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PYROPHOB – A post-fire ecosystem research project to inform management for resilient forest development

PYROPHOB – Ein Ökosystemforschungsprojekt auf Waldbrandflächen als Grundlage für das Management einer resilienten Waldentwicklung

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Abstract

PYROPHOB (fire-resistant) is the name of an interdisciplinary research project that is running for five years from 2020 to 2025. In this project, eight institutions are investigating the ecological effects of wildfires and subsequent forest management strategies in pine forests (plantations) in Brandenburg (NE Germany), with the aim of formulating practical recommendations for managing fire-prone forests and the effective restoration of post-fire forest areas. We provide a brief overview of what is known about the effects of wildfire on abiotic and biotic parameters in temperate pine forests, as well as the effects of silvicultural treatments. To date, we know little about how different components of biodiversity are linked in post-fire forest ecosystems and how management affects their functioning. By describing the project, we illustrate the requirements for the implementation of such an applied research project. We emphasize the importance of the study design for dealing with interdisciplinary questions and for the quantitative synthesis of research results. The project comprises a set of standardised field plots in two wildfire areas covering different post-fire management options. Fifteen study sites were established, including two reference sites in unburned pine stands, each with ten study plots as replicates. In situ nitrogen mineralisation, litter decomposition tests and soil biological activity are used for soil biological characterisation. Microclimate data is measured continuously. Standing and lying dead wood and tree regeneration are recorded as key indicators of the success of forestry treatments. Further methods comprise terrestrial laser scanning, remote sensing techniques as well as surveys of vegetation and above and below ground biomass. Identification of fruiting body-forming fungi, phytoparasites and ectomycorrhizal fungi is supported by marker gene sequencing. Faunistic indicators comprise predatory soil arthropods (pairs of emergence tents and soil traps), saproxylic beetles (flight traps and funnel traps), moths (automated window traps), mammals (camera traps), and breeding birds (visual and acoustic observation). We discuss the strengths and limitations of the project design. We are able to systematically capture short-term temporal shifts in parameters and trends in post-fire ecosystem development. Research in a real landscape with ongoing environmental changes and interventions presents challenges for experimental design, data analysis and interpretation. The drivers of ecosystem development are rarely completely independent or perfectly balanced, and lack of replication is inevitable. The two fires did not occur in the same year and season, resulting in different initial conditions for the colonisation of the burned areas. Finally, a large part of one study area was again affected by a fire in 2022, which destroyed direct comparability with the other sites. Despite these obstacles the project has started to generate valuable results to address management and conservation challenges.

Keywords: biotic interactions, deadwood, ecological monitoring, ecosystem services, forest management, microclimate, soil, biodiversity, forest fire

Erweiterte deutsche Zusammenfassung am Ende des Artikels

1. Background and aim of the project

PYROPHOB means fire-resistant and is the eponym of an interdisciplinary scientific research project, entitled “Strategies for developing pyrophobic and climate change resilient forests on wildfire areas”. The project is investigating the ecological effects of forest fire events and different subsequent forest restoration management strategies on post-fire forest development in Brandenburg, NE Germany and aims to formulate recommendations for practitioners and decision-makers on how to manage such areas.

In Germany, forests cover about one third of the country’s surface (BMEL 2016) and, along with arable land and grasslands, are the most important ecosystems severely affected by anthropogenic land use. The natural vegetation cover, which mainly consisted of deciduous forests has been largely replaced by production forests, mainly represented by even-aged Scots pine and spruce plantations (Leuschner & Ellenberg 2017). In contrast to the Mediterranean or the boreal zones, the role of fire in the functioning of local forest ecosystems has traditionally been marginalized in the temperate forests of Central Europe (Tinner et al. 2005, Niklasson et al. 2010, Müller 2019). Nevertheless, local wildfires (i.e., "any unplanned and uncontrolled fire started on shrubs or forest" according to the definition of Tedim & Leone 2020) may always have played a role in certain ecosystems during the postglacial period (Adámek et al. 2015). Clearly, as climate change progresses, there will be an increase in the risk of climate change-related forest fires, even in temperate broadleaved forests. (Seidl et al. 2011, UBA 2015, Maringer et al. 2016, Conedera et al. 2023). Irrespective of the fire risk, most forest fires in Central Europe have been and continue to be caused by humans (Ganteaume et al. 2013, Adámek et al. 2018, Gnilke & Sanders 2021).

