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Natural Recovery of Terrestrial Ecosystems after the Cessation of Industrial Pollution: 1. A State-of-the-Art Review

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Abstract—In recent decades, atmospheric emissions from industrial enterprises have been reduced in many countries, which makes it possible to analyze the patterns of ecosystem recovery. The review provides an annotated list of studies of natural recovery (i.e., without involving any reclamation measures) of terrestrial ecosystems near industrial plants that have ceased or significantly reduced their emissions. Seventy-three studies of biota recovery (70 publications) performed near 22 plants (mainly metallurgical ones) have been identified; other 18 and 14 studies deal with analysis based on repeated records of the dynamics of the content of pollutants in plants and animals and in soils, respectively. Numerous gaps in the knowledge of natural recovery have been revealed: uneven study of different biomes and ecosystem types, fragmentariness (absence) of data on many taxa, the prevailing number of single-component studies within a specific area, and dominance of relatively short observation series with a small number of time points. These gaps make it so far impossible to generalize data on a global scale. Shortcomings in the presentation of results in publications (incomplete data on the dynamics of emissions and dates of material collection) also make it difficult to generalize data.

Keywords: dynamics, resilience, secondary successions, soil, vegetation, lichens, invertebrates, birds, small mammals, industrial barren, air pollution, emission reduction, toxic load, heavy metals

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Industrial pollution of the environment can be a strong ecological factor: concentrations of potentially toxic metals, metalloids, and other pollutants in soil often exceed the background values by dozens, hundreds, and thousands of times near metallurgical enterprises [1, 2]. High levels of pollution can cause the disappearance of many species, which, in turn, radically changes the original appearance of ecosystems and leads to disturbances of ecosystem functions [3]. Dead forests and lifeless "moonscapes" near enterprises are one of the most striking examples of negative effects of human activity that are given in ecological textbooks. Long-term field experiments that were started (beyond the will of researchers) during the launch of the enterprise have been actually carried out in contaminated areas. The record of their results is interesting in terms of analyzing the response of ecosystems to strong external effects and understanding the mechanisms of their resistance [4].

In recent decades, industrial emissions have been reduced in many countries, primarily in Europe and North America, for different reasons: the closure of enterprises due to their danger or unprofitability, transition to new technologies, or transfer of production to other countries [5–7]. However, regardless of reasons, the cessation of the release of pollutants into the environment allows ecologists to analyze the patterns of natural recovery of ecosystems: How reversible are changes caused by pollution? Is it possible to expect natural recovery to the original state? If it is possible, how long will it last? What species will be the first to return to polluted sites? Why can the recovery be retarded? What inhibits and what accelerates recolonization? The emergence of model situations (sites near enterprises that have reduced their emissions) makes it possible to seek answers to these questions not only through speculative reasoning or mathematical modeling, but also via analysis of empirical data. The subject area under discussion is so far at the initial stages of development; therefore, it is important to establish the current level of knowledge, reveal poorly developed issues, and outline promising study areas.

It is primarily necessary to clarify the terminology. In English publications, two terms are used to denote the return of an ecosystem from a disturbed state to its original condition: "recovery" (the process and/or result of its natural regeneration, i.e., without any intentional external intervention) and "restoration" (a regeneration based on certain human manipulations for proper development of the process). Unfortunately, there is only one term in Russian—"vosstanovlenie" (meaning both recovery and restoration), which may lead to uncertainties in interpretation. Therefore, to avoid confusion, I consider it necessary to use additional words in Russian that are not necessary in English to denote the natural regeneration of an ecosystem: "natural recovery," "spontaneous recovery," or "self-recovery." It is also better to clarify the second term (in particular, when it is used simultaneously with the first one): "active restoration," "managed restoration," and "controlled restoration." In this review, the omission of clarification means natural recovery proper. It should also be noted that, for the sake of brevity, the "cessation of emissions" also means their "significant reduction" in this paper.

There are so far few studies on the natural recovery of ecosystems, in particular, compared to studies of the opposite process, namely, ecosystem degradation due to pollution. Their number is also significantly lower than that of studies in the field of analysis of primary successions (including the self-regeneration of dumps of metallurgical and mining production) and secondary successions initiated by the cessation of other severe disturbing effects: chronic (tillage, pasture loads, salinization, etc.) or catastrophic (felling, fires, oil spills, etc.) effects. Contrast with numerous studies on managed restoration (development of reclamation technologies, assessment of the efficiency of different practices, analysis of the course of secondary successions, etc.) is particularly impressive, even if we take into account that only few of these studies deal with the consequences of industrial pollution. This area is developed much more intensively: an international Society for Ecological Restoration has been operating since 1981 (www.ser.org); three specialized journals have been issued since that time (*Ecological Restoration* (since 1981), *Restoration Ecology* (since 1993), and *Ecological Management & Restoration* (since 2000)), and reviews and textbooks have been also published (e.g., [8]).

In 2020, the UN General Assembly announced the 2021–2030-year period to be the United Nations Decade on Ecosystem Restoration (https://www.decadeonrestoration.org). Along with financial, political, social, economic, and technical causes, the six main barriers to achieving the goals of the global program include lack of scientific knowledge about the patterns and best practices of managed restoration. However, this also indicates the relevance of studies of natural recovery, since the management of this process should be more or less based on the knowledge about the patterns of post-technogenic dynamics of ecosystems without human intervention [9–11].

The subject of this review has rather narrow limits: (1) only terrestrial ecosystems (excluding bogs); (2) point sources of atmospheric emissions, i.e., sources with an incomparably smaller size than the areas polluted by them; and (3) natural recovery, i.e., recovery without involving any reclamation or other experimental manipulations. In most cases, the review considers the impact of metallurgical plants on biota, which, in turn, generally include non-ferrous smelters, i.e., atmospheric emissions of polymetallic dust and sulfur, nitrogen, and fluorine compounds during primary smelting of copper, nickel, lead, zinc, and aluminum.

The purpose of this review is to characterize the current state of studies on the recovery dynamics of terrestrial ecosystems after the cessation (reduction) of emissions from industrial enterprises, consider possible drivers of recovery, reveal gaps in the knowledge, and discuss the methodology for data analysis and prospects for further research. The review consists of three parts: the first part characterizes the current state of research, the second part considers the features and drivers of secondary successions, and the third part discusses the methodological issues and research prospects.

STUDIES OF THE BIOTA RESPONSE TO EMISSION REDUCTION

Selection Criteria for Publications

The selection criteria for publications were as follows: (1) the compliance with the subject of the review (terrestrial ecosystems, point sources of atmospheric pollution, and absence of reclamation or experimental manipulations); (2) the availability of detailed descriptions (as a rule, journal articles); (3) the availability of quantitative data, rather than only mentions without proper interpretation, such as "signs of recovery are already visible" or, on the contrary, "the recovery has not yet been completed."

Publications were found in all accessible ways: (1) inquiries in bibliographic databases (Scopus, RSCI (Russian Science Citation Index), and Google Scholar) based on keywords in different combinations: "recovery", "dynamics", "ecosystem/soil/vegetation/insect/*fauna/*invertebrate/bird/mammal/lichen," "pollution/contamination/emission/metal," "smelter/factory," and "cessation/reduction/closedown/closure/shutdown" (and the same combinations in Russian), followed by reviewing annotations and/or full texts and assessing their correspondence to the selection criteria; (2) inquiries in bibliographic databases based on the geographical names of areas with enterprises that ceased their operation; (3) viewing the lists of cited literature in publications that we found; (4) viewing the lists of works of the authors of publications that we found in bibliographic databases; and (5) inquiries of colleagues. I believe that the review accumulated data on most of the currently available results of studies meeting the above-mentioned criteria.

I did not consider the natural recovery of ecosystems as a result of a decrease in regional pollution, i.e., the recovery conditions when it is impossible to clearly differentiate the action of one point source from other similar sources or from the transboundary transport of pollutants. Analysis of the consequences of the reduction of atmospheric pollution (primarily with sulfur dioxide) for spruce forests near the Giant Mountains (Karkonosze) in the Czech Republic from 1995 to 2006 [12] and epiphytic lichens in London from 1979 to 1999 [13], as well as for the diversity of lichens and mosses throughout Great Britain from the mid-20th century to the early 21st century, can serve as examples [14]. This limitation also excluded from consideration numerous studies on the dynamics of biota in the Upper Silesia (Poland), where the significant overlap of impact zones of many enterprises makes it difficult to analyze the consequences of reduction of emissions from one certain plant among them.

Data Collection Schemes

Data collection schemes in studies of recovery dynamics can be divided into two groups: (1) those based on repeated records of the state of ecosystems in the same spatial points; (2) those based on a single survey of sites at different distances from the enterprise (i.e., in the pollution gradient) after the cessation of its emissions.

The first scheme makes it possible to directly estimate recovery rates, the accuracy of which is determined among other things by the number of time slices. The second scheme provides only indirect and rough estimates of the time of recovery "completion"; in addition, this estimate is possible only if there is information (at least at the qualitative level) about the direction of the parameter change in the pollution gradient before the reduction of emissions. For instance, if a survey performed 30 years after the closure of the plant revealed no changes in the parameter with proximity to the plant, while the parameter previously decreased in this direction (or near similar sources), it can be stated that the complete recovery requires no more than 30 years. However, "no more" can mean 30 or 20 or 10 years. If the parameter in this example continues to decrease with proximity to the plant even after 30 years, it is true to say that the recovery takes no less than 30 years; however, "not less" can also be any number after this limit, e.g., 50 or 100 years. Despite this great uncertainty, the results of studies performed according to the second scheme can be used to estimate the lower boundary of the recovery period.

Another scheme is also theoretically possible by analogy with the traditional approach in the study of ecological successions: the construction of a chronosequence of sites of the same type near several enterprises that ceased their emissions at different times and interpretation of differences between the sites as time changes (space-for-time substitution). However, I do not know any studies performed in this way. Moreover, it is hardly possible to solve the problems of correct construction of a chronosequence from several emission sources due to obviously incomparable conditions in areas distant from each other.

Tables 1 and 2 show an annotated list of studies based on the first and second schemes, respectively. The first table includes 52 identified studies in areas of 16 emission sources (54 publications) and the second table presents 21 identified studies in 11 areas (16 publications); a total of 22 studies were identified, since five sources are the same in the tables. All the publications except one could be attributed unambiguously. The exception was the description of lichens and mosses from a industrial barren in the Monchegorsk area [34]: although the survey was single, all the previous studies generally documented the absence of these groups for the barren; therefore, this study was assigned to the first scheme.

Studies Based on Repeated Records

The distribution of the studied emission sources is very uneven by any of the possible criteria. Thus, studies with respect to the type of production covered mainly non-ferrous metallurgy enterprises (copper, nickel, lead, and zinc smelters (ten of the 16 plants) and aluminum smelters (three plants)), while each of the other types included only one enterprise (petrochemical plant, mineral fertilizer plant, and cement plant). Almost all the sources are in Europe (including the Urals) (14 polluters) and only two sources are in North America. The distribution by biomes is also uneven; it is approximately equal only in two natural zones: the boreal forest zone (9) and temperate forest zone (7); in other words, tundras, steppes, deserts, and tropical forests were out of the scope. In most cases, studies were focused on forest recovery, including analysis of the extreme stages of their digression (46 of the 52 studies); only six studies are related to meadows. A similar unevenness was recorded earlier, when the level of knowledge of the degradation of biota under the effect of emissions from point sources was analyzed [4]. The unevenness is even more pronounced in studies on recovery, primarily due to a significantly smaller number of surveyed sources.

