Assessment methodologies and mitigation measures for the impacts of road projects on soils – ROADSOIL

Guidelines for soil management in road projects

- best practice for protecting soils and mitigating impacts during road planning, construction and road operation

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Assessment methodologies and mitigation measures for the impacts of road projects on soils – ROADSOIL

D7.2 Guidelines for soil management in road projects - best practice for protecting soils and mitigating impacts during road planning, construction and road operation

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Executive summary

Soils provide vital functions and ecosystem services that we all depend on, but land-use changes and global climate change threaten many of those functions and services. Road projects have a vital responsibility in safeguarding and supporting European soils through informed and responsible land-take, reduced soil sealing, reduced soil compaction during construction, and control of potentially contaminated soils. This calls for methods to assess the impact of road projects and for mitigating measures for offsetting, compensating, and minimising the environmental impacts on soil resources.

ROADSOIL guidelines. To address these responsibilities, guidelines were developed in the ROADSOIL project to provide methodologies for assessing and quantifying the impacts of road projects on soils and to outline practical mitigation measures to offset and minimise these impacts. This concerns areas directly affected by land take, areas temporarily used for transport or storage of soils, and areas used for agricultural or ecological compensation based on soil resources from road projects. The guidelines accentuate comprehensive and critical actions and measures in all project phases: including the planning, construction, management and operation phases. The ROADSOIL guidelines may further supplement regional, national and international legislation and other guidelines. However, guidelines have to be adapted to a country's specific conditions. For certain recommendations, a change of policy might be necessary to avoid conflicts with other legislations. For example, the reuse of surplus soil frequently conflicts with the country's waste legislation. Key messages from the guidelines are:

Involve soil expertise. Early involvement of soil experts is critical to achieve successful soil management in road projects when combined with continuity in follow-up. Systems for training and certification of soil experts is recommended combined with in-house training and capacity building in the road administrations and with the contractors to better benefit from the experts. This is a major measure to eliminate a critical bottleneck for future development of sustainable soil management. This also applies to the training of machine operators on-site, where project-specific training has achieved very good results. Given priority, these actions will raise the baseline for soil management and reduce the environmental impact of road projects.

The **soil management plan** as outlined in an Environmental Impact Assessment (EIA) and refined in the detailed planning, is the core of best practice in soil management. The soil management plan explains in detail which measures need to be implemented to avoid, mitigate or compensate for the soil impacts during the road construction process. Quality checks during and after the construction work assures that the soil protection measures have been implemented according to the recommended regulations. It is essential that these plans are adjusted to the soil properties, climate and terrain in the area of road projects, and account for predicted climate change.

Strategies for soil stripping and storage. For reuse in landscaping or in compensation measures**,** topsoil (A-horizon) and subsoil (B-horizon) to be affected by construction work are best stripped and stored in separate stockpiles. Stockpiles are shaped and spaced to ease weed and invasive alien plant management and seeded with a competitive grass cover to maintain soil qualities. Keep land in cultivation for as long as possible before stripping to avoid propagation of unwanted plant species.

Measures to control runoff and manage stormwater are required.

Strategies to reduce soil compaction in landscaping and compensation measures. The risk of soil compaction of both subsoil and topsoil has to be addressed during machine operation, soil handling and storage. Basic principles to prevent compaction include operation of heavy machinery on C-layer soil horizons only, and never on A- or B-horizons unless the soil is frozen or very dry. Strip soil for temporary storage and use construction roads or matting systems for short term use as transport corridors. To prevent machine operation on wet soils and simplify management of machine operations on a day-to-day basis, a decision support system is recommended. The recommended system is based on a decision tree where critical values for soil moisture are presented for a given soil texture and on-site measurement of soil moisture will guide operation of machinery. Information on construction machinery has been added to the Terranimo® toolbox to predict risk of soil compaction, to simplify the planning of earthwork and use of machinery. This approach depends on active use of soil data to inform machine operation and will build awareness and best-practice with contractors.

Strategies for soil reuse and reconstruction. An initial survey of topsoil and subsoil qualities will provide the required information to prioritise soil allocation to different uses, landscaping, agriculture, forestry or urban greening. A list of critical soil parameters to investigate for this step is provided and here soil experts can give valuable input and recommendations. For landscaping and compensation measures, soil profiles are rebuilt horizon by horizon in narrow strips where machine operation on relocated soil is avoided. All driving is done on the C-horizon during reconstruction. Temporary construction roads should be used for mass transport as far as possible. If there are shortages of topsoil, constructed soil can be made on-site from crushed rock blended with organic material and natural mineral soil. Coarser material can be used as drainage layers and contribute to mass balance of the project.

Quantify and monitor road impacts on soils. Road projects affect soils both during construction and during operation. To document these effects and evaluate compensation measures indicators of soil parameters can be monitored over time. A list of indicators (soil organic carbon, pH, total Nitrogen, plant available phosphorus, salinity, soil texture classification, clay, silt and sand content, bulk density) is provided that will capture the state of measurable soil properties and can be used to evaluate the soil function parameters listed in the EIA Directive (compaction, sealing, erosion and organic content). Systematic use of soil data and indicators of soil processes and functions will over time contribute to capacity building and also provide data to improve mapped background information of soil resources in the landscape.

Invasive alien plant species (IAP) and pathogen management. It is critical to assess the occurrence of soil-borne pathogens in the planning phase of soil projects as these may cause quarantine of soil materials for many years. The database run by the European and Mediterranean Plant Protection Organization (EPPO) provides relevant information about such threats. Spread of IAP is a threat to biodiversity and numerous ecosystem services all over Europe. EU regulation and national regulations describe action against defined species. Updated information about IAP occurrence is needed in the planning phase of all road building projects.

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1 INTRODUCTION

1.1 Scope and context

European soils are under pressure from a complex set of drivers (Stolte et al. 2015). Road projects have a large share of this impact, both in the long and short term, through land-take, soil sealing, and soil compaction during construction, and through pollution and redistribution of potentially contaminated soils in the management and maintenance phase. Key soil concepts used in the guidelines are defined in a separate textbox below (*Soil terminology used in guidelines*). As the natural soil formation is a very slow process (FAO 2019), soil is to be considered a non-renewable resource within a reasonable timeframe, so action is required to halt the loss and degradation of soils. This calls for methods to assess the impact of road projects and for mitigating measures for offsetting, compensating, and minimising the impacts of road projects on soils. Road projects also influence hydrological processes, and rearrangement of drainage systems of sufficient dimensions for climate change is closely linked to soil functions. This involves the process chain from planning and construction to management and maintenance of road projects. To provide tools to achieve some of these, CEDR 2019 launched a call to develop practical guidelines for soil management in road projects. This report presents these guidelines, with a focus on the planning, construction and management phases.

Figure 1. *Soil sealing is a serious impact of road projects on soil. Photo: Silvia Tobias.*

The objectives of these guidelines are to develop methodologies for assessing and quantifying the impacts of road projects on soils and outline practical mitigation measures to offset and minimise these impacts. The guidelines address soil management in

- areas directly affected by land take
- areas temporarily used for transport or storage of soils
- areas used for agricultural or ecological compensation or restoration based on soil resources from road projects.

Here, measures and actions during planning, construction, management, and maintenance of roads are considered, although some of the information is also of use in the earlier phases. Hence, the target audience differs between the subsequent phases from planners and administration to contractors and their staff.

The key issues that will be considered are

- overview of guidelines and soil information for the planning phase
- approaches to soil management plans
- indicators to quantify and monitor impact of road projects on soil functions
- measures to avoid soil compaction
- approaches to relocate soil and rebuild soil profiles for agricultural and ecological compensation measures.

These guidelines present key approaches to soil management in road projects. The reader should be aware that detailed protocols are not possible and would be risky, due to the huge differences in soil and climate between regions, and the large variation in soil characteristics even within a single road construction project. To properly address the local conditions, soil expertise should be included early in the project.

1.2 Existing European guidelines for soil protection on construction sites

Most European countries provide guidelines on soil protection in road construction explaining measures to be taken in the planning phase. Generally, there is no differentiation between soil protection guidelines in road projects and other construction projects. This document specifies precautions for soil protection that are particularly important in the course of a road project. A few examples of guidelines from European countries are mentioned below, an extensive overview is provided by Geiges et al. (2021).

A comprehensive guideline is the United Kingdom's "Construction Code of Practice for the Sustainable Use of Soils on Construction Sites". This document first refers to the legal basis and related guidelines. It then discusses measures to be taken before the start of construction (chapter "Pre-construction planning") as well as follow-up measures (chapter "Soil aftercare"). In the relevant chapters, the document refers to existing standards, for example on the handling of topsoil. The LA 109 “Geology and Soils” (Highway Agency, 2019) specifies the requirements for assessing and reporting the effects of highway projects on geology and soils.

The Swiss guidelines on soil protection in construction projects, published by the confederation (Federal Office for the Environment FOEN, 2015), address different professional sectors. Many regional authorities have published their own guidelines relying on the national guidelines but pointing out regional or local features. In this way, the national guidelines provide uniform minimum criteria of soil protection in construction, and the specifications in the regional guidelines provide those of particularly sensitive local soils.

For road projects in countries that do not provide any soil protection guidelines, the guidelines at hand can serve as general instructions for soil protection in road construction projects. Moreover, in cases where the national guidelines are less specific, these ROADSOIL guidelines can provide additional information. However, soil protection plans need to be adapted to national legislation, local soils, terrain and climate as copy/paste solutions from general recommendations will not be sufficient for implementing relevant procedures. The ROADSOIL guidelines should therefore serve as an inspiration to make more specific national recommendations.

1.3 User guide to guidelines

The guidelines were developed based on current scientific knowledge and accumulated practical experience. These aspects are summarised in the project reports (Geiges et al. 2022a, Geiges et al. 2022b, ten Damme et al. 2023, Nemes et al. 2023, Haraldsen and Tobias 2023). Information from the reports of the CEDR ControlInRoad project (Trognitz and Follak 2018) is also used. Guidelines were then built around key information identified in these reports.

The text is structured according to road project phases: planning and construction phase of road projects, and the operation and maintenance of existing roads (Figure 2). For each of these phases, the guidelines follow the same structure where current challenges are identified, and these will point to specific topics that are treated in turn. For each of these topics how-to approaches and best-practice examples are provided when possible. The different themes can be read independent of the others, and important cross references are included.

To ease understanding of the guidelines, key soil terminology is given in a glossary.

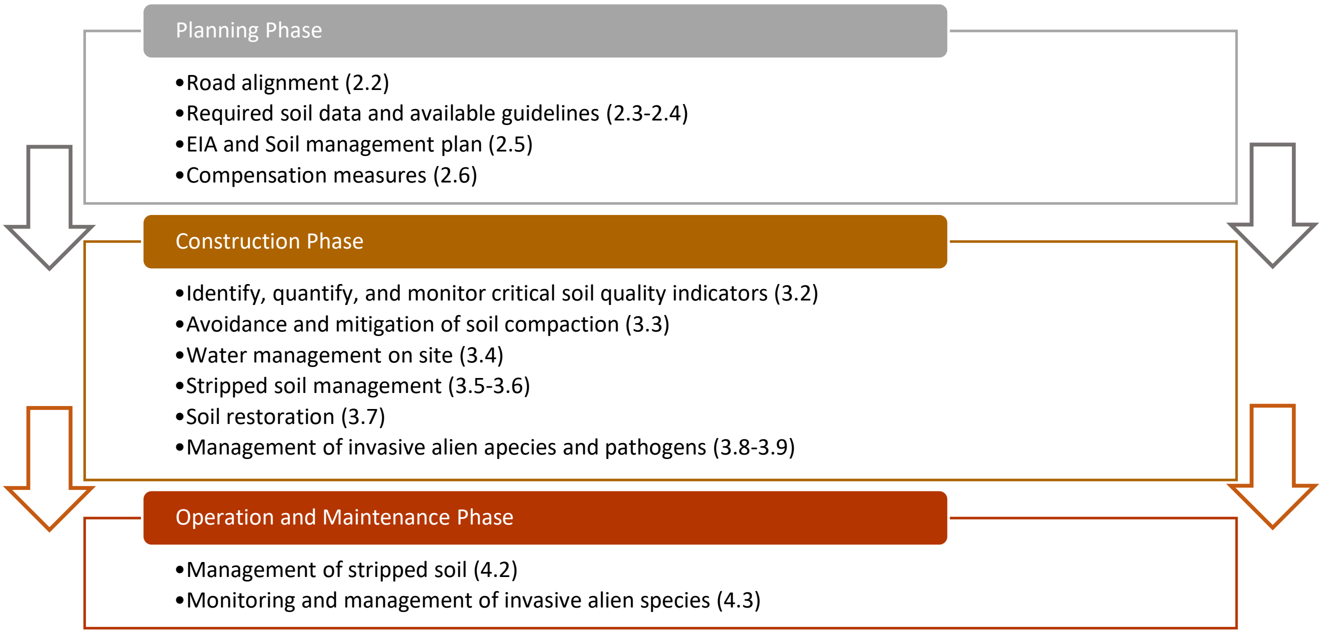


Figure 2: *The different phases of road construction projects and the focus of soil protection measures within each phase that are addressed in these guidelines.*

SOIL TERMINOLOGY USED IN GUIDELINES

Soil – the upper layer of earth composed of mineral material (sand, silt, clay and rock fragments), organic material, air and water where the properties are determined by origin, climate, physical, chemical and biological processes.

