Prediction of Vegetation Succession in Human-Disturbed Habitats Using an Expert System

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Abstract

Detailed information, both quantitative and observational, on the course of vegetation succession in various human-disturbed habitats in Central Europe was used to construct an expert system named SUCCESS. Using the system, it is possible to predict tentatively the sequence of seral stages and dominant species exchange in successional seres initiated on bare ground and lasting up to 50 years. Simple information on geographical position, type of substratum, relief, moisture, nutrient content, character of surrounding vegetation, and size of the disturbed area is taken into consideration to predict site-specific succession in the particular habitats. The expert system is supposed to help landscape managers, nature conservationists, and environmental impact assessment experts in decision-making procedures to take into account the development of vegetation in man-made sites. Moreover, it also summarizes scientific information on the pattern of vegetation change in human-disturbed habitats in the geographical area considered.

Introduction

The development of expert systems for application to restoration ecology is a potentially important area of research. The impetus for such a trend is that people with relatively little ecological or botanical training are often put in charge of complex restoration projects. Expert or consultation systems are tools that certainly can help them to make management decisions. Expert systems are easy to use and provide straightforward answers to simple questions (Luken 1990). For practical use, they are usually more efficient than mathematical models because they are based on a wide variety of information, including experiential, and not only on quantitative data and mathematically derived functions. In the application of the expert system technology, vague intuitive knowledge and precise quantitative information are combined (Noble 1987; Jackson 1990).

Spontaneous (without intentional human intervention) or managed vegetation succession plays, or potentially can play, an important role in restoration projects. But information on the course of succession in a particular situation is not usually available, and obtaining such information by a special research project is a lengthy process. Thus, an expert system summarizing knowledge on succession in various seres can help to arrive at an appropriate restoration scheme. The approach also makes it possible to integrate a substantial amount of detail on the seres and participating species in the form of supplementary comments, as well as various recommendations on management. We believe that expert systems such as described here would find a wide use in predicting succession in various habitats by practitioners involved in ecosystem restoration, landscape management, environmental impact assessment (EIA), and so forth. Repeated requests from practitioners for our consultations on the course of succession in various disturbed sites under their management were an important stimulus to our effort to construct the expert system.

Many successional sequences (seres) have been described in the literature, some of them in remarkable detail (Burrows 1990; Glenn-Lewin et al. 1992). In several cases, variability in one type of sere was studied over a large geographical area (Schafale & Christensen 1986; Osbornová et al. 1990). But little research has focused on analyzing the pattern of successional change in more seres over a large region. This approach was taken in our previous studies describing vegetation changes in 15 different seres in Central-European man-made habitats (Prach et al. 1993; Prach & Pyšek 1994*a*, 1994*b*; Prach et al. 1997). In these studies, spontaneous succession as a possible means of ecosystem restoration was emphasized, and we advocate the same approach here. Moreover, knowledge of spontaneous succes-

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sional processes provides a basis for directing succession (Luken 1990). Besides the seres observed in detail, we gathered a body of observational information on the course of succession in many other types of disturbed habitats throughout the region; the need to summarize the information also stimulated us to create the expert system.

Methods

Input Data

We used two kinds of information for the knowledge base of the expert system: data from detailed quantitative studies on particular seres and observational information obtained from our long-term field experience. In both cases, the main criterion for evaluating the successional changes was the exchange of dominant species during succession. The quantitative data were based mostly on studies in permanent plots located in differently aged, comparable seral stages in which species cover was estimated year by year by point-quadrat method, micromaps, or visual cover estimations in phytosociological relevés. The permanent plots were sampled for 12–22 years, depending on a particular sere. Some seres were described by unrepeated analyses of differently aged seral stages comparable in terms of site conditions. Methods and particular seres were described in more detail by Prach and Pyšek (1994*a*, 1994*b*) and Prach et al. (1997). The successional seres included in the expert system are listed in Figure 1, all running from bare ground to stages up to 50 years old. Within the range of these main successional types, more particular pathways were usually recognized as modified by local conditions.

