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Mineral nutrition of natural regeneration of Scots pine on coastal dunes in South-West Estonia

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Abstract. The content of nutrients in soil and needles of second-growth pines was studied on dunes of different relative height (23 m, 10 m, 5 m) in the coastal area of the Baltic Sea in South-West Estonia. Results give an insight into the nutrition status of pines on the plain and on the slopes and tops of dunes. The data obtained indicate that the logarithmic relationship is statistically significant between N, K, and Mg contents in the needles and soil and the height of the sample point on the dune. Deficiency of nutrients for the growth of pines, especially that of N and K, had developed on dunes. The study showed that on dunes the nutrition conditions and concentration of nutrients in needles depend significantly on the relative height of the growth site on the dune.

Key words: dune, natural regeneration, needles, nutrients, *Pinus sylvestris*, soil.

INTRODUCTION

The coastal landscape of South-West Estonia is characterized by dunes and coastal ridges formed from the sediments of the melting glacier after the last ice age. During the period of the transgression of the Litorina Sea (ca 4000–5000 years BP) intensive formation of dunes took place (Örd, 1972a). These coastal formations are known today as the Rannametsa dune ridge, which proceeds from Uulu near Pärnu to the Latvian border. By now the coastal dunes have become stabilized and are covered with pine forest, of which pure pine forest makes up 89.5% (Pärn, 2003). The conditions for forest growth on dunes vary, depending primarily on the time the dune was formed, the height of the dune, and soil fertility. The prevailing soils on Estonian coastal dunes are Podzols of varying level of podzolization (Kõresaar, 2003a, b). Generally the soils on dunes are extremely poor in nutrients (Paal, 1997), strongly to moderately acidic (pH_{KCl} 2.6–5.1), have

a relatively low humus content (0.4–0.7%), and often a less than 5% moisture content (Örd, 1972b). The content of nutrients in dune soils varies depending significantly on geomorphological conditions. Soils on plains before the dune and on the bottom of the dune are richer in nutrients than those higher on the dune as the waters flowing down the dune and the decomposition of organic matter originating from plants accumulated at the bottom of the dune enrich these areas with nutrients (Mandre, 2000, 2003).

According to the classification of forest site types used the dune forests in South-West Estonia are of *Cladina*, *Vaccinium vitis-idaea*, *Calluna*, and *Vaccinium myrtillus* type. On highest dunes that have stabilized later unique *Cladina* pine forest with stunted gnarly trees with crooked trunks can be found. On the slopes of dunes where the soils are somewhat more fertile *Vaccinium vitis-idaea* pine forests with less crooked trees grow. Second growth is the richest in pure pine forests of *Cladina* and *Vaccinium vitis-idaea* type (Pärn, 2003). However, at the bottom of dunes and in depressions between dunes the forests are richer in species. In the case of higher dunes growth conditions differ between the slope, bottom, and top of the dune and thus the forest site type can vary over one and the same dune. In interdunal depressions also *Vaccinium uliginosum* site type can be found. *Vaccinium vitis-idaea* site type is characteristic on lower than 10-m-high dune ranges and plain damp coastal sands. On higher ridges and on tops of dunes *Cladina* and *Calluna* site types occur. *Vaccinium myrtillus* pine forests grow in lower and damper areas.

Scots pine (*Pinus sylvestris* L.) is a tree species growing in various climate zones in soils rich in humus as well as those poor in nutrients, surviving in largely varying ecological conditions. However, for normal growth and production Scots pine like all other plants has its requirements for qualitative and quantitative composition of nutrients. Large variation of edaphic and climatic conditions in dune fields has brought about a large variation also in the functioning and structure of the forest ecosystem, including the physiological status of Scots pine. It was observed that the content of carotenoids and chlorophylls in pine needles may fall from the bottom of a dune towards its top as it is significantly affected by nutrition conditions (Mandre & Korsjukov, 2003). According to Klõšeiko (2003), dispersion analysis indicated differences between the average sucrose content in the needles of pines growing at different heights on dunes but the content of carbohydrates does not correlate with the photosynthetically active radiation on the top and bottom of a dune.