Soil compaction - occurs when soil particles are pressed together leading to fewer large pores, less total pore volume and higher density. These changes reduce water infiltration and aeration of the soil and increase the physical resistance to plant root growth.

Soil ecosystem service – based on soil properties, functions, processes and biodiversity, soils contribute a number of provisioning, regulating and supporting ecosystem services to human benefits.

Soil expert – a person that has the expertise and experience to assess soil properties in the field and laboratory. This person additionally has the knowledge to interpret the data in the way that he/she can estimate the soil's susceptibility to erosion, compaction, or decay of organic matter, as well as the performance of the soil functions. Soil experts should be involved in road projects from an early stage on throughout the road planning and construction process and complement the team of engineers, geologists, surface water specialists, ecologists etc.

Soil formation – natural process of soil generation through physical and chemical weathering processes and biological activity; establishment of a soil profile with different layers (soil horizons)

Soil functions - interacting soil processes generate a set of key functions of soils. These are productivity, nutrient cycling, carbon storage, water storage and filtering, and habitat for biological activity. These functions are the basis for the ecosystem services.

Soil moisture – the term soil moisture refers to the water content of the soil, which can be expressed in terms of volume or weight. Its balanced availability together with air in the soil is key to the soil functions. In the context of this report, its presence strongly influences soil strength. It can be measured in-situ or in the laboratory on small samples. It is naturally added by precipitation or run-on from adjacent locations, and it is naturally removed from the soil by e.g., evaporation, plant transpiration, runoff or drainage.

Soil moisture tension - soil water potential or soil moisture tension is a measure of the force per unit area that must be exerted to remove additional water from the soil and is expressed in units of pressure. Soils of different texture have different soil moisture tension vs. soil moisture content characteristics, with sandy soils releasing more water easily, while silty and especially clayey soils holding on to water tightly.

Soil processes - four basic processes occur in soils: (i) gain, (ii) loss, (iii) transformation (change) and (iv) translocation (movement) of material.

Soil profile - the vertical section of the soil from the surface to the parent rock material. The profile separates the different horizonal layers of soil differing in properties depending on soil forming processes.

Soil properties - the combination of physical, chemical and biological properties of the soil. Examples of such properties are texture, structure, porosity, density, aggregate stability (physical), concentrations of specific compounds, pH, soil organic C, cation exchange capacity, salinity (chemical), biodiversity, microbial biomass, soil enzyme activity, and basal respiration (biological)

Soil quality - the capacity of a soil to provide ecosystem services, usually described be indicators of chemical, biological and physical soil properties, processes, and functions.

Soil strength - soil strength refers to the mechanical resistance of the soil to physical stress. It has been widely used to assess the degree of soil compaction and the soils' ability to withstand physical stress (pressure or shear). In the context of this report "**precompression stress**" is used as a measure of the soil's ability to withstand compressive force without structural failure.

Soil texture – the proportion of sand, silt and clay sized particles that make up the mineral fraction of the soil (<2 mm). Sand sized particles can be 1000 times larger than clay sized particles; therefore, different textural compositions can lend vastly different properties to the soil. Coarser material includes gravel (2-60 mm in diameter), stones and rock fragments (60-200 mm in diameter), and boulders and rock fragments (>200 mm).

Soil unsealing - removal of constructed impervious surfaces such as road surfaces and converting the area to alternative land use

Definitions are based on EEA (2016) and Tobias et al., (2018).

2 SOIL MANAGEMENT IN THE ROAD PLANNING PHASE

2.1 Current challenges of soil protection in road planning

A large part of the impact on soil that a road project can cause is already determined with the planning of a road. Therefore, soil protection aspects should be included in all steps of the road planning procedure:

1. The national strategic road planning process
2. Specific road project: identification of route corridors
3. Road Project alignment and design options
4. Road project design with Environmental Impact Assessment (EIA)
5. Road Project approval from the relevant competent planning authority
6. Detailed design and tender preparation.

Section 2.2 explains how to integrate soil protection in the steps of road planning at the appropriate level of detail. However, current road projects in most European countries are rarely about building completely new roads through a natural landscape. The majority of current road projects in Europe include

- road widenings, i.e., adding new lanes to existing roads
- bypasses around villages and towns
- new road sections, such as new motorway feeders, to increase accessibility and distribute traffic on several access roads.

These road projects are usually carried out in densely populated regions with extensive sealed areas, and are often in conflict with other land uses, particularly agriculture. These road projects need careful planning.

In the road planning phase, special attention should be given to soil sealing because, in this phase, it is determined how much soil will be permanently sealed. Soil sealing is the most severe damage to soil and destroys all soil functions. In addition, the process of road construction and operation can cause soil compaction, erosion, contamination, and loss of organic matter. Including aspects of soil protection in the road planning phase means assessing the potential impacts on soil and finding solutions to avoid, mitigate or compensate for them. In this context, particular challenges are:

- Finding alternatives to new soil sealing
- Defining appropriate measures to compensate for new soil sealing
- Selecting the road alignment to avoid sensitive and valuable soil
- Establishing a plan for the management of surplus soil
- Environmental Impact Assessment and soil management plan.

2.2 Planning processes

Road planning includes various steps at different strategic and operational levels at which specific impacts on soil have to be addressed accordingly. Aspects of soil protection should be included at early stages of the road planning process to create the best possible conditions to avoid negative impacts on soil. It is recommended to involve a soil expert in the entire process to advise on soil protection measures for the specific cases. What should be considered in the road planning steps is compiled below:

- **National strategic planning process:**
The national transportation plan indicates the road projects in a country and should respect the national target limits of soil sealing when such limits have been established. It should also strive to achieve the EU target of net zero soil sealing by 2050. Preferably, national transportation plans should already include traffic management strategies as alternatives to road extension (e.g., speed limitation, digital toll stations, road pricing systems). In addition, the national transportation plan should be compatible with other national policy master plans, such as for the preservation of natural habitats, cultural heritage, agricultural or forest land. The Strategic Environment Assessment (SEA) is an appropriate instrument to evaluate the national transportation plan according to these aspects.

- **Identification of route corridors:**
Corridors should be selected based on inventories of natural habitats, landscape qualities, cultural heritage, prime arable land etc. to select the road corridor with the least overall impact. These diverse requirements can however be in conflict. A soil expert can help setting priorities balancing the values of a given land with how difficult it may be to compensate a land-take based on soil data. In the case of road upgrading to eliminate traffic bottlenecks, alternatives to additional soil sealing should be evaluated. If road-widening is the best solution, the management of surplus soil should be carefully planned in the following steps because contaminated soil must be expected (see section 3.5).

- **Alignment and design options:**
This planning step has a crucial influence on how much soil will be affected by a road project and how severe the impact on soil will be. This applies to the road area itself and all surrounding landscaping, including cut and cover and other tunnels. The alignment should avoid soils which are susceptible to compaction (e.g., fine-grained soils) or to loss of organic matter (organic soils, peat soils). Land with these soils should be excluded from terrain modelling or open-cast tunnelling. Conversely, agricultural soils affected by temporal soil storage can often be restored well and should be preferred, although land management options may be limited for several years (see section 3.7 for soil restoration). Compensation for the impact on soil, particularly soil sealing, should be planned at this stage. To reduce net soil sealing, priority should be given to unsealing road sections which can be downgraded or eliminated because of the new road. Other measures should be planned to compensate for the loss of agricultural (or forest) land or natural habitats. More detail about compensation measures is given in section 2.6.

- **Project design with Environmental Impact Assessment (EIA):**
This step of the road planning procedure is crucial for soil protection because the soil protection measures are specified here in a binding manner. In a thorough EIA, the specific impacts on soil due to the planned road project are assessed, although in some countries these details are developed later in the

project. The total mass balance calculation is normally included in the total plan for the road projects. Based on this a separate soil management plan which should include the calculation of the volume of soil that will be temporarily stored, and the surplus soil that has to be reused elsewhere. A soil management plan should be in accordance with the EIA and specify the measures to mitigate or compensate for these impacts. More detail about the EIA and soil management plan is given in section 2.5.

- **Engagement of the relevant planning authority**:
  This step of the road planning phase should engage the soil protection authority or other planning authorities according to national legislation in the EIA and soil management plan.
- **Detailed design and tender preparation**:
  At this stage, the measures specified in the soil management plan should be designed in detail. This includes a flexible schedule for the construction work so that earthworks can be interrupted if the soil is too wet (see sections 3.3 and 3.4). Other work with less impact on soil or on less susceptible soils should be given priority in such cases. It is important to specify the soil protection measures or functional criteria to be fulfilled in all relevant stages of the tendering processes and to justify their costs. If vulnerable soils are affected (organic soils or soils susceptible to compaction), soil protection measures may be complex and costly.

2.3 Soil information required for road planning

Soil information is indispensable for the planning of soil protection measures. It provides the basis for estimating the potential damage to the soil due to the road construction, as well as the reusability of the surplus soil. In the context of road projects, information is needed about the soil's susceptibility to mechanical stress (compaction, erosion) or to drainage (peat soils), and about chemical pollution, invasive alien species and soil pathogens. A soil expert should interpret the soil information and suggest necessary soil protection measures in the site-specific context. According to the road planning steps, soil information is necessary at different levels of detail (specific examples are given in Example 1):

- *Corridor identification and selection*
  Country-wide soil maps or land-use / land-cover maps covering large geographic areas are useful at this stage, although their information might be of low spatial resolution. These maps indicate potentially vulnerable soils, e.g., peat soils. Maps showing nature protection areas or spatial planning requirements of e.g., arable land protection should be checked as well. These provisions might be accompanied by a building ban or the obligation to take compensation measures.
- *Alignment and design options:*
  Soil maps at a scale of 1:25.000 or larger are useful at this stage. They provide information about the soil types from which the soil's sensitivity to mechanical stress or drainage can be estimated. Spatial information about soil pollution, inventories of suspected contaminated sites, and inventories on invasive alien species and soil pathogens should also be checked to gain information about

(potential) soil contamination and infestation, which is particularly relevant for the reuse of surplus soil.

- *Road project design with EIA:*
  Whenever available, detailed soil maps should be used at this planning stage. However, such high-resolution soil maps often do not cover the entire area of the construction lot or are not available. Field investigations are indispensable for the EIA to verify or supplement existing soil maps, or to replace them. A soil expert should assess the original soil conditions before the start of the construction work in the field. On this basis, the necessary soil protection measures are determined and set out in the soil management plan. In extensive and complex road projects, the field investigations in the EIA context might be preliminary investigations with few, widely spaced sampling points. In this case, the soil management plan should specify the required detailed field investigations at the design stage (see below for more detail about field investigations).
- *Detailed design and tender preparation:*
  Detailed soil mapping in the field might be necessary at this stage, if the soil information gained in the EIA process is not sufficient to organise the construction site in detail. Proper field investigations are then the basis for deciding on appropriate soil protection measures which avoid damage to the soil. The costs for field investigations have to be included in the tender. It has to be noted that this work helps avoiding additional costs for repairing damage to soil.

Field investigations during the EIA or detailed design of road projects include the following steps:

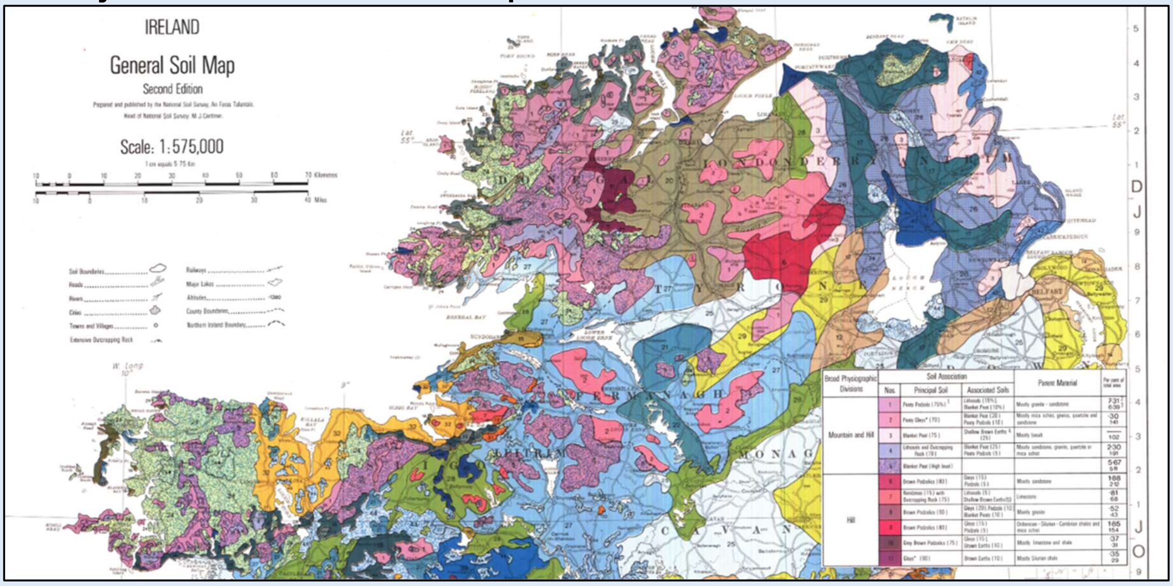
- Description of the terrain, the local climate and land use to assess environmental influence on the soils
- Soil profile descriptions with soil pits, supplemented by augering
- Soil structure assessment to estimate susceptibility to compaction and erosion
- Identify and localise drainage systems
- In case of potential contamination: soil samples for laboratory analyses of pollutants
- Evaluation of flora and fauna for invasive alien species
- Additionally recommended: installation of soil moisture monitoring devices for real-time assessment of the soil's susceptibility to compaction
- Recommended for the use of modelling tools: take soil samples for measuring bulk density and soil organic carbon content (cf. section 3.2-3.3, Table 1).

