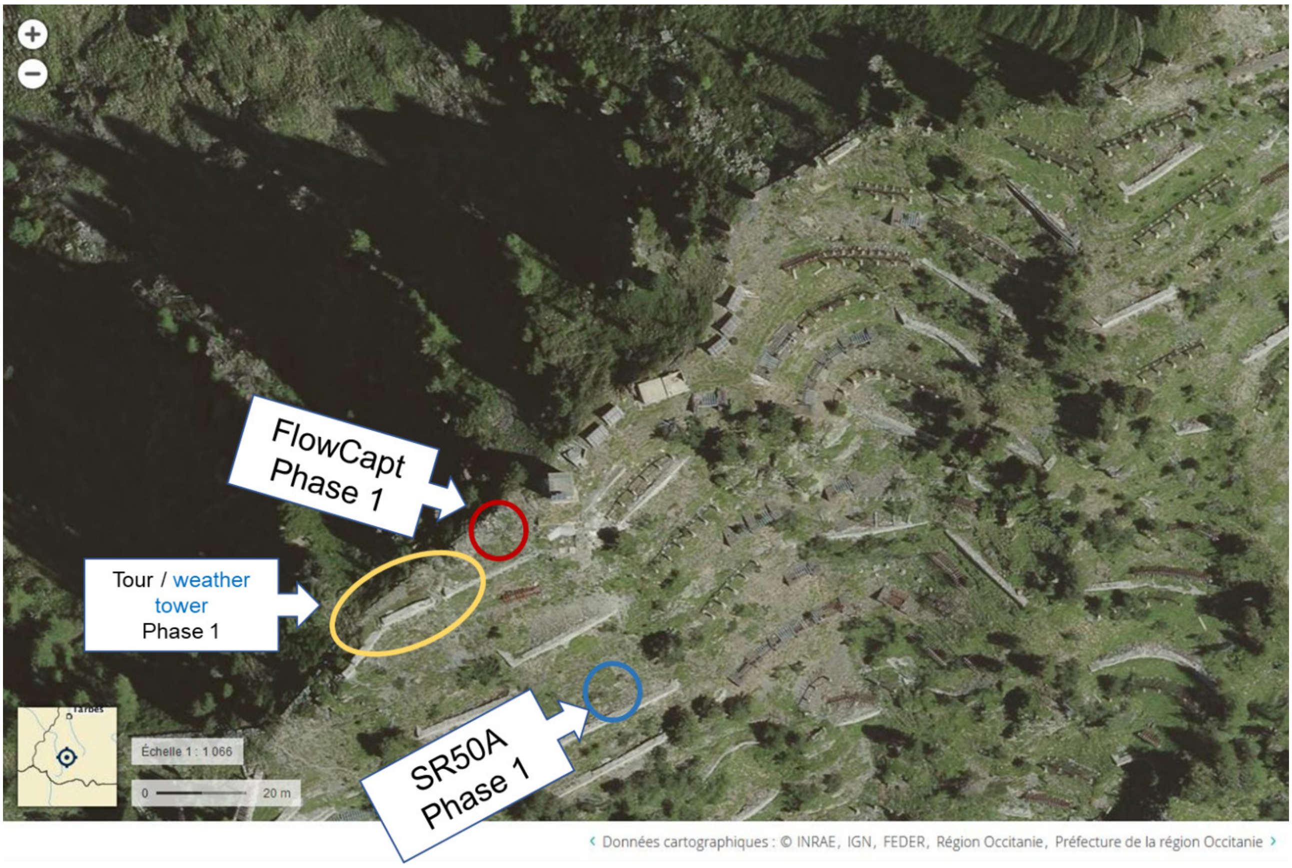


Figure 9. Potential location of the weather tower, the FlowCapt FC4 sensor/probe and the SR50A in Capet in the first stage.

The FlowCapt sensor must be exposed to the wind. It must be high enough not to be covered by snowdrifts and ridges. Finally, the snow height measuring device must be located below the ridge so that it is possible to correlate the snow transport data with the height of the snowpack in the deposition areas.

In a second stage, it would be possible to document the effect of wind on the movement of snow towards the avalanche starting zones that could reach the municipality of Barèges and to be able to follow in real time the thickness of the snowpack in the starting zones.

FlowCapts FC4 and SR50A snow height sensors could be installed at one or two other locations as needed (Figure 10). In addition to retrieving data, the SR50A coupled with data transmission modems and small dataloggers (CR300) could serve as automated snow poles. The FlowCapt and SR50A set-up can be inspired by the video produced by the FlowCapt supplier available at: https://www.isaw-products.com/flowcapt-fc4/

As regards NBS co-benefits monitoring in Capet, possible effects on the environment and ecosystems, societal effects, and potential effects on the local economy could be taken into account. The former of these will be investigated through monitoring of plant health in the plantations, monitoring of plant mortality and re-planting if needed. Societal and economic co-benefits will be monitored through annual meetings with authorities, and through interview surveys with stakeholders, including the general public (sense of safety) and local businesses (tourist business, maintenance company, helicopter company, etc.).

The planned monitoring activities at Capet Forest are estimated to be in the range of 30'000 to 50'000 €/year.

Additional information on both ongoing and new monitoring activities in Capet Forest are included in Annex 5.

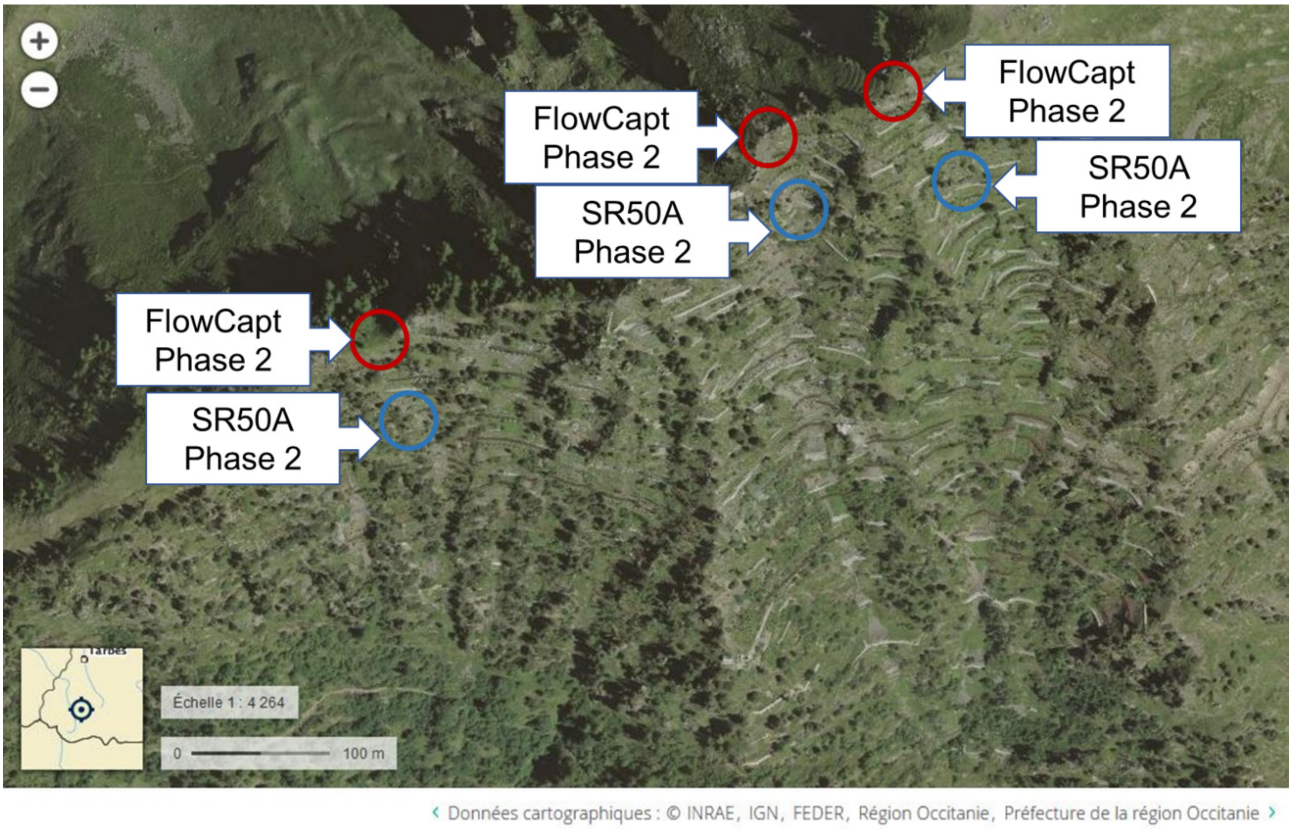


Figure 10. Potential locations of the FlowCapt and SR50A in Capet in the second phase.

2.2.4 Erill-la-Vall

2.2.4.1 Ongoing monitoring activities

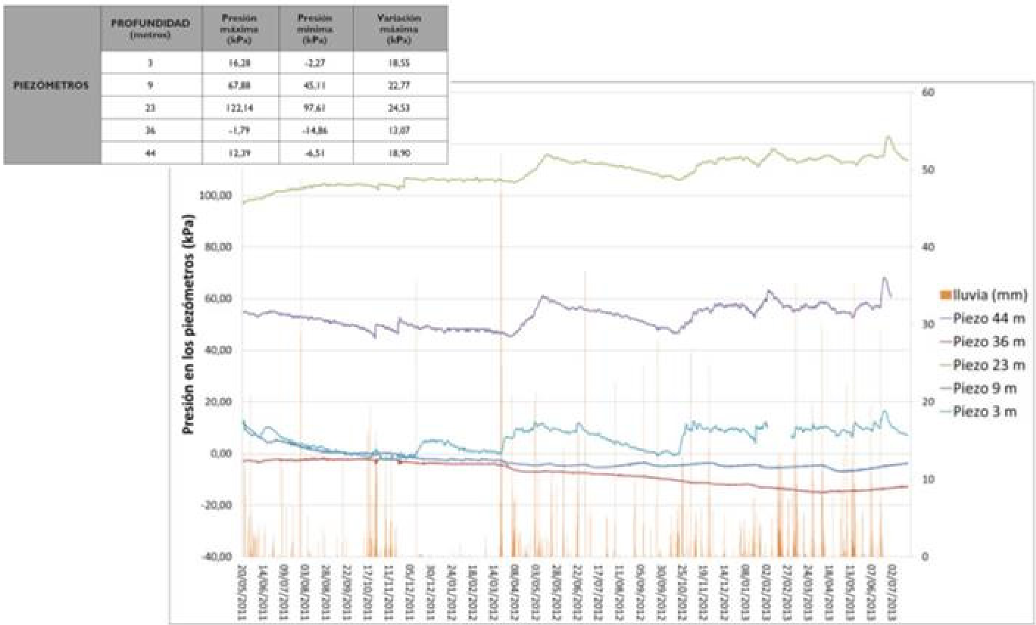
The Erill-la-Vall site has had monitoring equipment installed since 2007. The monitoring equipment was further expanded in 2009 and finalized in 2021 with the support of PHUSICOS project. Acquired data were used as a major part of a PhD thesis on debris flow hazard at the site (Räimät, 2018). The installed monitoring equipment includes:

- a weather station;
- a micro-seismic network;
- turbidity and flow measurements in the gully;
- 5 piezometers installed in a borehole drilled to bedrock behind the landslide scarp, recording to a depth of 15 m.

All physical monitoring data are available through a web portal (service.iotailor.com/dashboard/) open to the public. Figure 11 shows one example of monitored piezometer data and rainfall. The goal is to establish a near real-time early warning system for the area.

The topographic changes are routinely monitored through UAV photogrammetry and Lidar survey twice per year. In addition, flights are done after precipitation events with more than 0.5 l/minute or more than 35 l/accumulated/event. From a geotechnical point of view, the monitoring plan and corresponding equipment is complete. However, more detailed soil monitoring (soil loss and/or soil improvement) would be useful and should be discussed regarding future plans.

In addition, co-benefits related to environment and ecosystems, societal effects, local economy, and technical and feasibility aspects are monitored through regular visits, maintenance of the installations and interviews with stakeholders. Furthermore, some monitoring activities concerning socio-economical co-benefits have been carried out in September 2022, when local company with local workers, contracted for the implementation of the measures, were interviewed (3 workers involved).



	PROFUNDIDAD (metros)	Presión máxima (kPa)	Presión mínima (kPa)	Variación máxima (kPa)
PIEZOMETROS	3	16,28	-2,27	18,55
	9	67,88	45,11	22,77
	23	122,14	97,61	24,53
	36	-1,79	-14,86	13,07
	44	12,39	-6,51	18,90

Figure 11. Example of monitoring data from the borehole behind the slide scarp at the Erill-la-Vall site. Pore pressures from 5 piezometers are shown vs. daily rainfall between May 2011 and July 2013.

