Soil toxicity at historic charcoal production sites

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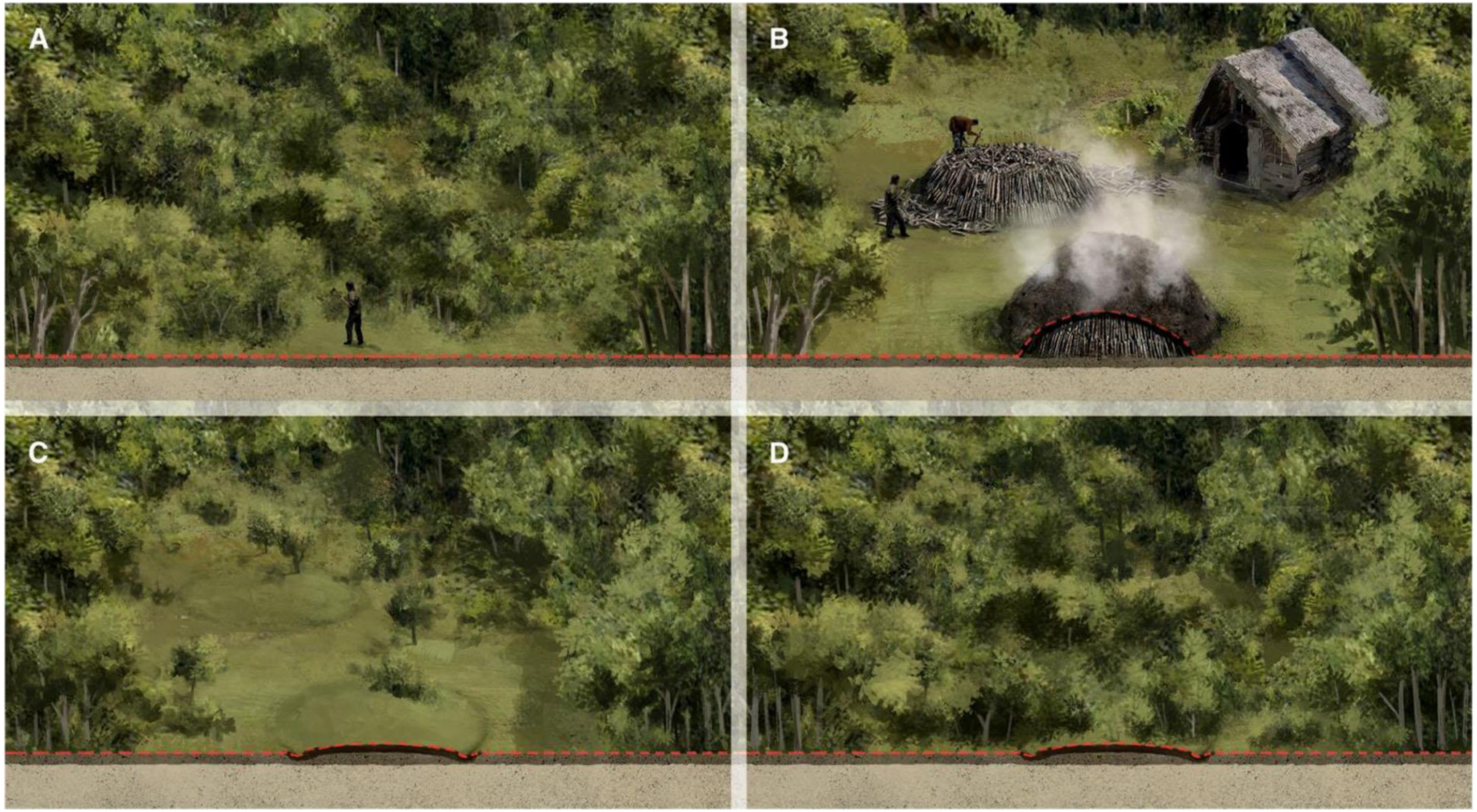
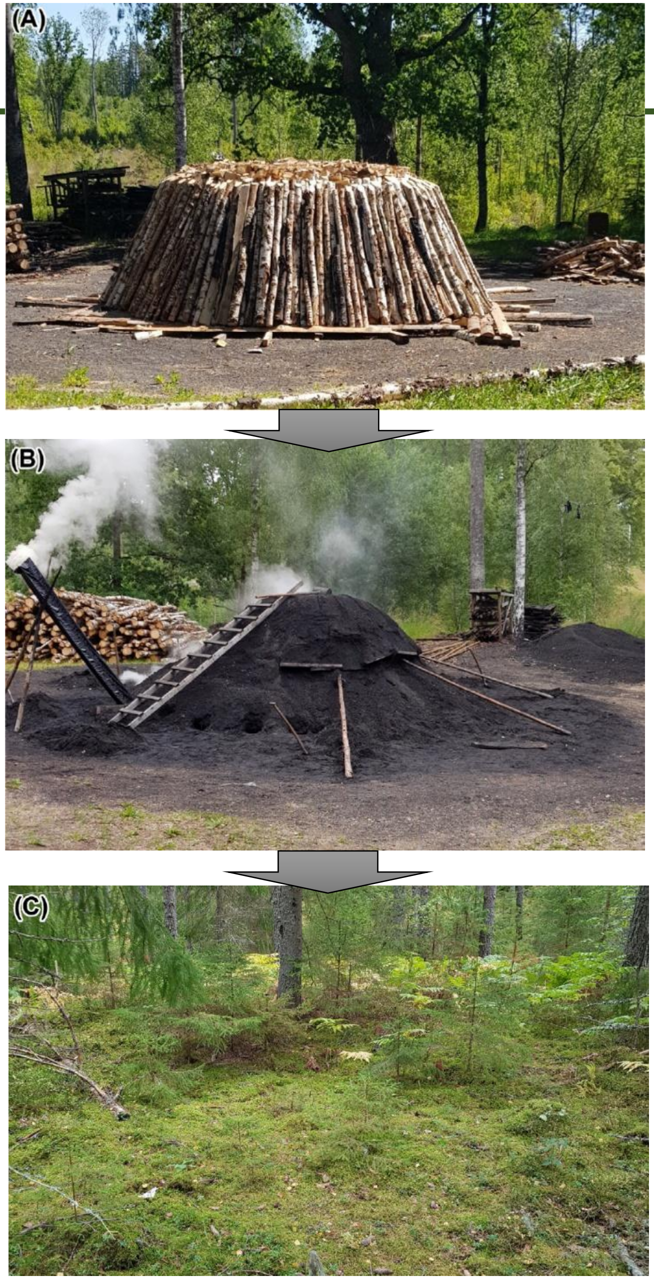
Background

The in situ pyrolysis of wood was a common practice in European forests in the past, until the 19th century.

Charcoal, tar and potash were the main products of this process





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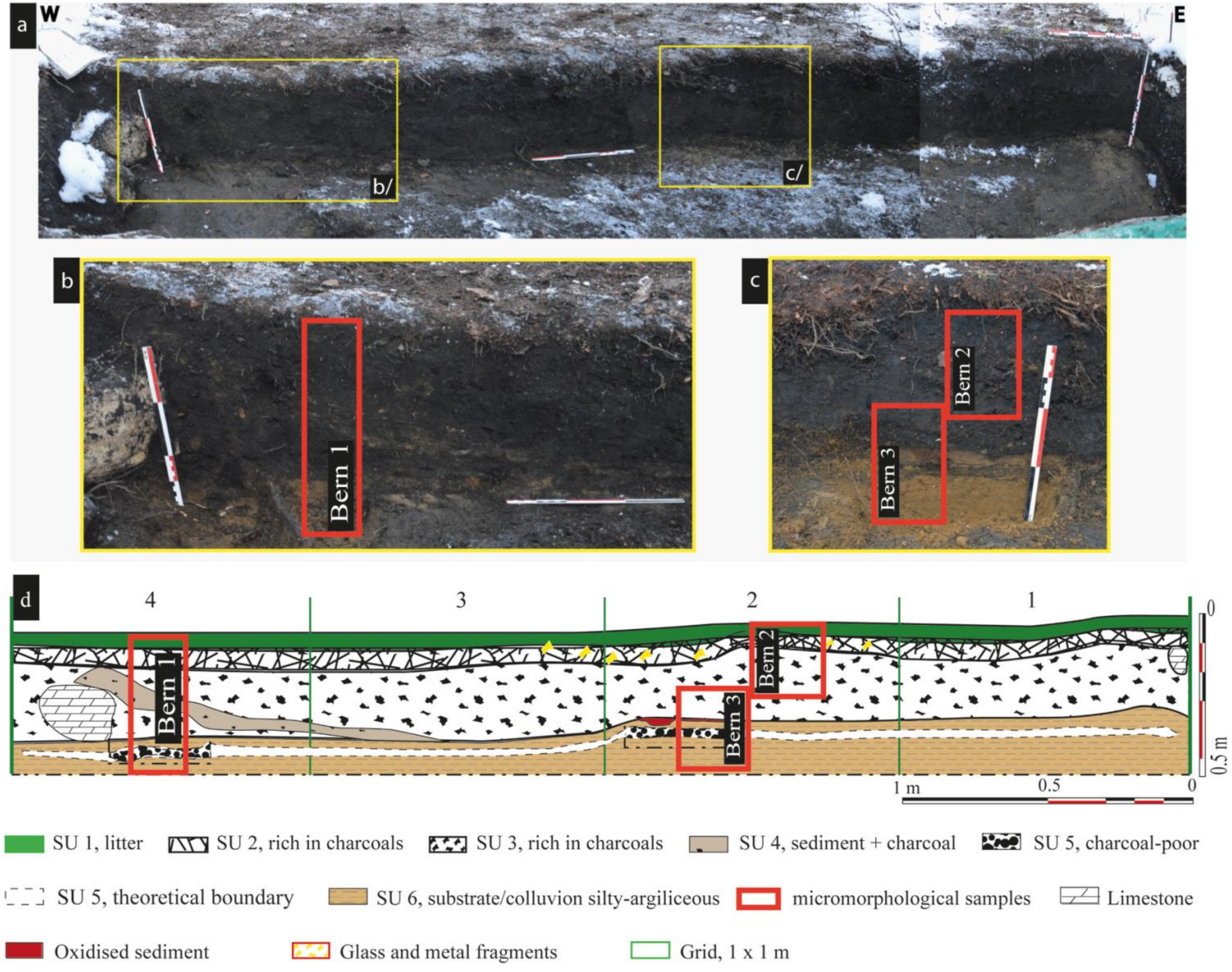
Background

Relict charcoal hearths (RCHs) – evidence on charcoal production in the past



High resolution reconstruction of modern charcoal production kilns: An integrated approach combining dendrochronology, micromorphology and anthracology in the French Pyrenees

Léonel Fouédjeu [a,*], Mélanie Saulnier [a,b], Mathieu Lejay [c,e], Martin Dušátko [b], Vincent Labbas [a,c], Alistair S. Jump [d], Sylvain Burri [c], Sandrine Buscaino [a], Vanessa Py-Saragaglia [a]