Nomenclature of plant species follows Rothmaler (1986).

Structure of the Expert System

The CLIPS inference engine, as a part of the CLIPS expert system shell, version 6.04 (CLIPS 1993), was used as a core of the expert system named SUCCESS. It is embedded in a standard 16-bit application running on the Microsoft Windows™ platform, developed in C++ programming language.

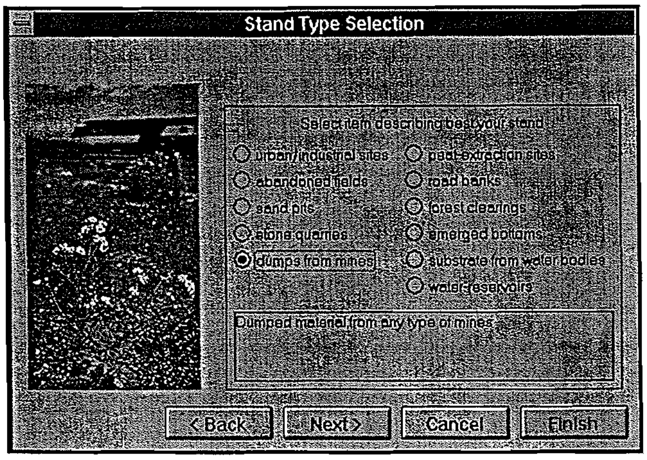
The user interface has the standard look and feel of the Microsoft Windows™ application. The functionality of the SUCCESS program is centered around the steps started by invoking the Setup Wizard. The questions asked by the Setup Wizard are as follows:

(1) *Geographical position.* To specify geographical coordinates and vegetation region, the user can click on the respective site on the map that appears in the window. Three basic types of vegetation regions are considered: warm regions in lowlands up to about 350 m above sea level (*thermophyticum*), cold mountain regions usually above 900 m a.s.l. (*oreophyticum*), and the remaining regions (*mesophyticum*). The terms represent phytogeographical classification described by Skalický (1988). The expert system was originally developed for the territory of the Czech Republic, but this simple classification of regions can be applied also in the surrounding central European countries.

(2) *Stand type.* The user is asked to select one of the stand types available in the SUCCESS program (Fig. 1). The selection made here determines which of the following wizard pages are displayed, considering pre-selected information and possible disabled values. The disabled values for a selected stand type may be those that cannot occur or that are so infrequent that no information is available.

(3) *Nutrient status.* There are two possibilities for determining the approximate availability of nutrients. One of four categories can be selected directly on the basis of the user's experience with the site: low, medium, high, and very high availability of nutrients. Alternatively, nutrient status can be estimated by means of the implanted database of the Ellenberg indicator values (Ellenberg et al. 1991) by selecting those plant species that occur in the considered site. The relationship of each species to nitrogen status is expressed by a nine-degree ordinal scale (Ellenberg et al. 1991). The average Ellenberg indicator value is then calculated, and one of the nutrient status categories listed above is automatically selected.

(4) *Water availability.* Again, a simple four-degree scale is used: xeric, mesic, wet, and very wet. An estimation using the respective Ellenberg scale is automatically made on the basis of indicator values of spe-



Select item describing best your stand

○ urban/industrial sites
○ abandoned fields
○ sand pits
○ stone quarries
● dumps from mines
○ peat-extraction sites
○ road banks
○ forest clearings
○ emerged bottoms
○ substrate from water bodies
○ water reservoirs

Dumped material from any type of mines

Figure 1. The dialog box for selection of stand types considered in the expert system.