As mentioned before, field investigations are carried out to assess the original soil conditions before starting the construction work. However, after completion of the construction work, the same field assessment should be repeated to confirm conservation of the original soil quality, or to determine measures to repair the damage to the soil caused by the construction work. Usually, a large amount of valuable soil data is collected during field investigations according to standard soil-science methods. Therefore, it is recommended to systematically make these data available in a public repository as Open Government Data.

Example 1. Soil maps for the different road planning stages

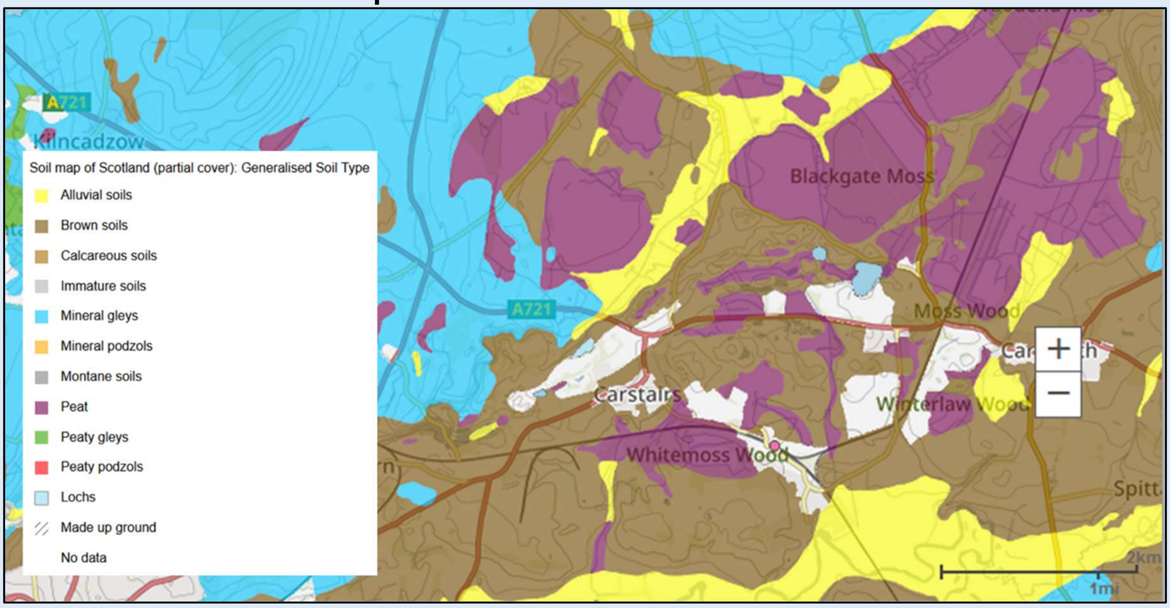
Background: Soil maps at various spatial scales are helpful in the different phases of a road construction project. For the identification of route corridors, a country-wide small scale soil map can provide helpful information. For the EIA and determining specific soil protection measures, high-resolution soil maps should be used, supported by field surveys. In the following, the different scales of soil maps are illustrated with examples.

Country-wide low-resolution soil maps:



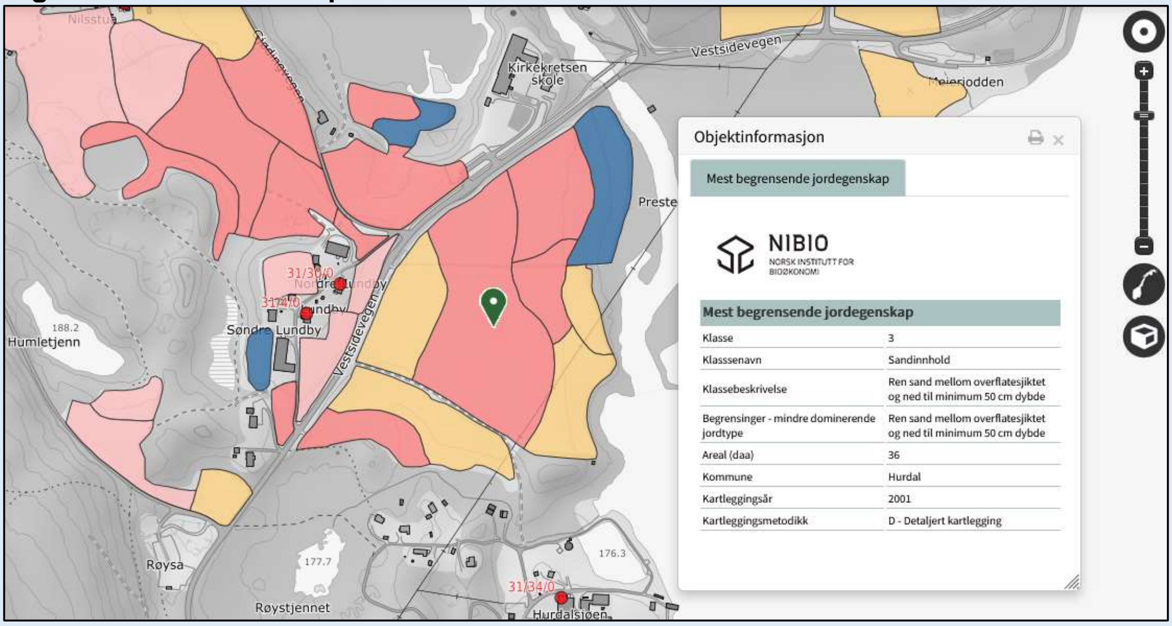
Small-scale countrywide soil maps (or maps of the soil use potential) such as the general soil map of Ireland can be useful in the process of route corridor identification.
Source: https://www.teagasc.ie/environment/soil/soil-maps/

Medium-resolution soil maps:



Soil maps such as the Scottish Soil Map at a scale of 1:25,000 provide a basis for developing the road project alignment and design options.
Source: https://map.environment.gov.scot/Soil_maps/?layer=2

High-resolution soil maps:



For the road project design and the environmental impact assessment, large-scale soil maps such as those from Norway with a scale of 1:5,000 are useful. Source: kilden.nibio.no

Field investigation:

In addition to using the various soil maps, it is necessary to gather soil information through field investigations prior to construction to assess the original state of soil quality. Photo: Sigrun H. Kværnø

2.4 EIA and soil management plan

The environmental impact assessment (EIA) is a decisive step in the road planning phase for estimating the impact of the project on the soil and to specify measures to avoid, mitigate and compensate for these impacts (cf. section 2.2). It should include the period of soil restoration and subsequent management after termination of the construction work. As road projects are complex and designed at different stages, the EIA can be divided into different stages: a general EIA for the preliminary design, and a comprehensive EIA for the detailed design of the road project.

The conclusions from the soil section of the comprehensive EIA report should result in a **soil management plan**. Based on the analyses documented in the EIA report, the soil management plan specifies the necessary soil protection measures to minimise damage to soil. The recommendations on the content of a soil management plan can vary depending on the local conditions and the construction project itself. Soil management plans are standard practice in some European countries (e.g., Switzerland, Germany, Norway, Austria), while practice in other countries varies (Geiges and Tobias, 2022; Haraldsen and Tobias, 2023). The soil management plan should be coordinated with other plans elaborated during an EIA, such as archaeological cultural heritage impact assessments. It is critical that all contractors are made aware of all relevant legal regulations before any earthwork is initiated, including planning of soil sampling and soil storage sites. In Ireland, for example, an erosion sediment control plan, IAS management plan, or construction environmental management plan are also developed in during the EIA process. An example of the benefits of a soil management plan is given in Example 2.

The soil management plan should contain all details about soil management in the specific road project so that it can be used as a checklist, by the people responsible for the earthworks and by the authorities approving the work. A generic soil management plan should include the following points:

- **Assessment of the initial soil conditions.** A soil expert should assess the initial condition of the soil in advance of construction work. A minimum indicator set is suggested in Table 1 (section 3.2). Soil maps are helpful, but field investigations are indispensable for assessing the necessary soil details and the spatial variation in critical soil properties.

- **Mitigation measures during the construction phase.** Measures to avoid or mitigate soil compaction are for example the selection of the most suitable machinery and/or the use of excavator support mats. Soil moisture monitoring is necessary to make sure machines are used within the soil’s tolerance to mechanical stress. Potential interruptions of the construction work because of wet soil conditions should be scheduled (see also section 3.3). Measures for erosion control on slopes, such as seeding with grass, and for stormwater management on construction sites should be specified.

- **Temporary soil storage and management of surplus soil.** A mass balance shows how much soil can be reused on-site to achieve the targeted quality of the restored soil, and how much surplus soil to handle off-site. This section includes determining the area, size, and shape of temporary storages of stripped soils. In addition, options of reusing surplus soil off-site should be elaborated, e.g., for compensation measures. Finally, the handling of polluted and infested soils should be outlined with the aim of avoiding the disposal of valuable soil material. This has to be in line with the country's legislations on waste and polluted soils management.

- **Soil aftercare and final soil quality check.** After completion of the actual construction work, the temporarily used areas and compensation areas should be restored for their planned use. Careful management with little mechanical impact is usually required for restored agricultural soil during four to five years. As the soil will need time to settle and stabilize it is normally recommended to await installation of drainage until the soil has stabilized. The implementation of these measures should be documented, and a soil expert should assess the final soil quality. This documentation can be helpful in potential litigations with landowners. Potential additional monitoring required under the EIA, such as IAS monitoring, should be included in this documentation.

- **Management, supervision, and communication of the soil management plan.** A soil expert should be assigned to set up and implement the soil management plan. The soil expert should be involved in all phases of the construction project to decide about the appropriate soil protection measures under the given soil conditions. This person should be provided with the necessary authority to intervene in the construction process, such as prescribing the interruption of construction work because of wet soil.

Good examples of soil management plans providing some details on soil and site management can be found at:

- Department for Environment, Food and Rural Affairs, UK (www.defra.gov.uk): Construction Code of Practice for the Sustainable Use of Soils on Construction Sites

- Invest Northern Ireland (nibusinessinfo.co.uk): Prevent soil damage during construction projects

Example 2. Benefits of a soil management plan

Background: A soil management plan provides the basic structure for how soil should be protected during a construction project and is binding for all stakeholders involved, from the construction company to the soil protection experts and the environmental authority. The soil management plan ensures that all stakeholders implement the necessary soil protection measures and quality controls at the appropriate time. If a soil management plan is consistently implemented, a healthy and fertile restored soil can be handed over to the owner after construction is completed. If this is not done, or if no soil management plan is applied, the construction work can leave major damage to the soil with negative consequences for cultivation. Below, examples of successful and less successful soil management is given.

Example without preliminary planning of the rehabilitation of the soil:

The soil was rehabilitated without prior soil quality assessment and definition of appropriate soil protection measures. After construction, the soil could not be cultivated because it was heavily compacted and contained many large stones (left). Costly extra work was invested to loosen the soil and remove the stones (right) in order to make the cultivation of the soil possible. Photo: T. K. Haraldsen.

Example with preliminary planning of the rehabilitation of the soil:

In this project, the rehabilitation and follow-up management of the soil was defined in advance. The soil was built up in layers with measures to avoid compaction (left). Thus, cultivation was successfully resumed on schedule (right). Photo: T. K. Haraldsen.

2.5 Planning agricultural and ecological compensation measures

Ecological and agricultural compensation is carried out with the intention to offset negative environmental effects of road projects through investments in management, restoration and protection. This is the last step in the mitigation hierarchy, suggesting that measures to avoid, minimise or restore functions on site are considered before compensation. Art. 6.4 of the EU Habitat Directive prescribes compensation for impacts on natural habitats due to infrastructure projects which is implemented at the country level in the nature conservation legislation. There can be additional regulations prescribing the compensation for lost agricultural land or forest. The legislation for nature and environment protection, agriculture and forestry, and spatial planning should be checked for the obligation to compensate for the loss of these land-uses.

