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Interrelationships between soil cover and plant cover depending on land use

Tiina Köster[a,b] and Raimo Kõlli[b]

[a] Agricultural Research Centre, Saku, Teaduse 4/6, 75501 Harju County, Estonia
[b] Estonian University of Life Sciences, Kreutzwaldi 1A, 51014 Tartu, Estonia; tiina.koster@pmk.agri.ee, raimo.kolli@emu.ee

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Abstract. Interrelationships between soil cover and plant cover of normally developed (or postlithogenic) mineral soils are analysed on the basis of four sampling soil groups. The four-link pedo-ecological sequence of analysed soils, rendzinas → brown soils → pseudopodzolic soils → gley-podzols, forms a representative cross section in relation to the normal mineral soils of Estonia. All groups differ substantially from each other in terms of soil properties (calcareousness, acidity, nutrition conditions, profile fabric and humus cover). The primary tasks of the research were (1) to elucidate the main pedo-ecological characteristics of the four soil groups and their suitability for plant cover, (2) to evaluate comparatively soils in terms of productivity, sustainability, biodiversity and environmental protection ability and (3) to analyse possibilities for ecologically sound matching of soil cover with suitable plant cover. On the basis of the same material, the influence of land-use change on humus cover (epipedon) fabric, properties of the entire soil cover and soil–plant interrelationship were also analysed. An ecosystem approach enables us to observe particularities caused by specific properties of a soil type (species, variety) in biological turnover and in the formation of biodiversity.

Key words: matching soil and plant cover, soil–plant relationships, land use change, soil type-specific biodiversity.

INTRODUCTION

Soil cover is a determining factor in the development of plant cover and its diversity (Laasimer 1965; Chertov 1981; Ibanez et al. 1998). In every region of the world the composition and properties of soil cover have certain distinctive regional singularities (Deckers et al. 1998; IUSS 2006; Toth et al. 2008). The composition and properties of each soil type in a soil cover are inherited from soil parent material. The parent material variability (or geodiversity) may be caused by soil texture variations (from sand to clay), mineralogical and chemical composition, calcareousness and acidity. The pattern of soil cover induced by geodiversity (or pedodiversity) in turn plays a decisive role in forming the plant cover of natural areas and its floristic composition. For better understanding of mutual influences of soil cover and plant cover in a geographical region, the feedback influences of their functioning and main components (soil, plant) should be studied at the ecosystem level, on typical-to-region soil types and primarily within the specific management conditions (Fisher et al. 2002; Bazilevich & Titljanova 2008; Paal et al. 2011).

Research on soil–plant relationships is needed for arrangement of land management based on an ecosystem approach and to explain pedo-ecological causes of plant cover diversity. As the character of plant cover is greatly influenced by land management, soil–plant relationships should be studied comparatively in natural and cultivated ecosystems. There is much research in which soil–plant interrelationships (expressed by productivity and biological cycling) are treated systematically in accordance with pedo-climatic conditions and land use (Kõlli 1987; Targulian & Krasilnikov 2007; Bazilevich & Titljanova 2008), but we found only a few studies about pedodiversity as a basis for biodiversity (Karpachevskij 1977; Ibanez et al. 1998; Guo et al. 2003).

In Estonia, many studies deal with soil–plant interrelationships in the pedo-ecological conditions, with adequate emphasis on the role of soils in the formation and functioning of ecosystems (Sepp 1962; Laasimer 1965; Lõhmus 1973; Reintam 1997b; Kont et al. 2004; Arold 2005). Additionally, valuable research is available in which soil is treated in complex with other ecological conditions, and which emphasizes the coenological and floristic aspect of system functioning (Krall et al. 1980; Zobel 1992; Laasimer & Masing 1995; Paal 1997; Paal et al. 2010). Both research directions have been of equal value in enlarging our understanding of functional particularities of forest, grassland and agro-ecosystems in the northeastern edge of the European Plain (EC 2005).

Interrelationships between soil cover and plant cover are analysed on the basis of sampled soil groups (or soil associations). For this purpose the four-link cross section or discrete pedo-ecological sequence (PES) of soils, which is composed of key regional soils and characterizes Estonian normal (or postlithogenic) mineral soils (from drought-prone skeletal calcareous rendzinas to wet acid sandy gley-podzols), is used (Kõlli et al. 2008). The abnormal (or synlithogenic) mineral soils are not treated in this work.

The main tasks of the soil–plant interrelationships study are (1) to elucidate main pedo-ecological characteristics of the PES soil groups and suitability for plant covers (by species, associations, crops); (2) to compare and evaluate properties of soil groups from the aspect of productivity, sustainability, biodiversity and environment protection ability and (3) to prove the importance of ecologically sound matching of local area soil (soil cover) with suitable plant cover (forests, grasslands, crops) from the environmental protection aspect.

The study of interrelationships on the basis of key soil groups at the ecosystem level enables us (1) to emphasize the importance (or site) of specific biodiversity of soil type in treating soil-related aspects of biodiversity and (2) to characterize the influence of land-use change on soil properties, by means of comparative analysis of natural and cultivated ecosystems formed on the same soil types.

MATERIALS AND METHODS

General methodological principles

The basis of the research is an ecosystem approach, with special interest in interrelationships between soil cover and plant cover (as main components of terrestrial ecosystems). The stated problems are treated from the pedo-centric viewpoint: the ecosystems for research were selected on the basis of soil cover as the determining component in the formation and development of an ecosystem. The soil groups selected for comparative analysis are presented in Table 1 and Fig. 1. All four sampling soil groups differentiate substantially from each other by main soil properties (calcareousness, acidity, nutrition conditions, profile fabric and characteristics of humus cover). Therefore, the differences between various soil groups are significant, but the coincidence of their properties is insignificant.

Soil names and their codes in the tables and text are given according to the Estonian Soil Classification (ESC) (ELB 2012). Besides the ESC, for the purpose

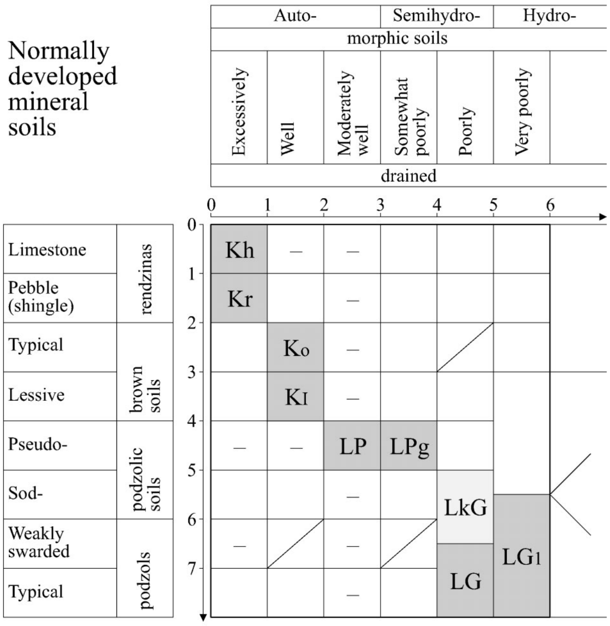

Fig. 1. Location of the pedo-ecological sequence of studied soil groups on the matrix table of normal mineral soils. Soils: Kh, limestone rendzinas; Kr, pebble rendzinas; Ko, typical brown soils; KI, lessive brown soils; LP, pseudopodzolic soils; LPg, gleyed pseudopodzolic soils; LkG, podzolic gley-soils; LG, gley-podzols; LG1, peaty podzols.

Table 1. Nomination of sampling soil groups by the Estonian Soil Classification (ESC) and distribution of analysed soil groups among Estonian normally developed mineral soils

Nomination of soil groups by ESC			Percentage of soil group from normal mineral soils area 1) on			
No.	Name	Code	total land	forest land	arable land	grassland
1	Rendzinas (limestone, pebble, shingle)	Kh, Kr (Kk)	2.9	1.1	3.7	3.1
2	Brown soils (typical, lessive, gravelly)	Ko, KI (Kor)	9.1	4.2	18.7	12.6
3	Pseudopodzolic soils (glossic, gleyed)	LP, LPg	13.1	5.9	24.9	5.7
4	Gley-podzols (gley-, peaty)	LG, LG1	5.2	13.4	0.9 2)	4.0 2)
1–4	Totally PES soils	8(10) soil species	30.3	24.6	48.2	25.4

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1) The distribution % of total, forest and arable land is calculated after Kokk (1995), on grassland – our approximate estimation; 2) to the area of gley-podzols (LG) and peaty podzols (LG1) the area of podzolic gley-soils (LkG) was added.

of harmonization, the internationally recognized World Reference Base for Soils (WRB) was used (IUSS 2006), which also allows comparison of soil groups via widely known soil qualifiers (Table 2). In our databases soil texture is given as a rule after Kachinsky (1965). The accordance of classification systems elaborated for characterization of soil texture (Kachinsky *versus* WRB) and of different moisture conditions of plant cover, humus cover and soil cover are presented in Table 3.

A PES of soils was used not only for the analysis of soil–plant relationships, but also for the study of changes in interrelationships connected with land use change (Fig. 2). The comparative research into natural and cultivated ecosystem components – soil cover, plant cover and humus cover (formed by the interaction of the first two covers) – was conducted within the limits of adequate four soil groups.

Terminology

Soil cover (or solum) embraces the superficial earth layer or soil resource influenced by soil-forming processes. Soil cover depth extends from the surface to the unchanged parent material, or the C horizon. In the presence of the BC horizon, the thickness of soil cover was measured to the middle of the BC horizon. Soil cover consists of humus cover (topsoil) and subsoil. Humus cover (topsoil or epipedon) encompasses the most active superficial soil component, which is closely coupled with plant cover and via which the dominant component of carbon cycling takes place. Humus cover consists of the forest floor, humus or raw humus and peat horizons.

The smallest classification unit identified following soil-forming processes (soil genesis) is a soil species, according to the ESC. Soil species are subdivided into varieties on the basis of texture. The PES of soils is formed on the background of certain (optional) soil-forming (pedo-ecological) conditions; its purpose is to provide representative and comparative characterization or cross section of soil cover of a particular region.

