Protocol for assessment of waste materials for use in reconstructed soils

1. Introduction

1.1 Soil

Soil is a fundamental and finite resource that fulfils a number of functions and services which are central to the health and wellbeing of the planet and all ecosystems, along with sustainable development. Humans are part of the global ecosystem. With the risks associated from climate change ever increasing, it is important to look at the benefits of good soil management and the role of waste materials within a circular economy. This provides an incentive to safeguard these vital resources.

1.2 Threats to soil

Soil degradation is a critical and growing global problem. Increases in the world's population has added to pressure on soil, and its natural capital faces continuing decline[1,2]. One potential solution to the loss and degradation of topsoil is the creation of soils from otherwise waste materials, where appropriate excess materials, generated through construction, or other human activities, as waste, are carefully mixed to create a product with the characteristics of a healthy, functioning soil. These are called *reconstructed soils* and their applications include manufacture of topsoil for urban landscaping and materials for high value markets such as horticulture and agriculture. Reconstructed soils could reduce the pressure on valuable topsoil and support both sustainable development and food security, contributing to a circular economy. Furthermore, as the components of reconstructed soils can be varied, they could be developed to perform *better* than natural soils for their desired functions. As such, a sustainable, highly-performing reconstructed soil deployed for food growth would be a precious resource, adding to efforts to achieve a circular, low carbon economy.

1.*3 Reconstructed soils*

Reconstructed soils are substrates comprised, at least in part, of waste materials produced by human activity. Reconstructed soil differs from *reconstituted soil*; the latter is achieved by adding mineral and organic matter to the top layer of partially degraded soil[3]. While reconstituted soil is a solution to rescue soils on the path to degradation, reconstructed soil is a replacement for completely degraded or missing soil[4]. Reconstructed soils are not a new concept, though their use may exceed the to-date perceived capability of soils made from waste materials. Previous names for reconstructed soils have included artificial soils[5] and technosols[6]. Technosols were classified as a Reference Soil Group from the World Reference Base for Soil Resources[7] that ''combine soils whose properties and pedogenesis are dominated by their technical origin" and include, *inter-alia*, soils derived from wastes originated from human activities. The preparation of Technosols from mixtures of unconsolidated wastes, such as sludges and fly ash, may be an important and feasible method of re-using waste products and restoring degraded areas[8], while at the same time recycling essential nutrients and stabilising the organic matter (OM) present in such materials. Environmental problems resulting from the use of these mixtures can be avoided if the characteristics of the materials employed are well known and adequate for such purposes. Moreover, the characteristics of the final products obtained should be suited to the pedoclimatic conditions and to the types of soil use in the area to be restored.

A number of medium to long-term studies of reconstructed soils has provided the opportunity to assess their performance against natural soils[5,9,10] and the results have been promising. For example, in a mine-restoration study in SE Brazil, reconstructed soils made from limestone spoil and placed under sugarcane (2-7 years) and pasture (20 years) revealed soil quality indices that were similar or superior to an adjacent natural soil, while the carbon stocks in the reconstructed soil under pasture were 2.7 times higher[9]. In northern France, soils were constructed from thermally-treated industrial soil, papermill sludge and green waste compost, and planted with grasses. Over 12 years, organic carbon stocks in these reconstructed soils were up to 5 times higher than in natural analog soils[10]. Schofield et al.[5] studied an organic-rich reconstructed soil comprised of green waste, composted bark, sand and clay from a visitor attraction in SE England, UK, which houses a diverse ecosystem containing thousands of plant species from around the world. Factors such as soil N-retention were in the range expected for natural soils, though the soils appeared to be vulnerable to increased N-loss through the soils becoming carbon-limited. This loss was reduced through biochar addition, highlighting the potential for biochar to both suppress nutrient-loss and promote carbon sequestration[11].

This document presents a protocol (blueprint) for the assessment of a reconstructed soil produced from waste material, and parameters that should be considered. The protocol acknowledges the importance of recognised methods operating within the regulatory systems of England and France for the management of waste materials and soils.