After a period of decreasing forest fire incidence in Germany, the number of forest fires and the area affected increased significantly in the years 2018, 2019 and 2022 (BLE 2019, 2020, 2023) due to severe drought and high temperatures (cf. UBA 2021, UFZ 2022). North-eastern Germany is particularly affected due to the continental, dry and warm climate in summer (UBA 2015) and the fact that Scots pine dominates the tree species composition of the forests (e.g. more than 70% of the forest area of the Federal State of Brandenburg [LFB 2022, Welle et al. 2022]). Conifer monocultures, especially Scots pine stands growing under drier conditions, have been particularly affected by forest fires in central Europe (Adámek et al. 2016, Kolb 2017, Ciesielski et al. 2022). Scots pine forests and especially plantations are vulnerable to fire because the green vegetation organs of Scots pine have a low ignition temperature and high calorific value (Mißbach 1982); they form a relatively sparse canopy, which facilitates high temperatures in the forest interior and drying of the ground layer (Adámek et al. 2016). Also, and probably more importantly, they accumulate a lot of combustible material. These are mainly dry needles with flammable resin and essential oils, which strengthen and accelerate fires (Aleksić et al. 2009, Ganteaume et al. 2009, Adámek et al. 2016) and a relatively thick layer of humus on the topsoil (e.g. Leuschner et al. 2013), which dries out on sandy soils during dry periods. In addition, understorey vegetation such as grasses is abundant and dries out very easily, thus becoming a flammable fuel (cf. Aleksić et al. 2009). In addition to the tree species, the stand structure also plays an important role in the susceptibility of forest stands to fire. Here, Scots pine thickets and pole stage forests are particularly susceptible to fire because the fuel is located close to the ground, or because thin, easily drying deadwood, such as dry branches on the tree, can form a fire bridge to the treetop (Mißbach 1982, Süssner 2020), and the continuous canopy allows crown fires to spread laterally.

High fire risk is associated with extreme climatic events or periods, and some calamity risks are mutually reinforcing (Seidl et al. 2011, Millar & Stephensen 2015), such as the combination of drought and Diplodia tip blight of Scots pine (Brodde et al. 2023). All this underlines the urgent need to study the ecological effects of forest fires in Central Europe and in pine plantations in particular (Viegas 2014). Effective restoration of forest ecosystem development and functioning after damaging events such as forest fires, and ecosystem-based adaptation of forests to climate change, are major challenges for forest ecosystem management to maintain forest functions. Keeping the fire risk in forests as low as possible in the future is a key challenge. On the one hand, this includes reducing the hazards that cause fires, which are largely attributed to human activities (Adámek et al. 2018, BLE 2023). On the other hand, establishing more resilient forests must be a priority.

Due to the long neglect of the importance of forest fires in temperate European forests, the focus on technological solutions for fire prevention (e.g. Mißbach 1982, Müller 2020, 2023) and the mostly small spatial extent of the fires, current ecological knowledge is still limited (cf. Adámek et al. 2018). It is well known that fires in pine stands in Central Europe and neighbouring regions cause high tree mortality, drastically reduce understorey vegetation and the organic layer and also alter physical, chemical, and biological processes in the soil (Marozas et al. 2007, Bartsch & Röhrig 2016, Vacchiano et al. 2014). After fire, the remainning ash layer increases soil pH and has an initial fertilising effect (Certini 2005, Vacchiano et al. 2014, Dzwonko et al. 2015, Bartsch & Röhrig 2016), but nutrients may leach out from the rooting zone into deeper soil layers over time (Certini 2005, Vacchiano et al. 2014, Bartsch & Röhrig 2016). The post-fire microclimate is characterised by extreme surface temperatures, lower relative air humidity and reduced soil moisture (Marcolin et al. 2019, Blumröder et al. 2022). Loss of soil organic matter following a fire is supposed to have a negative impact on soil water retention in coarse-grained sandy soils (Bartsch & Röhrig 2016) and is often associated with increased soil hydrophobicity, which reduces infiltration and promotes surface runoff.

The vegetation regenerates through the colonisation of wind-dispersed species, but also the seed bank and some surviving underground plant organs (Kwiatkowska-Falińska et al. 2014, Dzwonko et al. 2018, Wohlgemuth & Moser 2018). It differs significantly from the pre-fire vegetation and is temporarily more species-rich due to more nutrient-rich conditions and the absence of competitive species (Marozas et al. 2007, Adámek et al. 2016, Dzwonko et al. 2018, Wohlgemuth & Moser 2018). Among the woody plants, there are mainly wind-dispersed pioneer tree species such as birch (*Betula* spp.), European aspen (*Populus tremula*) and willows (*Salix* spp.), which establish spontaneously and rapidly. Their relative proportions and total numbers vary from case to case (Jahn 1980, Beghin et al. 2010, Moser et al. 2010, Wohlgemuth et al. 2010, Stähr 2012, Dzwonko et al. 2015, Orczewska et al. 2016, Wohlgemuth & Moser 2018). During natural succession, open pioneer vegetation with disturbance indicators shifts towards a more shade-tolerant, forest-specific- vegetation (Adámek et al. 2016, Bartsch & Röhrig 2016). The fungal community composition in post-fire forest areas is quite specific (Butin & Kappich 1980, Jahn 1980) and comprises a fast succession within the first years (Moser 1949), but fungal species richness is generally reduced by fire events (Dove & Hart 2017). There is also a significant impact of wildfires on fauna in temperate forests, but this has been less well studied in Europe than on other continents with higher fire incidence (González et al. 2022). It is clear that insects and other arthropods respond very differently to fire (Moretti et al. 2004, 2006). Little is known about the interactions between abiotic and biotic parameters, and how different elements of biodiversity are interrelated in post-fire forest ecosystems (cf. Fischer et al. 2010), i.e., the relationships between plant, soil invertebrate and fungal diversity (Wardle et al. 2004, van der Heijden et al. 2008, Fischer et al. 2010, Soliveres et al. 2016).