Background

The scale of the phenomenon

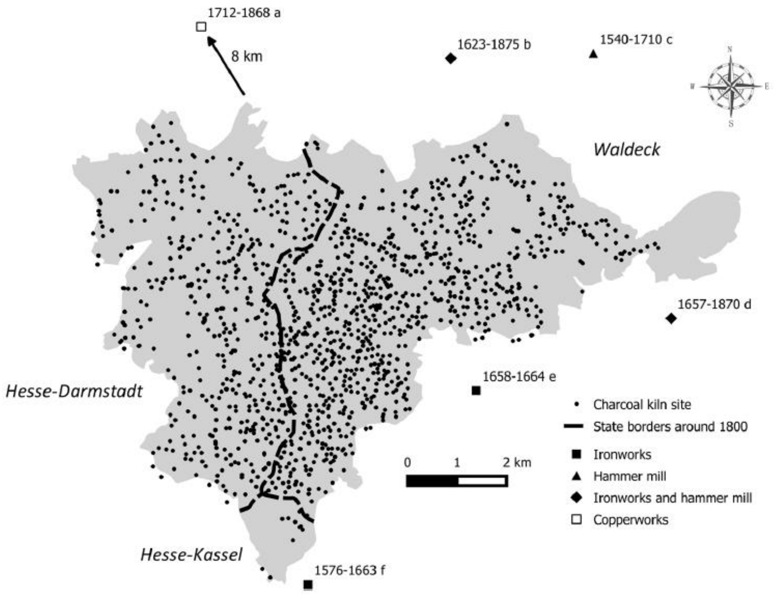
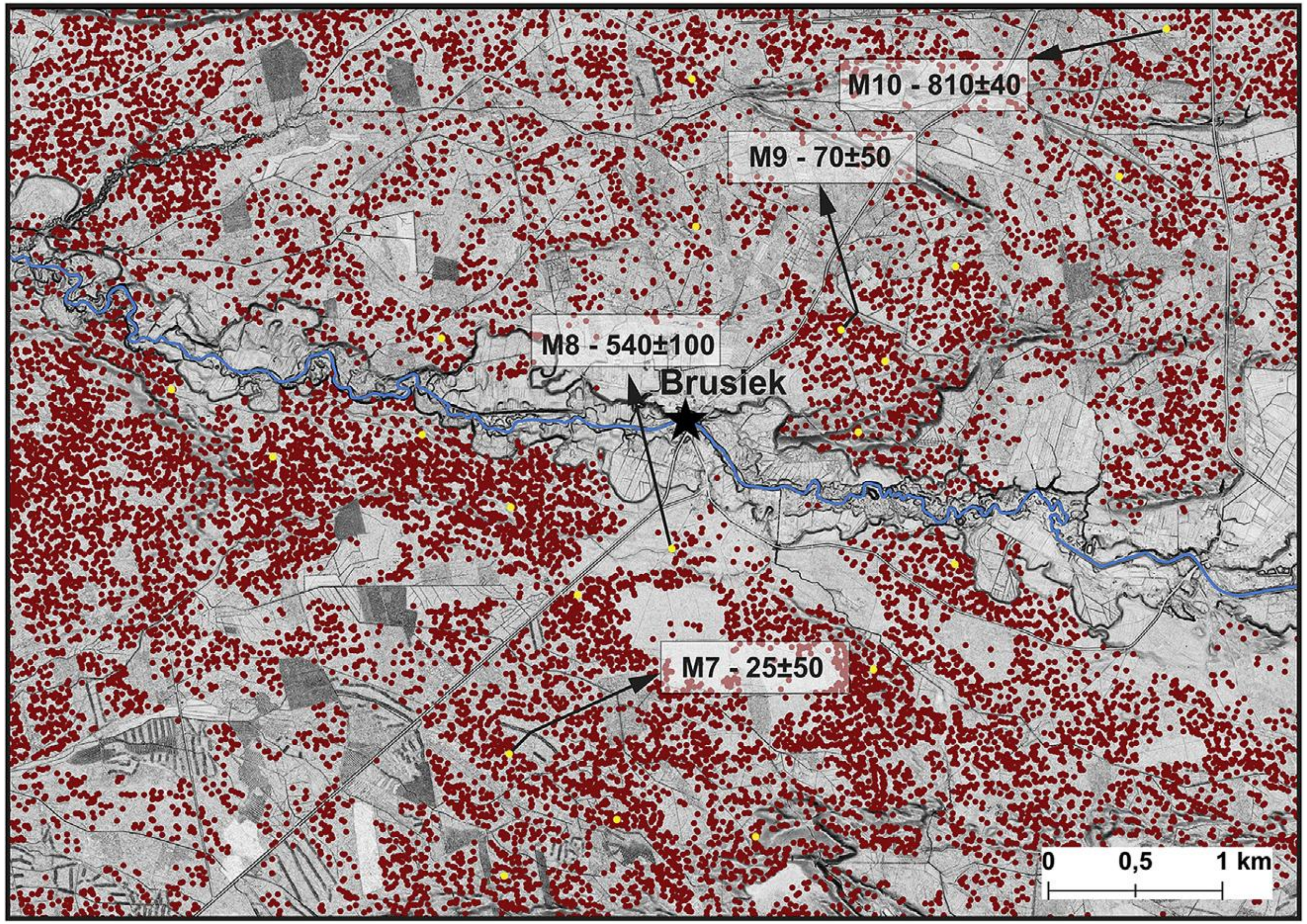


Fig. 3 The study area Kellerwald-Edersee National Park with the location of the mapped charcoal kiln sites, historical industrial sites, and historical state boundaries. The different ironworks and hammer mills of the Haina Hospital are not illustrated, since they obtained no charcoal or fuelwood from the study area. a: Thalitter, b: Bericher Faktorei, c: Vornhagen, d: Kleinern, e: Gellershausen, f: Frankenau

Charcoal kiln sites, associated landscape attributes and historic forest conditions: DTM-based investigations in Hesse (Germany)

Marcus Schmidt[1], Andreas Mölder[1*], Egbert Schönfelder[1], Falko Engel[1] and Werner Fortmann-Valtink[2]



High concentration of charcoal hearth remains as legacy of historical ferrous metallurgy in southern Poland

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State of knowledge

Environmental aspects

- Environmental determinants of RCH distribution → ++++
- Plant species distribution → ++
- Nutrient cycling → ++

Pedological aspects

- Soil morphology and classification → ++
- Soil-forming processes → +
- Soil physical properties → +++
- Soil chemistry → ++
- Soil microbiology → +
- Soil organic matter → +

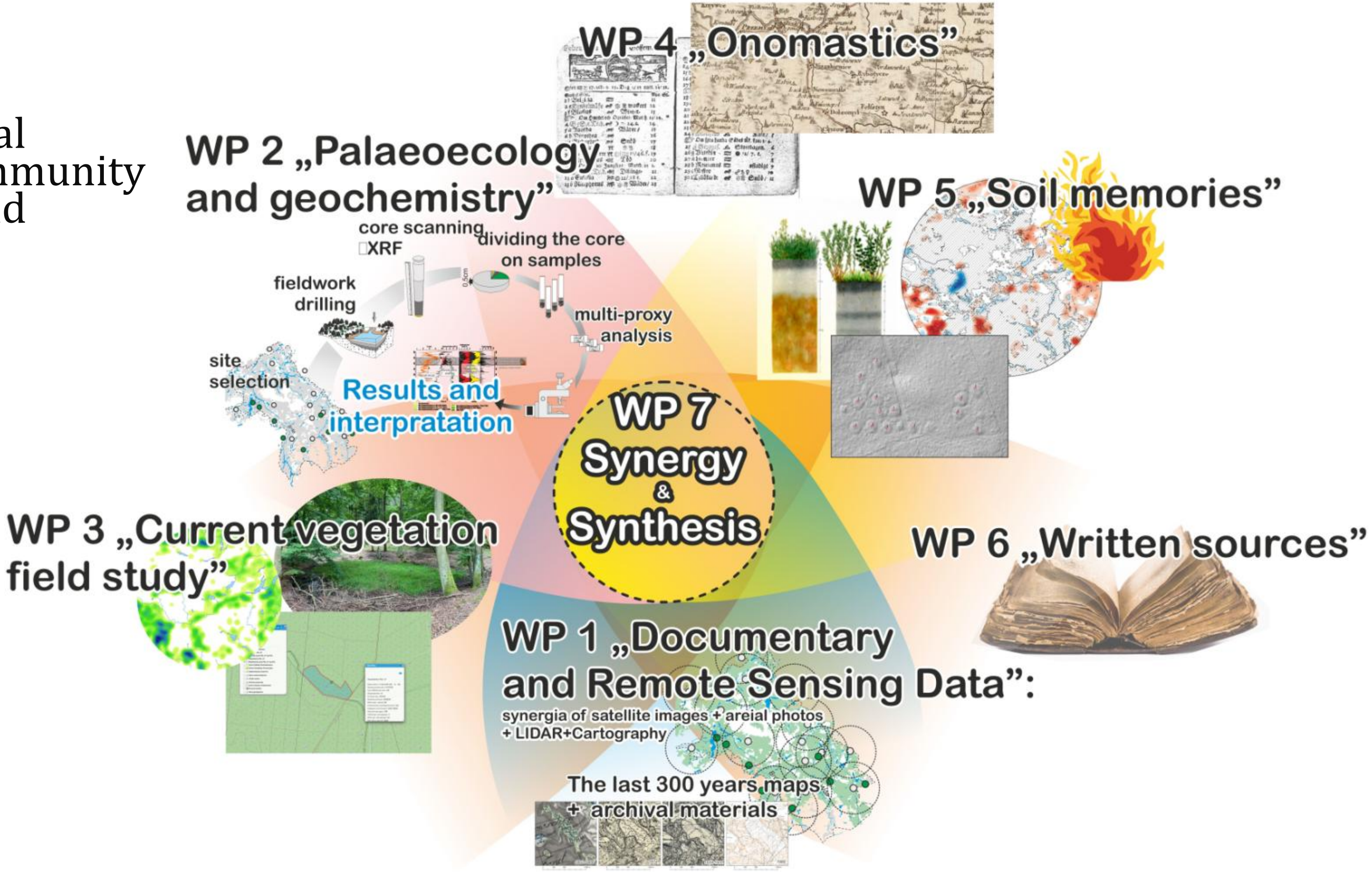
Knovledge level: + scarce; ++ poor; +++ medium; ++++ high; +++++ very high