1.4 Regulatory context

Current regulations across the EU prohibit the general reuse of groundworks subsoil, river sediment and quarry sludge (fine clay particles suspended in water) in agriculture. However, motivation to increase reuse and reduce waste disposal has led to recent regulatory changes[12]. These changes incorporate circular economy principles enabling movement of material off-site under specific conditions as set out in the legislation; essentially the material becomes a product if the receiving site can take responsibility for ensuring a match to local terrain and appropriate use. This 'waste recovery' legislation is still in the development phase with new guidance opening up opportunities for reuse in France[13]. A key feature of the guidance is to avoid material being classified as 'waste', by identifying suitable uses for it as early as possible in the life cycle process. Similar guidance in place in England has successfully empowered construction to recycle 88 % of its waste by co-developing 'Soil Management Plans'[14,15] as part of the overall on-site construction strategy. These identify a re-use of top/subsoil and other wastes prior to excavation and the wasteful shipment of materials to landfill. The UK government's 25 Year Environment Plan[16] aspires to the sustainable management of England's soils by 2030, but the Waste Strategy for England[17] does not address the loss of soils to landfills. Furthermore, addressing barriers to the reuse of waste materials is limited to a municipal context, missing the opportunity for addressing waste reuse in sectors outside of construction and local government.

2. Soil components and function

2.1 Physical characteristics of soil

Soil is composed of five ingredients - minerals, soil organic matter, living organisms, air, and water. Soil minerals are divided into three size classes - clay, silt, and sand, and the percentages of particles in these size classes is called soil texture. Soils are classified on the basis of texture. The knowledge of soil texture is critical in managing soils, and governs characteristics such as stability, susceptibility of erosion and the capacity to retain water. As such, a reconstructed soil must have physical characteristics compatible with its proposed deployment.

2.2 Chemical characteristics of soil

The chemical components of soil dictate its quality. Plants and organisms require a number of elements to survive and grow, including carbon and other major and trace elements (nutrients), as shown in Figure 1.

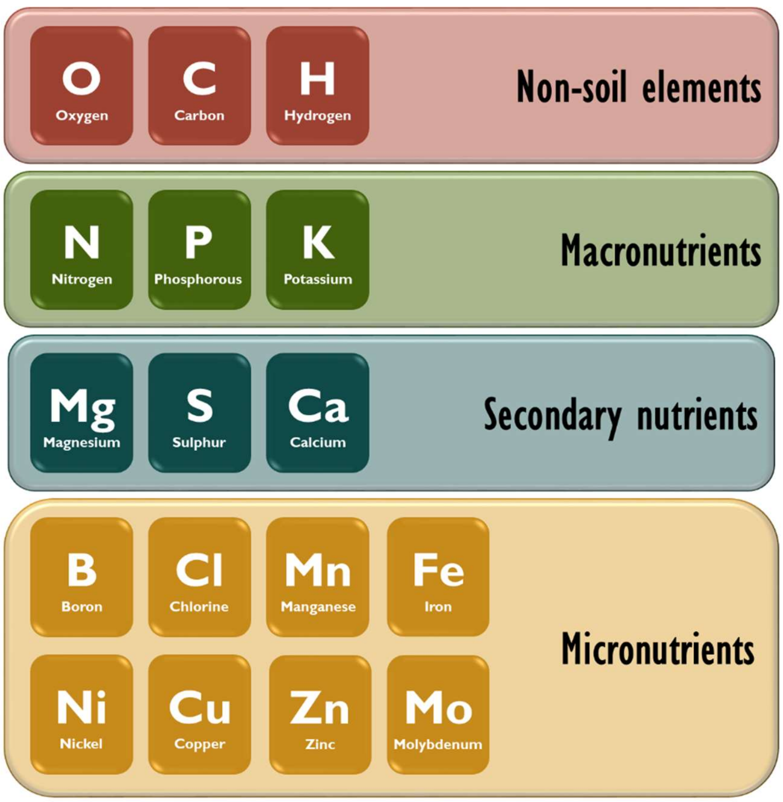


Figure 1. Essential nutrients of soil.

Soil organic carbon offers a range of benefits to soils and the wider environment. It provides structural integrity, a source of nutrients for vegetation, regulation of hydrology and a habitat for the soil organisms that drive a range of key biogeochemical processes[18]. Additionally, increasing soil carbon stocks can help to reduce atmospheric greenhouse gas concentrations, which contributes towards the mitigation of climate change[19].

The primary nutrients required by plants *from the soil* are nitrogen, phosphorus and potassium. Secondary nutrients are calcium, sulfur and magnesium, with other necessary elements referred to as micronutrients (Figure 1).