Typically, larger burned forests in Central Europe outside of strictly protected nature reserves are not left unmanaged and are silviculturally treated to initiate the establishment of a desired tree species composition. This is despite evidence that treatments such as post-fire salvage logging or ploughing drastically alter site conditions (Parro et al. 2015, Marcolin et al. 2019) and may negatively affect natural regeneration dynamics by contributing to a harsher post-fire microsite environment. The presence of dead wood has been found to play a facilitating role in seedling establishment (Béland et al. 2000, Marcolin et al. 2019, Sewerniak et al. 2023). Regeneration rates of soil organic matter, carbon and nutrient stocks were also found to be higher under natural regeneration compared to artificial restoration after soil preparation (Sewerniak et al. 2023). However, the ecological functioning of post-fire temperate forest ecosystems in relation to the forest management strategy implemented is poorly understood and its contribution to fire resilience and climate change adaptation has not been investigated.

The proper and continued functioning of ecosystems must be ensured to maintain the processes and services required for human well-being. These include the pools and fluxes of water, carbon and nutrients, the maintenance of soil fertility, clean water and air, the provision of food and construction material, pollination and pest control (Daily 1997, Garland et al. 2021). It has been shown repeatedly that ecosystem processes and services are mostly positively dependent on the species richness of ecosystems (e.g., Tilman et al. 2014, Soliveres et al. 2016). Understanding the interactions between forest management, biodiversity, and ecosystem functioning requires observational and comparative studies in real-world ecosystems at an appropriate spatial scale over longer periods of time (cf. Fischer et al. 2010), including and especially post-fire sites.

To comprehensively address the post-fire ecosystem components and important feedbacks between them, we have established a comprehensive project for functional ecosystem and biodiversity research, PYROPHOB (www.pyrophob.de). The aim of the PYROPHOB project is to study the changes in abiotic and biotic properties and to record ecological structures and processes after forest fires in order to formulate practical recommendations for the management of post-fire forests. In the long term, the results of the project will contribute to the development of climate change resilient pyrophobic forests. Ideally, these would be characterised by a diversity of ecological functions and processes, a high level of biodiversity and a higher proportion of broadleaved trees, which contribute to a lower risk of forest fires, better microclimatic cooling and buffering capacity, adequate water and nutrient retention capacity, high soil biological activity, high tree vitality and economic value.

Here, we present the project design and the key fields of data collection of an application-oriented ecosystem research project on forest fire areas by describing the main features of the PYROPHOB project. We emphasize the importance of the study design with replicate plots for interdisciplinary research, for addressing overarching questions, and for the quantitative synthesis of research results, completed by the translation of findings into recommendations for action. Finally, we highlight the role and importance of the PYROPHOB project for knowledge acquisition, teaching and training, public awareness, and implementation in forestry and conservation practice.

2. Design of PYROPHOB project

2.1 Main rationale of design

The project will investigate the relevant ecosystem components of the burned study sites and their interactions as far as possible (Fig. 1): After the fire, in addition to the ash layer, varying quantities and qualities of organic material remain (i.e., standing and lying deadwood, incompletely burned organic layers, charcoal fragments, soot particles, soil organic matter (SOM) in the mineral topsoil, partly living trees). These are successively decomposed; nutrients and dissolved organic carbon (DOC) are discharged into the groundwater. While the remaining organic matter provides the basis for the initial colonisation by fungi (saprobionts including pyrophilous specialists) and animals (especially saproxylic beetles), the inorganic soil nutrients are the basis for the recolonisation of the burned areas by tree regeneration and understorey vegetation, in which they are then partially stored. Later, new mycorrhizal symbioses develop to support vegetation growth. Subsequently, dead plant, fungal and animal matter is decomposed into humus, which is incorporated into the nutrient cycle. Food webs are formed from primary producers to arthropods and mammals, with feedback to the regrowing vegetation. The prevailing microclimate is regulated by the remainning vegetation, e.g. through the dissipation of solar radiation by photosynthetically active organisms and the shading of dead trees, and influences the above-mentioned components and processes. The unburned neighbouring stands (used as reference sites in our project) play a role as a source for the colonisation of the burned areas and may in turn be influenced by the post-fire communities (e.g. pathogens and other forest pests). In particular, the remaining organic matter including deadwood, the microclimate, the inorganic soil conditions and the vegetation are directly influenced by these, the vegetation also by e.g. a possible activation of the seed bank or the destruction of plants by ploughing.