Uncontaminated surplus soil and bedrock material can be reused for compensation measures as far as this is in accordance with the country's waste and environment legislation. For example, the depth of degraded agricultural soils, such as drained organic soils or heavily compacted soils, can be increased with surplus top- and subsoil. This can help compensating for high-quality agricultural land that is lost due to road projects. Surplus soil used for this purpose must not be polluted with contaminants nor infested with noxious organisms. In addition, these upgraded soils have to be treated in the same way as freshly restored soils, i.e., with cautious management during several years. Examples of compensation approaches are illustrated in Examples 3 to 7.

Unsealing road sections is a possibility to reduce net soil sealing. Unsealed road sections have been converted into urban green spaces in several towns and cities for example in Germany, Austria, Switzerland, and Norway. Unsealing of obsolete road sections is beneficial in rural areas as well (Example 7). It can compensate for the loss of natural and agricultural land. Other measures to reduce net soil sealing are permeable surfaces which can help increase stormwater infiltration and relieve the road from surface runoff peaks. They should be considered for any corollary road infrastructure, such as work access roads or parking lots of motorway service areas.

Special attention should be given to organic soils and groundwater dependent ecosystems, particularly fens and peat bogs. These ecosystems are very susceptible to drainage because aeration makes the organic matter (peat) in the soil decay and, consequently, may destroy the entire ecosystem. Organic soils are naturally water saturated close to the soil surface. If they are cut by earthworks, there is a high risk that they will drain. Therefore, direct and indirect impact on organic soils and groundwater dependent ecosystems should be avoided in road projects. Attention should also be given to measures that may alter drainage patterns or water tables in the surroundings.

Wetland restoration is increasingly seen as an alternative to mitigate drained organic soils and could be a compensation measure in the context of a road project. The prerequisites are an intact peat layer in the soil profile and permanent freshwater supply. The topsoil is usually nutrient-rich decayed organic material and has to be removed to rebuild a nutrient-poor wetland ecosystem.

Example 3. Compensation of agricultural areas

Location: Switzerland

Construction Project: Storage area for a project (ASTRA Bridge) of the national road authority.

Background: The Swiss National Roads Office required space for the storage and testing of a mobile bridge to be used to bypass construction sites more efficiently (ASTRA Bridge). Some of the land required has been identified as prime arable land. According to the Sectoral Plan of Cropland Protection Federal Office for Spatial Development ARE (2020), if such land is permanently sealed or loses its quality during a construction project, it should be compensated for by upgrading an alternative area of the same size to have the same quality as prime arable land. The implementation of such a compensation is regulated at regional level. Suitable areas for the compensation are selected in cooperation with the contractor, a soil protection expert and environmental offices, preferably close to the place of the soil sealing. In various cantons, the soil protection offices have published maps of anthropogenically degraded land which should be considered first for such upgrading.

Measure: An agricultural compensation measure was implemented in an area 15 km away from the construction site. The C horizon was levelled out to meet the requirements of the Sectoral Plan of Cropland Protection on inclination and evenness of the terrain to enable efficient management with agricultural machinery. A drainage system was installed to ensure long-term drainage. The subsoil and the topsoil were then heaped in strips. As specified in the soil management plan, the farmer and landowner hand-seeded a catch crop for the first winter and afterwards cultivated grassland in a conservation-oriented manner for two years. After this period, a soil protection expert verified that targeted soil quality had been achieved, and the area was handed over to the landowner.

The surplus soil of the construction site was used to upgrade this piece of degraded land to prime arable land quality to compensate for the loss of prime arable land. The soil was built up in strips, first the subsoil layer was heaped and right afterward the topsoil layer was added (right corner of the site). Photo: Dominik A Müller (2022).

Example 4. Ecological compensation

Location: Central Switzerland

Construction Project: National road- and railway construction projects

Background: Two tunnel projects, one for a national road bypass of a town and one for the tunnel of the “New Railway Link through the Alps (NRLA)”, produced a large amount of rubble. This provided the opportunity to restore the delta of the Reuss river at the southern end of Lake Lucerne. As a consequence of extensive gravel exploitation from the lake until the 1970s, the natural river delta and shallow water zones had been completely destroyed

Measures: A total of 3.3 million tons of surplus material from the tunnel constructions was used to re-create the delta area with shallow water zones and islands (Bühlmann 2018; Justizdirektion des Kantons Uri & Amt für Umweltschutz 2018). The Swiss water protection act generally prohibits the disposal of construction waste in open water bodies. However, the restoration of degraded aquatic ecosystems is another objective of the law and, therefore, non-contaminated surplus material from construction sites can sometimes be used to re-establish shallow waters (BUWAL, 1999). There was a separate EIA for this ecological restoration project with detailed descriptions of the heaping techniques to avoid muddying of the water.

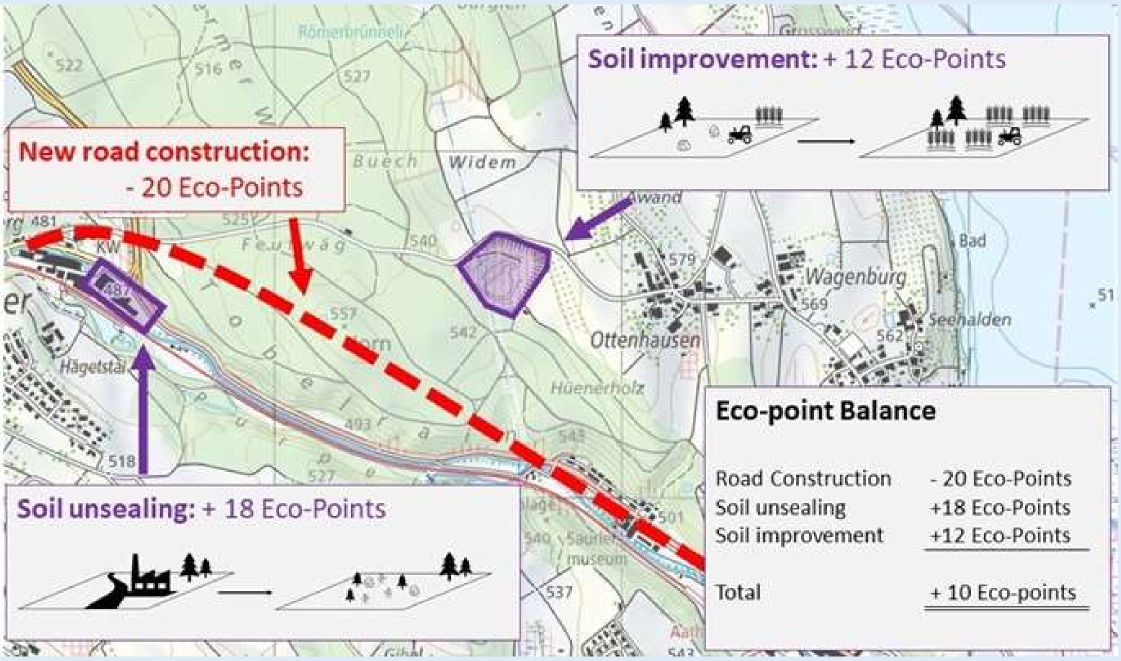
The Reuss delta with shallow water zones and the artificial islands. The three islands on the left are for natural habitats and the three on the right for swimmers. (Photo: Matthias B. Andrews).

Results: With this measure, 12 hectares of shallow water zones and six islands, three for swimming and three for natural habitats, were created. This project made it possible to reuse large amounts of surplus material with short distances between the locations of excavation and reuse of the material.

Example 5. Eco-point system

Location: Germany

System: Germany introduced a system of eco-points that are credited to ecological compensation measures. The intention was to promote the restoration of natural habitats even if such projects are locally and temporally independent of construction projects. This makes it attractive to develop extensive compensation projects on stock. See figure for an illustration of the system.



Simplified example explaining the eco-point system: (a) When a company builds a road of 5 km, it has to compensate for with measures worth e.g., 20 eco-points, defined by an expert on the basis of regional legislation. (b) The company improves an agricultural area and receives 12 eco-points. (c) Instead of planning a small improvement worth 8 eco-points, the company decides to unseal an unused industrial area, which entitles it to another 18 eco-points. The company now has a total of 30 eco-points from compensation measures. It needs 20 of them to compensate for the current project and can use another 10 to compensate for future construction projects.

Risks: Although this system strongly supports compensation projects, it carries the risk that the actual damage to the soil in a specific construction project is not sufficiently compensated for. Construction companies might implement cheap and easy compensation measures without considering the specific damage to the soil and the environment. For example, instead of unsealing an artificial surface to compensate for soil sealing caused by a new road, the developer might create a dry meadow on an already unsealed area to foster biodiversity. Furthermore, reports show that although the eco-points are used and traded with, many of the measures have actually not been implemented.

Example 6. Restoration of a wetland as ecological compensation

Location: Hamar, Norway

Construction Project: Expansion of the E6 highway

Background: Compensation measures were implemented to achieve a «no net loss» of nature during the expansion of the E6 highway from two to four lanes. The highway crosses the RAMSAR nature protection area Åkersvika at Hamar, Norway and the objectives were regulated by the municipal subdivision plan. The regulations also included designation of a new separate wetland reserve.

Measures: In this project all soil with alien invasive species was removed and all infected wood and soil material by *Phytophthora ramorum* was removed from the area for and replaced with suitable soil from the road project and construction sites. Although measures were taken to combat invasive alien species, *Solidago canadensis* had reappeared in autumn 2022 (Haraldsen & Tobias 2023). This emphasises the need to manage invasive species in the surrounding landscape, and not only within the borders of the project. Short-term goal achievement has now been evaluated and indicate overall reasonable results, yet with some concerns about invasive species, non-local plant material, and loss of some biotopes (Norwegian Environment Agency, 2022).

Part of the RAMSAR area Åkersvika before road construction (left) and after compensation measures (right), https://kilden.nibio.no.

Example 7. Road unsealing as ecological compensation

Location: Northern Switzerland

Construction Project: New motorway to bypass two villages

Measures: For ecological compensation, 2 km of the old country road connecting two village centres were dismantled (Tobias et al., 2018). The pavement and gravel foundation were broken up and recycled as far as possible. In the remaining ditch, a series of wet and dry habitats were created. Two brooks were connected, some shrubs and trees planted, and piles of stone constructed. Hay from nutrient-poor, species rich grassland was spread on the area to let the seeds grow naturally

a)

b)

c)

Vegetation development over time: a) 1995 (photo by M. Fries); b) 2003 (photo by S. Tobias); c) 2012 (photo by S. Tobias).

Results: Thirteen years after unsealing, a European semi-xeric grassland *(Mesobromium erecti)* had been established hosting a number of red-list plant species. In addition, the area gained in recreational value. The soil remained heavily compacted as it used to be the basis of the road. Soil profiles could not be dug deeper than 25 cm, and they show a very shallow A-horizon followed immediately by a highly compacted C-horizon. Even though the intended plant communities established successfully, the soil's multifunctionality is strongly reduced. It is a habitat only for plants with shallow roots which can handle extreme wet and dry situations. In addition, the infiltration capacity is very limited and, therefore, ground water accumulation is almost impossible.

Soil profiles of the unsealed road section: a) at a wet site; b) at a dry and gravelly site (photos by S. Tobias). The soil is now a Densic Regosol according to IUSS Working Group WRB (2015) with artificially compacted sandy loam.

2.6 Key recommendations for the planning phase

- **Choose the road alignment with minimum impact on soil. Protect wetlands from encroachment by road projects.**
- **Plan the soil protection measures in the road construction project according to the most detailed guidelines available nationally or regionally, addressing measures before, under, and after the construction work.**
- **Collect existing soil data from land affected by construction work and organise collection of missing data. Select indicators to document and monitor impact on soil quality and establish baseline data for these.**
- **Develop a soil management plan to mitigate impact on soil during construction phase including soil restoration. Assign a soil expert to supervise the process from an early phase. Reserve the necessary area for temporal storage of stripped soil.**
- **Plan compensation measures for the loss of agricultural or forest land and natural habitat near to the road project.**
- **Implement strategies to prevent soil compaction during earthworks, target suitable machinery and approaches based on collected soil data.**

3 SOIL MANAGEMENT IN THE ROAD CONSTRUCTION PHASE

3.1 *Current challenges of soil protection*

The actual road construction causes the most severe damage to soil because soil is removed, stock-piled and restored. Such actions can lead to soil compaction, erosion, loss of organic matter (particularly in peat soils), the transfer of contaminated soils and spread of IAS. Road construction sites usually cover large areas and last for several years. Hence, a large volume of soil is affected during considerable time. Therefore, soil protection measures have to be prepared early before the actual construction starts. Accordingly, this chapter includes two steps of the road construction phase: i) organisation of the construction site (chapters 3.4- 3.6), and ii) implementation of the construction work (chapters 3.5 to 3.7).

