Project n. PL013388
OMRISK

IMPACTS AND RISKS FROM ANTHROPOGENIC DISTURBANCES ON SOILS, CARBON DYNAMICS AND VEGETATION IN PODZOLIC ECOSYSTEMS

Specific Targeted Research or Innovation Project

SIXTH FRAMEWORK PROGRAMME
SPECIFIC MEASURES IN SUPPORT OF INTERNATIONAL COOPERATION
INTEGRATING AND STRENGTHENING THE EUROPEAN RESEARCH AREA
INCO RUSSIA + NIS-1
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Coordinator organisation: Università degli Studi di Torino, DIVAPRA

PROJECT EXECUTION

The OMRISK project starts from the consideration that boreal forests and podzolic soils supporting forest vegetation are of utmost importance in the global carbon cycle. The role of Russian forest vegetation as a potential sink for carbon is well known, but soils have even a higher capacity to store carbon and the illuviation of organic matter in podzolic soils could enhance this phenomenon. Soil Organic Matter (SOM) that accumulates in the spodic horizons may be protected from mineralisation due to the lower microbial activity and strong interactions with the inorganic phases. However anthropogenic disturbances may deeply interfere in the podzolic ecosystem functionality and this sink of C may turn into a source.

The objectives of OMRISK were to evaluate the risks of C release caused by human actions, through the assessment of the changes in ecosystem functionality. Some anthropogenic disturbances, such as contamination can be avoided only a global scale, while others can be prevented more easily if scientific results are transferred into best-practises to protect the role of the podzolic ecosystem. To reach the general objective the project was split into WPs related to different kind of disturbances which have been studied in different study areas of the Russian Federation. The specific objectives were:

1. *Evaluation of the effects of revegetation of spoiled areas on carbon cycle, taking into account both species and community succession and triggering of pedogenic processes*
2. *Evaluation of the effects of anthropogenic contamination on the dynamics of podzolic environments and on their capacity to act as a sink of carbon*
3. *Evaluation of the effect of forest management practises on carbon dynamics in podzolic environments, with special emphasis to the risk of carbon release and loss of productive forest soils associated to harvest operations*

Upon the achievement of these specific objectives the data obtained have been used for the final objective of the project:

4. *Development of new models, or the implementation of existing ones, to extrapolate the results of organic matter and vegetation dynamics to several environments of the same type of ecosystem and analyse the consequences of the different man interferences.*

The need to study several parts of the ecosystem involves the presence of a consortium characterised by different specific fields of research. There are thus eight participants in OMRISK:

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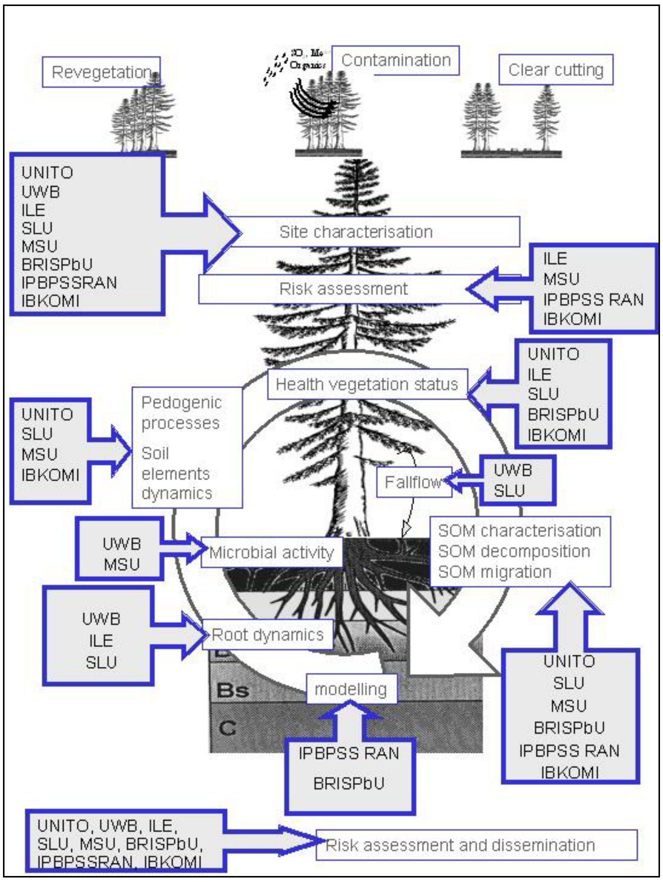
The activities of all participants are linked together (Figure 1) to take into account the different topics which are the objects of the OMRISK project.