Climatic and pedo-ecological conditions of Estonia

Local climatic conditions, with typically warm summers and moderately mild winters, place Estonia in the temperate zone of the Atlantic-continental region. Mean annual air temperature varies within +4.5–6.0 °C and annual precipitation is 600–700 mm (Jaagus 1999).

Estonian soil cover is characteristic of northeastern Europe, where due to relatively cold and humid conditions, gley- and mire soils dominate (Toth et al. 2008). The dominant parent materials are derived from glacial and

Table 2. Identification and characterization of soil groups by the World Reference Base for Soils (WRB)

Soil group		Qualifiers[1)]
No.	Reference soil by WRB	
1	Leptosols	*leptic / lithic*, *rendzic / calcaric*, *hyperhumic*, *episkeletic*
2	Cambisols, Luvisols	*cambic*, *mollic*, *luvic / cutanic / endoskeletic*, *endocalcaric*, *eutric*
3	Albeluvisols	*albic*, *luvic*, *glossic*, *umbric / fragic*, *endogleyic*, *stagnic / dystric*, *abruptic*
4	Podzols	*spodic / fibrihistic*, *epigleyic*, *albic*, *ortsteinic / arenic*, *dystric*

[1)] Three groups of qualifiers separated by '/' are, respectively: main characteristics of reference soil / prefix qualifiers / suffix qualifiers.

Table 3. Moisture conditions, texture and humus cover types of soil groups

Group No.	Moisture conditions[1)]	Dominating soil group texture[2)]	Humus cover type	
			on forest soils	on arable soils
1	Dry, fresh	Gravelly loam on pebble, loam on limestone	Dry calci-mull, fresh calci-mull	Skeleti-calcaric mild
2	Fresh	Loam on gravelly loam	Fresh mull, fresh moder-mull	Neutral mild, eluvic moder
3	Fresh, moist	Loamy sand on loam, loam	Fresh moder, moist moder	Acid low humuous, eluvic moder
4	Wet, peaty	Sand	Wet mor, peaty mor	Oligotrophic raw humuous

[1)] Adequate estimations for soil cover: dry – drought-prone; fresh – normally moist; moist – gleyed, endogleyic, temporally over-moist; wet – gley-, epigleyic, permanently over-moist; peaty – peaty-gley-, epigleyic, permanently strongly over-moist. [2)] Content of physical clay (particles with Ø <0.01 mm) in fine earth (particles with Ø <1 mm): loam 20–40%, loamy sand 10–20% and sand <10%.

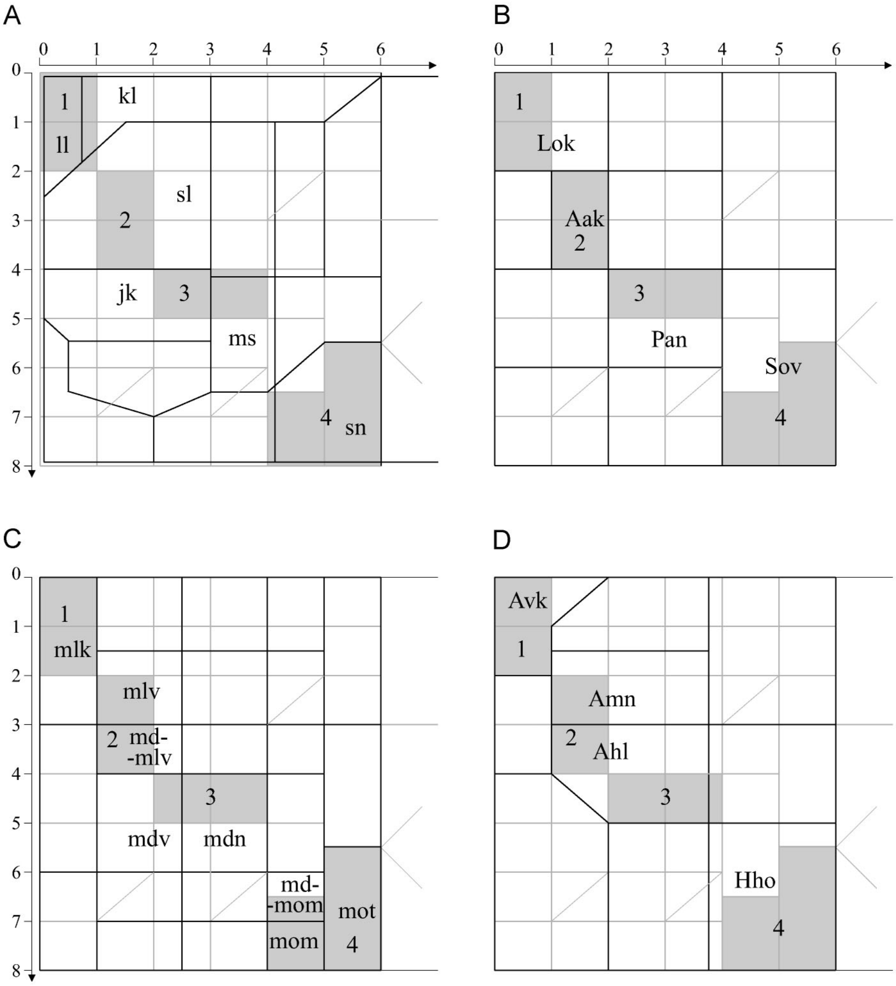

Fig. 2. Relationships of plant covers and humus covers with soils in different land use conditions. For soil groups 1–4 see Tables 1 and 2; for scalars of matrix table see Fig. 1. Related studied soil groups: (**A**) forest site types – ll, *Acrostaphylos*-alvar; kl, *Calamagrostis*-alvar; sl, *Hepatica*; jk, O*xalis*; ms, *Myrtillus*; sn, *Vaccinium ulginosum*; (**B**) grassland types – Lok, dry alvar; Aak, dry typical; Pan, moist heathy; Sov, poor paludified; (**C**) humus cover types of forest soils – mlk, dry calci-mull; mlv, fresh forest-mull; md-mlv, fresh moder-mull; mdv, fresh moder; mdn, moist moder; md-mom, wet moder-mor; mom, wet mor; mot, peaty mor; (**D**) humus cover types of arable soils – Avk, calcareous low humuous; Amn, neutral mild humuous; Hho, oligotrophic raw-humuous.

aquaglacial *Quaternary* deposits. Pleistocene tills make up approximately half of the parent material of mineral soils. Glaciofluvial, glaciolacustrine, alluvial and aeolian sediments re-worked from tills are distributed throughout the tills (Raukas 1995).

Estonian pedo-ecological conditions are favourable for the formation of soil resulting from organic carbon accumulation in topsoil and the leaching of nutrients by podzolization (Reintam 1998). The mobilization of humus into biological weathering and intensive turnover of substances in the soil–plant system are also induced in these conditions (Reintam 1997a, 2007). The soil cover of Estonia is relatively varied, due to the alternation of carbonate and humus-rich soils with acid soils which are relatively poor in nutrients and organic matter, and, conversely, the interchanging of the soil moisture regime from dry to wet.

Normally developed mineral soils form ca 72% of total Estonian soil cover (Kõlli et al. 2009). The decreasing orders of their textures (loam 37%, sand 34%, sandy loam 22%, clay 7%) and moisture regimes (wet 47%, fresh 30%, moist 20%, dry 3%) are given after Kokk (1995). Approximately 53% of soils are formed on calcareous and ca 47% on non-calcareous parent material.

In terms of plant cover, Estonia belongs to the transitional area between south-taiga forest and spruce-hardwood subzones, located in the southern part of the boreal forest zone (Laasimer & Masing 1995). Floristically, Estonia belongs to the boreal mixed-forest sub-region, where plant cover is relatively rich in species (Kull & Zobel 1991). Due to human influence, plant cover may be classified as natural (forest), semi-natural (grasslands, drained wet mineral soils) and cultivated (arable lands). The grassland vegetation is mostly of secondary origin, having been formed under a long-lasting influence of haymaking and pasturing (Laasimer & Masing 1995). In recent decades, intensive afforestation of both grasslands and arable lands has occurred (Astover et al. 2006).

Methods used for assessments and calculations

The analysis is based on qualitative and quantitative parameters of ecosystems. Among qualitative parameters, along with WRB qualifiers, local classification systems (soils, forest site type, humus cover types, soil agro-groups, natural grasslands, environmental protection ability) were used.

Quantitative parameters for characterization of soil groups (soil organic carbon and organic matter pools, agrochemical parameters, pedometrics of soil profiles) were taken from the database 'Pedon' formed mainly on the basis of our research (Kõlli 1987), from the serial edition *Soils of the Estonian SSR in Numbers* (EAP 1989) and other published works on the studied soils (Asi et al. 2004; Kõlli et al. 2010).

For estimation of total phytomass and annual phyto-productivity (APP) of forest ecosystems, the methods employed by the International Biological Program were used (Rodin et al. 1968; Kõlli 1987). To accumulate the comparative data of soils in the sampling areas, we selected forests of approximately the same age (premature to mature) and stand stock density (0.6–0.9) (Kõlli 1987). The phytomass and APP for tree and underwood layers were determined by model trees; the total phytomass of ground vegetation in forests, and of arable and grasslands ecosystems, was found by means of test plots (model plants on cultivated areas). The APP of herbaceous plants was established by the maximum phytomass of the vegetation period. For estimation of productivity level, long-term cereal yields on arable lands and hay yields on grasslands were also used.

Soil quality classes were used for comparative analysis of soil group productivity. The soil quality evaluation tables and formulae may be qualified as particular models elaborated on the basis of large amounts of experimental field data. The forest quality index was found by height of dominant trees at a certain age. The quality of arable soils was determined by soil type, texture, and depth and humus content of the A-horizon, but for grassland soils, according to yield. The instructions for determination of soil quality may be regarded as models, where, given the correct input parameters, the adequate-to-actual soil quality output (point, class) is received (ELB 1992). Suitability of soil for cultivated crops was estimated in a 10 point scale (Kõlli 1994). For statistical analysis the program STATISTICA 7 was used.