2.2.4.2 New monitoring activities

New monitoring activities should consist of keeping and improving the current monitoring system. Clearly, more work could be done on the area, both based on new field work and more analyses and interpretation on the 15 years of monitoring data.

Maintenance costs of the monitoring facilities are estimated to be between 3'000 and 5'000 €/year (labor, dashboard, batteries).

Additional information on both ongoing and new monitoring activities in Erill-la-Vall are included in Annex 6.

2.3 Gudbrandsdalen Valley, Norway

2.3.1 Øyer

2.3.1.1 New monitoring activities

Because of the late implementation of the measures in Øyer, physical monitoring of the effects of the interventions is not in place yet. The following is therefore suggested monitoring, which would have to be implemented after PHUSICOS. However, a comprehensive baseline study of ambits and main indicators from WP4 of PHUSICOS (Autuori et al., 2019) that was carried out forms a good base for future monitoring. Future monitoring should focus on:

1) Verifying the condition of the channel;
2) Assessing the retention and sediment storing effect of the weir/check dam and the blue-green park area;
3) Documenting the ecological state/biodiversity in the creek;
4) Document reestablishment of vegetation in the two test areas.

Condition of the channel refers to that the nominal geometry of the channel is maintained that it is not filled with debris or vegetation, the substrate is intact, and the vegetation of the surrounding area is healthy.

The weir creates a partial retention of upstream water and results in a controlled flow of water over the weir to the lower portion of the stream. Monitoring of the water depth behind the weir provides data to estimate flow rates in the stream and to assess capacity utilization. Monitoring of turbidity in the water indicates erosion and sediment transportation processes. Local precipitation and other weather variables should be collected using a dedicated weather station at the site. Data collection over time from the weir and the weather station can yield correlations between capacity utilization and local / regional precipitation.

Local weather monitoring

Measurements are made using a dedicated system for monitoring weather parameters. Systems for this purpose are available in a range of qualities and prices. For this purpose, a medium level scientific system is sufficient.

Weir monitoring

Measurements are made using a dedicated water level sensor monitoring the height (depth) of the water on the upstream side of the weir, and a dedicated turbidity sensor measuring the suspended solids in the water. These are common measurement techniques and the sensors needed are widely available as standard commercial products. The sensors are to be connected to a data logging system. Frequency of measurements could be relatively low (6 h intervals) with an optional higher logging rate seasonally or triggered by measurements of water level or local precipitation exceeding a threshold level.

Channel condition monitoring

The condition of the channel is important to ensure that the flow of the stream is not impeded by accumulating sediments, other debris in the streambed, or if erosion of the banks or channel bed is damaging the channel. This can be done by 4 approaches:

1) Remote monitoring:
    a) Publicly available aerial photography; comparisons after new campaigns
    b) Optical or other types of satellite data, also for vegetation growth/health, repeat every 3-5 years. The following photo imagery could be used:
        - Regional and national authorities periodically perform aerial surveys, and these data are publicly available as a photo archive (norgeibilder.no). Comparing aerial photos from different surveys allows changes over time to be visually identified (Figure 12).
        - Satellite data are routinely collected over Norway. Data from certain satellites are free public access, other data (typically higher resolution) require purchasing. Optical satellite data images can be compared to detect visual changes. The satellite images can also be processed to identify features or qualities, for example the image can be processed to calculate the NVDI which is an optical index related to vegetation. Comparing NVDI results from subsequent images can be used to assess the health and extent of vegetation growth. Substantially more advanced satellite data processing is generally available, but at this scale the resolution would be to coarse and not that useful for monitoring.
        - Drone-based photogrammetry/RTK techniques can be used to create local, high resolution digital terrain maps of the location. A drone flies a photogrammetric survey, and these images are processed to produce a 3D point cloud model of the surface. By comparing the 3D models over time (subsequent surveys) changes can be identified and quantified.

2) Crowdsourcing can be done by relying on the local citizens to report anything unusual they observe regarding the constructed stream. The municipality could design a small informational sign describing the NBS implementation, which purpose it serves, what sort of things to look out for indicating problems and provide an email address where citizens can send a photo if they observe something that does not seem right (Figure 13);
3) Inspections, at regular intervals by a community engineer after any major flooding events.

Co-benefits for the environment and ecosystems will be done by physical inspections or/and regular sampling for assessing water quality and aquatic biodiversity, as well as the re-establishment of the vegetation along the creek, and, particularly in the two test areas. For societal and local economy co-benefits, interviews with stakeholders will be performed. These include municipal and regional authorities and the inhabitants of the area regarding their perception of the surroundings, including safety after the interventions. The local construction company to which the work was subcontracted, will also be interviewed regarding their experiences and potential for new, similar jobs.

Additional information on new monitoring activities is included in Annex 7.

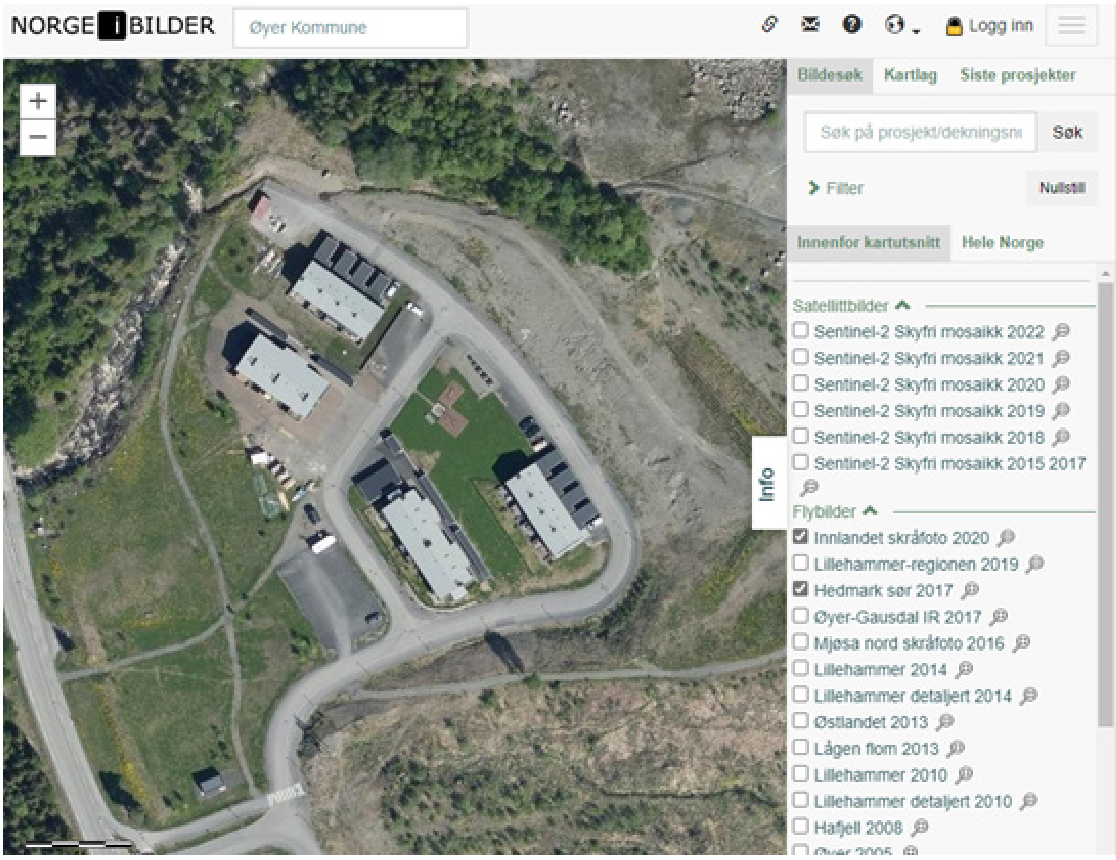


Figure 12. Public access to aerial survey data

Figure 13. Example of crowdsourcing. A sign describes the NBS implementation, which purpose it serves, what sort of things to look out for indicating problems and provide an email address where citizens can send a photo and information if they observe something considered to be of interest.

2.3.2 Skurdalsåa

2.3.2.1 New monitoring activities

As for the interventions in Øyer, the measures in Skurdalsåa were completed very late in the project (end of December 2022), and physical monitoring of the effects has not been implemented. However, a comprehensive baseline study of ambits and main indicators from WP4 of PHUSICOS (Autuori et al., 2019) was carried out; it provides a good base for future monitoring, which should focus on:

a) Local weather parameters, particularly precipitation, by a dedicated weather station deployed at the location.
b) Verifying the condition of the dam and, particularly the discharge gate; periodic visual inspection and photographic documentation by regular visits or crowdsourcing, particularly after flooding events.
c) Verifying the volume of water retained by the dam by a non-contact sensor based on radar, which alleviates problems associated with water in the dam freezing and using the sensor to gauge water retention capacity.
d) Continuing the registration of flood damages in Skurdalsåa. Compare this to historical data, to see the effect of the measure.

e) Measure the effect of more frequent and bigger fluctuations in the water level in Svintjønna (probably too comprehensive but would be interesting).

Regarding environment and ecosystems, investigations should be carried out to assess the effect of possibly bigger fluctuations in water level in Lake Svintjønna, as well as the ecological state along the river.

Potential societal and economic benefits will be monitored through interviews with various stakeholders, such as farmers (use the water for irrigation), inhabitants along the river, cabin owners, fishing associations, etc.). For local economy, assessing possible changes in property values due to reduced flood risk would also be of interest.

Dam condition monitoring

This and similar dams are small structures which are constructed in place and formed to the existing terrain. They are relatively small and as such are difficult to see using existing data sources (the community's periodic aerial surveys, or satellite data).

Monitoring should be based on periodic visual inspection and photographic documentation of the condition of the dam. The collection of photographs could be done via crowdsourcing and/or during physical visits to the dam:

- *Crowdsourcing* could be done by setting up a small information sign containing a description of the NBS, a request of visitors to take a photo (with their smartphone) and post it to media (with a #tag) or send it by email to a recipient email or telephone number.
- *Physical visits/visual inspections* of the dam should be performed after any major event resulting in flooding or abnormally high-water levels recorded by the retained water volume (water level) monitoring system.

Retained water volume (Water level)

Water level measurements are made using a dedicated sensor installed behind the dam, monitoring the height (depth) of the water retained. The sensor is a non-contact sensor based on radar, which alleviates problems associated with water in the dam freezing. These are common, commercially available sensors. The sensor would be connected to a simple data logger/ data communication node.

Frequency of measurements could be relatively low (6 h intervals) with an optional higher logging rate seasonally or triggered by measurements exceeding a threshold level.

Local precipitation

A scientific grade weather station may be deployed at the location to monitor weather parameters (specifically local precipitation) which will provide data to better understand the response of the dam system to local precipitation events. The weather station would provide data to an online data registration system.

Further details about ongoing and new monitoring activities in Skurdalsåa can be found in Annex 8.

3 Summary of undertaken and planned monitoring activities

Due to the late implementation of several NBS at the demonstrator case sites, the performed monitoring significantly differs from site to site. At the Erill-la-Vall site, monitoring started as early as in 2007, whereas at other sites, such as the Skurdalsåa site in Norway, only baseline data exist, and monitoring starts at the end of the project. Below is a short summary, site by site. More details can be found in Annex 2-8.

3.1 Serchio River Basin, Italy (Annex 2)

Monitoring has mainly focused on the Risk Reduction and Environment & Ecosystem ambits and started as early as October 2020 with sampling campaigns. Later, continuous monitoring with installed probes started in April 2021. Several chemical and physical parameters are measured at 15 days intervals or continuously. All measured parameters are listed in Annex 2, along with information about the measuring systems. In addition, project partner CGT has carried out geophysical measurements of topography and topographic changes (subsidence is a persistent problem in the area) by measurements from air as well as from the ground, in addition to using satellite data. These remote sensing techniques also prove areal information of soil moisture, turbidity in canal waters and crop conditions. Baseline measurements were performed in 2018-19, and some of the measurements, such as subsidence measurements, have been done every 3 months since.

Co-benefit monitoring, focusing on the Society and Local Economy ambits, is being monitored by interviewing several stakeholder groups from March 2023, although some initial interviews have been carried out in connection with Living Lab sessions since 2018.

The physical/chemical monitoring by water samples and probes in the canals and the sedimentation basin will continue with the present frequency, in cooperation with the University of Pisa, for at least five years. Detailed plans for the next geophysical surveys and analyses of satellite data have not been made yet but is expected to last at least over the same period. This is to be settled through a discussion between CGT/University of Siena and ADBS. ADBS is responsible for and coordinating all monitoring activities.