The challenges for soil protection during the organisation of a road construction site are:

- Planning the steps of earthworks according to the vulnerability of the soils affected. The work on soils that are susceptible to compaction can sometimes only be carried out during a short time period of the year when these soils are dry enough. The construction process has to be planned in a way that allows to postpone certain steps and advance others.
- Defining the areas for temporary storage of soil. This requires a detailed calculation of the soil volume that will be stripped. In addition, the different soil layers (A-, B-horizon) should be stored separately.

When the road construction work is running the challenges for soil protection are:

- Quick checks of soil moisture in order to decide if the next step of earth work can be conducted. This requires simple methods which can be applied in the field to assess the soil's current susceptibility to compaction.
- Selection of the construction machinery according to the soil's current susceptibility to compaction. The risk of soil compaction caused by a certain machine does not necessarily mean a total interruption of the earth work. Another option can be selecting a machine of less weight or ground pressure (tracked vehicles instead of tyres).
- Soil stripping, establishment and management of temporary soil storage sites. This includes measures to control erosion and the spread of invasive alien species.
- Soil restoration after termination of the road construction work. This is a matter of the time and machinery needed after the actual construction work is terminated. It also entails the same challenges as mentioned above, i.e., checking soil's susceptibility to compaction and selecting the appropriate machinery, apply to this final piece of work.

3.2 Identify, quantify, and monitor critical soil quality indicators

Soil quality or health indicators are useful for assessing the initial state of soil, i.e., prior to any road-related activities take place, and for monitoring potential changes of the state of soil in the road construction and road operation phases. The initial state can be used in the planning phase to evaluate the impact of different road alignments on soil functioning. This is estimated based on measurable soil properties – preferably supplemented with information on climate, land use and soil management. Moreover, knowledge of the initial state of the soil allows identification of areas for compensating and mitigating measures and may serve as a target-state.

Following earlier assessments of soil quality or health, a range of indicators have been proposed (see Table 1, Table A2.1 and A2.2 in ten Damme & Keller 2022). It is particularly important to consider a combination of chemical, physical, and biological soil characteristics, and to evaluate soil at different depths. Threshold values exist for some of these soil characteristics, indicating limits at which soil functions are greatly impaired. However, for other soil characteristics, such threshold values have not yet been established, or cover a wide range due to differences in terms of soil types, land use and climatic zones (EEA 2022). Here a minimum list of indicators for soil qualities (functions and states) is suggested, that are useful in describing and monitoring road impacts on soils (Table 1). These indicators give basic information that requires a soil expert to interpret for the site-specific context. These indicators can be used to assess the soil function parameters listed in the EIA Directive (compaction, sealing, erosion and organic content). Lower and upper levels of the indicators in Table 1 are not provided, as these will differ between projects based on soil origin and climate. To systematically collect and use these data will contribute to education and learning about soil processes with construction operators and the road administration.

Table 1. *Suggested indicator set to describe and monitor road impacts on soil.*

*The table is based on ten Damme & Keller (2022). Optional indicators are marked with an**

Indicator	Method
Soil organic carbon	ISO 10694:1995
pH (H_2O)	ISO 10390:2005
Total Nitrogen*	CSN EN 13654-1
Plant available phosphorus*	No unifying standard available. Use regional indicators for agricultural fertilizer planning
Salinity*	ISO 11265:1994
Soil texture classification*	Textural classification system, such as WRB (2022)
Clay, silt and sand content	ISO 17892-4:2016
Bulk density	ISO 11272:2017

In addition, field measurements of soil moisture are critical for proper soil management at construction sites, both for operation of machinery and handling of soil. Approaches for soil moisture evaluation is given in Example 9.

3.3 Soil compaction risk assessment on construction sites

3.3.1 Operation limits for construction machines

Tools to predict risks of soil compaction using heavy machinery are essential in soil management. These can be simple chart-based systems, as presented in Example 8, or more site-specific systems as presented in 3.3.2. Approaches to measure soil moisture is shown in Example 9.

3.3.2 On-site estimation of soil strength using a decision tree model

Soil strength can be predicted using measurements of soil moisture and soil properties. Nemes et al. (2022) provide a classification and regression tree (CART) model that facilitates quick on-site assessment of soil conditions using basic soil information (soil texture) and real-time soil moisture status measured using a field-tensiometer that logs the soil moisture tension of the soil (expressed in hPa).

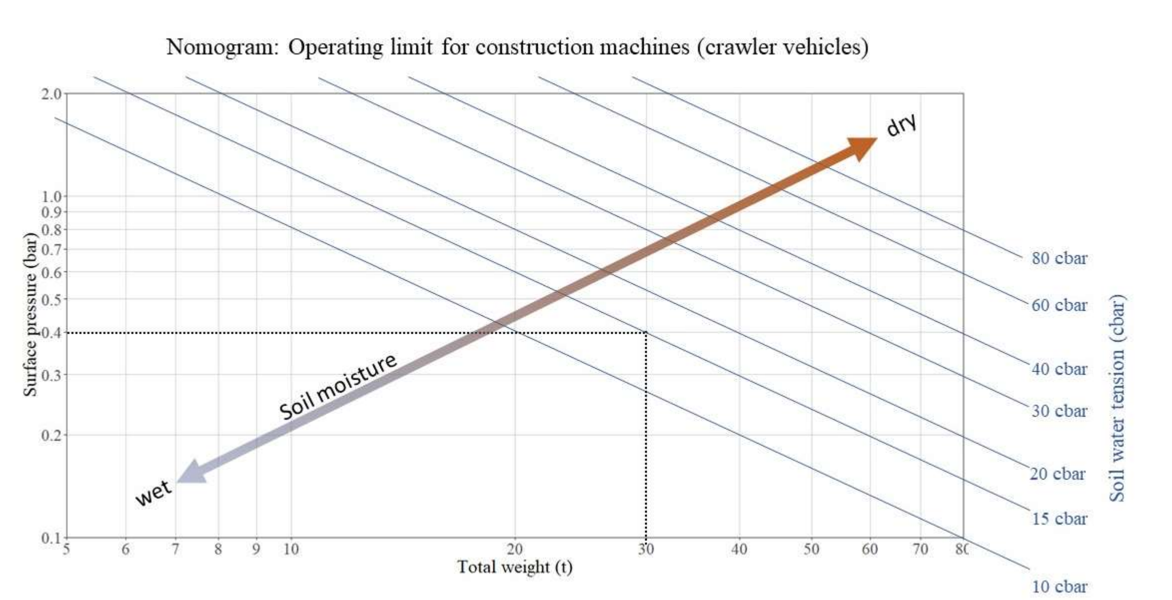
The provided real-time decision aid tool will help assess the given soil's vulnerability to compaction on the given day, which the contractor should relate to the expected soil stress by the different machinery available for use, prior to starting any soil work. Using this tool can help decide which, if any, machine should be used to work at the given site that day to minimise the risk of soil compaction. Limitations of the machinery is to be established in the planning phase but needs re-evaluation on the construction site. The tool can be provided to the contractor as a printable PDF, and guidance on how to use it is provided in the tool's documentation. A short version of the method is described in Appendix 1.

Example 8. Nomogram – operation limits for construction machines

Location: Switzerland

Tool: In Switzerland, the “Nomogram: operation limits for construction machines“ (Bundesamt für Energiewirtschaft, 1997) has been successfully implemented as a tool to manage soil operations for more than two decades. A nomogram yields the maximum soil moisture in terms of soil moisture tension for a given vehicle, based on the total vehicle weight and mean ground pressure. A nomogram is only intended to be used for tracked vehicles.

Method: Using a nomogram, requires a soil moisture monitoring station (with tensiometers). This station is to be set up in an area not affected by the construction site and determines the average soil moisture of topsoil and subsoil. The operation limits for construction machines are determined according to the following procedure The total weight of the machine and the surface pressure (weight (kg) per contact area of the track (m^2)) are determined. Now it can be derived from the nomogram whether the load is above or below the operating limit for the soil moisture. If the determined value is below the limit, the soil is too moist, if the value is above the limit, it is dry enough.
As an example (dashed lines) for a surface pressure of 0.4 bar and a total machine weight of 30 ton, the operating limit is at 15 cbar. If the value is less than 15, the risk of compaction is too high, and the machine should not be used. Conversely, if the value is higher, e.g., 20 cbar, the soil is dry enough and the machine can be used.



A nomogram is used to define the operating limit for construction machines (tracked vehicles) and is sourced from the Soil Protection Guidelines for Pipeline Construction (1997) published by the Swiss Federal Office of Energy ((Bundesamt für Energiewirtschaft, 1997). Illustration: T. Geiges

Example 9. Soil moisture measurements

Background: Put simply, the wetter the soil, the more susceptible it is to compaction. Soil moisture is therefore a meaningful indicator of whether or not a soil is susceptible to a given load or handling. With experience, soil colour or current weather conditions can give good indications of soil moisture. However, assessment of soil moisture should be based on measurements whenever possible. Soil moisture can be measured as soil water content per volume or mass of soil, or how tightly bound the water is to the soil particles, often called the soil water potential, soil moisture tension or capillary tension. Different equipment is available to measure and monitor these characteristics. Tensiometers are frequently used to measure soil moisture tension, while equipment using time domain reflectometry (TDR) technology are used to measure volumetric water content. Some calculations between measurements can be done using information on soil texture.

Method: A tensiometer is a water-filled permeable rod with a ceramic tip that measures the capillary tension of the water in the soil. The measured value is called soil moisture tension and its unit is cbar or hPa. The drier the soil, the more water it will pull from the tensiometer and the higher the soil moisture tension (see illustrations below). The ceramic tip of the tensiometer measures soil moisture tension at one single point in the soil profile. Therefore, it is important to place the ceramic tip at the depth that is relevant for the construction work. This can be the topsoil or subsoil of a natural soil, or a certain depth within stockpiles of top- and subsoil. 35 cm is a standard depth for monitoring soil moisture tension on Swiss construction sites. The idea is that the subsoil should be dry enough so that it will not be compacted by construction machines driving over the soil. The monitoring site should be located in an area with similar soil conditions as the construction site which is not disturbed by the construction process. For representative measurements, a minimum of three to five tensiometers should be installed in the same depth. Due to the low number of samples, the median value is more reliable than the mean.

For scanning larger areas and different profiles, portable equipment is handy and can be used for measurement of volumetric water content in topsoil (A-horizon), subsoil (B-horizon) and for measurements of soil moisture in soil storage piles. Such systems often have a calibration for organic and mineral soils. It is recommended to calibrate the system according to the approximate total porosity of the soils. The measurements need to be interpreted according to the materials consistence, stickiness and plasticity at the time of measurement**.**

> 20 cbar	Dry
10-20 cbar	Humid
6-10 cbar	Very humid
< 6 cbar	Wet

Tensiometer (left) and a tensiometer station with 5 tensiometers and a rain gauge (right), Photos: Jacqueline Riedi. The table shows the approximate relation of measured values and soil moisture.

An example of a portable system using TDR technology to measure volumetric water content. Photo: Hans M Hanslin

3.4 Water management on site

Equally important as the control of compaction is the control of water in the construction area. Stripping of soil materials may lead to cut and breakage of drainage systems, and broken drainage pipes need to be repaired to prevent water saturation (Figure 3).

Figure 3. *Broken drainage pipe after restoration of temporary mass storage site causing water saturation, deep wheel tracks and a large area with weeds instead of agricultural crops (Photo: Trond Knapp Haraldsen).*

Ponding water in depressions where soil materials are stored must be avoided because this may lead to soil compaction during storage due to the weight of the soil deposit. Increasing wetness of loamy and clayey soils will cause the soil materials to be plastic, and the soil structure will be lost during storage due to the static load (Figure 4). Temporary drainage systems should be installed on the construction site which can be simple ditches or wood-channels that are simple to modify. With the progress of the construction work, the terrain of a construction site can change significantly and, consequently, watersheds and flow regimes might shift.

Temporary soil deposits and freshly restored soil particularly need protection from waterlogging. Soil deposits should not be built in hollows, but on knolls. Soil restoration should start at the highest point of the terrain and continued downwards. In this way, rainwater can drain out of the deposits or fresh restorations to the lowest point of the construction site.

Figure 4. *Water ponding in autumn at a construction area with soil piles. Photo: Trond Knapp Haraldsen*

3.5 Management of stripped soils

3.5.1 Temporary storage of soil or stockpiling

In all road construction projects, it is very important to plan areas for soil storage. If agricultural areas are used for temporary storage of soil, it is very important that both topsoil and subsoil are loosened by excavator after storage, and the function of drainage systems is confirmed. Access to temporary storage areas should also be protected from compaction. This can be done by removing the topsoil and subsoil from the access track, or by constructing an access track using, for example, excavator mats (Chapter 3.3). If this is not possible, the compacted soil layers should be loosened again after the earthworks have been completed. The compaction caused by the static load of soil piles may also need to be loosened. Although mechanical subsoil loosening, referred to as deep loosening, deep ripping, or subsoiling, is a common practice to loosen up dense soil layers below the topsoil, the benefits of subsoiling are often not long-lasting due to re-compaction by the overburden topsoil and field operations (Piccoli et al. 2022). There is a need for loosening subsoil under optimal soil moisture conditions. When the soil is too wet and loose, the soil might be smeared and compacted. When the soil is too dry, thick clods are formed (Schulte-Karring & Haubold-Rosar 1993). Mixing of A- and B-horizon materials during subsoiling may cause thinning the organic matter content of the topsoil and have negative impact on the soil structure. Loosening by excavator, originally described by Rolf (1993) has been shown to give good effects. By this method the B-horizon can be loosed to the desired depth before replacing the A-horizon (Haraldsen & Tobias 2023).