Particular attention should be paid to uneven levels of knowledge of different taxa: with account of the general small number of studies of natural recovery, the number of available studies on a certain object is rarely more than 5. The predominance of gaps can be well visualized by an emission source × object × organization level matrix (see Fig. 1). During its formation, the biota objects and parameters were grouped into relatively large categories. Objects that had ever been the subject matter for pollution induced degradation were also included (even if they were not studied in terms of recovery).

The formal number of absolute "blank spots" is only 4 of the 21 combinations of object × organization level: soil microarthropods and other mesofauna groups, pollinating insects, and parameters of the organismic level of small mammals and herbaceous plants. However, studies on many other groups and

Table 1. Characteristics of studies of the natural recovery of the biota of terrestrial ecosystems, performed based on direct comparison of different periods near enterprises that ceased (or significantly reduced) their emissions

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
Three closely located copper–nickel smelters in Sudbury, Canada. Active since 1888, 1913, and 1928; emission was maximal in the 1960s and significantly decreased after 1972 (closure of one plant and reconstruction of the two others)	Comparison of two periods—with high (1967–1972) and reduced (1984–1993) emissions—for the area of the industrial barren	21	Woody and herbaceous plants	Appearance and distribution of species (visual comparison of diachronous pairs of landscape photographs)	In the second period, grasses (bent grass and lime grass), horsetails, sorrel, and birch appeared and expanded their range in the industrial barren, which was previously almost completely devoid of higher vegetation (quantitative estimates are absent)	[15]
	Comparison of two periods—with high (1970) and reduced (1989) emissions—for the heavily polluted site (industrial barren and adjacent sites)	17	Vegetation cover	Areas of sites interpreted as “barren” and “semi-barren” (based on the interpretation of aerial photographs)	The area of “semi-barren” decreased by 22% in the second period compared to the first one as a result of expansion of coniferous trees towards the plants. The reduction in the barren area was mainly determined by the reclamation (seedling planting and other measures)	[16]
	Comparison of three periods—with high (1968, literature data) and reduced (1978 and 1989–1990) emissions—in five pollution zones (with very heavy, heavy, moderate, weak, and background pollution)	18	Epiphytic lichens	Number of species and ratio of areas with different numbers of species	The area of the “lichen desert” decreased by 5 times in the second period compared to the first one and disappeared in the third period. The area of zones with a small number of species decreased from the first to the third period. Pollution-sensitive species (*Usnea hirta* and *Evernia mesomorpha*) were recorded 5 km from the plant in the third period, while they were absent here before	[17]
	Annual monitoring in 1970–2001 (31 years) at the airport weather station (20 km from Sudbury, moderately polluted site)	29	Vegetation cover	Average annual wind speed at a height of 10 m	Decrease in wind speed by one-third from 1973 to 1995, followed by its stabilization near the nearest weather stations. Interpreted as an indicator of woody vegetation recovery (it is impossible to differentiate the contributions of natural recovery and reforestation)	[18]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
Two closely located zinc smelters in Palmerton, United States. Active since 1898 and 1913; emission was maximal in the 1970s; closed in 1980	Comparison of two periods—before (1972, literature data) and after (2006) the cessation of emissions—in four sites (initially heavy pollution)	26	Epiphytic, epilithic, and epigeic lichens	Species diversity, abundance, and species composition	The abundance of epigeic and epilithic lichens increased by 2.9 times and that of epiphytic lichens by 2.3 times by the second period compared to the first period; the diversity (Shannon index) increased by 8.4 and 3.6 times, respectively. Eight species were recorded in the first period and 35 species in the second; however, there are no pollution-sensitive species	[19]
Copper smelter in the town of Rönskär, northern Sweden. Active since 1930; emission was maximal in the late 1960s and sharply decreased after 1984	Comparison of two periods—with high (1983–1990) and reduced (2000–2006) emissions—in five sites (heavy, moderate, and background pollution)	22	Pied flycatcher (*Ficedula hypoleuca*)	Clutch size, reproductive success, fledgling weight, and blood parameters (hemoglobin, hematocrit, etc.)	In the second period, the reproductive success increased in the heavily polluted site	[20]
Lead smelter in the town of Zerjav (Slovenia). Active since 1896; emission was maximal in the 1970s, significantly decreased after 1978, and almost completely ceased after 1990	Comparison of two periods of emission reduction—before (1981, literature data) and after (2001)—in nine sites (heavy pollution), meadows in place of coniferous and beech forests	11 (23)	Herbaceous vegetation	Number of species and species composition	In the first period, there were no plants closer than 300 m from the plant; in the second period, they occupied the entire area of the barren. By the second period, the number of species increased from 15–30 to 20–45	[21]
Copper–nickel smelter in the town of Harjavalta, Finland. Active since 1945; emission was maximal in 1945–1947, significantly decreased in 1991, and almost completely ceased after 2003	Comparison of two periods—before (1991–1993) and after (1994–1997) emission reduction—in four–five sites (heavy, moderate, and background pollution), coniferous forest	(6)	Pied flycatcher and great tit	Clutch size and number of fledglings	In the second period, the number of fledglings in the heavily polluted site increased in both species (but did not reach the background level); the clutch size increased only in one species	[22]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Annual monitoring in 1991–2013 (23 years) in two sites (heavy and background pollution), coniferous forest. The material for the first 7 years partially coincides with [22]	10 (22)	Pied flycatcher	Clutch size, number of fledglings, date of reproduction onset, and nesting density	A clearly defined trend towards an increase in the clutch size and number of fledglings in the heavily polluted site (especially in the first years after the emission reduction). However, the difference with the background site continued to be observed until the end of observations, which was explained by a delayed recovery of trophic chains	[23]
	Comparison of two periods—before (1991–1992) and after (2007–2009) emission reduction—in two sites (heavy and background pollution), coniferous forest	6 (18)	Pied flycatcher and great tit	Eggshell thickness	In the first period, the eggshell thickness was statistically significantly lower in the polluted site than in the background one; there are no differences between the sites after the cessation of emissions	[23]
Copper–nickel smelter in the town of Monchegorsk, Kola Peninsula, Russia. Active since 1937; emission was maximal in the 1970s–1980s and significantly decreased after 1999	Comparison of two periods—with high (1981–1983) and reduced (2005–2008) emissions—in four sites (heavy and moderate pollution); the control site was studied once (only the second period), spruce forest	(9)	Tree and shrub layers	Composition, degree of defoliation, and crown density	In heavily polluted sites, spruce continued to dry out coincided with a clearly defined expansion of deciduous trees (birch and willow). In moderately polluted sites, the degree of defoliation decreased (by 20%) and density of spruce crowns increased in the second period	[24]
		(9)	Herb–dwarf-shrub layer	Species richness, projective cover, and composition	In polluted sites, the number of species increased by 17–57%, the projective cover increased, and the ratio of the abundance of dominants changed by the second period	[24]
		(9)	Mosses and lichens	Species richness, projective cover, and composition	Heavily polluted sites were colonized by lichens (crustaceous and fruticose lichens), which were previously absent here, as well as by pioneer moss species	[24]
		(9)	Soil algae	Species richness and abundance	In the heavily polluted site, the species number and abundance increased by the second period	[24]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Monitoring in 1982–2017 (36 years) in five–seven sites (heavy, moderate, and background pollution), pine forest	(17)	Pine (*Pinus sylvestris*)	Vitality structure, needle lifespan, and dechromation of needles	By the end of observations, the vitality index (the integral weight based on the proportions of healthy, weakened, and dying trees) in the moderately polluted site became closer to the background level. It increased in the heavily polluted site but remained two times lower than the background level. After 2005, previously absent healthy trees were recorded in the heavily polluted site. In polluted sites, the needle lifespan increased and the degree of their dechromation decreased (but did not reach the background level) by the end of the period	[25–27]
	Dendrochronological reconstruction for 1880–2006 in five sites (heavy and moderate pollution), spruce forest	(7)	Spruce (*Picea obovata*) and pine	Radial increment (indices)	The difference in the spruce increment indices between the polluted and control sites became positive after 2000, whereas it was negative during the 15–20-year period of high emissions. The effect is more pronounced in the upper parts of slopes than in the lower ones, which is explained by more favorable soil conditions owing to the accumulation of organic matter in the lower parts. For pine, the difference in the indices remains negative throughout the observation period	[28, 29]
	Dendrochronological reconstruction for 1960–2014 in two sites (heavy and background pollution), pine forest	(15)	Pine	Radial increment (linear and areal increment, absolute values)	A sharp increase in the radial growth area in the polluted site after 2000, which has even exceeded the background values in the last three years. The time trend is insignificant in the background area	[30]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Repeated censuses in sites with individuals marked in 1992–1993 during the period of relatively high (1996–1999) and reduced (2005–2006) emissions, 11 sites (heavy, moderate, weak, and background pollution), coniferous forest	(7)	Birch *Betula pubescens* ssp. *czerepanovii*	Mortality and recruitment	In the heavily polluted site, mortality remained high and was not accompanied by recruitment during the period of reduced emissions. Complete death of birch was predicted in heavily polluted sites when the survived (pollution-resistant) trees reached the maximum age of their lifespan in the absence of recruitment. In moderately polluted sites, recruitment increased after the emission reduction, which was determined by the absence of competition with coniferous trees	[31]
	Comparison of two periods—with high (1978 and 1992) and reduced (2000, 2002, and 2005) emissions—in the heavily polluted site (data on the exact location are unavailable)	(6)	Vegetation cover	Vegetation Index (NDVI)	In 2002 and 2005, the vegetation index increased by two times compared to the minimum values in 1978, which was interpreted as the onset of ecosystem recovery (conclusions are not based on statistical analysis)	[32]
	Comparison of two periods—with high (1989 and 1999) and reduced (2009) emissions—in two sites (heavy and moderate pollution), pine forest	(10)	Blueberry (*Vaccinium myrtillus)*	Morphometric parameters (leaf area, crown size, etc.), calendar age, ratios of ontogenetic states	By the second period, the differences in the morphometric parameters increased between the polluted and control sites (decrease in size), which was explained by an increase in soil pollution. From the first to the second period, the age spectrum in polluted sites shifted towards young individuals and the cenopopulation density decreased by 2 times (due to the death of shrubs), while cenopopulations in the control site were characterized by natural coincided with an increase in the density by 1.3 times	[33]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Descriptions for 2017–2018 in seven sites with very heavy and heavy pollution (1.7–10 km) and comparison with previous years (exact location is unknown, literature data)	(19)	Mosses, liverworts, and (epigeic) lichens	Number of species, species composition, and projective cover	In sites with very heavy pollution (up to 3–5 km from the plant), single individuals of bryophyte and lichen species resistant to pollution were recorded, although they were earlier absent there (supposedly)	[34]
	Annual monitoring in 13 sites in the pollution gradient (heavy, moderate, and weak pollution) in 1993–2014 (22 years), spruce forest	(15)	Willow leaf beetles (four species)	Species abundance, host plant quality, and mortality due to parasites and predators	The abundance of two species sharply decreased after 2000, which was explained by an increase in their mortality due to natural enemies. The other two species had a non-directional dynamics. Changes in the abundance were interpreted by the combined effect of emission reduction and air temperature increase on the plant–phytophage–predator system	[35]
	Annual monitoring in 29 sites in the pollution gradient (high, moderate, low, and background pollution) in 1991–2016 (26 years), spruce forest	(17)	Birch insects (25 species/groups)	Species abundance and feeding activity (proportion of damaged leaves)	The temporal trend of change in the feeding activity differs between heavily polluted (decrease from the beginning to the end of observations), moderately polluted (increase), and background (no changes) sites; the dynamics was explained by a decrease in emissions. Analysis is based on linear correlations for all observation years; therefore, it is impossible to differentiate the period after the emission reduction	[36]
	Comparison of two periods—with high (1991–1992, literature data) and reduced (2005–2006) emissions—in four sites (heavy, moderate, and weak pollution), spruce forest	(7)	Soil macroinvertebrates	Group composition, abundance, biomass, and trophic structure	There are no signs of recovery in all respects. The state of communities remains suppressed, which was explained by a slow recovery of the thickness and quality of forest litter degraded due to erosion	[37]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Annual monitoring in 1936–2014 (79 years) in the moderately polluted site, spruce forest. Comparison of different periods for heavily polluted sites (exact dates are unavailable)	(15)	Small mammals	Species abundance	In the moderately polluted site, the abundance of bank vole increased after 2002, while it was absent or occasional there during the period of high emissions. In the heavily polluted site (4 km from the plant), single shrews were recorded in 2001 and 2003, while they were previously absent there. Conclusions are not based on statistical analysis	[38]