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Further information on OMRISK are available at the project web site: www.omrisk.unito.it
The project started on the 15.06.2005 and finished on the 14.06.2008

Evaluation of the effects of revegetation on C cycle and soil development
The opening of quarries induces severe degradation of soils and forest cover, hence interfering with C cycle and with ecosystem functionality. When the quarries are abandoned natural vegetation succession or artificial plantation allow at least a partial remediation of the environment and represent a large potential to re-establish the ecosystem, similarly to primary succession after strong natural disturbances. Typically, spoil material does not contain organic matter and it presents unsuitable water regime and nutrient deficiency, but is highly reactive and can undergo rapid changes in physical and chemical properties. Thus the restarting of the pedogenic processes may be relatively rapid and is of crucial importance to recover soil functionality and allow plant growth. Chronoseries are the best way to study the evolution of the environment with time and follow the processes that determine the restarting of soil functionality and then the re-establishment of the whole ecosystem. Therefore the objective of the WP3 was to obtain quantitative data on podzolic environment ecosystem after total destruction at open quarries in the Staraja Maluxa, near St. Petersburg in NW Russia. The specific objectives were 1) to evaluate the inflow of organic matter to the soil; 2) SOM characteristics and decomposition rate; 3) the evaluation of vegetation succession processes; 4) the assessment of pedogenic processes.
For this aim a chronosequence of soils that developed under almost pure pine stands for 3, 6, 10, 20, 40 and >60 years was selected. Additionally, a time 0 site, without vegetation was chosen as a reference area. From the data obtained in the field, the process of vegetation development was clearly visible. On the 3-10 years old plots xerophytes and mesophytes grasses and shrubs, together with solitary pine trees with spotty grass-mosses cover, indicate the lack of a well developed

reservoir for moisture in the soil, and the fast drainage of rainfall because of the coarse texture. No organic horizon was present at the surface and the mineral soil consisted of a C horizon. At the 10 and 20 yrs-old sites, the situation was similar to the younger ones, with higher Scots pine trees and the presence of *Calluna vulgaris, Vaccinium myrtillus* and *V. vitis-ideae* in the herb layer. Under this cover an O/A overlaid a C horizon while the 40 yrs-old site was characterised by well developed trees with a close canopy and the soil was constituted by a continuous mor-type forest floor and A and BC mineral horizons. In the mature sites, > 60 yrs old the soils were characterised by a sequence of horizons O, O/E and BC or O, E, Bs, and BC.

The inflow of organic matter to the soil was determined by considering the needle biomass, the field layer and the bottom layer, the root biomass. Needle biomass increased with increasing stand age from 0.4 to 560 g m^{-2}, corresponding to a rate of 0 to 280 g $m^{-2}yr^{-1}$ with the highest value in the 60-year- old stand. This trend paralleled the increasing basal area of the stands with age. Above ground litterfall biomass from combined understory layers (sum of field and bottom layers) ranged from 0-34 g m^{-2} yr^{-1} increasing with stand age. In the 20 and the 40-year-old stands there was a clear dominance of the field layer over the bottom layer as regards the litterfall biomass, but in the 60-year-old stand the bottom layer contributed ten times more litter than the field layer due to the abundant moss layer. As can be seen from the results the remediation takes time and still 60-years after revegetation the understory vegetation was rather sparse. The C stock of the understory vegetation was roughly half of the biomass weight since the C concentration was around 50%. The amount of N stored in the understory vegetation ranged between 0.8 and 3.0 g m^{-2} with the highest amounts in the older stands. The root biomass data showed that Scots pine was already the dominant tree species in the initial stages of sand re-colonisation. There is evidence of other tree species in the rooting zone at 20 years after disturbance, but their contribution to living root biomass decreased in time and at 60 years has disappeared. At this stage, the stands were dominated by pine, total living root biomass reached nearly 700 g m^{-2} in the top 60 cm of soil. Root necromass was also increasing from 7 to 91 g m^{-2} at 60 years. Microbial biomass was low at the beginning of pine development but increased rapidly especially in the forest floor. The development of altered organic horizons (OH) after 60 years was well followed by the increase in microbial biomass in the oldest soil. With age, there was a significant increase of microbial biomass also in the E and Bs horizons.