Organic carbon concentration was determined by wet digestion of carbon with acid dichromate, extractable acidity by titration with 0.1 M NaOH after adding 1 M CH_3COONa solution and soil reaction (pH_{KCl}) in 1 M KCl 1 : 2.5 (Vorobyova 1998). The basic cations were determined by 1 M CH_3COONa extraction procedure (SPAC 1992). Cation exchange capacity (CEC) and percentage base saturation were calculated according to the sum of bases and extractable acidity. The results of analyses are expressed in pools (or superficial densities) per humus cover and soil cover (or solum) as a whole on the basis of soil bulk density.

RESULTS

Nomenclature, distribution and properties of soil groups

The four soil groups selected for analysis represent ca 1/3 of the total area of Estonian normal mineral soils (Table 1, Fig. 1). The representative pedo-ecological cross section rendzinas → brown soils → pseudopodzolic soils → gley-podzols starts with drought-prone soils rich in calcareous limestone. The next two links of PES are the most broadly acknowledged for wide-range agricultural use (forming ca 44% of arable land), medium-textured high-quality automorphic soils. Brown soils are distributed in the northern and central regions, pseudopodzolic soils, in southern Estonia. The PES ends with permanently wet and strongly acidic, low-productivity sandy soil.

The WRB qualifiers (modifiers) that were used for characterizing and comparing the soil groups are presented in Table 2. By the grouped list of qualifiers, where the main reference soil characteristics are also given (1st part of qualifiers), the significant pedo-genetic difference between sampling soil groups may be asserted. The only overlapping characteristics may be found for qualifiers *albic* and *dystric*, which are common for Albeluvisols (pseudopodzolic soils) and Epigleyic and Fibrihistic Podzols (gley-podzols), and *luvic*, which is common for Luvisols (lessive brown soils) and Albeluvisols.

Soil texture has the basic role in the development of soil properties in natural conditions (Table 3). The sampling soil groups differ substantially in the dominant fine earth textures (sand, loamy sand, loam) and in their gravel (from absent to excessive) stages. Unlike texture, moisture conditions may be profoundly transformed by drainage: the moist soils of group 3 may, in transformation, become similar to fresh soil, and wet and peaty soils (group 4), similar to moist soils. An important qualitative characteristic of soil is its humus cover type (or humus form), which reflects soil humus status, biological activity and textural-mineralogical potential of both topsoil (epipedon) and subsoil, and therefore the entire soil cover.

The generalized characteristics of sampling soil groups are presented in Table 4 and Fig. 3. The thickness of soil cover depends first on the development of eluvial processes in soil. The CEC of soil cover as an integrated parameter depends on both the nature of organic and mineral components and soil cover depth. Of great indicative value is soil texture, which is expressed by physical clay concentration (particles <0.01 mm by Kachinsky 1965, adequate to which is the sum of particles of fine silt and clay by the WRB) and stock. In ecological research the stock of organic carbon and nitrogen concentration in different soil layers is also very important. With increasing soil acidity and stages of eluviation and gleyification, the accumulation of non-decomposed organic matter constituting the forest floor (exogenous organic carbon) increases considerably. This is accompanied by transforming humus quality, as instead of *humic* humus, *fulvic* humus is formed.

Each of the four soil groups may be subdivided into subgroups, according to pedo-genetic differences. These differences are caused by various features (Table 1); in some cases the geographical region of soil distribution (as determinant of soil-forming conditions) is of great importance.

Soil associations of rendzinas (group 1), which are distributed on the undulating till and flat limestone plains of North and Northwest Estonia, and on the islands, differ in terms of parent material fabric (formed on limestone or calcareous pebbles and shingle). Rendzinas are characterized by shallow soil profiles (O–A–R for Kh and O–A–(B)–C for Kr and Kk) in natural areas. The dominant fine earth texture (particles with diameter <1 mm) of both soils is loam. Therefore, dominant soil varieties in this group are medium-textured (loamy) limestone rendzinas (Kh, 52%) and pebble rendzinas (Kr, 48%). The light-textured shingle rendzinas (Kk) occur only to a reduced extent (<1%) on coastal ridges.

Rendzinas have a high base saturation stage, due to a high percentage of limestone. The humus cover is shallow and rich in calcareous gravel. These soils are susceptible to drought, which is a limiting factor for plant growth. The properties of Estonian rendzinas and their interrelationships with plant cover have been addressed in numerous studies (Sepp 1960, 1962; Lillema 1962; Lõhmus 1974; Laasimer & Masing 1995; Paal 1997; Sammul et al. 2003).

Brown soil associations found in group 2 have a *cambi-argic* profile formed by argillization in situ or by argi-eluviation in rich non-siliceous sesquioxides and biologically active conditions (Reintam 1998). Brown soils (Ko, Kl, Kor) are formed mainly on calcareous yellow-grey till (>95%), under favourable hydrothermal, redox and biological relationships; the calcareous red-brown till (<5%) is a parent material only to a reduced extent. By natural drainage, brown soils are classified as well-drained. In the course of soil survey four soil varieties were identified: typical (47%) and lessive (30%) loamy brown soils, and typical (13%) and lessive (10%) brown soils on sandy loam under-layered by calcareous

Table 4. Generalized characteristics of soil covers by studied soil groups

Characteristic[1]	No. of soil group[2]			
	1	2	3	4
Thickness of soil cover or solum, cm	23a[3]	52/74[4]b/c	92d	76c
SOC stock in forest soil solum, Mg ha^{-1}	80–100	85–105	60–75	100–120
SOC stock in arable soil solum, Mg ha^{-1}	70–90	80–100	65–75	60–80
Mean solum SOC stock of soil group, Mg ha^{-1}	75b	91c	67a	114d
CEC of solum, 10 kmol ha^{-1}	65–75	140–155	165–190	130–160
Stock of physical clay in solum, 10 Mg ha^{-1}	75–90	200–300	300–350	60–150
N stock in solum (For/Arb)[5], Mg ha^{-1}	4/5–7	3–5/8–10	2–3/7–8	0.8–1.2/4–5
SOM stock of forest floor, Mg ha^{-1}	8–10a	7–9a	10–15b	50–75c
Ratio Chh/Cff[6]	14c	14c	5.7b	<0.5a

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[1] SOC – soil organic carbon, CEC – cation exchange capacity, N – nitrogen, SOM – soil organic matter;
[2] for soil group names see Tables 1 (by ESC) and 2 (by WRB), whereas the exception is soil group 4, where in arable areas the data are presented for podzolic gley-soils (LkG), which are modified by cultivation of gley- and peaty podzols (LG, LG1); [3] letters next to the data indicate significant difference at $p < 0.05$; [4] respectively Ko and Kl; [5] For – forest soils, Arb – arable soils; [6] ratio of organic carbon in humus horizon (Chh) to organic carbon in the forest floor (Cff) or ratio of endo- and exogenous organic carbon.

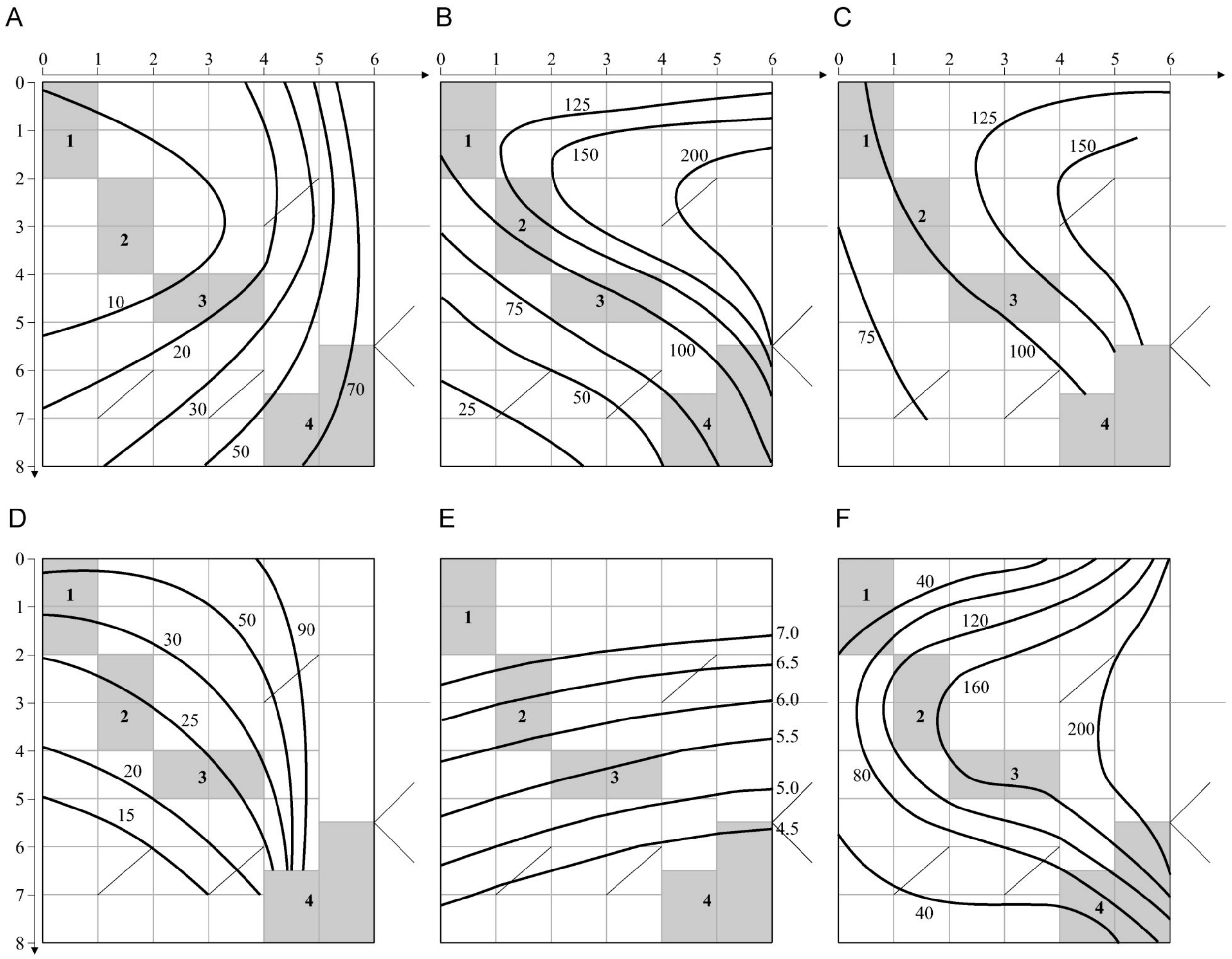

Fig. 3. Generalized properties of sampled (exerpt) soil groups. For soil groups 1–4 see Tables 1 and 2; for scalars of matrix table see Fig. 1. Soil properties on the background of soil matrix expressed by means of isolines: **A**–**C**, pools of organic matter (Mg ha^{-1}), (A) in forest floor, (B) in humus cover of forest soils, (C) in humus cover of arable soils; **D**, organic matter content (g kg^{-1}) in humus cover of arable soils; **E**, pH$_{KCl}$ of humus cover of arable soils; **F**, water available to plants, in mm per 75 cm soil layer.