Ore mining and processing plant in the town of Lisvall, northern Sweden (dust with PbS and ZnS). Active since 1943; emission was maximal in the 1980s; closed in 2001	Comparison of two periods—with high emissions (1988–1990) and with no (2004–2006)—in two sites (heavy and background pollution)	5	Pied flycatcher	Clutch size, reproductive success, fledgling weight, and blood parameters (hemoglobin, hematocrit, etc.)	In the first and second periods, all the parameters (except the weight of fledglings) are lower in the polluted area than in the background zone and there are no signs of recovery	[39]
Copper–nickel smelter in the town of Nikel, Kola Peninsula, Russia. Active since 1942; emission was maximal in the 1970s and significantly decreased in 2002; closed in 2020	Annual monitoring in two sites (moderate and background pollution) in 1994–2012 (19 years) and in another site (moderate pollution) in 1985–2003 (19 years)	(10)	Small mammals	Species abundance	By the end of observations, the abundance of northern red-backed vole increased more significantly in the polluted site than in the background zone; the trend is opposite for grey red-backed vole (conclusions are not based on statistical analysis)	[40]
Copper smelter in the town of Revda, Middle Urals, Russia. Active since 1940; emission was maximal in the 1980s, significantly decreased after 2003, and almost completely ceased after 2010	Comparison of three periods—with high (1989), moderately reduced (1998), and significantly reduced (2008) emissions—in five sites (background, moderate, and heavy pollution), coniferous forest	(5)	Tree layer	Wood stock, stand density, and percentage of dead wood	The stock and density changed synchronously in all sites, explained by the effect and aftereffect of a hurricane-caused windfall. In the heavily polluted site, the increase in the percentage of dead wood (on trunk numbers) was disproportionally high (up to 80%) by 2008 compared to the other sites, which indicates the continuing death of trees	[41, 42]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Comparison of four periods—with high (1989), moderately reduced (1999), significantly reduced (2007), and almost completely eliminated (2013) ceased in five sites (background, moderate, and heavy pollution), coniferous forest	3 (10)	Herb–dwarf-shrub layer	Species diversity, composition, and biomass	The diversity increased synchronously in the background site and moderately polluted site, which was explained by the effect of windfall resulting in habitat lighting. In the heavily polluted site, the diversity did not change and the proportion of horsetail decreased and that of colonial bent grass increased in the biomass. The stability of the suppressed state in the heavily polluted site was explained by the persisting soil toxicity and a thick layer of undecomposed forest litter	[41, 42]
	Comparison of two periods—with high (1995–1998) and almost completely ceased (2014–2016) emissions—for five pollution zones in a 40 × 50 km area, coniferous and deciduous forests	6 (13)	Herb–dwarf-shrub layer	Species diversity of six groups with different ways of diaspora dispersal (within the sample plot and pollution zone)	The species richness remained extremely low in the heavily polluted zone, which was interpreted as evidence of the stable degraded state. The recovery capacity depends on the way of diaspora dispersal: positive shifts in species richness were recorded only for myrmecochores (mainly in the moderately polluted zone) and typical anemochores (in all zones)	[43]
	Comparison of two periods—with high (1990–1992) and almost completely ceased (2014–2018, annual monitoring, 5 years) emissions—in four sites (heavy, moderate, and background pollution), coniferous forest	8 (15)	Epiphytic lichens	Species composition, structure of communities, and abundance	In the second period, the area of the "lichen desert" began to be colonized by new species. In heavily and moderately polluted sites, the species abundance and diversity increased (annually by one to two species from 2014 to 2018); however, there are so far no species sensitive to pollution. The retardation of recovery was explained by the persisting dry microclimate in the polluted sites, as well as by an increased concentration of metals in bark	[44, 45]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Monitoring in two sites (heavy and background pollution) each 1–2 years (2005, 2006, 2008, 2011, 2012, 2014, and 2015; 7 years), deciduous forest	5 (12)	Birch-feeding insects	Feeding activity (proportion of damaged leaves)	In the polluted site, the feeding activity of phyllophages tends to increase by the end of observations, which led to the leveling of differences between the polluted and background sites after the cessation of emissions (however, the sites still significantly differ from each other)	[46]
	Comparison of two periods—with relatively high (2006–2008) and almost completely ceased (2015–2017) emissions in three sites (heavy, moderate, and background pollution), dry meadow	8 (15)	Mollusks in herb layer	Species composition and abundance	In the first and second periods, mollusks were absent in the heavily polluted site. In sites with background and moderate pollution, the abundance and diversity was 2–3 times lower in the second period than in the first one, which was explained by unfavorable weather conditions (drought in 2016). One species previously absent in the polluted site appeared there in the second period	[47]
	Comparison of three periods—with high (1990–1991), reduced (2004), and almost completely eliminated (2014–2016) emissions—in four sites (heavy, moderate, and background pollution), coniferous forest	6 (13)	Soil macroinvertebrates	Group composition, number, and trophic structure	The abundance of pollution-sensitive groups (earthworms, potworms, and mollusks) increased in moderately polluted sites and the range of their distribution became 2 km closer to the plant. No recovery was observed in heavily polluted sites (the difference with the background level does not change)	[48, 49]
	Descriptions in three sites (heavy, moderate, and background pollution) in 2019 compared to their descriptions in 2015–2016 from works [50, 51], coniferous and deciduous forests	9 (16)	Organogenic soil horizons	Humus forms	Non-typical humus forms previously absent in polluted sites were recorded here, which indicates active colonization of the forest litter by earthworms and other macro invertebrates. The proportion of these humus forms is 75% of all profiles in moderately polluted sites and 40% in heavily polluted sites	[52]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Annual monitoring in 1989–2020 (20 years before and 10 years after 2010) in three sites (heavy, moderate, and background pollution), coniferous and deciduous forests	10 (17)	Hole-nesting birds	Abundance, species composition, and community structure of the birds occupying nest-boxes	In the heavily polluted site, the total population density (especially in the deciduous forest) increased and the dominants changed after 2010. The changes were explained by the recovery of vegetation cover favorable for pied flycatcher (the dominant species after 2012), rather than by the previously dominant common redstart	[53]
	Annual monitoring in 1989–2020 (20 years before and 10 years after 2010) in three sites (heavy, moderate, and background pollution), coniferous and deciduous forests	10 (17)	Pied flycatcher	Clutch size, number of fledglings, reproductive success, and date of reproduction onset	In the heavily polluted site, the clutch size, number of fledglings, and reproductive success clearly tended to increase after 2010, which cannot be explained only by the shift in the reproduction onset to earlier dates (as a result of climate warming). By the end of observations, the difference from the background level is no longer observed in the polluted areas only for the feeding success (the other parameters still have lower values)	[54]
	Annual monitoring in 1990–2020 (19 years before and 10 years after 2010) in three sites (heavy, moderate, and background pollution), coniferous forest	10 (17)	Small mammals	Species composition, species ratio, alpha, beta, and gamma diversity, and abundance	By the end of observations, the total abundance did not change in the heavily polluted site and increased by 2 times in the moderately polluted site. In the background site, the abundance increased by 30%, which was explained by the natural succession of vegetation. By the end of observations, the shrew abundance increased in moderately and heavily polluted sites and the dominant bank vole was replaced by northern red-backed vole in heavily polluted sites. By the end of observations, the structural differences increased between the communities from the polluted and background sites	[55, 56]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Comparison of two periods—with high (1995–1998) and almost completely ceased (2013) emissions—based on maps of occurrence in the impact area of the plant (40 × 50 km area), coniferous and deciduous forests	3 (10)	European mole (*Talpa europaea*)	Position of the distribution range boundary with respect to the smelter	The range of the mole distribution became 10–15 km closer to the smelter in areas with a light soil texture and remained almost unchanged in areas with a heavy soil texture	[57]
Copper smelter in Karabash, South Urals, Russia. Active since 1910; emission was maximal in the 1960s–1970s; it was absent in 1990–1997 and then resumed after 1998; it significantly decreased after 2006 and almost complete ceased after 2016	Comparison of two periods—with high (1983) and completely ceased (1996 and 1997) emissions—in the site with very heavy pollution (industrial barren)	7	Herbaceous plants	Species diversity and composition	Only sparse specimens of several tolerant species were recorded in the first period. In the second period, the number of herb species increased by 8 times (up to 20–30); in particular, it doubled in 1997 compared to 1996. Changes covered only the lower parts of slopes; on the tops, the state of vegetation still remained suppressed, which was due to unfavorable microclimate conditions (earlier snow melting) and soil erosion	[58]
			Soil algae	Species diversity and composition	In the second period, the number of species doubled (from 8 to 16) and the previously absent species characteristic of forest biotopes appeared	[58]
	Annual monitoring in 2000–2008 (9 years) in the heavily polluted site (the exact location is unavailable)	(2)	Vegetation cover	Vegetation index (NDVI)	In 2007–2008, the vegetation index slightly increased (by 10–15%) compared to the minimum values in 2004–2005, which was interpreted as the onset of ecosystem recovery (conclusions are not based on statistical analysis)	[59]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
Aluminum smelter in the town of Ziar nad Hronom, Slovakia. Active since 1953; emissions decreased after 1963 (?)	Comparison of two periods—with high (1962–1963) and reduced (1984) emissions—in four pollution zones, different biotopes (deciduous forest, forest belts, etc.)	(21 ?)	Nesting bird population	Species composition and abundance	In the first and second periods, the abundance and diversity decreases with proximity to the plant; the abundance and diversity in forest biotopes is higher in the second period than in the first one (conclusions are not based on statistical analysis)	[60]
Cryolite plant in the town of Polevskoy, Middle Urals, Russia. Active since 1907; emission was maximal in the 1950s–1960s and significant decreased after 1974; closed in 2013	Comparison of two periods—with high (1960s, literature data) and reduced (1986–1995) emissions in the heavily polluted site, pine and birch forests	(21)	Woody plants	Range of distribution	In the first period, woody vegetation was absent at a distance of less than 11–13 km from the plant; only sparse suppressed specimens of birch, aspen, and willow (20–30 cm high) were recorded at a distance of 1.5 km. By the second period, the range of distribution became closer to the plant: groups of 10-year-old birch trees appeared within a radius of 1 km from the plant and groups of 20–30-year-old birch trees (up to 10 m high) at greater distances	[61]
			Herb–dwarf-shrub layer	Species number	In the site of up to 5 km from the plant, the number of species was 15–24 in the first period and increased to 19–49 in the second one (the absence of complete data makes it impossible to carry out a detailed comparison)	[61]
Aluminum plant in the town of Kandalaksha, Kola Peninsula, Russia. Active since 1951; emission (HF and dust) was maximal in the 1970s–1980s and significantly decreased after 2005	Comparison of two periods—before (2001) and after (2011) emission reduction—in five sites (heavy, moderate, weak, and background pollution)	(6)	Litter microflora	Number and biomass of bacteria, actinomycetes, and fungi	The trends in biomass change with proximity to the plant were the same in the first and second periods: the biomass of fungi decreased, biomass of actinomycetes increased, and no changes were observed in the biomass of bacteria (due to a higher pH value (by 2 units). The biomass of bacteria increased and that of fungi and actinomycetes decreased in all areas in the second period compared to the first one	[62]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
Mineral fertilizer plant in the town of Jonava, Lithuania. Active since 1965; emission (sulfur and nitrogen compounds, ammonia, and dust) was maximal in the 1970s and significantly decreased after 1989	Monitoring in four sites (heavy, moderate, and background pollution) each 3–5 years in 1982–2002 (6 years), pine forest	(13)	Pine	Crown defoliation	In polluted sites, crown defoliation began to decrease after 1990 and reached the background level by the end of observations. The recovery of crowns was possible even when they were almost completely (90%) defoliated. The recovery of crowns was more pronounced in dominant trees than in subordinate ones; its process was slower in stands with a greater density	[63–65]
	Dendrochronological reconstruction for 1932–2010 in four sites (heavy, moderate, and background pollution), pine forest	(21)	Pine	Radial increment	The radial increment began to increase after 1991–1992 and reached the background level and even exceeded it by the end of observations	[63–65]
Phosphate fertilizer plant near Jena, Germany. Active since 1960; emission (apatite, soda, and Cd) was maximal in the 1970s; closed in 1990	Annual monitoring in 1990–2002 (13 years) in the heavily polluted site and in 1990–1999 (10 years) in the moderately and weakly polluted sites, limestone meadow	12	Herbaceous vegetation	Number of species and functional groups and diversity indices (number of effective species and evenness)	In the heavily polluted site, the single-species community (halophytic *Puccinellia distans*) was transformed into a multispecific one: the number of herb species linearly increased from 1990 to 1999 (from 1 to 50), followed by its stabilization (in 2000–2002); woody species appeared after 1997 and their number then increased. The number of species was consistently high in the weakly polluted site and increased in the moderately polluted site similarly to the heavily polluted site; however, it reached the saturation level earlier (in 1997)	[66, 67]
	Annual monitoring in 1990–1996 (5–6 years) in three sites (heavy, moderate, and weak pollution), limestone meadow	6	Insects and arachnids in herb layer	Species diversity and abundance of functional groups	In all sites, the temporal trends of diversity are not pronounced for all functional groups. In the heavily polluted site, the abundance of sucking phytophages (leafhoppers) and chewing hunters (coleopterans) decreased by the end of observations	[66]