3.2 The Pyrenees demonstrator case sites, France and Spain

As the four different locations in the Pyrenees are exposed to a range of different hazards, the monitoring activities also vary, both in parameters and in extent. The two sites along the road between France and Spain, Santa Elena and Artouste have some of the same relatively simple monitoring elements, whereas the two other sites, Capet Forest and Erill-la-Vall are quite different, both in complexity and time for monitoring. For all the sites, there are also a strategy for monitoring of soil parameters, explained in Appendix A, but no detailed plans for following up and executing this strategy have been made at each location.

Santa Elena, the Pyrenees, Spain (Annex 3)

The monitoring of the implemented measures at Santa Elena started with the mounting of a web-camera in August 2022, to overlook the progression of the construction. The web-camera will be kept operating for at least 5 years post-PHUSICOS, to monitor the development of the terraced slope and the growth of the implanted vegetation, with a filming frequency of 1/5 minutes.

Planned monitoring, in addition to the web-camera, will consist of regular inspections, at least every 15 days, done by the regional road authorities. In addition, drone flights with photography and Lidar will be carried out regularly, once per year, and after major precipitation events. Monitoring of co-benefits started after completion in the spring/early summer of 2023, and is to be carried out through interviews with different stakeholder groups, as well as individual users of the road. All monitoring will be maintained at least 5 years post-PHUSICOS. CTP is responsible for the organization, but the monitoring is carried out in cooperation with the regional road authorities and the EGTC Pireneos-Pyrénées.

Artouste, the Pyrenees, France (Annex 4)

Most monitoring activities of the slope at Artouste commenced after the implementation was completed in April 2023, except for an interview survey among users of the road in March 2023, regarding the perceived sense of safety. The most important post-implementation monitoring comprises regular quarterly visits with visual inspection of block movement, state of the installed measures, possible impact marks on trees and structures, and blocks which may have reached the road. Additional visits will be done after extreme events. These inspection visits will be done for a period of at least 10 years. For the co-benefits, environmental and ecosystem parameters will be part of the regular inspections. Interview surveys with the various road users will continue with a yearly frequency for at least 5 years. EGTC Pireneos-Pyrénés is responsible for all the monitoring at the site.

Capet Forest, the Pyrenees, France (Annex 5)

Except for visits to inspect, replant dead plants and repair tripods where necessary, no monitoring was done until after all implementation was complete in July 2022. In addition, major avalanches in France are recorded in a central national database, where historical events can be found, forming a baseline for avalanche activity in the area. Planned monitoring comprises both physical visits, drone flights and instrument installations. Following a snow Lidar mapping flight in February 2023, snow-height measuring device is installed in the summer 2023. A pressure monitoring device mounted on one of the existing snow fences, located in the central side of the avalanche path, will record avalanches hitting this structure. Physical visits to inspect the state of the planted trees and the protective structures will be carried out annually. In addition, there are plans to include the site in a national network of multi-parameter seismic stations, which may record seismicity caused by avalanches, but also potential earthquakes as avalanche triggers. The Society and Economy co-benefits are to be monitored through interview surveys among the important stakeholder groups, such as the tourist business, maintenance company, helicopter company, etc., as well as the public bodies.

Furthermore, there are plans to install further instrumentation, comprising an advanced weather station, measuring a range of climate parameters, automatic snow probes, sensors to monitor snow drift, and cameras to monitor real-time snowpack evolution and weather conditions.

All monitoring activities at the site is the responsibility of the French National Forest Office (ONF) who will also cover the expenses. The monitoring is planned to continue for at least 5 years.

Erill-la-Vall, the Pyrenees, Spain (Annex 6)

Because of previous projects, the site has been monitored since 2007, with equipment expansion in 2009 and in 2021 with PHUSICOS support. The monitoring is all related to the Risk reduction ambit, and consists of a weather station, a micro-seismic network, turbidity- and flow measurements in the main gully, and 5 piezometers in a 55 m deep borehole drilled behind the landslide scarp. In addition, topographic changes are monitored through drone photogrammetry and Lidar surveys twice per year, and extra surveys after extreme precipitation events. These surveys will also capture the evolution of the planted vegetation on the constructed terraces. All physical monitoring data are available through a web platform. Regarding the Risk Reduction ambit, the currently ongoing monitoring activities and instrumentation is fairly complete. Potential improvements could include more parameters on soil- and biodiversity fields, e.g., following the methods and protocols described in Appendix A.

Co-benefits have not yet been well monitored, but interview surveys with stakeholders regarding the Society and Local Economy ambits started in the fall of 2022, and this is planned to proceed in the coming years. CTP is responsible for organising the monitoring activities, whereas the local company ‘Geo-hazard Advisors’ operates all the instrumentation and carries out the physical monitoring. Time limit for the monitoring is not set yet; nevertheless, monitoring is expected to continue for more than 5 years with the measures implemented within PHUSICOS project.

3.3 The Gudbrandsdalen demonstrator case site, Norway

NBS have been implemented at two locations in the valley of Gudbrandsdalen, Norway, both to mitigate against flood risk, and due to several issues, described in Deliverable D2.4, they were implemented late in the project, namely in December 2022 and January 2023. Therefore, proper monitoring is only at the planning stage and not established yet.

Øyer, Gudbrandsdalen Valley, Norway (Annex 7)

The planned monitoring is yet to be designed in detail and implemented, but the plans comprise physical inspections and aerial photography at regular intervals, in addition to a crowdsourcing program for the Risk Reduction and Technical& Feasibility ambits. Furthermore, the plans involve automatic logging of water level and turbidity in the stream. For the Environment & Ecosystem ambits, water sampling with analyses of total organic carbon and nutrients, and investigations of the faunal state in the stream are planned along with regular visual inspection of the growth of the planted and natural vegetation along the creek and in the two test fields. The societal ambit will be handled through interviews with stakeholders, in particular involving the inhabitants in the new family housing at the site.

The frequency and the duration of the activities have not be decided yet. The Innlandet County Administration is responsible for organising the activities, in close cooperation with Øyer municipality.

Skurdalsåa, Gudbrandsdalen Valley, Norway (Annex 8)

As for the Øyer site, the NBS monitoring in Skurdalsåa is not currently working and, thus, it is only at the planning stage. The plans have many of the same elements as in Øyer, with crowd sourcing and physical inspection visits, to monitor erosion and deposition along the river, and the condition and operation of the newly modified old dam. Automated logging of water level and turbidity, as well as analyses through water samples are other aspects under consideration. As the interventions significantly modify the littoral zone of the lake, increasing the difference between maximum and minimum lake level, investigations of the benthic fauna, water plants and zooplankton should be done regularly. Specifically, a 3-year frequency is considered effective. The societal ambit will be monitored through interviews with the most important stakeholders, including the inhabitants along the flood-prone river, the cabin owners by the affected lake, and others using the watershed for recreational purposes. Farmers using the lake for irrigation purposes is a relevant stakeholder group, as well.

As for the case in Øyer, the Innlandet County Administration is responsible for organising the monitoring activities, which will be carried out in close cooperation with both Sør-Fron municipality and the local dam cooperative, which is the owner of the dam.

In the following Table 1, the main features of monitoring activities at each site are reported.

Table 1 – Features of monitoring activities at PHUSICOS demonstrator cases

Demonstrator Case	Site	Ongoing monitoring activities	Planned monitoring activities	Monitoring duration beyond PHUSICOS	Responsible of monitoring	Monitoring current implementation stage	Deliverable D4.7 Annex
Serchio River (Italy)	Serchio River (Italy)	Sampling campaigns (since 10/2020); monitoring via probes (since 04/2021); geographical measurements (since 2018); interviews (since 2018)	Sampling campaigns; monitoring via probes; geophysical surveys and analyses of satellite data, interviews	5 years	ADBS		2
Pyrenees (France and Spain)	Santa Elena (Spain)	Web-camera monitoring (since 08/2022); regular inspections, drone flyghts; interviews	Web-camera monitoring (since 08/2022)	5 years	CTP, Regional local authorities, EGTC Pireneos-Pyrénées		3
	Artouste (France)	Visual inspections	Visual inspections; interview surveys	10 years (Risk Reduction assessment) ; 5 years (Co-Benefits assessment)	EGTC Pireneos-Pyrénés		4
	Capet Forest (France)	Visit inspections; replant; snow lidar mapping (02/2023)	Physical visits, drone flights and instrument installations; climatic parameters measurement; interview surveys	5 years	French National Forest Office (ONF)		5
	Erill-la-Vall (Spain)	Weather station recording; micro-seismic network assessment; turbidity and flow measurements; drone photogrammetry and Lidar surveys; interview surveys	Weather station recording; micro-seismic network assessment; turbidity and flow measurements ; drone photogrammetry and Lidar surveys; interview surveys	5 years	CTP		6
Gudbrands-dalen (Norway)	Øyer	*Not performed yet*	physical inspections and aerial photography; automatic logging of water level and turbidity; water sampling; investigation of	*Not defined*	Innlandet County Administration and Øyer municipality		7

Demonstrator Case	Site	Ongoing monitoring activities	Planned monitoring activities	Monitoring duration beyond PHUSICOS	Responsible of monitoring	Monitoring current implementation stage	Deliverable D4.7 Annex
			fauna stage; interviews				
	Skurdalsåa	*Not performed yet*	Erosion monitoring; water level and turbidity; investigations of the benthic fauna, water plants and zooplankton; interviews	3 years	Innlandet County Administration; Sør-Fron municipality; Local dam municipality		8

	Not implemented yet
	Early-stage of implementation
	Medium stage of implementation
	High stage of implementation
	Advanced stage of implementation

3.4 Final comments for the monitoring at the demonstrator case sites

Mainly due to the late implementation of most interventions, almost all the important monitoring have to be performed beyond PHUSICOS project. In fact, only at the Italian site, the Serchio River Basin/Lake Massaciuccoli and at the Pyreneean site Erill-la-Vall, monitoring has been ongoing for enough time and data have been acquired during the project. All sites have plans for monitoring during several years to come, mainly following the assessment framework developed by PHUSICOS WP4 and reported in D4.1, with specific reference to the selected indicators and parameters included in the plans.

The delays in NBS implementation have several reasons, as widely discussed in other deliverables (e.g. D2.4). Nevertheless this is a unfortunate, as project funding is no longer available to arrange and follow up the planned monitoring. Therefore, the monitoring activities to be performed are dependent on the dedication and, more importantly, the funding (external to the PHUSICOS project) of the organisations and the public bodies involved. The latter is also strictly related to the local or regional political context for the allocation and the prioritization of financial resources. Therefore, it is fair to state that, despite good plans, the degree of monitoring to be performed at some of the locations described in this report in the years to come is somewhat uncertain. This is an important learning point. Plans for monitoring must be specific and detailed at an early stage in the planning of NBS interventions. The costs of the monitoring activities must be budgeted for, and responsibilities must be clearly distributed from an early stage. This would enable the required instrumentation to be purchased and installed as soon as practically possible and analyses and other activities started for the earliest stage, also considering the depreciation rate of the equipment supply within research projects.

4 Monitoring Sheet Template

The monitoring template framework was developed to collect all the information concerning ongoing monitoring activities and potential monitoring activities that site owners and their consultants would be carrying out after PHUSICOS end (Annex 1).

It shows a simple structure, including in the first column the monitoring goals and objectives, such as the Ambit from the PHUSICOS framework assessment tool the related monitoring activities work within and their beneficiaries. The second column concern the ongoing activities and the potential actions already done for monitoring (i.e. the used instrumentations and their location) with the detection of the responsible person and eventually data collection (type of data, time series, frequency).

The following columns concern potential future monitoring activities, are related to the monitoring goals in first column (Goal 1, 2, 3...etc.). Specifically, they specify whether new activities are going to be performed, with specific reference to the data collection, the roles and the responsibilities, the added value to be provided and the communication plan to be activated. Namely, information on the location and technical features of new monitoring stations are required, the frequency of data collection, the fundings of the instruments' financing and management, the adding value predicted to be achieved. Methods on how the activities will be disseminated, publicized and shared will be finally provided.

Following the above-mentioned structure and thanks to the site owners, the facilitators and the PHUSICOS partners, for each case study the tables in Annex 1 have been arranged. They certainly can be intended as a starting point, strictly based on the data currently available, for the arrangement of structured monitoring plans useful to assess the benefits/detrimental aspects of the NBS solutions developed in the frame of PHUSICOS project.

Annex 1. Monitoring sheet template.