3. Testing for soil quality

3.1 Assessing soil quality

The complexity of soils creates significant challenges to establishing the robust science base needed to support key decisions on their future management. As such, the management of soil is lower down the list of political priorities and the focus on soil security a more recent development (Johnson et al., 2022)[20]. This situation also creates a space for progress on the appreciation and understanding of soils and waste materials that can act as reconstituted soils or soil amendments. While there may not be universal agreement on the determinands of soil quality, outside of a specific application (e.g. geotechnical or agricultural), a spectrum of analyses to characterise the quality of a soil is desirable as a means of assessing its suitability for a particular purpose. The Food and Agriculture Organisation of the United Nations (FAO) has identified 7 key soil qualities for crop production, based on the Harmonised World Soil Database; these are shown in Table 1.

Table 1. Soil qualities and related soil characteristics based on the Harmonised World Soil Database

Soil Qualities (SQ)	**Soil Characteristics**
SQ1 Nutrient availability	Soil texture, soil organic carbon, soil pH, total exchangeable bases
SQ2 Nutrient retention capacity	Soil organic carbon, soil texture, base saturation, cation exchange capacity of soil and of clay fraction
SQ3 Rooting conditions	Soil textures, bulk density, coarse fragments, vertic soil properties and soil phases affecting root penetration and soil depth and soil volume
SQ4 Oxygen availability to roots	Soil drainage and soil phases affecting soil drainage
SQ5 Excess salts	Soil sodicity and soil phases influencing soil conditions
SQ6 Toxicity	Calcium carbonate and gypsum
SQ7 Workability (constraining field management)	Soil texture, effective soil depth/volume, and soil phases constraining soil management (soil depth, rock outcrop, stoniness, gravel/concretions and hardpans)

The parameters of soil amendments, such as compost, are assessed and, in the UK, should meet the British Industry Standards (BSI) PAS-100 certification. The management of soils in construction within the UK should be carried out in line with the Code of practice for the sustainable use of soils on construction sites, which includes reconstructed soils.

The deployment of a reconstructed soil will take into account the local catchment and underlying geology as well as the needs of the plan into which it is to be integrated. As such, threshold levels for parameters or components may be less important, and useful, than information on what is needed and how the soil can be tested and prepared to meet these needs. Table 2 shows a number of parameters which are deemed to be key to assessing the quality, and suitability of the soil. The parameters fit within the seven SQ indicators presented in Table 1 and can be analysed by established techniques, which are also included and explained.

Table 1. Threshold measurements for soil quality/health

Measurement	Technical options	Comments	Requirements
Soil Organic Carbon	Loss on ignition (LOI);	Loss on ignition (LOI) is one of the most widely used methods for measuring organic matter content in soils but does not have a universal standard protocol. The ignition temperature and duration should be noted as part of the analysis (Hoogsteen et al. 2015) [21] – *note limitations below.*	Muffle furnace
	Elemental analysis	Elemental Analysis can also measure total carbon and organic carbon, with the latter parameter requiring acid pre-treatment. Without this the value would be **total carbon**, which would not be sufficient for soils with a **high inorganic carbon content**.	Elemental analyser
Total Nitrogen	Elemental analysis	This does not necessarily indicate the bioavailability (plant availability) of nitrogen within the soil. If this is needed then an extraction of the soil, using an appropriate extractant, should be performed and the pre- and post-extraction nitrogen concentration measured in the soil.	Elemental analyser, freeze drier

Total Phosphorus Plant-available phosphorus	Inductively coupled plasma – optical emission spectrometry (ICP-OES). The soil sample is digested in a strong acidic solution prior to analysis. Olsen P method	This technique can also measure concurrent metal concentrations, which can serve as a further check on soil quality with reference to contaminants. This is a tried and tested approach in the agriculture sphere for the measurement of plant-available phosphorus. It may be inappropriate for mildly to strongly acidic soils, with pH at or below 6.5 (do Corma Horta and Torrent, 2007)[22].	Inductively coupled plasma optical emission spectrometer, acidic reagents for digest. A UV-vis spectrophotometer and chemical reagents to form a colorimetric complex. https://www.fao.org/3/cb3644en/cb3644en.pdf
pH	pH meter (in suspension with high purity water)	pH paper may be used, depending on the resolution needed.	pH meter; buffer solutions (pH 4, 7; pH 10 optional)
Cation Exchange Capacity	Can be estimated based on LOI and clay content Ammonium acetate method	 This is an established method involving treatment of the soil with salt solution to measure CEC using ammonium as the proxy cation.	 UV-vis spectrophotometer (Dal Pont et al., 1974)[23] or fluorimeter (Holmes et al., 1999)[24] for measurement of ammonium, and derivatising reagents required for the respective methods.
Potentially Toxic Elements (PTE)	Inductively coupled plasma – optical emission spectrometry (ICP-OES). The soil sample is digested in a strong acidic solution prior to analysis.	PTE levels are generally contextualised in this way. It is important to note that levels of PTEs may vary naturally depending on catchment and may not be correlated with PTE availability. If the latter is required then an extraction step may be desirable.	Inductively coupled plasma optical emission spectrometer, acidic reagents for digest.