Table 1. (Contd.)

Area, source of emissions	Data collection scheme design	T, years	Object	Test parameters	Recovery results	Publication
	Comparison of three periods—with high emissions (1980 and 1981) and 1 year (1991), and 6 years (1996) after their cessation—in three sites (heavy, moderate, and weak pollution), limestone meadow	6	Herpetobiont carabid beetles	Species number and abundance and size (body volume) distribution of individuals in the community	By the end of observations, the number of species increased in all sites, in particular, in the heavily polluted site (from 20 to 45). The average size of an individual in the community decreased in heavily and moderately polluted sites, while it did not change in the weakly polluted site. A repeated analysis of the data showed that this conclusion is true only for species with a mixed diet, while carnivorous and phytophagous species have the opposite trend, i.e., their average size increases [68]	[68, 69]
Cement plant in the town of Sitkovska-Noviny, Poland. Active since 1962 (cement dust); emission significantly decreased after 1990–1991	Comparison of three periods—1 year (1992–1994), 11 years (2000–2001), and 16 years (2008–2009) after emission reduction—in the heavily polluted site, three biotopes (deciduous and coniferous forests and meadow)	(16)	Mollusk communities	Species number, composition, and abundance	There are no clear patterns: from the first to the third period, the abundance decreased in the deciduous forest, did not change in the coniferous forest, and increased in the meadow (the conclusions are not based on statistical analysis)	[70]

T is the maximum duration of the study of recovery after the complete or almost complete cessation of emissions (in brackets—after a significant emission reduction). Areas are grouped by the type of enterprise (metal smelters, aluminum factories, other factories); within the same type, they are grouped by the temporal decrease after the cessation (reduction) of emissions. The characteristics of emission sources were extracted from the cited publications and refined according to [3] and open data on the Internet.

parameters are very rare and do not provide a very detailed information, which makes the real picture even less "rosy." There are only fragmentary data on soil microbocenosis (in two of the three cases, the results are related only to soil algae [24, 58] and there are no data on the species composition of micromycetes communities, rate of organic matter decomposition, and soil respiration), herpetobiont invertebrate communities (none of the identified studies was carried out in metallurgical plant areas), and parameters of the organismic level of birds (only one study on changes in eggshell thickness [23]). Only four objects can actually be considered studied in a little more detail than others: herbs and dwarf shrubs (seven areas), trees and shrubs (five areas), bird populations (four areas), and lichen communities (four areas).

The distribution of emission sources by the number of objects studied near them is extremely uneven: one has to state with regret that integrated studies are the exception rather than the rule. They have been actually carried out only in two areas: near Monchegorsk and Revda (11 objects of the 21 combinations in each area). Most likely, these two areas will rank first in terms of comprehensive research for a long time: taking into account the high activity of the current research teams, it can be predicted that the continuation of long-term monitoring will not only provide new time points but also expand the range of study objects.

Most often, the recovery of only one object was studied (albeit relatively in detail) near one specific source (ten of the 16 areas). For instance, only the

Table 2. Characteristics of studies of the recovery of the biota of terrestrial ecosystems based on a single survey of areas near enterprises that ceased (or significantly reduced) their emissions

Area, source of emissions*	Year of study	T, years	Number of sites in the pollution gradient	Object	Test parameters	Pattern of change in parameters with increase in pollution (towards the source of emissions)	Publication
Open sulfide ore furnaces near the town of O'Donnell, Sudbury, Canada. Was active from 1916 to 1929	1994	65	9	Herbaceous and moss–lichen layers	Number of species, composition	A clear gradient of decrease in the number of plant species (from 30 to 4–7 per 1 m^2) with proximity to the location of furnaces (the total gradient is 300 m); the furnace section itself has no herbaceous vegetation due to the extremely high concentration of Ni, Cu, and Co (see Table 5)	[71]
	1995	66	8	Complex of soil decomposers	Decomposition of coniferous and deciduous litter (mass decrease in six months)	The decomposition rate is lower than the background value only in the most contaminated site; the maximum values are in the middle part of the gradient	[71]
Copper–nickel smelter in Sudbury (1972)	2001	29	6	Tree and herb–dwarf-shrub layers	Species diversity and structural complexity of the community	A clear gradient of decrease in all parameters of diversity with proximity to the plant (the number of tree and herbaceous species decreases from 12 to 1 and 30 to 8, respectively)	[72]
	2012**	40	5	Epiphytic, epixilic, and epigeic lichens	Diversity and species composition	Changes are nonlinear: the species number and Shannon index are the same in the sites closest to the plant and background sites; the maximum values are observed at the intermediate pollution level. However, many pollution-sensitive species (*Usnea* spp., *Bryoria* spp., *Evernia mesomorpha, Hypogymnia physodes,* etc.) are absent in the site closest to the plant	[73]
	2001	29	5	Soil microorganisms	Abundance (number of colony-forming units) of high-level taxa	The abundance of most groups decreases with proximity to the plant; however, almost all the regression relationships are statistically insignificant	[74]

Table 2. (Contd.)

Area, source of emissions*	Year of study	T, years	Number of sites in the pollution gradient	Object	Test parameters	Pattern of change in parameters with increase in pollution (towards the source of emissions)	Publication
	2006–2007	34–35	5	Herpetobiont insects	Diversity (Shannon index) at the level of super-specific taxa and abundance	Trends of changes in the increasing gradient of pollution differ for different groups: decrease (abundance of predators and detritivores and diversity of phytophages), increase (abundance of phytophages and diversity of predators), maximum level under medium loads (abundance of parasites and diversity of detritivores), and absence of changes (diversity of parasites). Most of the regression relationships are statistically insignificant	[75]
	2006–2008	34–36	5	Birds and mammals	Zoochory intensity (proportion of consumed blueberry and acorn seeds)	A clear decreasing gradient of zoochory due to large and small mammals (from 70–80% to 0) with proximity to the plant; low values of bird zoochory in all sites	[76]
Zinc smelter in the town of Mortagne-du-Nord, northern France. Active from 1901 to 1962	1999	37	14	Soil macrofauna	Abundance, group composition, and number of morphospecies	The total abundance decreased by 3 times in meadows and 2.4 times in poplar plantations in polluted sites compared to unpolluted ones; in both cases, the decrease is due to the decline of earthworms (by 86 and 6 times, respectively). The diversity is higher in polluted sites than in unpolluted ones	[77]
	1999	37	6	Earthworms	Abundance and species composition	The abundance and diversity sharply decreased towards the plant (from 270–390 to 2 ind./m^2 and from 6–8 to 1 species, respectively) due to the retention of extremely high concentrations of Zn, Pb, and Cd in the soil (see Table 5)	[78]

Table 2. (Contd.)

Area, source of emissions*	Year of study	T, years	Number of sites in the pollution gradient	Object	Test parameters	Pattern of change in parameters with increase in pollution (towards the source of emissions)	Publication
Lead and zinc smelter in the town of Trail, Canada. Active since 1896; emission was maximal in the 1920s and sharply decreased after 1941	1971	30	20	Tree, shrub, and herb–dwarf-shrub layers	Species composition, number of species, biomass, stand density, and age of trees	The number of tree, shrub, and herb species and basal area of coniferous (but not deciduous) trees clearly decrease towards the plant	[79]
Zinc smelters in the town of Palmerton (1980)	2006	26	13	Tree, shrub, and herb–dwarf-shrub layers	Species composition, number of species, projective cover, and seedling density	The abundance of tree, shrub, and herb–dwarf-shrub layers clearly decreases towards the plant. The number of species varies greatly; therefore, the dependence on the distance from the plant is statistically insignificant. No regeneration of the stand is observed near the smelters	[80]
Copper smelter in the town of Gusum (Sweden). Was active from 1661 to 1991	2009	16	6	Earthworm *Dendrobaena octaedra*	Abundance	The abundance decreases from 20–30 to two ind./m^2 towards the smelter	[81]
Lead smelter in the town of Santo Amaro, Brazil. Was active from 1960 to 1993	2008	15	14	Plant communities	Projective cover and species composition	The projective cover decreases from 80–100 to 20–30% and the species composition changes towards the smelter	[82]
				Herpetobiont invertebrates	Abundance, group composition, and number of morphospecies	There are no clear trends due to the high variability in the abundance and diversity of most groups. The abundance of arachnids is lower and that of hymenopterans is higher near the smelter than in remote areas	[82]
				Soil fauna	Feeding activity (bait-lamina test)	The activity decreases from about 50% to about 5–10% towards the plant (however, the values are higher in some sites near the plant, reaching 20–30%)	[82]

Table 2. (Contd.)

