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Reclamation and Reconstruction of Terrestrial Ecosystems on Mine Sites - Ecological Effectiveness Assessment

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ABSTRACT

The work presents and develops an original concept of mine site reclamation viewed as an ecosystem reconstruction process. Ecological effectiveness assessment criteria for the reclamation process were provided to serve as examples. They included soil-plant relationships, factors connected with plant community development (biomass and diversity of communities), pedogenesis dynamics and examples of mine soil classification, ecosystem macronutrients budget on reclaimed mine sites and multi-faceted evaluation of reclamation – carbon sequestration in new ecosystems and the balance of energy efficiency. In addition, selected examples of the reclamation process monitoring were provided as well as of possible application of natural succession in the reclamation process.

***Key words*:** Post-mining sites, Reclamation, Restoration, Ecosystem, Ecological assessment, Soil, Plant and succession

INTRODUCTION

The criteria for the assessment of reclamation depend on how the needs and goals of the reclamation treatments aimed at ecosystem reconstruction are defined. According to most international legislation, reclamation of degraded terrestrial ecosystems (the paper does not deal with reclamation of water ecosystems such as creation of artificial water lakes) includes

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treatments aimed at restoring or enhancing the value in use of soils and areas by following necessary procedures such as improving the physical properties of the soil, regulating water conditions, soil regeneration applying technical or biological methods, strengthening embankments and road construction. The reclamation obligation is usually imposed on the entity responsible for total or partial loss of value in use of areas and soil following the completion of mining operations. Such reclamation should be carried out in accordance with a project, which already in the preparatory phase should determine the development trends and the most important environmental, social and economical conditions of reclamation. The environmental conditions include mainly the climate, geological structure and quality of the rock overburden, or treated coal waste heaps and tailings or even fly ash deposits and slag which constitute the parent rock of the reconstructed mine soil. Most frequently, the reclamation phase ends with the completion of planned technical and biological treatments and further procedures in line with the approved development trend such as afforestation, tree planting or introduction of shrubs is often implemented as a separate range of activities. The occasionally applied temporary greening is a separate issue.

Current expectations of the reclamation effects on the part of the entities which take over reclaimed areas (owners, managers) as well as social and environmental expectations are high in most industrialised countries. Moreover, insufficient exchange of information and experiences between researchers and particularly practitioners dealing with reclamation in different countries and on different continents still constitutes a major problem.

RECLAMATION OF POST-MINING SITES EFFECTIVENESS ASSESSMENT BASED ON ECOLOGICAL CRITERIA

Taking account of previous experience in this field, it may be clearly concluded that reclamation should involve not only the restoration of value in use to soil degraded through a range of agro technical measures, but also the reconstruction of entire ecosystems and landscapes (Bogdanowski, 1988; Dilla and Möhlenbruch, 1989; Krzaklewski, 1990; Bell, 2001; Hüttl and Bradshaw, 2000; R. Hüttl and Weber, 2001).

The ecological definition of reclamation (Bradshaw, 1983; Krzaklewski, 1988; Hüttl and Bradshaw, 2000) states that it a process of restoring the ecosystem and its functions and according to some (Krzaklewski, 1988), this process may even be defined as the recreation of bio-ecological conditions in which the exchange between the soil and the plants provides a successful plant succession and intensive development of soil-forming processes. Reclamation may also be defined as acceleration and direction of the ecosystem succession process in which the introduced plant and animal communities interact and transform the biotope (Krzaklewski, 1993; Pietrzykowski *et al.,* 2010). To sum up, it may be said that reclamation may be considered complete at a time when a self-sustaining system, *i.e.,* a bio-ecological system in which an exchange of matter and energy takes place*, i.e.,* an ecosystem is formed (Pietrzykowski and Krzaklewski, 2007a). According to the classical definition by Sir Arthur George Tansley from 1935 (cited by Golley, 1993), the ecosystem should be an integrated system of biotic and abiotic elements in which all trophic levels contain a set of species ensuring circulation of matter and energy flow.

An important issue is the criteria for assessing the impact and success of reclamation in the course of which the ecosystem formation process takes place (Krzaklewski, 1988; Bradshaw, 1983; Bell, 1996; Bell, 2001; Hüttl and Bradshaw, 2000; Ludwig *et al*., 2003). The effects of forest reclamation may be evaluated over longer time intervals. The history of organized reclamation treatment in the world dates back to the end of 19th and early 20th centuries and only now we are able to assess the several-decade-old "new" ecosystems.

Afforestation is potentially the best sustainable strategy for reclaiming mine lands to their former state (Parrotta *et al.,* 1997; Filcheva *et al*., 2000; Singh *et al.,* 2002; Dutta and Agrawal, 2003; Pietrzykowski and Krzaklewski, 2007). In temperate climate zones in the northern hemisphere forests are a climax biome, the best organised and dominant among terrestrial ecosystems. For this reason, *e.g.,* in Europe, North America, South America and Asia, a large portion of the post-mining landscapes are reclaimed to forest (Katzur and Haubold-Rosar, 1996; Parrotta *et al.,* 1997; Torbert and Burger, 2000; Hüttl and Weber, 2001; Kaar, 2002; Dutta and Agrawal, 2003; Knoche, 2005; Zipper *et al.,* 2011). Expanding the above discussed ecological definition of reclamation in relation to forest ecosystems, it may be assumed that the reclamation procedure and assessment of its effects depend on the aims (Fig. 1).

The greater the investment, the bigger effects may be achieved in the form of growth of tree-stands and biomass (Pietrzykowski and Krzaklewski, 2007; Pietrzykowski and Socha, 2011). This can be reached by forming habitats consisting of homogeneous, potentially most productive substrates with the introduction of monocultures. However, it is not beneficial due to low biodiversity and stability as well as potential susceptibility to fungus and insect gradation.

On the other hand, including the process of natural succession in developed ecosystems and using diverse geological overburden mostly deposited unselected reduces expenses and increases biodiversity by a range of geological formations, but also usually results in lower growth of trees and biomass. Therefore, the measures taken in specific conditions should follow from an analysis of environmental and economic conditions and the

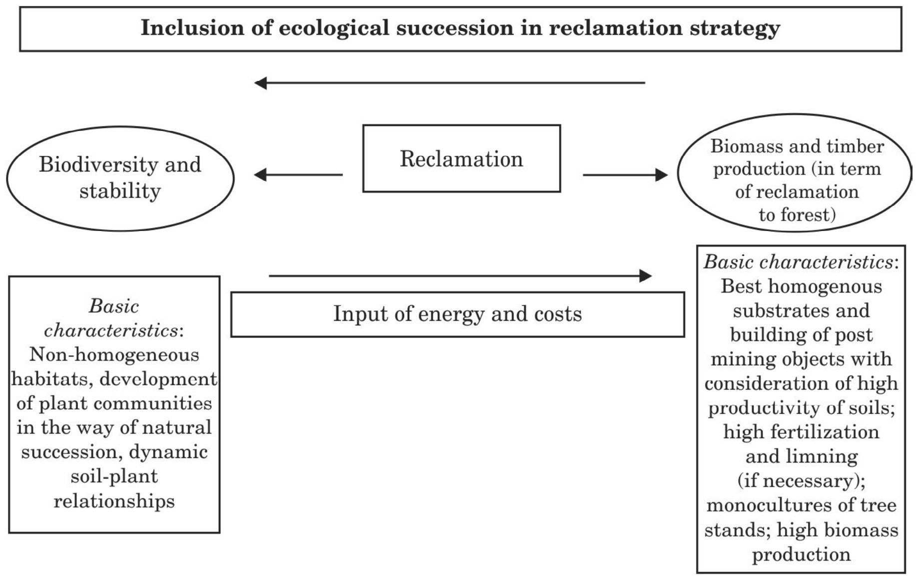

Fig. 1: Development of the ecological concept of reclamation strategy depends on main aim and approaches (originally by M. Pietrzykowski).

aims and the optimal solution is somewhere in-between the two extremes (Fig. 1). This means that natural succession should be taken into account (included in the developed system mosaic), the introduction of monocultures avoided and the production of biomass optimised (through a suitable diversity species, a sufficient dose neutralisers on acidic soil, mineral fertilization (Pietrzykowski, 2014). Correct identification of habitat conditions at mine sites and planning species composition in afforestation both have a fundamental impact on the stability of reclaimed stands and developed forest ecosystems (Gale *et al*., 1991; Heinsdorf, 1996; Burger and Kelting, 1999; Knoche *et al.,* 2002; Pietrzykowski, 2014). Diagnosis and classification of habitats on mine soils reclaimed for forestry is of paramount importance for a proper selection of species composition in afforested sites (Krzaklewski and Pietrzykowski, 2007; Pietrzykowski, 2014). Proper selection of tree species means their ecological requirements are appropriately adjusted to habitat conditions (climate, soil fertility and humidity).