Soil organic matter was carried out by using different approaches both for quantitative and qualitative studies. Extraction methods included 1) chemical fractionation carried out using a sequential NaOH extraction of both humic (HA) and fulvic acids (FA) or a one-step NaOH extraction by collecting all HA and FA fractions together; and 2) density fractionation using Na politungstate, separating SOM in three different fractions, free particulate organic matter (FPOM), occluded particulate organic matter (OPOM), and organic matter intimately linked to minerals (MOM). The bulk SOM and the different fractions were then characterised by a number of chemical and spectroscopic analyses, including elemental analysis, calorimetry, liquid state ^{13}C NMR, FT-IR, EPS, lignin oxidation, electrophoresis. From the results it appears that the little inherited SOM present in the sandy substrate was mainly represented by aromatic material. With plant development SOM accumulated with a net increase after 20 years, both in the forest floor and in the mineral soil. After 60 years the stock of carbon reached values of about 4 kg m^{-2}, values that are approaching those observed at adjacent sites not interested by mining activities. At the beginning of plant development SOM was represented by fresh unaltered material accumulating in the forest floor and deriving from needle litter fall and some herbaceous species. With stand development, a rapid translocation of unaltered particulate organic material from the forest floor into the mineral soil occurred, due to the soil coarse texture. The organic material was fresh, unaltered with a high C_{HA}/C_{FA}. Lignin derived phenols were represented mostly by the vanillyl units derived from the gymnosperms species. After 20-30 years, the litter presented some evident signs of decomposition and humification, but the HA and FA characteristics and the caloricity data highlighted a low degree of oxidation. Therefore, the products of humification at the initial stages of soil formation are not exactly humic substances, but can be classified as "prohumic". This may be due to the limited biological activity at the initial stages of forest establishment. Moreover, a high concentration of acidic phenols and lignin derived products in the deeper horizons of the 20 year old site was observed indicating that the more acidic compounds produced by litter decomposition were not retained by the sand substrate and leached downward the profile.

Thereafter, the amount of FA prevailed on the HA both in the organic horizons and in the mineral soil. In the mineral soil FA/HA showed that in 40 years cheluviation/illuviation processes have been starting and were already well expressed in only 60 years. In the 60 yr old site humic acids were characterised by a larger amount of carboxyl and metal-O-C groups in Bs horizon than in the E one, suggesting that the Bs formation was related to the migration of complexes of humic substances with iron and other metals and their precipitation after saturation by cations. The amounts of oxidised fulvic acids increased with age in E horizons. The migration of humic substances in the E and Bs horizons was related to the low-molecular size fractions, as highlighted by electrophoretic fractionation of humic acids. The data of lignin analysis corroborated the feature observed in the HA and FA. Lignin derived phenols were progressively more oxidised and in the oldest stands they accumulated downward the profile in the Bs horizons, strongly linked to the mineral component.

The characteristics of SOM and its interaction with the mineral fractions were reflected in the degree of decomposability. The SOM decomposition rate experiments indicated that organic matter from organic and mineral horizons of 10 years old soil was essentially less stable than organic matter of older soils. The most expressed differences in soil organic matter stability were visible in the 60-years old soil and in the mature soil, both in the E and B horizons while for organic horizons such differences were not so evident because of the same origin in the forest floor. These data confirm that the establishment of organo-mineral complexes plays a key role on SOM stabilization even at the beginning of soil formation.

The accumulation of SOM along the chronosequence was accompanied by various modifications of soil properties: the pH declined rapidly both with time and downward the profile due to SOM and to increasing microbial respiration. The increase of protons and of acidic organic compounds caused mineral weathering as observed by the increase of clay content, and iron and aluminum oxides, both in crystalline and amorphous forms. Pedogenic transformations were followed also by evaluating phosphorus (P) cycle. The different P forms showed that in only 40 years P was completely displaced from the primary minerals to plants and returned into soil mainly as organic P. The orthophosphate ions deriving from primary mineral dissolution or by organic matter mineralization partly accumulated on the reactive mineral surfaces and, at a less extent, form strong bonds with oxides.

Mirroring the increase of SOM and the formation of pedogenic minerals with highly reactive surfaces, the sites showed an improving soil fertility as deduced by the increasing cation exchange capacity, and bioavailable nutrients (NH_4^+, NO_3^- and $H_2PO_4^-$).

All these data confirmed that the natural vegetation succession established after the abandonment of the quarry has allowed a partial remediation of the environment. The most visible signs of soil formation were related to SOM accumulation and pH decrease, but other properties have been affected and led in only 60 years to the formation of podzolic soil indicating that the pedogenic processes are very rapid in this environment. The tight link between biosphere and soil has allowed the re-starting of the ecosystem functionalities and may represent an important resource for the restoration of such strongly disturbed areas.

Evaluation of the effects of contamination in podzolic environments

The Cherepovets area was selected to study the effects of anthropogenic contamination on podzolic ecosystems, as the town is one of the major industrial centres of European Russia. The area belongs to the Southern Taiga climatic zone, the soils are Podzolic and the situation was therefore comparable to the Central Forest Reserve (CFR), one of the few pristine Southern Taiga ecosystems, which was selected as a reference area. The urban soils in Cherepovets showed high concentrations of heavy metals, mainly Zn (up to 4400 mg kg^{-1} of 1M HNO_3-extractable form), although the spatial variability was rather high and the average contents were relatively low (e.g.