Area, source of emissions*	Year of study	T, years	Number of sites in the pollution gradient	Object	Test parameters	Pattern of change in parameters with increase in pollution (towards the source of emissions)	Publication
				Soil microbocenosis	Soil respiration, microbial mass, and enzymatic activity	All the parameters decrease with proximity to the smelter: respiration, by 1.7–4 times, microbial mass, by 2.5–4 times, and dehydrogenase and acid phosphatase activity, by 3.5–10 times	[82]
				Complex of soil decomposers	Decomposition rate of plant material	The rate constant decreases by 10 times (from 0.27–0.45 to 0.03–0.05) towards the smelter	[82]
Lead (formerly zinc) smelter near the town of Noyelles-Godaut, northern France. Was active from 1893 to 2003	2011	8	3	Wood mouse (*Apodemus sylvaticus*)	Frequency of liver and kidney histopathologies	The frequency of severe histopathologies is higher in the polluted site (in particular, for the liver)	[83]
Phosphate fertilizer plant near Jena (1990)	1997	7	12	Soil microbocenosis	Microbial mass, soil respiration, and dehydrogenase activity	The microbial mass is lower and respiration and dehydrogenase activity is higher in polluted sites. The absence of a clearly defined effect of pollution was determined by the low availability of Cd and F in soils on limestones	[84]
Copper–nickel smelter in Harjavalta (2003)	2010	7	10	Small mammals	Species diversity, species composition, and abundance	The abundance is 5 times lower near the plant than in sites with background and moderate pollution; the diversity does not change in the pollution gradient	[85]
Copper smelter in Revda (2010)	2014–2016	6	110	Moss cover	Species diversity, occurrence, and abundance	For the site with the radius of 10 km from the plant, the diversity clearly decreases towards the plant (up to the formation of a single-species community)	[86]

T is the number of years after the complete or almost complete cessation of emissions; areas are presented in the decreasing order of T; *, the characteristics of the emission sources are given in Table 1 (in this case, the year of the complete or almost complete cessation of emissions is given in brackets); **the year of the study was not indicated in the description of the methodology.

recovery of pied flycatcher populations was studied near the copper–nickel smelter in Harjavalta [22, 23], although the state of many other objects was also recorded for the period of high emissions from this plant (see [3]), which could potentially be used as a starting point for analyzing their recovery.

At the same time, other territories where large-scale projects on studying ecosystem degradation were

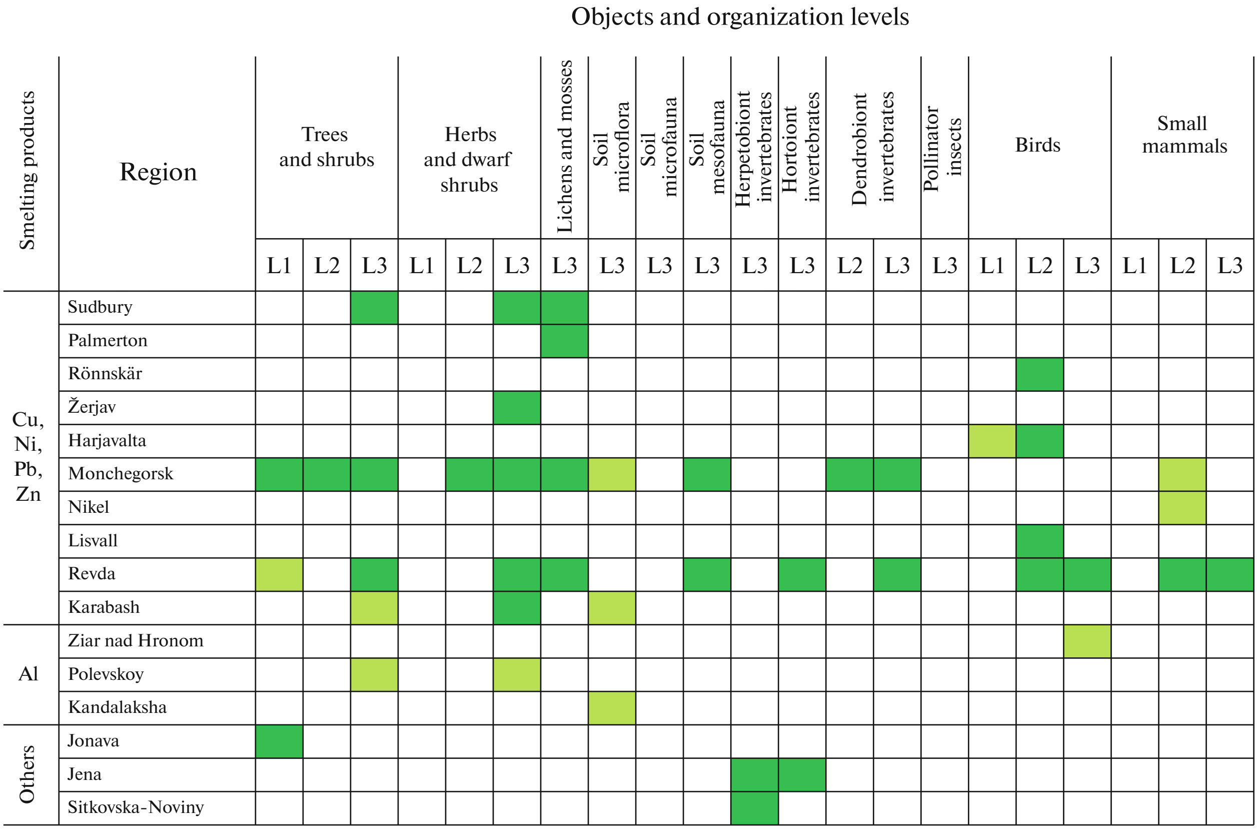

Fig. 1. Characteristics of the level of knowledge of natural recovery based on repeated records of different objects in areas of industrial enterprises (the names and order of enterprises correspond to those presented in Table 1). Organization levels: L1, organismic level, L2, population level, and L3, cenotic level. Light green shading means fragmentary data on the recovery and dark green shading means a detailed study.

previously carried out had even less advantages. It is no exaggeration to say that the current knowledge of the negative impact of industrial pollution on biota is based on publications of the 1970s–1980s, which concerned four plants: in Sudbury, Palmerton, Gusum, and Avonmouth. However, ecosystem recovery was studied in relative detail only in the Sudbury area (mostly during managed restoration). Only one study of natural recovery based on repeated records of the state of the biota has been carried out for the Palmerton area [19], and there are no such studies for the Gusum and Avonmouth areas to the best of my knowledge.

In half of the cases, analysis of natural recovery is based on a comparison of two time slices: before and after the cessation of emissions (27 of the 52 studies, see Table 1); studies based on three or four time slices are less common (7). Annual monitoring (covering 6 to 30 years) was performed only in 11 studies. It should be emphasized that regular long-term recording is the most preferable, since this makes it possible to obtain the least biased characteristics of recovery trends. To some extent, lack of long time series can be compensated by dendrochronological reconstructions (there are three of them [28, 30, 65]: from 54 to 126 years); however, it is not always easy to interpret the results based on these reconstructions due to many confounding factors.

Most of the studies analyze recoveries during the first 10 years (21 studies) or 11–20 years (22) after the cessation of emissions; only nine studies cover a longer period (20–30 years). This short duration makes it possible to assess only the initial stages of recovery. However, this disadvantage can be considered temporal, since further studies of currently active research teams will make it possible to solve this problem.

We can hope that the disadvantages of incorrect sampling design and the absence (or inadequacy) of statistical analysis in publications are also temporary. This problem was already the subject of special consideration in previous reviews [4, 87]. Without going into details, one should emphasize the importance of using experimental units (sampling plots), rather than evaluation units (samples within a sampling plot) in statistical analysis. This requirement is no less, if not more, important for studies of recovery dynamics than for analysis of the biota degradation under the effect of pollution.

The current state of knowledge about the patterns of natural recovery will be characterized in the second part of the review. Here, three important aspects should be noted. First, it is obvious that biota responses to the cessation of emissions can be very various: the conclusions of different authors about the recovery rates are often not only inconsistent with each other but also contradict to each other (even for the same area). Although most authors tend to believe that natural recovery is a long-term process (e.g., [19, 31, 33, 37, 41, 43, 45, 48, 55]), there are also supporters of the opposite viewpoint (e.g., [22–24, 32, 58, 59]). The difference in conclusions may result from the specific features of certain situations or use of different parameters or time scales. In any case, one should consider it important to determine the causes of these differences and use quantitative estimates of recovery rates. Second, the patterns and rates of recovery differ between areas with heavy (industrial barrens) and moderate pollution [24, 31, 36, 41–43, 47, 56]; therefore, these variants should be differentiated in the further generalization of information. Third, in addition to emission reduction, it is obvious that other environmental factors, in particular, climate changes [35, 36, 46, 53, 54, 65] and local disturbances, e.g., windfalls [41, 42], also play a significant role. This requires at least a careful interpretation of the results to dynamics drivers.

Studies Based on a Single Survey

Studies according to the second scheme slightly increased the geographical coverage compared to studies based on the first scheme: one of the studied sources is in the Southern Hemisphere, in the tropical forest zone [82]. In turn, the study of other emission sources and biota objects remained uneven.

Areas near decommissioned enterprises are not always considered within the framework of natural recovery; they are more often used for other purposes, in particular, for (1) developing soil reclamation methods (e.g., assessment of the effectiveness of ameliorants 7 years after the closure of the lead smelter in Noyelles-Godaut) [88]); (2) analyzing the mechanisms of adaptation of organisms to high concentrations of metals (e.g., the study of genetic adaptations of earthworms to a high concentration of copper 16 years after the closure of the copper smelter in Gusum [81, 89]); (3) "mining" toxic substrates for laboratory toxicological experiments (e.g., the study of the effect of metal-contaminated feed on the diet of gypsy moth caterpillars 44 years after the closure of the smelter in Sudbury [90]). Although all these studies are indirectly related to the problem of natural recovery, they can serve as an circumstantial evidence of the long-term pollution aftereffect near plants decommissioned many years ago. However, the gradient of past pollution is not always considered in the context of recovery analysis even if the objectives of the research are to study the impact of enterprise emissions on biota (e.g., [77, 78]).

The range of the period from the time of cessation of emissions to the record of the biota state is 6–66 years for the 11 areas included in the analysis (see Table 2), which expands the time range compared to the scheme of repeated records (see Table 1). In most of the studies (17 of the 21 studies), the authors found a clear trend of variation for all studied biotic parameters with proximity to no longer existing emission sources; this trend is true for areas with the recovery period of not only 6–16 years but also 26–40 years. Consequently, the period of 40 years can so far be taken as an estimate of the duration that is obviously insufficient for complete natural recovery in most cases. A decrease of the parameters near the source of past pollution is also shown for the longest recovery period studied to date (66 years) [71]. However, it is hardly reasonable to directly compare this case with emissions from metallurgical plants themselves, since it concerns the extremely barbaric methods of preliminary ore burning in the open air on ground level, which was not used anywhere else.