In sites reclaimed for forestry, it is at present possible to assess most ecosystems and tree stands at young phase and in some cases, at a phase closer to the maturity. Assessing the progress of reclamation there is possible referring to an assessment of a new ecological system developing by way of succession supported by various treatments in conditions of total anthropogenic transformation. For practical applications including development plans and legal regulations, it is important to determine the time for the restoration of the ecosystem and for completion of reclamation is. However, determining the exact duration seems rather impossible. While the definitions in accordance with the laws in force in most countries, specifies the criteria for complete restoration following the performance of specific treatments provided in the reclamation project with sufficient precision, the ecological definition which refers to ecosystem reconstruct, does not clearly determine such criteria. It is difficult to clearly determine when a restored biological system becomes an efficient and energetically self-sufficient ecosystem and which assessment criteria should be adopted for such a status (Bell, 1996; Bell, 2001; Hüttl and Bradshaw, 2000; Knoche *et al.,* 2002; Pietrzykowski and Krzaklewski, 2007; Pietrzykowski and Krzaklewski, 2007b). Undoubtedly, however, it is; possible to predict the trends and pace of change taking place in the reconstructed mine soils. It would also be very important to determine a period of time in which a restored ecosystem develops a dynamic but also stable and efficient level of matter and energy circulation, which is an essential function of the reconstructed system. The similarity criterion may also be adopted of the restored plant communities to the adjacent areas typical of a given plant and climatic zone (biome).

Constant monitoring of the restored ecosystems, particularly soil and plant communities, is a very important part of the reclamation process (Ludwig *et al.,* 2003). There are numerous examples of well-performed reclamation treatments and appropriate monitoring of restored ecosystems all over the world. It is difficult to cite them all (from Europe, North America, Asia and Australia), but a good example of the implementation of such monitoring may be areas of the Powder River Basin (PRB) in the state of Wyoming in the Western United States (U.S.). The region produces a significant percentage (approximately 40%) of the total sub-bituminous coal in the United States. To date coal mining in the state of Wyoming has taken up an area of over 54 thousand hectares of which over 27 thousand hectares have been reclaimed (Foulke *et al.,* 2002). Such a huge scale of opencast coal mining involves large-scale transformation of land and landscape. These are mainly geomechanical and hydrological transformations, which have significant impact on local ecosystems. Thus, in the PRB restorative treatment implemented by way of reclamation is regarded on an equal basis as mining operations in the area. Reclamation in the U.S. is regulated by state and federal law and Surface Mining Control and Reclamation (SMCR) Act of 1977 by the U.S. Congress is the main legal act relating primarily to coal mining reclamation. Under this act damage caused by mining must be repaired by properly conducted reclamation. In standard terms it includes restoration of the local topography and soils using technical and biological methods. It is recommended, if possible from the technological point of view, that the top layer of natural soils removed from the overburden should be used to cover the tipped rock (this is called topsoiling). This is followed by a number of agrotechnical treatments and finally by revegetation, *i.e.,* the restorations of vegetation cover. The type of vegetation depends on the local conditions and the type of natural plant formations occurring originally in the mined territory. Of course from the point of view of ecology, it is debatable to what extent the restored ecosystems can resemble the natural ones. Reclamation carried out in the region of PRB in Wyoming is understood as a process which takes places over time, not just a certain range of technical and biological treatments, which render soilless land productive. Such a meaning of reclamation is consistent with modern scientific terminology and "good practice" from around the world. Implemented restoration involves several phases (stages) and their progress must be monitored by a multidisciplinary team of specialists. Reclamation is carried out successively and follows the progressing frontline of operations. Rock overburden, previously stripped to provide access to the deposit, is replaced in the resulting open cast. Next, the formerly planned surface features are formed to go with the local topography. The so shaped tips are covered with a layer of a substrate from the upper horizons of natural soil originally covering the area. The natural soils in this region have a marked compressed horizon with *spodic* properties and a significant accumulation of sodium, which is a big agrotechnical problem. In this phase also streams and retention reservoirs are restored, however the water courses in the area are mostly ephemeral (periodic). Next, rock groups adapted to the original landscape are formed. This is a very important element of restoring biotopes for wildlife, including birds, deer and reptiles. Small groups of rocks are home to smaller mammals. In year one after the formation, land intended for revegetation is seeded with rye and wheat. In autumn at the end of the growing season it is reaped and the straw is left behind. This is done to improve humidity conditions for the target vegetation seed mixture introduced in the spring of next year. The species composition of seed mixtures includes species from natural communities of prairie plant formations. There is no fertilisation or mulching because it was considered that the procedures are too expensive in relation to the effects in the local climate. The mines sites are located in the great plains of North American prairies. The climate is continental with an annual rainfall of about 300 and sometimes even 200 mm, summers are hot and winters are cold and snowy. Most of the currently mined land was previously used as extensive pastures. Originally this was an area of the so-called low and mixed prairies with prevailing low species of grass such as feather grass (*Stipa comata*), *Sporobolus cryptandrus*, couch grass (*Agropyron smithii*). In some areas, due to very heavy grazing these species disappeared and gave way to low grasses and perennial plants such as prairie junegrass (*Koeleria cristata*), evening primrose (*Oenothera fremontii*), butterfly weed (*Asclepias pumila*), *Carex filifolia*, *Aristide purpurea*, *Triode pilosa* and many others. In these areas forest communities are to be found only near watercourses in the form of riparian poplar forests with *Populus acuminata*, *P. angustifolia* and *P. sargentii*. A characteristic plant associated with excessively grazed prairies is big sagebrush (*Artemisia tridentata*). It is a perennial plant which grows in tufts and patches, sometimes in the form of a shrub, with silvery- bluish leaves and a very strong smell. It is interesting to note that it is not eaten by cattle but constitutes an important part of the winter diet of the bison which was originally found there. This species is very important in the strategy of restoring plant communities on reclaimed land. An invasion of alien species such as the Eurasian burning bush (*Kochia scoparia*) also poses a major problem. Taking into account natural processes of succession and dynamics of communities is an important issue in the vegetation cover recovery strategy. This is due to the fact that reproduction and immediate introduction of all species characteristic of the prairie is not possible. Cattle grazing introduced three years after revegetation is a significant factor in shaping the dynamics of communities. Regular, selective grazing by cattle encourages competition between herbaceous species and big sagebrush and benefits the latter species. Regular monitoring of the restored plant communities is conducted every three years. It comprises control of the species composition of the communities, vegetation coverage as well as building up of floristic and syntaxonomic relations. Only after a period of 10 years reclamation, final assessment is made based primarily on the surface coverage by vegetation and biodiversity assessment of communities. In the areas further to the east with a slightly milder climate, the monitoring period and the transfer of land following reclamation may be shortened to five years. Reclaimed areas are taken over first by a special state agency and later they may be sold to the state or federal authorities or to private owners.

The assessment of reclamation is a complex task, just as the ecosystem itself is complex. So far the following assessment criteria of the stages and the pace of reclamation in the restored ecosystem and soil-forming process have been used: the amount of accumulated organic matter (soil organic matter SOM, humus), thickness of the organic and mineral soil horizons, the rate of accumulation of organic carbon and nitrogen and carbon microbial biomass (Anderson, 1977; Roberts *et al.,* 1988; Prosser and Roseby, 1995; Daniels *et al*., 1999; Rumpel *et al.,* 1999; West and Wali, 2002; Pietrzykowski and Krzaklewski, 2007b), biological activity of soils and soil biota (Insam and Domsch, 1988; Šourková *et al*., 2005; Frouz *et al*., 2006; Chodak *et al.,* 2009), rooting depth (Fabijanowski and Zarzycki, 1969; Anderson, 1977; Daniels *et al*., 1992). On the other hand, to determine the rate of succession, the number of species appearing by way of succession was determined, especially vascular plants (Begemann, 1976; Jochimsen, 1996; Pietsch, 1996; Wali, 1999; Pietrzykowski, 2008). Biodiversity of communities, the share of forest, non-forest and shrub species as well as community biomass (as one of the possible measures of productivity of the developing ecosystems) were also assessed. A very important criterion for the determination of the stability of developing ecosystems is to determine the efficiency of the circulation in these elements (Knoche *et al.,* 2002; Pietrzykowski, 2010) and the index of nutrient-use efficiency as in the case of "natural" forest ecosystems (Waring and Schlesinger, 1985). An attempt was also made to determine the ratio of nutrients accumulated in the biomass of tree stands growing on mine sites to the pool of nutrients available in the soil (Pietrzykowski, 2010; Pietrzykowski *et al.,* 2013), which may provide a basis for further studies on the stability and nutrition of tree stands growing on mine sites.