Zn=203 mg kg^{-1}) when compared to some extremely contaminated areas. Abnormal concentrations of Ca, Mg and Fe were also found, indicating multiple sources and a high qualitative variability of the inputs. The metal concentrations generally decreased with increasing distance from the town, in contrast with the data reported in previous works on that area, and in the experimental site of the OMRISK project (CHP), located approximately 5 km south of town, the heavy metals contents were higher than in the CFR, but still within acceptable limits. Zn was again the most represented heavy metal (up to 279 mg kg^{-1}), and Ca and Mg concentrations were twice as higher than in the CFR. The differences between the two areas (CHP and CFR) were visible only in the organic horizons, where anthropogenic elements accumulated. In the O horizons from CHP the pH was higher than in CFR, thus affecting the mobility of elements, together with the high contents of organic matter. Emissions from town also provided other elements as anions, such as Cl^-, SO_4^{2-}, and NO_3^- which were therefore more abundant in the soil solution taken from CHP than in CFR. Also in the case of anions, the concentrations sharply decreased immediately below the organic horizons. The presence of SO_4^{2-} provided an additional mechanism to buffer the acidity of the organic horizons. Adsorption of sulphate was in fact rather high in these layers (up to 24 meq kg^{-1}), and occurred through ligand exchange, releasing therefore OH^- into the soil solution. This was not the case for nitrate, which is not specifically adsorpted. Even if the heavy metal concentrations were higher close to the soil surface, root development did not show any significant difference among horizons, and the metal contents in the fine roots taken from CHP, although higher on the average, were not significantly different from those found in CFR. The needles taken from CHP had higher contents of basic elements (Ca, Mg, K, Na) and a slightly higher concentration of Zn. Therefore only a limited uptake from the soil, followed by translocation of potentially toxic elements, has occurred in the above ground part of the ecosystem, probably because of the low mobility induced by soil pH and SOM content. The biomass of fine roots, their production and turnover did not show any significant difference between the pristine and the contaminated site as well, although differences in the proportion of tree species were found. At the CHP site, spruce roots contributed to more than 90% to fine root biomass, while at CFR a more marked dynamism in tree vegetation was visible from the presence of roots from other species, mostly pioneer broadleaves. This greater vegetation dynamism of the pristine site was clearly depicted from the analyses of aboveground cover (trees, shrubs, herbs and mosses) with a higher number of species at CFR, although at CHP some grass species which are indicative of anthropogenic disturbances were also found. As a consequence, the standing biomass of spruce in CHP was much higher than in CFR, but the pools of organic carbon in soils were not significantly different. This was probably related to different losses of organic carbon through oxidation to CO_2 or as dissolved organic carbon. The standard respiration, which is a parameter providing the rate of CO_2 emission from organic materials, was more than double in CHP with respect to the CFR (0.10 ±0.02 vs 0.05 ±0.02 mg CO_2 g^{-1}dw h^{-1}), when the fresh forest litter was considered and, although less striking, the differences were maintained in the humified organic horizon. Considering that spruce litter is more recalcitrant to decomposition with respect to that of broadleaves, these results indicate that microbial activity is not limited by the metals which accumulate in the organic horizons. Bacterial cells were present in higher amounts in CHP and the greater number of species indicated a higher biodiversity in bacteria and fungi. This increase in microbial biodiversity may be a consequence of the presence of higher contents of Ca, Mg and K, and of higher pH. Besides the losses of carbon as CO_2 the possibility of leaching of soluble organic matter deeper in the soil profile in CHP may also contribute to lowering the surface C pools. When the first mineral soil horizons (down to 30 cm) are considered in pool calculation the trend which was visible for organic horizon was not visible any more with 4.60±2.42 and 6.23 ±2.93 kg C m^{-2} in CHP and CFR, respectively. This may be the result of the higher abundance of spruce, as the effect of variation in tree species was visible not only on the forest litter composition, but also on the first mineral horizons. Based on these results, no negative effect is visible at present on the different parts of the ecosystem; the evaluation of vegetation health again confirmed these data, with no significant differences in pristine and contaminated areas. However,