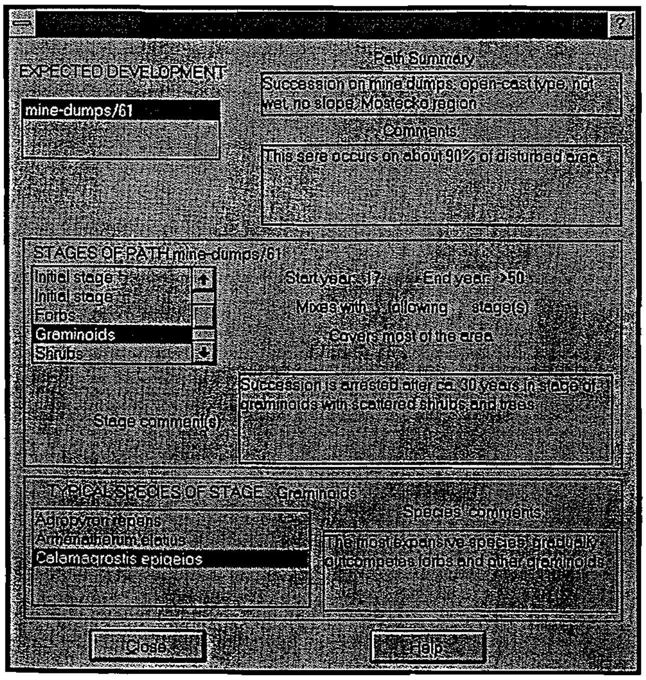
cies selected in the previous step (3), and the moisture status is suggested. Alternatively, a new species selection can be done specifically for the estimation of the moisture status.

(5) *Substratum type.* The type of substratum must be specified where relevant: sand, silt, clay, organic, gravel, or rock.

(6) *Summarizing page.* A summary is provided of the choices made by the user. At this stage, the choices can be reviewed and eventually corrected by returning to the respective page.

Some other information on site characteristics may be required, if relevant for the course of succession in particular seres, including the type of dumps (conic colliery spoils or dumps from strip coal mining); slopes, plateaus, or depressions; size of the disturbed area; vicinity of forest; and specific mining district in the case of coal-mining dumps.

After receiving the required answers, the program SUCCESS reaches conclusions and suggests the successional pathways most likely to occur under the specified conditions.



mine-dumps/61

Path Summary: Succession on mine dumps, open-cast type, not wet, no slope, Mostecko region

Comments: This sere occurs on about 90% of disturbed area

STAGES OF PATH mine-dumps/61

Initial stage
Initial stage
Forbs
Graminoids
Shrubs

Start year: 17 End year: >50

Mixes with following stage(s)

Covers most of the area

Stage comment(s): Succession is arrested after ca. 30 years in stage of graminoids with scattered shrubs and trees

TYPICAL SPECIES OF STAGE: Graminoids

Agropyron repens
Arrhenatherum elatius
Calamagrostis epigeios

Species' comments: The most expansive species, gradually outcompetes forbs and other graminoids

Figure 2. The summarizing dialog box where information on the particular sere, seral stage, and dominant species is displayed in a compact form. Compare with Appendix 1.

Results: Output of the Expert System

General Information

The output information is displayed in text form in the log window (Appendix 1). Beside that, a summarizing dialog box presents the information in a more compact form (Fig. 2). If alternative pathways are suggested in the upper part of the dialog box, the user can select one and then the seral stages are listed in the middle part. Similarly, the bottom part of the dialog box displays information on individual species typical of the seral stage selected in the middle part of the dialog box.

SUCCESS considers several types of successional stages: (1) Aquatic, open water at the beginning of succession in an aquatic environment; (2) Bare, a bare substratum at the beginning of succession in a terrestrial environment; (3) Initial, annual plants dominate; (4) Forbs, perennial forbs dominate; (5) Graminoids, grasses and/or sedges or rushes dominate; (6) Shrubs, stage with shrubs reaching important cover, usually over 30%; (7) Trees, trees reach important cover, usually over 30%.

The full sequence of the stages cannot always be distinguished in all seres, but the stages reflect well the progress of succession (Glenn-Lewin et al. 1992).