The plans for road projects normally include stripping and temporary storage of masses within the project area, and a planned use for landscaping and compensation measures is described. Both for temporary storage and permanent use, the soil material should be separated by the horizons, i.e., topsoil piles (A-horizon) and subsoil piles (B-horizon). Further, the B-horizon should preferably not be mixed with materials without soil structure development (C-horizon) which instead may be used directly for landscaping. As storing the horizons separately requires large areas, a balance must be sought between targeted reuse of the A- and B-horizons, available land and costs.

Traditionally, subsoil material was landfilled causing a large demand for landfill areas. Instead of landfilling, processing of all soil material should be encouraged in all road construction projects so that it can be used at least for road verges or urban green spaces. Fine-grained till and morainic soils may be improved by sorting out rock boulders and stones. Beneficial use of such materials is as construction roads which also serve as drainage systems (Figure 5).

Figure 5. *Beneficial use of rock boulders and stones as fundament for construction road and drainage system. Photo: Trond Knapp Haraldsen*

Soils above certain pollution limits should not be reused in the root zone, neither in verges nor embankments of the upgraded road. Slightly polluted soil materials may be used below the root zone according to national regulations. Chemical soil analyses are required to check the content of pollutants. On this basis and in accordance with the current environmental and waste legislation, it has to be decided, whether the soil can be reused in the root zone, below the root zone or must be landfilled.

When the stored soil is relocated for landscaping or compensation measures, the following procedures are recommended:

- Install gravel and stone tracks to transport the soil from the point of stripping to the place or temporal storage or final heaping. These tracks can also have a drainage function.

- Strip and stockpile topsoil (A-horizon) and subsoil (B-horizon) separately. A restored soil should be laid on bedrock, layer of rock boulders and stones, or earth material without soil structure (C-horizon), followed by subsoil with developed soil structure (B-horizon), and topsoil (A-horizon) on top.
- Strip, transport and heap the soil material only when it is not susceptible to compaction, i.e., if it is dry enough (see section 3.3) or frozen.
- Use excavators to gently heap the subsoil and the topsoil.
- Use tracked vehicles to spread the soil over the restoration area. If tyre vehicles are used, loosen the wheel tracks with excavator before placing the next horizon.
- If the soil material has too high stone content (>10 vol. %), remove stones and boulders mechanically,
- Place stones and boulders at the bottom of the restoration area before subsoil and topsoil are heaped. They can serve as drainage system (see 3.7)

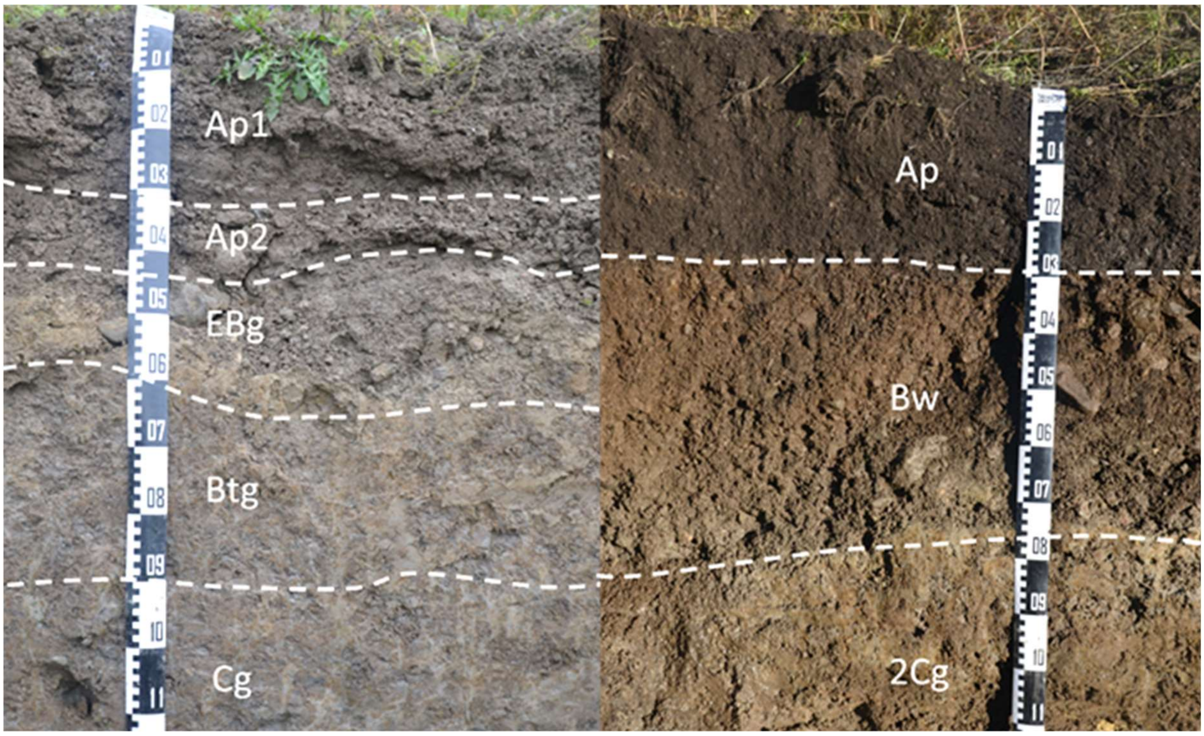


Figure 6. *Examples of two soil profiles that show the horizontal layering with A, E, B and C horizons. Here both A horizons have been affected by ploughing (p). The C horizons are only marginally affected by soil forming processes. The profile on the left also has an E layer, where eluvial loss of silicate clay, iron, aluminium, silicon, or some combination of these has occurred. Photos: Trond Knapp Haraldsen*

The impact on soil can be reduced if the soil is not stockpiled but displaced at a new location immediately after stripping. This, additionally, requires less area for temporary soil storage at the construction site and reduces the costs. When temporary storage is needed, topsoil and subsoil should be stored separately, and the height of the deposits should normally not exceed 1.5 m for topsoil and 2.5 m for subsoil to avoid compaction by static load and anaerobic conditions in the deposits if stored on agricultural land. This might require large areas for soil storage on a construction site, occupying productive land for extended period.

An alternative to storage of small piles at a large area is to make larger piles for long time storage and take out soil to make small piles (max. 1,5 m height) some days before the soil is to be used for restoration. The height of the storage piles should be adjusted according to the soil texture and repeated handling of soils requires knowledge of soil characteristics to limit damage. Piles with sandy materials can be higher than piles with loamy and clayey soil materials. This procedure is effective to make uniform moisture content and make the soil crumbling without clods. Such procedure is commonly used by companies producing constructed soil and has been found to be very useful for pretreatment of the soil before sorting out gravel and stones. Soil loosening at storage areas with excavator is needed as soil compaction during transport from the piles is unavoidable. In any case, the soil deposits should be seeded with a mixture of deep-rooting grasses or catch crops. As the vegetation needs to be cut two to three times during the growing season, the height of the storage piles should be designed for such procedures by relevant equipment/machines. This controls soil erosion and silting as well as the spread of weeds and IAS.

3.5.2 Soil profile rebuilding

The principle of soil profile rebuilding is to strip and store the horizons separately and rebuild the soil profile horizon by horizon (Figure 7) as soil restoration on site, or as soil relocation and rehabilitation elsewhere. It is important that the top- and subsoil layers are stripped and stored separately to conserve soil structure and the living conditions of the soil organisms. There are two basically different techniques of soil restoration:

- **Area filling**: the restoration area is covered with the subsoil which is sown with a catch crop and given a rest of six to twelve months to settle down. Then the topsoil is spread over the area.
- **Strip filling**: the subsoil and topsoil are filled in strips of three to five meters (as far as an excavator can through the soil) in the same working step.

The choice of the restoration technique depends on the availability and the susceptibility to compaction of the sub- and topsoil, the extent and shape of the restoration area, and the available machinery. Preferably, the soil is directly relocated without temporary storage. This requires good coordination of the work at the donor and recipient sites (see also Example 10).

Freshly restored soils are very susceptible to compaction, regardless of the restoration technique. Therefore, only minimal agricultural management without heavy machinery should take place on the restored soil during a period of several years (min. four to five years). The farmer should be contractually obliged and compensated for careful subsequent management. In the most successful soil restoration projects normal yields of arable crops can be obtained after a few years of aftercare when the soil has stabilized. The need for installation of drainage systems will depend on soil texture, normal precipitation and slope of the fields. If needed, it is recommended to install drainage systems first one or two years after replacement of the soil horizons when the soil has settled and been stabilized. Shaping the soil surface in the aftercare period may be needed in order to avoid areas with ponding water.

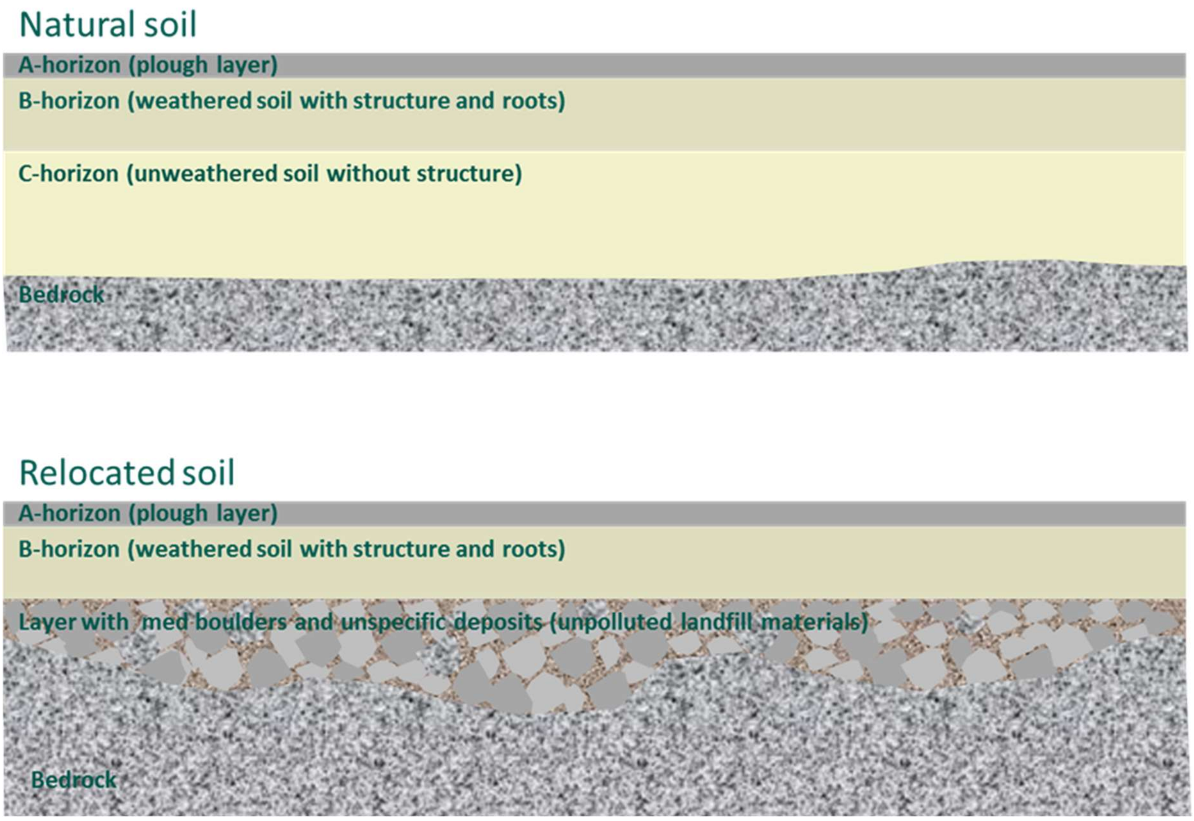


Figure 7. *Generic profiles of a natural and restored soil (Source: Modified from Hauge & Haraldsen 2017).*

Example 10. Soil relocation horizon by horizon

Location: Lillehammer, Norway

Project: Soil relocation from Hagejordet development to a local farm, transport distance 1.6 km

Measures: Soil reconstruction of arable land at a stony grazing area for deer, - “a quartet for two excavators and two trucks”.