The results of four studies suggested that there was no significant change in the parameters in the gradient of past pollution. One study showed the stability of the species richness of epiphytic lichens in the Sudbury area [73]; however, analysis of the structure of communities makes it obvious that there is a significant difference between the background sites and the closest site to the plant, where many pollution-sensitive species are absent. Parameters for which the inevitable reduction is unobvious even in the impact areas of modern plants (the abundance of some groups of soil macrofauna [75, 82] and soil respiration [84]) were used in other three sites.

STUDIES OF THE DYNAMICS OF ACCUMULATION OF POLLUTANTS IN BIOTA

The concentrations of metals in the tissues of organisms depend not only on their content in the environment but also on many other factors specific to a certain element, taxon, and territory. Accumulation levels are interpreted in two ways: as an indicator of environmental pollution and as an evaluation of the direct toxic load on the organism or on trophic chain links. In the context of the problem of natural recovery, the first aspect is not so important, since it can be considered only as an objective confirmation of the official data on the dynamics of emissions, while the second is necessary for understanding the mechanisms of ongoing processes.

Table 3 provides accumulated data on studies of the dynamics of metal concentrations in plants and animals near enterprises that have ceased their emissions. As in the analysis of the biota response, studies on the dynamics of regional pollution were not included. Comparison of metal concentrations in the tissues of pied flycatcher and bank vole during the period of heavy (1981–1982) and weak (1996–1997) pollution for the entire Scania region (southern Sweden) can serve as an example [105]. In addition, due to a significant uncertainty in interpretation, data of single measurements near enterprises closed long ago were not considered.

In areas near metallurgical enterprises, the main contribution to the metal contamination of the aboveground parts of vascular plants is made by the deposition of polymetallic dust on their surface [106]. The only path of metal uptake to mosses and lichens is via the air. Therefore, it is not surprising that almost all the studies recorded a sharp and rapid decrease in the metal content in vascular plants [46, 94, 95, 97, 101, 102] and even more so in mosses [96] after the cessation of emissions. The following example is illustrative: the lead smelter in Noyelles-Godaut ceased its emissions in March 2003 and the lead concentration in wheat straw cultivated within a radius of 2–3 km from this smelter decreased to 3.8 mg/kg as early as the July of this year, while it was 41.2 mg/kg in 1997–2001; the same trend was recorded for the lead concentration in grain, which decreased from 1.3 to 0.2 mg/kg [101].

The situation differs for animals: most often, the concentrations of metals did not change or slowly decreased in the tissues (excrements) of birds [20, 39, 99, 100] and small mammals [92]. The authors explained this fact by the inertia of trophic chains (including detritivores) due to the preservation of a large pool of metals in soils. As will be shown below, this view is supported by empirical data.

Almost all studies of the dynamics of metal concentrations in plants after emission reduction did not set the task to differentiate the aerial and root pathways of metal uptake and analyzed samples without preliminary washing from dust. It is possible that concentrations would decrease in the washed samples of the aboveground parts of plants or in their roots as slowly as in animal tissues. Unfortunately, there are no data on the dynamics of metal concentrations in the tissues of soil animals; presumably, its study would also reveal the stability of accumulation levels after the cessation of emissions.

STUDIES OF THE DYNAMICS OF POLLUTANT CONCENTRATIONS IN SOILS

Studies based on Repeated Records

Strangely enough, there are much fewer studies of the dynamics of concentrations of metals and other pollutants in soils based on direct comparison of several time slices than studies of changes of biota parameters (see Table 1) or metal accumulation in organisms (see Table 3), although the latter is more laborious. In total, 13 studies were identified near nine emission sources (Table 4). Analysis of the dynamics of biotic parameters is often not accompanied by the record of changes in metal concentrations in the soil. On the contrary, publications provide data for only one period and use these data only for justifying the choice of study sites or zoning of the study area (e.g., [35]). However, the long-term stability of the metal content discussed below makes it reasonable to use this approach.

One should note the variety of views on the trends of change in the concentration of metals: they may differ even within the same area. For instance, different research teams came to opposite conclusions about the dynamics of metal concentrations in the Monchegorsk area: some of them documented their decrease [24, 28, 32], while others recorded the absence of changes or even their increase [95, 108]. The causes of these contradictions may be as follows: (1) a large spatial mosaicity (on a scale of hundreds of meters or several kilometers) of the characteristics of landscapes that determine the behavior of metals in soils. Here, the key factor is the difference in the orography of the terrain, which determines an uneven deposition of metals and their further redistribution within the landscape [96]. This may result in a multidirectional dynamics of metal concentration even in closely located areas, which is important to take into account when different teams are involved in the study; (2) a high mosaic pattern of metal accumulation on a scale of tens to hundreds of meters; as a result, sampling points can be confined to areas with high or low concentrations at different times even within the studies of the same team; (3) differences between sampling methods (as a result, soil horizons in different periods may not be completely identical or the sampling depth may differ within the same horizon). Since metal concentrations in aerial-polluted soils usually exponentially decrease with depth [1], the difference of even several centimeters can significantly influence the results; (4) systematic differences between methods of chemical analysis if they were not identical in different periods.

These causes make us be careful during the compilation of diachronous data from several publications, in particular, if their authors are not from the same team. Here are some examples that made us refrain from considering conclusions about metal dynamics based on these compilations.

According to several studies, the maximum concentrations of zinc and cadmium in the forest litter near zinc smelters in Palmerton were 135 000 and 1750 mg/kg in 1970 [114], 24 000 and 1192 mg/kg in 1987 [115], and 5500 and 202 mg/kg in 2006 [80]. At first glance, the conclusion is obvious: it is unlikely that this dramatic dynamics would not reflect a "true" decrease in concentrations. Unfortunately, the exact coordinates of the sampling sites are given only in the latter cited arti-

Table 3. Characteristics of studies of the dynamics of the concentration of pollutants in biota objects based on repeated records near enterprises that ceased (or significantly reduced) their emissions

Area, source of emissions*	Data collection scheme design	Object	Element	Pattern of dynamics of the concentration	Publication
Copper smelter in Revda (2010)	Comparison of two periods—before (2008) and after (2011, 2012, and 2014) emission reduction—in two sites (heavy and background pollution)	Birch *Betula pubescens* and *B. pendula* (leaves)	Cu, Pb, Cd, and Zn	In the background site, concentrations varied insignificantly between years. In the heavily polluted site, Pb concentrations decreased by 40 times and concentrations of the other elements by 1.6–3 times by 2014	[46]
	Single measurement in 2012 in three sites (heavy, moderate, and background pollution)	Leaves of ten herbaceous species, washed and untreated samples	Cu, Pb, Cd, and Zn	There is no difference between washed and untreated samples for all sites, which is interpreted as the absence of surface pollution of leaves with technogenic dust	[91]
	Comparison of two periods—with relatively high (2004, literature data) and almost completely eliminated (2015) emissions—in five sites (heavy, moderate, and background pollution)	Fir bark	Cu and H	In polluted and background sites, the Cu concentration decreased by 4–6 and 2 times, respectively, in the second period compared to the first one. The second period is characterized by a clearly defined gradient of increase in Cu concentration and decrease in the pH value towards the plant	[45]
	Annual monitoring in three sites (heavy, moderate, and background pollution) in 1990–2015 (20 years before and 5 years after 2010)	Bank vole (stomach contents and liver)	Cu, Pb, Cd, and Zn	In the background site, Pb concentrations decreased by 1.7–2.5 times by the end of the period. In the heavily polluted site, Cd concentrations increased by 2 times by the end of the period. There are no clear trends for the other elements from the heavily polluted site (and all elements in the moderately polluted site)	[92, 93]
Copper–nickel smelter in Monchegorsk (1999)	Comparison of three periods—with high (1991–1993), moderate (2000), and reduced (2007) emissions—in three sites (heavy, moderate, and background pollution)	Spruce and fir (needles of different ages)	Ca, Mg, K, Fe, Mn, Cu, Ni, Zn, S, and P	In the heavily polluted site, Fe, Cu, S, and Ni concentrations decreased by the end of the period: Fe, by 2–4 times, Cu, by 6–10 times for spruce and 2.4 times for pine, Ni, by 2–4 times for spruce and 1.7 times for pine, and S, by 25–40%	[94]
	Monitoring in 1981–2014 (8 years) in three sites (heavy, moderate, and background pollution) each 3–7 years	Pine needles and leaves of five shrub species	Cu and Ni	In the heavily polluted site, Cu and Ni concentrations decreased by 2–11 and 3–16 times, respectively, by the end of observations. Interspecific differences are observed both during the period of high and low emissions (which was explained by the structural features of the leaf blades)	[95]

Table 3. (Contd.)

Area, source of emissions*	Data collection scheme design	Object	Element	Pattern of dynamics of the concentration	Publication
	Comparison of two periods—with heavy (1991) and reduced (2011) emissions—in 17 sites (heavy and moderate pollution)	Mosses *Hylocomium splendens* and *Pleurozium schreberi*	Cu and Ni	By the second period, concentrations decreased significantly: by 3–7 times in the moderately polluted site and by up to 20 times in the heavily polluted site. A significant spatial unevenness was recorded for the decrease in concentrations, which was explained by the effect of the wind rose, orography, and unaccounted factors	[96]
	Comparison of two periods of emission reduction—before (2002) and after (2011) emission reduction—in seven sites (heavy, moderate, and background pollution)	Spruce (needles of the current and third year and bark)	Cu, Ni, and S	In polluted areas, S concentrations did not change in needles and decreased by 2–3 times in the bark by the second period; the trend differs for metal concentrations: a significant decrease in the needles (Ni by 1.2–2.0 times and Cu by 1.9–4.2 times) and a slight decrease in the bark (by 1.4 times)	[97]
Copper–nickel smelter in Harjavalta (2003)	Comparison of two periods—with high (1991) and reduced (2009) emissions—in 18 sites (0 to 12 km from the plant)	Pied flycatcher and great tit fledglings (liver)	Cu, Ni, Cd, Pb, As, and Se	Concentrations of all elements decreased in both species at all distances from the plant. Near the plant (at a distance of 0 to 2 km), concentrations of Ni, Cd, Pb, and As decreased by 5–20 times and reached the background level	[98]
	Comparison of two periods—with high (1991) and partially reduced (1996) emissions—in three sites (heavy, moderate, and background pollution)	Pied flycatcher and great tit fledglings (bone)	Pb	By the second period, the concentrations decreased by 10 times in both species	[22]
	Comparison of three periods—with high (1992–1994) and moderately (2002) and significantly (2008) reduced emissions—in two sites (heavy and background pollution)	Pied flycatcher and great tit fledglings (excrements)	Cu, Ni, Cd, and Pb	In the polluted site, concentrations sharply decreased in 1993 compared to 1992, but were then relatively stable. In all years, concentrations were higher in the polluted site than in the background one, which was explained by the remaining pool of metals in the soil	[99]
Ore mining and processing plant in Lisvall (2001)	Comparison of two periods—before (1988–1990) and after (2004–2006) the closure—in two sites (heavy and background pollution)	Moss *Pleurozium schreberi,* ant *Formica* spp., and pied flycatcher fledglings (liver, blood, and excrements)	Pb and Zn	In the polluted site, concentrations decreased by 25–50% in all substrates (not always statistically significant); in the first and second periods, they significantly exceed the background values	[39]

Table 3. (Contd.)