An additional factor in the assessment of the effects of reclamation is the assessment of both the economic and the ecological (environmental) performance. For such purposes defining the so-called energy efficiency of reclamation was proposed computed on the basis of the balance of energy input and gain and the general accumulation of energy in the ecosystem and its individual components (Pietrzykowski and Krzaklewski, 2007a).

Generally, in the light of the presented analysis of the literature, it seems that the focus in assessing the success of reclamation and monitoring of the restored ecosystems should be placed on ecological and soil aspects, *i.e.*, those that capture the features and properties of soils defining their ecological role in the functioning of the restored ecosystem and biocenosis. The assessment of the effects of reclamation may therefore be based on a comprehensive analysis of a number of properties of initial soils and characteristics of plant communities in the ecosystems in mine sites.

INTERACTIONS IN THE SOIL - VEGETATION SYSTEM IN THE PROCESS OF ECOSYSTEM SUCCESSION ON RECLAIMED MINE SITES

The ecological definition of reclamation follows directly from the succession process, so it is important to take a closer look at some of the issues relating to the process in mine sites. The concept of primary succession assumes that dynamic changes in plant communities are mainly due to species competition for limited habitat resources and particularly nutrients, water and light (Wali and Freeman, 1973; Tilman, 1990; Chapin, 1993; Marrs and Bradshaw, 1993). Primary succession takes place in areas not previously occupied by plants such as glacial fields, outcrops of rock, volcanic terrain (Odum and Barrett, 2005). The process of primary succession of soil, plants and animals also occurs in areas of large-scale transformation of the earth's surface caused by mining operations (Wali and Freeman, 1973; Kielhorn *et al.,* 1999; Wali, 1999). Plant and animal communities (biocenosis) appear in new habitat conditions and initial soils form underneath (Wali and Freeman, 1973; Krzaklewski, 1977; Jochimsen, 1996; Wali, 1999; Krzaklewski, 1993; Kielhorn *et al.,* 1999; Pietrzykowski, 2008). In developing the concept of the succession process, most approaches favor the preparation of a universal model of changes in vegetation in a given area, including the stages or phases of vegetation coverage. Although most of the research on the development of the soil and the vegetation proceeded independently, it has long been known that soil succession cannot be separated from the plant and animal succession as they are two aspects of the same process (Braun-Blanquet, 1951). According to the oldest pioneering research (Dokutchaev, 1898 cited by Jenny, 1980), the soil development process was a function of climate and living organism impact on parent rock over time. In the pioneering works of Tuxen of 1931 (cited by Jenny, 1980) the plant succession process was a function of climate, soil and organic matter content. Together with parallel development of research on soil formation and the accompanying vegetation changes it was observed that the functions describing these processes should take into account the same factors, namely, the climate, the impact of living organisms, topography, parent rock type and time (Jenny, 1980). At present it is known that the study of the ecological succession process of plant communities in a given area should take into account also other factors such as the colonisation ability and the reproductive strategy of species, types of interactions between species and populations, including interactions between plants, animals and micro-organisms. With regard to the development of the soil, especially in mine sites where parent rock is the first decisive factor, the history and geology of the area are also important (Wali, 1999).

Studies on the development of soil and changes in plant communities in the process of succession were conducted in the 1950s by Dickson and Crocker (1953) and Olson (1958) and in the 1990s, for instance, by Burt and Alexander (1996). Documented research results show that in natural conditions stages of plant succession correspond with the development of soil-forming processes (Rode, 1995; Elgersma, 1998; Hobbie *et al.,* 1998; Pietrzykowski, 2008).

Pioneering research in this area on mine sites was conducted by Skawina in the 1950s (Skawina, 1953) in Upper Silesia Region (southern Poland). This research focused on the development of soil forming processes in coal tips. He considered the following factors most important in the soil-formation process at such sites: the type and age of the tipped material, the height and shape of tips, the severity of erosion and weathering processes, thermal activity and microclimate, water properties, chemical properties and the type of plant communities in the adjacent areas (Skawina, 1953).

Many authors, *e.g.,* Bauer and Galonske (1975), Krzaklewski (1977), Jochimsen (1996), Pietsch (1996) and Pietrzykowski (2008) indicated the possibility of managing the succession process and the use of vegetation communities from succession in the course of reclamation. There were also numerous works devoted to vegetation which spontaneously grows on tips and open casts. The pioneering studies include a publication by Fabijanowski and Zarzycki (1969) on spontaneous vegetation on an external tip of a sulphur mine in Piaseczno (southern Poland). A work by Krzaklewski (1977) included pioneering results on the possible use of spontaneous vegetation from succession as an indicator of potential habitat conditions on the slopes of Adamów Lignite Mine heap (central Poland). His source results allowed for the development a group of methods, the so-called phytosociological and soil diagnosis of habitat conditions in mine sites (Krzaklewski, 1977; Krzaklewski and Pietrzykowski, 2007).

From an ecological point of view, forest reclamation may be defined, as already mentioned, as the development process of the subsequent stages of succession which impact the future community. On this basis it may be assumed that the most harmonious restoration of soil and forest ecosystem happens by way of spontaneous succession. The use of this process for the purpose of reclamation may be regarded as a reclamation method based on cooperation with nature (Krzaklewski, 1988).

In this approach reclamation is to provide such development pace and trends to soil formation processes to achieve its rapid formation. In reclaimed areas soil restoration processes are accelerated by appropriate treatment, whereas in unreclaimed areas these processes occur spontaneously by way of natural succession. Analyses of changes in initial plant communities and in soils developing underneath are made possible by long-term studies on regular experimental plots or by reconstruction of their course in chronosequence.

Mine sites in temperate climatic conditions provide an interesting subject in the study of primary succession. It is possible to establish study areas on them with similar habitat conditions (in terms of climate, parent rock, hydrological relations and similar surface features), but of different age. Chronosequence may be recreated on the basis of documented mining progress or the time from the launch of reclamation treatments (Withman and Wali, 1975; Little and Ward, 1981; Daniels *et al.,* 1992; Leirós *et al*., 1996; Wali, 1999; Hüttl and Weber, 2001; West and Wali, 2002). Despite criticism of the notion of defining community chronosequence based on toposequence information as an alternative to long-term ecological research on succession (Pickett, 1987), it was used both for natural areas (inland dunes, glacial fields, lagoons and lake shores) (Dickson and Crocker, 1953; Syers *et al.,* 1970; Little and Ward, 1981; Burt and Alexander, 1996; Hobbie *et al.,* 1998; De Kovel *et al.,* 2000), as well as for mine sites (Anderson, 1977; Pietch, 1996; Wali, 1999; Pietrzykowski, 2008). The results of such research may be considered reliable, however, in the case of communities forming under the same habitat conditions but of a different age. The studies based on a reconstruction of the chronosequence provide data on the changes occurring in the soil, because the factors that play a role in the formation of soil change relatively slowly. It may be assumed that within certain limits, for instance of several years, factors such as the low variation of bedrock and the fluctuations of the water table may be offset by the time factor (Syers *et al*., 1970).

RECLAMATION EFFECT ASSESSMENT BASED ON VEGETATION CHARACTERISTICS

An important indicator for assessing the output conditions of biological reclamation and its progress is vegetation which spontaneously appears in such areas (Krzaklewski, 1988). Plants in the areas under reclamation treatment act as bio-indicators because their presence (absence) and response (of individuals in the population) indicate the intensity of the ecological factor. The occurrence of plants in a given area is determined by factors such as the availability of water, temperature, solar energy, availability of nutrients and interactions. Every plant species has specific requirements from the environment. For this reason, vegetation have long been used as an indicator of habitat conditions, *e.g.,* by Ellenberg (2009, reprint from 1965) including in environmental engineering practice (Begemann and Schiechtl, 1986) and for reclaimed mine sites as an indicator of the success of reclamation (Krzaklewski, 1977; Wolf, 1987; Krzaklewski and Pietrzykowski, 2007). Spontaneous appearance of vegetation on wasteland provides information not only about wasteland habitats, but also gives an indication of trends in habitat conditions, which is important for mine sites where soil properties frequently undergo dynamic changes (Pietrzykowski, 2014). Various possibilities for using vegetation from succession in the reclamation treatment were presented in detail by Krzaklewski (1993) and Krzaklewski and Pietrzykowski (2007).