Monitoring goals and objectives		**Ongoing or completed monitoring activities**		**New monitoring activities**						
				Parameters and indicators to be monitored	**Monitoring techniques**	**Data collection**		**Roles and Responsibilities**	**Added value**	**Communication plan**
Ambit*	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Ambit 1	*Goal 1*	*Activity 1*	*Data 1*	*Parameter 1*	*Method 1*	*Station 1*	*Data 1*	*Role 1*	*Evaluation 1*	
					Method 2					
					…					
			Data 2	*Parameter 2*						
			Data 3	*Parameter 3*						
			…	…						

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities						
				Parameters and indicators to be monitored	Monitoring techniques	Data collection		Roles and Responsibilities	Added value	Communication plan
*Ambit**	*What are we going to monitor? Who will benefit from monitoring activities?*	*Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities*	*Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)*	*Which and how many parameters to be monitored?*	*Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)*	*Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features*	*How frequently data should be collected? Please provide some information about*	*Who does what? Who is going to pay for these activities? Please provide some information or suggestions about*	*Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about*	*To whom will this information be disclosed? What channels will be used to communicate it?*
		Activity 2								
		Activity 3								
		…								
	Goal 2									
	Goal 3									
	…									

**Ambits: Risk reduction; Technical & Feasibility Aspects; Environment & Ecosystem; Society; Local Economy.*

Annex 2. Serchio River DC, Italy.

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities: Parameters and indicators to be monitored	Monitoring techniques	Data collection		Roles and Responsibilities	Added value	Communication plan
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk Reduction / Environment & Ecosystem	*Manual sampling to monitor chemical and physical parameters of the water*	*17 monitoring stations in the south-east area of Lake Massaciuccoli*	*Starting date: October 2020* *Manual sampling: every 15 days* *Calibration probes: every 4 months* *Parameters:* • *Water level* • *Ph* • *Temperature* • *Conductivity* • *Redox potential* • *Dissolved O2* • *Turbidity* • *Nitrate* • *Ammonium* • *Trace elements*	*Monitored parameters (Column 4)*	*Direct monitoring*	*No movement of stations currently serviceable is foreseen* *Improve data organization through the implementation of a single infrastructure for the data collection from all monitoring stations and ground surveys*	*Minimum frequency of 15 days*	*ADBS/UNIPI*	*Increasing the length of the time series results in a better understanding of the critical issues and medium-term effectiveness of NBSs* *Creating a single repository of all monitoring data allows for easier and more effective analyses, aimed at assessing trends and correlations*	*Local authorities, farmers, population, local association, technicians, scholars* *Web-platform*
Risk Reduction / Environment & Ecosystem	*Continuous monitoring of:* • *chemical and physical parameters of the water* • *solid transport* • *rainfall events* • *velocity and water depth*	*Installation, calibration and maintenance of n. 4 (+2 during installation) monitoring stations using HydroLab HL-7 multiparameter probes, 24Ghz Doppler radar rain gauge* *4 monitoring stations + 1 rainfall station are located in Studiati area; 2 monitoring probes are located in the sedimentation basin* *Dashboard arrangement for the presentation of monitoring data*	*Starting date: April 2021* *Sampling: every 15/30 minutes* *Calibration probes: every 3 months* *Parameters* • *Ph* • *Temperature* • *Conductivity* • *Redox potential* • *Hach LDO dissolved oxygen* • *Nitrate ion NO3-* • *NH4+ ammonium ion* • *Turbidity* • *Rainfall classes: rain, snow, sleet, rain, frost, hail* • *Droplet size: from 0.3 to 5 mm with 11 classes of 0.5 mm each* • *Rainfall intensity: 0.01 to 200 mm/h* • *Particle velocity: 0.9 to 15.5 m/s* • *Hydrometric level*	*Monitored parameters (Column 4)*	*Direct monitoring*	*No movement of stations currently serviceable is foreseen* *Improve data organization through the implementation of a single infrastructure for the data collection from all monitoring stations and ground surveys*	*Minimum frequency of 15 min*	*ADBS/UNIPI*	*Increasing the length of the time series results in a better understanding of the critical issues and medium-term effectiveness of NBSs* *Creating a single repository of all monitoring data allows for easier and more effective analyses, aimed at assessing trends and correlations*	*Local authorities, farmers, population, local association, technicians, scholars* *Web-platform*

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities						
				Parameters and indicators to be monitored	**Monitoring techniques**	**Data collection**		**Roles and Responsibilities**	**Added value**	**Communication plan**
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk Reduction	*Land Subsidence in the Massaciuccoli area.* • *Public and academic entities, Stakeholders (Habitants, Farmers, Valley Authorities, Municipalities, University Departments,…).*	*Differential surface elevation measurements through* ***high precision topographic levelling*** *technique.* *Measurements have been carried out through fieldwork activities by using GNSS and digital level along loops of benchmarks.* *The responsible for the monitoring activities is, at present, the University of Siena, Centre of GeoTechnologies (CGT).*	*Multitemporal numerical measurements (every three months since 2021) of benchmarks.*	*Ground displacements (land subsidence in the Massaciuccoli area)*	***High precision topographic levelling*** *for differential surface elevation measurement.* *Measurements can be carried out through fieldwork activities by using GNSS and digital level along loops of benchmarks.*	*No monitoring stations are required.* *The installation of artificial benchmarks should be considered in absence of natural stable elements.*	*Every three months.*	*University of Siena, Centre of GeoTechnologies (CGT)* *Autorità di Bacino Distrettuale dell'Appennino Settentrionale.* *It requires the work of n.3 operators in order to carry out the fieldwork activities and measurements.*	*The high precision levelling survey can be carried out to monitor specific areas that requires a deeper analysis for particular land subsidence conditions (e.g., anomalies from the normal seasonal and artificial trends).*	*Population, Farmers, Valley Authorities, Municipalities, Scholars*
Risk Reduction	*Relative and absolute (considering a reference stable point) land subsidence (mm/year) in the Massaciuccoli area.* • *Public and academic entities, Stakeholders (Habitants, Farmers, Valley Authorities, Municipalities, University Departments,…).*	***Persistent Scatterers radar Interferometry (PSI)*** *from Dec2019 to Oct2022. The analysis has been carried out through a powerful desktop PC, with Ubuntu operating system installed, and the following software: SNAP, Matlab and the Snap2stamps package (python scripts - https://github.com/mdelgadoblasco/snap2stamps). For the output analysis a GIS (Geographic Information System) software such as ESRI ArcGIS or QGis are necessary (Windows system).* *The responsible for the monitoring activities is, at present, the University of Siena, Centre of GeoTechnologies (CGT).*	• *Copernicus – Sentinel satellite imagery 1A (Dec'19-Oct'22) and 1B (Dec'19-Dec'21), ascending and descending orbits, 4 images per month. The satellite imagery is available freely at: https://search.asf.alaska.edu/#/ .* *Geodatabase containing the processed images and the analysed PS.*	*Ground displacements along the LOS (mm/year) carried out through the PSI analysis.*	***Persistent Scatterers radar Interferometry (PSI)****.* *The analysis can be carried out through a powerful desktop PC, with Ubuntu operating system installed, and the following software: SNAP, Matlab and the Snap2stamps package (python scripts - https://github.com/mdelgadoblasco/snap2stamps). For the output analysis a GIS (Geographic Information System) software such as ESRI ArcGIS or QGis are necessary (Windows system).*	*No monitoring stations are required.* *The use of metallic artificial targets (persistent scatterers) can be evaluated in absence of other elements.*	*Satellite imagery from 1A and 1B Sentinel – Copernicus (ascending and descending) is available with a frequency of 4 images per month for free.* *https://search.asf.alaska.edu/#/*	*University of Siena, Centre of GeoTechnologies (CGT)* *Autorità di Bacino Distrettuale dell'Appennino Settentrionale.* *It requires personnel (n.1 operator) with knowledge of python scripts, Matlab, GIS and interferometric techniques.*	*The PSI analysis allows to monitor the subsidence remotely (in lab), for a large area, and can be compared with results provided by the high precision topographic levelling.*	*Population, Farmers, Valley Authorities, Municipalities, Scholars*

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities						
				Parameters and indicators to be monitored	**Monitoring techniques**	**Data collection**		**Roles and Responsibilities**	**Added value**	**Communication plan**
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk Reduction / Environment & Ecosystem	*Vegetations and crops conditions, suspension in water along canals (for erosional studies).* • *Public and academic entities, Stakeholders (Habitants, Farmers, Valley Authorities, Municipalities, University Departments,…).*	***UAV surveys*** *were conducted periodically (with several sensors, such as RGB, multispectral and hyperspectral) in order to create not only multitemporal DEMs and orthophotos but also with the purpose of evaluating the vegetation/crops conditions, the SMI-Soil Moisture Index and the suspended content in water canals nearby farms. The data processing was carried out using multiple software, such as Metashape, Parge and ENVI (Windows systems).* *The responsible for the monitoring activities is, at present, the University of Siena, Centre of GeoTechnologies (CGT).*	*Multitemporal UAV surveys, DEMs and orthophotos acquired by means of RGB, multispectral and hyperspectral sensors.*	*Vegetations and crops conditions, suspension in water along canals (for erosional studies), soil organic content, chemical water content and morphologic/topographic variations by photogrammetric and LiDAR surveys.*	***UAV surveys*** *can be carried out periodically (with several sensors, such as RGB, multispectral and hyperspectral) in order to create not only multitemporal DEMs and orthophotos but also with the purpose of evaluating the vegetation/crops conditions, the SMI-Soil Moisture Index, and the suspended content in water canals nearby farms. The data processing should be carried out using multiple software, such as Metashape, Parge and ENVI (Windows systems).*	*No monitoring stations are required. The use of artificial targets can be necessary for data processing and georeferencing.*	*Dependent on vegetation/crops seasonal growing and related water level in canals.*	*University of Siena, Centre of GeoTechnologies (CGT) – acquisition and pre-processing University of Pisa (UniPI) – additional processing and results analysis. It requires the work of n.3 operators in order to carry out the fieldwork activities and measurements.*	*UAV surveys allow to carry out multiple qualitative evaluations and to obtain photogrammetric outputs using several and different mounted active and passive sensors (e.g., RGB, multispectral, hyperspectral, thermal and LiDAR). The use of UAVs for these surveys is versatile and adaptable to a wide range of objectives.*	*Population, Farmers, Valley Authorities, Municipalities, Scholars*
Risk Reduction	*3D models, DEMs and DTMs for topographic and geomorphological application.* • *Public and academic entities, Stakeholders (Habitants, Farmers, Valley Authorities, Municipalities, University Departments,…)*	***An autogyro/gyroplane*** *survey was conducted in 2018 for mapping the terrain (through DEM and orthophoto) before the "buffer strips" installation. The photogrammetric cameras allow to reconstruct very high resolution 3D digital models that find their main application in the topographic and geomorphological field.* *The responsible for the autogyro survey is, at present, the University of Siena, Centre of GeoTechnologies (CGT).*	*DEM, DTM and orthophoto of the entire research area of the Phusicos Project produced by data acquired from an autogyro/gyroplane survey.*							

Monitoring goals and objectives		**Ongoing or completed monitoring activities**		**New monitoring activities**						
				Parameters and indicators to be monitored	**Monitoring techniques**	**Data collection**		**Roles and Responsibilities**	**Added value**	**Communication plan**
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk Reduction				*Soil geochemical and physical characteristics.*	***Laboratory analyses*** *can be performed on soils of areas of interest. Few examples of analyses that could be carried out:* ***Physical analyses*** *- Textural and granulometric analysis.* *- Analysis of soil water content.* *- Determination of Atterberg Limits.* *- Calculation of the Activity Index, Consistency Index and determination of the land workability and trafficability.* ***Geochemical analyses*** *Determination of soil pH, electrical conductivity, nitrogen and phosphorus content and Organic Matter.*	*No monitoring stations are required.*	*The soil of areas to be analysed can be sampled with a frequency depending on the study objectives.*	*University of Siena, Centre of GeoTechnologies (CGT)*	*The main evaluations that could be carried out through these analyses are the relationships between subsidence and soil types.*	
Society / Local Economy	*Living Labs Activities*	*Workshops with the main stakeholders (May 2018)*	*Number and type of participants; Production of dissemination and informative tools*	*Activities progression*	*Number and typology of participants*			*ADBS*	*Increase knowledge and awareness of the implementation and use of NBSs*	*Local authorities, farmers, population, local association, technicians, scholars* *Web-platform*
		Workshops with freelancers and technicians from public authorities (May 2018)	*Number and type of participants; Production of dissemination and educational tools*	*Activities progression*	*Number and typology of participants*					
		Dissemination activities towards civil society (students of various levels and ages, etc.) (May 2018)	*Number and type of participants; Production of educational tools*	*Activities progression*	*Number and typology of participants*					
	New jobs	*Interviews with operators and farmers and ISTAT classification (March 2023)*								
	Sale harvest from buffer strips and cover crops	*Interviews with operators and farmers (March 2023)*								
	Increase in tourism	*Interviews with Tourist Info Point operators and ISTAT classification (March 2023)*								

Annex 3. Santa Elena case study, Pyrenees DC, Spain.