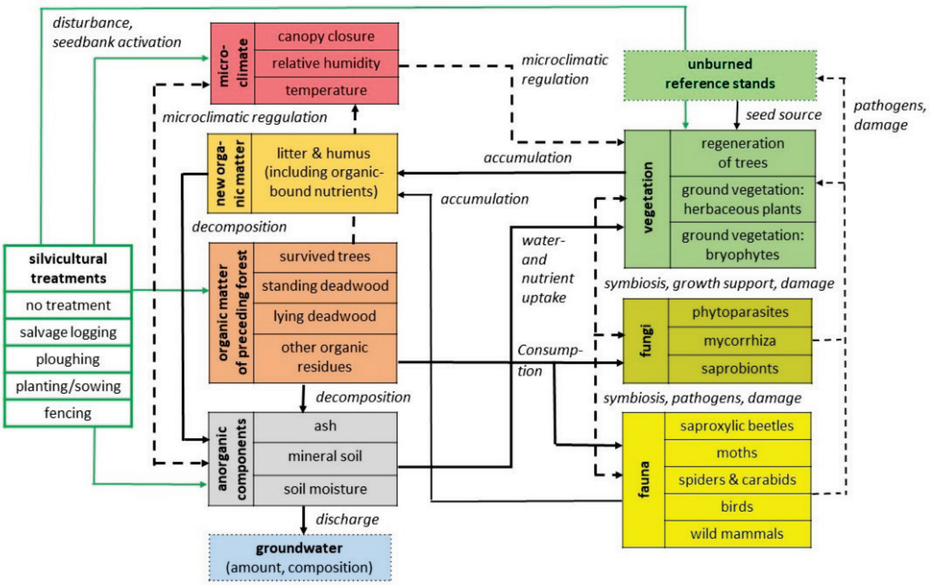

Fig. 1. Schematic representation of the ecosystem components examined as a part of PYROPHOB. Specific parameters are collected empirically and their mutual interactions are analysed. The inorganic and dead organic components are on the left, the biotic components on the right. Relevant components outside of the actual ecosystem are dashed. The main fluxes are shown as solid lines, the other influences and interactions as bold dashed lines. The direct effects of forest treatments are indicated by green arrows. The comparison between the different forest management variants (treatments) allows conclusions to be drawn about the effects of the different reforestation strategies. Recommendations for action for management practice can be derived from this.

Abb. 1. Schematische Darstellung der im Rahmen von PYROPHOB untersuchten Ökosystemkomponenten. Spezifische Parameter werden empirisch erhoben und ihre gegenseitigen Wechselwirkungen analysiert. Links sind die anorganischen und toten organischen Bestandteile, rechts biotische angeordnet. Relevante Komponenten außerhalb des eigentlichen Ökosystems sind gestrichelt. Die wesentlichen Stoffströme sind mit durchgezogenen Linien dargestellt, die übrigen Einflüsse und Wechselwirkungen mit dicken gestrichelten Linien. Die direkten Auswirkungen von Waldbehandlungen sind mit grünen Pfeilen markiert. Der Vergleich zwischen den verschiedenen Waldbewirtschaftungsvarianten (Behandlungen) ermöglicht Rückschlüsse auf die Wirkungen der einzelnen Aufforstungsstrategien, aus denen Handlungsempfehlungen für die Praxis abgeleitet werden.

The synthesis of the specific findings for each ecosystem component should allow us to describe the effects of the various forest management variants on the ecology and development of the burned areas. Therefore, it is important to understand as precisely as possible the underlying interactions between the parameters as shown in Figure 1.

Given this framework, our main research questions are: (1) How does forest fire in Central European Scots pine plantations change abiotic and biotic factors in the post-fire environment? (2) How do different post-fire forest management treatments affect abiotic site conditions, biodiversity, levels of associated ecosystem functions and development? (3) How quickly and effectively can certain forestry measures be used to stimulate the development of a new forest that would be less vulnerable to fire than untreated burned forests?

Recommendations for action will be derived from the holistic ecological perspective and communicated to practitioners. The project aims to assist forest owners in establishing less fire-prone and more resilient mixed broadleaved forests on post-fire sites instead of highly flammable conifer monocultures, and to evaluate the effectiveness of different strategies. As a result, we aim to identify the most appropriate treatments from an ecological and silvicultural perspective, taking into account potential future wildfire events.

A key methodological aspect of the PYROPHOB project is a system of standardised sample plots, which are used by all research groups from the eight institutions involved. Such a common study design is crucial for statistical comparisons across environmental factors, taxa and management types. Generally, we follow the concept of the DFG Biodiversity Exploratories (Fischer et al. 2010; https://www.biodiversity-exploratories.de/en/), a large-scale and long-term open research platform for functional biodiversity research, which comprises a hierarchical set of standardised field plots in three different regions of Germany (Schorfheide-Chorin, Hainich-Dün, Schwäbische Alb) covering manifold management types and intensities in grasslands and forests. We established a network of field plots in burned forests and their vicinity, but without spatial repetition in different regions. Within the 15 study sites spread over two adjacent study areas reflecting different forest management measures and fire intensities, there are three levels of monitoring intensity for the sample plots (Fig. 2, Supplement E1): (1) sample plots for all biodiversity and environmental assessment methods, which can be performed on a high number of replicated plots, and (2) very intensive plots (VIPs), which are predefined subsets of three sample plots per site used to study biodiversity or ecological processes in more detail, often using very labour- or cost-intensive methods for which the use of all sample plots is not feasible. (3) One VIP plot per site was selected as a VIP soil plot. Here, next to the VIP area, the ground was opened up to accommodate continuous monitoring devices that could not be built without significant disturbance to the area. In addition, some extensive field work, such as UAV-based remote sensing or monitoring of highly mobile species, is carried out at the site level. The rationale and selection of each of these plot types is described in more detail below.