Biodiversity which refers to the abundance of vegetation is an important element in the ecological characteristics of plant communities. The number of species is taken to represent the community abundance and the number of life forms, the number of growth forms, the number of taxonomic groups and life strategies are a measure of diversity. However, community species diversity is analysed in comparison to various environmental factors. Environmental indicators such as overall diversity index H and dominance index C (provided by Shannon and Weaver in, 1963) and evenness index J (according to Pielou, 1975) are used to assess the abundance and spatial diversity of communities (Begon *et al*., 1996). These indicators are calculated on the basis of frequency, abundance and population density of each species. The ecological value of the restored ecosystems is indicated by the occurrence of rare and protected species. These indicators were also used for mine sites (Wali, 1999; Pietrzykowski, 2008). In order to assess forest ecosystem succession in the reclamation process it is also important to list the share and the number of species characteristic of classes of forest and non-forest community associations and the so-called ecotones. To assess phytocenosis emerging on reclaimed sites, the size of community biomass was also used as it may be a measure of habitat productivity (Pietrzykowski and Krzaklewski, 2007a; Pietrzykowski and Socha, 2011).

In the process of succession in mine sites there is usually an increase over time in phytocenosis diversity expressed as Shannon's H index (Wali, 1999; Pietrzykowski, 2008). Similarly, in the early stages of the vegetation synanthropisation process, there is a marked increase in floristic diversity, but over time impoverishment of communities occurs and their subsequent take-over by a small group of species. There is still insufficient data on direct comparison of communities in mine sites with ecosystems similar to "natural" ones. In the course of comparative studies on a sand mine open cast in southern Poland (Pietrzykowski, 2008) it was found that the values of Shannon H diversity indicator for the oldest communities on areas left for natural succession and those undergoing reclamation treatment were similar to values reported for forest communities in coniferous forest habitats.

One of the possible criteria for the assessment of ecological succession to forest communities on reclaimed land may be an increase over time in the number of species characteristic of forest associations. In principle, it should be progressive, but sometimes over a longer time interval, both the total number of species and of species belonging to forest associations on reclaimed land may fall, sometimes it may remain constant for a long time, or even regress in extreme cases. Such dynamic changes are characteristic of phytocenosis in stages of initial formation of phytosociological relations (Wolf, 1987).

The occurrence of rare species of plants in biocenosis generated in the process of succession such as orchids on Poplar plantations (Adamowski and Conti, 1991) or reclaimed mine sites (Pietrzykowski, 2008) is a well-known phenomenon in anthropogenically altered sites. It is favoured by diverse microhabitat conditions of these areas, dependent on lithology and the way in which overburden is managed. Often, as a result of non-selective depositing of different geological formations, planned or accidental fluctuations in water conditions in soils, a mosaic of habitats appears on mine sites and this leads to a mosaic of plant communities (Bauer, 1970; Glenn-Lewin, 1979; Pietrzykowski, 2008).

The resulting mosaic of communities may be successfully used as an element increasing the biodiversity of communities and the ecosystem. There are different possibilities of applying the process of ecological succession in reclamation and notions concerning the inclusion of communities formed in such a process in the restored ecosystems. Ways of managing ecological succession in mine sites have been also indicated (Krzaklewski, 1977; Krzaklewski, 1993; Luken, 1990). In the 1990s, Szczakowa Sand Mine open cast (in southern Poland) launched a novel method of forest reclamation by Krzaklewski (Pietrzykowski and Krzaklewski, 2009) involving the use of vegetation obtained by way of succession. The first stage of preparatory works included mapping of vegetation from succession which appeared on the site abandoned for several years after the termination of mining. This was followed by a study of soils, groundwater depth; later a map was made of potential habitats with varying degrees of abundance and vegetation cover with dominant species. Reclamation treatment for selected groups was planned based on such material. An example is a group of areas with no vegetation or with herbaceous vegetation cover of <50% (herbaceous communities with *Corynephorus canescens*). This group was scheduled for a full cycle of reclamation treatments including organic matter addition, the introduction of legume plants and mineral fertilisation. Next, a group of areas was identified with vegetation cover from 50 to 75%. This group was scheduled for a series of partial reclamation treatments: fertilisation and legume green manure (as above), but no organic matter addition. For areas with vegetation cover >75% (areas dominated by communities with a predominance of *Calamagrostis epigejos* and *Poa compressa* with aq cover of herbaceous vegetation from 75% to 100% and >50% in the shrub and young tree layer (*Pinus sylvestris, Betula pendula, Populus tremula, Salix caprea*), with individual examples of *Pinus sylvestris* and *Betula pendula* in the tree layer, only NPK mineral fertilising was planned. A further selected group consisted of areas with vegetation characteristic of coniferous forest habitat with a cover of >50% in the tree layer, >25% in the lower layer (shrubs) and >75% in the herbaceous layer, the only scheduled treatments involved the regulation of woody species composition (removal of trees in overly concentrated biogroups and planting in the resulting gaps). A separate category selected for reclamation were areas which included wetlands located along the watercourses (drainage channels) and in areas with high levels of ground water (about >40 cm). Such areas were included as an important element enhancing the biodiversity of the restored ecosystems and a habitat of rare species. The discussed method was successfully implemented in the area of 257 hectares on the open cast of Szczakowa Sand Mine (Upper Silesia Region, southern Poland) (Pietrzykowski and Krzaklewski, 2009).

RECLAMATION ASSESSMENT ON THE BASIS OF SOIL FORMATION DYNAMICS, SOIL ORGANIC MATTER, C AND N ACCUMULATION AND SOME EXAMPLES OF MINE SOILS CLASSIFICATION

Soil is an integral and essential part of any terrestrial ecosystem. According to the generally accepted definition, the soil is defined as a natural formation of the top layer of the earth's crust, made of rock weathered as a result of long-term impact of living organisms and climatic factors under specific surface features (Jenny, 1980; Kovda and Grishina, 1984). One of the main tasks of reclamation and restoration of terrestrial ecosystem is to restore the soil (Hüttl and Bradshaw, 2000; Johnston and Crossley Jr. 2002).

From the cognitive point of view on mine sites it is possible to conduct research into the processes which shape plant communities and soils in primary succession, including comparative studies between reclaimed and non-reclaimed areas (Anderson, 1977; Pietrzykowski, 2008).

Time is a key factor in soil formation. From the time scale necessary for the formation of natural soils it is difficult to draw far-reaching conclusions about soils forming on mine sites regarding changes in their properties, classification and development of soil-forming processes. In natural conditions, the youngest, several-year-old soils occur in alluvia and new outcrops (*e.g.,* due to landslides) and the oldest soils in low latitudes date back to the Tertiary period. In the literature there is a concept of soil "maturity", indicating relative stability of soil made of bedrock in given climatic conditions (Jenny, 1980). Data provided in literature on the time required for young soils to assume the features of developed soils differ largely. For example, the time required to produce Podzolic soil with a 10-cm humus horizon is estimated to be 1000 to 1500 years. On the other hand, there are views that even 5,000 years after Podzolic soil has formed, differentiation of the profile is not complete (Kovda and Grishina, 1984).

Parent rock is one of the key factors in soil formation and its properties determine the extent and trends in soil-forming processes which take place in the presence of other factors. It is subject to many physical and chemical transformations. In the case of young soils, which include anthropogenic soils, in the early stages of development soil-forming processes are dominated by the type of soil-forming material which determines the main trends in soil formation. Other stages of soil formation in mine sites depend mainly on grain size, mineral composition of parent rock and only then on the impact of the introduced vegetation which plays a much bigger role in natural habitats and soils. However, it is known that the role of vegetation introduced in the course of biological reclamation is an important stimulator of the first phase of soil formation, especially in barren soils. In the case of land reclaimed for forestry it is only with the development of plant communities, especially phytocenosis dominated by trees, that the quantity and quality of organic precipitation reaching the forest floor and later development of organic (humus) horizons in the soil depend on the species composition of the introduced tree stands (Węgorek, 2003; Katzur and Haubold-Rosar, 1996; Pietrzykowski, 2008). Diversification of soil horizons on reclaimed land is a much longer process than changes in the chemical properties of initial soil. The latter take place in the early years and are often rapid in character. Currently, the oldest recorded age of soils formed in mine sites with more organised and large-scale operation where scheduled reclamation treatment was conducted is a little more than 100 years. Probably the oldest scientific association in Europe involved in greening tips and other industrial wasteland was the Midland Reafforesting Association established in 1903 (Pietrzykowski *et al*., 2010). At the beginning of the twentieth century reclamation was carried out in Australia, Germany and the U.S. (Anderson, 1977; Bell, 2001). The earliest attempts at reclaiming sand mine open casts, for example, in Poland date back to 1929 (Pietrzykowski *et al*., 2010). However at the time there was no legislation or organised reclamation treatment. Sand mine open casts were not shaped following the close of operation, drainage networks were not provided prior to biological reclamation. Also older mine sites are known, sometimes even dating back to the Neolithic era, where studies were conducted on the relationships between secondary soil cover and vegetation (Adamczyk, 1962).