The aim of the present study was to ascertain the dependence of the eco-physiological status of second-growth Scots pine on the height of dunes, considering the variation of the growth substrate and mineral nutrition of trees, which significantly affect the growth and bioproduction of trees. Needle and shoot diagnostics was used to estimate the status of trees on three dunes of different height.

METHODS

The study was carried out in three Scots pine stands growing on dunes of different height in South-West Estonia in 2004 and 2006. The study sites were located on the dune of Tõotusemägi of relative height of 23 m (58°7′56″ N, 24°30′36″ E), and north of Tõotusemägi on a dune 10 m high (58°13′51″ N, 24°30′47″ E) and a dune 5 m high (58°14′28″ N, 24°31′21″ E). Sampling sites were selected on the western sides of the dunes so that they were located on the bottoms, slopes, and tops of the dunes (Fig. 1). In each sampling site 10 model trees of average height were selected, and needle diagnostics was applied to estimate their nutrition condition. The age of the second growth in the sampling sites differed somewhat: on Tõotusemägi 30–40-year-old second growth dominated (Pärn, 2003), on the 10-m-high dune the second growth was on average 28 years old, and on the 5-m-high dune 31 years old. However, for needle analysis only needles of the same age were used.

Needle samples were collected from the central part of the tree crowns. To estimate mineral nutrition, N, P, K, Ca, and Mg concentrations in one-year-old needles were determined in the Laboratory of Plant Material of the Agricultural Research Centre (Saku, Estonia). The concentrations of Ca, K, and Mg were determined in dried and homogenized needle material using an atomic adsorption

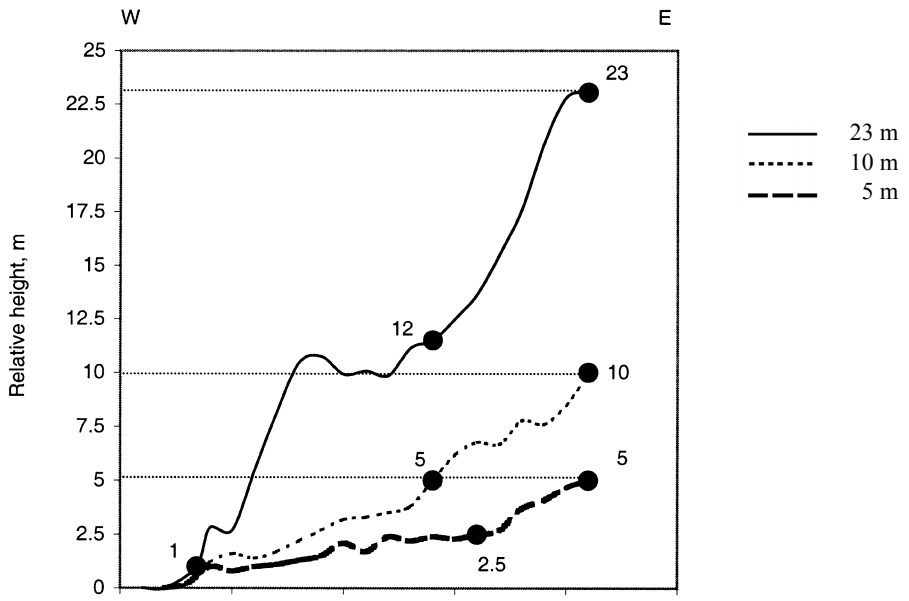

Fig. 1. Schematic course of the transects on the dunes and the location of the sampling sites.

analyser AAA-1N (Karl Zeiss, Germany); N was determined applying the Kjeldahl method, and for P determination an inductively coupled optical emission spectrometer ICP-OES (Perken-Elmer, USA) was used.