Each stage has the attributes "start" and "end" to specify the probable years of beginning and ending of the stage (measured in years since the start of the succession). In many cases the time span is only arbitrary because there are usually gradual transitions between the distinguished stages. The stages also often form a mosaic because succession is not always synchronous over the whole considered area.

The box for comments on the stage of succession includes supplementary information about variability in physiognomy, species composition, duration, occurrence of the particular stage, possible arrestment of succession, restoration practice, role in the landscape, and so forth. The information is gradually being completed, and the expert system is fully open in this respect.

The box for comments on species includes remarks on the occurrence, population dynamics, and ecological demands of the species present in succession. It is also open to the input of new information (in the present version, only the authors of the expert system are entitled to add new data).

Succession on Dumps from Coal Mining as an Example

The output of the expert system is illustrated here by three main successional pathways running on extensive dumps from strip coal mining in the Most region. This site represents the largest active mining area in central Europe and is located in the northwestern part of the Czech Republic at 50°35′N, 13°35′E, at an altitude of 250–270 m a.s.l. Brown coal is extracted by open-cast mining in layers reaching, in some cases now, nearly 200 m in depth. The dumps cover about 200 km^2. Some of this area has been reclaimed, but many large dumps are still left untreated after dumping and are thus ex-

Figure 3. Spoil heaps from strip coal mining in the Most region of the northwest Czech Republic. Photographs illustrate the outputs of the expert system SUCCESS presented in Figure 2 and Appendix 1. Upper: First year after dumping; an initial expansion of *Phragmites australis* (common reed) in the wet depression is evident. Middle: Seven years after dumping; broad-leaved forbs prevail but grasses, especially *Calamagrostis epigeios*, start to expand; *Sambucus nigra* (elder) forms the loose shrub layer; newly dumped material is seen in background. Lower: Thirty years of spontaneous vegetation development (succession) in which two grasses, *C. epigeios* and *Arrhenatherum elatius*, prevail; woody species are represented mainly by *Betula pendula* (birch) and *S. nigra*.

posed to spontaneous primary succession (Fig. 3). The dumps are composed mostly of gray Tertiary clay with small inserts of sand and gravel sediments. The succession has been studied here since 1977 using permanent plots and transects located in various stages of different age, which enabled us to reconstruct, with a sufficient level of exactness, past successional changes for the period of 0–43 years with prediction up to 50 years (for details see Prach 1987; Prach et al. 1997).

The following successional pathways were distinguished in three distinct habitats recognized on the dumps:

First, flat and slightly inclined sites represent the main habitat type covering most of the dump area (about 90%). Basic information on the course of succession in this habitat is presented in Appendix 1. The typical sequence of successional stages starts with annual and biennial species and continues with stages dominated by perennial forbs and then with stages of scattered shrubs and trees with dominant graminoids in the ground layer. The last stage is more or less arrested, so that only quantitative changes occur. Between the 25th and 43rd years of succession, we observed an increase in cover of the competitive clonal grass *Calamagrostis epigeios* (wood small-reed) (from about 25% to about 40%), a slight decline of *Arrhenatherum elatius* (false oatgrass) (from about 40% to 30%), and a decrease in cover of several perennial forbs. The dominant species in the respective stages are listed in Appendix 1a.

The total cover of vegetation increased from zero to nearly 100% by about the 15th year of succession. Woody species reached the cover of approximately 10% of the total area by about the 20th year. They did not expand farther, apparently because of competition from the herb layer.

This successional sequence occurs in all relief types except very wet depressions and very steep slopes (over ca. 45°). On dry tops and southern slopes, the rate of succession is slower compared to sites with higher water content. Annual and biennial plants persist longer, up to ca. 12 years of succession in the former sites, and lose their dominance earlier, in about the 6th year of succession, in the latter sites. Annuals are usually replaced by perennials in the 8th or 9th year of succession as indicated in Appendix 1. Similarly, faster succession was recognized on more favorable sandy and gravel substrata sporadically occurring on the dumps.

