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Characteristics of residues from heathland restauration and management: implications for their sustainable use in agricultural soils or growing media

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Abstract Heathlands are among the most important semi-natural cultural landscapes in Northwestern Europe. High-intensity management techniques are necessary to restore and maintain their unique flora and fauna, but generate substantial amounts of residues that have no sustainable reuse so far. This research therefore aims at characterizing these residues and at evaluating their potential as soil amendment or growing medium constituent. Residues are primarily characterized based on their origin and on the management technique used to extract them. We evaluated the spatial distribution of the different residue types and assessed if the used typology also reflects the physicochemical characteristics of the extracted product, by cluster analysis. Finally, the characteristics of the residues were compared with industrial standards and legal limits for growing media or soil amendments and to other growing media constituents. Our results show a difference between extraction techniques, where sods (plaggen) from forests and heathlands have higher bulk densities, lower organic matter contents, lower organic compounds and lower biodegradation potential, compared to heathland chopper. Analyses further confirm the potential of the residues as a raw material for growing media or soil amendments. pH and EC values fall within acceptable ranges (<6 and <750 µS/cm) and nutrient contents are low, with beneficial effects on C:N and C:P ratios. Field and pot experiments are now needed to evaluate effects on plant growth.

Novelty Statement The local and sustainable valorization of residual biomass is increasingly important for a circular economy. Nature restauration and conversion projects in heathlands and forests across western Europe generate substantial amounts of biomass, which is not effectively utilized due to a lack of knowledge regarding spatial distribution, temporal availability and material heterogeneity and characterization. This study proposes to classify these residues in types, depending on their origin in terms of vegetation type and the extraction technique used. For each type, the physicochemical properties are evaluated and compared to industry standards for use in sustainable growing media component or in soil amendments.

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1. Introduction

Heathlands are among the most important semi-natural cultural landscapes in Northwestern Europe, and are considered as an endangered habitat [1]. Their status as ‘Special Areas of Conservation’ under the EU Habitat Directive (92/43/EEC) and inclusion in the Flemish Ecological Network have offered an increased protection for the conservation of these endangered habitats, yet underline the importance of appropriate management [2, 3].

High-intensity management techniques have been designated as necessary to reestablish the original flora and fauna in heathlands, regenerate dwarf shrubs and prevent the succession to other vegetation types [2, 4]. The two most effective methods in preserving and re-creating the open character of heathlands are plaggen and choppering [2, 5, 6]. Plaggen (or sod-cutting) implies the removal of the complete above-ground biomass, the ecto-organic layer and part of the soil’s A-horizon. Choppering is in essence a technique in between mowing and plaggen, which removes the above-ground biomass and part of the ecto-organic litter layer but leaves the A-horizon largely untouched. Low-intensity management - such as grazing, mowing and burning - can be applied as supporting and sustaining measures, but have been shown not to be sufficient for restoring heathlands or for preserving heathland health in systems with high nutrient deposition [4, 7, 8]. Additionally, in order to meet habitat quantity objectives or connect isolated patches of heathlands, other land-cover types are being converted to heathlands and similar more open habitats. These are primarily pine plantations with low ecological value. Methods applied for this conversion after removal of the standing biomass are comparable to heathland restoration measures, i.e. plaggen and choppering [1, 2, 9, 10].

These high-intensity techniques are cost-intensive and result in large amounts of residual biomass (landscape residues), with smaller yields for choppering compared to plaggen (250 versus 750 m^3 ha^{-1}, respectively [11]). Disposing of these residues is costly (4 to 8 € m^{-3}) and not economically sustainable (W. Kwanten, personal communication, 2017). Therefore, repurposing and industrial valorization of these renewable organic resources is advocated and contributes to closing material cycles and the bio-economy [12, 13].

Due to increasing environmental concerns [14], efforts are made and needed to reduce the use of peat in growing media [15–17]. Currently, the main building components in a growing medium are peat, composted bark, wood fibre, coco coir pith and greenwaste compost. These are thus the principal constituents influencing the composition of growing media [14, 18] and there is an increased need to find novel principal constituents. The landscapes residues are renewable organic resources, which potentially can be valorized as growing media constituent in growing media [19]. For the production of growing media suitable for the professional and the hobby market, a wide variety of constituents are used and combined, whereby the different biological [20, 21] physical [18], chemical [19] and economical [19] characteristics of the constituents are taken into account.

Currently, only high-quality grass cuttings and wood residues from conservation areas are effectively processed into products of value such as compost, feed and stable litter; or used to produce energy [6, 22–24]. The bulk of the management residues from low-input high-diversity systems, i.e. low-quality grass, chopper and plaggen, are not yet repurposed [6]. Their low compostability, high acidity, imbalanced nutrient content and considerable fraction of mineral soil make them unsuitable for feed or energy production, and hamper composting or fermentation [25]. However, low nutrient contents, low EC, low pH and high organic matter contents might be an advantage for their use as growing media component or soil amender [11, 23]. Despite the need for information on the valorization potential of these residues, scientific studies remain scanty. So far, studies on the use of chopper residues included mainly very good quality chopper residues from less-degraded heathlands [11, 23, 26], which are not necessarily representative for the large range of biomass residues generated from heathland restoration and forest conversion. Uncertainty about quantity and quality remains a major hurdle. Information on available residue quantities and their quality is important for valorization, and information on the temporal and spatial availability and the heterogeneity in their chemical, physical and biological properties is lacking. Moreover, a myriad of terms is used to describe the perceived properties of available lots, which is confusing to potential end users.

The current study aims at (i) providing ranges for key physicochemical and biological characteristics for each residue type (ii) exploring possible valorization paths for these residues in the horticultural sector; i.e as growing media constituent or soil amendment for ornamental plants and tree nurseries, and (iii) establishing a functional typology of heathland management residues, to allow a better in-field evaluation of their valorization potential. Given the effort currently effectuated in Flemish heathland conservation and restoration as habitats in the EU Habitat and Birds Directives, the region of Flanders was chosen as a case-study.

2. Material and methods

2.1. Study area

This study was performed in Flanders, Northern Belgium, Western Europe (50°41’14’’ – 51°30’18’’ N; 2°32’43’’ – 5°54’38’’ E). The region is characterized by a maritime temperate climate with a mean annual precipitation of 733-832 mm and a mean annual temperature of 9.5-10 °C [27] and consists of different ecoregions along a north-south gradient in soil texture gradient, ranging from sandy in the north to silty in the south. As heathlands are characteristic for sandy and nutrient poor soils, focus was laid on the Provinces of Antwerp and Limburg, where these soils mainly occur.

The heathlands occurring in the study area can be described as typical Northwestern European lowland heathlands dominated by *Calluna vulgaris* but often rich in other plant and insect species. As relics of vast areas of heathland in the 19th century, these are now largely protected as Natura 2000 sites, preventing further habitat loss. Nevertheless, heathlands still suffer from atmospheric pollution, mainly of nitrogen and Sulphur, due to industrialization and intensification of agricultural practices, leading to species decline [9, 28, 29], and benefitting competitive grass species such as Purple moor grass (*Molinia caerulea).*

2.2 Spatial data acquisition

Non-structured interviews during stakeholder-workshops, including nature agencies and nature conservators, indicated that the perceived valorization potential of residues mainly depended on the vegetation type and on the management technique used. Hence, to allow for maximum applicability at a management and company level, the typology was based on readily available and spatially specific data on vegetation traits [30, 31], combined with management technique (Table 1). Spatially specific vegetation traits were extracted from the BWK (‘Biologische WaarderingsKaart’ or Biological Valuation Map (BVM)) established by INBO in 1978, and updated in 2014.