Area, source of emissions*	Data collection scheme design	Object	Element	Pattern of dynamics of the concentration	Publication
Copper smelter in Rönskär (1984)	Comparison of two periods—0–6 years (1984–1990) and 16–22 years (2000–2006) after the cessation of emissions—in five sites (heavy, moderate, and background pollution)	Birch leaves, ants *Formica* sp., and pied flycatcher fledglings (liver and excrements)	Pb	In all sites, concentrations decreased in all substrates: by 9–40% near the plant and by 25–60% in moderately polluted sites. In polluted sites, concentrations significantly exceed the background values in the first and second periods	[100]
	Comparison of two periods—with higher (1983–1990) and lower (2000–2006) emissions—in five sites (heavy, moderate, and background pollution)	Ant *Formica* sp. and pied flycatcher fledglings (liver, blood, and excrements)	Cu, Zn, Cd, and As	Concentrations did not change or were higher in the second period than in the first one, which is interpreted by the persisting high soil pollution. In polluted sites, concentrations exceed the background values in the first and second periods	[20]
Lead smelter in Noyelles-Godaut (2003)	Comparison of two periods—before (1997–2001) and 4 months (July 2003) after the closure of the smelter (March 2003)—in 40 sites (heavy and moderate pollution, 0.8–5.6 km from the plant)	Wheat (grain and straw)	Pb and Cd	By the second period, Pb concentrations decreased from 41.2 to 3.8 mg/kg in straw and from 1.3 to 0.2 mg/kg in grain (reaching almost the background level). Cd concentrations decreased from 2.2 to 1.4 mg/kg in straw and did not change in grain (0.4 mg/kg, which is 4 times higher than the background level)	[101]
Lead smelter in the village of Sulitelma (Norway). Was active from 1887 to 1987	Comparison of three periods—before (1982) and 5 years (1992) and 13 years (2000) after the closure—in seven sites in the pollution gradient	Blueberry (leaves and berries)	Cu and Pb	Before the closure of the smelter, Cu concentrations in berries increased by 3 times with proximity to the smelter; this trend is almost absent after the closure of the plant, which was explained by the cessation of dust input	[102]
Aluminum smelter in the town of Holyhead, North Wales, Great Britain. Was active from 1971 to 2009	Monitoring each 1–4 weeks from the date of closure to the 14th week after the closure and additionally on the 36th week (12 time points)—in four sites (heavy pollution, not more than 1 km from the plant)	Grasses, lichen *Ramalina siliquosa*, sycamore leaves, and *Pinus contorta* and *Picea sitchensis* needles	F	Decrease in concentrations in all objects: the background level was reached by the 7th week for grasses and by the 36th week for the other plants	[103]
Aluminum smelter in Kandalaksha (2005)	Comparison of two periods—before (2001) and after emission reduction (2011)—in five sites (high, moderate, and low pollution)	Black crowberry (*Empetrum hermaphroditum)*	F	By the second period, the concentration decreased by 1.4 times in the site near the plant and did not change in the other sites	[104]

* The characteristics of the emission sources are given in Tables 1 and 2 (the year of cessation (significant reduction) of emissions is given in brackets); unless otherwise stated, plant and lichen samples were not washed prior to analysis.

Table 4. Characteristics of studies of the dynamics of the concentration of pollutants in the soil based on repeated records near enterprises that ceased (or significantly reduced) their emissions

Area, source of emissions*	Data collection scheme design	Horizon (depth, cm)	Element	Form of the element**	Pattern of dynamics	Publication
Copper smelter in Revda (2010)	Comparison of three periods—with high (1989), reduced (1999), and almost completely ceased (2012) emissions—in five sites (background, moderate, and heavy pollution), spruce–fir forests	O, A (0–5)	Cu, Pb, Cd, Zn, and H	A	In all sites, the Cu concentration decreased in the forest litter by 1.5–3 times and only near the plant in the humus horizon. Concentrations of Pb, Cd, and Zn did not change or did increase, which was explained by a decrease in their mobility due to the recovery of pH to the pre-industrial level	[107]
Copper–nickel smelter in Monchegorsk (1999)	Comparison of two periods—with high (1983) and reduced (2005 and 2008) emissions—in five sites (heavy, moderate, and background pollution), spruce forests	O	Cu and Ni	T	The data on concentrations are reduced to a relative index (Saet's pollution index). The index decreased by 2.3–5.7 times for heavily polluted sites and increased by 2.1–2.3 times for moderately polluted sites in the second period compared to the first one (conclusions are not supported by statistical analysis)	[24, 28]
	Comparison of two periods—with high (1980s) and low (2007) emissions—in three sites (heavy, moderate, and background pollution; data on the exact location are unavailable)	O	Cu and Ni	?	Cu and Ni concentrations decreased by 1.4 and 1.7 times, respectively, in heavily polluted sites and by 1.3 (Cu) and 2.6 (Ni) times in moderately polluted sites in the second period compared to the first one (conclusions are not supported by statistical analysis)	[32]
	Monitoring each 2–3 years (1981–2014), 11 time slices, in three sites (heavy, moderate, and background pollution)	O	Cu and Ni	A	By the end of the period, concentrations increased in all sites, in particular, in moderately and heavily polluted sites, which was explained by the continued input of polymetallic dust and low mobility of metals. Cu concentrations increased more significantly (by 6.8 times) than Ni concentrations (by 2.2 times)	[95, 108]

Table 4. (Contd.)

Area, source of emissions*	Data collection scheme design	Horizon (depth, cm)	Element	Form of the element**	Pattern of dynamics	Publication
	Monitoring in the heavily polluted site in 2001–2011 (9 years)	O	Cu, Ni, and Zn	T	There was no trend of change or concentrations increased by the end of observations. The content depended on the intensity of precipitation: concentrations were higher in the year with minimum precipitation and lower in the year with maximum precipitation	[109]
	Monitoring in three sites (heavy, moderate, and background pollution) in 1993–2012 (20 years), two microbiotopes (under crowns and between crowns)	O	Cu and Ni	W	The concentration of metals in soil waters was estimated using lysimeters. In heavily polluted sites, the removal decreased by the end of observations, which was explained by a decrease in the input of metals. The trend was nonlinear in the moderately polluted site, which was interpreted by differences in precipitation amount in different periods	[110]
Copper–nickel smelter complex in Sudbury (1972)	Comparison of two periods—before (1972, literature data) and after the closure of the smelter (1992)—in eight sites (heavy, moderate, and background pollution)	A (0–5)	Cu, Ni, Al, and H	W	In heavily and moderately polluted sites, the pH increased by 0.3–0.5 units by the second period (up to 3.9–4.0), but did not reach the background level (4.4). In the heavily polluted site, concentrations of metals decreased sharply: Ni, by 37 times, Cu, by 11 times, and Al, by 9 times; this was explained by ongoing soil erosion and a decrease in the content of organic matter	[111]
		A (0–1, 1–5, 5–10)	Ni	T	In the heavily polluted site, concentrations decreased in all layers, in particular, in the 0–1 cm layer (by 3–20 times—from 1200–3300 to 100–500 mg/kg) by the second period. In the 5–10 cm layer, concentrations decreased from 600–1000 to 25–100 mg/kg	[112]

Table 4. (Contd.)

Area, source of emissions*	Data collection scheme design	Horizon (depth, cm)	Element	Form of the element**	Pattern of dynamics	Publication
Copper smelter in Glogow, southwestern Poland. Active since 1959. Emission significantly decreased after 1985 and almost completely ceased after 2000	Monitoring (1972–2006), sampling each two years (18 years) in two polluted sites (poplar plantings and agricultural land)	A (0–20)	Cu	T	On agricultural lands, concentrations gradually decreased. In poplar plantations, concentrations after the reduction increased to the initial levels again, which was explained by the removal of copper from deeper soil layers by tree roots	[113]
Lead smelter in Noyelles-Godaut (2003)	Comparison of two periods—before (1997–2001) and 4 months (July 2003) after the closure of the plant (March 2003)—in 40 sites (heavy and moderate pollution, 0.8–5.6 km from the plant)	A (0–25)	Cd and Pb	T	The average concentrations and pattern of their dependence on the distance from the plant did not change	[101]
Phosphate fertilizer plant near Jena (1990)	Comparison of four years—before (1990) and one year (1991) and 6 and 7 years (1996 and 1997) after the closure of the plant—in three sites (heavy, moderate, and weak pollution), limestone meadows	A (0–10)	Cd, F, P, and H	T	By the end of the period, pH decreased from 9 to 7.3–7.7 in the heavily polluted site, from 8.3 to 7.5 in the moderately polluted site, and from 7.7 to 7.3 in the weakly polluted site	[66, 84]
Aluminum smelter in Kandalaksha (2005)	Comparison of two periods—before (2001) and after emission reduction (2011)—in five sites (heavy, moderate, weak, and background pollution)	O	F and Al	T	In the first and second periods, concentrations exponentially increased with proximity to the plant. The F concentration decreased by 2 times in all sites by the second period compared to the first period	[62]
Holyhead aluminum smelter (2009)	Monitoring in four heavily polluted sites (not more than 1 km from the plant) each month after the closure (five time slices)	A (0–2)	F	T	Decrease in concentrations by the 36th week after the closure: from 1017 to 230 mg/kg in one site and from 200–300 to 70–120 mg/kg in the other sites. The period during which the content decreased by half the initial level was 261 days in the site with the maximum concentration and 46–87 days in the other sites	[103]

Table 4. (Contd.)

Area, source of emissions*	Data collection scheme design	Horizon (depth, cm)	Element	Form of the element**	Pattern of dynamics	Publication
Cement smelter in Sitkovska-Noviny (1991)	Comparison of two periods—1 year (1992) and 18 years (2009) after emission reduction—in the heavily polluted site, three biotopes (deciduous and coniferous forest and meadow)	O, A (0–3)	H and Ca	T	By the second period, pH decreased by 0.2–0.5 units (but remained at the neutral level) and $CaCO_3$ concentrations decreased by 10–20%	[70]

* The characteristics for emission sources are given in Tables 1–3 (the year of emission cessation is given in brackets); **Forms of the elements: T, total or pseudo-total concentration, A, acid-soluble form, W, water-soluble form.

cle; however, based on a set of features, it can be revealed that the "area near" in these three studies is interpreted somewhat differently and the sampling points with maximum concentrations are 1–3 km from each other; in addition, the distance between the nearest point and the plants "gradually increases" from the first to the third publication. Taking into account that the concentrations of metals in soils usually decrease exponentially with distance from the emission source [116], it is the spatial rather than time difference can explain the decrease in the concentrations. Comparison of concentrations for more or less unambiguously equivalent sites (but not with maximum metal concentrations) shows no significant decrease: the concentrations of zinc and cadmium were 4200 and 200 mg/kg in 1987 [115] and 4800 and 103 mg/kg in 2006 [80].

Another example concerns a plant near the town of Nikel. In [117], the authors compared their own data for 2012 with the materials from other researchers for 1996 [118]. This comparison gives the following firm conclusion: "We can state that soil pollution ... has not decreased and, at the same time, has not increased over the past decade" ([117], p. 628). In both cited papers, the metal content decreased exponentially with distance from the plant; however, according to [118], the concentrations of nickel and copper were 1500–2000 and 1500–2600 mg/kg in the immediate vicinity (up to 5 km) from the plant, while they were 1000–5500 and 1000–4000 mg/kg according to [117] (in the latter case, most of the values were over 2000 mg/kg for both elements). In other words, this suggests the opposite conclusion: metal concentrations increase over the period between these two studies.