loam. Soils formed on red-brown till soils are also included in the latter textural group. Brown soils have favourable conditions for plant growth (substantial water holding capacity, relatively high CEC, favourable hydrophysical properties, suitable air and water regimes). Classification, properties and soil–plant relationships of Estonian brown soils have been thoroughly investigated (Laasimer 1965; Reintam 1973, 1998; Paal 1997; Paal et al. 2010).

Pseudopodzolic soil associations of group 3 (formed without or with gleyzation) are distributed mostly on undulating reddish-brown till plains in southern Estonia. They were developed on two-layer deposits, where loamy sand (or silt) lay on loamy till. The main soil-forming processes in these soils are ferrolysis with Fe-segregation, deferritization and surface gleying (Reintam 1998). These conditions are favourable for the formation of mobile humus as well as for intensive biological weathering and turnover of substances in the plant–soil system.

Among fresh, moderately well-drained pseudopodzolic soil (LP) associations with normal moisture conditions on red-brown tills, the dominant soil texture is loamy sand on loam. The ratio of soil variety of loamy sand on loam to the variety with loam texture is 9 : 1. If formed on yellow-grey till pseudopodzolic soils, the ratio of the same soil varieties is 2 : 1. The gleyed (moist, somewhat poorly drained) pseudopodzolic soils (LPg) are formed on red-brown till and their texture is loamy sand on loam. Therefore, soils (76%) that formed on red-brown tills dominated over the formed yellow-grey (24%) and normally moist (fresh) soils (75%) dominated over gleyed (moist) pseudopodzolic soils (25%).

In rainy periods, the textural discontinuity of pseudopodzolic soils causes excessive water to persist in a contact layer between the two different materials. The water regime of these soils is relatively unstable as they may dry out in droughty periods. In forests their topsoil is predominantly acid, but their subsoil may have a neutral reaction. The functioning, properties and classification of Estonian pseudopodzolic soils were broadly treated by Reintam (1973, 1997b) and Kõlli (1987).

Gley-podzols and peaty podzols (group 4) were developed on acid sands in permanently wet moisture conditions, which cause the formation of a thin peaty forest floor (on LG) or shallow peat horizon (on LG1) instead of a humus horizon. These soils are divided into two varieties according to the degree of paludification, which is reflected in the soil profile by the degree of soil mineral part gleyification and by the extent of peat forming in the epipedon. The percentage ratio of gley-podzols and peaty podzols for their specific area is 58 : 42, but for the overall forest the ratio is 62 : 38. In terms of natural drainage, gley-podzols may be classified as poorly drained and peaty podzols as very poorly drained (SSDS 1993). Although podzolization is an important process in their formation, to divide them according to podzolization degree is not meaningful. But, regarding podzolization, different kinds of iron-sesquioxide and humus accumulation *spodic* horizons, varying in horizon thickness and degree of cementation (from non-cemented to strongly cemented), may be formed. The interrelationship between gley-podzols and plant cover has been discussed in relation to forests (Lõhmus 1973, 1974; Valk & Eilart 1974; Chertov 1981).

The PES soils considered in our work do not characterize the full range of normal mineral soils. For example, the hydromorphic gley-soils are not analysed. These have a sophisticated soil–plant relationship, or the typical podzols and podzolic soils formed on well-drained acid sands, all of which are widely distributed in Estonia.

Characterization of plant covers of soil groups

Soils may be characterized indirectly by forest site type and grassland type, as the floristic composition of above-ground vegetation largely reflects (depending on external influences) the plant growing properties of the soil cover (Krall et al. 1980; Paal 1997; Lõhmus 2006). Natural plant associations indicate the soil water regime, nutrient supply and acidity, verifying with this the soil type (Zobel 1992; Zinko et al. 2006). The forest site types distinguished by Lõhmus (2006) and grassland types established by Krall et al. (1980) for the studied soils are given in Table 5 and Fig. 2A, C. On cultivated soils approximately the same task is associated with soil agro-groups, which have been created on the basis of soil texture and moisture conditions for characterization of the suitability of soil for agricultural purposes (ELB 2012).

The generalized plant cover characteristics for the studied soils in different management conditions are presented in Table 6. It appears that our selection of the above-ground structure of forest ecosystems (floristic composition, variously functioning layers and the relative role of phytomass of different origin) adequately reflects the main soil properties and differences among soil groups. Of course, in alternative conditions of the tree layer (clearings, young and open stand), the study of the influence of soil properties on plant cover and *vice versa* is complicated. In the case of forest ecosystems, brown and pseudopodzolic soils have the highest total above-ground phytomass, and rendzinas and gley-podzols, the lowest. Among the number of species within the different ecosystem layers, we counted only those which have at least minimal measurable functional importance. The

Table 5. Accordance of soil groups with forest site type, soil agro-groups and grassland types

Soil group No.	Model forest site type (code)	Soil agro-groups (code and short characterization)	Natural grassland type (code)
1	*Acrostaphylos*-alvar (ll)	C1 – unsuitable for field crops, suitable for grassland husbandry	Dry alvar (Lok)
2	*Hepatica* (sl)	A22 – medium-textured automorphic soils well suitable for field crops	Dry typical (Aak)
3	*Oxalis* (jk), *Oxalis–Myrtillus* (jk–ms)	A – medium-textured automorphic (A21) and well-drained gleyed (A42[1]) soils well suitable for field crops	Dry heathy (Pak), moist heathy (Pan)
4	*Vaccinium ulginosum* (sn)	B33[1] – light-textured well-drained gley soils, reasonably suited to field crops, well suited for grassland husbandry	Poor paludified (Sov)

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[1] Group codes A42 and B33 are valid if soils are sufficiently drained.

Table 6. Generalized characteristics of plant covers by studied soil groups

Characteristics		No. of soil group[1]			
		1	2	3	4
Dominant species of tree layer[2]		Pc, Pn	Pc, Pn, Qu, Be	Pc, Pn, Be	Pn
Number of species[3]	Underwood	7–9 (11)	8–10 (17)	6–8 (10)	3–4
	Herb layer	25–30 (32)	30–35 (52)	20–25 (34)	5–10 (13)
	Moss layer	4 (6)	5–8 (10)	7–10	5–7
	Shrub layer	2 (3)	0–2	2–3	4–6 (7)
Above-ground phytomass in dry weight	Tree layer, Mg ha^{-1}	108.5a[4]	159.4b	197.3c	105.8a
	Underwood, 10^2 kg ha^{-1}	14.8a	42.8b	13.2a	11.4a
	Herb layer, 10^2 kg ha^{-1}	6.1c	6.2c	3.4b	0.5a
	Moss layer, 10^2 kg ha^{-1}	12.5a	11.6a	11.4a	45.0b
	Shrub layer, 10^2 kg ha^{-1}	0.3a	0.3a	1.9b	13.9c
Number of plant associations	Geobotanical approach For/Grl[5] (Laasimer 1965)	2/3	3/2	1/2	1/2
	Grasslands (Krall et al. 1980)	5	5	6	2–3
	Grasslands (Paal 1997)	4	6	4	2
Suitability for crops	B–R–P[6]	6–5–4	10–9–9	9–10–10	7(5)[7]–8(5)–8(4)
	A–C–Fg[8]	8–4–4	9–9–9	4–9–9	3(1)–5(3)–8(6)

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[1] For soil group names see Tables 1 (by ESC) and 2 (by WRB), the exception is soil group 4, where arable areas data are presented for podzolic gley-soils (LkG), which are modified by cultivation from gley- or peaty podzols (LG, LG1); [2] tree species: Pc – spruce, Pn – pine, Qu – oak, Be – birch; [3] species, which have certain importance from the functional aspect; the maximum number of species is given in brackets; [4] letters next to the data indicate significant difference at the $p < 0.05$ level; [5] respectively in forest and in grassland; [6] suitability of arable soils for crops B–R–P: respectively barley, rye and potato; [7] in brackets suitability of undrained LkG soil for crops; [8] A–C–Fg: alfalfa, clover and field grasses.

richest, according to the number of species, are forest ecosystems on brown soils, followed by rendzinas.

The floristic composition of plant cover on rendzinas and gley-podzols differs significantly from all others, but the differences in the composition between brown and pseudopodzolic soils are not as clearly visible. The ground vegetation and underwood are richer in plant species and are more developed on brown soils than on more acid pseudopodzolic soils. The only exception is a more abundant shrub layer on gley-podzols.

In grassland ecosystems with brown lessive and pseudopodzolic (non-gleyed) soils, a substantial extent of overlapping plant associations with key species *Agrostis capillaris*, *Festuca rubra*, *Trifolium repens* and *Anthoxantum odoratum* is observed. Such associations (*Trifolio repentis–Festucetum rubrae*, *Agrostio capillaries–Trifolietum repentis*, *Agrostio capillaries–Anthoxanthetum* and others) were formed on previous arable land under the influence of cattle grazing (Paal 1997).