2.2 Study areas

PYROPHOB is implemented in two large burned Scots pine forest areas in the Federal State of Brandenburg (NE Germany) approximately 50 km southwest of Berlin (Fig. 2). In both areas, the fires were not adequately fought from the start due to suspicion of contamination with old ammunition. The region is mainly characterised by large Scots pine plantations on dry, sandy Pleistocene meltwater deposits with a climate between Atlantic maritime and continental (Scholz 1962). Regional soil maps (BÜK300) show mainly

Cambisols partly influenced by groundwater (LBGR 2023). Mean annual temperature (1991–2020) is 9.7 °C, with 0.8 °C in January and 19.3 °C in July, and mean annual precipitation is 559 mm (climate station Baruth [Mark], DWD 2023). Local pine stands are dominated by *Pinus sylvestris* L. and the herb layer by *Deschampsia flexuosa* (L.) Trin., accompanied by *Calamagrostis epigejos* (L.) Roth and *Carex arenaria* L. Bryophyte layers are often dense including *Pseudoscleropodium purum* (Hedw.) M. Fleisch. ex Broth., *Pleurozium schreberi* (Brid.) Mitt., *Hypnum cupressiforme* agg., *Dicranum polysetum* Sw. and *D. scoparium* Hedw. Mixed oak forests on acidic soils are considered as potential natural vegetation (Hofmann & Pommer 2005). With these characteristics, the study area is representative for large parts of the NE lowland in Germany as well as the neighbouring regions in Poland and the Polesian forests along the Belarus-Ukraine border.

One study area (TB) is located close to the city of Treuenbrietzen (approximately 52.04331° N, 12.92220° E, 79–110 m a.s.l.), with glacifluvial, slightly loamy sands mostly far from groundwater. On 23 August 2018, a forest fire started in its southwestern part, spread in a northeasterly direction, gaining in intensity and crossing a railway track and a road. By the time it was extinguished nine days later, the fire had destroyed 334 ha of even-aged pine stands (Landesbetrieb Forst Brandenburg, Waldbrandbericht 2021 [unpublished report]). After the fire, different silvicultural treatments were applied to the area. The north-eastern part in private ownership (members of the Waldgenossenschaft Bardenitz-Pechüle) was completely salvage logged a few months after the fire. Parts of the clearing were ploughed and planted mainly with Scots pine, sessile oak, red oak and birch trees, while other parts remained untreated after logging. In contrast, the southwestern part (owned by the city of Treuenbrietzen until 2022) was in the main part only partially salvage logged (removing 50–75% of the stems) or even left without any forest interventions (in particular, a research site established by the city of Treuenbrietzen and the Eberswalde University for Sustainable Development in a previous project called CLEVERForst before the start of PYROPHOB). The partially salvage logged areas were ploughed or raked, and planted or sown with different tree species such as native sessile oak (*Quercus petraea* (Matt.) Liebl.) and non-native red oak (*Q. rubra* L.). Some of the areas in both the municipal and private forest were fenced off to protect them against wild animals browsing.

The other study area (JB) is located approximately 8 km east on the former military training ground of Jüterbog (approximately 52.08642° N, 13.04933° E, 52 m a.s.l.), which now is a designated wilderness area owned by the Brandenburg Wilderness Foundation (Stiftung Naturlandschaften Brandenburg, https://stiftung-nlb.de/de/). The foundation took advantage of the historical chance to acquire and secure large wilderness areas on former

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Abb. 2. Lage des PYROPHOB-Projekts in Deutschland und Karte der Untersuchungsflächen mit den einzelnen Plots und VIPs in den Untersuchungsgebieten a) Treuenbrietzen (TB) und b) Jüterbog (JB) auf der Grundlage von Luftbildern von 2019 (TB) and 2022 (JB). Forstliche Maßnahmen auf den Untersuchungsflächen sind durch verschiedene Farben (Beräumung) bzw. Muster (Bodenbearbeitung) dargestellt. Die Untersuchungsflächen C-J und U, V, Z wurden im Juli 2020 eingerichtet, wobei die Flächen C-G nur bis Juni 2022 untersucht wurden. Die Flächen B, K, X und Y wurden im April 2021 eingerichtet, wobei die Flächen B und K nur bis Juni 2022 untersucht wurden. Fläche L wurde als Ersatz für die abgebrannte Referenzfläche G im Herbst 2022 eingerichtet.