Goals of the project

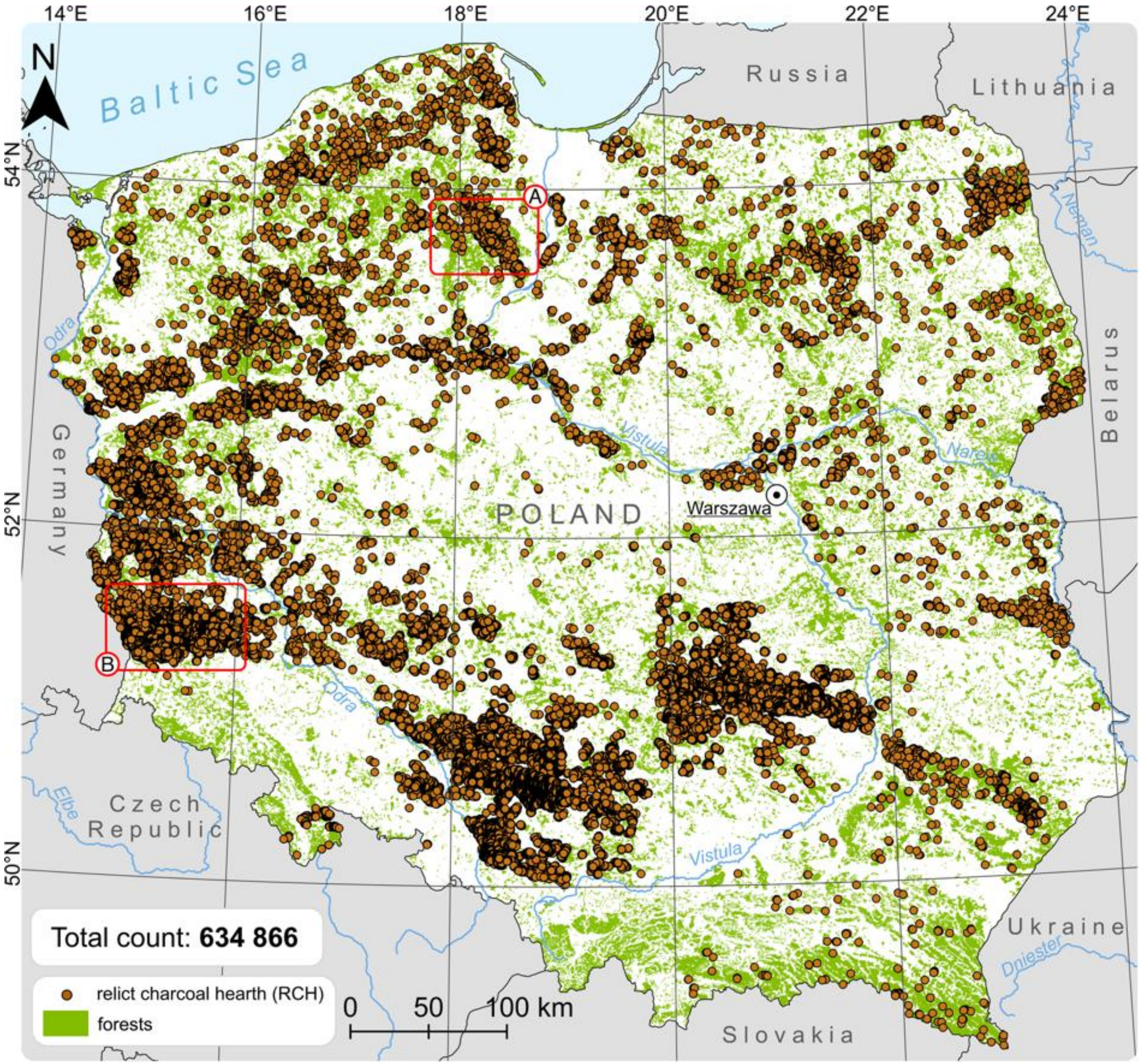
- to identify the timing and intensity of charcoal production in northern Poland in the context of environmental and economic conditions

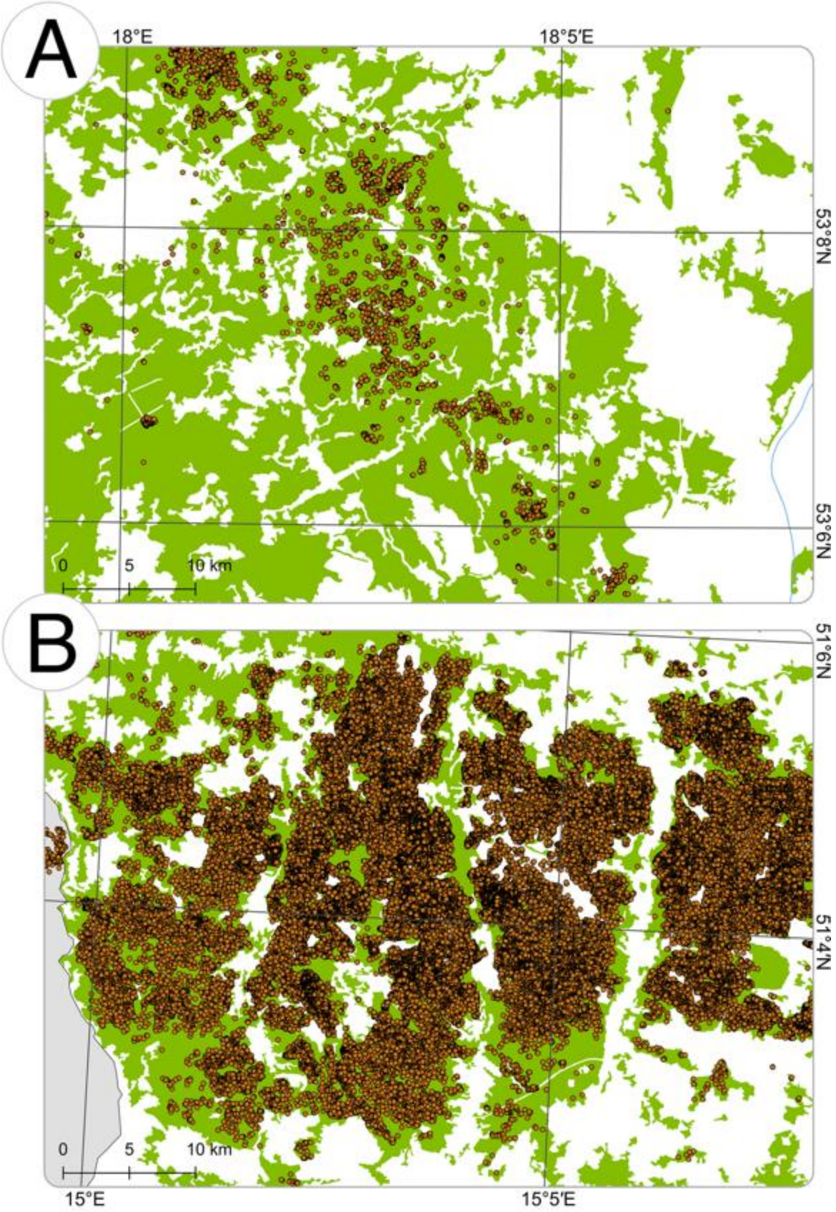
- to evaluate the impact of historical charcoal production on plant community structure, plant-soil feedbacks and soil cover characteristics

  - soil classification
  - soil spatial variability
  - soil nutrients
  - soil organic matter
  - soil sorption complex



Mapping of RCHs in Poland



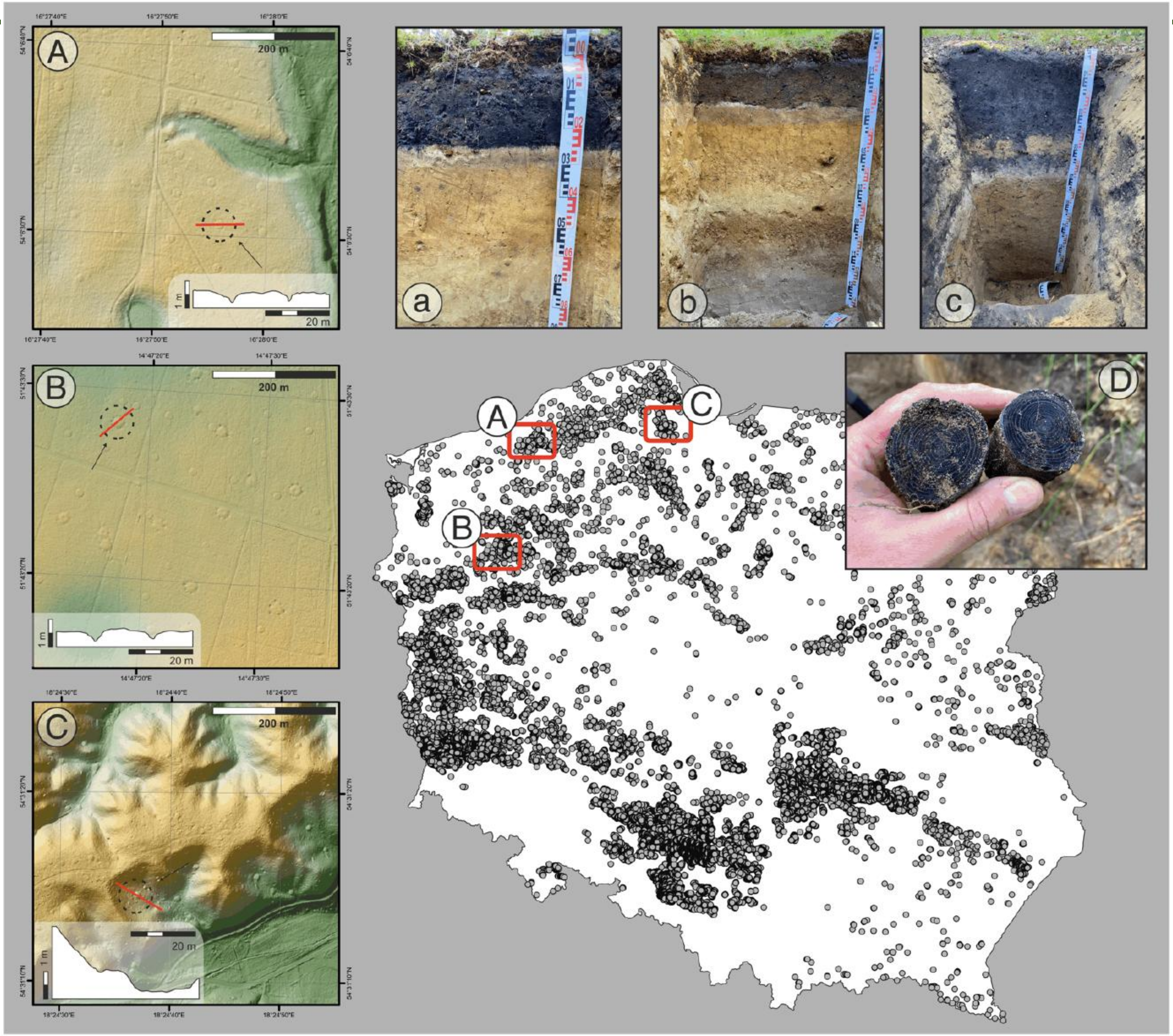


Pedological studies - methods

3 stands:
- Fluvioglacial ladscape (A)
- Aeolian landscape (B)
- Moraine landscape (C)

3 locations (RCHs) per stand

3 soil profiles per location:
- RCH center
- RCH ditch
- Control (≈ 30 m from RCH)



Pedological studies - methods

Soil analyses and methods:

- bulk density, total porosity (gravimetric methods)
- particle-size distribution (pipette and sieve method)
- pH (potentiometrically)
- total organic carbon (TOC) and total N (dry combustion, Vario MacroCube, Elementar)
- total P, Fe and Al (ICP-OES, Avio 200, Perkin Elmer, microwave digestion in 40% HF + 65% HNO_3 + 60% $HClO_4$)
- „free" Fe oxides (ICP-OES, extraction by Jackson procedure)
- amorphous oxides of Fe and Al (ICP-OES, extraction by Schwertmann procedure)
- exchangeable acidity (Sokolov method)
- basic cations (ICP-OES extraction in 1 mol/l ammonium acetate, pH = 7.0)