Temporal availability of residues and dominant management technique per selected vegetation map polygon were assessed by means of a questionnaire among nature associations and agencies. Questions were related to three topics: (i) the location of high-intensity management interventions undertaken between 2010-2015, (ii) the specification of the used techniques and (iii) the area affected by the intervention. The latter was used as a proxy for residue volume, as preliminary non-structured interviews had shown that residue volumes are not typically recorded. Finally, *vegetation units* and *management shapefiles* were overlaid to obtain surface areas per residue type.

Table 1 Definition of different residue types based on the combination of vegetation groups derived from the BWK and used management technique. Abbreviations used further in this paper are indicated between brackets

[Table 1]

2.3. Sampling and analysis

Thirty-eight residue samples were obtained from residues collected during high-intensity management interventions in heathland or converted pine forest between November 2014 and March 2017. Contractors typically combine residues from a specific area into lots that are temporarily stored at the edge of the intervention area (Fig. 1). Composite bulk samples were obtained by combining five random bulk samples from each residue lot. In total, two samples were taken in residues from pristine heathlands (HC1), 27 in residues from degraded heathlands (HP+HC2) and 9 in residues from converted pine forests (FP).

[Fig 1]

Fig. 1 Example of residue lots, where residues were collected per type after management intervention, i.e. heath chopper quality 2 (HC2, left); forest plaggen (FP, middle) and heath plaggen (HP, right)

In the lab, composite samples were split in three parts; one part was oven dried at 70°C and grounded (HammerMill, 2 mm mesh), one part frozen at -18°C and one part stored in the fridge at 4°C.

All oven-dried and grounded samples were analyzed in three replicates for pH (EN 13037), electrical conductivity (EC; EN 13038), total C (TC) and total N (TN) content (total combustion; EN 13654-2, Thermo Scientific – Flash 2000 CHN analyzer, MA, USA). Organic matter content (OM%) and ash content were analyzed by mass loss during ashing at 550°C (EN 13039). Total concentrations of P, K, Ca, Mg and Na were measured by CCD simultaneous ICP-EOS (VISTA-PRO, Varian, Palo Alto, CA), after controlled ashing and digestion with HNO_3 (65%). Plant-available concentrations were measured by ICP after ammonium-lactate extraction. Additionally, Neutral Detergent Fiber (NDF), Acid Detergent Fiber (ADF) and Acid Detergent Lignin (ADL) were determined, according to the Fibersac method derived by Van Soest et al. (1991). Biodegradation potential was then calculated as:

$$\frac{\%\text{hemicellulose} + \%\text{cellulose}}{\%\text{lignin}}$$

with %hemicellulose = % NDF- %ADF and %cellulose = %ADF - %ADL. The higher the ratio, the higher the biodegradation potential [32]. In addition, a random selection of 8 samples (from different residue types) was tested for N-immobilization potential (n=3). Samples were incubated for one week at 37°C, after the addition of 350 mg N L^{-1} KNO_3. In Annex 2, N-immobilization (%) was calculated based on the difference between theoretical and actual water-extractable N. N-immobilization is indicated by positive values, while net N-mineralization is indicated by negative values [33]. A 100% immobilization means that all the added KNO3 (350 mg mineral N L^{-1}) is immobilized.

A random selection of 21 samples in total was made for physical analysis. Samples of the four different residue types (HC1, HC2, HP, FP) were included (Annex 3). Parameters included bulk density and dry matter content at 105°C (DM, EN 13040), porosity, easily available water (EAW), shrink % and water holding capacity (WHC) [34]. EAW was calculated as the difference between water volume at pF1 and pF2. Physical parameters were determined according to EN 13041.

Finally, a preliminary study was performed for biological traits for one sample of each residue type (HC1, HC2, FP and HP). A DNA Multiscan® analysis (Scientia Terrae vzw) was performed to detect and identify plant-pathogenic and beneficial fungi in the residues. The abundance of the detected organisms were indicated as low (1), intermediate (2) or high (3) based on expert judgement (PCS Ornamental Plant Research, Laboratory for danger pests and diseases, 2016). Plant-parasitic nematodes were extracted by applying the Automatic Zonal Centrifuge (AZC) method, and counted and identified by microscopy (Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Merelbeke, Belgium).

2.4 Statistical analyses

Statistical differences between residue types were assessed by using ANOVA followed by Tukey multiple comparisons of means (*$p<0.05$) for normally distributed data, and by Kruskal-Wallis One-way ANOVA followed by Dunn’s multiple comparison test for non-normally distributed data (*$p<0.05$) in R- 3.2.2. for Windows. Finally, an unsupervised cluster analysis (K-means) was performed to evaluate the appropriateness of the typology based on vegetation type and management technique.

3. Results and discussion

In this study we aimed to (i) give ranges for key characteristics of the residues classes, (ii) find a pragmatic typology for residues in the field and (iii) discuss valorization as 1) growing media, and 2) soil amendment. Our major findings for each aspect are discussed below.

3.1 Residue typology and characterization

Based on current management practices and available data on dominant vegetation, we proposed a pragmatic typology of residues into heath plaggen, forest plaggen and two qualities of heath chopper (Table 2). All samples were characterized chemically (3.1.1) and physically (3.1.2.). Based on these results, section 3.1.3. describes the appropriateness of this pragmatic typology.

3.1.1. Key ranges for chemical properties

Table 2 presents an overview of values for 18 chemical properties of three residue types (HC2, HP, FP) and compares those to ranges for compost, Sphagnum peat and coir pith. As a reference, optimal ranges and legal limits for growing media for ornamental plants have been added to the table. No optimal ranges for soil amenders were indicated either because they are not available and/or they are type specific (e.g. optimal ranges for composts). HC1 samples were not considered, as the number of cases was very low (n=2; Annex 1).

pH was a stable property across different residue types (no significant differences) and typically acid, ranging between 2.9 and 5.4 (Annex 1). Several authors mention a rise in pH during storage of biomass residues, but that was not evidenced for the plaggen and chopper in this study [35]. EC ranged from 75.7 to 409.3 µS cm^{-1} among all residues, which is fairly low for natural biomass residues.

The OM of the studied residues was much lower compared to that of Sphagnum peat, compost or coir pith, although HC2 had some samples with OM contents similar to these of composts [36–40]. HP showed significant lower OM contents compared to HC2. Standard deviations for OM and TC (total carbon content) were high, showing a great variation among samples, comparable to the varying OM contents of composts [19, 41, 42]. Peat and coir pith are reported to be more homogeneous for these properties. For coir pith [41], a relationship between physicochemical properties and particle size was found [11, 41]. In [11], sieving had a positive impact on the OM content of HC1, with increased OM content in the fraction 2-20 mm compared to the <2 mm fraction and a higher OM content in the larger particles after sieving with a 5 mm grid. The same results are expected for HC2, HP and FP samples.

The carbon/nitrogen ratio (C:N), an indicator of organic matter origin, maturity and stability, was significantly higher for HC2, compared to HP, and similar to that of peat or some composts. All C:N ratios > 30 originated from HC2 samples, while residues with C:N ratios < 20 were all classified as HP. Risks for N-immobilization increase with increasing C:N ratios and, according to literature, ratios of >15 [43], 20-40 [44–46] or >30 [20, 47] represent values at which nitrogen starts to be immobilized. For the subset of 8 randomly selected samples, both low (<5%) to limited (<30%) N-immobilization and limited N-mineralization was observed (Annex 2). The highest N-immobilization was determined for the two HP samples with 24±2 % and 22±4 %, followed by the two FP samples with 16±3 % and 15±8 %. A limited N-mineralization was observed for heath chopper samples, except for sample 161216_BC_HH, an HC2 sample from heathland with tree encroachment. No linear link was found between the measured C:N ratios and the N-immobilization or N-mineralization, for these eight samples, probably given the limited range in C:N ratios. Similar results were obtained by [26, 48] for HC1 samples. Sphagnum peat moss (20:1-80:1), coir (75:1-186:1) or sawdust (130:1-625:1) have significant higher C:N ratios and show higher N-immobilization [49, 50].