To characterize the growth substrate of the trees, soil analyses were made from samples taken in each sampling site from a 30-cm deep layer ($n = 5$), considering that about 80% of the assimilating roots of pines are located at a depth of 11–30 cm (Orlov & Koshel′kov, 1971). In the soil samples pH_{H2O} and the concentrations of N, P, K, Ca, and Mg were determined in the Laboratory of Agrochemistry of the Agricultural Research Centre. Standard methods of soil analysis were used: the concentrations of P and K were determined by the Egner–Riehm double lactate method and those of Ca and Mg by the Egner–Riehm–Domingo ammonium acetate–lactate method (ISO/11260, 1995). Total N was determined by the Kjeldahl method (ISO/11261, 1995) and the pH of the soil was measured as the potential acidity in H_2O (ISO/10390, 1994).

The data obtained were processed statistically to find relationships between the height of the dune and the concentrations of nutrients in soil and plant tissues. Regression analysis was used (R^2). The differences between sampling sites were evaluated using *t*-test with the level of significance 0.05.

RESULTS AND DISCUSSION

Chemical characterization of the soils

In South-West Estonia sand dunes characteristic of southern coasts of the Baltic Sea dominate (Cramer, 1993; Ratas & Rivis, 2003). The sands of dunes have been observed to vary in the chemical and physical composition (Raukas, 1968; Martin, 1978). Analysis of the growth substrate of the dunes studied revealed significant variation in the concentration of nutrients between dunes of different height as well as at different heights of one and the same dune. The variation of nutrients at different heights of the same dune was especially vivid on Tõotusemägi, the highest dune studied. It was ascertained that the soil was rich in nutrients at the bottom of the dune (Fig. 2, Table 1). Waters flowing down the dune and decomposition of organic material of plant origin accumulated at the bottom of the dune enrich the substrate with nutrients in this area; therefore, relatively higher concentrations of N, K, and Mg were observed there than on the other sites. The concentration of these elements decreases upwards and on the top of the dune a sharp shortage occurred.

A similar trend was observed also on the lower dunes (Fig. 2, Table 1), although the differences between the bottoms and the tops of these dunes were less conspicuous. This suggests that the amount of nutrients flushed down by precipitation and snow water from the lower dunes is insignificant and unlike on