- radiocarbon dating of charcoal parts

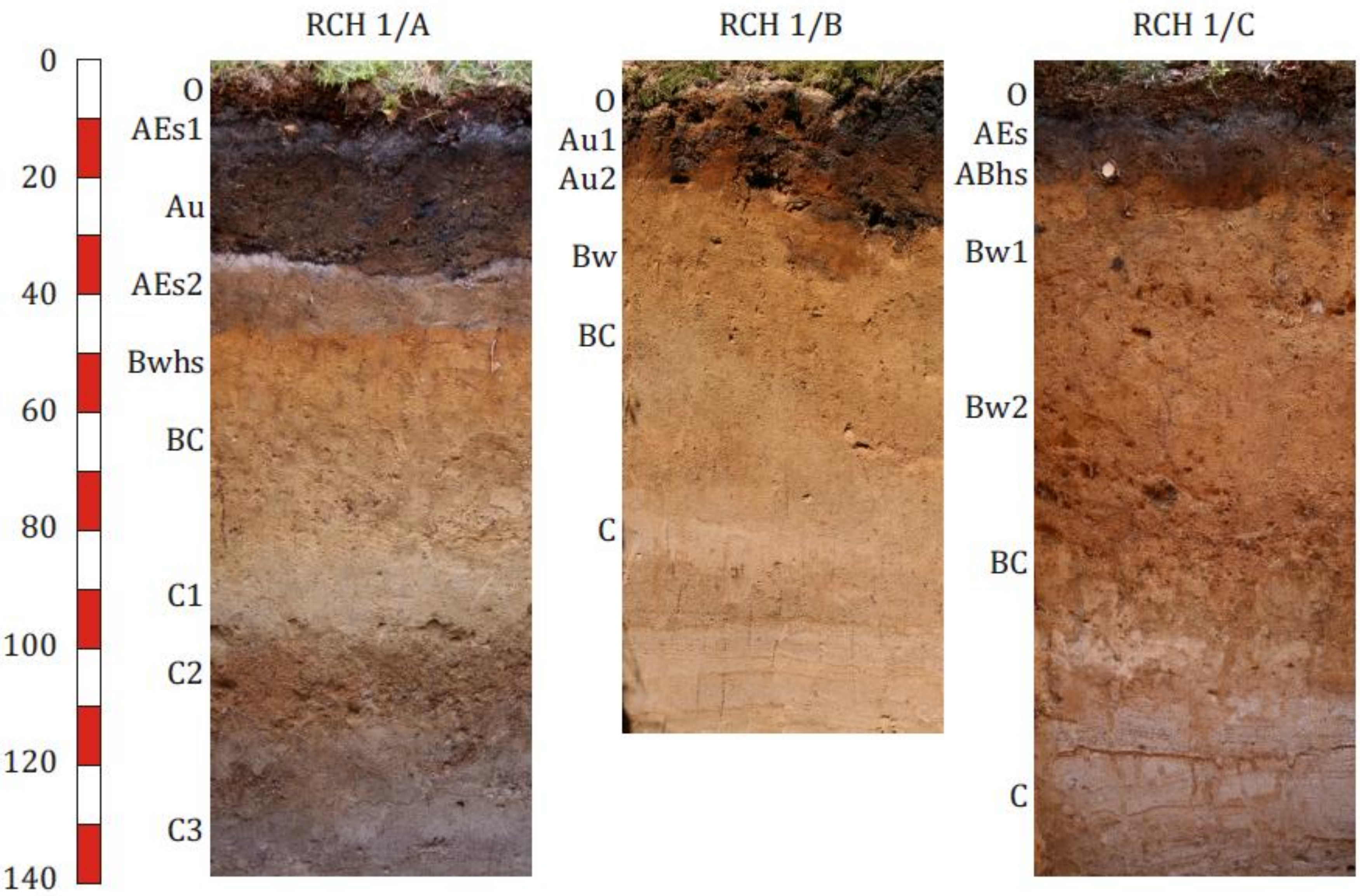
Soil characteristics of RCH soils in fluvioglacial landscape

Stand 1

RCH 1/A
Spolic Technosol
(Arenic, Dystric, Pyric, Protospodic, Transportic)

RCH 1/B
Spolic Technosol
(Arenic, Dystric, Pyric, Protospodic, Transportic)

RCH 1/C
Dystric Brunic Arenosol
(Protospodic)



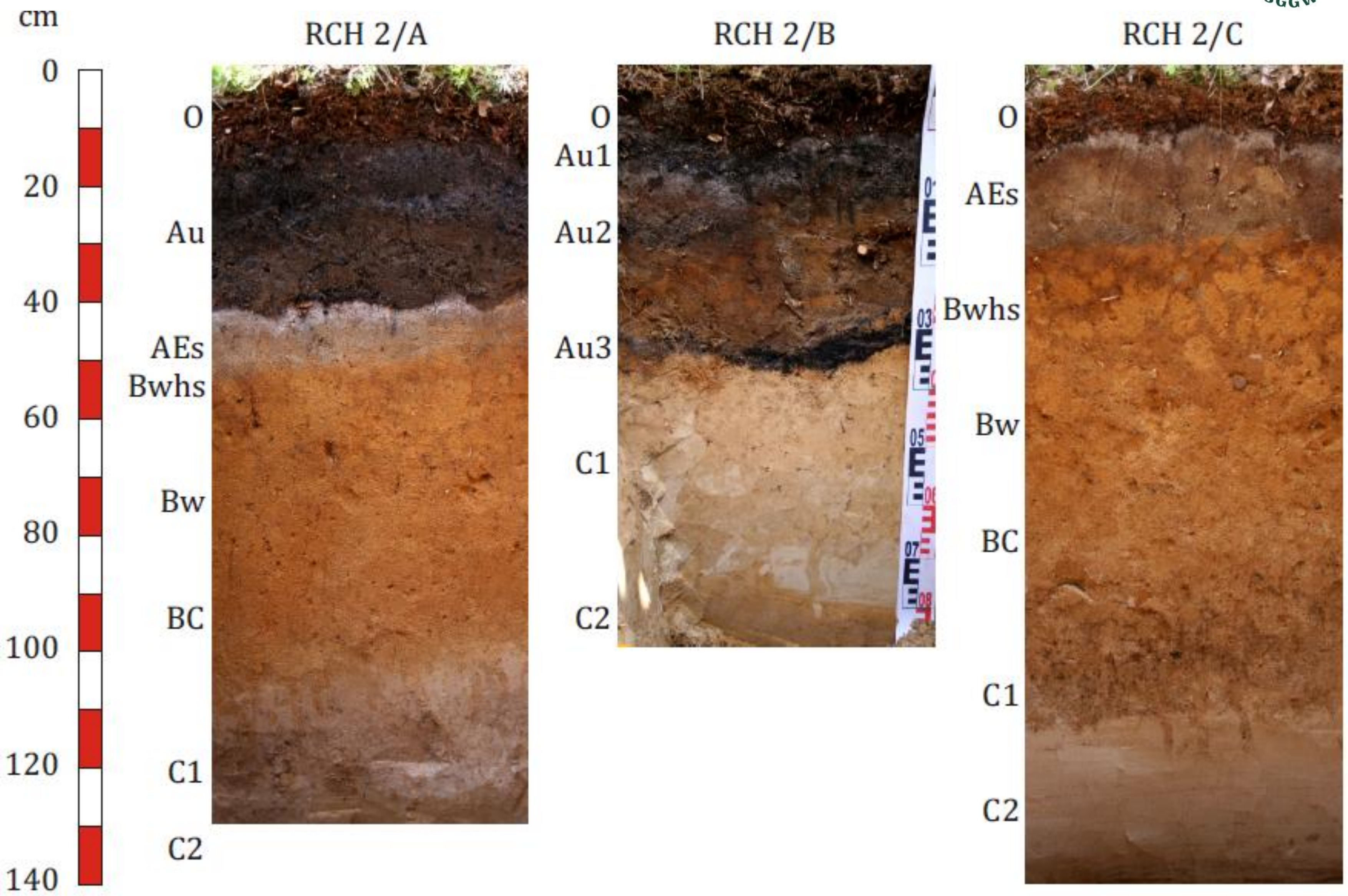
Soil characteristics of RCH soils in fluvioglacial landscape

Stand 2

RCH 1/A
Spolic Technosol
(Arenic, Dystric, Pyric, Protospodic, Transportic)

RCH 1/B
Spolic Technosol
(Arenic, Dystric, Pyric, Protospodic, Transportic)

RCH 1/C
Dystric Brunic Arenosol
(Protospodic)



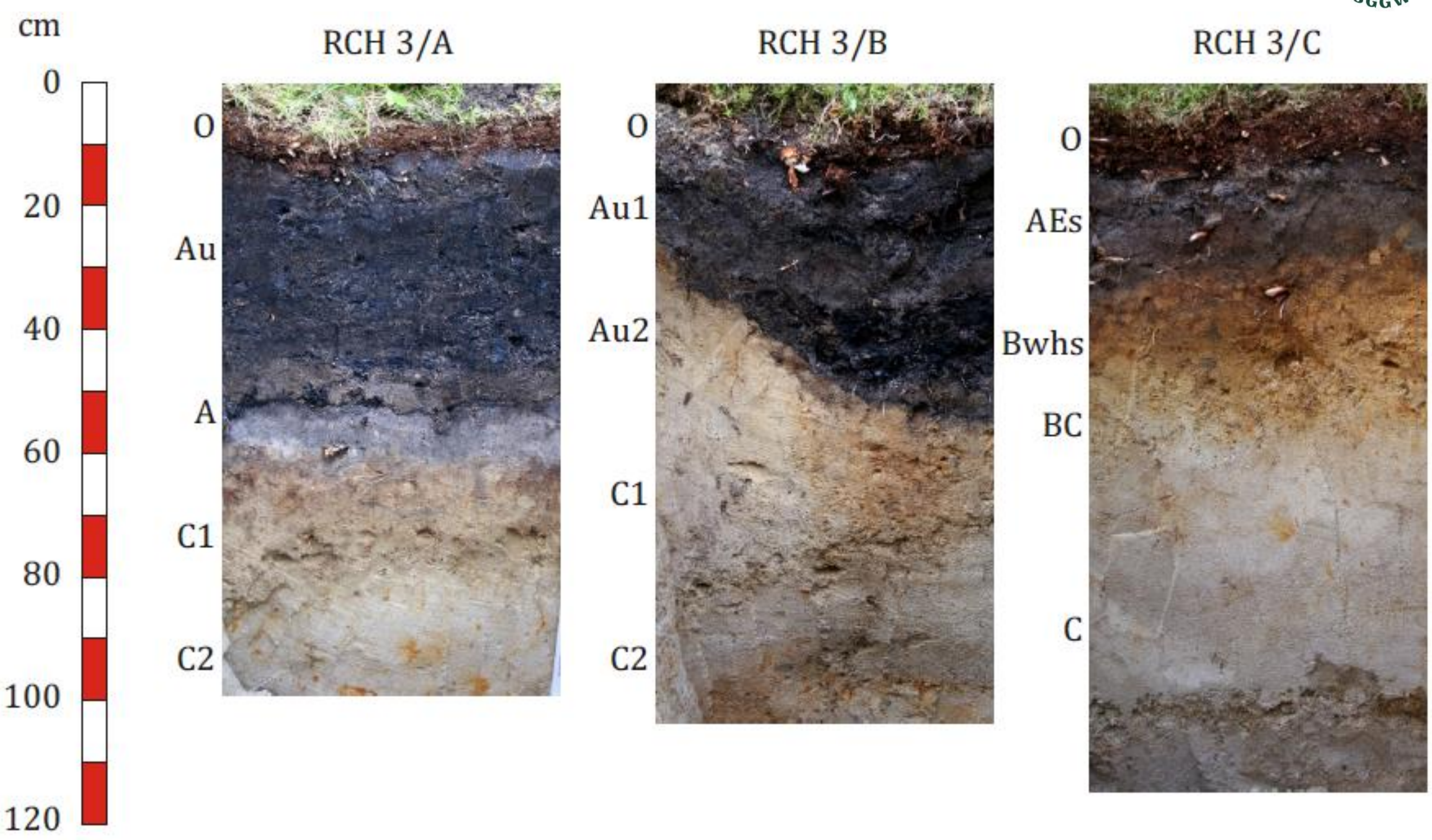
Soil characteristics of RCH soils in fluvioglacial landscape