the non-harmful situation seems to be related to a sort of fertilisation effect caused by the presence of nutrients, such as nitrate, Ca, and K, reaching the soil through atmospheric depositions. If the soil pH would decrease, the mobilisation of metals from the litter might occur, involving deep variations in ecosystem functionality. In podzolic ecosystems the dynamics of Al and organic matter are the characteristics most probably affected by variations in pH; the presence of heavy metals may in turn have other additional effects. The mobilisation of Al was enhanced when a heavy metal-enriched acid solution was leached through a soil column, and the E horizons were those contributing the most to the loads of Al. In E horizons in fact, Al was present in the interlayer of clay minerals, giving rise to pedogenic chlorite, and thus may be released easier than from the other more crystalline mineral forms. The importance of this mechanism was confirmed by the concentration of Al in stream waters, which showed similar amounts of element to the E soil solutions. In podzolic ecosystems, the migration of Al normally occurs in organically-bond form, thus providing an additional output of organic C from the soil. The losses of dissolved organic carbon were the highest where the pH was the most acidic; the amounts of base cations were lower, as well as the pools of SOM. Thus the highest losses of SOM and Al occur together. The C outputs through losses by leaching were found to vary from ~20 to ~100 g $m^{-2}y^{-1}$, depending on soil type (Podzolic, as in CHP, or Peaty-podzolic-gleyed soil, on less drained flat surfaces).
The results of this WP allowed to conclude that the resistance of the podzolic ecosystem to anthropogenic contamination is high due to a favourable combination of conditions. The high variability of the industrial emissions provided the systems with base cations and other nutrients in addition to heavy metals, thus globally enhancing the fertility conditions of acidic podzolic soils, and stimulating microbial activity. On the other hand, the high contents of organic matter in organic horizons and the increase in pH provided a physico-chemical barrier to heavy metal mobility and uptake by trees. Thus, the functioning of the ecosystem does not differ from that of a pristine comparable site, with the exception of a decrease in biodiversity of plant tree species. The decrease in species variability however may have been caused by anthropogenic factors other than airborne contamination. As a consequence of these conditions, the present pools of carbon in soils and roots of contaminated and comparable pristine sites are also similar. This is however only a steady-state, which may change upon any variation in the quality and quantity of industrial emissions. If the situation changed towards more acidic conditions, the pools of C would decrease, mainly because of leaching of dissolved organic carbon, and the HM released from litter would enhance the mobilisation of Al. The lower biodiversity in the above-ground biomass could then become a limiting factor in ecosystem resilience.

Evaluation of forest management on carbon dynamics
Forests cover 39 x 10^6 ha in the Komi Republic, and conifers dominate (81%). The most widely used practise for wood harvesting is clearcutting, which is also the recommended one in local regulations. Depending on the type of harvesting, from 25 to 37% of the total C stocks, including living biomass in the calculation, are removed. Three sites were selected close to the Ust'Kulom village; in this district, the forest area is about 2.35 x 10^6 ha, and is mainly formed by exploitable forests (88%). One experimental site consisted of a pristine unmanaged spruce forest of the Middle Taiga climatic zone (Plot 1), the other two sites differed in time elapsed since clear cutting: Plot 2 underwent clear cutting during winter 2000-2001, while Plot 3 was harvested in 1969-70. Within each site, 5 subplots were selected where all measurements (soil C pools, microbial activity, root parameters, litter incubation etc..) were carried out. The 3 plots were comparable in climatic conditions, topography, geology and in the original composition of the forest cover. The tree species composition is 60% Spruce and 40% Fir, with a minor presence of birch at site 1, and was identical before clear-cutting at site 3. Site 2 showed instead a slightly higher abundance of spruce. Clearcut was done on 50 ha areas, leaving only the trees with diameter < 10 cm. At present, the plots clearly differed in vegetation because of the natural plant succession. Site 3 showed the presence of broadleaved species, together with spruce, while at plot 2, only young spruce, birch and