A good instrument for determining agro-ecological characteristics of arable soils is the ten-point scale soil suitability rating for crops (Kõlli 1994; Table 6). The phytomass of weeds and their floristic composition are an important pedo-ecological indicator for characterizing arable soil properties (as well as cultivated grasslands) (Laasimer 1965; Bender 2006; Older 2007). The weed species which reflect arable land status and site properties are very numerous and ambiguous (Lososova et al. 2004). The presence of certain weed species depends, first of all, on cultivated crops and the agrotechnology applied (Bender 2006; Older 2007). The following weed species indicate arable soil properties: rendzinas – *Anthemis tinctoria*, *Rubus caesius*, *Sinapis arvensis*; brown soils – *Thlaspi arvense*, *Potentilla arvense*, *Soncjus* sp.; pseudopodzolic soils – *Viola arvensis*, *Scleranthus annuus*, *Raphanus raphanistrum* and drained podzolic gley-soils – *Ranunculus repens*, *Polygonum persicaria*, *Juncus* sp., as they may frequently be found in association with other species.

The best characteristics for comparative analysis of the functioning of soil groups are the directly determined productivity parameters formed on their ecosystems (Table 7). The total phytomass of forest and its tree layer may be taken as an indirect parameter, on which the development of above-ground vegetation and underwood (among this re-growth) depends. The best characteristic for the analysis of functioning efficiency of the forest ecosystem is its APP, which correlates strongly with forest quality classes and the annual soil organic carbon balance (Fig. 4). As an indicator of the productivity of

Table 7. Generalized characteristics of plant cover productivity by soil groups

Characteristic	Type of ecosystem$^{2)}$	No. of sampling soil group$^{1)}$			
		1	2	3	4
APP$^{3)}$ of tree layer and underwood, 10^2 kg ha^{-1}	FES	53.0b$^{4)}$	90.2c	88.9c	35.1a
APP of ground vegetation, 10^2 kg ha^{-1}	FES	9.2b	11.0b	6.7a	13.2c
Generalized limits of APP, Mg ha^{-1}	FES	5–9a	12–14b	13–15b	5–8a
Standard yield of cereal grains (by E. Kitse, unpublished data), Mg ha^{-1}	AES	1.64	2.65	2.40(2.31)$^{5)}$	1.91(1.37)$^{5)}$
Above-ground phytomass of barley, Mg ha^{-1}	AES	6–8	8–9	7.5–8.5	ND$^{6)}$
Natural grasslands hay yield, 100 kg ha^{-1}	GES	4–5	13	13–14	5
Annual falling litter, Mg ha^{-1} yr^{-1}	FES	4–7	7–8.5	6–8	3–5
Annual falling litter of barley, Mg ha^{-1} yr^{-1}	AES	2–3.5	4–4.5	3.5–4.2	ND
Mean SOC annual balance, Mg ha^{-1} yr^{-1}	FES	2.2–2.3	3.6–3.7	3.4–3.5	1.7–1.8

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[1] For soil group names see Tables 1 (by ESC) and 2 (by WRB); the exception is soil group 4, where on the arable area data are presented for podzolic gley-soils (LkG), which are modified by cultivation of gley- and peaty podzols (LG, LG1); [2] FES – forest, AES – agro- and GES – grassland ecosystems; [3] APP – annual phytoproductivity, in dry matter; [4] letters next to the data indicate significant difference at $p < 0.05$; [5] in brackets the yield on undrained soil; [6] ND – not determined.

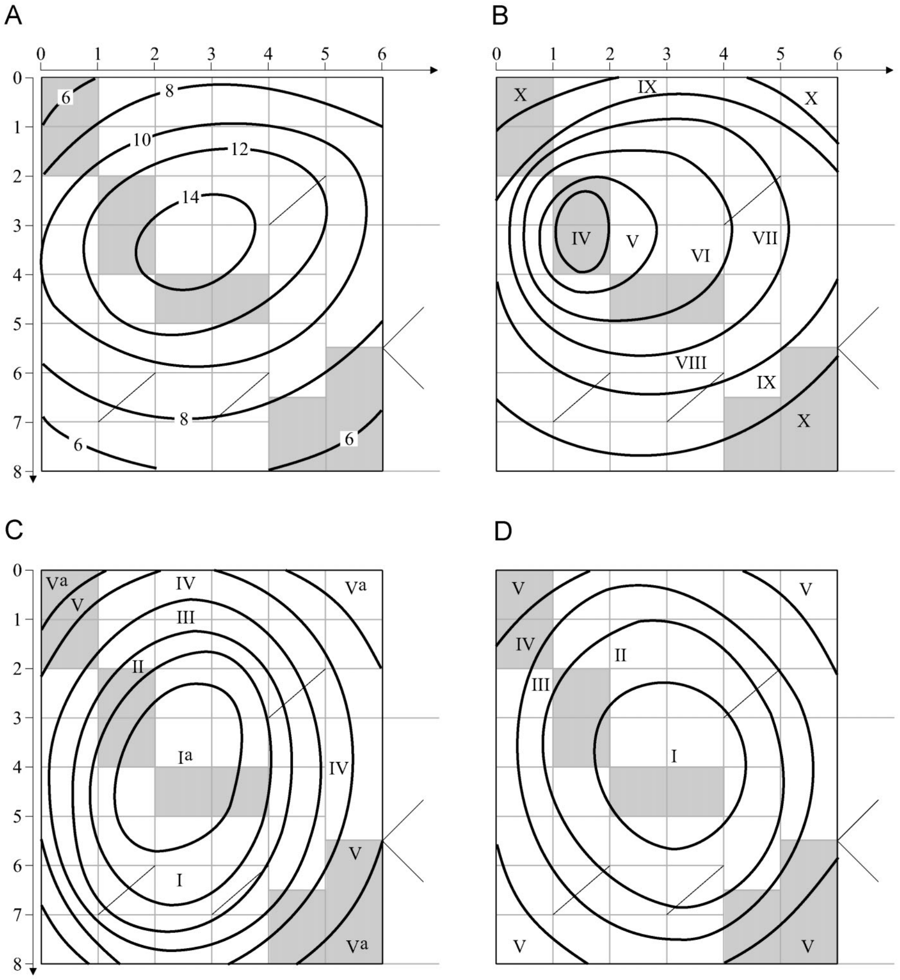

Fig. 4. Productivity and quality parameters of soils. For soil groups (grey) and scalars of matrix table see Fig. 1. Soil pedo-ecological parameters: (**A**) annual phytoproductivity (Mg ha^{-1} yr^{-1}) of forest ecosystems; (**B**) soil quality classes (IV–V – high, VI – intermediate, VII–VIII – low, IX–X – very low) of non-drained arable soils; (**C**) forest quality classes (I^a – the highest, V^a – the lowest); (**D**) environment protection ability (I – good, II – relatively good, III – satisfactory, IV – relatively weak, V – weak) of soils.

arable soils, it is rational to use the phytomass of specific species for testing. We used the above-ground phytomass of barley determined at the time of its maximum development.

Very low productivity is characteristic of natural grasslands formed on wet and peaty podzols. These natural grasslands have relatively good hay yield, when the wet/peaty podzol is transformed into (sod-)podzolic gley-soils. The same level of productivity is also found in semi-natural grasslands formed on set-aside, previously cultivated, sod-podzolic sandy gley-soils.

Estimates (soil quality points and classes) which enable quantitative comparisons of soil groups in the limits of certain land use type, whereas the principles used in these estimations are very different by land use (arable, forest and grasslands), are presented in Table 8. Soil quality (points, classes) of arable land reflects the potential productivity of soils with great accuracy. The actual productivity in agricultural land depends greatly on inputs of mineral and organic fertilizers, as well as on the selection of cultivated plant species. A stronger correlation between soil quality classes and alternative productivity characteristics (total phytomass, APP) may be found in the case of forest ecosystems. Annual phytoproductivity correlates well with soil environmental protection ability, which may treated as integrated indices of ecosystem functioning (Fig. 4D).

Land use and land use change

The best soils have been taken into agricultural use during the last century and in most of Estonia optimum land use is close to its limit. Most of the best soils, in terms of texture, moisture conditions, fertility and absence of constraints, are used for agriculture. However, specific corrections (such as reforestation and amelioration) are needed to use the remaining local land.

The arable land pattern of Estonia was formed almost entirely by cultivation of forest land. The preferred soils for cultivation were thick rendzinas, typical and lessive brown, pseudopodzolic and podzolic soils (Kokk 1995). The dominant textures of arable soils nowadays are loam and loamy sand (totalling 77%). At present, approximately half of the total Estonian soil cover lies under forests, where mire soils, gley-soils and podzols have dominated. The suitability of brown and pseudopodzolic soils (as soils of universal use) for various crops is much higher compared to rendzinas and gley-podzols (Table 6). The pebble rendzinas are suitable for deep-rooted species such as alfalfa (*Medicago sativa*) and white melilot (*Melilotus albus*).

Gley-podzols and peaty podzols are classified as typical forest soils because of their unsuitability for cultivation. Yet, to a limited extent (<0.5%), these soils have also been taken into agricultural use, following intense artificial drainage and liming. However, instead of gley-podzols and peaty podzols, podzolic gley-soils with oligotrophic raw humus were formed (Table 3). Such transformation may also occur in the course of natural processes, caused by destruction of the tree layer and development of the grass layer. On arable land and on natural grassland, podzolic gley-soils have formed in >96% of cases, instead of gley-podzols and peaty podzol. Therefore, in analysing changes in land use of group 4 soils, the properties of gley-podzols (gley-, peaty or LG and LG1) and podzolic gley-soils (LkG) formed on sands are compared (Table 9).

Land use changes in both directions may take place: natural land is cultivated, and arable lands are set aside, although the causes of these changes may vary widely. Common to all these processes, however, is that the subsoil rests practically unchanged (potential fertility remains), and that topsoil functioning should be arranged in accordance with the production capability of soil varieties.

In the land use dynamics of the studied soil groups, the clearly recognizable regularities, which are characteristic of the entire Estonian soil cover, may be followed.