Soil texture	% sand, silt and clay Sieve soil to 2 mm to measure the proportion of material > 2 mm. Use appropriate mesh size to distinguish sand, silt and clay from each other.	Sand 0.05-2 mm Silt 0.002-0.05 mm Clay < 0.002 mm	Sieves of appropriate mesh sizes
Water holding capacity (WHC) and available water capacity	Soil saturation with high purity water, followed by a period to allow gravitational water to dissipate. This will yield WHC for a soil (g water held / g of dry soil present). Subsequently, soil at its WHC needs to be placed under suction and water released up to a suction pressure of 1500 kPa measured. Available water being g water released between WHC and 1500 kPa / g dry soil present).	Knowing how accommodating soil media is to water, this parameter would be useful to predict, for example, waterlogging or drought stress.	Gravimetric apparatus

4. Waste materials deployed in the ReCon Soil Project

The following sections present information on the waste components used to create or amend soils during the ReCon Soil project. Each soil contained at least one waste component and information on the waste material and its extraction and deployment are shown. All soils and soil amendments were trialled experimentally.

4.1 Clay amendment added to agricultural soil (*Reconstructed Soil 1*)

This waste component was extracted from a site as close as possible to the site of deployment. Its characteristics are described in Table 3

Table 3. Description of a clay-laden excavated soil used as a soil amendment.

Component description	Excavated soil coming from clayey lithology, sourced in Brittany, France.
Need/potential use for component	Improves the structure of silty soils subject to crusting and flooding; improves moisture content and water holding capacity of the soil.
Assessment/treatment needed prior to deployment in a reconstructed soil as a soil amendment.	Treatment was needed to optimize its mixing with soil: i) wet treatment consisting of mixing this component with water and spraying the amendment directly onto the soil before ploughing, as shown in the photo below.  ii) dry treatment, consisting of drying and crushing this component, and dispersing the resulting powder directly onto the soil before ploughing (not tested in ReCon Soil, but tested in other projects).

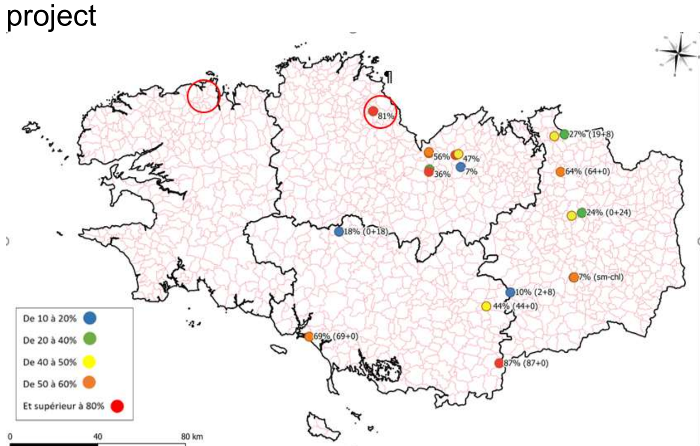
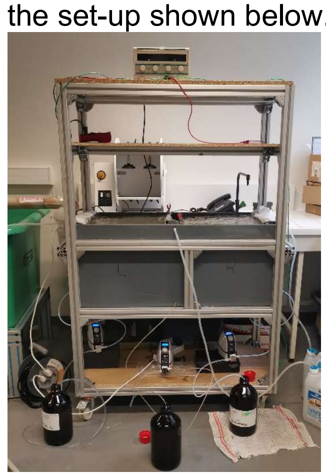
<table>
<tr>
<td>Other considerations (e.g. abundance and proximity to deployment site)</td>
<td>The availability of this component depends on the earthworks close to deployment site. A Life Cycle Analysis (LCA) shows that the distance of the earthworks to the deployment site should not exceed 30 to 50 km. Moreover, not all the lithologies in Brittany are suitable (e.g. they don’t contain enough clay minerals). For this project, the excavated soils came from a site located in the commune of Lanvollon in the Côtes d'Armor (empty red circle encircling the 81% below) which was chosen because it met two main criteria:
- It was the closest to the experimental site of CATE in Saint-Pol-de-Léon (second empty red circle in Figure 1);
- the Clay fraction (< 2 mm) contained 81% smectite and other swelling minerals.
This site was located > 30 km from the deployment site of CATE, but was selected for the needs of the project