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities						
				Parameters and indicators to be monitored	Monitoring techniques	Data collection		Roles and Responsibilities	Added value	Communication plan
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk Reduction	*Erosion*	*A webcam, mounted on August 2022 to follow the construction of the NBS, on a pole on the opposite side of the road, covers the slope and the road below*	*Starting date: August 2022* *Filming frequency: every 5 minutes* *Parameters:* • *Stability of protection system*	*Volume and particle-size classification of mobilized materials*	*Direct monitoring through visual inspections of blocks on the terraces and on the road* *Drone flights for detailed topographic mapping*	*No monitoring stations are required.*	*Minimum frequency of 15 days*	*CTP in cooperation with regional road authority cleaning the road routinely, for regular reports based on visual inspection*		*Local authorities, population, local association, tourists, commuters* *Web-site*
Environment & Ecosystem	*Plant growth*	*A webcam, mounted on August 2022 to follow the construction of the NBS, on a pole on the opposite side of the road, covers the slope and the road below*	*Starting date: August 2022* *Filming frequency: every 5 minutes* *Parameters:* • *Vegetation evolution*	*Stability of vegetation* *Degree of durability and resistance of woods*	*Physical inspections*	*No monitoring stations are required.*	*Once a year at least*	*CTP*	*Clearing of weeds in favour of bushes and trees with deeper roots. Check if repair or replacement is necessary within the expected lifetime of the wooden gabions.*	*Local authorities, population, local association, tourists, commuters* *Web-site*
Society / Economy	*Sense of safety*	*Interviews to commuters and other drivers*	*Starting date: March 2023* *Parameters:* • *Sense of safety*	*Sense of safety* *Status of the measures*	*Interviews*		*Yearly for at least 5 years* *Quarterly for at least 5 years*	*CTP in cooperation with regional road authority*	*Public and private actors involved in road maintenance, natural hazards mitigation and landscape restoration will be invited once a year to visit the site for discussions of replicability.*	*Local authorities, population, local association, tourists, commuters* *Web-site*

Annex 4. Artouste case study, Pyrenees DC, France.

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities						
				Parameters and indicators to be monitored	Monitoring techniques	Data collection		Roles and Responsibilities	Added value	Communication plan
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk Reduction				*Rockfall probability: number of blocks;* • *Size of blocks;* • *Origin and possible trajectory.*	*Direct monitoring through visual inspections*	*No monitoring stations are required.*	*quarterly ordinary visits or in case of extreme conditions or events, for at least 10 years*	*EGTC Pirineos – Pyrénées in cooperation with the public unit for road management*	*NBS effectiveness against rockfall risk*	*Local authorities, population, local association, tourists, commuters* *Web-site*
Risk Reduction				*Visual inspection of the active solutions:* • *Displacement of the structures.* • *Analysis and evaluation of possible failures in the joints (to the ground and between elements of the structure).* • *Wood durability and strength.*	*Direct monitoring through visual inspections*	*No monitoring stations are required.*	*quarterly ordinary visits or in case of extreme conditions or events, for at least 10 years*	*EGTC Pirineos – Pyrénées*		*Local authorities, population, local association, tourists, commuters* *Web-site*
Risk Reduction				*Visual inspection of the passive solutions:* • *Impacts on the structure (height, damage, etc.).* • *Damage or impact on living trees supporting the barrier.*	*Direct monitoring through visual inspections*	*No monitoring stations are required.*	*quarterly ordinary visits or in case of extreme conditions or events, for at least 10 years*	*EGTC Pirineos – Pyrénées*	*Monitoring will mostly consist in regular visual inspections and corresponding reports on the state of the solutions and on the adequate management of the forest, ensuring its healthy state and degree of regeneration*	*Local authorities, population, local association, tourists, commuters* *Web-site*

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities: Parameters and indicators to be monitored	Monitoring techniques	Data collection		Roles and Responsibilities	Added value	Communication plan
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Society / Economy	*Sense of safety*	*Interviews to commuters and other drivers*	*Starting date: March 2023* *Parameters:* • *Sense of safety*	*Sense of safety* *Status of the measures*	*Interviews*		*Yearly for at least 5 years* *Quarterly for at least 5 years*	*EGTC Pireneos-Pyrénées in cooperation with regional road authority*	*Public and private actors involved in road maintenance, natural hazards mitigation and landscape restoration will be invited once a year to visit the site for discussions of replicability.*	*Local authorities, local association, tourists, commuters, local population who work in the area: Pyrenean National Park, Artouste ski resort, Departmental Government, SHEM (Hydroelectric Company of the South).* *Web-site*

Annex 5. Capet Forest case study, Pyrenees DC, France.

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities: Parameters and indicators to be monitored	New monitoring activities: Monitoring techniques	New monitoring activities: Data collection		New monitoring activities: Roles and Responsibilities	New monitoring activities: Added value	New monitoring activities: Communication plan
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk Reduction	*Snow avalanche risk*	*Permanente recording of avalanches in the Institutional avalanche monitoring programmes supported by the Ministry of the Environment*	*Permanent (https://www.avalanches.fr/)*	*Pressure monitoring*	*Instrument mounted on an avalanche fence (grey measure) but which will record avalanches hitting the structure.* [*https://www.onf.fr/onf/+/131f*](https://www.onf.fr/onf/+/131f)	*instrument will be mounted on one of the avalanche fences*	*Minimum frequency of 15 days*	*ONF*	*it will record all avalanches hitting the structure*	*Local authorities, population, local association, tourists* *Web-site*
Environment & Ecosystem	*Plant growth*			*Stability of vegetation Degree of durability and resistance of woods*	*Physical inspections*	*No monitoring stations are required.*	*Once a year at least*	*ONF*	*Maintenance and possible repair of tripods. Yearly monitoring of mortality and recovery after planting, especially in relation to drought.*	*Local authorities, population, local association, tourists* *Web-site*
Society / Economy	*NBS efficiency*	*Interviews (workers, helicopter company, wood companies, etc)*	*Starting date: September 2022 Parameters:* • *Number of workers in NBS construction and implementation*	*Status of the measures*	*Interviews*		*Yearly*	*ONF-RTM with Municipal authorities and technicians*	*To inform about the status of the infrastructures.*	*Local authorities, population, local association, tourists* *Web-site*

Annex 6. Erill-la-Vall case study, Pyrenees DC, Spain.

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities						
				Parameters and indicators to be monitored	**Monitoring techniques**	**Data collection**		**Roles and Responsibilities**	**Added value**	**Communication plan**
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk Reduction	*Erosion*	*All physical monitoring data are available through a web portal (https://service.iotailor.com/dashboard/55ca1e70-7182-11ed-9b45-9b509d11ba72?state=W3sicGFyYW1zIjp7fSwiaWQiOiJkZWZhdWx0In1d&publicId=044e2c70-7caa-11ed-b10e-f1266bddd787) open to the public.* *The topographic changes are routinely monitored through UAV photogrammetry and Lidar survey twice per year.* *flights are done after precipitation events with more than 0.5l/minute or more than 35l/accumulated/event.*	*Starting date: 2007* *Equipment:* • *a weather station;* • *a micro-seismic network;* • *turbidity and flow measurements in the gully* • *5 piezometers installed in a borehole drilled to bedrock behind the landslide scarp, recording to a depth of 15 m.*	*Same as ongoing activities*	*Same as ongoing activities*	*No additional monitoring stations are required.*		*CTP*	*Follow up with annual regular maintenance, and when necessary after events, including labour, hardware and software updates.*	*Local authorities, population, local association, tourists, commuters* *Web-site*
Environment & Ecosystem	*Plant growth*	*The topographic changes are routinely monitored through UAV photogrammetry and Lidar survey.*	*Frequency: twice per year*	*Evolution of the planted and original vegetation; growth, occupied area, etc.*	*Same as ongoing activities*	*No monitoring stations are required.*	*Twice per year*	*CTP*	*Follow up with annual regular maintenance, and when necessary after events, including labour, hardware and software updates.*	*Local authorities, population, local association, tourists, commuters* *Web-site*
Society / Economy	*Sense of safety*	*Interviews to local inhabitants*	*Starting date: March 2023* *Parameters:* *Sense of safety*	*Sense of safety*	*Interviews* *Reports and visits*		*Yearly*	*CTP*	*Neighbours, technicians receive regular reports on the status of the gully. Other interested actors invited to visit (for inspiration).*	*Local authorities, local association, tourists, commuters, local population* *Web-site*

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities: Parameters and indicators to be monitored	Monitoring techniques	Data collection		Roles and Responsibilities	Added value	Communication plan
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Society / Economy	*NBS efficiency*	*Interviews (workers, helicopter company, wood companies, etc)*	*Starting date: September 2022* *Parameters:* • *Number of workers in NBS construction and implementation*	*Evolution of the planted and original vegetation; growth, occupied area, etc.*	*Interviews*		*Yearly*	*Ctp*	*To inform about the status of the infrastructures.*	*Local authorities, population, local association, tourists* *Web-site*

Annex 7. Øyer case study, Gudbrandsdalen Valley, Norway.

Monitoring goals and objectives		**Ongoing or completed monitoring activities**		**New monitoring activities**						
				Parameters and indicators to be monitored	**Monitoring techniques**	**Data collection**		**Roles and Responsibilities**	**Added value**	**Communication plan**
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk reduction / Technical & Feasibility Aspects	*Channel condition monitoring*			*Sediment, debris, erosion, damage*	*Crowdsourcing*	*The whole channel and surrounding area*	*Continuous by e-mail and pictures*	*The municipality receives input from local citizens*	*Evaluate the effect and resilience based on the collected data. This can be done after 5 years.*	*Local authorities, population, local association, tourists* *Web-site*
					Inspections		*After extreme events/flooding that may have damaged the NBS, or every year*	*The municipality implements this in their inspection plan*		
					Remote monitoring (review of aerial photography/photo comparisons)		*Review of aerial photography periodically (every 3 – 5 years, or when a new photogrammetry campaign has been performed)*	*The municipality implements this in their inspection plan*		
Risk reduction	*Water level in the channel*			*Water level*	*Automatic logging*	*Exact location in the creek is yet to be decided*	*Continuously*	*Costs for automatic logger is included in the PHUSICOS budget. Both the municipality and the County will follow up on the data.*	*Evaluate the effect and resilience based on the collected data. This can be done after 5 years, and after a flood event/extreme precipitation etc.*	*Local authorities, population, local association, tourists* *Web-site*
Risk reduction	*Turbidity*			*Turbidity – number of particles in the water.*	*Automatic logging*	*Exact location in the creek is yet to be decided*	*Continuously*	*Costs for automatic logger is included in the PHUSICOS budget. Both the municipality and the County will follow up on the data.*	*Evaluate the effect and resilience based on the collected data. This can be done after 5 years, and after a flood event/extreme precipitation etc.*	

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities: Parameters and indicators to be monitored	Monitoring techniques	Data collection		Roles and Responsibilities	Added value	Communication plan
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Environment & Ecosystem	*Ecological state in the channel*			*TOC (Total organic carbon), nitrogen, phosphorous*	*Water sample*	*On a suitable place in the creek – yet to be decided*	*Yearly*	*The municipality does the sampling. The County is prepared to pay for the analysis.*	*The results will indicate how successful the measure has been as a nature-based solution, and if it has enhanced the biodiversity.*	*Local authorities, population, local association, tourists* *Web-site*
				ASPT- and PIT-index (benthic fauna and invertebrates)	*The method is described in the Norwegian guidebook "classification of environmental state in water", according to the Water Framework Directive*	*On a suitable place in the creek – yet to be decided*	*Every third year*	*A consultancy firm does the sampling and analyse the results. The County is prepared to pay for the analysis.*		
	Revegetation in the test areas			*Growth, species*	*Visual inspection*	*In the test areas*	*Yearly*	*Yet to be decided*	*This will show which species that naturally will re-establish along the creek*	
Society	*Perception of the area*			*Safety, attractiveness, use, future improvements*	*Interviews*	*Inhabitants and possibly other users of the area*	*Every third year*	*The County*	*Will tell us something about how the inhabitants perceive the area with regards to the parameters.*	*Local authorities, population, local association, tourists* *Web-site*

Annex 8. Skurdalsåa case study, Gudbrandsdalen Valley, Norway.