Stand 3

RCH 1/A
Spolic Technosol
(Arenic, Dystric, Pyric, Protospodic, Transportic)

RCH 1/B
Spolic Technosol
(Arenic, Dystric, Pyric, Protospodic, Transportic)

RCH 1/C
Dystric Brunic Arenosol
(Protospodic)



Soil characteristics of RCH soils in fluvioglacial landscape

Typical features of the RCH soils in fluvioglacial landscape:

- anthropogenic transformation of soil profile
- the presence of anthropogenic horizons/layers (Au) enriched in products of wood pyrolysis

- sandy texture (fine sands of aeolian origin)
- acidic pH
- low content of N
- low contents of total Fe and Al
- physical characteristics typical for sandy soils
- distribution of sesquioxides reflecting weathering and leaching under percolative water regime
- low CEC
- strong predominance of acidic cations in soil sorption complex

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Historical charcoal production as a factor in soil cover heterogeneity in a fluvioglacial landscape – A case study from northern Poland

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ABSTRACT

Although in situ wood thermal processing, as a common practice in European forests in historical times, has been confirmed in many studies, the environmental implications of that process remain poorly explored. In this study, we focused on evaluating the impact of that process on forest vegetation and soil cover heterogeneity in a fluvioglacial landscape dominated by Brunic Arenosols. This study covered three 70–95-year-old stands of Scots pine in northern Poland. Three soil profiles, including from the relict charcoal hearth (RCH), from the surrounding ditch and a control, were examined from each stand, as well as associated vegetation. The studies showed that 19th century charcoal production platforms were overgrown with 20–60% fewer plant species than control stands. The effect on soils varied according to their characteristics. The presence of anthropogenic horizons consisting of a mixture of burnt soil material, ashes, charcoal particles, and other products of wood pyrolysis was the most distinguishing feature of RCH soils classified as Spolic Technosols (Arenic, Dystric, Pyric, Protospodic, Transportic). Typically, these horizons were characterised by lower bulk density, and higher porosity, as well as higher contents of total organic carbon, nitrogen, and exchange cations than the control soils. The differences between the RCH and control soils were highlighted by a comparison between the pools of the components in a soil column (pedon). Clear tendencies were not recorded for pH, the phosphorus content and stocks, the forms of iron and aluminium, the saturation of the soil sorption complex with bases or the trophic index. This may be due to the long-term neutralising effect of forest vegetation, dominated by Scots pine. Moreover, the results of our study may indicate the problem of toxicity of the RCH soils, which should be undertaken, considering the utilitarian importance of the issue.

1. Introduction

Increasing human activity is one of the key factors that has influenced the structure and functions of terrestrial ecosystems over past millennia. Among these terrestrial ecosystems, forests are often considered to be natural or semi-natural environments and refuges of biodiversity. Naturally, in the vast majority of cases, this is a false premise because modern forests often represent stands of simplified and non-natural species compositions that are incompatible with their site conditions. It has been estimated that the large-scale human impact on the forest ecosystems of present-day Poland began in the 13th century (Ślaski, 1951), with the highest impact intensity having been reported

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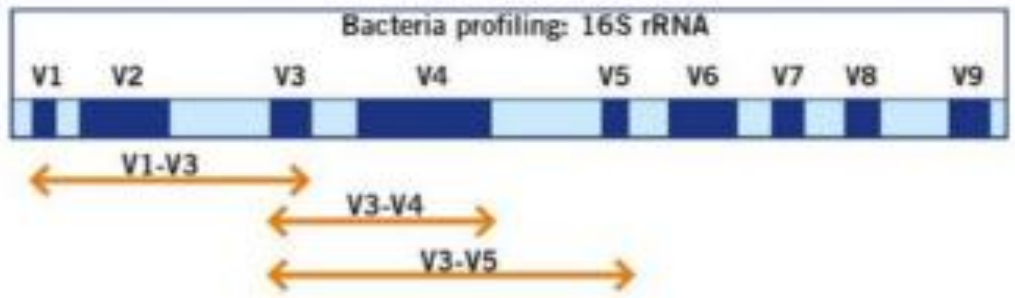
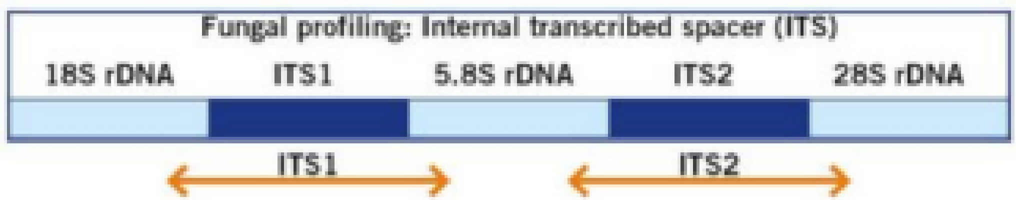
Soil microbiome of RCH soils

- Isolation of genomic DNA from samples taken from the central part of the RCH, the surrounding ditch, and control → amplification of the V3-V4 regions of the 16S rRNA gene (bacterial communities) and ITS1 (fungal communities) → bioinformatic analysis





Soil microbiome of RCH soils

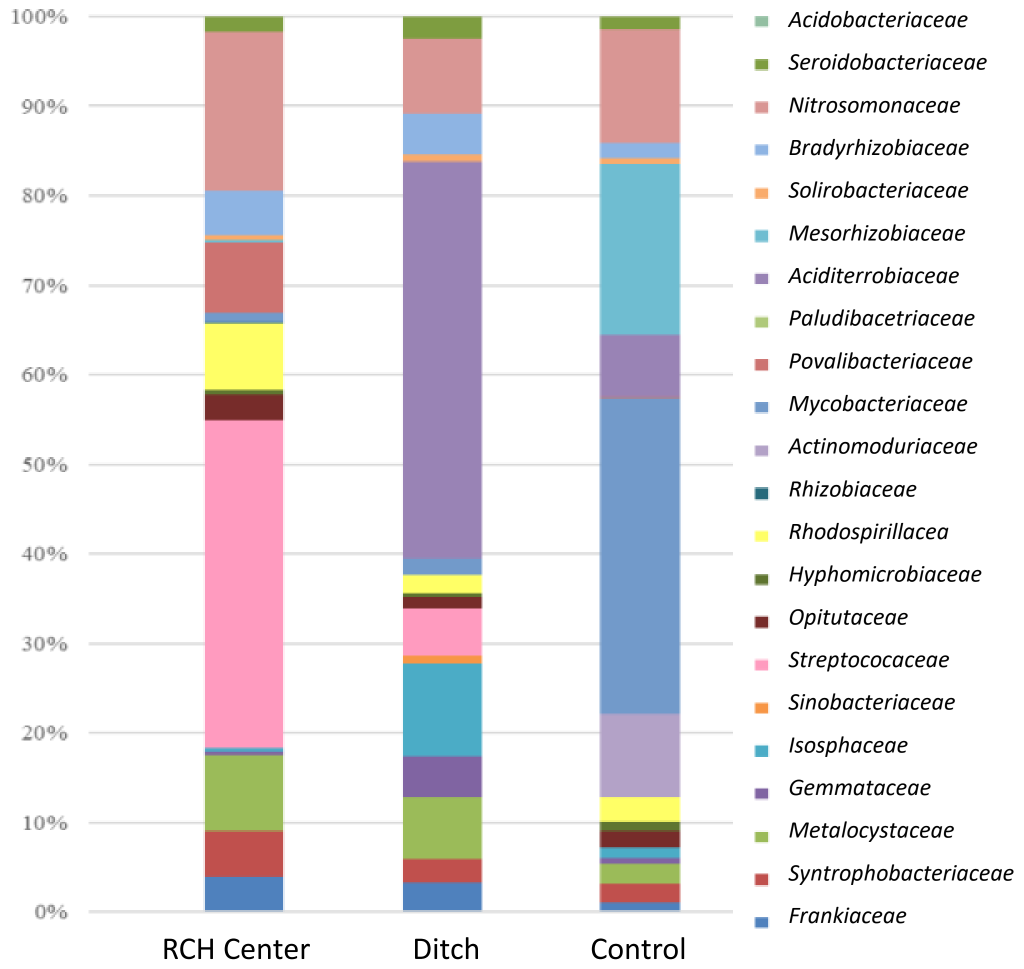
Shannon, Simpson, and Chao diversity index values in the tested soils in fluvioglacial landscape, marked for fungal and bacterial communities

	Biodiversity index	Bacteria			Fungi		
		RCH center	RCH ditch	Control	RCH center	RCH ditch	Control
Stand 1	Shannon	5.70	3.80	6.09	4.56	2.11	3.99
	Simpson	0.99	1.33	0.92	0.83	1.79	0.75
	Chao	196	124	198	184	115	176
Stand 2	Shannon	7.90	3.12	6.88	3.27	1.04	2.25
	Simpson	1.03	1.95	0.99	0.59	1.17	0.66
	Chao	216	146	193	166	123	152
Stand 3	Shannon	4.58	3.17	5.22	5.12	3.34	4,28
	Simpson	0.75	1.09	0.99	1.05	1.48	1.16
	Chao	167	114	158	146	102	137