The second successional sequence occurred on steep slopes. Because of unstable substratum on the slopes, only well-adapted species capable of vegetative spreading can occur in these sites. Among the species present in the dumps (in total, 400 species were recorded), only *Tussilago farfara* (colt's foot) was observed to form a high cover here. The colonization of steep slopes starts usually in the second year with a low cover of *Tussilago.* This gradually increases and usually reaches about 40% after about 15 years of succession. No further successional changes were observed during the whole period of the study, except a limited and local expansion of *Calamagrostis epigeios* inside the *Tussilago* stands (Appendix 1b). *Tussilago* undoubtedly contributes to the stabilization of the substratum. The extent of this habitat is also influenced by the process of dumping and reaches up to approximately 5% of the total area.

The third successional sequence occurred in depressions with water table near the surface, usually flooded. The typical species sequence and duration of particular stages are presented in Appendix 1c. The exchange of the early successional dominant *Typha latifolia* (bulrush) by the late successional *Phragmites australis* (common reed) is a distinctive feature of this sere. The extent of this habitat varies from dump to dump, depending on the process of material dumping. Generally, the very wet depressions cover approximately 5% of the dump area.

Discussion

The great promise of artificial intelligence development in the late 1960s turned out to be exaggerated. Its only real legacy is expert systems. They were never overly ambitious: their goal is to automate routine intellectual tasks, the tasks that an expert in a certain field does again and again (Giarratano & Riley 1994). Expert systems can never replace human experts for many reasons, one of them being their lack of interactivity with respect to the solved problem: the expert system (at least of the diagnostic type, used in development of the SUCCESS program) takes a one-time snapshot of the facts and is quite dependent on the quality of the information provided by its users. On the other hand, if a problem is clearly defined, an expert system can escape another danger, that of providing incompetent advice on the borders or outside of its knowledge potential. The SUCCESS program was constructed considering all these criteria.

Hundreds of expert systems have been developed for use in industry, space flights, medicine, defense, and business. But we are aware of none similar in scope and structure to SUCCESS. Some are close, such as SETSARIO (Hill 1990) and TRISTAR (Hunt et al. 1991), which predict succession in set-aside fields and secondary vegetation changes under changing management in already-established herbaceous vegetation, and the system predicting invasiveness of plant species (Tucker & Richardson 1995). Another expert system was developed in 1992 at Texas A&M University by R. Coulson to forecast the infestation of forest plantations by southern pine beetles (CLIPS 1993). For general discussion of expert systems in ecology, see Noble (1987) and Luken (1990).

We are aware that the successional pathways suggested by the expert system are approximate, despite the fact that most predictions are based on detailed quantitative studies in permanent plots. But any particular successional sere in any particular site is affected by many factors, including chance (Pickett et al. 1987; Walker & Chapin 1987; Brand & Parker 1995), so it is impossible to include and quantify all of them. Hence the predictions are necessarily approximate, especially for species composition (this holds less for the sequence of life forms and stages defined on the basis of physiognomy of vegetation; Burrows 1990). The exact predictions are also limited by the fact that it was only possible to include rough categories of environmental characteristics because a more-detailed assessment would decrease the practical possibilities of using the expert system. The categories of moisture and nutrient contents can be estimated without any detailed measurement. Terms such as xeric, mesic, and wet are usually sufficient for predicting vegetation change (Peet 1978; Osbornová et al. 1990). If the user is not sure about moisture or nutrient status he or she can use the attached database of the Ellenberg indicator values, which provides a reasonable estimate (ter Braak & Gremmen 1989). The environmental factors included—site moisture, amount of available nutrients, relief and substratum types, character of surrounding vegetation, and size of the disturbed area—are generally considered to be the decisive factors driving succession (Glenn-Lewin et al. 1992; van Andel et al. 1993; Bazzaz 1997). It must be borne in mind, however, that quantitative assessment of these factors was not available for each sere included in the expert system, and also that not all of these factors have the same relevance in each sere.