Method: Drainage ditch at the compensation site was straightened, stones and boulders were sorted out of the soil and used as drainage strings with outlet to the open ditch. A-horizon material was taken up from the construction site by excavator and taken to the compensation site, where the material was piled at the eastern part of the area. Then B-horizon material was transported from the construction site and placed directly on the field at the compensation site and levelled out with an excavator. After the terrain was formed with the desired slope, the A-horizon was placed as new topsoil. 0.1 ha arable land was relocated early summer 2022 using excavator both at the construction site and the compensation site and two trucks were used for the soil transport between the sites. The field was sown with a forage grass mixture in autumn 2022 and is expected to give full yield in 2023. In this project soil reuse was mandatory, but with the short transport distances, the approach was beneficial compared to landfilling.

Stony grazing field (left) and relocated soil with low stone content (right), Photo: Trond Knapp Haraldsen

3.6 Management of soil pathogens

There are many species in soil which may cause plant damage and are of regulatory interest on EU or national levels. The European and Mediterranean Plant Protection Organization (EPPO) maintains a database, which provides all pest-specific information that has been produced or collected by EPPO. The database contents are constantly being updated by the EPPO Secretariat (EPPO 2022a).

The database includes:

- Basic information on more than 95 000 species of interest to agriculture, forestry and plant protection: plants (cultivated and wild) and pests (including pathogens and invasive alien plants). For each species: scientific names, synonyms, common names in different languages, taxonomic position, and EPPO Codes are given.
- Detailed information on more than 1 700 pest species that are of regulatory interest (EPPO and EU listed pests, as well as pests regulated in other parts of the world). For each pest: geographical distribution (with a world map), host plants and categorisation (quarantine status) are given.
- EPPO datasheets and PRA reports.
- EPPO Standards.
- Pictures of plants and pests (more than 13 000).
- Articles of the EPPO Reporting Service (since 1974).

Most European countries have implemented national regulations for the EU listed pests, which ensure joint effort to reduce the spread of these pests. As several of the pest species are host specific, the previous land use and crop rotation is very important for risk assessment with regard to the listed pests. For example, potatoes and other *Solanum* species may be infected by several of the listed species, where the potato cyst nematodes (PCN) *Globodera pallida* and *Globodera rostochiensis* are of greatest concern. Updated datasheets about these species are available at EPPO (2022b) and local authorities should be consulted for priorities according to risk assessments.

3.7 Management of invasive alien plant species (IAP) during road construction

Problems with invasive alien plant species (IAP) along roads is an accelerating challenge (Follak et al. 2018) and many invasive species efficiently use road verges as habitats and corridors for dispersal across landscapes. IAP clearly have to be controlled in road projects, both to support ecological contributions of the road verges and as part of the responsibilities across sectors. Trade-off with the use of road verges to support biodiversity, however, frequently leads to suboptimal management for both objectives. Management of invasive species in general is well covered elsewhere, hence these guidelines focus on the issues concerning soil management. Prevention and early-intervention strategies are the basis for best practice management of IAP, as outlined for example by Transport Infrastructure Ireland (2020) and should be implemented throughout the project.

In the construction phase, key elements are how vegetation is managed during soil handling and storage, and how exposed soil surfaces are managed before active vegetation establishment.

Critical aspects are:

- Provide timely training and information for people working on constructions using existing and region-specific guides with schematic procedures for IAP control on construction sites. This includes online tools and apps for rapid identification of species.
- Map occurrence of IAP along the road transect and temporal construction areas, but importantly, also on adjoining and neighbouring land to plan for management throughout the construction phase.
- Declare and deposit soil infected with high-priority invasive alien species according to legal regulations.
- Apply preventive measures to control seed dispersal from established stands in the larger landscape by cutting wind-dispersed species during flowering but well before seed set. If plants are cut too early, a larger number will reflower later in the season. Make agreements with owners of adjoining land early in planning. Ideally, start this management two years prior to construction start.
- Maintain land under cultivation for as long as possible.
- Apply quality control and certification of incoming soils and grade the use depending on the occurrence of IAP. As a topsoil cover, only soils without problematic species (as defined by regional authorities) are accepted. Responsibilities for follow-up monitoring of soils and control have to be developed/programmed.
- Prioritise vegetation composition and management strategy of new road verges and other areas affected by the construction to match the IAP load in the landscape and the potential to support biodiversity. Establish competitive grass vegetation that can be cut frequently where the load is high.
- Keep soil piles covered with competitive grass cover that is regularly cut during temporal storage and keep areas around piles free of invasive species and aggressive weeds through regular mechanical or chemical control. To allow for this, provide proper design of piles with gentle slopes, and sufficient area between piles to allow for machinery to do mechanical weed control. Geotextiles may only be used for short-term solutions, as they are less effective in protecting against IAP and do not maintain the soil quality as well as a vegetation cover. Monitoring of the efficiency of preventive measures and adaptive management/control is to be part of the quality control.
- Start monitoring of road stretches immediately after completion to support early detection and preventive action. Establish procedures to report the detection of IAS. Do not wait until the project is handed over from the contractor. Monitoring IAP should be required in the process of EIA.
- In many road projects large amounts of soil are already infected by IAP and emerging technologies, such as soil steaming, show promising results. As an example, one prototype from SoilSteam AS has given 100% control of IAP, including Japanese Knotweed (*Reynoutria japonica*) and lupins

(*Lupinus polyphyllus*), at a capacity of up to 40 tons soil/hour. Soil treated by this method can be reused e.g., in urban greening.

3.8 Key recommendations for the road construction phase

- **Identify and allocate suitable soil qualities in the road project for compensation measures and landscaping**
- **Establish protocols to predict risks of soil compaction due to heavy machinery and during soil storage. Predictions can be chart-based systems or simple decision trees based on relevant soil data and choice of machinery can be based on models such as Terranimo.**
- **Establish protocols for day-to-day management of machinery and operations based on soil moisture measurements to prevent soil compaction. Make sure that personnel are trained in the chosen system, preferably on site.**
- **Manage surface water on site with flexible drainage systems that can be adapted to terrain modifications.**
- **Store stripped soil in separate piles for each soil horizon. Design the piles for simple vegetation management and seed with a competitive grass for long term storage to prevent weeds and invasive species.**
- **Rebuild soil profiles for landscaping and compensation measures horizon by horizon, either with area- or strip filling. Provide careful agricultural management of freshly restored soil for at least four to five years.**
- **Loosen compacted soil under access roads and storage areas on completion using excavators. Verify that drainage systems are functioning.**
- **Manage soils with pathogens or invasive species according to current legislation. Apply quality control and certification of incoming soils and grade the use depending on the occurrence of invasive plant species**
- **Apply preventive landscape management of invasive plant species. This includes training of personnel, mapping of invasive species along the road transects, on temporal construction and storage areas, and on adjoining and neighbouring land, and targeted species-specific strategies to prevent dispersal**

4 SOIL MANAGEMENT DURING ROAD OPERATION AND MAINTENANCE

4.1 Current challenges of soil protection under road operation

During road operation, the soil is normally only exposed to a low potential of negative impacts. However, two important aspects need to be considered. On the one hand, there can be an increased infestation of invasive alien plant species along roads, as vehicles lead to the spread of IAP in particular (see 4.3 below). On the other hand, soils along roads are often exposed to pollution.

4.2 Management of excavated soil

Excavated soil from trenches, ditches, sedimentation basins etc. along roads can be contaminated by a diverse cocktail of microplastics, de-icing salts, organic compounds, and metals, usually well above thresholds for suitable reuse. In most cases, the only alternative is landfilling of deposits on public authorised landfill sites, according to the legislation (EU Landfill Directive or similar regulations). In some countries, this also includes content of high priority invasive species. Upon analyses, excavated soil may however also be declared for other use along the road. Quality control of excavated soil and graded use depending on the documented levels of contaminants, is recommended. Recent developments of industry grade solutions to clean soils may provide a more sustainable management of some excavated soils in the near future.

4.3 Management of invasive alien plant species

For soil management, IAP control is mainly about sustainable approaches to prevent establishment, dispersal and accumulation of seeds and other diaspores on and in the soil. Management of IAP in general and information on the more problematic species are given elsewhere. An important part of this is to raise awareness about preventive measures during regular management, but also during repair and reconstruction. Key elements are as follows:

- Use inventories to map occurrence of prioritised IAP along roads and collect information on their growth and development throughout the year to find the best times to do management. The key is to prevent seed set, but also deplete resources by repeated cutting. Match this information with maps or information on the more sensitive areas and road verge stretches of high ecological quality, to prioritise actions. This depends on routines and responsibilities being developed and programmed.
- Involve environmental authorities responsible for managing IAP and landowners next to the road with similar challenges. Decide where to prioritize action.
- Apply adaptive cutting regimes where cutting frequency and timing is adjusted close to existing populations of IAP to prevent expansion. This

includes cutting equipment and methods that do not damage the vegetation cover and leave patches of exposed soil.

- When maintenance leaves areas of exposed soil within a few hundred metres from stands of invasive species, make sure these areas are seeded as soon as possible to re-establish vegetation cover and prevent establishment of unwanted species. This could be achieved by bringing suitable seeds on the machinery or establish routines that regularly or timed to periods after management, spot and reseed such patches of exposed soil. For larger work such as cleaning of ditches and trenches, this needs to be included in the protocols also including responsibilities for follow-up monitoring and actions. This strategy is clearly in conflict with strategies to promote biodiversity, where patches of bare soil are important for the vegetation dynamics. So, apply the reseeding strategy only where it is needed.
- Management of the more problematic IAP requires species-specific actions for control and eradication. These methods are well documented and often involve soil disturbance. Make sure vegetation is re-established in exposed soil as above.
- To prevent build-up of a soil seedbank requires repeated cutting of established stands to prevent seed set and seed ripening. Remove cut material to prevent post-ripening of seeds, recirculation of nutrients and potential negative effects of shade and chemical leaching from plant material.
- Research has shown that seed transport with maintenance machinery is an efficient dispersal for some of the IAP, as *Lupinus polyphyllus*. Make sure that cleaning of machinery between assignments is part of the quality work of the contractors.
- Apply a logistics system where batches of excavated soils from trenches, ditches etc. that contain invasive species diaspores are labelled and traceable. Target reuse to areas where the respective species may be controlled, or where the soil will be covered by a layer of clean soil. Legislation may limit the reuse of soils with certain IAP.

4.4 Key recommendations for road operation and maintenance

- **Excavated soil from trenches, ditches, sedimentation basins etc along roads can be contaminated and has to be declared according to analyses of content and reused or disposed according to current legislation.**
- **Continue monitoring and management of invasive plant species along roads and apply preventive measures such as adaptive cutting regimes and prevention of exposed soil close to established stands.**

5 CAPACITY BUILDING AND TRAINING

5.1 Challenges in capacity building and training

Training of the personnel who handle soil on construction sites is a key measure for soil protection (Geiges and Tobias, 2022). The challenge is still how to declare specific training as a requirement for attaining the building permission or closing a contract. Training courses providing certificates might be a solution (see example 11).

Although in some European countries technical knowledge on soil protection in road construction has been established among various actors, it still needs to be translated into policies. Decision-makers play a decisive role in developing regulations for environmental protection but are often unaware about soil as a life supporting natural resource.

Further, much of soil handling and management in road projects depends on specialised expertise. Hence, road projects would benefit from improved interaction between administrations, larger contractors and soil experts from evaluation of offers and competence, details of the EIA and soil management plans and monitoring. This would require internal capacity building with road authorities that also includes a stronger ownership of knowledge development and data management and will enable knowledge exchange across sectors.

5.2 Training of specific target groups

Specific training courses for soil experts working on construction sites have a strong impact on soil protection according to experiences from Germany, Norway, Austria, and Switzerland. The key players in soil protection in (road) construction are soil experts and the operators of the construction machines. Consequently, these target audiences should be addressed with specific training courses. However, decision-makers should also be informed better about soil as a resource. Specific courses for them are rare, the course “Soil Science for Policymakers” at Cornwall College (UK) is an example.

The Swiss training course of certified soil protection experts for construction sites qualifies environmental experts to advise the construction managers about soil protection measures in the planning and construction phases of road projects (Example 11). These soil experts are instructed to interpret soil maps and do the field investigations particularly for construction sites, and to supervise the soil protection measures on the construction sites.

The Norwegian Research Institute NIBIO offers an on-site training course for machine operators/ contractors (Example 12). In this course, the machine operators learn to distinguish soil layers according to their colours, to assess soil structure and measure soil moisture in field by soil moisture sensors. Moreover, they learn about the relationship between the properties observed in soil profiles and those visible from the excavator’s driver seat which enables them of careful soil translocation and restoration. If these practical courses are directly related to the specific road projects, where local climate, soil properties and management operations are discussed, the following up of the construction work is easier for the road builder.

The video produced for the ROADSOIL project about practical management of soil materials for reconstruction of agricultural soils will be a good contribution as educational material for contractors, consultants and road builders. The video is available at VIMEO (https://vimeo.com/829180968/7007adda53).