Significant differences between residue types were found for lignin and hemicellulose contents, which was also reflected in significant differences in biodegradation potentials. The share of cellulose and lignin is much lower compared to coir pith [20]. Biodegradation potentials were comparable to composts, with values between 1-1.3 for stable composts and 1.5-1.8 for less stable composts [44].

The raw residues in this study had a high C:P ratio and HC2 possessed significant higher P contents compared to HP and higher Mg contents compared to HP and FP. In general, the residues contained low total concentrations of K and Mg compared to other materials or bulking agents used for composting, such as grass clippings or coir pith [51–54]. Plant-available nutrient concentrations of P, K, Mg and Ca were generally within the recommended ranges for the production of ornamental plants, in contrast to low nutrient concentrations in peat and too high K concentrations in composts and coir pith [53–56]. However, in this study, plant-available nutrients were extracted in ammonium lactate (AmLac), while nutrients in [48] were extracted in ammonium acetate (AmAc) similarly to the optimal range proposed by [57] for use in potting soil.

Table 2 Chemical composition of the different residue types, with HC2 = heath chopper quality 2, HP = heather plaggen and FP = forest plaggen. n=number of samples. Values are averages of the n samples per residue type. Values in parentheses are standard deviations for the n samples per type. As a reference, optimal ranges or legal limits for growing media are indicated. Ranges for composts, Sphagnum peat moss and coir pith are added to ease comparisons. Letters denote significant differences of means. Parameters with the same letter are not significantly different from each other (p<0.05)

[Table 2]

[1] EC = electrical conductivity, TOC = Total Organic Carbon, TN= Total Nitrogen, DM= Dry Matter, Cell. = Cellulose, P = total P, P-av = available P (ammonium lactate extraction)

[2] according to [41]

[3] Belgian Legislation KB Meststoffen 28 January 2013, available on fytoweb.be and [57, 58]

[4] [33, 45, 59, 61, 76]

[5] Sphagnum peat with moderate degree of decomposition [19, 33, 57–59, 61, 78]

[6] [41, 53, 54]

3.1.2 Key ranges for physical properties

Physical characteristics for the selected subset of 21 samples are summarized in Table 3 (full dataset in Annex 3). Although no universally accepted optimum physical specifications do exist for growing media, Table 3 accounts for an agreement on acceptable ranges for physical properties as a reference for the residues, Sphagnum peat, composts and coir pith [19, 41, 53, 54, 63–66]. Physical properties were not significantly different depending on residue types and were mainly satisfying the acceptable ranges, except for bulk density, for which 9 samples exceeded the optimum value of 400 g L^{-1}. Ranges are wide for bulk density and influenced by vegetation unit and management method. If only management method is taken into account, chopper confirms to have a significant lower bulk density compared to plaggen, with 313 ± 124 g L^{-1} versus 450 ± 147 g L^{-1} , respectively (not mentioned in Table 3). The highest densities were found for a HP and a FP sample with values of 788 and 623 g L^{-1}, respectively. The lowest density (146 g L^{-1}) was measured for a HC2 sample. Bulk densities of these residues are comparable to these of green compost or solid waste composts (341-556 g L^{-1}) and contrast with the low bulk densities of Sphagnum moss peat (80-130 g L^{-1}) and coir pith (25-89 g L^{-1}). As mentioned by [39], each growing medium constituent contributes to the bulk density of the medium. Additionally, the heterogeneity in density for chopper and forest plaggen illustrates a need for optimization in the technique and the amount of mineral soil removed, to obtain a more constant sand content and density.

The DM content of the residues was within the optimal range (45-65 %) and comparable to peat. Porosities were similar to those of the described composts, higher compared to manure composts [67] and lower compared to those of peat and coir pith. EAW was comparable to compost and slightly higher than for peat. Coir pith appears to have a wider range, dependent on the source [53, 66, 68]. WHC was lower compared to peat but higher compared to e.g. pine bark [69].

Table 3 Physical characteristics of the different residue types with HC2 = heath chopper quality 2, HP = heath plaggen and FP = forest plaggen. n=number of samples. Values are averages of the n samples per residue type. Values in parentheses are standard deviations for the n samples per type. As a reference, legal limits and assumptions for acceptable ranges for growing media are indicated. Ranges for composts, Sphagnum peat moss and coir pith are added to ease comparisons. Letters denote significant differences of means. Parameters with the same letter are not significantly different from each other ($p<0.05$)

[Table 3]

[1] DM = Dry Matter, WHC = Water Holding Capacity; EAW = Easily Available Water (pF2-pF1)
[2] according to [57, 89]
[3] according to [20, 33, 45, 76]
[4] Sphagnum peat with light to moderate degree of decomposition [19, 20]
[5] [53, 66, 68]
[6] Internal information from Greenyard Horticulture

3.1.3. Appropriateness of the typology

Principle component analysis (PCA) revealed that residues mainly differ in terms of bulk density and WHC for the physical parameters and in cellulose, hemicellulose and lignin content and in OM with regard to chemical parameters (Annex 5, Fig. 3 and Fig. 4). Cluster analysis shows that management technique is the most dominant determinant for residue chemical quality and physical properties (Annex, Fig. 3 and Fig. 4). For physical data, the influence of management technique is probably not only translated in differences between chopper and plaggen samples, but is also visible in a subset of the chopper samples that were clustered in the plaggen cluster. This were typified by a higher sand content: the amount of mineral material that is removed during choppering is generally less than during plaggen, but can vary considerably (W. Kwanten, personal communication).

3.2 Valorisation potential

3.2.1 Growing media

Good and constant physical and chemical properties of the residues are important for their consideration as growing media constituents for ornamental plant production [19, 52, 71]. One of the most important chemical parameters is alkalinity because of its impact on solution pH and nutrient availability [72]. Growth of acidophilic plants is negatively influenced by high pH, because of the limited availability of most micronutrients, especially iron, manganese, copper, zinc, and boron [73, 74]. Porosity and optimal air and water ratio are the most important physical properties [75].

Similar to peat, all samples (except two) had a pH below the optimal range for ideal growing media (5.3-6.5) but pH values of 25 out of 36 samples met the requirements set-up by the Belgian Legislation for ‘universal potgrond’ (4.5-7). Therefore, residues from forest and heathland management would better fit as growing medium constituent for acidophilic plants, such as *Rhododendron* sp. and *Azalea* sp. The fairly low EC ranged within acceptable limits ($<500\ \mu S\ cm^{-1}$) for growing media constituents. This is in contrast to other growing media constituents such as composts, with values generally exceeding the acceptable limits [19, 72, 76], and coir pith for which salinity is known as an issue [53, 72]. Salinity is often a barrier for the use of composted materials in growing media [66].

The reported OM contents are within the optimal range for growing media for ornamentals and fit the Belgian legislation [58] to be defined as growing media component with low organic matter (>25%) [58], with the exception of one FP and four HP samples with contents lower than 20%. For consideration as growing media constituent, it is advised to sieve the residues with OM contents lower 50% to increase OM contents, which is described by [58] to define growing media constituents as ‘terreau’ or ‘potting soil’. If 50 % OM is not reached after sieving, a valorization as soil improver might be preferable. In general, residues had OM contents similar to the chopped heath, HC1 residue type, considered as a bulking agent for compost in [48].