Opencast mining undoubtedly significantly affects the transformation and distortion of surface features, hydrological conditions and the entire landscape, but it also provides new opportunities to shape the environment (Häge, 1996; Hüttl and Bradshaw, 2000). Soils forming in the contemporary times on mine sites (*i.e.,* open casts and tips) may be classified as Anthropogenic soils, *Spolic* and *Urbic* soils with a poorly developed profile. According to the classification of the World Reference Base for soil resources (FAO and ISRIC, 2006), soils with an accumulation of more than 35% (vol.) of anthropogeomorphic soil material are classified as Anthropic Regosols with *spolic* diagnostic horizon (in the case of waste materials from industrial activities such as material from mine workings, construction of roads, *etc.*), or with *urbic* diagnostic horizon (in the case of earth mixed with construction rubble and similar type of waste). According to FAO-UNESCO soil classification (FAO and ISRIC, 2006) mine soils in post-mining areas may be considered as *Urbic* Anthrosols and had poorly developed organic mineral initial horizons (A) and initial horizons of forest litter (Oi) and partially decomposed organic layers (Oe). According to USA Soil Taxonomy (USDA-NRCS, 2010) the soils were all Typic Udorthents with O-A-C horizon sequences. More options are provided by the German soil classification Bodenkundliche Kartieranleitung (BK) (2004) where soil names take into account the causative factor. To provide an example, soils formed from made ground are referred to in BK 2004 classification as “Lockersyrosem” (in German “locker” means loose).

A more extensive classification of anthropogenic soil forming substrates taking into account their properties, stability over time and changes to the environment, with emphasis on anthropogenic operations as a factor involved in the formation and transformation of soils, was presented in a paper of the Working Group on Urban Soils of the German Soil Science Society (Arbeitskreis Standtboden der DBG) (Burghardt, 1996). The classification distinguishes substrates according to how they are deposited including made and mined soil (railway embankments, streets, banked land), “tipped” soil (this includes post-mining sites and mine tips), water storage sites (including liquid waste storage sites, settlement ponds, dust landfills), casting (former smelting sites, tips) and others, relating to the different types of soils in urban, construction and investment areas. Further on, substrates were divided according to the impact of anthropogenic material on the soil: additives, fertilisers, pollutants, banked layers of foreign material covering the soil and material separating genetic horizons of soils.

A simplified classification of the so-called “technogenic” materials which constitute anthropogenic soil substrate was provided for the practice of Soil Science and the needs of the urban environment protection by Hiller and Meuser (1998). According to this classification, the substrates were divided into construction rubble, slag (blast furnace, metallurgic and smelting), dust and ashes (including from the combustion of coal in power plants), mining substrates and coal (including materials from tips), municipal waste and residues (sewage, municipal and others).

Classification of mine soils in sand mine open casts was proposed by Pietrzykowski (Pietrzykowski *et al.,* 2010); this was followed by classification for most substrates of mine sites in Central and Eastern Europe. In sand mine open casts (Pietrzykowski, 2008) soils from areas which had undergone natural succession were considered as a subtype of initial Arenosols and Industrial and Urban soils with undeveloped profile while on reclaimed areas they were regarded as only one subtype, that of industrial and urban soils with undeveloped profile. The study pointed out that also in mine sites, in case of soils in areas which had undergone natural succession, anthropogenic subtypes may be distinguished, but also soils with characteristics similar to subtypes of natural soils (*e.g.,* Arenosols, Regosols). This approach resulted from the need to emphasise the dual baseline for the development of soils. Although in both cases the main modifying factor was anthropogenic operation, in one of them mining had terminated without compromising the natural sedimentary structure of layers constituting bedrock for the developing soils (classified as Arenosols), while in the other case, the anthropogenic factor was clear and decisive because the natural structure of parent rock had been disturbed (Pietrzykowski, 2008). In the case of soils forming in reclaimed areas, the degree of anthropogenic interference was obviously much bigger and associated with reclamation treatments. Distinguishing this variety was justified in some cases of the investigated soils in sand mine open casts where ground water is a very important factor in the soil formation process and the development of gleying is associated with heavier, poorly permeable horizons (Pietrzykowski and Krzaklewski, 2006). Initial soils forming underneath communities from succession on boulder clay associated with lignite open cast mining in Saskatchewan in Canada (Anderson, 1977) were classified as Regosols and Entisols (Regosols and Entisols according to WRB classification (FAO and ISRIC, 2006). Similarly, Néel *et al.* (2002) classified soils on reclaimed mine sites with a developed A-C profile as Entisols. Initial soil developing from heavier sediments (clays) in the reclaimed lignite tip in Lower Lusatian Basin were classified according to FAO-UNESCO (FAO and ISRIC 2006) classification as Regosols (Katzur and Haubold-Rosar, 1996) and the soils developing from loose sands were considered to be anthropogenic soils (*Urbic* Anthrosols). According to the German classification (BK, 2004) these soils were considered to be subtype "Lockersyrosem Kipp aus kippreinsanden" (Hartmann *et al*., 1999; Schaaf, 2001). The morphology of these soils sometimes distinguished the top layer of overburden obtained earlier from agricultural soils covering the area before the onset of mining. In the case of soils on mine and industrial sites where the soil forming process has not started yet, literature applies the term (mentioned on the occasion of the classification of anthropogenic soil substrates, (Hiller and Meuser, 1998)) "technosoils" (Jochimsen, 1996) and the term "mine soils" to generally refer to soils restored on mine sites in the process of reclamation (Leirós *et al.* 1996). Pietrzykowski (Pietrzykowski *et al.,* 2010) proposed a classification based on the level of profile development, *i.e*., soil with an undeveloped profile (Urbic Anthrosol, according to FAO classification 1988/2003) (FAO and ISRIC 2006), variety of mine soil, tip (depending on the type of post-mining facility: above-ground tips or excavation cast, which is important for the type of water management), next due to grain size loamy-sand, sandy loam, *etc*. are added depending on grain size. This classification is most appropriate for the requirements of forestry where features crucial for the survival of the introduced trees (origin of sediments, physical features of the site and the related water management) are described in the name of the type, subtype and variety of soil.

The development of humus horizons and carbon accumulation rate are some of the basic criteria for classification allowing considering soils on reclaimed sites as soils as the term is generally understood. The thickness of the organic and mineral horizons and the content and rate of accumulation of organic carbon and nitrogen and C:N ratio (organic carbon and total nitrogen) are also, like in the evaluation of initial natural soils, the criteria in the assessment of the soil formation process in mine sites (Wali and Freeman, 1973; Anderson, 1977; Prosser and Roseby, 1995; Cherr *et al.,* 2006; Schaaf, 2001; Pietrzykowski and Krzaklewski, 2007a). Organic matter plays an important role in the early stages of initial soil formation on mine sites and is an important indicator in the assessment of the success of reclamation (Roberts *et al.,* 1988; Rumpel *et al.,* 1999; Ellerbrock *et al.,* 1999; West and Wali, 2002; Pietrzykowski and Krzaklewski, 2007a). As previously shown, the quantitative and qualitative features of the organic matter like in the case of natural soils significantly affect changes of other properties of initial soils on mine sites including the cations exchange capacity (CEC), field water capacity, microbiological and biochemical properties (Insam and Domsch, 1988; Leirós *et al*., 1996; Wali, 1999).

In conditions of natural forest ecosystems and timber managed forests which are not heavily impacted by industry, the properties of the organic horizon and type of humus are always clearly related to the species composition of tree stands and in the process of forest ecosystem succession, the formation of organic horizons is clearly linked to the development of these plant communities. For example, in studies of the process of forest succession on the inland dunes the formation of a defined debris horizon (with a thickness of 3 cm) at the earliest on sites aged 43 years under stands dominated by the pine tree (De Kovel *et al.,* 2000). In cold climates in the zone of glacial fields of Alaska a defined organic horizon was reported in initial soils under communities from succession aged 38 years (Burt and Alexander, 1996). In abandoned open casts following the mining of sand and gravel sand in Virginia (USA) it was found that reclamation treatments (the use of potentially fertile mineral deposits, composting, fertilising and liming) resulted in a clear differentiation of organic soil horizons as early as in the age range from 5 to 10 years (Daniels *et al*., 1999).