5.3 Key recommendations capacity building and training

- **Establish structures for training and certification of independent soil experts for road projects in cooperation with academic or professional organisations. These experts can follow specific road projects from planning to completion ensuring proper soil management.**
- **Establish and promote systems for on-site training of machine operators and contractors for best-practice soil management. This will facilitate networks across contractors, academic- and professional organisations.**
- **Promote in-house training and capacity building of national and regional road authorities to promote stronger ownership and understanding of soil data generated in soil projects, and improved focus on soil management in tender processes.**

Example 11. Certified soil protection experts for construction sites

Location: Switzerland

Expertise: A private company (sanu future learning ag) offers training to become a soil protection expert on construction sites which builds on the basic knowledge of a science or engineering degree and with the basics of soil science. The course ends with a mandatory exam to obtain certification.

Certification: The Swiss Soil Science Society certifies the soil protection experts on construction sites according to their “regulations for the certification as soil protection expert on construction sites” (Swiss Soil Science Society, 2005). The society’s board appoints the “commission of selection and acknowledgement” who awards the candidates the title of “Soil Protection Expert on Construction Sites of the Swiss Soil Science Society” (SPECS-SSSS). The certification is not only based on courses and a final exam, but also work experience and credentials from the authorities as well as construction companies are required. Successful graduates are listed on the Swiss Soil Science Society’s website as “certified soil protection experts on construction sites”. Cantonal soil protection offices usually prescribe the appointment of such an expert during the environmental impact assessment (EIA) for which they refer to the SSSS-list.

Challenges: During a transition phase of several years, experienced professionals could achieve their certificate without examination but by proving their experience with the relevant documentation. This ensured fair conditions for both newly trained and experienced experts, which in turn made the certification system attractive for all involved.

Course Content:

- **Basics of soil science**: soil diversity, formation, structure and functions, as well as soil diagnostics and analysis and soil restoration. Management of invasive alien species (IAS).
- **Basics of soil protection:** the role of soil protection experts and authorities as well as the legal system and the approval process for construction permits in the context of different land use systems (e.g., forestry or agriculture).
- **Soil protection techniques:** measures to protect the soil, e.g., against pollution, compaction or erosion, and measures to repair any damage caused, and the related costs of such measures.
- **Tendering, planning and construction phases:** basic knowledge about designing a construction project, organisation of a construction site, construction phases, techniques and machines as well as the roles and tasks of the various actors involved.
- **Communication techniques** including conflict management and negotiation.
- **Case studies and practical exercises**

Example 12. Training of machine operators on site
Location: Norway
Expertise: Soil experts with experience from construction projects
Equipment: Excavator (provided by contractor), soil moisture sensor kit (e.g., Delta T ML3, SM150 or similar), spade, measuring tape, Munsell Soil Color Charts
Challenges: Site specific, practical course on soil properties, terminology and description of soil horizons
Training content: ➢ Soil horizons (A-, B-, C- and organic horizons) ➢ Borders between horizons ➢ Soil colours, mottles and drainage properties ➢ Soil structure, types and grade ➢ Soil consistence at description (crumbling, stickiness, plasticity) ➢ Depth of root development ➢ Stones and boulders ➢ Drainage systems and observations of free water ➢ Soil moisture measurements, ground water table ➢ Soil properties which can be observed from the seat in the excavator (horizons, colour, structure, consistence, stones and boulders, hard layers)

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APPENDIX 1

Practical guide to the in-field decision aid tool to assess soil strength

Executive summary

Soil compaction negatively affects soil functions including food production, water cycling, climate regulation, and biodiversity. To prevent soil compaction by construction machinery, mechanical soil stresses exerted by machinery need to be evaluated against the soil's tolerance to compression stress (soil strength) prior to soil work. Soil strength is a dynamic soil property that may change day-to-day because it does not only depend on soil texture but also on the actual soil moisture content. Here a decision tree model is presented for daily in-field use by contractors. Knowledge of soil texture (sand, silt, clay content) and soil moisture status (represented by soil moisture tension) is required for using the model. The model will estimate soil strength (represented by precompression stress in kPa) that is to be compared with soil stress exerted by the machinery to be used. This decision aid tool will help deciding which of the machines – if any – can be used on the given soil in its given moisture condition.

Introduction

Soil compaction is a recognised soil threat that is known to impair or alter many of the soil's functions. Therefore, appropriate measures should be taken at road construction sites to reduce the occurrence of soil compaction, and preferably avoid it altogether. The ROADSOIL project developed and optimised a human-readable decision tree model that helps avoid soil compaction when using construction machinery.

A European database of basic physical and mechanical soil properties has been assembled and used to test a variety of predictive decision models that differed in the amount of soil properties used as input parameters. The study concluded that the minimum information for reliable predictions of soil strength (i.e., the soil's tolerance to compression stress) is the soil's texture and its current moisture status. In a second step, the estimated soil strength is compared to the expected soil stress by construction machinery.

Input requirements

In order to use this decision-aid tool, the user needs three pieces of information:

1. **Soil texture:** This is a static soil property that is derived from the soil's particle (or grain) size distribution. Prior to the start of construction, a soil map should be consulted to identify the soil texture classes of the affected areas. Once those are delineated, bulk soil samples need to be collected from both the topsoil and the subsoil of each soil unit. In the laboratory, these samples are analysed for soil particle-size distribution. The sand, silt and clay content need to be determined and reported in mass %, where the three values need to sum to 100%. As soil texture is a static soil property, these data need to be collected only once, during the planning phase or just prior to the beginning of construction work.

2. **Soil moisture status:** This is a dynamic soil property that may change unfavorably within a short time, especially in the event of rain. Therefore, soil moisture status should be checked every time prior to starting soil-work, and potentially revised in the case of rainfall during construction work. The

decision model uses *soil moisture tension* as moisture status indicator, which is measured by a hand-held tensiometer designed for in-field use. The device should be used according to the manufacturer's instructions and its readings should be recorded. Depending on the tensiometer model, it may display soil moisture tension (or suction, a positive value) or soil matric potential (a negative value). In case of the latter, soil moisture tension is the positive equivalent of the negative matric potential, and it needs to be converted to hPa (hectopascal) in case it is displayed in another unit.

Depth of soil moisture sensing: It is most important that subsoil compaction is avoided, given that it cannot be remediated with conventional tillage. Therefore, soil moisture tension should be measured in the subsoil. Based on experience in Switzerland, 35 cm depth is recommended. However, a soil expert should decide about the applicable locations and depths of soil moisture measurements according to the soil types and texture assessed in point 1.

3. **Soil stress caused by machine loading:** This information is specific to the machine to be used, the track characteristics or tyre type and inflation pressure. Each such combination will exert a certain amount of compressive force (stress) due to wheel loading. Soil stress needs to be known for the given machine and the target depth (e.g., 35 cm) and expressed in kPa. This value is then compared to the precompression stress values predicted by the decision tree model and the result of the comparison provides the basis for the contractor's decision with respect to performing work with a particular machine on the particular soil in its given moisture condition.

The decision tree model and its use

The developed decision tree is presented on the last page of this Appendix. When the user is familiar with its use and interpretation, it can be used as a stand-alone tool. In the following, the tree model and its use are demonstrated using a narrated copy on the next page.

As described, the user will need to know the soil's sand, silt and clay content and its actual soil moisture tension in order to use the tree model. Using the tree model essentially means the application of a series of logical (YES-NO) decisions using the required input data and the presented criteria in the model. To demonstrate the model's use, we are going to use the example of a hypothetical test soil that has 22% sand, 46% silt, and 32% clay content, and has a soil moisture tension of 100 hPa.

Reading the tree model starts from the top, and each subsequent step is conditional to the outcome of the previous step. Each squared box presents a decision criterion (question), and each grey balloon presents an estimated precompression stress value in kPa. For each soil texture and soil moisture tension, there is only one possible outcome, and once a grey balloon is reached, there are no further steps to take. Coloured arrows provide visual aid to follow the different steps of using the decision tree for the test soil.

STEP 1: The user reads the first criterion on soil moisture tension, and follows the branch to the second level according to the outcome of the logical decision. For the test soil defined above, the response to the first question is YES (100 hPa is less than 318 hPa), therefore we follow the **LEFT** branch.

STEP 2: For our test case, the user is next asked if sand content is greater than or equal to 7.1%, for which the answer is yes (22% is greater than 7.1%), therefore once again the **LEFT** branch is followed.

STEP 3: Since we did not reach a grey balloon yet, a 3rd criterion is checked, which is again related to soil moisture (is soil moisture tension < 135 hPa?). Given the value of the test soil (100 hPa) we again choose the **LEFT** branch, and answer an additional question.

STEP 4: At the 4th level clay content must be compared (IF >=13%), and for the test soil the answer is yes once again, i.e. the **LEFT** branch is followed, and a 5th question is asked.

STEP 5: At the 5th level silt content must be compared (IF >= 62%), and for the test soil the answer is no, thereby the **RIGHT** branch is followed, and a grey balloon is reached with a value of 75 in it.

In this case, a sequence of 5 logical responses (LEFT-LEFT-LEFT-LEFT-RIGHT decisions) have provided an estimated 75 kPa precompression stress value for the test soil. Naturally, the set of questions and decisions will differ for each soil. It is conditional even for the same soil since its moisture status will keep changing. For example, if soil moisture tension for the same soil was e.g., 400 hPa, we would have reached the final estimate in only 2 steps, given that the first answer would have been NO, instead of yes. The same soil may present different values potentially every day.

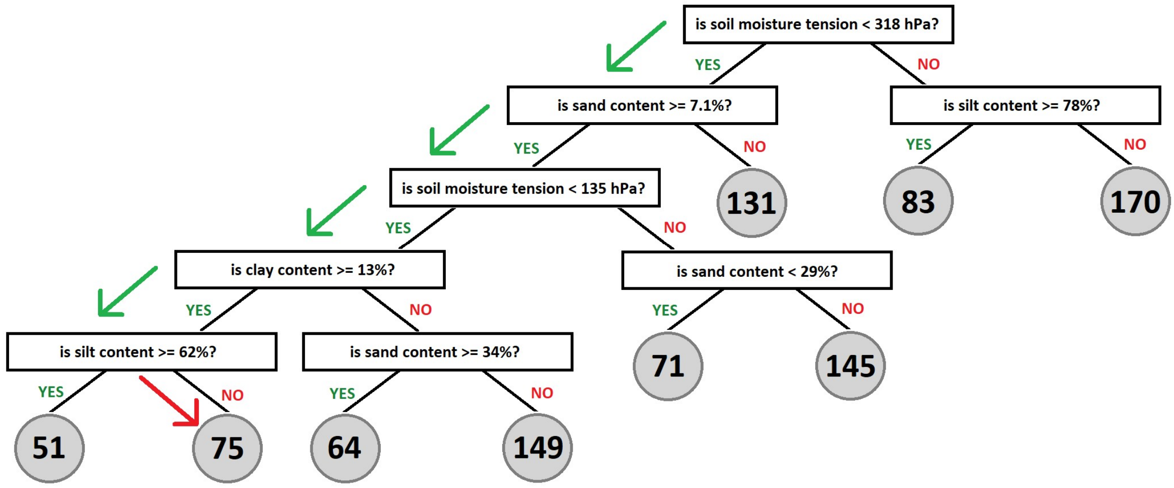

Figure A1: Demonstration of the decision model's use for a soil with 22% sand, 46% silt, and 32% clay content, and a soil moisture tension of 100 hPa. The resulting precompression stress estimate is 75 kPa.

Interpretation of the result - decision outcomes

The demonstrated estimate of 75 kPa precompression stress – the soils tolerance to compression stress. The value from the decision tree needs to be compared with the stress exerted by the machine (in kPa), and the user's decision is guided by how they compare.

- **If soil stress by a machine's loading exceeds the soil's stress tolerance**, the risk of soil compaction is high, the particular machine must not be used to work on that soil in its given moisture condition. The planned work should be delayed, or an alternate machine with lesser than the critical loading should be used.
- **If soil stress by the machine's loading is close to the soil's stress tolerance but does not exceed it**, any work should be done with extreme

care, given that deeper soil layers may be moister (i.e. less stress tolerant). If possible, work should be delayed somewhat, especially if precipitation is forecast for the day.
- **If soil stress by the machine's loading is well under the soil's stress tolerance**, the risk of soil compaction is low, work may proceed with care.

Additional notes:

- Soil and the landscape are variable; therefore, the machine operator may encounter notably wetter, less stress tolerant areas of soil. Work should be delayed on such areas.
- Rainfall may make soils substantially less stress tolerant within minutes or hours. Work should be planned with the weather forecast in mind.

Quick guide to the decision tree model

- Have the soil's sand, silt, clay content and newly measured moisture tension information, measured at the right depth, ready

- Start from the top of the tree, and using the above information make a series of YES-NO decisions until you reach a grey circle. The value in the circle **("A" value** below) is the soil's estimated precompression stress (stress tolerance) in kPa.

- Compare value A with the compaction stress expected from the available machine's (and tyre's) load (**"B" value** below")

  - if A > B, there is low risk of soil compaction
  - if B > A, there is **high risk** of soil compaction
  - if A and B are close, care should be exercised