For the use as growing media constituents, the measured N-immobilization can be problematic when residues constitute a large proportion of the medium, but fertilizers can be added to compensate [56]. The measured C:N ratios were comparable to C:N ratios of 25:1 described by [40] to obtain optimal results for plant growth. The obtained results show that coir pith or sawdust can be substituted by these residues. Even Sphagnum peat moss is often characterized by C:N ratios between 20 and 80. Mixing different constituents to compose growing media is often applied to improve their physical condition [56]. The bulk density of potential growing media based on residues could be decreased with the addition of peat, or coir pith for peat-free growing media. However, with coir pith, attention should be paid to the high EC and K^+ concentrations, as mentioned earlier.

If DM values are lower than the optimal range, as for coir pith, water can be added, but if the growing media are too wet, it may cause problems such as root rotting. Total porosity of the residues approximated or reached the optimal values of >85%. Some authors [77, 78] even consider porosity still to be satisfying at values between 50-80% by volume. Air capacities and shrink volumes were comparable to the recommendations. WHC is an important factor in container grown plant production, given the restricted volume that plants can exploit [78]. Blending these residues with Sphagnum peat moss would increase WHC of the growing medium [79]. This was observed in preliminary pot-experiments based on various peat volumes replaced by residues from heathland and forest management [80]. GreenYard Horticulture defined optimal ranges for different growing media constituents, based on experience, research, numerous analysis, aimed application, origin of the constituent, … For heath chopper, the optimal range for WHC was 125-225 g / 100 g DM (Personal communication, GreenYard Horticulture), which is comparable to the obtained values. These physical conditions indicate that, instead of a standalone growing medium, these residues should be mixed with other constituents to create an optimal growing medium, without growth reduction. In [80], growth of acidophilic plants was similar for growing media in which 30 to 60 v/v% of the peat-based growing medium had been replaced by the residues, compared to the control peat-based growing medium. With more than 60% v/v it seems that the physical characteristics change too much to result in optimal growth. As such, we might argue that the residues may act as a partial peat substitute but still have to be mixed with growing media constituents with high WHC, high porosity and low bulk density, such as Sphagnum peat or coir.

Results of the biological characterization of a subset of 4 residues are listed in Annex 4. Plant-pathogenic fungi were encountered in all 4 samples, while plant-parasitic nematodes were encountered in HP, HC1 and HC2 but not in FP. The encountered pathogens and nematodes underline the importance of further research for a broader set of samples, but are not a threat for acidophilic ornamentals (PCS, personal communication). Additional biological screening is needed to confirm low levels of plant-pathogens for a wider variety of cultures and to address the effects of residues on soil biology. For the use of the residues as a growing media constituent or soil amender, the presence of weed seeds and heavy metals should also be considered. In [80], heavy metals and weeds have been analyzed for the same 4 residues. Heavy metal concentrations were below the maximal limits described in the VLAREMA and within the European Commission [81, 82]. As other studies mentioned a few samples of heathland chopper with heavy metal concentrations exceeding the limits, additional analyses should be effectuated for all samples to avoid potential pollution problems.

3.2.2 Soil amendments

Residues were also assessed for their value as soil amender. For this valorization, optimal ranges do not exist as optimal properties depend on the targeted aim of the soil amender. Soil organic carbon is an important indicator for fertile and healthy soils, by increasing WHC and cation adsorption capacity and improving soil structure. However, European soil carbon stocks are decreasing[1]. To meet environmental standards on nutrient leaching, the amounts of N and P that can be added with organic or mineral fertilizers are often regulated, in Flanders by the Flemish Manure Decree [82]. Therefore, we mainly evaluated the residues as an alternative soil carbon source aiming at an increase in soil organic carbon without increasing nutrient leaching. For this, a high OM content [56] combined with high C:N and C:P ratio are beneficial for the residue quality for consideration as soil improver.

The high C:P ratios of the residues considered in this study make them ideally suited for improving soil carbon content of P rich soils [48] because more C is added to the soil per unit of P by using these residues, in comparison to, for example, manure [23, 51] or green compost [83]. Also the C:N ratios are appropriate for the valorization as soil amender. Nowadays, organic wastes such as green waste are often composted to transform the organic wastes into biologically stable and easier to handle materials, and subsequently used in agriculture and horticulture [84]. Several advantages are linked to compost, such as high nutrient levels, suppression of diseases, and their availability [76, 85–88]. Nevertheless, their high pH and high electrical conductivity [39, 76, 87, 89] is less favorable for some plants. Hence, the studied residues could favor species originating from forests, such as tree seedlings, and might be beneficial for plants with low pH requirements, such as *Rubus* sp. and *Vaccinium* sp [90].

A potential avenue is to combine the residues with organic fertilizers characterized by high nutrient levels, in order to increase carbon stocks of degraded soils. For instance, mixing these residues with manure could contribute to a reduction of N-losses during the composting process of manure. Moreover, the residues considered in this study have on average a higher share of lignin and low biodegradation potentials, comparable to the study of [48], in which heathland residues were used as bulking agent for compost. In general, the residues contained low total concentrations of K and Mg compared to other materials or bulking agents used for composting, such as grass clippings or coir pith [51–54]. However, no regulations exist for K, Mg of Ca in materials used as soil amendment or growing media component, although these macro-nutrients are essential for a good plant growth. Nutrient contents of residues as soil amenders will therefore need to be corrected by supplementing with e.g. chemical fertilizers [56].

3.2.3 Availability

The vegetation groups extracted from the BWK and the management information reported with the questionnaire are summarized in Fig. 2. The BWK map indicates that Flanders contains 1355 ha of pristine heathlands and 5344 ha of degraded heathlands, with the majority of these located in Antwerp and Limburg; and 32954 ha of pine

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[1] https://www.eea.europa.eu/data-and-maps/indicators/soil-organic-carbon-1/assessment

forests. Most residues were generated during projects financed by LIFE, the EU's financial instrument contributing to the protection of the environment and climate. Conversion projects of pine plantations into heathlands account for 50% of the reported intervention area, and all use plaggen as management technique, after removal of the pine trees. On heathlands, apart from the less intensive management techniques mentioned in the introduction, both chopper and plaggen are used for degraded heathlands, while pristine heathlands are only choppered. In the period 2010-2015, following areas were managed yearly (averages for 2010-2015): 43.3 ha of plaggen as heathland restauration technique; 78.4 ha of plaggen for plantation conversion after tree removal and an additional 34.4 ha of choppering heathland. Assuming a management depth of 10 cm (chopper) to 15 cm (plaggen), this corresponds to 31 400 m³ chopper and 188 400 m³ plaggen per year. Management or conversion works typically occur between August and February, to avoid disturbing nesting birds.

A challenge for the sustainable repurposing of residues from heathland management, confirmed in the interviews, is the annual variation in amount of residues. The annual averages mentioned above are an average based on the period 2010-2015 and varies from year to year: between 6 ha in 2010 to a peak of 107 ha in 2014, for the sum of the area choppered and plagged during that year. For repurposing of residues from heathland management, coordination may be needed to achieve a constant flow of residues, which would ease further valorization. Today, residues are already stored in heaps but more research is needed to evaluate their characteristics and quality within time and define how long residues can be stored before repurposing. Moreover, managed surfaces are lower limits because not all management works are reported, nor included in the database.