Figure 1. Samples with XRD analysis in Brittany containing swelling minerals (smectite etc.) - XRD analysis carried out as part of the mapping of the shrinkage and swelling hazard in Brittany.</td>
</tr>
</table>

4.2 Dredged sediments added to agricultural soil (*Reconstructed Soil 2*)

This waste component comprised reclaimed and treated sediment. Its characteristics are described in Table 4

Table 4. Description of a dredged sediment used as a soil amendment.

Component description	Dredged estuarine sediments from Tancarville (Seine River tributary), France.
Need/potential use for component	The sediment increases the organic and carbonate contents of soils, which in turn improves the structure by forming aggregates that reduce soil erosion. The high organic matter content and fine texture also improve the water holding capacity. The sediments are rich in nutrients that are required by plants, such as P, N, K, and S.
Assessment/treatment needed prior to deployment in a reconstructed soil as a soil amendment.	The dredged sediments are analysed and characterised in terms of physico-chemical properties (mainly pH and electric conductivity or salinity), grain size distribution (or texture), and metal, mineral, organic, and carbonate contents. Accordingly, the sediments are be treated to make them safe for use in reconstructed soils (e.g. reduce salt and metal contents). The treatment method used was electrokinetic remediation. Sediments were brought to the lab and treated for up to 21 days. 120 L of sediment can be treated at a time, using the set-up shown below.  The treated sediment was re-analysed after treatment to assess its suitability for addition to soil.

Other considerations (e.g. abundance and proximity to deployment site)	The dredged sediments were collected from Tancarville, which is ~28 km away from the lab where the sediments were treated. Sediments are periodically dredged from this region and therefore relatively abundant as a resource. There are also nearby depositional sites where dredged sediments are stored. After treatment, the sediments were transported to the experimental site (CATE, Saint-Pol-de-Léon), which is ~430 km from the lab. A better alternative, going forward, would be sediments reclaimed from a site closer to the planned deployment site.

4.3 A reconstructed soil from organic and inorganic waste components *(Reconstructed Soil 3)*

This reconstructed soil comprised reclaimed and treated sediment. Its characteristics are described in Table 5

Table 5. Description of a dredged sediment used as a soil amendment.

Component description	*Green waste:* 32.5 % of soil to provide a readily degradable source of organic material. *Composted bark:* 32.5 % of soil to provide bulk, structure and a more slowly degrading organic material. *Sand:* 25 % of soil to provide a mineral component and structure, aiding soil drainage. *Clay:* 10 % of soil; lignite clay – a waste product of china clay extraction.
Need/potential use for components	The components mixed together in these proportions create a soil that has been deployed under different climatic conditions (e.g. Eden Project, Cornwall). 
Assessment/treatment needed prior to deployment in a reconstructed soil as a soil amendment.	Treatment beyond the composting process is not required, based on a spectrum of analyses on the mixed soil (e.g. metal analysis).
Other considerations (e.g. abundance and proximity to deployment site)	Green waste can be sourced from local municipal operations; sand and clay are available as waste products of industrial operations in Cornwall, UK.