The increase in the thickness of organic-mineral horizon over time was observed, *e.g.,* under developing pine tree stands on sandy land reclaimed in Lower Lusatia Basin Mine District (Rumpel *et al*., 1999). The thickness of Ai horizon cited in German studies reached 2 cm at the age of 11 years and 5 cm at the age of 32 years. On a tip in Piaseczno (southern Poland) the thickness of organic-mineral horizons was on average 10-12 cm in sands after 30 years and 5 cm in clay (Węgorek, 2003). In reclaimed areas of open casts following the mining of mineral sands in Florida, U.S., the formation of an initial horizon of humus accumulation of 0.5 to 5 cm was found already in 10-year-old soils, however the rate of increase in thickness correlated positively with the grain size composition of soils and to a lesser extent with age (Daniels *et al*., 1992; Bendfeldt *et al*., 2001).

The properties of top soil horizons including the type and subtype of humus are considered as readily variables components in the assessment of forest habitats (Krzaklewski and Pietrzykowski, 2007; Pietrzykowski, 2014). In the case of habitats on mine sites, it is difficult to determine clearly the type and subtype of humus (in natural forest soil as the organic horizons subsequence) at the current stage of soil formation. Soils that are in initial development stage contain ecto-humus which most frequently resembles *semimor* (*mor* in the development stage) or initial *moder*. The OL leaf litter horizon is usually clearly developed as is sometimes the initial Of horizon. The OLf symbol is most frequently proposed for ecto-humus horizons of mine soils (Pietrzykowski and Krzaklewski, 2007c; Pietrzykowski *et al.,* 2010). Rumpel *et al*. (1999) reported that *mor* type humus with L/Of horizon occurred under 32 year old pine tree stands introduced in the course of reclamation on sandy soils of Lower Lusatia Basin and *moder* type humus on sites aged from 11 to 17 years. In dense stands, (*i.e*., since the development phase of young forests), the species composition is first when it comes to the impact on humus properties. It was found that, like in the case of natural conditions, what impacts the processes of organic matter mineralisation and humus formation most beneficially are multi-species tree stands rather than monocultures, especially of conifers such as the pine tree (Heinsdorf, 1996).

It follows from literature data on diverse mine sites that the percentage and total accumulation of carbon in the soil like in the case of primary succession is of progressive nature. For instance, in the Lower Lusatia Basin Mine District (Germany) reclaimed land was reported to have a significantly higher content of organic carbon in the upper organic and mineral horizons of soils forming on coaly sediments under pine tree stands and was 6.5% at the age of 32 years (Rumpel *et al.,* 1999). Such high carbon content in initial soils on lignite tips may be associated with the presence of carbon of geological origin. Following studies on a tip in Piaseczno (southern Poland), Węgorek (2003) reported the carbon content in sandy soils after 30 years from the start of the reclamation treatments of less than 0.4%, highlighting the dependence of the carbon content on mechanical soil composition. In studies conducted in Spain, 3.0% organic carbon was reported for upper horizons of initial soils as early as 5 years from the beginning of reclamation (Varela *et al.*, 1993).

Given the percentage content of carbon in the soil and the horizon thickness it is possible to calculate the total organic carbon accumulation and estimate its average pace. This makes it possible to determine both the rate of soil formation, as well as to assess the potential of carbon dioxide (CO_2) sequester of mine soils (Shrestha and Lal, 2006). According to comparative studies carried out in Szczakowa Sand Mine open cast on the evolution of soils and plant communities in the process of succession and in the course of complete reclamation, it was clearly indicated that reclamation increases the accumulation of humus in the soil. It was found that after 25 years soil in sites where natural succession took place accumulated about 9.0 $Mg \cdot ha^{-1}$ of organic carbon and soils on reclaimed sites approximately 14.5 $Mg \cdot ha^{-1}$ (Pietrzykowski and Krzaklewski, 2007c). Studies conducted on inland dunes in the Netherlands under initial communities from succession aged 5 years provided the value of carbon accumulation in endohumus at 6.0 $Mg \cdot ha^{-1}$ and under a 120 year old mixed forest of 104.0 $Mg \cdot ha^{-1}$ (De Kovel *et al.*, 2000). In case of forest habitats on organic and organic-mineral horizons of Podzolic soils developing on boulder and glaciofluvial sands, the amount of the accumulated soil organic carbon (SOC) can be estimated at about 76.0 to 122 $Mg \cdot ha^{-1}$, whereas in the case of Podzols developing on eolian sands at about 126.0 $Mg \cdot ha^{-1}$ (Pietrzykowski, 2010b).

Upward trends of organic carbon accumulation over time were observed in sites with natural succession in the North Dakota coal basin in the U.S. and the rate of accumulation of carbon amounted to 131 $kg \cdot ha^{-1} \cdot yr^{-1}$ (Wali, 1999; West and Wali, 2002). Anderson (1977) reported the organic carbon accumulation rate from reclaimed sites of 282 $kg \cdot ha^{-1} \cdot yr^{-1}$ and Schafer and Nielsen (1979) of 256 $kg \cdot ha^{-1} \cdot yr^{-1}$. The research carried at Szczakowa Sand Mine open cast indicates that the rate of carbon accumulation in endohumus horizons of initial soil averaged 186 $kg \cdot ha^{-1} \cdot yr^{-1}$ under the communities from succession and 296 $kg \cdot ha^{-1} \cdot yr^{-1}$ under the tree stands introduced in the course of reclamation (Pietrzykowski, 2008). Assuming that the organic carbon accumulation rate in developing soils remains steady at the above level, it may be fairly accurately estimated that the volume of carbon stock in soils under communities from succession would reach a state similar to the stock of carbon accumulated in Podzols in about 350 years, whereas in the case of soils on reclaimed sites this would be in about 250 years. Of course it is difficult to predict the dynamics of carbon accumulation in the future, as it depends on many variables, however similar results were obtained on the basis of a model of carbon accumulation in soils in the communities from succession on a lignite open cast in the U.S. prairies. In these studies, it was estimated that mine soils would reach carbon accumulation comparable to natural soils of adjacent areas in approximately 250 to 300 years (West and Wali, 2002).

Although a key objective in carbon management research is to enhance the natural capacity and ability of plants and soils to sequester carbon in terrestrial ecosystem developed on post-mining site is still poorly understood. In current studies by Vindušková and Frouz (2012) meta-analysis and other statistical methods on data from 93 temperate post-mining sites in the Northern Hemisphere were used. These studies deal with data collected on different ecosystems, that had been revegetated by forest or grassland either by reclamation or natural succession and the rate of SOC accumulation in relation to site age and vegetation type were described. However, this study was the first to summarize SOC accumulation rates in post-mining soil of the northern temperate zone, there was still data gap for and analyzes at different soil-substrate and analyzes of plant/soil relationships and estimation for whole post mine new ecosystems are needed.

Nitrogen is another nutrient the accumulation of which is associated with the development of organic horizons and accumulation of organic matter in the process of pedogenesis on reclaimed sites. According to the literature, in the case of soils developing on reclaimed sites, nitrogen is scarce and the pace of its accumulation may be significantly impaired (Leirós *et al*., 1996). The rate of nitrogen accumulation in mine soils developing under communities from succession on lignite tips (U.S. prairie zone) was estimated at about 24 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$ in the first 17 years and even 36 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$ up to the age of 30 years (Wali, 1999). However, then a decrease was observed in the rate of nitrogen accumulation to about 16.2 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$. Similar trends were also observed by Anderson (1977) in studies from Canada (the part with cold continental climate). Lower rate of nitrogen accumulation (14.8 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$) for organic and mineral horizons in mine soils (in North America) was provided by (Schafer and Nielsen, 1979). According to the studies conducted in Poland in Szczakowa Sand Mine open cast (Pietrzykowski and Krzaklewski, 2007c) the rate of nitrogen accumulation in the soil (globally in organic and organic-mineral horizons) in the communities from succession was estimated at about 17.6 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$ (on average over 25 years) and in the case of reclaimed sites much more, *i.e.,* about 40 $kg{\cdot}ha^{-1}{\cdot}yr^{-1}$. The extremely beneficial impact of lupine green manure (yellow lupin crop *Lupinus luteus* L.) and mineral fertilisation on high nitrogen accumulation in the early years at biological reclamation phase was emphasised.