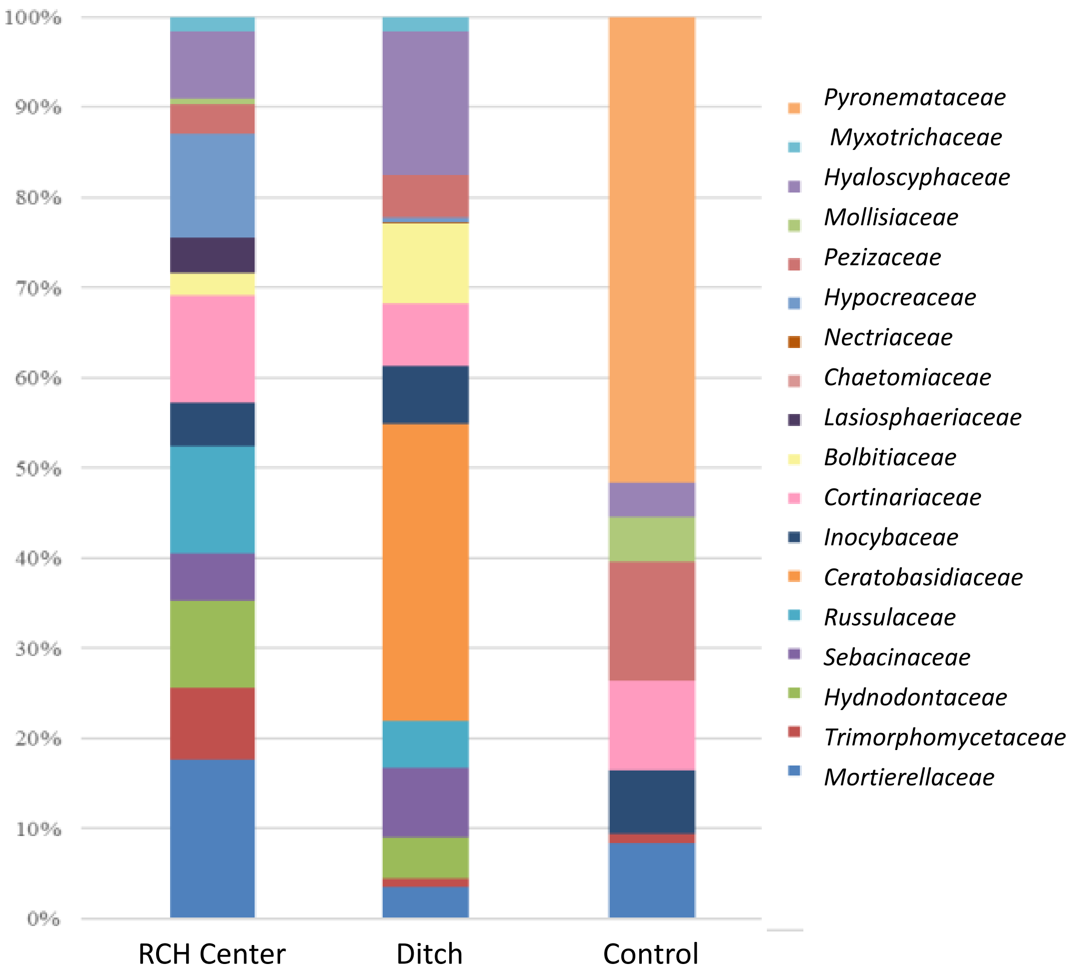
Soil microbiome of RCH soils

Composition of soil microbiome

Bacteria



Fungi



Soil microbiome of RCH soils

Key findings based on microbiological studies:

- RCH and control soils strongly differ in terms of microbiome composition
- Stronger impact was observed for fungi than bacterial communities
- RCH soils are characterized by lower bacterial and fungal diversity compared to control
- The most unfavorable environment for miroorganisms are RCH ditches
- A strong predominance of species typical for areas recovering after fires was observed in RCH soils

The problem of soil toxicity

Germination and root growth inhibition tests

Germination test

% of germinated seeds in relation to control

Stand 1	
RCH center	
A	0.0
Aa	11.1
Es	11.1
BvC	0.0
Bv	11.1
C1	0.0
C2	-11.1
C3	0.0
RCH ditch	
Aa1	11.1
Aa2	11.1
Bv	0.0
BvC	-11.1
C	-11.1
Control	
AEs	0.0
Bv1	11.1
ABhs	11.1
Bv2	0.0
BvC	-11.1
C	0.0

Stand 2	
RCH center	
Aa	55.6
AEs	22.2
Bv	0.0
Bvhs	33.3
BvC	0.0
C1	-11.1
C2	22.2
RCH ditch	
Aa1	22.2
Aa2	0.0
Aa3	22.2
C1	22.2
C2	-11.1
Control	
AEs	10.0
Bvhs	10.0
Bv	20.0
BvC	0.0
C1	10.0
C2	20.0

Stand 3	
RCH center	
A	11.1
Aa	11.1
C1	-11.1
C2	0.0
RCH ditch	
Aa1	11.1
Aa2	11.1
C1	-11.1
C2	0.0
Control	
AEs	0.0
Bhs	11.1
BhsC	-11.1
C	11.1

Root growth inhibition test

inhibition of root grow in relation to control (%)

Stand 1	
RCH center	
A	54.0
Aa	57.2
Es	82.5
BvC	53.9
Bv	42.3
C1	60.7
C2	32.7
C3	76.3
RCH ditch	
Aa1	82.9
Aa2	82.6
Bv	70.7
BvC	79.7
C	64.6
Control	
AEs	84.5
Bv1	67.1
ABhs	83.9
Bv2	39.2
BvC	64.6
C	73.1

Stand 2	
RCH center	
Aa	80.1
AEs	85.5
Bv	79.7
Bvhs	85.7
BvC	79.5
C1	77.1
C2	81.7
RCH ditch	
Aa1	88.7
Aa2	82.2
Aa3	81.9
C1	59.5
C2	82.0
Control	
AEs	85.1
Bvhs	73.7
Bv	71.9
BvC	83.6
C1	68.9
C2	82.6

Stand 3	
RCH center	
A	67.0
Aa	76.4
C1	77.6
C2	71.5
RCH ditch	
Aa1	83.8
Aa2	81.5
C1	79.5
C2	83.1
Control	
AEs	81.2
Bhs	76.6
BhsC	72.0
C	74.7

Toxicity assessment

no toxicity low medium high

Looking for potential sources of toxictiy of RCH soils

Potential sources of soil toxicity

- Extremely low availability of nutrients
- Strong acidification and aluminum stress
- Contamination with trace elements
- Contamination with PAHs
- Other factors not included in this study

Soil nutrient assessment

N (mg/kg)

Stand 1	
RCH center	
A	1328.0
Aa	917.5
Es	381.5
BvC	323.5
Bv	254.0
C1	202.0
C2	92.0
C3	132.0
RCH ditch	
Aa1	1181.0
Aa2	820.5
Bv	256.0
BvC	210.0
C	149.0
Control	
AEs	1022.0
Bv1	481.0
ABhs	460.0
Bv2	211.0
BvC	150.0
C	144.0

Stand 2	
RCH center	
Aa	974.5
AEs	266.5
Bv	415.0
Bvhs	220.5
BvC	164.5
C1	179.5
C2	180.5
RCH ditch	
Aa1	1154.0
Aa2	749.5
Aa3	1383.5
C1	225.5
C2	268.0
Control	
AEs	445.5
Bvhs	422.0
Bv	222.0
BvC	166.5
C1	136.0
C2	126.0

Stand 3	
RCH center	
A	697.5
Aa	424.0
C1	351.5
C2	167.0
RCH ditch	
Aa1	1850.5
Aa2	3206.5
C1	278.5
C2	201.0
Control	
AEs	903.0
Bhs	680.5
BhsC	283.5
C	189.5

P (mg/kg)

Stand 1	
RCH center	
A	240.6
Aa	321.1
Es	312.8
BvC	451.1
Bv	294.4
C1	237.0
C2	339.4
C3	112.3
RCH ditch	
Aa1	244.5
Aa2	361.4
Bv	243.1
BvC	233.1
C	145.5
Control	
AEs	182.4
Bv1	487.8
ABhs	255.3
Bv2	328.5
BvC	167.7
C	115.4

Stand 2	
RCH center	
Aa	255.2
AEs	210.1
Bv	575.1
Bvhs	308.1
BvC	198.1
C1	138.8
C2	211.8
RCH ditch	
Aa1	261.9
Aa2	508.0
Aa3	301.3
C1	216.2
C2	265.6
Control	
AEs	206.1
Bvhs	510.9
Bv	215.2
BvC	152.1
C1	115.9
C2	121.7

Stand 3	
RCH center	
A	323.1
Aa	258.9
C1	587.1
C2	119.9
RCH ditch	
Aa1	243.4
Aa2	187.1
C1	188.7
C2	150.6
Control	
AEs	252.8
Bhs	725.2
BhsC	248.2
C	125.9

K (mg/kg)

Stand 1	
RCH center	
A	6793
Aa	7029
Es	6973
BvC	7139
Bv	8977
C1	8263
C2	8431
C3	6824
RCH ditch	
Aa1	6442
Aa2	7068
Bv	7394
BvC	7333
C	6668
Control	
AEs	5718
Bv1	6149
ABhs	7422
Bv2	7387
BvC	6668
C	6469

Stand 2	
RCH center	
Aa	4916
AEs	5757
Bv	5877
Bvhs	6635
BvC	6543
C1	8781
C2	16137
RCH ditch	
Aa1	6740
Aa2	6485
Aa3	6167
C1	15469
C2	20009
Control	
AEs	4899
Bvhs	5712
Bv	6160
BvC	5541
C1	5647
C2	7762

Stand 3	
RCH center	
A	6183
Aa	5839
C1	6663
C2	6124
RCH ditch	
Aa1	5672
Aa2	5235
C1	7527
C2	7419
Control	
AEs	4568
Bhs	5393
BhsC	6548
C	4361

Soil nutrient assessment

Ca (mg/kg)

Stand 1	
RCH center	
A	1108.1
Aa	1107.6
Es	870.9
BvC	688.8
Bv	1514.9
C1	1423.5
C2	1383.4
C3	914.5
RCH ditch	
Aa1	1056.2
Aa2	1003.0
Bv	1289.9
BvC	1455.8
C	1130.8
Control	
AEs	954.9
Bv1	531.4
ABhs	1360.3
Bv2	1395.1
BvC	1131.9
C	990.4

Stand 2	
RCH center	
Aa	645.9
AEs	711.6
Bv	898.9
Bvhs	1251.7
BvC	1336.5
C1	1144.5
C2	1651.2
RCH ditch	
Aa1	919.1
Aa2	980.2
Aa3	793.1
C1	1407.0
C2	1510.1
Control	
AEs	685.6
Bvhs	597.5
Bv	1001.0
BvC	926.0
C1	951.1
C2	821.1

Stand 3	
RCH center	
A	650.1
Aa	564.2
C1	550.3
C2	956.3
RCH ditch	
Aa1	621.0
Aa2	813.3
C1	1426.5
C2	993.5
Control	
AEs	699.5
Bhs	422.4
BhsC	759.9
C	827.9

Mg (mg/kg)

Stand 1	
RCH center	
A	335.7
Aa	230.5
Es	207.2
BvC	163.0
Bv	462.1
C1	465.0
C2	613.5
C3	335.2
RCH ditch	
Aa1	205.0
Aa2	220.4
Bv	431.9
BvC	666.4
C	235.9
Control	
AEs	117.3
Bv1	116.6
ABhs	311.0
Bv2	479.4
BvC	520.3
C	310.1

Stand 2	
RCH center	
Aa	115.4
AEs	230.6
Bv	199.0
Bvhs	475.5
BvC	520.7
C1	433.9
C2	746.7
RCH ditch	
Aa1	271.6
Aa2	331.5
Aa3	185.3
C1	681.5
C2	1228.8
Control	
AEs	255.6
Bvhs	303.0
Bv	389.8
BvC	481.7
C1	303.3
C2	285.1