References

1. Banwart S (2011) Save our soils. Nature 474:151–152
2. Koch A, McBratney A, Adams M et al (2013) Soil security: solving the global soil crisis. Global Policy 4:434–441.
3. Séré, G., et al. (2008). "Soil construction: A step for ecological reclamation of derelict lands." Journal of Soils and Sediments **8**(2): 130-136.
4. Vidal-Beaudet, L., et al. (2012). "Modelling long-term carbon dynamics in soils reconstituted with large quantities of organic matter. European Journal of Soil Science 63, 787–797." European Journal of Soil Science **63**: 11.
5. Schofield, H.K., Pettitt, T.R., Tappin, A.D., Rollinson, G.K., Fitzsimons, M.F. 2018. Does carbon limitation reduce nitrogen retention in soil? Environ. Chem. Lett. 16 (2), 623–630.
6. M. Camps Arbestain, Z. Madinabeitia, M. Anza Hortalà, F. Macías-García, S. Virgel and F. Macías. 2008. *Extractability and leachability of heavy metals in Technosols prepared from mixtures of unconsolidated wastes.* Waste Management 2008 Vol. 28 Issue 12 Pages 2653-2666.
7. IUSS Working Group WRB, 2006. World reference base for soil resources. 2006. World Soil Resources Reports 103, FAO, Rome, Italy.
8. Punshon, T., Adriano, D.C., Weber, J.T., 2002. Restoration of drastically eroded land using coal fly ash and poultry biosolid. Science of the Total Environment 296, 209–225.
9. Ruiz, F., et al., 2020. Soil quality assessment of constructed Technosols: Towards the validation of a promising strategy for land reclamation, waste management and the recovery of soil functions. Journal of Environmental Management 276, 111344.
10. Rees, F., et al., 2019. Storage of carbon in constructed technosols: in situ monitoring over a decade. Geoderma 337, 641-648.
11. Schofield, H.K., et al., 2019. Biochar incorporation increased nitrogen and carbon retention in a waste-derived soil. Sci. Total Environ. 690, 1228-1236.
12. EC (2020). Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the regions- A new circular economy action plan for a cleaner and more competitive Europe. COM(2020) 98 final of 11 March 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN.
13. Legifrance (2022). Code de l'environnement. [Environmental Code] "Title IV: Waste (Articles L541-1 to L542-14)". https://www.legifrance.gouv.fr/codes/section_lc/LEGITEXT000006074220/LEGISCTA000006143752/#LEGISCTA000006143752, Republique Francaise.
14. CLAIRE (2011). The Definition of Waste: Development Industry Code of Practice. https://www.claire.co.uk/component/phocadownload/category/8-initiatives?download=212:definition-of-waste-development-industry-code-of-practice, Defra.
15. CLAIRE (2014). Use of the definition of waste: Development industry code (DoW CoP) in London and the South East.

16. Defra. 2018. 25 Year Environment Plan https://www.gov.uk/government/publications/25-year-environment-plan
17. Defra. 2018. Resources and waste strategy for England. https://www.gov.uk/government/publications/resources-and-waste-strategy-for-england
18. P.E. Levy, C.D. Evans, P. Smith, (2009). UK land use and soil carbon sequestration, Land Use Policy, Volume 26, Supplement 1, pp. S274-S283, ISSN 0264-8377, https://doi.org/10.1016/j.landusepol.2009.08.006.
19. Bossio, D.A., Cook-Patton, S.C., Ellis, P.W. *et al.* The role of soil carbon in natural climate solutions. *Nat Sustain* **3,** 391–398 (2020). https://doi.org/10.1038/s41893-020-0491-z
20. Karen L. Johnson, Neil D. Gray, Wendy Stone, Bryce F.J. Kelly, Mark F. Fitzsimons, Cathy Clarke, Lynsay Blake, Stephen Chivasa, Florence Mtambanengwe, Paul Mapfumo, Andy Baker, Sabrina Beckmann, Lena Dominelli, Andrew L. Neal, Tariro Gwandu. 2022. A nation that rebuilds its soils rebuilds itself- an engineer's perspective. Soil Security 7, 100060, ISSN 2667-0062 ; https://doi.org/10.1016/j.soisec.2022.100060.
21. Hoogsteen, M.J.J., E. A. Lantinga, E. J. Bakker, J. C. J. Groot, P. A. Tittonell. 2015. Estimating soil organic carbon through loss on ignition: effects of ignition conditions and structural water loss. European Journal of Soil Science 66, 320-328. doi: 10.1111/ejss.12224
22. do Carmo Horta M., José Torrent. 2007. The Olsen P method as an agronomic and environmental test for predicting phosphate release from acid soils. Nutrient cycling in Agroecosystems 77, 283-292.
23. Dal Pont, G., Hogan, M., Newell, B., 1974. Laboratory techniques in marine chemistry. II. Determination of ammonia in seawater and the preservation of samples for nitrate analysis. Commonwealth Sci. Indust. Res. Org., Div. Fish. Oceanogr. Rep., 55, 8 pp.
24. Holmes, R.M., Aminot, A., Kérouel, R., Hooker, B.A., Peterson, B.J., 1999. A simple and precise method for measuring ammonium in marine and freshwater ecosystems. Can. J. Fish Aquat. Sci. 56, 1801–1808.