The development of this expert system was based on the results of our studies in the Czech Republic (area of about 80,000 km^2). According to our experience and scattered published data it can be used in adjoining parts of Germany, Austria up to the Danube River, Silesia in Poland, and parts of Slovakia and Hungary, except the warm Pannonian lowland where many temperature-demanding species take part in corresponding successional seres (Wolf 1985; Szegi et al. 1988; Mucina et al. 1993; Jochimsen 1996; Jarolímek et al. 1997). Tentatively, it may be used even in more distant parts of Europe, especially in habitats, such as water bodies, where successional development is less variable over a large geographic area (Krahulec et al. 1986). But we believe that the approach used in constructing the expert system presented here can be generally used to summarize available knowledge on vegetation succession.

The variability of successional changes can be well illustrated on dumps from mining. The first remarkable feature to be taken into account when studying the succession on dumps from mining is their origin: those resulting from strip mining differ from those heaped into the resulting more or less conic shape. The latter are usually formed by less stable, often stony material that is less suitable for colonization, especially by annuals. Perennial clonal plants usually start succession (Pyšek & Pyšek 1989; our unpublished data). On eroded slopes of the conic dumps, vegetation is usually sparse. The late-successional stages are usually similar between both types of dumps, however, and are often formed by birch woods with *Calamagrostis epigeios* in the ground layer. The surrounding vegetation plays an important role: if surrounded by forests, small, isolated dumps are easily colonized by forest species (Prach & Pyšek 1994*b*). The fastest development towards a closed forest was observed in small dumps inside a forest in the wet, montane regions, unless the substratum was adverse in its chemistry and structure (Banásová 1976).

The role of relief type and site moisture is illustrated in the presented outputs of the expert system. The substratum, gray clay of the Miocene period, is not so adverse for vegetation succession as is often thought (Štýs 1981). According to our unpublished data, it has a high nutrient content, especially of nitrogen, which can be explained by a high atmospheric deposition. The high nitrogen content is also indicated by the occurrence and luxuriant growth of nitrophillous species such as *Atriplex sagitatta* (shining orache), *Artemisia vulgaris* (mugwort), and *Sambucus nigra* (elder).

All three successional pathways from the Most region finally reach a stage when the succession is in fact arrested by (1) the presence of a strong competitor and its long persistence (van der Valk 1992), (2) protracted instability of substratum on the slopes, and (3) lack of diaspores of species typical of climax communities predicted for the area (such species are virtually missing from the heavily industrialized and urbanized areas). A similar pattern was observed on dumps in coal mining districts in neighbouring countries such as Germany, Hungary, and Poland (references given above and personal observations).

From the viewpoint of restoration ecology, vegetation spontaneously formed on the dumps contributes to the stabilization of substrata, acts against water and wind erosion, visually isolates "artificial" relief types, and provides refugia for many organisms. These refugia are often more effective when found in spontaneously revegetated areas than in stands formed by remodeling of the surface and replanting of trees because the latter sites are more uniform in terms of the diversity of microhabitats (Bejček & Tyrner 1980). But the latter approach is unfortunately most preferred by engineers who oversee reclamation processes in the territory. Spontaneously revegetated sites harbor many more plant species than do plantations or the surrounding industrialized area. Also, the occurrence of rare, retreating species, including some rare ruderals, is typical of the spontaneously revegetated dumps. Last but not least, the spontaneous processes are cheaper than any other means of reclamation.

The described expert system has the potential to be developed further. It could be enlarged for application to a larger geographical area than Central Europe. It could be integrated with geographic information systems, used to accumulate further knowledge to provide recommendations for directing succession, and altered to incorporate potentially dangerous weeds and invasive aliens that might enter the landscape most easily via early successional stages (Drake et al. 1989). The second version of the expert system has recently been passed to the Ministery of Environmental Protection of the Czech Republic for distribution to potential users. Their experiences will be reported to the authors of the system and used for improvement of future versions of SUCCESS.