Stand 3	
RCH center	
A	151.0
Aa	153.9
C1	155.4
C2	352.9
RCH ditch	
Aa1	172.2
Aa2	230.1
C1	183.1
C2	126.0
Control	
AEs	186.5
Bhs	141.1
BhsC	428.8
C	301.7

TOC:N

Stand 1	
RCH center	
A	28.5
Aa	33.5
Es	19.5
BvC	15.7
Bv	6.2
C1	3.8
C2	7.2
C3	1.5
RCH ditch	
Aa1	35.8
Aa2	19.6
Bv	10.3
BvC	5.2
C	2.7
Control	
AEs	20.6
Bv1	14.1
ABhs	12.7
Bv2	3.2
BvC	2.0
C	1.7

Stand 2	
RCH center	
Aa	36.1
AEs	22.7
Bv	17.2
Bvhs	6.9
BvC	3.2
C1	1.7
C2	3.6
RCH ditch	
Aa1	27.7
Aa2	24.4
Aa3	30.2
C1	6.4
C2	4.6
Control	
AEs	22.3
Bvhs	13.6
Bv	5.1
BvC	3.7
C1	1.8
C2	2.0

Stand 3	
RCH center	
A	42.3
Aa	20.2
C1	12.6
C2	3.9
RCH ditch	
Aa1	29.4
Aa2	25.4
C1	8.1
C2	2.8
Control	
AEs	21.2
Bhs	15.8
BhsC	8.1
C	1.8

Soil pH and aluminum stress

pH-H_2O

Stand 1	
RCH center	
A	3.5
Aa	4.2
Es	4.5
BvC	4.5
Bv	4.5
C1	4.5
C2	4.4
C3	4.7
RCH ditch	
Aa1	3.4
Aa2	3.7
Bv	4.4
BvC	4.6
C	4.8
Control	
AEs	3.6
Bv1	4.3
ABhs	4.5
Bv2	4.6
BvC	4.7
C	4.7

Stand 2	
RCH center	
Aa	3.8
AEs	4.2
Bv	4.7
Bvhs	4.6
BvC	4.6
C1	4.6
C2	4.3
RCH ditch	
Aa1	3.2
Aa2	4.1
Aa3	4.1
C1	4.6
C2	4.4
Control	
AEs	3.9
Bvhs	4.6
Bv	4.7
BvC	4.7
C1	4.7
C2	4.6

Stand 3	
RCH center	
A	4.1
Aa	4.5
C1	4.6
C2	4.7
RCH ditch	
Aa1	3.5
Aa2	3.5
C1	4.2
C2	4.5
Control	
AEs	3.9
Bhs	4.4
BhsC	4.4
C	4.6

Ca:Al (mol/mol)

Stand 1	
RCH center	
A	0.03
Aa	0.03
Es	0.02
BvC	0.02
Bv	0.02
C1	0.03
C2	0.04
C3	0.02
RCH ditch	
Aa1	0.01
Aa2	0.00
Bv	0.02
BvC	0.03
C	0.07
Control	
AEs	0.02
Bv1	0.01
ABhs	0.05
Bv2	0.07
BvC	0.18
C	0.11

Stand 2	
RCH center	
Aa	0.01
AEs	0.01
Bv	0.06
Bvhs	0.08
BvC	0.05
C1	0.00
C2	0.01
RCH ditch	
Aa1	0.00
Aa2	0.01
Aa3	0.03
C1	0.01
C2	0.02
Control	
AEs	0.01
Bvhs	0.05
Bv	0.13
BvC	0.15
C1	0.24
C2	0.12

Stand 3	
RCH center	
A	0.04
Aa	0.06
C1	0.15
C2	0.43
RCH ditch	
Aa1	0.01
Aa2	0.02
C1	0.03
C2	0.09
Control	
AEs	0.01
Bhs	0.03
BhsC	0.05
C	0.18

Critical value: Ca:Al = 1.0

Contamination with trace elements

Mn (mg/kg)

Stand 1		Stand 2		Stand 3	
RCH center		RCH center		RCH center	
A	157.2	Aa	137.7	A	91.3
Aa	95.7	AEs	28.8	Aa	33.1
Es	23.8	Bv	12.4	C1	7.6
BvC	11.3	Bvhs	4.9	C2	5.4
Bv	5.3	BvC	2.6		
C1	3.2	C1	2.2		
C2	2.0	C2	3.1		
C3	1.8				
RCH ditch		RCH ditch		RCH ditch	
Aa1	172.8	Aa1	122.1	Aa1	223.6
Aa2	44.5	Aa2	36.0	Aa2	435.6
Bv	10.9	Aa3	138.6	C1	11.9
BvC	4.7	C1	6.6	C2	3.8
C	2.7	C2	4.7		
Control		Control		Control	
AEs	115.3	AEs	48.3	AEs	75.6
Bv1	13.9	Bvhs	11.2	Bhs	14.8
ABhs	22.8	Bv	5.2	BhsC	9.3
Bv2	2.1	BvC	4.1	C	2.7
BvC	1.8	C1	2.2		
C	2.2	C2	2.1		

Cu (mg/kg)

Stand 1		Stand 2		Stand 3	
RCH center		RCH center		RCH center	
A	5.3	Aa	4.0	A	4.8
Aa	4.2	AEs	2.4	Aa	3.2
Es	4.2	Bv	3.2	C1	4.1
BvC	3.6	Bvhs	3.6	C2	3.7
Bv	3.5	BvC	4.0		
C1	4.2	C1	4.0		
C2	7.0	C2	5.3		
C3	4.6				
RCH ditch		RCH ditch		RCH ditch	
Aa1	6.7	Aa1	5.0	Aa1	4.0
Aa2	4.4	Aa2	3.6	Aa2	6.5
Bv	5.3	Aa3	5.4	C1	3.8
BvC	4.5	C1	4.3	C2	3.5
C	4.6	C2	8.1		
Control		Control		Control	
AEs	3.9	AEs	4.3	AEs	2.3
Bv1	3.5	Bvhs	3.6	Bhs	2.4
ABhs	3.6	Bv	4.6	BhsC	2.7
Bv2	4.4	BvC	4.8	C	2.2
BvC	3.5	C1	4.5		
C	3.5	C2	3.2		

Zn (mg/kg)

Stand 1		Stand 2		Stand 3	
RCH center		RCH center		RCH center	
A	9.6	Aa	11.7	A	19.8
Aa	11.5	AEs	7.3	Aa	5.7
Es	5.3	Bv	15.6	C1	20.0
BvC	15.5	Bvhs	13.5	C2	6.4
Bv	10.0	BvC	9.6		
C1	7.0	C1	7.2		
C2	16.3	C2	13.7		
C3	3.5				
RCH ditch		RCH ditch		RCH ditch	
Aa1	5.3	Aa1	9.2	Aa1	8.9
Aa2	7.0	Aa2	9.5	Aa2	15.3
Bv	9.2	Aa3	12.4	C1	9.2
BvC	6.4	C1	14.3	C2	9.3
C	7.4	C2	25.2		
Control		Control		Control	
AEs	9.6	AEs	5.9	AEs	5.9
Bv1	13.4	Bvhs	14.8	Bhs	13.6
ABhs	14.2	Bv	12.4	BhsC	14.0
Bv2	14.7	BvC	8.7	C	10.8
BvC	5.8	C1	12.8		
C	5.3	C2	9.7		

Contamination with trace elements

Ni (mg/kg)

Stand 1		Stand 2		Stand 3	
RCH center		RCH center		RCH center	
A	2.6	Aa	3.0	A	1.9
Aa	3.1	AEs	0.4	Aa	1.1
Es	1.9	Bv	1.9	C1	3.3
BvC	4.2	Bvhs	3.1	C2	1.9
Bv	3.6	BvC	2.3		
C1	3.8	C1	1.8		
C2	7.8	C2	4.5		
C3	2.0				
RCH ditch		RCH ditch		RCH ditch	
Aa1	2.8	Aa1	3.2	Aa1	1.0
Aa2	2.6	Aa2	1.4	Aa2	2.1
Bv	4.8	Aa3	2.0	C1	1.9
BvC	3.2	C1	4.0	C2	1.8
C	2.5	C2	8.7		
Control		Control		Control	
AEs	1.2	AEs	0.5	AEs	0.7
Bv1	2.1	Bvhs	2.4	Bhs	3.3
ABhs	3.2	Bv	5.4	BhsC	3.7
Bv2	4.0	BvC	2.8	C	1.7
BvC	1.7	C1	3.0		
C	1.2	C2	2.2		

Pb (mg/kg)

Stand 1		Stand 2		Stand 3	
RCH center		RCH center		RCH center	
A	24.0	Aa	14.2	A	8.2
Aa	6.3	AEs	9.3	Aa	9.2
Es	10.3	Bv	4.2	C1	4.1
BvC	3.7	Bvhs	2.5	C2	1.7
Bv	3.0	BvC	2.6		
C1	2.7	C1	1.1		
C2	4.7	C2	2.8		
C3	1.5				
RCH ditch		RCH ditch		RCH ditch	
Aa1	31.0	Aa1	14.6	Aa1	18.4
Aa2	12.5	Aa2	10.9	Aa2	9.5
Bv	3.2	Aa3	8.6	C1	3.5
BvC	2.4	C1	3.1	C2	2.1
C	2.1	C2	4.4		
Control		Control		Control	
AEs	13.5	AEs	10.7	AEs	13.1
Bv1	7.6	Bvhs	3.1	Bhs	5.0
ABhs	2.6	Bv	2.5	BhsC	2.6
Bv2	3.8	BvC	2.2	C	3.0
BvC	1.9	C1	1.8		
C	1.5	C2	2.0		

Cr (mg/kg)

Stand 1		Stand 2		Stand 3	
RCH center		RCH center		RCH center	
A	7.2	Aa	6.4	A	6.6
Aa	7.7	AEs	3.8	Aa	5.9
Es	5.2	Bv	5.2	C1	7.4
BvC	7.7	Bvhs	6.1	C2	2.9
Bv	9.6	BvC	5.4		
C1	8.0	C1	3.6		
C2	10.6	C2	16.9		
C3	4.4				
RCH ditch		RCH ditch		RCH ditch	
Aa1	5.7	Aa1	8.5	Aa1	4.7
Aa2	7.2	Aa2	6.4	Aa2	5.2
Bv	6.7	Aa3	4.7	C1	4.3
BvC	5.8	C1	13.9	C2	2.5
C	5.2	C2	30.5		
Control		Control		Control	
AEs	4.6	AEs	3.8	AEs	4.6
Bv1	5.6	Bvhs	5.3	Bhs	7.4
ABhs	6.6	Bv	5.4	BhsC	5.9
Bv2	6.7	BvC	3.6	C	4.8
BvC	2.7	C1	3.5		
C	2.9	C2	6.7		