Sorbus trees were present, together with a rich herb layer. The present spruce standing biomass at plot 3 was 159±44 m^3 ha^{-1}, which was comparable with the 199±46 m^3 ha^{-1} of the pristine site. When grasses, shrubs and mosses were taken into account, a good recovery of the ecosystem after 36 years was found: Cluster analysis was in fact unable to separate the areas from Plot 1 from those of Plot 3, while the subplots identified in the recently clearcut area were well separated. Ecosystem recovery was also visible in vegetation health status: significant harmful effects on spruce trees were only found at the recently clear-cut area, and were probably caused by strong overshadowing of these individuals until clear-cutting has occurred.
According to the International Soil Classification System (WRB 2006), the soils at Plot 1 and 3 were Silty-abruptic Albeluvisols, while an Haplic Podzol was found at the recently clearcut site. In all cases, however, podzolisation was present. The Russian soil classification allowed to evidence that the soil cover at the three plots was a complex mosaic of the main sub-types of Podzolic soils: iron-illuvial Podzolic (Pf), Podzolic ones (P), humus-iron-illuvial Podzolic (Phf) humus-leaked Podzolic (Ph) and peaty-gleyed Podzolic (Pg), which reflected the moisture conditions of the sites. In the first years after clear cutting, an enhancement of moisture conditions has occurred giving rise to variations in the quality of SOM and in the relative proportion of Podzolic soil sub-types. The presence of the Phf subtype increased at the expenses of the typical podzolic soil. Another consequence of increased moisture was the increase in water soluble organic matter pools in the mineral soil horizons (from 400 to 460 g m^{-2}). In the organic horizons instead the water soluble C stocks decreased after clear cutting, thus suggesting an increased mobility of organic matter. The other fractions of organic matter were also affected, with a different distribution through the profile of humic substances. A decrease in humin was visible, together with a deeper distribution of the most "labile" forms of humic acids, as determined by the Russian fractionation system, thus confirming an increased mobility of SOM, also pointed out by FT-IR analyses showing an increase in carboxyl groups. When the pools of humic substances were taken into account, an increase from Plot 1 (0.95 kg m^{-2} of humic and fulvic acids down to 30 cm) to Plot 2 (1.46 kg m^{-2}), followed by a decrease in Plot 3 (1.36 kg m^{-2}) was visible. When the total stocks of C are considered (down to 1 m), the contents followed the same order: Plot 2 > Plot 3 > Plot 1, with 7.4, 6.8 and 6.5 kg C m^{-2}, respectively. The reasons for this trend were related to the increase in C stocks of mineral horizons after clear cutting, to the variations in litter composition when the natural vegetation succession has reached the stage we found at Plot 3, and to differences in litter decomposition. The C to N ratio reflected all these variations, and suggested a slowing down of decomposition. A lower mass loss of needle litter was in fact found at the disturbed site (Plot 2) than at the pristine forest (Plot 1), and in addition, physical disturbances to the soil, such as those related to the compaction by heavy harvesting machines on tracks, further reduced decomposition. This was probably related to moisture conditions, as when the litterbags were incubated deeper in the profile at the same disturbed site, decomposition was enhanced. The mass loss was accompanied by a sharp decrease in water-soluble (60-80% of the initial contents) and in ethanol-soluble substances (60-70% of the initial amounts). The mass loss was accompanied by a loss in the most easily leached elements, such as Ca and Mg; the losses of elements were higher when the litterbags were incubated deeper in the profile, in agreement therefore with the increase in moisture observed after clearcutting. The results on mass loss were confirmed for the organic horizons by the standard respiration. The respiration rate of the humus layer was more than three times higher in the pristine forest (Plot 1) with respect to the 2000-2001 clear cut area (Plot 2), suggesting that the lower decomposition found using litter bags was coupled with a higher recalcitrance to decomposition of humus. The contribution of fine roots to C stocks was similar in Plot 1 and 3 (250-300 g biomass m^{-2}), although sharp differences in species composition were found, as expected. The fine root production instead differed between these two sites, with a lower production at the pristine forest. At site 2, the fine root production has increased over the three years of sampling, reflecting the recovery of the area after clearcutting. The necromass turnover of fine roots, i.e. a measure of the disappearance of fine root necromass to microbial respiration or SOM, was 3 times higher at Plot 3 with respect to the

pristine site, likely because of the presence of more easily degraded roots of *Betula*, *Sorbus* and *Populus*. At site 2, the fine root necromass was very high, comparable to fine root biomass, and the necromass turnover was extremely low compared to the other sites. This may be the result of the decrease in decomposition, thus again confirming the results obtained for litterbags, but may also be related to survival of fine roots after clear cutting until starch reserves in coarse roots and stumps have been exhausted. The vitality of fine root tips did not show any differences in the pristine and clearcut areas, but a trend towards a decrease in the length of fungal mycelium was visible in Plot 2. At the recently clearcut area, a low abundance of ectomycorrhizal fruitbodies confirmed qualitatively the variations in symbionts, while also in this aspect, Plot 3 showed a good recovery. From all the results obtained in this area, the recovery of the podzolic ecosystem was visible at about 35 years after clearcutting and no losses of soil organic carbon were identified. It is important however to note that this was the first time the system underwent clearcutting, thus its resilience may not be the same upon successive claercuttings.

Development of models to extrapolate the results of organic matter and vegetation dynamics

The first step in the development of this objective was to improve the available models EFIMOD and ROMUL, which has been developed by project teams earlier, and to use them to simulate and forecast the consequences of climatic and environmental changes, and forest management practices, accounting for carbon sequestration, biodiversity conservation taking into account the uncertainties of forest and soil inventory data and the effects of the main factors that determine stand growth and the cycling of elements in the forest ecosystems.

First, to improve the existing versions of the models, the SOM pools of mineral soil have been subdivided according to their degree of transformation, estimated on the basis of the C to N ratio of fractions of fresh litter. Thus a pool which is completely humified (stable (passive) humus) and another one, poorly decomposed and partially humified (peaty pool) have been inserted. The rate of decomposition of these fractions was obtained in laboratory experiments which lasted up to 12 months. The curves of mass losses were fitted using two equations of the ROMUL model describing fresh litter (L) and a complex of humic substances with undecomposed debris (F), taken in the simplified form and in correspondence with model description of that subdivision. The rates of mineralization and humification varied significantly depending on litter type. The dependences of coefficients values on nitrogen and ash contents were also analyzed to prove and enhance their parameterizations been using in the ROMUL model. To assess the sensitivity of the model to initial parameters, a Monte-Carlo procedure in relation to high variances of litter fall and climate variations resulted in small sensitivity of leading variables. We found that sensitivity of small Monte-Carlo changes of coefficients' values increase with stage of decomposition. The rate of mineralization of stable humus is the most sensitive to changes.