Monitoring goals and objectives		**Ongoing or completed monitoring activities**		**New monitoring activities**						
				Parameters and indicators to be monitored	**Monitoring techniques**	**Data collection**		**Roles and Responsibilities**	**Added value**	**Communication plan**
Ambit	***What are we going to monitor? Who will benefit from monitoring activities?***	***Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities***	***Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)***	***Which and how many parameters to be monitored?***	***Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)***	***Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features***	***How frequently data should be collected? Please provide some information about***	***Who does what? Who is going to pay for these activities? Please provide some information or suggestions about***	***Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about***	***To whom will this information be disclosed? What channels will be used to communicate it?***
Risk reduction	Flood damage along the river	Flood damage along Skurdalsåa River has been registered and digitalised for the big flood events in 2011 and 2013	Map with damage points	Places that experience flood damage	Coordinate different databases and registrations to collect damage points along the river.	Along Skurdalsåa River	After a flood event	Cooperation between the municipality, the County, and the landowners	Compare flood damage before and after implementation of the measure.	*Local authorities, population, local association, tourists* *Web-site*
	Monitoring the condition of the dam			Debris, erosion, damage, water level	Crowdsourcing	Svintjønna Lake, the dam area, and the river downstream	Continuous by e-mail and pictures	Cooperation between the municipality, the County, and the dam owners	Evaluate the effect and resilience based on the collected data. This can be done after 5 years.	
					Inspections		After extreme events/flooding that may have damaged the NBS, or every year	Dam owners		
	Water level			Water level in Skurdalsåa River	Automatic logging	Exact location in the river is yet to be decided	Continuously	Costs for automatic logger is included in the PHUSICOS budget. Both the municipality and the County will follow up on the data.	Evaluate the effect and resilience based on the collected data. This can be done after 5 years, and after a flood event/extreme precipitation etc.	
	Turbidity			Turbidity in Skurdalsåa River						
Environment & Ecosystem	Water quality in Skurdalsåa River	Several parameters have been measured in Skurdalsåa River (TOC, turbidity, phosphorus, nitrogen etc.).	Yes. Results can be found here.	TOC (Total organic carbon), nitrogen, phosphorous	Water sample	On existing measure station. See here.	Yearly	The municipality does the sampling. The County is prepared to pay for the analysis.	Compare results before and after and see if changes can be detected.	*Local authorities, population, local association, tourists* *Web-site*

Monitoring goals and objectives		Ongoing or completed monitoring activities		New monitoring activities: Parameters and indicators to be monitored	New monitoring activities: Monitoring techniques	New monitoring activities: Data collection		New monitoring activities: Roles and Responsibilities	New monitoring activities: Added value	New monitoring activities: Communication plan
Ambit	*What are we going to monitor? Who will benefit from monitoring activities?*	*Do we already have some ongoing/completed monitoring activities? If so, please provide some information about monitoring stations location and technical features, and responsible of monitoring activities*	*Do we already have some data? Please provide some information about data collection (type of data, time series, frequency)*	*Which and how many parameters to be monitored?*	*Which methods and techniques should be adopted to monitor the parameters? Please provide some information about (e.g. direct survey, remote sensing, modelling, etc.)*	*Which and where the new monitoring stations should be installed? Please provide some information about monitoring stations location and technical features*	*How frequently data should be collected? Please provide some information about*	*Who does what? Who is going to pay for these activities? Please provide some information or suggestions about*	*Which evaluations do you plan to carry out with the monitoring of this parameters? What additional value it can provide? Please provide some information about*	*To whom will this information be disclosed? What channels will be used to communicate it?*
Environment & Ecosystem	Changes in the littoral zone in Lake Svintjønna			Benthic fauna, zooplankton, chlorophyll A, water plants (need to look closer on indicators).	Methods are described in the Norwegian guidebook "classification of environmental state in water", according to the Water Framework Directive	In the littoral zone	Every third year	A consultancy firm does the sampling and analyse the results. The County is prepared to pay for the analysis.	Will tell us which effect the measure has on biodiversity in the littoral zone.	*Local authorities, population, local association, tourists* *Web-site*
Society	Perception of the measure			Safety, irrigation, effect on the area around Svintjønna	Interviews	Users (including cabin owners) around Lake Svintjønna and inhabitants along Skurdalsåa River	Every third year	The County	Will tell us something about how the inhabitants perceive the area and the measure with regards to the parameters.	*Local authorities, population, local association, tourists* *Web-site*

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Appendix A

Soil and plant indicators for NBS implemented in the Capet Forest and the Santa Elena roadcut

Contents

A1 Choosing the indicators for monitoring ecosystem processes

A monitoring plan should include an adequate **set of indicators** that must be carefully measured before the NBS is deployed.

Useful and operative indicators should satisfy the following requirements (Doran, 2002; EEA, 2023):

(a) they must inform about key ecosystem processes,
(b) they must integrate physical, chemical, and biological properties,
(c) they must be sensitivity to management and climatic variations,
(d) they must be reliable, reproducible, and applicable to a wide range of sites, and
(e) they must be accessible and practicable for agricultural specialists, producers, conservationists, and policy makers. Accessibility involves the availability of analytical methods, and that the indicator must be interpretable by the end-user.

Due to the great quantity of services provided by soil and given that geological events alter many soil characteristics in the physical, chemical and biological fields, sets of indicators are necessary instead of a single indicator. Indicators they must represent the state of different soil functions referent to the base-line value and to the desired value, that correspond with the value of the indicator in the reference state.

Together with the final value, the expected evolution trend toward recovery should be provided, together with a timeline.

A2 Soil and plant indicators for NBS implemented in the Capet Forest and the Santa Elena roadcut

This appendix focuses on plant and soil functions that provide very relevant co-benefits in the field of climate change mitigation and of habitat for biological activity: carbon storage, nutrient cycling, and habitat for biological activity.

A2.1 Preselection process

Unfortunately, up to now all efforts to procure a universally applicable set of indicators to evaluate NBS proficiency in improving the environmental services provided by the soil-plant system have been in vain.

This is due to the context-dependent condition of soil-plant relationships that are greatly influenced by biogeography, local climate, geology, topography and land use, and also by less conspicuous features such as land use history and landscape structure. Moreover, a myriad of factors affects the ability of plants and soil organisms to colonize newly created or restored areas, i.e., to spread, stablish, and thrive.

Adding to this challenge, even if some indicators can be used universally (e.g., the percentage of plant cover), their optimal reference value and the rate of change in the way from the baseline value to the reference value is again case-specific.

In the PHUSICOS project, the study cases of the Santa Elena roadcut and the Capet Forest are in the same mountain range, and the affected ecosystems share some important attributes such as very adverse topography, mountain climate, instability of the geological substrate, and no exploitation of forests (apart from grazing in the uppermost parts of the Capet Forest).

Therefore, as a first step we drew up a prospective list of soil and plant properties that we studied for their sensitiveness to the maturation of the new soil-plant systems created in the Santa Elena roadcut and of the improved plant cover in the Capet Forest. The list was based on the expertise of the research team and includes the properties shown in Table 1.

These properties were measured in the area of influence of the two NBSs, using a stratified sampling design, which means that we divided the study areas in homogeneous vegetation units according to their state of maturity, and distributed sampling points randomly within each of these units. By doing so, we identified which properties discriminate between maturity stages of the plant-soil system and are therefore useful to inform about the correct maturation of the recreated (in Sta Elena) or improved (in the Capet Forest) systems.

Plant morphological traits and life forms were more indicative of post-operation progress than species composition. Soil biological properties were clearly more sensitive to post-operation ecosystem maturation than soil physical and chemical properties, which suggested that the monitoring program should include indicators based on the soil biota together with functional plant indicators, and that some soil physical and chemical indicators should also be measured to aid to interpret the global progress of the system.

Table 1. *List of soil and plant properties studied in the PHUSICOS project for their potential use as indicators of improved soil and plant services in the study cases of the Santa Elena roadcut and the Capet Forest.*

SECTOR	ECOSYSTEM SERVICE	INDICATOR	Unit
Soil	Belowground C sequestration	Total organic carbon stock (Total C_{org})	$g C . m^{-2}$
		Labile organic carbon (C_{org} in the fast pool)	$g C . m^{-2}$
		Recalcitrant organic carbon (C_{org} in the slow pool)	$g C . m^{-2}$
		Physically protected organic C	%
	Soil physical resilience	Soil erodibility (aggregate stability)	mm
		Soil bulk density	$g cm^{-3}$
	Biodiversity provision	Microbial diversity	
		Microbial species richness	number of species
		Microbial species diversity	unitless
		Microbial species eveness	unitless
		Microbial catabolic diversity	unitless
		Invertebrate functional diversity	
		Flagellates	$mg C g^{-1}$ dry soil
		Amoebae	$mg C g^{-1}$ dry soil
		Ciliates	$mg C g^{-1}$ dry soil
		Total protists	$mg C g^{-1}$ dry soil
		Bacterial feeder nematodes	$mg C g^{-1}$ dry soil
		Fungal feeder nematodes	$mg C g^{-1}$ dry soil
		Plant-feeder nematodes	$mg C g^{-1}$ dry soil
		Omnivore nematodes	$mg C g^{-1}$ dry soil
		Predatory nematodes	$mg C g^{-1}$ dry soil
		Total nematodes	$mg C g^{-1}$ dry soil
		Predatory Mites	$mg C g^{-1}$ dry soil
		Nematophagous Mites	$mg C g^{-1}$ dry soil
		Nematophagous prostigmatic mites	$mg C g^{-1}$ dry soil
		Collembola	$mg C g^{-1}$ dry soil
		Fungivorous cryptostigmatic mites	$mg C g^{-1}$ dry soil
		Fungivorous Prostigmata	$mg C g^{-1}$ dry soil
		Diplura	$mg C g^{-1}$ dry soil
		Symphyla	$mg C g^{-1}$ dry soil
		Protura	$mg C g^{-1}$ dry soil
		Total microarthropods	$mg C g^{-1}$ dry soil
	Biodiversity functions	Carbon mineralization by the soil food web	$g C m^{-2} y^{-1}$
		Theoretical soil food web stability	y^{-1}
Plants	Aboveground C sequestration	Total aboveground carbon stock	$t C ha^{-1}$
	Biodiversity provision & treats	Species richness	number of species
		Species diversity	unitless
		Eveness	unitless
		Invasive species	Number of species
	Soil protection	Soil vegetation cover	%

Plant morphological traits and life forms were more indicative of post-operation progress than species composition. Soil biological properties were clearly more sensitive to post-operation ecosystem maturation than soil physical and chemical properties, which suggested that the monitoring program should include indicators based on the soil biota together with functional plant indicators, and that some soil physical and chemical indicators should also be measured to aid to interpret the global progress of the system.

A2.2 Selected plant and soil indicators

Based on the abovementioned preliminary screening, we combined sensitive plant and soil properties to produce a set of indicators that can be used to monitor both study cases. The final set of indicators is shown in Table 2.

***Table 2**. Soil and plant indicators selected for monitoring the effect of the NBSs implemented in the Capet Forest and Santa Elena cases on soil and plant environmental services.*

	Environmental service provided	
	Climate change mitigation	Biodiversity provision
Plant Indicators		
I.1 Aboveground carbon stock	X	
I.2 Aboveground carbon sequestration	X	
I.3 Total plant cover	X	X
I.4 Woody plant cover	X	X
I.5 Land cover evolution		X
I.6 Mortality and growth of planted saplings		X
I.7 Invasive species		X
Soil physical and chemical indicators		
I.8 Soil organic carbon content	X	
I.9. Carbon sequestration in soil	X	
Soil biological indicators		
I.10 SBQ Index (soil microarthropods)		X
I.11 Taxonomic and functional diversity (soil microbes)		X

A2.2.1 Plant indicators

Nearly 85% of the terrestrial aboveground carbon (C) is stored in forests (Rodger, 1993), which play a key role in the global carbon cycle through retiring a substantial amount of carbon dioxide (Cc) from the atmosphere. C stock in living woody vegetation (shrubs and trees) is the result of the balance between its increase by plant growth and its decrease by cutting or by mortality (Vayreda et al., 2012). When growth surpasses losses, the result is a net CO_2 sequestration; on the contrary, if losses exceed growth, the result is a release of CO_2 to the atmosphere (CO_2 emission).

Both, the C stock and CO_2 sequestration of forests, are indicators of ecosystem services related to climate regulation; the stock, because storing C is a way to maintain CO_2 (a greenhouse gas) out of the atmosphere, and sequestration because forests help to remove CO_2 from the atmosphere and, as a consequence, to reduce the impact of climate change.

- *Sampling method*

Both study sites (Santa Elena and the Capet Forest) should be sampled for aboveground C stocks and CO_2 sequestration in years 2, 4, and 6 after the end of the operations, and every five years thereafter. Samplings should be done in late spring or in summer when there is no snow and there are more hours of sunlight.

In the Capet Forest, 32 sampling plots will be randomly located in in the whole area using a regular net of 100 m × 100 m, in total 32 sampling plots (Fig. 1).