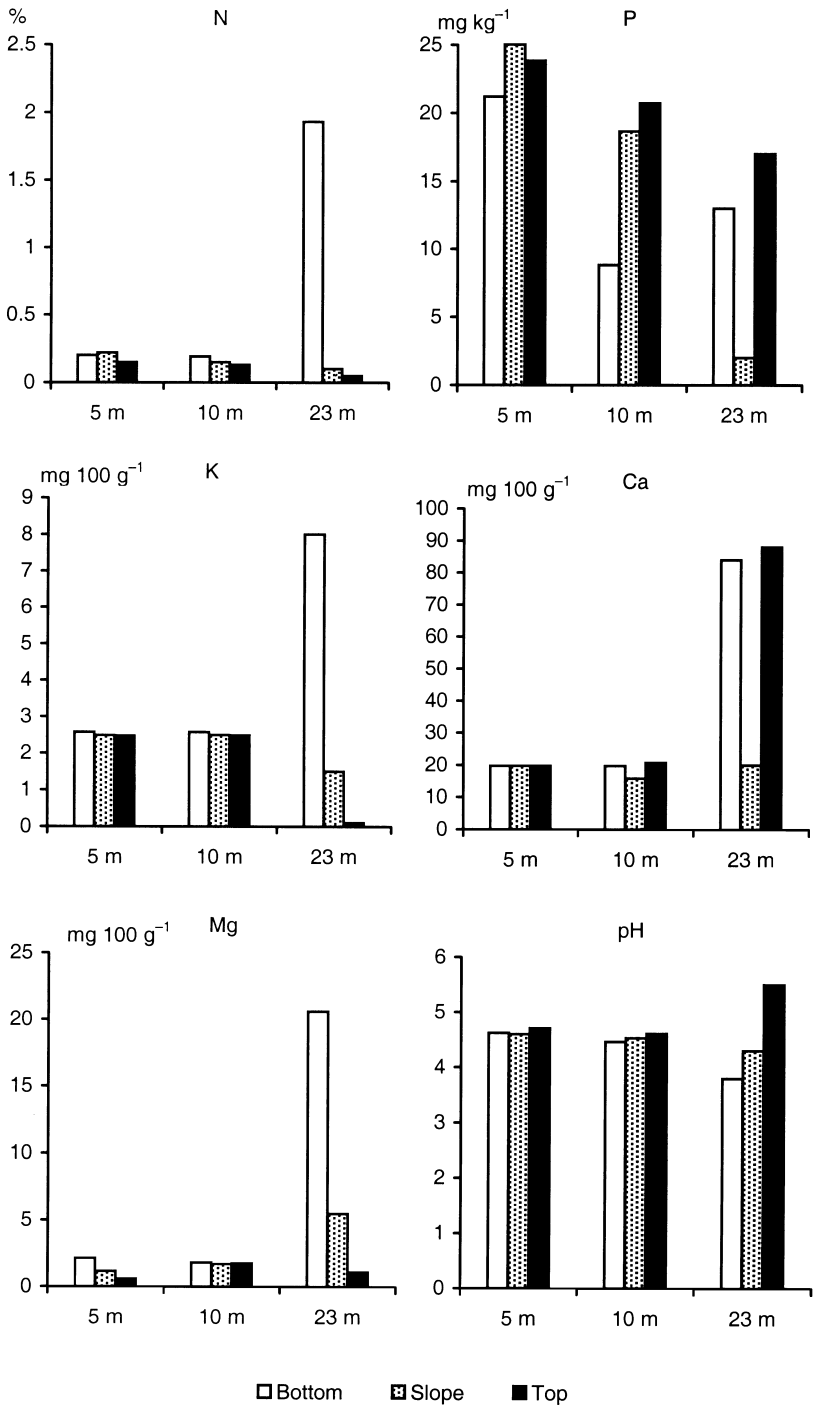

Fig. 2. Concentration of mineral elements and the pH of soil in the 0–30-cm horizon.

Table 1. Mean concentration of mineral elements in soil and its correlation (R^2) with the location of sampling sites on the dune

Relative height of the dune, m		pH	N, %	P, mg kg^{-1}	K, mg 100 g^{-1}	Ca, mg 100 g^{-1}	Mg, mg 100 g^{-1}
5		4.64	0.19	23.36	2.51	19.80	1.30
	R^2	*0.724*	*0.623*	*0.318*	*0.636*	*0.002*	*0.914*
10		4.53	0.16	16.07	2.52	18.80	1.77
	R^2	*0.993*	*0.936*	*0.831*	*0.828*	*0.063*	*0.255*
23		4.53	0.69	10.67	3.20	64.00	9.07
	R^2	*0.967*	*0.7244*	*0.095*	*0.842*	*0.011*	*0.876*

Tõotusemägi, no sizeable amounts of N, K, and P are accumulated at the bottoms of the lower dunes. On Tõotusemägi the concentrations of P and Ca in the soil are relatively high on the top of the dune as well as on its bottom, whereas the concentrations are extremely low on its steep slopes. The concentration of P in the soil increases towards the top also on the lower dunes, but no significant difference was observed in the case of Ca concentration.

The soil pH_{H2O} rises from the bottoms of the dunes towards their tops. Significant differences between the soil pH of different sampling sites were observed only on the highest dune (*t*-test, $p = 0.004$). The logarithmic dependence between soil characteristics and the height of sampling sites was statistically significant on Tõotusemägi for the soil pH ($R^2 = 0.967$) and the concentrations of N ($R^2 = 0.724$), Mg ($R^2 = 0.876$), and K ($R^2 = 0.842$). A logarithmic dependence between the location of a sampling site and the soil pH and N and K concentrations was observed also on the lower dunes (Table 1).

It should be stressed that in the studied dune field the concentration of all nutrients was extraordinarily low in the soil, and in most cases the concentration of elements depended on the height of the sampling site on the dune.