The problem of evaluation of trends in forest ground vegetation dynamics has been further developed through the division of ground vegetation into ecological-coenotic groups (ECG) on the basis of multidimensional statistical processing of collected database with geobotanical descriptions, which give a possibility to join common characteristics of a group of plants with well-known characteristics such as age of forest dominants, soil nutrition, and some ecological site characteristics (soil moisture, pools of soil organic matter and deadwood etc.). This approach allows for application of the model of forest growth and elements cycling EFIMOD, which simulates the changes of these characteristics at forest development and growth at different scenarios of forest management.

First, for each forest stand in a model forest, its forest type was assessed by combining dominant tree species in overstorey and dominant ECG in understorey. The individual-tree based model of the forest-soil system EFIMOD has been used for simulating dynamics of forest ecosystem parameters. The model outputs are the dynamics of stand main dendrology parameters (mean height, diameter etc.), tree species composition, coarse woody debris, soil organic matter, soil moisture and fertility etc. under different cuttings. Second, accordingly to dominant tree species and dominant ECG indices of vegetation diversity were computed for each forest type. Finally, the computed indices of vegetation diversity were linked to the ecological-coenotic forest types obtained at the initial step, and thereby the ground vegetation diversity was assessed for each forest stand in the model forest. We used average plant species richness per square unit and also designed a discrete scale of species diversity ranging from 1 to 5, where 1 corresponded to the least number of species per square unit, and 5 - to the greatest number of species per square unit, with increase of 10 species per step.For this case study, a forest lot with 104 stands of a total area of 273.4 ha was selected in the "Russky Les" Forestry located on the podzolic soil at central Russian Plain, which has a good database on geobotanical descriptions. According to the inventory data, pine and birch dominated on the majority of the selected stands. There was practically no deadwood due to previous cuttings and ground fires usual for dry pine forests. Species diversity ranks changed in accordance with the dynamics of the forest types. At the initial step of the simulation, pine forest stands poor in species prevailed (species diversity ranks 1 and 2). Then, up to the 75th step, species diversity ranks increased almost to the same extent in scenarios of natural development and clear cutting due to the increase of the number of stands with boreal and nemoral group domination (the latter stands were richer in the number of plant species in comparison with pure piny forest stands). After the 75th step, the sum of species diversity ranks under the natural development scenario became remarkably bigger than the sum of species diversity ranks under the clear cutting scenario. At the end of the simulation, in the first scenario average species diversity rank was 3.4, while prevailing were the forest stands with species diversity rank 4. In the second scenario, final average rank was 2.6, while prevailing were the forest stands with species diversity rank 2. The reason for the difference between the scenarios was the increase of the number of rich (in species) nemoral and nitrophilous stands under the natural development, and the absence of nitrophilous stands accompanied by the moderate increase of the number of nemoral stands under the clear cutting.

After clearcutting, the natural restoration of disturbed forest territories proceeds through succession stages. During these stages the accumulation of SOM in forest floor and mineral topsoil changes with changing vegetation.

This non-equilibrium approach was applied to the sites selected to study natural revegetation (WP3) The 3-, 10-, 30- and 60-years old, and also mature Scots pine forest plots in naturally-revegetated spoil banks of Maluxa glacio-lacustrine sand quarry in Kirovsky district of Leningrad region (50 km East of St. Petersburg) were studied. Field Measurements demonstrated the increasing and stabilization of SOM pools in pine forest chronoseries. By running the ROMUL model we found the most realistic scenarios that provided the most adequate correspondence to the experimental data in short term model runs. Then the model was applied to a highly contaminated site on the base of WP4 studies, the contamination decreases the rate of OSM decomposition. It was found that the accumulation of SOM that was present in one the considered sites could be achieved only under involving of all possible sources of litterfall: spruce needles and twigs, coarse woody debris and increased root litter (double amount in comparison of aboveground spruce litterfall). In this case mass of forest floor decreased and humus increased slightly during the first 10 years of simulation. SOM steady state was formed after 10 years of simulation. The equilibrium between litter input and mineralization from the first steps of modeling could be found if we take into consideration the pH influence on the rate of litter decomposition. The effect of pH on SOM decomposition and accumulation was therefore assessed. ROMUL was then applied to the study sites of WP4, the areas selected to evaluate the effects of clearcutting, to analyse SOM dynamics in the Komi spruce forests. The steady state of soils in old spruce forest was used to find soil variables dynamics, which were then checked with the experimental data obtained in the field. Thus this dynamics of soil variables would correspond to ecosystem evolution without disturbances. The virgin spruce forest could be treated as a stable, i.e. with zero balance between carbon input and output. Then we simulated clear-cut in terms of changing of 1) litter flow, and 2) temperature and moisture of forest floor and mineral soil. Soil climate is changing after cuttings due to decreasing of transpiration by trees and decreasing of shadowing. We developed a corresponding scenario and obtained time series of forest floor and soil moisture and temperature in correspondence with these changes in vegetation. The rate of decomposition of stable humus also changes after clear-cut. Using these assumptions we simulated the 50-years runs of ROMUL for untouched spruce forest before cuttings. The results show an almost stable state of total soil organic matter pools. The following steps were to simulate the changes after clear cutting and transition changes in the regenerated mixed forest for the period of 40 years taking into consideration time data from experimental plots 1-3. The results matched well these data. The results of the simulation gave us the possibility (as further steps) to calculate: 1. CO_2 emission from soil; 2. impacts of different types of cuttings on the main soil variables including CO_2 emission at and between cuttings; 3. simulate forest growth with EFIMOD model for given soil dynamics.