Another indicator in the assessment of soil-forming processes in mine sites is the ratio of organic carbon to nitrogen (C organic-N total-ratio). It is a useful indicator in assessing the dynamics of changes which occur in the restored soil environment such as the intensity of transformation processes of organic matter of the soil, the rate of mineralization of organic matter and availability to plants of nitrogen released during the decomposition of organic matter in the soil (Janssen, 1996). At high C organic-N total-ratio (more than 33) stocks of mineralised nitrogen may be consumed by soil microorganisms and consequently the accumulation of inorganic nitrogen can be inhibited. In case of newly deposited sediments where the process of soil formation has only just begun, the phenomenon may occur from time to time (Wali, 1999). In the case of mine soils, a high C-N ratio may also be associated with decreased decomposition of biomass produced by the pioneering plant communities (Schafer and Nielsen, 1979).

An important criterion for assessing the development of soil organic matter (SOM, humus) is its fractional composition. With humus in initial organic and mineral horizons of soils on reclaimed sites, the share of carbon associated with humic and fulvic acid groups in relation to carbon in the soil after the extraction is of significant importance. It provides indirect information about the progress and advancement of the humification processes of organic matter over time (Kononova *et al.,* 1961). An increase in organic matter decomposition rate in soils of progressing age was found in the reclaimed lignite tips in the Lower Lusatian Basin Maine District (Rumpel *et al.,* 1999) and in soils developing on reclaimed Szczakowa Sand Mine open cast in southern Poland (Pietrzykowski and Krzaklewski, 2007c). Volume of optical density (extinction ratio at a wavelength of 465 and 665 microns) of humic acids, *i.e.,* Kh E_{465}: E_{665} was applied for the assessment of the development of the humification process of organic matter in mine soils (Anderson, 1977; Wójcik, 2002; Pietrzykowski and Krzaklewski, 2007c; Pietrzykowski, 2010c). Determination of optical density may be useful in the assessment of the condensation process of humic acid aromatic rings, which in turn indicates their progress at the time of their structure expansion (Kononova *et al.,* 1961). To provide an example, a comparison of Kh E_{465}:E_{665} of soils developing in Szczakowa Sand Mine open cast in the age groups on reclaimed and unreclaimed sites indicated that after 25 years, the progress in the development of humic acids structure was similar for both site categories (Pietrzykowski and Krzaklewski, 2007c). Similar progress in the development of humus, determined by the ratio of Kh E_{465}:E_{665} was observed in mine soils in the cold continental climate (Canada) even following 28 years (Anderson *et al*., 1974) for humus in initial soils on reclaimed lignite tips.

What is of great importance in the determination of soil biological efficiency in forest habitat studies is the rooting depth (Pietrzykowski, 2008). It is a feature which distinguishes in vertical section the pedogenic and the saprolite zones, *i.e.,* the depth below which the impact of living organisms and organic matter disappears. It could also constitute an important factor in assessing the development of soils in mine sites (Fabijanowski and

Zarzycki, 1969; Anderson, 1977). Typically, an increase in the depth of the rooting zone over time is reported in mine sites (Daniels *et al*., 1992; Pietrzykowski, 2008). This criterion may however be used primarily for facilities such as open casts or tips, with a relatively high degree of homogeneity of the sediments composing the sill (*e.g.,* sand mine open casts) (Pietrzykowski, 2008). As in the case of other criteria for the assessment of the effects of reclamation which have already been mentioned and are based on soil properties, it is the particle size and the degree of soil compaction which determine the root depth. In the case of toxically acidic sediments subjected to neutralisation, an additional significant role for the rooting depth is played by neutralisation depth (Anderson, 1977; Daniels *et al.,* 1992; Katzur and Haubold-Rosar, 1996).

ASSESSMENT OF RECLAMATION AND STATUS OF DEVELOPED ECOSYSTEMS BASED ON NUTRIENT ACCUMULATION AND NUTRIENT MUTUAL RELATIONSHIPS BETWEEN PLANT AND SOILS

Referring to the environmental definition of reclamation, we conclude that the condition for its success is the efficient circulation of matter, *i.e*., the exchange of nutrients between soil and vegetation and other elements of the biocenosis (zoocenosis). Inanimate elements of the ecosystem (the biotope) are made up of chemical compounds (mineral and organic substrates), whereas plant (phytocenosis) and animal communities (zoocenosis) are animate elements of the ecosystem (biocenosis) (Krebs, 2001). In the course of reclamation all the factors affecting a smooth functioning of ecosystems are shaped from the beginning like in the process of primary succession (Wali, 1999). Reclamation processes clearly stimulate the accumulation of organic matter as well as nutrient and energy accumulation in the ecosystem (Pietrzykowski and Krzaklewski, 2007a; Pietrzykowski, 2010a). In this context the question also posed in this work may be asked: "When do restored ecosystems become fully self-sufficient and stable ecosystems?" (Bell, 2001; Bendfeldt *et al.,* 2001; Hüttl and Bradshaw, 2000; Knoche *et al.,* 2002; Pietrzykowski and Krzaklewski, 2007a).

The tree stand is an animated element of the forest ecosystem which most radically modifies the developing environment (microclimate, lighting and biochemical conditions) for other organisms which appear by way of natural succession. The health and growth of tree stands introduced on the reclaimed sites is directly dependent on the potential of the substrate (parent rock) of the developing soils to meet their nutritional needs as they increase gradually along with an increase in biomass. An impaired nutrient circulation cycle, inadequate proportion of organic matter formed *in situ*, which in natural conditions provides a significant reservoir of nutrients in a process of "self-nutrition" of forest phytocenosis (Baule and Fricker, 1970) and occasional presence of sources of phytotoxicity in soils formed on reclaimed mine soils constitute the main differences between ecosystems developing on mine sites and natural forest ecosystems (Pietrzykowski, 2010a; Pietrzykowski *et al.,* 2013).

The starting point for the assessing of nutrient exchange efficiency between the components of the ecosystem (including mainly vegetation and the soil) should be to identify their resources and the quantitative ratios between them. Thus, one of the ecological criteria for the assessment of the progress of reclamation may be nutrient accumulation in the restored bioecological system and more specifically the ratio of the nutrient amount in the vegetation biomass to the quantity available in the soil. A subsequent step is an analysis of the quantitative ratios of nutrients present in the soil in the forms available to plants to resources of these elements in general form as well as nutrient resources of initial organic horizons to resources in mineral horizons (Pietrzykowski, 2010a).

The potential of developing mine soils to meet the nutritional requirements of plants (fertility) depends on the share of nutrients in forms available to plants (the following exchangeable forms are considered as such: Na^+, K^+, Ca^{2+}, Mg^{2+} and the following available forms: K_2O, MgO, P_2O_5) in the total stock of a given element present in the total form. In the organic horizons, these values depend directly on the rate of decomposition and mineralisation of organic matter forming *in situ* and mineral horizons depend significantly on the rate of weathering of minerals contained in the substrate. As already mentioned, in natural habitats, especially in oligotrophic Podsol; soils characterised by low abundance but high biological efficiency, the main source of nutrients is to be found in the organic levels and is gradually released in the process of mineralisation (Baule and Fricker, 1970). This is essential for nutrition of the tree stands as low content of nutrients in the soil may be compensated by rapid biological circulation of elements. Humus soil, although still in the initial phase of accumulation also plays an important role in the nutrition balance of tree stands on reclaimed sites (Pietrzykowski, 2010a).

It may however be supposed that the mechanism of nutrient sorption, for example, by pine phytocenosis on tips has different dynamics than in natural habitats. Investigating the correlation between the nutrient accumulation in the soil and the supply of nutrients accumulated in phytocenosis biomass may indicate a model of relationships between the soil and vegetation in the stimulated by reclamation process the formation of the ecosystem in the mine tips (Pietrzykowski, 2010a). This may be of help in the stability assessment and forecast of afforestation introduced as part of the reclamation treatments on mine sites (Pietrzykowski *et al*., 2013).

BALANCE OF RECLAMATION ENERGY EFFICIENCY

The use of solar energy flux flowing through the ecosystem in the process of photosynthesis and biomass production is a measure of balance and functioning of such an ecosystem. The area where natural environment and productive problems overlap from the point of view of the energy balance is the cost of operation of the trophic chain and determination of the final product which in forestry may be tree mass, but also by-products and recently also non-productive functions.

The energy balance of forest ecosystem indicates that respiration intensity constantly increases with age of tree stands, whiles the gross production at first increases very rapidly and reaches a peak, then decreases slightly, levels off and remains constant. Net production (corresponding to the energy bound in the process of photosynthesis) first increases rapidly and reaches a marked peak, but then decreases as a result of the difference between the constantly increasing respiration intensity and constant gross production. In the case of mine sites it is difficult to predict whether the model developed for the natural forest ecosystems will work, as the data do not add up to a complete balance and the existing tree stands are mostly young (Fig. 2).