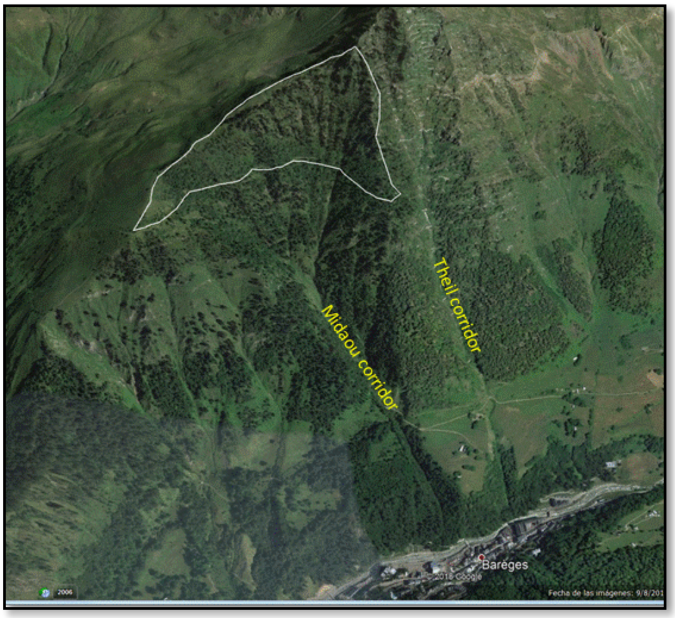

***Figure 1**. Work area in the Capet Forest. The monitoring area is encircled in white.*

Plots will be circular and of 10 m of radius. The centre of the plots will be located with a high precision GPS (less than 5 m of accuracy) in order to find them when they are resampled again in the future.

In Santa Elena, with a small (about 0,05 ha) affected area, 5 of the 10 terraces created in the road cut will be sampled (Fig. 2)

***Figure 2**. Work area in the Santa Elena roadcut. The monitoring area includes ten 2m wide gardeners of decreasing length (from 30 m for the lowest level to about 10m for the top level).*

In every sampling plot (in the Capet Forest) and gardener (in Santa Helena), all trees with a DBH (diameter of trunk at breast height) larger than 7,5 cm within the radius of the plot (distance to the centre corrected for slope) will be measured. For each tree, the DBH (measured with a diameter tape), the height to the top (with a distance metre or equivalent) will be measured and the species noted. In a subplot of 5 meters radius, the number of trees by species will be annotated distinguishing two size classes of regeneration: trees taller than 1 m and DBH < 2,5 cm and trees between 2,5 cm and 7,5 cm of DBH.

For each monitoring campaign, the total aboveground biomass per tree (kg/tree) and per plot is calculated using the equation that relates the tree DBH and height with aboveground biomass. This equation is species-specific, and it can be obtained from https://laboratoriforestal.creaf.cat/allometrapp/. All estimated biomass values are summed to obtain the biomass per plot and multiplied by 31,83 to obtain the value equivalent to one hectare (ratio between one hectare=10.000 m^2 and the area of the sampling plot, r = 10 m, A = 314,16 m^2). Finally, the value is multiplied by 0,5 (1 kg OM = 0,5 kg C) to obtain the C stock (tC ha^{-1}).

The aboveground C sequestration or the C stock change per plot ($t \cdot ha^{-1} \cdot yr^{-1}$) is the difference of the C stocks of two successive forest inventories divided by 5 (years).
The average value of all plots is calculated and multiplied by the area of the study site to obtain the total C stock (tC) and the total C stock change ($tC \cdot yr^{-1}$).

- *Desired evolution of the indicators over time*

In the absence of high intensity disturbances (unsustainable exploitation, snow slides, landslides, windstorms, wildfires, droughts, grazing...), carbon stock is expected to increase over time during the ecological succession until final stabilization. Through the succession process, scrub will replace grassland and trees will replace bushes.

The rate of change is different for the two study sites:

- at the Capet Forest, achieving a deciduous forest (aspen, silver birch, mountain ash) can take about 30 years, and 100 years are necessary to achieve a pine forest. Based on the values measured in reference stands, carbon stocks are expected to be about 7,5 tC ha^{-1} in the 30-year-old deciduous forest stands and about 49 tC ha^{-1} in the 100-year-old pine forests.
- at Santa Elena, 5 years are necessary to achieve a dense bush cover and 60 years to obtain a pine forest. Based on values from reference stands, carbon stocks are expected to be about 1,4 tC ha^{-1} in the 5-year-old *H. ramnoides* cover and about 42 tC ha^{-1} in the 100-year-old pine forests.

A2.2.2 Total plant cover and woody plant cover

Plant cover and its woody fraction play a key role in controlling erosion by intercepting rainfall and improving water infiltration, enhancing soil protection, and carbon sequestration and are considered indicators of water regulation and prevention of snow sliding and soil erosion. Moreover, the proportion of the recalcitrant soil carbon fraction is expected to increase as plant cover increases and includes growing proportions of woody species (Haynes, 2000; Pregitzer & Euskirchen, 2004).

- *Sampling method*

At both study sites, sampling should be done once a year in summer, at the phenological maximum of the plants, and be repeated every year for the first five years, and every five years thereafter.

Plots can be the very same as I.1 and I.2. for the Capet Forest and the Santa Elena roadcut. Total plant cover (including herbs, shrubs and trees) and woody plant cover (shrubs and trees only) will be annotated at each plot. The percentage of total and woody plant cover will be determined by visual estimation (in the field or from aerial photographs if available) of the percentage in vertical projection of the total and woody plant canopy covering the plot area.

- *Desired evolution of the indicators over time*

In the absence of high-intensity disturbances, total and woody plant cover is expected to increase exponentially until final stabilisation.

In the Capet Forest, it will take about 5-10 years to reach > 50% of total plant cover and about 30 years to reach >50% of woody plant cover. In Santa Elena, it will take about 3-5 years to reach >50% of total plant cover and about 5-10 years to achieve >50% of woody plant cover.

A2.2.3 Land cover evolution

Vegetation or land cover maps series over time are a valuable indicator of vegetation dynamics showing temporal changes due to primary or secondary succession, degradation or regression, regeneration or restoration of plant communities (Ichter et al., 2014).

- *Monitoring method*

Vegetation and cover maps will be very useful for monitoring these restoration targets. A vegetation map (with EUNIS habitat types; https://eunis.eea.europa.eu) or a land cover map (with CORINE units; https://land.copernicus.eu/pan-european/corine-land-cover) of both study areas and adjacent zones should be done every five years by photointerpretation of aerial images and completed with the field data obtained from samplings.

The map should include the entire study area and the adjacent zones that can influence or can be influenced by the reforestation (in the Capet Forest) or stabilisation and reforestation (in the Santa Elena roadcut) activities. The map will be useful to calculate changes in vegetation or land cover over time, to detect the evolution of the plantations and the possible impacts (landslides, avalanches, etc.).

- *Desired evolution of the indicators over time*

In the absence of high-intensity disturbance, sallow thorn (*Hippophae rhamnoides*) scrub and then a pine forest is expected to cover the restored road cut in Santa Elena. Under similar low disturbance conditions, in the Capet Forest area plant communities should evolve over time from reforested prairies at high altitudes to shrubs and pine forests. In addition, if avalanches are minimised by tree plantations, the avalanche corridors will "cicatrize" and will be gradually transformed from shrubs or young trees to mature forest.

The desired rate of change of the communities is the same as for indicators I.3 and I.4.

A2.2.4 Mortality and growth of planted saplings

- *Sampling method*

Both study sites (Santa Elena and the Capet Forest) should be sampled for these two indicators in years 2, 4, and 6 after the end of the operations and every five years thereafter. Sampling should be done in late spring or in summer when there is no snow and there are more hours of sunlight.

At the Capet Forest, all saplings were inventoried just after planting. For monitoring, one of every 4 tripod plantations (large or small collector) will be randomly chosen. In each collector (plantation units under tripods) the number of dead saplings per species will be registered and, for each living sapling, stem diameter (measured with a Vernier calliper 5 cm above the stem base) and height (with measuring tape) will be measured.

At Santa Elena, all planted saplings should be inventoried at the end of the operations, immediately after planting. For every sapling, the inventory will include species name, diameter (measured with a Vernier calliper 5 cm above the stem base) and height (with measuring tape). For monitoring, all saplings will be revisited to measure their diameter and height, noting dead individuals.

At both sites, and for each sampling campaign, the average value of the diameter at the base and the average value of the height of all living seedlings by species will be calculated (at the Capet Forest, this calculation will be done for each collector separately) The average increase in diameter and height per collector and per species will be obtained by comparing two successive sampling campaigns divided by the time (in years) elapsed between them.

The mortality rate (in %) by species (and by collector in the Capet Forest) will be calculated as the ratio between the number of dead saplings and the number of live seedlings from the previous sampling campaign. In the Capet Forest, the average mortality rate per species will be obtained by averaging the values of all collectors.

- *Desired evolution of the indicators over time*

Planted saplings are expected to foster the integration of the worked areas with plant communities covering the neighbouring reference mountains.

The mortality of the planted saplings should be minimized. Up to now, there are no available data about sapling mortality or growth curves of the planted species in the region which makes it impossible to stablish desirable values over time for any of the two indicators. Therefore, data produced from this monitoring will be very valuable to evaluate future restoration plans of plantations in the region.

A2.2.5 Invasive species

Non-native (exotic) plant species richness is negatively related to altitudinal gradients worldwide, and invasive species (species that compete strongly with native species and can alter ecosystem properties) are rare in the montane and subalpine belts of the European mountains. However, anthropogenic impacts and disturbances (roads, urbanised areas, ski resorts, earthworks, etc.) positively influence the invasion of non-native plants along the elevation gradients and in mountain ecosystems (Alexander et al., 2016; Clements et al., 2022). Restoration activities, such as reforestation and terrain stabilisation, can create short-term disturbances that can be exploited by non-native species to colonise and spread in restored habitats and their surroundings.

Once established, even in small proportions, invasive species are very difficult to eradicate and can have significant negative impacts on natural ecosystems, and socio-economic and human well-being.

- *Sampling method*

At both study sites, sampling should be carried out once a year in summer, at flowering peak, and repeated every year for the first five years (when the likelihood of the appearance of exotic species is greater).

At the Capet Forest, monitoring of invasive plants will require visual inspection of all collectors to determine the presence of invasive species.

At Santa Elena, all gardeners should be visually inspected (by walking, binoculars or drone flight) to determine the presence of invasives.

In both cases, the indicator for plant invasion will be expressed as the total number of invasive plant species for each monitoring campaign.

- *Desired evolution of the indicators over time*

In the short term, the likelihood of invasive species becoming established depends primarily on the proximity of propagules and the intensity of disturbance to the colonizable habitat. In any case, the likelihood of the presence of invasive species is low in the first years, and zero in the medium and long term.

A2.2.6 Alert flags and recommendations in the event of a warning

In the Capet Forest, the annual monitoring of the saplings carried out in the previous years (2017-2020) showed that mortality was low (<4%), and that mortality was getting lower year after year. Thus, it is likely that no reinforcement planting is necessary in the future. However, to guarantee higher tree diversity and plant cover, possible differences in mortality by species should be analysed. Unless some snow slide partially destroys a collector, reinforcement plantings will most likely not be necessary.

In Santa Elena, at the time of writing this monitoring plan, there are no data on plant growth and mortality because the road cut has not yet been reforested. If plant survival is very low, a new reinforcement planting will have to be planned. The annual monitoring of the survival rates, the percentage of total and woody cover, and the growth of the remaining saplings according to the species will make it possible to extract conclusions about which species are the most suitable for restoration in case that reinforcement plantings have to be done in the future. In future monitoring, within 5-6 years and yearly during late spring or early summer, it is advisable to replace field sampling with a drone flight to assess changes in woody vegetation cover.

At both study sites, the appearance of more than two exotic species or the presence of one (or more) species with a rapid spread than could compete with the saplings, will require rapid removal of all individuals of alien or invasive species and eradication programs.

A2.3 Soil indicators

Soil monitoring will be scheduled to coincide with plant monitoring, in years 2, 4 and 6 after the end of the operations, and then every five years, both in Santa Helena and the Capet Forest. Sampling campaigns should be conducted preferably in spring when soil and plant activity are high.

For all indicators, soil samples will be taken from the same plots designed for plant monitoring. In the Capet Forest, a 1m^2 square subplot will be delimited in the centre of each of the 32 sampling plots selected for plant monitoring (see 3.1.2.1 (a)), and all soil samples will be taken within this area. In Santa Elena, the same 5 terraces selected for plant monitoring will be sampled for soil. At each of these gardeners, three 1m^2 square subplots will be delimited 10 m away from each other beginning in the centre of each terrace (15 subplots in total). The material required for sample extraction will be specific for each indicator.

A2.3.1 General soil characterization in the Capet Forest and in Santa Elena

A detailed analysis of soil physical, chemical, and biological properties was made by members of the CREAF team in the Capet Forest as part of the description of the base line of the site, before the implementation of the NBS. All soil data are available from our centre upon demand and are also synthetized in Deliverable 4.5 (available from the PHUSICOS Website).