[Fig 2]

Fig. 2 Natura 2000 areas in Flanders (left) and zoom on the Provinces of Antwerp and Limburg (right). Natura 2000 areas are shown in green. The surfaces that were subjected to chopper or plaggen management between 2010 to 2015 in Flanders, are shown in blue. These were calculated based on available information, complemented by the information received by the interviewed nature conservators

4. Conclusion

This study provides a deeper understanding about the quality of residues from heathland and forest management. Different valorization strategies for management residues from heathland and converted pine forest have been explored based on their physicochemical and biological characteristics. Based on the results, we can conclude that these residues are suitable as growing media constituents, offering the possibility to partially substitute peat. Growing media with optimal physical and physicochemical characteristics for ornamental plants could be prepared by mixing adequate proportions of different constituents. Mixing these with materials with high OM content, high WHC, high porosity and low bulk density is advised to assure satisfying growing media qualities. The right proportions should further be determined. Additionally, sieving might be a suitable pre-treatment, to lower the sand fraction. It may also increase usability of residues with a lower OM content, by creating one high-grade fraction more suitable for use in growing media and a residue that can be validated as soil amendment. To nature managers, we might recommend to use chopper instead of plaggen to improve residue quality, as management technique confirmed to have an important impact on the physicochemical characteristics. Hence, amongst other advantages of chopper described in [2] (less residue production, higher removal of N per unit volume, faster application method, faster vegetation recovery), this study shows that chopper residues are easier to repurpose, compared to plaggen residues.

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TABLES

[Table 1]

Management technique	**Vegetation group (BWK)**		
	Pristine heathland	**Degraded heathland**	**Pine forest**
Plaggen		*Heath plaggen* (HP)	*Forest plaggen* (FP)
Chopper	*Heath chopper quality 1* (HC1)	*Heath chopper quality 2* (HC2)	

[Table 2]

Parameter[1]	**Optimal (or legal) range**	**HC2 n=13**	**HP n=14**	**FP n=9**	**Compost (GW and SWC) [4]**	**Sphagnum Peat[5]**	**Coir pith[6]**
pH-H_2O (-)	4.5-7[3] 5.2-6.3[2]	4.8 (0.3)^{a}	4.8 (0.3)^{a}	4.5 (0.3)^{a}	6.7 – 8.4	3.5-5	4.9-6.8
EC (µS cm^{-1})	<750[3] <500	238.0 (73.7)^{a}	238.9 (109.8)^{a}	203.0 (92.2)^{a}	480-1084	20-210	400-6000
OM (% DM^{-1})	>25[3] >80[2]	42.8 (11.4)^{a}	26.0 (11.4)^{b}	29.7 (9.0)^{ab}	25-75	94-99	89-97
TC (% DM)		21.1 (6.6)^{a}	13.9 (6.5)^{a}	17.3 (7.0)^{a}			
TN (% DM)		0.7 (0.3)^{a}	0.6 (0.29)^{a}	0.7 (0.3)^{a}			
C:N (-)		29.8 (6.2)^{a}	21.1 (3.3)^{b}	26.0 (2.7)^{ab}	15-20	20-80	75-186
C:P (-)		664.1 (402.1)^{a}	660.3 (273.5)^{a}	705.7 (254.8)^{a}	60-500		
P (g kg^{-1} DM)		0.4 (0.1)^{a}	0.2 (0.1)^{b}	0.2 (0.1)^{b}			
K (g kg^{-1} DM)		0.8 (0.4)^{a}	0.4 (0.2)^{a}	0.4 (0.1)^{a}			
Mg (g kg^{-1} DM)		0.4 (0.1)^{a}	0.2 (0.2)^{b}	0.3 (0.2)^{ab}			
P-av (mg L$^{-1)}$	30-70[3]	77.0 (68.7)^{a}	63.7 (102.1)^{a}	63.2 (70.9)^{a}	8.2-28	1.6-1.8	8.7-87
K-av (mg L$^{-1)}$	150-360[3]	354.4 (182.0)^{a}	157.2 (108.8) ^{a}	118.2 (87.5)^{a}	630-900	4-10	116-2059
Mg-av (mg L$^{-1)}$	150-300[3]	147.1 (92.3)^{a}	79.0 (55.8)^{a}	77.4 (68.3)^{a}	181-412	4.4	2.6-49
Ca-av (mg L$^{-1)}$	325-2100[3]	469.5 (220.7)^{a}	276.9 (214.0) ^{a}	290.8 (270.1)^{a}	1134-2691	27	7.8-98
Cell. (% OM)		7.9 (2.6)^{a}	3.7 (0.5)^{a}	3.7 (1.6)^{a}	8.7	17	23-43
Lignin (% OM)		12.5 (4.1)^{a}	7.5 (3.9)^{b}	11.0 (5.3)^{ab}	8.6	26	35-54
Hemicell. (% OM)		11.7 (3.0)^{a}	4.8 (1.9)^{b}	6.6 (2.8)^{b}	5	37	3-12
Biodegradation potential (-)		1.7 (0.7)^{a}	1.4 (0.7)^{b}	1.0 (0.2)^{b}	1.0-1.8[5]		

[Table 3]

Parameter[1]	**Optimal (or legal) range**	**HC2 n=10**	**HP n=8**	**FP n=3**	**Compost (GC and SWC)[3]**	**Sphagnum peat[4]**	**Coir pith[5]**
Dry bulk density (g L^{-1})	<400[2]	312.5 (124.3)^{a}	431.1 (159.0)^{a}	498.7 (121.1)^{a}	341-556	80-130	25-90
DM (% fresh^{-1})	45-65	60.2 (15.3)^{a}	50.1 (13.5)^{a}	62.7 (8.5)^{a}	53-70	50	25-40
Porosity (vol.-%)	>85[2] or 50-85	87.0 (4.7)^{a}	83.1 (5.4)^{a}	80.7 (3.5)^{a}	73-81	92-95	94-98
Air capacity (vol.-%)	10-30[2]	34.0 (13.1)^{a}	21.1 (3.8)^{a}	18.7 (5.7)^{a}	7-35	10-40	13-89
WHC (g 100g DM^{-1})	550-700[2]	229.6 (83.8)^{a}	192.9 (64.9)^{a}	153.7 (34.9)^{a}	160	550-850	600-800
Shrink (vol.-%)	<30[2]	21.7 (4.1)^{a}	25.6 (4.7)^{a}	22.7 (4.7)^{a}	23	20-21	15-25
EAW (vol.-%)[6]	25-30	27.9 (4.2)^{a}	25 (2.5)^{a}	26.7 (4.9)^{a}	24.4	22.5	0.7-36