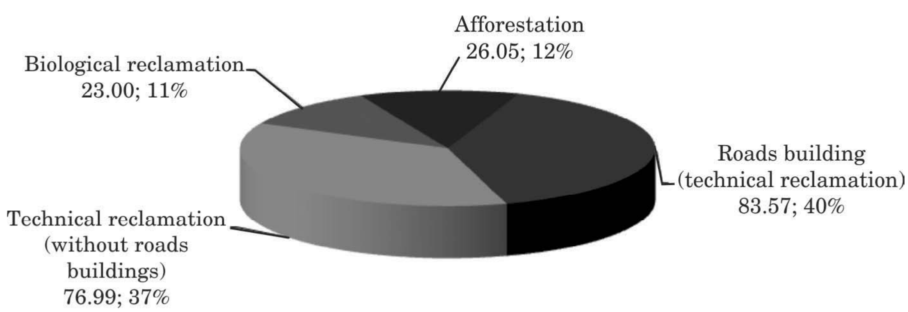

Fig. 2: Diagram showing the share of energy input in the implementation of the various reclamation phases in the total balance for a sample mine site (sand mine open cast, climatic conditions of Central Europe, Upper Silesia region). The provided value was 10^6 kJ ha^{-1} and the % share of a particular reclamation phase of in relation to total energy input amounting to 103.04 (10^6 kJ ha^{-1}), where the technical phase involves forming the floor of the cast, construction of drainage ditches, the biological phase - mineral fertilisation and 2 years legume cultivation as green manure; road construction – construction of necessary roads; afforestation - the introduction of forest plantations following the technical and biological phase) (based on Pietrzykowski and Krzaklewski, 2007a).

The main idea behind a comprehensive assessment of reclamation is to take into account both environmental and economic factors (Rodrigue *et al.,* 2002). A universal criterion in the assessment of reclamation may be the amount of energy accumulated in the developing ecosystem and reclamation energy efficiency (Pietrzykowski and Krzaklewski, 2007a).

Determination of reclamation energy efficiency is based on the calculation of the balance of energy input and gain and general level of energy accumulation in the ecosystem and its individual components (Fig. 3).

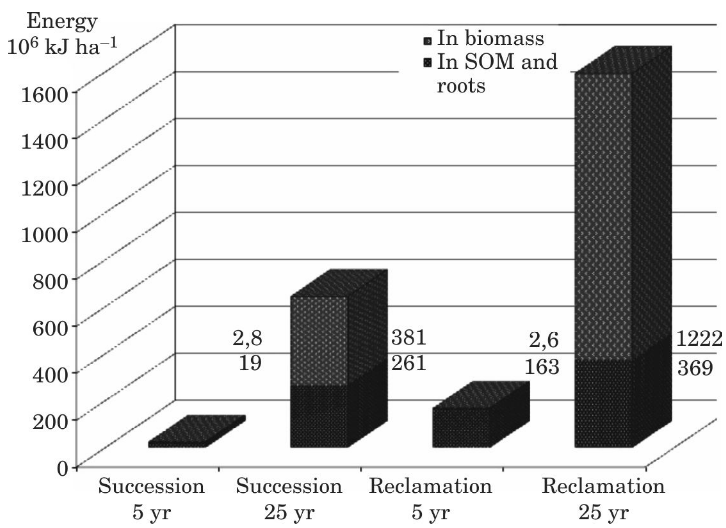

Fig. 3: The estimation of amount of energy associated with carbon in various parts of the developing ecosystems (SOM - soil organic matter, above-ground biomass and root biomass) as a result of reclamation and appearing by way of succession as seen on the example of a sand mine open cast (southern Poland, Upper Silesia Region). The data next to the bars represents, respectively, the above-ground and underground biomass of different ages plant communities (5 and 25 years) (by Pietrzykowski, not published data).

Energy accumulation and carbon content in the biomass of the individual biocenosis components makes it possible to characterise its organization from an individual to populations because it is then possible to reduce its basic differentiation to a single unit, *i.e.,* joules (J) or grams (g) (Krebs, 2001). The biomass produced by plants largely consists of cellulose and other polysaccharides whose elementary molecule is glucose. The stochiometrically calculated carbon ratio in molecular mass gives a factor to convert the produced organic matter mass into carbon and *vice versa*. Next, it is possible to convert carbon into glucose using a coefficient of 2.5. In turn, the amount of biomass produced, *i.e.,* carbon bound in the process of photosynthesis corresponds to the energy level bound in the process of photosynthesis and its equivalent is assumed at a level of about 17 to 21 kJ·g^{-1} dry weight depending on the diversity of its chemical composition, *e.g.*, varied lipid content. It seems that averaged values of this equivalent for plants containing mainly poly- and oligosaccharides as well as some protein of 20 kJ·g^{-1} dry weights are reliable. However, in case of carbon bound in the soil organic matter with a complex structure, a coefficient of 41 kJ·g^{-1} carbon is adopted in the ecology (Pietrzykowski and Krzaklewski, 2007a).

In the case of ecosystems developing on mine sites, the determination of energy accumulation in the ecosystem may serve as an indicator of the progress of its development in the course of reclamation. An assessment of the reclamation energy efficiency based on the balance of energy input and gain, calculated on the basis of carbon accumulation in the soil and in phytocenosis may pose interpretation difficulties due to the fact that the comparison of mechanical systems with self-supporting biological systems is a simplification, mainly because the natural ecosystems have very low primary efficiency while mechanical systems have relatively high efficiency (Odum and Barrett, 2005). In addition, the resource of accumulated carbon in the soil is subject to complex and time-varying cycles of circulation (Wali, 1999) and therefore, it is difficult to determine the energy status only based on the quantity of accumulated carbon in soil organic matter. Thus, in assessing the reclamation energy efficiency it is better to base calculations on community biomass. What is also important here is the fact that biomass can theoretically be treated as yield and converted into useful thermal energy (Bungart *et al.,* 2000). In addition, in ecological studies biomass size of vascular plant communities including the amount of biomass of trees representing the predominant share in forest biocenosis biomass, varies only a little in the growing season and may be estimated with sufficient accuracy based on dendrometric measurements and relevant empirical formulas.

In the conducted pioneering studies on the assessment of reclamation energy efficiency at Szczakowa Sand Mine open cast, a comparison was made of reclaimed sites and of those abandoned for natural succession to take place (Pietrzykowski and Krzaklewski, 2007a). The study demonstrated that forest ecosystems restored in the course of a complete reclamation, including technical development of biotope, biological reclamation and afforestation, significantly exceeded ecosystems forming by way of succession in parts of the open cast shaped in the course of technical reclamation with respect to the amount of energy bound in biomass and the soil (Fig. 3).

In fully reclaimed sites, the amount of energy accumulated in the aboveground biomass of plant communities after 25 years was about twelve-fold higher than the energy input in the course of reclamation treatments and reforestation, while on sites with succession approximately five-fold higher than the energy input in the course of biotope development by way of technical reclamation. On the basis of the obtained results, it was found that full reclamation, including the formation of the biotope, phytomelioration, agricultural practices and afforestation increases the amount of energy accumulated in the emerging ecosystem by about two-fold during the first 25 years from the commencement of reclamation (Pietrzykowski and Krzaklewski, 2007a).

CONCLUSIONS

Criteria for reclamation assessment of post-industrial areas depend on how the needs and objectives in the process of ecosystem reconstruction are defined, as well as on environmental conditions (mainly the climate and geological structure which affects the properties of the deposited substrates in the overburden from mines) and on deposition technology and construction of post-industrial facilities (selection of geological sediments, optimization of tip and open cast construction using the best possible sediments in the deposits, insulation of phytotoxic sediments). Obviously numerous ecological criteria for the assessment of reclamation success may be provided, including the diversity and structure of communities, productivity expressed as biomass and wood raw material increase, the dynamics of the soil formation process, particularly the quantity and properties of the accumulated organic matter and form of humus (organic soil horizon subsequence), carbon sequestration and its dynamics in various elements of the ecosystem, dynamics of element biogeochemical cycles and the flow of matter and energy in the ecosystem, as well as indicators of soil microbial activity. There are also economic - ecological criteria based on relationships of energy input and gain in the process of reclamation and accumulation in the ecosystem. The issue of the "quality" of the restored ecosystems in relation to the original ecosystems on lands prior to their being mined remains controversial; however, in view of the demand for energy and minerals, mine sites will continue to be appear and will need to be subjected to reclamation. It is therefore still of prime importance to improve the reclamation technology and the monitoring systems of newly developed ecosystems to mitigate the effects of mining.

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