Note: More information on the expert system SUCCESS 2.0 and its availability can be obtained after 1 January 1999 at the address of the first author.

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Appendix 1. The text form output of the expert system describing the main successional pathways on dumps from strip coal mining in the northwestern part of the Czech Republic: (a) a typical sere, (b) a sere on steep slopes, (c) a sere in very wet depressions. See text for comments.

Based on the entered information, the following successional paths are probable:

(a)

- **(1) Successional path 61:** Succession on mine dumps, open-cast type, not wet, no steep slope, Mostecko region
  - Stage comment: This sere occurs on about 90% of disturbed area. This path has seven stages, numbered (1.1) to (1.7)
  - **(1.1) Initial stage or pioneer plants**
    - Years: 1–3
    - Typical plants:
      - *Polygonum lapathifolium*
      - *Senecio viscosus* (only in wet years)
      - *Chenopodium* sp. div.
    - Stage comment: low total cover
  - **(1.2) Initial stage or pioneer plants**
    - Years: 4–6
    - Typical plants:
      - *Atriplex sagittata* (forms dense and tall cover, especially in depressions)
  - **(1.3) Initial stage or pioneer plants**
    - Years: 7–8
    - Typical plants:
      - *Carduus acanthoides*
      - *Sisymbrium loeselii*
    - Stage comment: stage occurs and persists longer on dry sites
  - **(1.4) Stage with dominant perennial forbs**
    - Years: 9–16
    - Typical plants:
      - *Tanacetum vulgare*
      - *Artemisia vulgaris*
      - *Cirsium arvense*
    - Stage comment: stage mixes with one or more adjacent stages
  - **(1.5) Stage with dominant graminoids**
    - Years: 17–limit
    - Typical plants:
      - *Calamagrostis epigeios* (the most expansive species; gradually outcompetes forbs and other graminoids)
      - *Arrhenatherum elatius* (especially on dumps with mesic meadows in vicinity)
      - *Agropyron repens*
    - Stage comment: succession is arrested after about 30 years in stage of graminoids with scattered shrubs and trees
    - Stage comment: stage mixes with one or more adjacent stages
  - **(1.6) Stage with shrubs**
    - Years: 17–limit
    - Typical plants:
      - *Sambucus nigra* (scattered over the whole area)
      - *Rubus* sp.div. (only locally dominant)
    - Stage comment: stage mixes with one or more adjacent stages
  - **(1.7) Stage with tree layer**
    - Years: 17–limit

(continued)

Appendix 1. Continued.

Typical plants:
  Betula pendula (the most common tree)
  Acer pseudoplatanus
  Fraxinus excelsior
Stage comment: stage mixes with one or more adjacent stages

(b)

(1) Successional path 62: Succession on mine dumps, open-cast type, not moist, steep slope. This path has three stages, numbered (1.1) to (1.3)

(1.1) Usually bare substrate, no vegetation
Year: 1
Typical plants: none

(1.2) Stage with dominant perennial forbs
Years: 2–limit
Typical plants:
  Tussilago farfara
Stage comment: stage mixes with one or more adjacent stages

(1.3) Stage with dominant graminoids
Years: 15–limit
Typical plants:
  Calamagrostis epigeios (only locally present)
Stage comment: stage mixes with one or more adjacent stages

(c)

(1) Successional path 63: Succession on mine dumps, open-cast type, permanently wet depressions, often flooded. This path has three stages, numbered (1.1) to (1.3)

(1.1) Usually bare substrate, no vegetation
Year: 1
Typical plants: none

(1.2) Stage with dominant graminoids
Years: 2–10
Typical plants:
  Typha latifolia
Stage comment: occasionally *Alopecurus aequalis, Agrostis stolonifera*

(1.3) Stage with dominant graminoids
Years: 11–limit
Typical plants:
  Phragmites australis (strong dominance)
Stage comment: occassionally *Eleocharis palustris, Schoenoplectus tabernaemontani*