Concentration of nutrients in pine needles

The soils of pine forests on dunes are extremely poor in several mineral elements. Therefore, besides stress due to moisture deficit the trees growing on dunes are exposed to stress due to shortage of nutrients. To evaluate the physiological status of second-growth pines on dunes, needle diagnostics was applied with special attention paid to the availability of macroelements vital for tree growth. For comparison scales of nutrient concentrations securing normal growth and optimum bioproduction of trees developed by Ingestad (1962), Wehrmann (1963), and Brække & Salih (2002) were used (Table 2).

Table 2. Content of mineral elements (%) in 1-year-old needles of pines and its correlation (R^2) with the location of the sampling site on the dune

Relative height of the dune, m		N	P	K	Ca	Mg
5		1.454	0.096	0.251	0.405	0.142
	R^2	*0.778*	*0.321*	*0.002*	*0.945*	*0.924*
10		1.422	0.086	0.240	0.419	0.129
	R^2	*0.873*	*0.900*	*0.824*	*0.132*	*0.941*
23		1.620	0.131	0.953	0.650	0.107
	R^2	*0.8622*	*0.977*	*0.948*	*0.374*	*0.942*

Generally, a problem in studies on mineral nutrition of plants is which elements should be considered in evaluating the status of plants. Some authors are of the opinion that it is important to find out the so-called limiting elements. In most cases N is the limiting element for coniferous trees (Laatsch, 1967; Ingestad & Lund, 1986; Mandre, 1995). Although N plays an extremely important role in the life of plants, under certain conditions some other element may be the limiting one. For example, for Scots pines growing on alvars N and P may simultaneously be the limiting elements (Riispere & Riispere, 1970), but in *Calluna* site-type pine stands K may be the limiting factor (Krauss, 1965).

Our analysis of nutrients in the needles of pines growing on dunes revealed great variation between concentrations in samples collected from different sampling sites (Fig. 3). The needles of pines growing on the tops of the dunes contained on average by 17% less N and nearly 27% less K than the needles of pines growing on the bottoms of the dunes. However, if we considered the optimum concentrations of elements in the needles necessary for the growth of Scots pine (Ingestad, 1962; Wehrmann, 1963; Brække & Salih, 2002), we found that the needles on dunes had 3 to 9 times less K. The needles of pines on the tops of the dunes contained on average 50% less N than needed. Needles showed also deficiency of P but the concentrations of Ca were higher than the optimum level presented by Ingestad (1962) and Wehrmann (1963) (Fig. 3, Table 3). Consequently, in addition to a significant deficit of some elements also an unbalanced composition of the mineral elements of the organism has developed on dunes. Taking into consideration the means of the limit values of Ca presented in Table 3, we can say that on the tops of the dunes the concentration of Ca was three times as high as optimum. It is generally known that an elevated concentration of Ca in plant tissues refers to physiological ageing of the organism (Miidla, 1984; Marschner, 2002). Thus, the high Ca concentration in the needles of pines growing on the tops of the dunes under unfavourable conditions refers to intensive physiological ageing