Table 8. Characteristics of forest (FES), agro- (AES) and natural grassland (GES) ecosystem productivity by means of soil quality classes and soil group environmental protection ability

Soil group		Soil quality points (act/drn)[1]	Soil quality classes in the case of			Environment protection ability	
No.	Name	AES	FES	AES	GES	Mean point	Class
1	Rendzina	29–33a[2]	IV–V	VI–VIII	IX	3.6	V
2	Brown soils	57–58d	I–II	V	VIII	10.6	I–II
3	Pseudopodzolic soils	50–51/53c/c	I	V	VIII–IX	12.1	I–II
4	Gley-podzols	18–20/29a/b	V	IX–X	X	4.4	IV

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[1] Act – quality points according to soil actual status and drn – the same after the soil drainage; [2] letters next to the data indicate significant difference at $p < 0.05$.

Table 9. Comparison of epipedon characteristics in forest and cultivated areas by soil groups

Characteristics$^{1)}$	No. of soil group$^{2)}$			
	1	2	3	4
Thickness of epipedon For/Arb$^{3)}$, cm	17/22a/a$^{4)}$	20/27a/b	19/26a/b	14/23a/a
BS of epipedon For/Arb, %	91/96	86/92	29/81	18/68
Ratio C : N For/Arb	17–20/9–11b/a	15–16/9–11a/a	17–18/10–11a/a	37–39/12–13c/b
$\mathrm{pH_{KCl}}$ For (O-hor)/Arb (A-hor)	5.0/>7c/b	5.0/6–7c/b	4.3/5–5.6b/a	2.9/>5.0a/a
$H_{8.2}$ For/Arb, kmol ha^{-1}	30–50/20–25	70–140/65–80	240–260/100–110	75–100/140–200

$^{1)}$ BS – base saturation stage, $H_{8.2}$ – hydrolytical acidity; $^{2)}$ for soil group names see Tables 1 (by ESC) and 2 (by WRB), whereas the exception is soil group 4, where on arable areas the data are presented for podzolic gley-soils (LkG), which are modified by cultivation of gley- and peaty podzols (LG, LG1); $^{3)}$ For – forest and Arb – arable soils; $^{4)}$ letters next to the data indicate significant difference at $p < 0.05$ between soil groups.

As a rule, most of the arable land has been formed from former forested areas. In the establishment of arable lands in northern and central Estonia, brown soils (together with their gleyed species) play the most important role, while in southern Estonia, the pseudopodzolic soil associations predominate. At the present time only a limited area of these soils is under forests and grasslands. The typical forest soils of group 4 are used as arable soils and grasslands only in exceptional situations. The agricultural use of rendzinas depends not so much on their suitability and fertility, as on geographic location and historical situation.

In 1955–1990, massive land reclamation, including the liming of acid arable soils, application of organic and mineral fertilizers and deepening of arable horizons took place. Nowadays, less favourable areas of arable land are set aside and large areas of semi-natural grasslands are abandoned to natural re-afforestation processes (Astover et al. 2006).

DISCUSSION

Soil type-specific pedo-ecological analysis of soil–plant interrelationships

The influence of soils (on group, type, species or variety level) on plant association and *vice versa* is the key question in studying soil–plant interrelationships. In natural and semi-natural areas forest and grassland plant covers were developed in accordance with soil properties and local climatic conditions. As a result of this mutual influence plant associations with a specific appearance were formed. Identification of forest site and natural grassland types and the plant-growing capacity of their soils, on the basis of the floristic composition of vegetation, was used successfully in practical forestry and to some extent in grassland husbandry during the last century (Valk & Eilart 1974; Krall et al. 1980; Paal 1997; Lõhmus 2006).

Is there a sense to develop more precise, detailed approaches for characterizing soils by means of site, or are there better alternatives? It seems that, at present, the approach described above has run its course, due to its inherent uncertainties. Obviously an attempt to characterize pedo-ecological site conditions on the basis of the floristic composition of ground vegetation in more detail is rather suspicious, in view of the insufficient ‘fine tuning capacity’ of plant cover. In addition, the floristic composition may be easily influenced by different external conditions (Tamme et al. 2010; Lindborg et al. 2012) and stage of development (e.g. age of the tree layer in forests, vegetation period on grasslands).

On the other hand, available site-specific soil information exists in the form of large-scale soil maps and typical soil profiles (calculated on the basis of hundreds of single profiles) on the soil varieties level (Kõlli et al. 2008; ELB 2012). At present it is possible to analyse the soil–plant interrelationships not only on soil groups, but at more detailed (species, variety) taxonomic levels. Therefore, it is best to characterize forest soil (edaphic) conditions directly based on soil variety properties. Data on humus cover properties add precision to this process. Comparison of both kinds of site characterization methods, (1) according to ground vegetation and (2) directly on the basis of soil properties, shows that the former works well only in a certain developmental stage of the tree layer. The latter method works continuously better and gives more reliable results in forecasting.

At the same time we agree that detailed floristic analysis by site types is of utmost importance from the purely botanic (how different plant species are associated and the theoretical aspect of plant diversity) and ecological aspects (Kull & Zobel 1991; Zobel 1992; Sammul et al. 2003; Pärtel et al. 2004; Zinko et al. 2006).

The base of the common site type of rendzinas (*Acrostaphylos*-alvar) is characterized by a modest fine earth stock in soil cover, high calcareousness and skeleton content, excessive natural drainage, low water holding capacity and an unstable water regime (Fig. 5). Their humus cover is classified as dry calci-mull, with a high concentration, but low stock of soil organic carbon in A horizon and biologically active unlayered *detritic* O horizon. The *Acrostaphylos*-alvar site type can be clearly distinguished from site types contiguous to it, from *Sesleria*-alvar by soil water regime and from (*Cladonia*) by differences in soil varieties. Some interference is obtained with the *Calamagrostis*-alvar site type. Spruce and pine forest, and juniper woodlands are dominant among forest ecosystems on this soil group.

The most important plant associations on alvar grasslands are *Ditricho–Sedo–Thymetum*, *Filipendulo–Trifolietum montani*, *Agrosteto*(*vineale*)*–Caricetum caryophylleae* and *Alchemillo–Festucetum* (Krall et al. 1980). These coincide to some extent with the plant associations proposed by Paal (1997): *Ditricho–Thymetum*, *Arrhenatheretum*, *Trifolio montani–Filipenduletum vulgaris* and *Helictotricho–Callunetum*. The extent of agricultural use of group 1 soils is limited (totalling <20%).

Hepatica (Fig. 5) is the most common site type for all brown soils (Ko, KI, Kor), but humus cover for more calcareous typical brown soils is fresh mull, and for lessive brown soils, and to a greater extent eluviated soils, fresh moder-mull type. The main plant associations forming grassland ecosystems are *Filipendulo–Seslerietum coerulea*, *Seslerio–Caricetum montanae*, *Scorzonero–Melampyretum*, *Cynesureo–Festucetum rubrae* with their numerous variants (Krall et al. 1980; Paal 1997). Brown soils are suitable for a wide range of agricultural uses (Table 6).

Brown (O–A–Baf–Egl–2B–2C) and light (O–A–Egl–2B–2C) pseudopodzolic soils are distinguished among pseudopodzolic soils. The difference between them is the absence or presence of a brown-coloured Baf horizon, formed by the accumulation of amorphous iron in the soil profile (Reintam 1973). However, very often these two varieties of pseudopodzolic soil alternate after a small distance, thus, separation of their pedon contours (patches) is complicated. The joint forest site type for fresh pseudopodzolic soils is *Oxalis*, but for moist varieties, mainly *Oxalis–Myrtillus*. The site type *Aegopodium* may also occur.

The dominant plant associations on natural grasslands with pseudopodzolic soils are *Agrosteto–Festucetum*