A similar description was made for the soils of the Santa Elena roadcut and the surrounding undisturbed forest areas (the data are available from the same source) before the beginning of the operations. However, unlike in the Capet Forest, where natural soils were not perturbed by works, in the stabilization of the roadcut of Santa Elena the natural soil was destroyed, and the newly created planting boxes were filled with sterile materials and graded aggregates topped with a layer of topsoil of undetermined characteristics and provenance. In the best-case scenario, this mixture might evolve towards a reasonable substrate allowing plant growing and, much later, towards a "technosoil" whose characteristics might be compatible with those of the surrounding soils after many years.

Any case, this mixture of materials should be characterized as soon as possible after the end of the operations to help interpret the evolution of the planted vegetation and to monitor the potential formation of soil in the planting boxes that now cover the roadcut. For this characterization, the same 5 terraces selected for plant monitoring should be sampled for soil. At each of the five terraces, two sampling points will be marked, 10 m away from each other in the centre of the terrace. At each sampling point, soil materials will be sampled at two depths (0-15 cm 20-35 cm) with a soil borer (Fig. 3). The samples will be sent in sealed plastic bags properly labelled to soil expert labs to be analysed for texture, water holding capacity, total and organic carbon, total nitrogen, available phosphorous, main cations, pH, cation exchange capacity, and electric conductivity.

A2.3.2 Soil organic carbon content and carbon sequestration in soil

Soil organic carbon loss is among the main drivers of environmental degradation in Europe and reversing this trend is among the priorities of the European Commission, both in agricultural environments and forests. Soil organic matter plays a central role in maintaining key soil functions and is an essential determinant of soil fertility and resistance against erosion (EC, 2002).

Soil carbon content (a quantity) and carbon sequestration in soil (a process) are different things. Soil carbon content can be directly measured from soil samples. Just as for aboveground carbon, carbon sequestration in soil is calculated by the difference in soil carbon content between two consecutive sampling dates.

Carbon sequestration is more difficult to monitor in soil than aboveground because changes in soil carbon content are slow and because of carbon can migrate vertically though the soil profile and scape to evaluation when working with the uppermost layers only.

- *Sampling and analysis method*

All samples will be taken undisturbed with soil borers of known dimensions, preferably 5 cm in diameter (or in side, depending on the corer shape) and always 15 cm deep (Fig. 3).

***Figure 3**. Soil sampling with two different types of soil corers of squared (5 x 5 cm side) or circular (5 cm diameter) section 15 cm long. Both types of corers can be opened lengthwise to obtain undisturbed soil samples of constant known volume.*

For monitoring purposes, we recommend adopting the same analytical method that was used to assess the baseline of carbon content (see deliverable D4.5). Soil organic carbon was measured from soil samples taken at 0-15 cm depth. Before analysis, the samples were air-dried, homogenized and sieved at < 2mm. The analytical process started with the elimination of all inorganic carbon by acidification of the sample. The resulting product was then totally oxidized by combustion with pure oxygen at about 1000 ºC. The resulting CO_2 was transported by helium, separated in a selective column and measured in an elemental micro-analyser. In laboratory, soil organic carbon content is usually expressed as grams of organic C per gram of dry soil (%C_{org}).

- *Desired evolution of the indicators over time*

Soil carbon content is expected to increase as the restored soil matures in equilibrium with the introduced vegetation, meaning that CO_2 is being sequestered belowground.

- in the Capet Forest, 30 years after the application of the NBS, a deciduous forest of aspen, silver birch and mountain ash should have developed, with soil organic carbon amounting to about 7,5%. In the pine forest that should cover the affected area 100 years after the implementation of the NBS, soil organic carbon content is expected to be about 20%.
- In Santa Elena, 5 years after stabilization, soil organic carbon content should be about 5,5% under a bushy plant cover. 60 years later, under a pine forest, soil C content should be about 10%

The rate of carbon sequestration in soils (as explained for plants) can be obtained by dividing the measured difference between two sampling dates by the number of years that have passed since the last sampling date.

A2.3.3 SBQ Index (for soil microarthropods)

The abundance and biodiversity of belowground organisms is overwhelming. Considering only soil invertebrates, 1 m^2 of soil can shelter up to 12.000 to 311.000 enchytraeids, 1 to 5 x 10^4 collembolans, and 1 to 10 x10^4 oribatid mites (Bardgett & Van Der Putten, 2014) among other less abundant groups. Soil fauna plays a key role in maintaining soil health and multifunctionality, as well as providing ecosystem services throughout processes such as organic matter shredding translocation and decomposition, soil structure formation, water regulation and nutrient cycling (Menta et al., 2020). Evaluating the whole soil diversity at the level species is almost impossible in practice at we prefer to work at the level of functional groups or of functional traits (Fig. 4). Some of these groups are extremely adapted to specific belowground conditions and therefore are highly sensitive to changes in soil quality (Delgado-Baquerizo et al., 2020).

- *Sampling and analysis method*

Soil microarthropods will be extracted from undisturbed soil samples 5 cm in diameter and 15 cm long by using batteries of Berlese funnels (Fig. 5). Each soil sample is placed on a screen (mesh size equal to 2 mm) at the top of a funnel and an incandescent light bulb (40-60 Watts) is placed about 30 cm above the sample. As the sample dries out soil animals are stimulated to move downward which eventually causes the soil animals to fall through the sieve into a container with a preservative solution usually consisting in 75% alcohol mixed with water or glycerol. The extraction can take about 7 days. Active funnels must be protected from drafts by protecting them into closed rooms.

From the observation, classification and counting of the extracted specimens at diverse resolution levels (ranging from total number of individuals to number of individuals of a particular species) under a stereomicroscope different index can be calculated.

For monitoring the effect of the NBSs applied in Santa Elena and the Capet Forest on soil microarthropod biodiversity, we propose the computation of the QBS index.

***Figure 4**. Some examples of the diverse morphotypes of soil mites (in the circle; D.E. Walter. https://beta.abmi.ca/biobrowser/species-group/mites-intro.html) and collembolans (in the rectangles; Andy Murray, https://www.chaosofdelight.org)*

From the observation, classification and counting of the extracted specimens at diverse resolution levels (ranging from total number of individuals to number of individuals of a particular species) under a stereomicroscope different index can be calculated.

For monitoring the effect of the NBS applied in Santa Elena and the Capet Forest on soil microarthropod biodiversity, we propose the computation of the QBS index.

***Figure 5**. Berlese funnels used to extract microarthropods from undisturbed soil samples. Source http://soilbugs.massey.ac.nz/collection_berlese.php*

All extracted specimens are observed using a stereomicroscope and identified to order level except for Collembola, Diplura, Protura and Myriapoda -at class level-, and Acari -at sub-class-level. Then an EMI (Eco-morphologic index) value is assigned at each group. QBI is calculated by summation of all EMI values. All details about the calculation of the QBI can be found in Parisi et al., (2005) and Menta et al. (2018).

The QBS index assumes that the higher the soil quality, the higher the number of microarthropod groups well adapted to soil habitats will be. Adaptation can this be assessed from the presence of diverse morphological characteristics, including reduction or loss of pigmentation and visual organs, reduced appendages (as antennae or legs), thinner cuticle, absence of organs adapted to jumping, etc.

- *Desired evolution of the indicators over time*

As the restored system matures and soil quality grows, the value of the QBS is expected to increase.

Soil microarthropods were extracted from samples taken from 5-year-old and 60-year soil reference systems in the Santa Elena zone, and from 30-year-old and 100-year-old reference systems in the Capet Forest during the assessment of the base line of soil quality before the implementation of the NBSs. The results are being processed to provide reference values and rates of change for the two case studies as soon as possible.

A2.3.4 Soil microbial taxonomic and functional diversity

Soil microbial communities play a pivotal role in terrestrial ecosystems by reintegrating the essential nutrients into biogeochemical cycles, by regulating the quality of the atmosphere and the hydrosphere, by reinforcing plant resilience and by influencing the composition of plant communities by altering competitive relationship between species (Nannipieri et al., 2003). The diversity of functions performed by microorganisms within ecosystems has been recognized as the missing link between biodiversity patterns and ecosystem functions. There is an increasing recognition that patterns of functional diversity may provide a more powerful test of theory than taxonomic richness.

Among a variety of analytical approaches to soil microbial diversity (Orgiazzi et al., 2015), metagenomic analysis provides a powerful tool for studying soil microbial functional capacities. Among all available metagenomics techniques, "Shotgun Metagenome Sequencing" reveals taxonomic profiling (diversity and abundance), as well as functional attributes of soil microbial communities. Functional gene analysis is included in the list of powerful indicators aimed to monitor soil biodiversity and ecosystem function across Europe.

- *Sampling and analysis method*

Metagenomic analyses are performed by expert companies that must be contacted sufficiently in advance of sampling campaigns to agree about the shipment of soil samples in a safe way. The company must be required to provide bioinformatic processing of the raw data.

Soil samples (about 40 gr each) are extracted from the top 15 cm of the soil with sterile individual sampling kits (ideally those used in medicine for stool analyses, Fig. 6) to prevent cross contamination between samples, and kept refrigerated until prompt shipment to the laboratory. If shipment is not immediate, the samples must be stored at a temperature below -20ºC.

***Figure 6**. Sampling kit (sterile spoon and container) for soil samples allocated to microbial DNA analyses.*

Shotgun analyses are recommended to make monitoring data comparable to those produced during the assessment of the baseline in both study cases.

- *Desired evolution of the indicators over time*

Despite being of great diagnostic value, this indicator is not easy to interpret in the absence of experts. The functional composition of the soil microbiota is expected to converge with that described for the reference systems (i.e., birch groves, tall brushes and pine forests) during the assessment of the baseline at both study sites (Fig. 7). All microbial data are available from the CREAF team if required for monitoring.

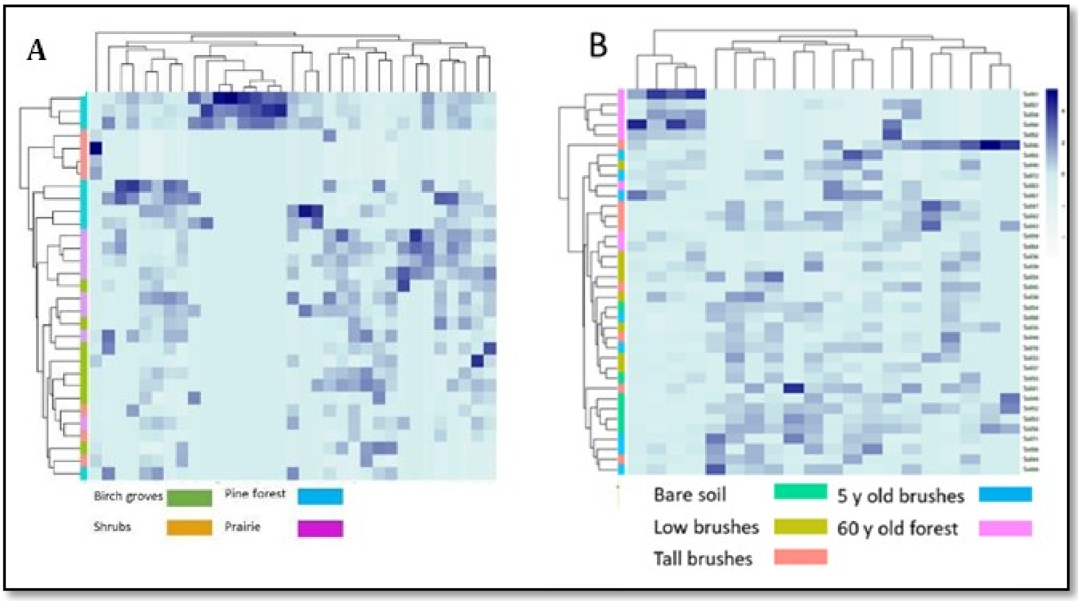

Figure7*. Microbial community characterization of soil under different plant communities in the Capet Forest (A) and the Santa Elena (B) sites during the assessment of the preoperational baseline.*

A3 Concluding remarks

Monitoring is a crucial part of NBS projects under a framework of adaptative management since it alerts about potential deviations of the effected environment from the desired evolution. Monitoring also allows learning from rights and wrongs, which is the only way to progressively improve practices.

Monitoring is also necessary to progress towards NBS standards and certifications, the lack of which is one of the main barriers for the widespread adoption of NBSs.
Monitoring programs require measuring specific indicators before implementing any NBS and periodically well after it has been implemented. This means that the monitoring plan must we incorporated since the beginning in the NBS project cycle (including the planning phase) and that it must be discussed with all social actors called to the communication activities carried out in living-labs.

Monitoring has associated costs, especially with environmental indicators are included. Therefore, monitoring costs must be included in the project budget and the responsibility for long-term monitoring must be clarified and guaranteed.

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