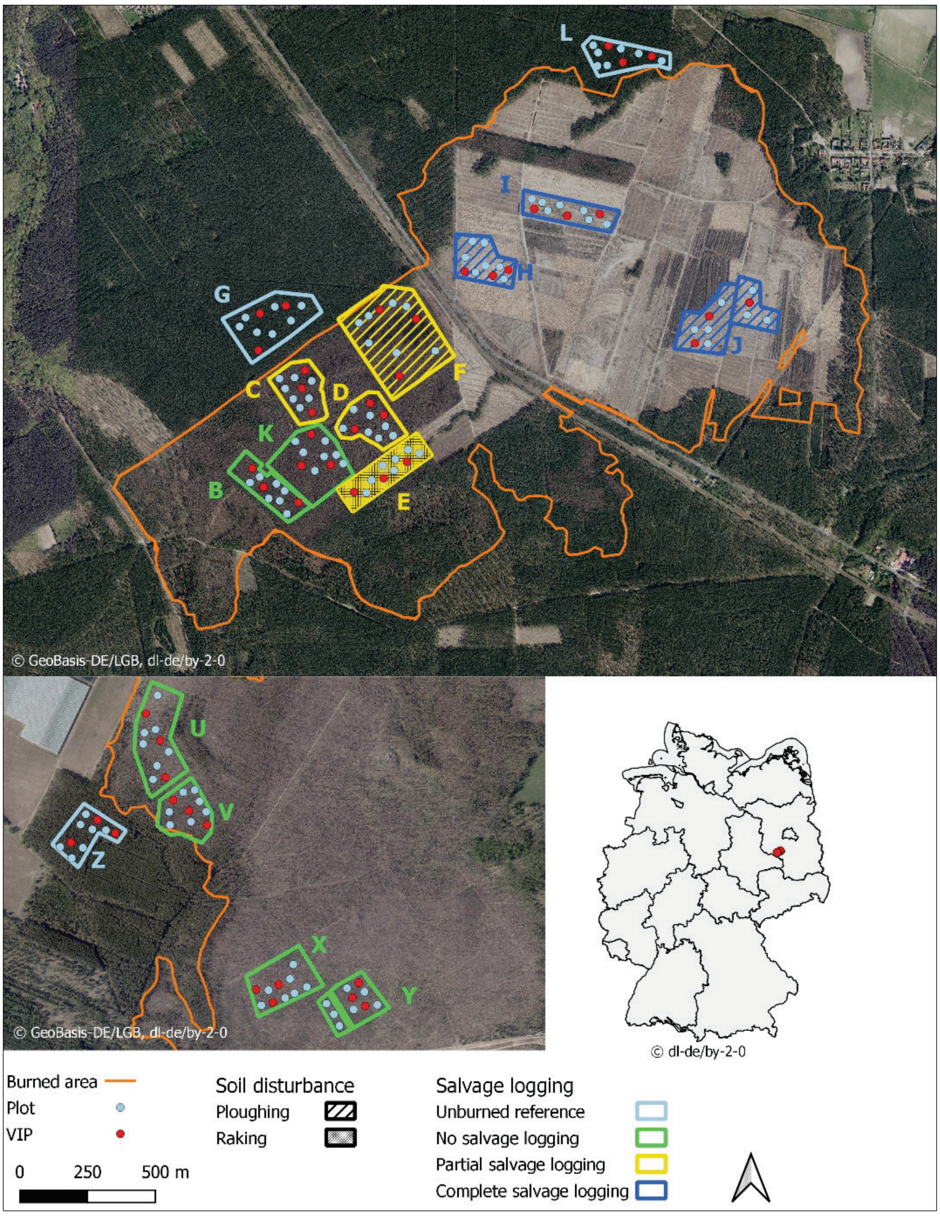

Fig. 2. Location of the PYROPHOB project in Germany and map of the study sites with the sample plots and VIPs in the areas of a) Treuenbrietzen (TB) and b) Jüterbog (JB) based on an aerial image from 2019 (TB) and 2022 (JB). Forest management of the study sites is indicated by different colours (salvage logging) and patterns (soil disturbance). Sites C-J and U, V, Z were established in July 2020, while sites C-G were only studied until June 2022. Sites B, K, X and Y were established in April 2021, with sites B and K only surveyed until June 2022. Site L was set up as a replacement for the burned reference site G in autumn 2022.

military training grounds in the German Federal State of Brandenburg after the withdrawal of the Soviet military from the former GDR. Wilderness development is realised in the majority of the area and natural processes run undisturbed. The established criteria for wilderness protection from the International Union for Conservation of Nature (IUCN Ib) serve as a basis and orientation for the treatment of the Foundation's areas. Zoning concepts for these areas identify wilderness zones, buffering areas and small areas for long-term maintenance. The natural development in the no longer managed areas includes events such as windthrow and breakage, insect calamities and damage caused by wild game animals. In order to prevent damages to the neighbouring areas and to ensure acceptance for the natural development, the wilderness area is buffered from surrounding areas. The PYROPHOB study area is partly within the buffer zone and has developed on pure sandy, pleistocene fluvial and aelic deposits (see Table 1). Besides other reoccurring fire events, JB was affected by a large wildfire which burned 744 ha of mostly pine and mixed pioneer forest stands 3–12 June 2019 (LFB 2021). After the fire, due to the wilderness concept, no silvicultural treatments were carried out on the JB area and no hunting was carried out any more.