For simulating and comparison of different scenarios of forest management a forested area with 21637 stands (forest inventory compartments) on 120,400 ha in the Manturovsky leskhoz (Kostroma Region) was selected for the case study. Four simulation scenarios were compiled by Scenarios Constructor as alternative options for the sustainable forest management: 1) *Natural development* (***Nat***). This scenario reproduces a full protection of the forest in all forest compartments without any cutting; 2) *Russian legal system (**LRU**).* The scenario describes managed forest with 4 thinnings (at 5^{th}, 10^{th}, 25^{th} and 50^{th} years), and the final clear cutting (90 year age for coniferous trees and oak, 60 year age for birch and lime) with successful natural regeneration by target species with mixture of deciduous species; 3) *Selective cutting system (**SCU**).* Managed forest with 2 thinnings in young and middle-aged stands, and then selective cuttings after the stand reaches the age of 80 years 4) *Illegal practice (**ILL**).* It represents heavy upper thinning and removing of the best trees, clear cutting without conservation of natural regeneration following by dominating of deciduous young stands. Analysis of the simulation results for the 50 years period in the four scenarios demonstrated similar patterns of carbon sequestration. There is a clear advantage of the selective cutting and natural development regimes (***SCU*** and ***Nat***) over clear-cut systems (***LRU*** and ***ILL***), both in relation to stand biomass and SOM. We found that the strategy of natural development is the best alternative from the viewpoint of the carbon sequestration in the forest ecosystem. Similar investigations should be done and compared for the Syktyvkar region based on the data of WP4.

The use of simulation models of SOM dynamics and forest ecosystem development can be a proper tool to specify the scales and trends of SOM dynamics because we can change at model run any kinetic parameters of SOM mineralization. The models give a possibility to take into account a feedback between soil and plant growth because main elements of nutrition, such as nitrogen, are released from mineralizing organic matter of above and belowground litter fall.

Model experiments have been done for explanation of the role of feedbacks between soil and vegetation. A set of model runs has been performed at two boreal forest sites (Scots pine, *Pinus silvesrtis* L, and Norway spruce, *Picea abies* L. Karst.). To simulate effect of SOM mineralization rate, we decreased and increased the rate constant of stable SOM mineralization around the calibrated value (0.00018 day^{-1}) in the basic simulation. This value was decreased by 3 times in model runs with increased stability of this pool. Inversely, the value of this parameter was 3 fold increased in exercises with SOM destabilization. The results of 80 years simulation are rather unexpected. The increasing of stable SOM pool at stabilization is significantly lower of its decreasing under destabilization. The forest biomass carbon is 50% lower of reference level in a case of passive SOM stabilization, and about twice higher in a case of SOM destabilization. It means that litter input from forest vegetation to soil has the same attribute: it is significantly higher than the reference level in the case of SOM destabilization. Correspondingly, this increases the accumulation of organic matter in the soil, but mostly in intensively decomposing organic layer and labile SOM in mineral topsoil. Moreover, the total carbon pool in forest ecosystem (sum of biomass, dead wood and soil C) is also strongly increased in a case of passive SOM destabilization and correspondingly reduced at SOM stabilization. This behaviour may be the result of the interaction of carbon and nitrogen cycles in the ecosystem. Stable humus (passive SOM) stores high amount of nitrogen that becomes slowly available in a case of SOM stabilization. Therefore, lower N pool leads to reduction of plant growth. This simulation experiment shows the significance of the effective ecosystem feedbacks for the evaluation of the different ecosystem processes, and moreover – SOM dynamics.

DISSEMINATION AND USE

The following scientific publications have been obtained during the three years of the project

Scientific journals (28 papers)

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