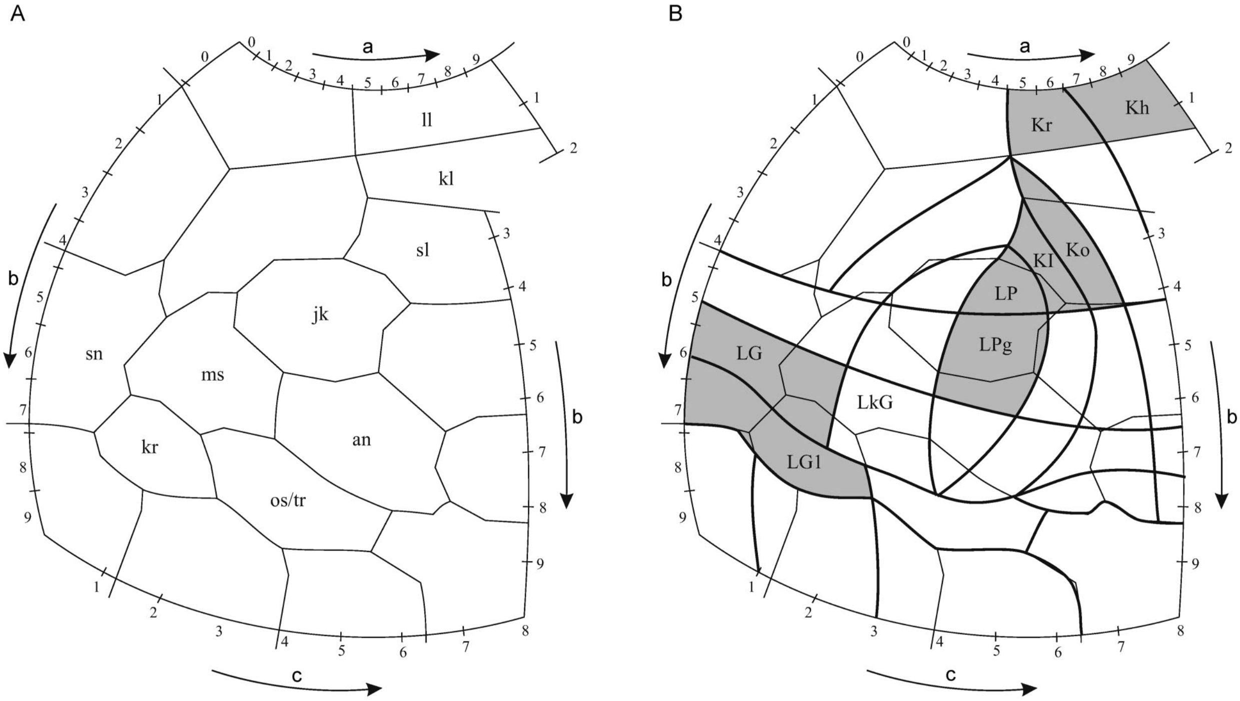

Fig. 5. Locations of studied forest site types and soils on the background forest site type ordination network by Lõhmus (2006). Scalars characterizing the ordination network: a, increasing calcareousness of soils; b, water regime: increasing water holding capacity of soil and decreasing ground water level from the surface; c, amelioration of plant nutrition conditions (from oligotrophic to eutrophic); (**A**) forest site types – ll, *Acrostaphylos*-alvar; kl, *Calamagrostis*-alvar; sl, *Hepatica*; jk, *Oxalis*; ms, *Myrtillus*; an, *Aegopodium*; sn, *Vaccinium ulginosum*; kr, *Polytrichum*; os/tr, *Equisetum/Carex*; (**B**) soils – Kh, limestone rendzinas; Kr, pebble rendzinas; Ko, typical brown soils; KI, lessive brown soils; LP, pseudopodzolic soils; LPg, gleyed pseudopodzolic soils; LkG, podzolic gley-soils; LG, gley-podzols; LG1, peaty podzols.

rubrae, *Anthoxantho–Agrostetum*, *Deschampsietum flexuosae* in fresh moisture conditions and *Potentillo–Deschampsietum* and *Caricetum paniceo–nigrae* in moist conditions. As pseudopodzolic soils are the best arable soils (Tables 5 and 6) in southeastern Estonia, the extent of their agricultural use is rather high (~64%). For better agricultural management gleyed pseudopodzolic soils should be artificially drained, which is usually not needed in the case of forests and grasslands.

Soil associations of gley-podzols and peaty podzols (soil group 4) may include degraded soil covers consisting of the *ortstein* cemented *spodic* horizon. The *ortsteinic* gley-podzols form altogether <5% of the soil group 4 area. According to forest site type, these soils are characterized mainly as *Vaccinium ulginosum* (Fig. 5). The low productivity of these soils is due to acid and wet conditions, in which the activity of soil biota is inhibited and the nutrients are not released by the mineralization of organic matter (Bolin et al. 2000). This results in stagnation of organic matter flow throughout the ecosystem and further paludification of soil cover. These developments are accompanied by soil acidification due to low base content in pine litter (Pritchett & Fisher 1987). The humus cover of wet mor or peaty mor type is formed (Table 3) by the accumulation of extra organic matter on top of these soils.

The characteristic plant cover in grasslands on gley-podzols is *Polytricho–Nardetum*, a type with very low productivity in spite of its high content of organic matter. On podzolic gley-soils (formed from gley-podzols and peaty podzols), the more productive *Caricetum canescentis–elongatae*, *Potentillo–Deschampsietum*, *Caricetum flavae*, *Nardo–Danthonietum* types of grassland may occur along with the above-named type.

The causal adequacy between soil and plant covers is clearly visible in circumstances where the interferences in soil cover properties are absent. The estimation of soil type on the basis of ground vegetation may be disturbed by several external factors (age of stand, stock density, cuttings), which causes considerable decrease or loss in the indicator value of ground vegetation.

The geographical aspect is also important in identifying the brown lessive and pseudopodzolic soils. As both soils may be formed either on yellow-grey or red-brown tills, these materials may be either calcareous or non-calcareous. This situation is reflected in joint (common) plant associations of these soils: *Cynosureo–Festucetum rubrae*, *Agrostio capillaris–Trifolietum repentis* and *Trifolio repentis–Festucetum rubrae* on grasslands.

In the analysis of soil–plant interrelationships of brown soils the geomorphological differences in soil-forming conditions should be explained. Brown soils may be distributed alongside the above-treated almost flat (undulating) moraine landscapes as well as in hilly (esker, drumlin, moraine hill) areas, which are distinguished by Masing (1969) as hillock forests. From the geobotanical aspect, these sites are characterized as *Fragaria* and *Corylus* forest site types (Paal et al. 2010).

In forests, the floral composition of ground vegetation and its productivity depend on properties of humus cover (forest floor in association with humus horizon) and on processes occurring in these layers. The feedback influence of subsoil is expressed not only via falling litter and stem flow characteristics, but also via tree layer composition and the formation of a particular type of humus cover. The influence of tree species (pine, spruce and some deciduous species) on soil properties is expressed in changes in topsoil pH, organic carbon content, C : N ratio, etc. Trials with Scots pine show the acidifying effect on topsoil if the contribution of nitrate to the N nutrition is ≤70% (Arnold 1992). Tree layers have no substantial effect on the properties of deeper soil horizons (Menyailo et al. 2002), but it should be emphasized that subsoil strongly influences topsoil processes (Kõlli 1987).

Paal et al. (2004) indicated the possibility of vegetation convergence or the formation of similar communities on different soils and sites. It may be possible, but it should be mentioned that in such cases, the driving force is the influence of feedback, first, of the tree layer, but also from all biotic factors and characteristics of the formed humus cover.

The soil–plant interrelationships in forests are characterized by highly variable feedback influences compared with both arable and grassland ecosystems (Karpachevskij 1977; Morecroft et al. 2004). For example, there are great differences in humus cover fabric and properties found under tree crowns and in open-to-light patches between trees. Giesler et al. (1998) noted that plant cover productivity and composition in boreal forests is connected to the variability in soil pH and the supply of base cations.

The influence of soils on plant cover is more clearly visible in forests than in natural grasslands, mainly due to the turnover of long-lasting uniform substances in forests. The correlation between soils and plants in semi-natural grasslands is frequently lower than in forests, because of disruptive human activity (e.g. mowing, pasturing).

Influence of land use change on soil properties and functioning

Humus cover is a space or contact area of soil–plant interaction, directly bound and significantly influenced by both plants and soils. Both influences are integrated in the properties of humus cover and its type (Table 4).

Humus cover results from various accumulation–humification–mineralization processes of plant residues and depends on existing ecological conditions and soil mineral-chemical potential (Bolin et al. 2000; Targulian & Krasilnikov 2007). Identification of the humus cover type enables researchers to characterize soil humus status, evaluate its adequacy for the existing pedo-climatic conditions and arrange sustainable soil management.

Land use change leads to a considerable change in soil cover properties and functions. When natural forest areas are converted into arable land, the forest floor on the soil surface is mixed with mineral horizons forming a substantially changed humus horizon. New types of humus covers are formed in place of natural humus covers (Table 3, Fig. 2C, D). The depths of humus cover in arable lands are significantly higher than in forest lands in all soil groups (Table 9). The mean depth of humus cover in arable areas is equal at least to plough depth. The stocks of organic carbon in the whole forest and the arable soil cover of rendzinas and brown soils are approximately similar (Table 4). Significant differences in organic carbon stocks between forest and arable soils are revealed in gley-podzols, where the soil organic carbon stocks are greater in forest soil than in arable soils. Great changes in the parameters of soil acidity and percentage base saturation in arable pseudopodzolic soils and podzolic gley-soils are due to liming, which is necessary for transforming the growth conditions favourable for cultivated plants.

The loss of topsoil organic carbon (mostly through reduced input of organic matter) by the conversion from natural into cultivated soil is well known (Post & Mann 1990; Davidson & Ackerman 1993; Murty et al. 2002). Rapid decline in soil organic matter is partly due to a lower fraction of non-soluble material in the more readily decomposed crop residues. Tillage, in addition to the mixing and stirring of soil, breaks up aggregates and exposes organo-mineral surfaces otherwise inaccessible to decomposers. The accumulation of organic carbon is reduced by ≥50% when pasture is converted to arable land, but can be increased by only 18–20% when the conversion is from arable land to pasture or forest (Guo & Gifford 2002).

Although the humus cover is profoundly transformed with land use change, the accordance of forest soil humus cover types with arable soils is generally observable in all soil groups (Table 3, Fig. 2C, D). This pedo-ecologically caused accordance is most evident in the conditions of low input agriculture. In the conditions of high input agriculture (fertilizing, liming, drainage) the relative roles of inherited soil properties are decreased and not clearly evident. The annual input of new organic matter and retained organic residues in arable soil varies largely due to crop rotation, soil management and climatic characteristics (Rychcik et al. 2006). The subsoil properties alter insignificantly in connection with land use change or rest in an almost unchanged status (Kõlli et al. 2010).

The transformation of arable soil into forest soil starts from humus cover; it takes over one decade to complete the conversion. When agricultural land is no longer used and natural plant cover is allowed to grow, then, according to Post & Kwon (2000), the accumulation of organic carbon in soil increases. The management methods used on cultivated soils have exhibited after-effects on grassland for several decades. The application of mineral fertilizers on wooded meadow 20 years ago is still causing decreased species richness (Sammul et al. 2003).

Problems with weeds arise with conversion of natural areas (forests, natural grasslands) into cultivated ones (arable lands, cultivated grasslands). The presence of some weeds depends on the cultivated plant species, but others result from pedo-ecologic and agro-technologic situations; their survival strategies and injuring capabilities are diverse (Laasimer 1965; Hyvönen & Salonen 2002; Bender 2006; Cimalova & Lososova 2009). Weeds can also have a positive influence, increasing biological diversity, and filling ecosystem niches in both spatial and temporal aspects. However, the main negative influence is lower cultivated crop productivity, which can be observed from the moment the critical abundance of weeds is exceeded. At this point, cultivated crop productivity is suppressed and, more broadly, total agro-ecosystem productivity is decreased, because weeds are less capable of producing phytomass than crops.