FIGURES

Fig. 1

Fig. 2

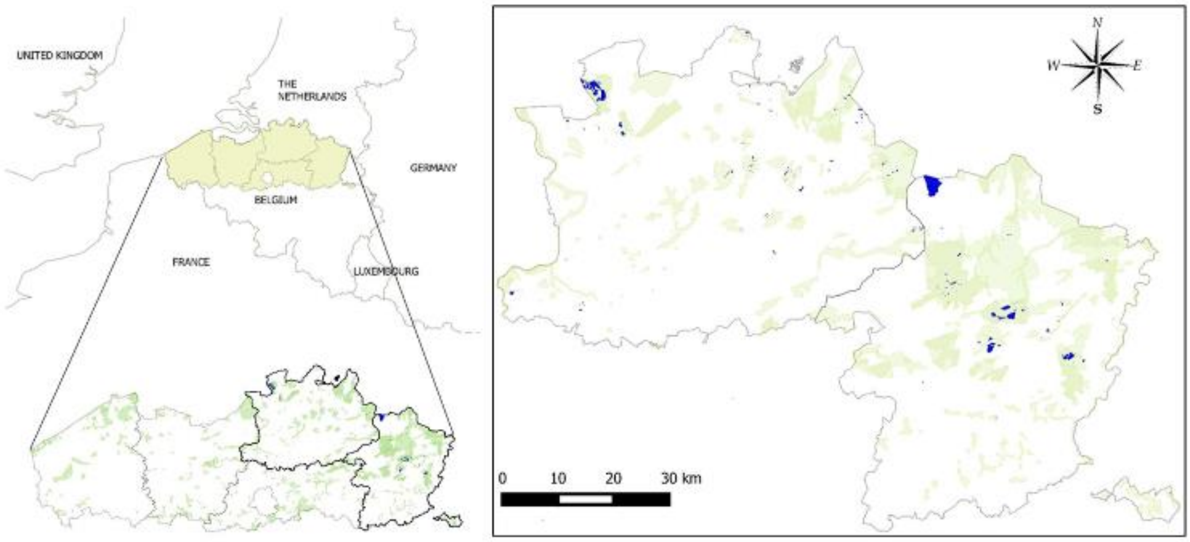
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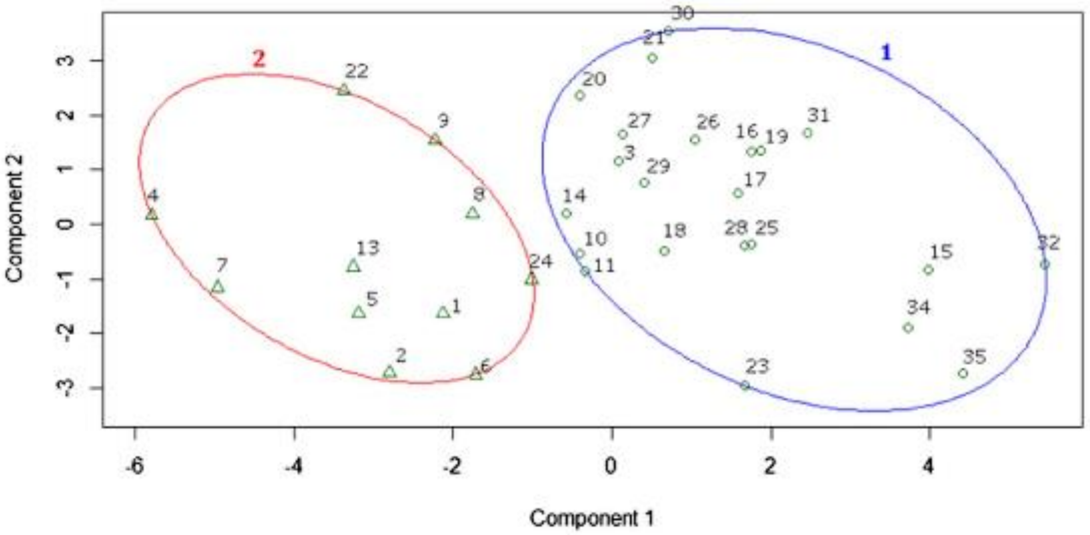
Fig. 3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Component 2
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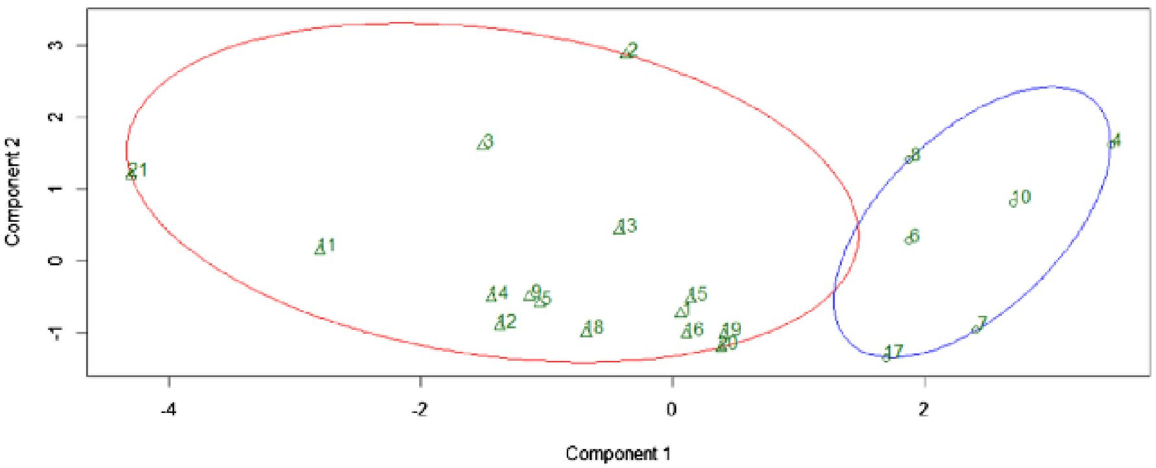
Fig. 4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ANNEX

Annex 1 Chemical parameters for the different samples

N°	Label	ID sample	DM	OM	Mn_total	P_total	K_total	Mg_total	Cellulose	Hemicellul.	Lignin	Biodegr. Potential
			% /fresh	%/DM	mg/kg ADM	mg/kg ADM	mg/kg ADM	mg/kg ADM	% / ADM	% / ADM	% / ADM	(-)
	HC1	150123-HC1-THD	97.1	21.3	23.8	215.3	341.6	171.5	1.9	3.8	6.9	0.8
	HC1	150512HC1-KAS	96.5	30.9	77.9	361.6	904.9	442.4	3.4	7.2	12.5	0.8
1	HC2	150123-HC2-THD	95.7	38.9	186.6	443.1	1093.6	475.0	6.5	10.2	12.0	1.4
2	HC2	150512-HC2-KAS	96.9	39.1	72.4	390.3	1191.8	375.5	8.0	15.8	13.1	1.8
3	HC2	161028-BC-RIE	97.1	31.9	42.3	273.5	410.3	179.0	4.6	9.3	10.8	1.3
4	HC2	161026-BC_KBE	95.4	58.6	65.2	400.6	1598.2	536.4	11.0	15.2	15.6	1.7
5	HC2	161216-HC2(a)-HH	96.0	48.0	177.2	396.2	1222.6	541.1	9.7	12.9	13.8	1.6
6	HC2	161216-HC2(b)-HH	96.5	43.7	150.2	290.9	742.4	350.0	11.5	12.7	6.3	3.8
7	HC2	161216-BC-HH	94.2	67.1	76.5	602.2	908.0	357.1	11.8	14.5	21.6	1.2
8	HC2	170313-CH(diep)-BBH	96.4	38.9	72.2	320.1	628.4	502.4	7.4	10.5	11.7	1.5
9	HC2	170313-HC2(3)-BBH	95.4	48.7	45.9	340.4	732.6	290.6	7.3	11.4	17.0	1.1
10	HC2	170313-HC2(4)-BBH	97.1	29.9	113.5	353.6	806.4	351.0	6.2	8.2	8.2	1.8
11	HC2	170313-HC2(5)-BBH	97.1	35.3	151.9	350.9	566.6	288.6	5.7	9.0	10.2	1.4
12	HC2	161118-BC-BH	97.6	27.2	23.3	183.0	265.1	140.7	3.5	6.8	8.0	1.3
13	HC2	170313-CH(gewoon)-BBH	95.9	48.9	70.2	293.1	820.6	694.7	9.1	15.9	14.9	1.7
14	FP	150123-FP-PNV	95.8	34.0	89.4	331.7	719.9	391.8	5.0	7.2	10.9	1.1
15	FP	150512-FP-KAS	99.1	10.7	14.0	135.5	341.1	165.2	1.7	2.4	3.1	1.3
16	FP	160914-FP-RH(n)	97.5	30.1	20.9	193.3	263.5	176.5	3.0	5.1	7.6	1.1
17	FP	160914-FP-RH(d)	97.6	29.7	19.6	227.2	258.1	171.6	3.1	6.0	9.9	0.9
18	FP	160922-FP-BLE	96.6	38.0	43.4	267.1	477.4	232.0	4.7	8.3	12.2	1.1
19	FP	160916-FP-KMT	97.7	29.2	18.5	200.4	257.7	160.0	2.6	4.5	7.3	1.0
20	FP	160914-FP-K	96.5	39.8	41.0	235.0	344.2	246.5	3.3	8.2	14.9	0.8
21	FP	160618-FP-TEU	97.5	26.4	36.3	222.0	304.6	228.5	3.1	5.7	11.7	0.8
22	FP	FP-VAC	97.3	51.1	51.2	420.5	460.6	656.9	7.0	12.2	21.8	0.9
23	HP	150512-HP-KAS	98.6	17.0	60.2	271.8	923.1	312.8	3.4	4.7	6.3	1.3