Although there are few studies of the dynamics of metal content, it is possible to discuss the general patterns of this process, since studies near emission sources can be considered as a supplement to numerous field and laboratory experiments, as well as to modeling the behavior of metals in soils. This issue will be discussed in more detail in the second part of the review during analysis of ecosystem recovery drivers. Here, I will provide only the dominant viewpoint: when there are geochemical barriers, soils can retain metals very firmly and their rapid removal is possible when the capacity of the barrier decreases or when it is destroyed.

In the case of atmospheric deposition of metals, the most important barrier is the organic one (forest litter and organic-mineral horizons); it determines the characteristic pattern of their vertical distribution within the soil profile: accumulation mainly in the upper layers of organogenic horizons and exponential decrease with depth. Some cases of a rapid decrease in concentrations of metals after the cessation of their atmospheric input may be associated with the destruction of the organic geochemical barrier. In particular, this explanation is true for the Sudbury area, where soil erosion accompanied by the removal of soil organic matter continued even after the reduction of emissions [111, 112]; this is also possibly valid for the Monchegorsk area [24, 29, 32]. If geochemical barriers (including not only organic ones) are effective, the migration of metals is very slow and, accordingly, their concentration is stable in soils, which was actually demonstrated in most of the studies [95, 101, 107–109, 113].

Historical Soil Pollution

One of the manifestations of the low mobility of metals in soils is a high level of residual pollution near enterprises that ceased their emissions long ago. This concerns not only plants that were closed decades ago, but also smelters of the Middle Ages or Roman Empire times. Table 5 summarizes data on 16 areas near these "phantom plants," which are ranked according to the time period after the cessation of their activity: from 1800 to 7 years.

In some cases, the concentration of metals is not lower near enterprises closed long ago than near modern ones: in both cases, the levels of pollution can exceed the background values by several orders of magnitude. Sometimes, sites of ancient pollution are located in reserves, e.g., in France [120, 121], where they differ little from the rest of the territory, and cannot be identified without involving additional archaeological and geochemical information. It is noteworthy that lead and cadmium in such areas can accumulate in the tissues of small mammals [120], which indicates the accessibility of the ancient soil pool of toxic metals for recent biota.

Due to the obvious differences in technologies, the pattern of soil pollution near medieval and ancient smelters is nonequivalent to the input of metals with atmospheric emissions from modern enterprises. This is primarily determined by a significant amount of artifacts (slag and ore) that were mixed with soil; in other words, this is about ancient technosols. In addition, the absence of information about emission volumes in the distant past also makes it difficult to compare the ancient technology with modern plants. Nevertheless, these data vividly illustrate the phenomenon of extremely strong retention of metals in soils. They also make it possible to empirically estimate the rates of migration of different elements down the soil profile and their removal out of it [119, 122]. The migration rate highly depends on soil properties; in particular, concentrations decrease much more rapidly in acidic soils [122] than in limestone soils with a neutral or alkaline reaction [123] over a comparable time. This issue will also be considered in more detail in the second part of the review.

PROBLEMS IN DATA GENERALIZATION

The main barriers to data generalization to reveal the general patterns of biota recovery are obvious and were mentioned above: (1) uneven study of different biota objects and fragmentariness of data for a number of taxa; (2) absence of data on many biomes and types of ecosystems; (3) few integrated studies within the same region; and (4) analysis covers only a short recovery period. On the whole, these disadvantages result from few studies of natural recovery. They show that the correct meta-analysis, especially on a global scale, is a matter for the future, since the currently available data are significantly insufficient.

In addition to objective barriers, there are also subjective factors related to the disadvantages of data presentation in publications: (1) flaws in the documentation of quantitative results and methods; (2) incomplete data on the history of the impact of enterprises on the environment; (3) inaccuracy (absence) of information about the time of the research. These subjective disadvantages can be no less critical for data generalization than the objective ones, since they sometimes become an impassable barrier to extracting the necessary information from publications. The first of them concerns any areas of ecology and has been often discussed [129]; the other two barriers are specific to the area under consideration. A detailed protocol for documenting the results of studies of terrestrial ecosystems near point sources of emissions was previously proposed [87]; I also recommend following this protocol to present results related to natural recovery. In addition, it is necessary to pay attention to the importance of information about the time of emission cessation (reduction) and research time.

The periodization of the dynamics of the toxic load on ecosystems is a separate task that often does not have a simple solution. This issue will be considered in the third part of the review. Real situations are most often far from the ideal case implying one-time cessation of emissions from the plant, as in the case of the closure of a furnace door. They usually decrease gradually or stepwise; therefore, it is not always possible to unambiguously indicate the time point from which the duration of the recovery period should be calculated. Therefore, it is desirable to have at least some detailed information about the history of the enterprise impact on the environment. Unfortunately, this data are often absent in publications and have to be collected from other sources “bit by bit”. In any case, it is unacceptable when the required date is not indicated more precisely than the remark that the decrease occurred “at the beginning of the current century.” In some cases, I could not include studies, such as [130], in the review, since they did not make it possible to reconstruct the history of emissions at least roughly.

Surprisingly, far from all publications clearly indicate the dates of collection of the material (sometimes they are not indicated at all). Here is an expressive example. In [73], it was concluded that air pollution in Sudbury is no longer the main limiting factor for lichen habitation, as was before. This conclusion begins with the words “Now we know that…” (p. 9330). Unfortunately, it remains mysterious what time exactly was meant by the authors under the word “now,” since the year of material collection is indicated neither in the description of the methods, nor in the presentation of the results, nor in their discussion. The sampling plots were laid in 2001, while the cited article was submitted to the journal in 2014. Consequently, the possible time range corresponding to the authors’ conclusion exceeds one decade: from 29 to 42 years after the closure of the smelter in 1972. The only point in the article where the recovery period is indicated (40 years) is its title. We can only hope that the authors are not inclined to round the values to the nearest “pretty” digit.

An opposite example (the absolute accuracy of time indication) is the work [103], which indicates both the exact day (!) of the closure of the aluminum plant in Holyhead and exact days of all rounds of material collection. The time indication to the day

Table 5. Examples of residual soil pollution near decommissioned non-ferrous metallurgy enterprises

Geographical location, source of pollution (years of activity)	T, years	pH	Element	Maximum concentration near the source of pollution, mg/kg	Publication
Clwyd county, northeastern Wales, Dee River mouth, Great Britain. Ancient Roman lead smelting workshops (100–150)	~1840	6.2–7.3*	Pb	1250–3000 (200000 at a depth of 1–2 m)	[119]
			Zn	550 (5000 at a depth of 1–2 m)	
Morvan Natural Park, central France. Ancient Roman iron-smelting workshops (130–426)	~1590	?	Pb	4520	[120]
			Zn	835	
Lozere granite massif, Cévennes, south of France. Medieval ore processing and lead smelting workshops (11th–14th centuries)	~800	?	Pb	14470–16950 (150000 in the soil and slag mixture)	[121]
Derbyshire County, Great Britain. Medieval lead smelting workshops (1300–1550)	~440	5.3–6.4*	Pb	60000–100000 (the soil contains slag)	[119]
			Zn	800–1200	
Atvidabergs, Sweden. Copper smelter (1790–1900)	95	3.8*	Cu	210	[122]
			Zn	230	
Marseilleveyre mountain range, Marseille province, France. Lead and silver smelter (1851–1925)	87	7.5–8.9	Pb	66600–83100	[123]
			Zn	21100–24600	
Rudawy Janowickie Mountains, southwestern Poland. Copper smelter (ore mining and copper smelting from the 14th century; the plant was closed in 1925)	85	4.5–4.9	Cu	1484–4011	[124]
			Zn	350–1503	
O'Donnell, Sudbury, Canada. Open ore furnaces (1915–1929)	66	3.8–4.4	Cu	1730–10050	[71]
			Ni	2070–8855	
City of Collinsville, Illinois, United States. Lead smelter (1904–1938)	66	?	Pb	12740	[125]
Alton town, Illinois, United States. Lead smelter (1902–1959)	45	?	Pb	4150–17200	[125]
Mortagne-du-Nord, northern France. Zinc smelter (1901–1962)	37	6.1	Zn	17960–35100	[77, 78]
			Pb	4720–8270	
			Cd	79–190	
Palmerton, Pennsylvania, United States. Two closely located zinc smelters (1898 and 1913–1980)	26	4.3–4.7	Zn	3300–3860	[80]
			Pb	875–1710	
			Cd	87–144	
Braubach, Rhineland-Palatinate, Germany. Lead smelter (1890s–early 1990s)	~25	3.6*	Pb	7500–7900	[126]
Prescot town, Great Britain. Copper refinery, production of bronze, copper, and cadmium alloys (1906–1991)	15	4.4	Cu	2180	[127]
			Cd	6.4 (71 at a depth of 30 cm)	
Santo Amaro town, Brazil. Lead smelter (1960–1993)	15	6.7–7.2*	Zn	42200–95940	[82]
			Pb	26070–37460	
			Cu	590–3200	
			Cd	60–770	
Noyelles-Godaut, northern France. Lead smelter (1893–2003)	7	5.6–8.0	Zn	2000–7500	[128]
			Pb	3000–9000	
			Cd	100–250	

T is the number of years after the cessation of emissions. The data refer only to organic-mineral horizons (without forest litter) and present the total content of metals; * pH of salt extract; water extract in other cases.

accuracy is redundant; in most cases, the month level accuracy is quite acceptable; however, the indication of the year is strictly required.

CONCLUSIONS

In total, we identified 73 studies (70 publications) near 22 enterprises that are directly or indirectly related to analysis of the natural recovery of the biota of terrestrial ecosystems after the cessation (significant reduction) of industrial emissions, mainly from metallurgical plants. Other 18 and 14 studies dealt with analysis of the dynamics of the concentration of pollutants in plants and animals and in soils, respectively.

Numerous gaps were revealed in the knowledge of natural recovery: an uneven study of different biomes and types of ecosystems, fragmentariness (absence) of information about many taxa, the prevalence of single-component studies within a specific area, and dominance of relatively short observation series with a small number of time points. In other words, the current state of research makes it possible to reveal only the patterns of the initial stages of natural recovery and can only provide a rough (due to the low resolution of analysis) and biased (due to fragmented data) picture. These gaps are so far an impassable barrier to data generalization, in particular, on a global scale. Nevertheless, this generalization is necessary, since even the available incomplete information gives grounds to believe that the variety of possible trajectories of recovery dynamics is significant.

Analysis of the recovery dynamics of ecosystems after the cessation of strong disturbances is a traditional area of ecological research, which has a long history and is closely related to the issue of resilience. However, the cessation of industrial pollution discussed here remains almost completely unaddressed. Thus, three recent meta-analysis [131–133], which considered the dynamics after the cessation of various disturbances (forest falls after hurricanes, felling, plowing up, oil spills, mining, overfishing, eutrophication, etc.), involved no study on biota recovery after the cessation of industrial emissions, although they were based on extensive databases including 166 [131], 240 [132], and 400 [133] independent studies. This disregard is quite understandable if we take into account the above-mentioned barriers; however, it can hardly be positively assessed, since it can lead to distortions of the general pattern and biases in the quantitative estimates of ecosystem resilience.

Reducing emissions from industrial enterprises is a global trend; therefore, one can confidently predict an increasing frequency of "gifts of fate" to ecologists in the form of the closure or cardinal reconstruction of plants. With this taken into account, any studies near still operating enterprises are prospective; i.e., they record the disturbed state of ecosystems that can further be taken as a starting point in analysis of their recovery dynamics after the inevitable reduction of emissions. The involvement of new areas in studies and continuation of previously initiated studies will provide further progress in this area.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interests.

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