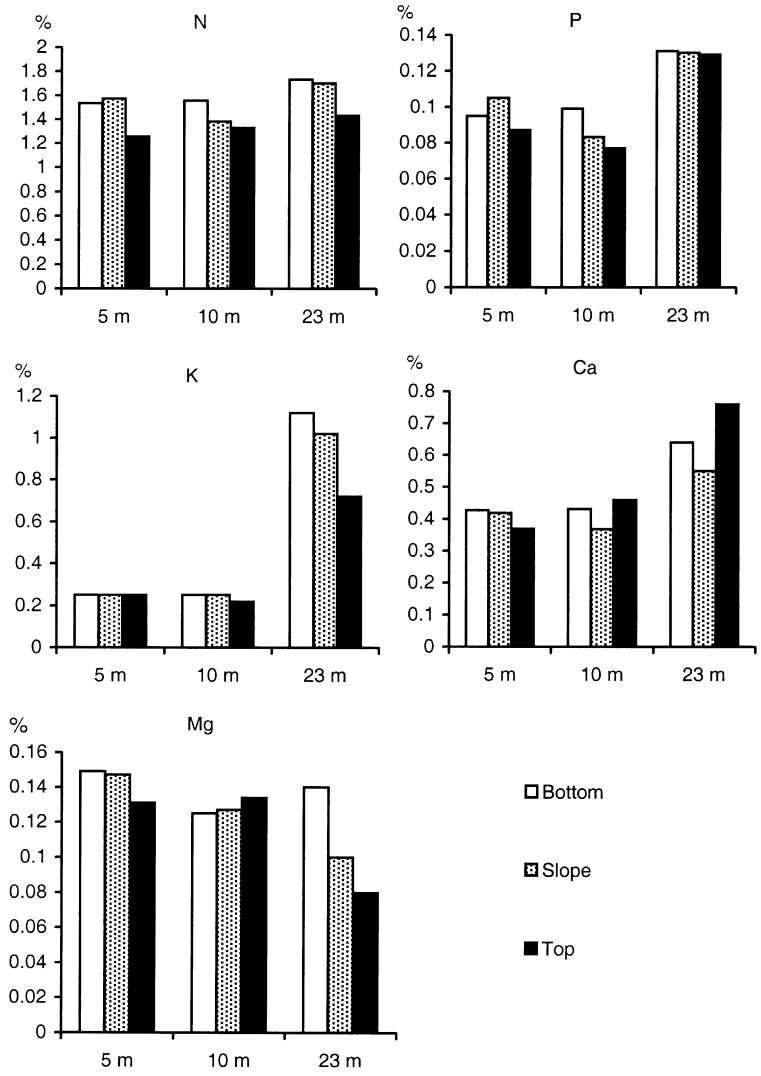

Fig. 3. Concentration of mineral elements in 1-year-old needles of Scots pines on dunes.

of these trees. Although the concentration of Mg was lower on the tops of the dunes than on the bottoms, the Mg concentration on the transect from bottom to top corresponds to the optimum level shown by Ingestad (1962) and Wehrmann (1963). Regression analysis revealed a linear dependence between the concentrations of N and Mg in the needles of pines growing on the dunes and in the soil (Table 4). The dependence was especially strong in the case of pines growing on the higher dunes (10 and 23 m).

Table 3. Optimum concentrations (%) of mineral elements in Scots pine needles

Element	Ingestad, 1962	Wehrmann, 1963	Brække & Salih, 2002
N	2.4–3.0	1.8–3.2	>1.8
P	0.15–0.4	0.2–0.3	>0.18
K	0.9–1.6	0.55–0.9	>0.6
Ca	0.04–0.3	0.05–0.24	>0.07
Mg	0.12–0.18	0.06–0.13	>0.08

Table 4. Regression coefficients (R^2) of the chemical composition of needles and soil

Element	Relative height of the dune, m		
	5	10	23
N	0.971	0.988	0.354
P	0.130	0.984	0.066
K	0.001	0.426	0.646
Ca	0.002	0.986	0.724
Mg	0.703	0.780	0.986

CONCLUSIONS

To sum up, we should say that the dunes in South-West Estonia have extremely variegated edaphic and stand characteristics. The environmental conditions for plant growth developed on the bottom, slopes, and top of one and the same dune vary greatly, as revealed by the concentrations of nutrients in the soil as well as by their accumulation in trees. In addition to the unbalanced content of nutrients in pine needles, a shortage of most elements necessary for tree growth was established on the dunes. No doubt, this affects the growth and bioproduction of Scots pine.

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Männi järelkasvu toitumistingimused Edela-Eesti rannikuluidetel

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Käesoleva töö eesmärgiks oli selgitada männi järelkasvu ökofüsioloogilise seisundi sõltuvust luidete kõrgusest, hinnates toitesubstraadi varieeruvust ja mändide mineraaltoitumust, millest sõltub oluliselt puude kasv ning bioproduktsioon. Puude

ökofüsioloogilise seisundi hindamiseks kolmel eri kõrgusega luitel kasutati okka- ja võrsediagnostikat.