In most of the areas affected by the fires, the aboveground humus layers were completely consumed, leaving only bare mineral soil covered by ash and partly by fallen needles of dead or dying pine trees (Fig. 3a, b). In large parts of the areas, the fire spread into the canopy layer. Even in parts affected only by the ground fire, there was extensive dieback across most of the burned area, most likely because the enormous heat around the stem bases killed the cambium layers (Fig. 3a).

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Fig. 3. Photos from the study areas of the PYROPHOB project. **a)** Scots pine plantation after the forest fire near Treuenbrietzen (19.11.2018): all vegetation is burnt, ash and pine needles of the dead trees cover the ground. **b)** Edge of the fire: the humus layer on the topsoil is almost completely burnt (Jüterbog, 22.10.2019). Forest treatment variants after the fire in the Treuenbrietzen area (with natural aspen regeneration): **c)** no management (01.05.2020), **d)** salvage logging (30.08.2019), **e)** partial salvage logging, soil preparation and oak planting (01.05.2020), **f)** salvage logging, ploughing and pine planting (30.08.2019), **g)** unburned reference site (plot L6) (20.07.2023), **h)** study site B (no management) after the second forest fire in 2022; part of the deadwood has not burned and aspen is already resprouting from root suckers (09.06.2023) (Photos: a–f) T. Heinken, g–h) M. Schüle).

Abb. 3. Fotos aus den Untersuchungsgebieten des PYROPHOB-Projekts. **a)** Kiefernforst nach dem Waldbrand bei Treuenbrietzen (19.11.2018): die gesamte Vegetation ist verbrannt, Asche und Kiefernnadeln der abgestorbenen Bäume bedecken den Boden. **b)** Rand des Brandes: die Humusauflage ist fast vollständig verbrannt (Jüterbog, 22.10.2019). Forstliche Behandlungsvarianten nach dem Brand im Gebiet Treuenbrietzen (mit Naturverjüngung der Zitterpappel): **c)** kein Management (01.05.2019), **d)** vollständige Beräumung (30.08.2019), **e)** Auflichtung, Bodenbearbeitung und Eichen-Pflanzung (01.05.2020), **f)** Kahlschlag, Pflügen und Kiefern-Pflanzung (30.08.2019). **g)** unverbrannte Referenzfläche (Plot L6) (20.07.2023). **h)** Fläche B (kein Management) nach dem zweiten Waldbrand in 2022; ein Teil des Totholzes ist nicht verbrannt und die Zitter-Pappeln treiben mittels Wurzelbrut bereits wieder aus (Fotos: a–f) T. Heinken, g–h) M. Schüle).


a)
b)
c)
d)
e)
f)
g)
h)

2.3 Selection of study sites and plots

Starting in 2020, two years after the fire in TB and one year after the fire in JB, **15 study sites (ten in TB and five in JB)** were established in forest parts reflecting the wide range of forest management variants and different fire intensities, and in two neighbouring unburned Scots pine stands (**reference sites, one in TB and one in JB**) (Tab. 1, Fig. 3g). Site selection also aimed to maximise within-site homogeneity with unit sizes of around 5 ha. To select the sites, we first made a pre-selection using several sources of information: satellite imagery, geological and soil maps, digital terrain models, forest inventories and information from local foresters. The final selection and demarcation was made together with the landowners, responsible foresters and forest authorities, following discussions and an on-site inspection. The 13 sites on the **burned areas cover seven different forest management variants (treatments)**. These resulted from different combinations of salvage logging, ploughing, raking, planting, sowing and fencing, including different timing of treatments (Tab. 2, Fig. 3c–f). The treatment variant without forestry interventions was represented by six sites (two in TB, four in JB), but with different fire severities, levels of game browsing and stand ages of the previous stands.

For each study site, we selected **ten sample plots as replicates** (Fig. 2). We defined **a subset of three** of these as main sampling plots particularly important for the study and called them **VIP – Very Important Plot**. This means that almost all the parameters examined (see Fig. 4) are recorded at least on these three plots if possible. At one VIP per site, additional plots were established for soil scientific and hydrological site characterisation, sampling and monitoring (**VIP soil plots**). Parameters that can be assessed with less effort and/or require a larger sample size due to higher spatial variation are assessed on all ten plots or only on the additional seven plots (see Supplement E1). In total, **150 plots** (= 45 VIP main sample plots and 105 additional sample plots) were part of the project (see section 3 for loss of plots).

2.4 Plot implementation

Each specific research group is responsible for certain tasks within the collaborative project, so different devices and methodologies are used to collect data. In the centre of each sample plot, a wooden pole was installed about 1.5 m from the ground and its exact position determined in 2020. This was the starting point for the data collected in the immediate vicinity (Fig. 4). Microclimatic data loggers were installed, stand structure, deadwood volumes and qualities, tree regeneration and understorey vegetation were mapped on all plots, and fungi and predatory soil arthropods (ground beetles and spiders) were recorded on a subset of these. Soil investigations are carried out just outside the boundaries of the VIPs. In one of these soil plots (VIP soil plot), a soil profile (1 m depth) was temporarily opened to characterise the soil type. Prior to refilling the pit, various devices were installed to continuously measure soil moisture (at the VIP soil plots) and temperature at six depths and to sample seepage water (zero tension lysimeters at all soil plots). Suction cups were also installed to sample soil solution at three depths (30 cm, 60 cm and 100 cm) from the surface next to the soil profile (VIP soil plot). Saproxylic beetles and moths are caught with traps, mammals are monitored in the vicinity of VIPs and breeding bird surveys are carried out across the sites.