24	HP	150123-HP-PNV	92.6	37.6	40.0	381.3	870.9	516.6	6.1	6.6	8.4	1.5
25	HP	150618-HP-TEU-1	97.3	26.8	35.8	211.0	462.5	291.7	4.7	4.8	8.8	1.1
26	HP	150618-HP-TEU-2	96.8	32.4	49.9	234.8	369.6	248.5	4.4	4.4	8.8	1.0
27	HP	150618-HP-TEU-3	96.1	36.9	39.0	274.4	444.3	271.6	5.1	5.9	12.1	0.9
28	HP	150618-HP-TEU-4	97.5	23.8	39.3	285.2	418.4	235.0	3.9	3.9	6.1	1.3
29	HP	150618-HP-TEU-5	96.2	36.2	34.7	207.1	358.9	212.4	4.5	8.2	14.3	0.9
30	HP	160920-HP-KMT-1	96.4	36.2	19.9	218.7	263.4	140.1	3.4	4.8	12.3	0.7
31	HP	160920-HP-KMT-2	98.0	25.9	10.2	156.6	229.0	123.6	1.8	3.1	6.4	0.8
32	HP	160914-HP-Fluxys	99.5	5.9	5.2	65.8	112.6	57.6	0.8	1.1	1.2	1.6
	HP	161216-HP-B	96.4	37.8	12.4	616.8	545.5	192.2	6.5	8.0	6.9	2.1
33	HP	16-HP-STV	99.0	10.8	18.1	198.2	286.4	128.1	2.8	3.6	2.7	2.4
34	HP	161216-HP-HH	99.1	8.4	11.8	131.8	188.0	82.8	1.9	3.9	1.8	3.2
35	HP	170905-HP-KMT	98.5	28.1	24.2	197.9	318.5	169.6	3.1	4.7	9.1	0.9
	SO	HR-VAC	97.0	53.6	99.8	374.7	1266.0	467.8	6.7	16.0	16.2	1.4
	SO	MA-VAC	96.5	63.5	145.3	503.7	2318.2	673.9	12.1	17.5	20.4	1.5
	SO	161026-M_KB	95.4	55.5	102.1	376.9	1736.0	543.1	17.7	21.0	14.3	2.7
	SO	170313-CH(maaisel)-BBH	92.9	87.3	134.7	417.0	1653.5	731.1	17.3	25.7	26.0	1.7

N°	**Label**	**ID sample**	**pH**		**EC**		**C**	**N**	**C:N**	**C:P**	**P**	**Ca**	**Mg**	**K**
K			mean	stdev	mean	stdev	%	%	-	-	Avail.	Avail.	Avail.	Avail.
	HC1	150123-HC1-THD	4.95	-	265.0	-	11.8			549.6	23.5	340.3	85.7	70.9
	HC1	150512HC1-KAS	3.95	-	214.0	-	17.9	0.5	38.5	494.8	94.4	542.9	168.7	380.4
1	HC2	150123-HC2-THD	5.0	0.1	86.0	--	17.3	0.6	30.3	391.2	68.4	827.2	224.1	341.4
2	HC2	150512-HC2-KAS	5.27	-	230.7	-	15.5	0.4	36.6	397.6	-	377.3	90.0	353.7
3	HC2	161028-BC-RIE	4.3	-	228.0	-	20.5	0.7	29.5	751.0	34.3	22.3	35.0	124.8
4	HC2	161026-BC-KBE	5.0	0.1	345.3	21.4	35.1	0.9	38.1	875.7	65.7	575.1	198.1	741.3
5	HC2	161216-HC2(a)-HH	4.7	0.2	224.7	2.5	17.2	0.6	30.5	435.1	294.3	218.7	86.2	277.3
6	HC2	161216-HC2(b)-HH	4.7	0.1	208.7	16.5	17.0	0.5	33.1	585.4	61.7	223.7	107.9	388.3
7	HC2	161216-BC-HH	4.3	0.2	143.5	21.2	17.9	0.4	40.7	297.1	53.3	450.3	39.0	99.3
8	HC2	170313-CH(diep)-BBH	4.9	0.1	305.3	15.0	22.3	0.8	26.1	695.7	71.8	736.0	258.1	386.0

9	HC2	170313-HC2(3)-BBH	4.5	0.1	252.3	37.6	24.5	1.0	24.5	721.2	62.4	291.1	84.10	273.1
10	HC2	170313-HC2(4)-BBH	4.8	0.0	310.3	20.3	17.9	0.9	20.5	506.5	73.2	485.7	82.7	197.3
11	HC2	170313-HC2(5)-BBH	4.8	0.2	217.3	7.6	15.6	0.6	27.2	444.0	73.2	485.8	82.7	197.32
12	HC2	161118-BC-BH	4.3	0.0	228.5	81.3	34.3	1.6	21.0	1877.1				
13	HC2	170313-CH(gewoon)-BBH	5.0	0.0	302.0	75.2	19.2	0.6	29.5	655.4	56.8	796.2	302.9	366.5
14	FP	150123-FP-PNV	4.8	0.0	106.0	2.0	19.4	0.8	24.8	584.7	54.1	765.6	200.3	282.0
15	FP	150512-FP-KAS	4.4	0.4	123.4	8.2	5.8	0.2	23.8	429.5	22.0	33.2	10.5	47.2
16	FP	160914-FP-RH(n)	4.5	0.2	203.5	16.3	16.1	0.7	23.6	830.8	35.1	196.0	53.4	83.3
17	FP	160914-FP-RH(d)	4.6	0.6	252.5	48.8	13.5	0.5	24.7	592.9	37.1	169.1	50.7	77.2
18	FP	160922-FP-BLE	2.9	2.2	179.9	21.5	9.6	0.3	27.3	359.4				
19	FP	160916-FP-KMT	4.4	0.1	207.3	47.5	15.9	0.6	27.9	791.9				
20	FP	160914-FP-K	4.6	0.1	251.5	68.6	23.7	0.8	29.6	1009.4	24.8	138.2	39.3	68.9
21	FP	160618-FP-TEU	4.4	0.2	223.3	34.8	24.9	0.8	29.6	1123.9	206.0	442.8	110.1	150.8
22	FP	FP-VAC	4.1	-	27.7	-	26.5	1.2	22.6	629.3				
23	HP	150512-HP-KAS	5.4	0.0	234.8	78.1	6.8	0.3	21.6	249.1	68.7	443.6	101.5	387.6
24	HP	150123-HP-PNV	5.3	0.1	154.0	8.0	17.8	0.9	19.8	466.0	11.5	748.3	158.7	153.1
25	HP	150618-HP-TEU-1	4.6	0.1	409.3	18.4	9.5	0.5	18.7	450.2	56.1	394.6	142.5	243.9
26	HP	150618-HP-TEU-2	4.7	0.2	340.0	74.1	17.8	1.0	18.4	759.8	26.1	269.1	107.8	175.5
27	HP	150618-HP-TEU-3	4.5	0.1	406.9	207.7	19.4	0.9	20.9	707.7	41.0	342.8	123.0	231.0
28	HP	150618-HP-TEU-4	4.9	0.1	325.7	9.0	13.6	0.7	20.2	478.6	366.4	260.8	89.8	177.3
29	HP	150618-HP-TEU-5	4.9	0.3	135.3	24.8	15.5	0.6	26.1	748.4	40.4	326.4	89.1	168.6
30	HP	160920-HP-KMT-1	4.2	0.0	216.0	-	23.8	1.0	24.1	1086.4				
31	HP	160920-HP-KMT-2	4.6	0.1	221.5	31.8	15.6	0.6	25.9	996.2	25.2	68.4	19.1	42.2
32	HP	160914-HP-Fluxys	4.7	0.0	127.5	31.8	4.1	0.3	15.8	618.5	4.6	<1	<1	4.1
	HP	161216-HP-B	-	-	-	-	19.1	1.1	17.8	309.2				
33	HP	16-HP-STV	4.5	0.1	396.3	29.0	6.3	0.3	18.7	320.4	38.9	122.2	28.4	88.1
34	HP	161216-HP-HH	4.7	0.3	75.7	8.5	4.5	0.2	20.9	338.4	22.0	69.8	9.0	57.5
35	HP	170905-HP-KMT	4.6	0.1	-	-	20.4	0.8	26.4	1028.8				