Uuringud toimusid Edela-Eesti kolmel eri kõrgusega luitel kasvavas männikus, mis asuvad Tõotusemäel suhtelise kõrgusega 23 m (58°7′56″ N, 24°30′36″ E) ja luidetel kõrgusega 10 m (58°13′51″ N, 24°30′47″ E) ning 5 m (58°14′28″ N, 24°31′21″ E). Proovipunktid valiti, arvestades nende reljeefset paiknemist luitel: jalamil, nõlval ja tipus. Igast proovipunktist valiti 10 keskmise kõrgusega mudelpuud, mille toitumisseisundi hindamiseks rakendati okkadiagnostikat.

Uuritud luidetel tehtud mulla analüüs näitas toitainesisalduse olulist varieeruvust eri kõrgusega luidetel ja ühe ning sama luite eri kõrgustel. Ilmekalt avaldus toitainete varieeruvus luite eri kõrgustel luitestiku kõrgeimal luitel. Selgus, et toitainete poolest rikas on muld luite jalamil. Luitelt allavoolavad veed ja jalamile kogunenud taimedest pärit orgaanilise massi kõdunemine rikastavad seda piirkonda toitainetega, mistõttu täheldati jalami mullas suhteliselt suuremat N-i, K ning Mg sisaldust. Tõusul luite tippu nende elementide kontsentratsioon väheneb ja luite harjal on see sügavas defitsiidis. Tõotusemäel on mullas sisalduva P ja Ca kogus suhteliselt suur luite tipus, samuti jalamil, kuid erakordselt madal järskudel nõlvadel. Madalamatel luidetel võib tinglikult täheldada sama tendentsi, kuid erinevused luidete jalamil ja tipus on vähemärgatavad. Ka madalamatel luidetel suureneb P sisaldus mullas luite tipu suunas, kusjuures Ca sisalduse osas ei täheldatud olulist erinevust.

Tõusul luidete jalamilt luite tippu suureneb mulla pH, kusjuures olulist erinevust erinevate proovipunktide mulla pH osas täheldati vaid kõrgeimal luitel (*t*-test, $p = 0{,}004$).

Luidetel tehtud männiokaste analüüs näitas toiteelementide sisalduse suurt varieeruvust, kusjuures luite-eelsetel tasandikel kasvavate mändidega võrreldes sisaldavad luidete tipus kasvavate mändide okkad keskmiselt 17% vähem N-i ja ligi 27% vähem K-d. Arvestades mändide kasvuks okastes vajaminevate optimaalsete kogustega (Ingestad, 1962; Wehrmann, 1963; Brække & Salih, 2002), täheldati, et luitel kasvavad männiokkad sisaldavad 3 kuni 9 korda vähem K-d. Tipumändide okkad sisaldavad aga N-i keskmiselt 50% vajaminevast kogusest vähem. Samuti on okastes P defitsiit, kuid Ca kontsentratsioonid on kasvuks vajaminevast optimaalsest kõrgemad. Järelikult on luidetel peale mõne elemendi olulise defitsiidi kujunenud ka tasakaalustamatus organismi mineraalses koostises. Luite tipus ebasoodsates kasvutingimustes kasvavate mändide okaste kõrge Ca sisaldus tekitab puude intensiivsemat füsioloogilist vananemist (Miidla, 1984; Marschner, 2002). Seevastu on Mg sisaldus luidetel kasvavate mändide okastes optimaalne.

Kokkuvõtteks võib öelda, et Edela-Eesti luitestik on erakordselt mitmekesine nii edaafiliste kui ka puistute karakteristikute poolest. Ühel ja samal luitel, jalamil, nõlvadel või luite tipus on taimede kasvuks kujunenud varieeruvad keskkonnatingimused, mis avalduvad nii mulla toitainete kontsentratsioonis kui ka nende akumulatsioonis taimedesse. Lisaks toitainete sisalduse tasakaalustamatusele okastes esineb enamikus mändidest kasvuks vajalike elementide defitsiit, mis kahtlemata avaldab mõju puude kasvule ja bioproduktsioonile.