An ecosystem approach to sustainable land use

Ecologically sound land management is based on an ecosystem approach which, along with general pedo-climatic (soils, microclimate) and external environmental conditions, takes into account the pedo-diversity and environmental protection ability of soils as internal (intrinsic) properties of the ecosystem. For attaining ecologically sound land use or to increase the efficiency of the utilization of soil resources, the disharmonies in matching plant cover with soil cover or biodiversity with pedo(geo)diversity should be overcome (Kask 1975; Chertov 1981; Fisher et al. 2002).

Although the ecosystem pattern in natural and cultivated areas is mainly induced from the pedo-ecological conditions of the region, it may be controlled by diverse activities of landowners. As a result of continuous human interactions with natural ecosystems, coupled human and natural systems are formed (Liu et al. 2007). These couplings have evolved from direct to more indirect interactions, from adjacent to more distant linkages, and from simple to complex patterns and processes.

The regularities of the causally bound development sequence, parent material (geodiversity) → soil cover (or pedodiversity) → ecosystems (with floristic composition adequate to soil and productivity), are more clearly revealed when interference and edge effects of contiguous areas are absent. In cultivated areas, aside from the natural background, different kinds of outside impacts with various influence intensity play the leading role (Liniger & Critchley 2007). To increase the efficiency of soil resource development, the principles of plant cover suitability for soils must be taken into account.

The total productivity of ecosystems formed on well-drained soil depends mainly on clay and organic matter content and stock in the soil profile (Kask 1975; Kõlli 1987; Kasparinskis & Nikodemus 2012). These parameters, indicating capabilities of soils, are also used as a basis for indirect evaluation of soil quality (ELB 1992; Kõlli 1994; Lõhmus 2006). The amount of annual flux in organic carbon depends largely on the dominant species of plant cover. As a rule, a few plant species or edificators are responsible for the prevailing part of phytomass areal density as well as annual substance fluxes. Accordingly, the maximum functioning of an ecosystem is observed in the presence of plant cover diversity optimal to soil (specific to the soil variety). If the floristic composition is unsuitable for soil plant cover, the activity of the ecosystem may be suppressed. An excessive biodiversity is unfavourable as well. Productivity may also be lower in the conditions of lower vs. optimal plant species richness, as the capability of some ecological niches is not used.

The most species-rich but relatively low-productive plant associations are formed on extensively used semi-natural grasslands on calcareous soils. Alvar site type forests and dry alvar natural grasslands on rendzinas have unique plant associations, and are the target of protection efforts. Pärtel et al. (2004) pointed out that the proportion of protected plant associations on these soils is unusually high in Northern Europe. For conservation of such unique associations, the soil cover should be maintained in its natural status or under extensive but low-productivity management conditions, such as mowing or pasture.

Society at large and landowners in particular should find a compromise in the ratio of protected areas for scientific purposes (conservation of high plant cover biodiversity) and conventionally (sustainable) managed territory, as the highest plant species richness is observed only in low input management conditions. For attaining stable and high ecosystem productivity, it is important to maintain soil biodiversity at an optimal level, or it should be soil type-specific.

Humus cover, which is formed from returned litter fall into soil fresh organic matter, is a good integrated indicator (aside from soil productivity) in the estimation of ecosystem functioning intensity, as the humus cover type characterizes the decomposition–humification process in the forest/grassland floor. The PES soils analysed reflect different humus cover formation conditions where the dry carbonate-rich medium is changing into wet acid conditions, resulting in differences in the fabric, structure, humus stocks and other properties of humus cover.

Soil functioning capability (quality) may be determined by different methods: (1) by the total phytomass and APP (Rodin et al. 1968; Kõlli 1987; Bazilevich & Titljanova 2008), (2) by yield of field crops and grasslands (Bender 2006; Older 2007), (3) by indirect (model-based) estimation according to different soil parameters (ELB 1992) and (4) by interpolation of generalized data (Panagos & van Liedekerke 2008). The most appreciated method, however, involves the evaluation of both ecosystem productivity and its functioning activity.

The activities for arrangement of ecologically sound soil management of an area are site-specific, that is, they depend on soil properties. Soil properties can change in very small areas, so there may be plant associations containing species not characteristic of soil properties. A mosaic soil cover leads to the formation of plant cover, which in some places is rich in species and variable in plant associations (Karpachevskij 1977). Without knowing the causality of interrelationships of soil and plant cover, the sustainable use of rural areas is problematic. For amelioration of soil management quality, the adequacy of land use (forests, arable or grasslands) and the suitability of their plant cover to soil cover should be critically analysed and corrected, where necessary. Without such determination, various disharmonies may occur between our endeavours and local site conditions. Using the principles of an ecosystem approach, it is possible by the choice of suitable land use, and well matched soils and plant cover to assure the functioning stability in forest and grassland ecosystems and step-by-step form conditions for increasing productivity of agro-ecosystems.

It is important to use new technologies and methods to improve conventional management of soil cover, thereby increasing soil productivity and quality. For the development of efficient conservation agriculture on arable soils, suitable crops should be chosen for soils; the opposite approach always requires corrections in soil properties. Reforestation of low-quality grasslands and fields is acceptable.

For safeguarding the healthy environmental status of areas, the functioning of soil cover should be arranged in accordance with local soil capability. For environmentally sound and continuous use of arable soils the annual losses of soil organic carbon and pool of nutritional elements should be compensated. Step-by-step improvement of soil fertility and soil productivity increase sustainable functioning and the environmental protection ability of soils.

CONCLUSIONS

Soil cover of a natural area has a decisive role in the formation of plant cover composition, productivity and diversity. Therefore the awareness of the composition and properties of soil cover and its relationship with plant cover in different land use conditions is the basis of ecologically proper and sustainable management of land (soil) resources.

The existing pedodiversity of an ecosystem should be taken as an abiotic base in the formation of optimal plant cover biodiversity for a specific location. It is important to maintain an ‘optimal to soil-type’ biodiversity; in most cases, the highest species richness is not a guarantee of the highest possible functioning intensity and autotrophic productivity. The ecologically sound matching of soil and plant cover is of pivotal importance from the aspect of ecosystem functioning sustainability and for good environmental status of an area.

Comparative analysis of soil–plant interrelationships along the pedo-ecological sequence rendzinas → brown soils → pseudopodzolic soils → gley-podzols shows that (1) the biodiversity of an ecosystem depends on soil properties and therefore biodiversity should be treated as a soil type-specific feature and (2) the character or type of humus cover is a good ecological indicator, because it adequately characterizes the outlines of the biological turnover between soil and plant, and clearly distinguishes all studied ecosystems from one another.

With land use change (from natural to arable and *vice versa*), more drastic changes occur in the fabric and properties of humus cover (as topsoil), but the subsoil rests in an almost unchanged state. In circumstances of low input as opposed to intensive agriculture, the inherited soil properties persist to a greater extent in the functioning of agro-ecosystems formed by cultivation.

Indirect characterization of forest soil (edaphic) conditions according to the floristic composition of ground vegetation should be turned into direct (i.e. according to soil properties) identification of an area’s growth conditions. Prerequisites for this are large-scale soil maps, in which soil distribution and properties are identified on the level of soil variety for entire Estonia.

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Muld- ja taimkatte vastastikused seosed sõltuvalt maakasutusest

Tiina Köster ja Raimo Kõlli

Väljavõtteliste mullagruppide andmete alusel on võrdlevalt analüüsitud mineraalmuldadel kujunenud metsa, agro- ja rohumaa ökosüsteemide muld- ning taimkatete vastastikuseid mõjutusi ja seoseid. Neljalüline (1–4) mineraalmuldade pedo-ökoloogiline kateena rendsiinad → pruun- → kahkjad → leede-gleimullad moodustab esindusliku läbilõike Eesti normaalse arenguga mineraalmuldadest, kus iga väljavõtteline mullagrupp erineb peamiste mullaomaduste (karbonaatsus, happelisus, profiili ülesehitus, huumuskatte iseloom jms) poolest. Analüüsitavate mullagruppide liigiline koosseis on järgmine: 1) kuivad (põuakartlikud) paepealsed ja koreserikkad rähksed mullad, 2) parasniisked leostunud ja leetjad mullad, 3) parasniisked ja ajutiselt liigniisked kahkjad (näivleetunud) mullad, 4) alaliselt liigniisked tugevasti happelised leede-glei- ja turvastunud leede-gleimullad. Töö peamisteks ülesanneteks olid: 1) anda kõigi mullagruppide pedo-ökoloogiline iseloomustus ja selgitada muldade sobivust taimkattele, 2) hinnata mullagrupi omadusi produktiivsuse, bioloogilise mitmekesisuse ja keskkonnakaitse võime(kuse) seisukohalt, 3) analüüsida võimalusi mis tahes regiooni muldkatte ökoloogiliselt tõhusaks sobitamiseks selle omadustele vastava jätkusuutliku taimkattega. Samadel mullagruppidel kujunenud erinevate ökosüsteemide võrdleva analüüsi abil selgitati välja muutused, mis toimuvad pealis- ja alusmulla omadustes seoses maakasutuse muutumisega. Uurimus näitab, et bioloogilise mitmekesisuse olemuse paremaks mõistmiseks tuleks mitmekesisust käsitleda lähtuvalt mulla (tüüp, liik, erim) koostisest ja talitlusest. Looduslike alade muutmisega haritavaks maaks suureneb paepealsete ja rähksete muldade huumushorisondi tüsedus (samas looduslike muldadega võrreldes huumuse kontsentratsioon väheneb). Lupjamise tulemusena on oluliselt suurenenud happeliste kahkjate (näivleetunud) muldade küllastusaste, mis läheneb oma näitajate poolest leetjatele ja leostunud muldadele. Haritavate maade mullad on oma omadustelt muudetud ühtlasemaks ja seega sobivamaks põllukultuuride kasvatamiseks. Metsade, põllu- ja rohumaade produktiivsus on suurim leostunud, leetjatel ning kahkjatel muldadel. Muldade kasutamine vastavalt nende omadustele on parim viis nende kaitseks. Muldkatte järkjärgulise produktiivsuse suurenemisega paraneb ka selle keskkonnakaitseline võimekus.