Annex 2 N-immobilization potential of 8 random selected samples (n=3 for each sample). Mean and standard deviation for each sample is given. Initial and final N-mineral concentrations are indicated. 350 mg N/L was added. Negative N-immobilization indicates a N-mineralisation. Positive N-immobilization indicates an N-immobilization. HP = Heath plaggen; FP = Forest plaggen ; HC2 = heath chopper ; M = grass cuttings.

ID sample	**Labels**	**NO_3^--N**	**NH_4^+-N**	**NO_3^--N**	**NH_4^+-N**	**N-immobilization**		
		mg L^{-1} substrate	**mg L^{-1} substrate**	**mg L^{-1} substrate**	**mg L^{-1} substrate**	**Per sample %**	**Mean %**	**Stdev %**
161216_HC2(a)_HH	HC2	5.0	5.0	294.1	5.0	16.9	-1.0	18
CN=30				425.5	5.0	-19.6		
				355.8	5.0	-0.2		
161216_HC2(b)_HH	HC2	5.0	5.0	413.4	13.2	-18.5	-25.5	9
CN=33				472.0	16.8	-35.8		
				426.8	13.4	-22.3		
161026_M_KB	M	5.0	5.0	331.2	5.0	6.6	8	2
CN=35				328.5	5.0	7.4		
				320.3	5.0	9.6		
160914-FP_RHn	FP	13.5	8.4	290.3	33.6	12.9	16.4	3
CN=23				271.3	33.7	18.0		
				251.9	33.7	18.4		
160914_FP_Kor	FP	15.8	23.1	262.5	56.7	8.8	14.8	8
CN=29				218.3	50.4	23.2		
				238.6	68.2	12.3		
161216_BC_HH	HC2	5.0	6.6	253.2	40.4	16.1	12	5
CN =40				267.7	40.5	11.9		
				282.3	43.1	7.0		
161118_BC_BH	HC2	5.0	5.0	307.2	43.6	-0.2	-12.1	16
CN =21				410.7	45.1	-30.2		
				331.7	38.8	-5.9		
161112_HP_B	HP	5.0	5.5	244.2	29.9	21.7	23.6	2
CN =18				224.0	34.4	26.2		
				237.6	31.8	23.0		
160914_HP_F	HP	7.7	8.3	229.4	31.7	25.4	22.4	4
CN =15				234.8	29.8	24.4		
		5.0	5.5	266.3	31.9	17.35		

Annex 3 Physical parameters of the different samples

	Label	ID Sample	Ashes%	DM%	Shrink%	Air volume%	Density (g/L)	Pores %	Humidity %	WHC
	HC1	150123-HC1-THD	63	69	25	22	434	82	31	168
1	HC2	150123-HC2-THD	41	51	25	20	351	84	49	220
2	HC2	161026-BC_KBE	55	92	19	42	344	85	8	151
3	HC2	161216-HC2(a)-HH	77	80	23	31	491	82	20	125
4	HC2	161216-HC2(b)-HH	57	67	13	49	146	94	33	371
5	HC2	161216-BC-HH	61	57	27	16	452	82	43	175
6	HC2	170313-CH(diep)-BBH	41	51	18	38	232	89	49	266
7	HC2	170313-HC2(3)-BBH	48	44	21	26	218	90	56	354
8	HC2	170313-HC2(4)-BBH	76	59	24	48	237	91	41	217
9	HC2	170313-HC2(5)-BBH	60	54	24	20	461	81	46	158
10	HC2	170313-CH(gewoon)-BBH	57	47	23	50	193	92	53	259
11	FP	150123-FP-PNV	75	69	26	17	623	77	31	115
12	FP	150512-FP-KAS	67	53	21	14	492	81	47	163
13	FP	160618-FP-TEU	51	66	21	25	381	84	34	183
14	HP	150123-HP-PNV	68	58	28	16	490	81	42	157
15	HP	150618-HP-TEU-1	60	47	23	26	371	85	53	191
16	HP	150618-HP-TEU-2	47	48	23	18	351	84	52	228
17	HP	150618-HP-TEU-3	48	37	30	24	262	88	63	295
18	HP	150618-HP-TEU-4	69	47	27	18	445	83	53	175
19	HP	150618-HP-TEU-5	86	41	21	23	381	87	59	202
20	HP	161216-HP-B	73	43	34	19	361	86	57	225
21	HP	161216-HP-HH	78	80	21	25	788	71	20	70

Annex 4 Plant-pathogenic fungi and plant-parasitic nematodes. Fungi are assessed by the DNA-Multiscan®. For each residue type, 1 sample was analyzed. Nematodes are assessed by automated zonal centrifugation. The quantity (number of individuals) per 100 ml or residue is indicated.

	HC1 **n=1**	**HC2** **n=1**	**FP** **n=1**	**HP** **n=1**
Plant-pathogenic fungi[1]				
Cylindrocladium sp.	2	0	1	0
Fusarium sp.	3	3	1	1
Fusarium oxysporum	1	1	0	0
Fusarium solani	0	1	0	0
Geotrichum candidum	3	2	1	1
Penicillium sp.	0	3	2	1
Plant-parasitic nematodes[2]				
Criconematidae	5	0	0	3
Helicotylenchus sp.	5	2	0	158
Rotylenchus sp (not *robustus*)	0	0	0	86

[1] abundance: 1 = low ; 2 = intermediate ; 3 = high

[2] number of detected individuals

Annex 5

[Fig. 3, Rstudio 1.0.143]

Fig. 3 Bivariate cluster plot for the chemical parameters. K-means cluster analysis was performed with k = 2. PC1 and PC2 explain 68.16% of the point variability. Samples 1-13 are labelled as HC2; samples 14-21 as HP and samples 23-35 as FP. The cluster analysis evaluates the appropriateness of the labels given to the residues. Observation are classified in clusters based on minimized sum of squares from points to the assigned cluster.

[Fig. 4, Rstudio 1.0.143]

Fig. 4 Bivariate cluster plot for the physical parameters. A K-mean cluster analysis was performed for k = 2. Samples from 1 to 10 were labelled as heath chopper, samples from 11 to 21 were labelled as plaggen. The cluster analysis evaluates the appropriateness of the labels given to the residues. Observation are classified in clusters based on minimized sum of squares from points to the assigned cluster