Contamination with trace elements

Trace element contents in charcoal particles

Profile and horizon	Mn mg/kg	Cu mg/kg	Zn mg/kg	Ni mg/kg	Pb mg/kg	Cr mg/kg	V mg/kg	Co mg/kg
1/1A - Aa	437.5	5.6	113.8	26.1	21.0	13.5	58.8	4.2
1/1B - Aa1	240.1	9.1	38.3	23.2	241.8	14.7	40.1	1.7
1/1B - Aa2	415.0	4.4	48.5	44.9	122.7	30.3	100.8	3.9
1/2A - Aa	386.8	8.7	118.9	32.3	192.2	13.5	68.0	4.4
1/2B - Aa1	197.0	12.5	57.5	14.2	279.0	15.9	25.1	2.4
1/2B - Aa2	280.8	4.2	85.3	18.6	18.3	7.2	24.6	5.1
1/2B - Aa3	415.0	4.7	113.3	15.9	17.8	3.0	14.4	5.1
1/3A - Aa	197.0	5.7	161.9	28.8	18.9	7.5	48.2	3.5
1/3B - Aa1	125.8	5.4	75.4	19.3	215.9	18.4	50.6	2.8
1/3B - Aa2	116.2	4.6	99.7	22.7	32.7	16.0	59.8	3.0

Contamination with PAHs

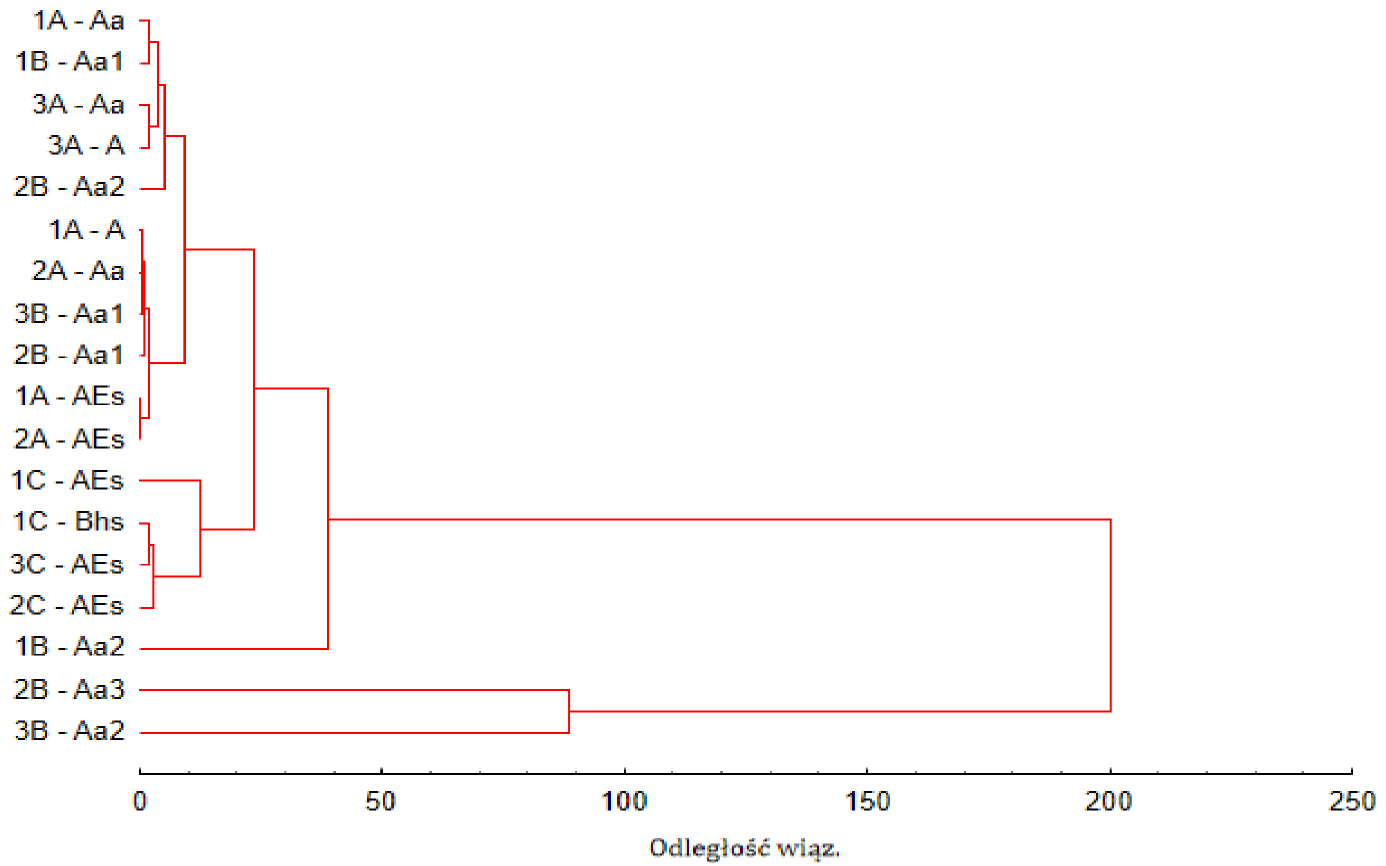
Content of PAHs in the studied soils (μg/kg)

	Stand 1							Stand 2						Stand 3				
	Center	Center	Center	Ditch	Ditch	Control	Control	Center	Center	Ditch	Dich	Ditch	Control	Center	Center	Dich	Ditch	Control
	Aa	A	AEs	Aa1	Aa2	AEs	Bhs	Aa	AEs	Aa1	Aa2	Aa3	AEs	Aa	A	Aa1	Aa2	AEs
Naphthalene	0.000	0.242	0.000	0.000	0.000	0.000	0.534	0.482	0.000	0.920	0.167	7.770	0.519	0.220	0.000	0.690	0.000	0.000
Acenaphthylene	0.000	0.010	0.000	0.115	0.000	0.098	0.016	0.011	0.040	0.000	0.161	9.343	0.071	0.019	0.073	0.000	0.858	0.000
Anthracene	0.000	0.000	0.000	0.000	0.000	0.000	0.022	0.000	0.000	0.127	0.000	66.672	0.000	0.000	0.000	0.009	0.582	0.000
Fluorene	3.366	0.422	0.000	3.821	14.986	6.632	0.767	0.586	0.000	0.244	0.000	0.000	0.983	0.875	2.095	0.376	48.416	2.435
Fluoranthene	0.000	0.000	0.056	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Benzo(a)anthracene	0.697	0.099	0.029	0.874	0.439	2.175	0.797	0.117	0.000	0.073	0.000	0.000	0.188	0.713	1.462	0.053	0.000	0.267
Pyrene	1.300	0.151	0.000	1.376	0.000	4.472	1.163	0.473	0.000	0.000	3.220	0.000	1.293	0.793	0.110	0.430	0.000	1.292
Chrysene	1.245	0.317	0.000	0.000	18.427	5.254	0.067	0.242	0.000	0.169	1.391	59.158	0.054	0.646	0.426	0.032	36.961	0.000
Benzo(a)pyrene	0.306	0.037	0.000	0.746	0.000	1.968	0.182	0.000	0.019	0.000	0.287	5.947	0.181	0.425	0.435	0.011	6.483	0.418
Dibenzo(ah)anthracene	0.174	0.060	0.000	0.127	0.618	0.430	0.000	0.044	0.000	0.000	0.000	4.299	0.386	0.211	0.074	0.005	9.412	0.302
Benzo(b)fluoranthene	0.859	0.304	0.000	1.519	4.158	3.067	1.091	0.160	0.034	0.128	0.000	26.647	0.568	1.051	1.406	0.047	31.978	0.639
Benzo(k)fluoranthene	0.425	0.109	0.000	0.219	0.258	1.109	0.172	0.000	0.018	0.118	0.280	3.734	0.263	0.340	0.486	0.003	8.784	0.268
Benzo(ghi)perylene	0.632	0.160	0.024	1.445	2.868	4.964	5.520	0.156	0.000	0.043	1.149	0.000	7.779	0.484	0.104	0.000	16.175	5.316
Indeo(1,2,3-cd)pyrene	0.433	0.162	0.000	0.464	1.055	1.986	0.666	0.000	0.012	0.052	0.000	2.130	0.457	0.537	0.096	0.013	14.812	0.398
SUM	9.436	2.072	0.110	10.705	42.809	32.155	10.997	2.271	0.124	1.874	6.655	185.701	12.742	6.313	6.767	1.671	174.462	11.336

Contamination with PAHs

Contribution of PAHs (% in total content)

	Naphthalene	Acenaphthylene	Anthracene	Fluorene	Fluoranthene	Benzo(a)anthracene	Pyrene	Chrysene	Benzo(a)pyrene	Dibenzo(ah)anthracene	Benzo(b)fluoranthene	Benzo(k)fluoranthene	Benzo(ghi)perylene	Indeo(1,2,3-cd)pyrene
1A - Aa				35.7		7.4	13.8	13.2	3.2	1.8	9.1	4.5	6.7	4.6
1B - Aa1		1.1		35.7		8.2	12.9		7.0	1.2	14.2	2.0	13.5	4.3
3A - Aa	3.5	0.3		13.9		11.3	12.6	10.2	6.7	3.3	16.6	5.4	7.7	8.5
3A - A		1.1		31.0		21.6	1.6	6.3	6.4	1.1	20.8	7.2	1.5	1.4
2B - Aa2	2.5	2.4					48.4	20.9	4.3			4.2	17.3	
1A - A	11.7	0.5		20.4		4.8	7.3	15.3	1.8	2.9	14.7	5.2	7.7	7.8
2A - Aa	21.2	0.5		25.8		5.2	20.8	10.7		1.9	7.0		6.9	
3B - Aa1	41.3		0.5	22.5		3.2	25.8	1.9	0.7	0.3	2.8	0.2		0.8
2B - Aa1	49.1		6.8	13.0		3.9		9.0			6.8	6.3	2.3	2.8
1A - AEs					51.0	26.8							22.3	
2A - AEs		32.7							15.5		27.8	14.6		9.4
1C - AEs		0.3		20.6		6.8	13.9	16.3	6.1	1.3	9.5	3.4	15.4	6.2
1C - Bhs	4.9	0.1	0.2	7.0		7.3	10.6	0.6	1.7		9.9	1.6	50.2	6.1
3C - AEs				21.5		2.4	11.4		3.7	2.7	5.6	2.4	46.9	3.5
2C - AEs	4.1	0.6		7.7		1.5	10.1	0.4	1.4	3.0	4.5	2.1	61.0	3.6
1B - Aa2				35.0		1.0		43.0		1.4	9.7	0.6	6.7	2.5
2B - Aa3	4.2	5.0	35.9					31.9	3.2	2.3	14.3	2.0	0.0	1.1
3B - Aa2		0.5	0.3	27.8				21.2	3.7	5.4	18.3	5.0	9.3	8.5



Conclusions

- This preliminary research on soil toxicity at historical charcoal production sites in forests constitute the first report of this phenomenon
- The results indicate soil toxicity at these sites, as confirmed by microbiological data and plant root growth inhibition tests
- Soil toxicity at historical charcoal production sites in forests is a complex problem that should be considered in the context of human activity and natural conditions. At the study site, soil toxicity is likely the function of the sandy soil's natural characteristics and centuries of pine cultivation (low pH and nutrient content, aluminum stress) and introduction of contaminants and by-products of wood pyrolysis in the form of trace elements and PAHs.
- Given the documented scale of the phenomenon, soil toxicity at historical charcoal production sites presents cognitive and practical challenges for forest management and requires more extensive research that considers diverse habitat conditions, vegetation species composition, and other variables.