Table 1. Information about the study sites of the PYROPHOB project. All sites were pure Scots pine (*Pinus sylvestris*) plantations at the time of the fire. Areas: TB = Treuenbrietzen, JB = Jüterbog. Sites B-G and K were owned by the city of Treuenbrietzen in 2020, H-J were privately owned and U-Z were owned by the Wilderness foundation (Stiftung Naturlandschaften Brandenburg). The age of the burned pine stands was determined using the data from the forest districts and checked in the field by counting growth rings on tree stumps if possible (C: Central, E: East, N: North, S: South, W: West). Soil texture according to KA5 (topsoil, 0-10 cm): Ss = pure Sand, Su2 = slightly silty sand, Su3 = silty sand. Historical land use was determined using the Schmettau map (1767-1787), the first Prussian ordinance survey map (1841) and the maps of the German Reich 1: 25,000 (1902, 1941). All forests were indicated as coniferous forests in 1941. Burn severity was determined using the difference Normalized Burn Ratio Index (dNBR) and fire type was determined using the NIR/green ratio, both based on multispectral satellite data.

Tabelle 1. Allgemeine Informationen über die Untersuchungsflächen des PYROPHOB-Projekts. Zum Zeitpunkt des Brandes waren alle Flächen Forsten aus Wald-Kiefern (*Pinus sylvestris*). Gebiete: TB = Treuenbrietzen, JB = Jüterbog. Die Flächen B-G und K befanden sich im Jahr 2020 im Eigentum der Stadt Treuenbrietzen, H-J im Privatbesitz und U-Z im Besitz der Stiftung Naturlandschaften Brandenburg. Das Alter der verbrannten Kiefernbestände wurde anhand der forstlichen Revierbücher ermittelt und vor Ort, wenn möglich, durch Zählen der Jahresringe an Baumstümpfen überprüft (C: Mitte, E: Ost, N: Nord, S: Süd, W). Westen). Bodenart nach KA5 (Oberboden, 0-10 cm): Ss = Reinsand, Su2 = schwach schluffiger Sand, Su3 = schluffiger Sand. Die historische Flächennutzung wurde anhand der Schmettauschen Karte (1767–1787), des Preußischen Urmesstischblatts (1841) und der Karten des Deutschen Reiches 1:25.000 (1902, 1941) ermittelt. Alle Wälder im Jahr 1941 waren als Nadelwälder ausgewiesen. Die Brandschwere wurde über den difference Normalized Burn Ratio Index (dNBR) basierend auf multispektralen Satellitendaten vor und nach dem Feuer, der Brandtyp über das NIR/grün-Verhältnis bestimmt.

location			area specifics before the fire			historical landuse				area specifics of fire event		
site	area	area size [ha]	forest age [years] in 2018	wilder-ness	soil texture	1767–1787	1841	1902	1941	fire year	fire type	burn severity
B	TB	4,9	64	no	Su2	forest	forest/open	forest	forest	2018	crown	low - moderate high
C	TB	3,2	71	no	Su2	forest	open	forest	forest	2018	crown	low - moderate high
D	TB	3,2	N: 68, S: 102	no	Su2	forest	open	forest	forest	2018	crown	low – high
E	TB	3,6	68	no	Su2	forest	open	forest	forest	2018	surface	low - moderate high
F	TB	10,0	68	no	Su2	forest/open	forest/open	forest	forest	2018	surface	low – high
G	TB	5,2	71	no	Su2	forest/open	open	forest	forest	unburned	-	-
H	TB	3,1	N:45, CS:39	no	Su2	open	open	forest	forest	2018	crown?	low – high
I	TB	3,0	W:98, E:73	no	Su2	open	forest/open	forest	forest	2018	crown?	low – high
J	TB	5,7	W:46, E:41	no	Su2	open	forest/open	forest/open	forest	2018	crown?	high
K	TB	5,4	SW:64, NE:70	no	Su3	forest	open	forest	forest	2018	crown	moderate low - moderate high
L	TB	2,8	66	no	Ss	forest	open	forest	forest	unburned	-	-
U	JB	5,2	N: 96, S: 76	yes	Ss	open	open/forest	forest	forest	2019	surface	low - moderate high
V	JB	3,0	N: 76, S: 66	yes	Ss	open	forest	forest	forest	2019	surface	unburned – moderate low
X	JB	4,0	99	yes	Ss	forest	forest	forest	forest	2019	crown	moderate high – high
Y	JB	3,1	29	yes	Ss	forest	forest	forest	forest	2019	crown	moderate high – high
Z	JB	2,8	66	yes	Ss	open	open	forest	forest	unburned	-	-

Table 2. Overview of the treatments after the fire on the study sites of the PYROPHOB project. All sites were Scots pine (*Pinus sylvestris*) forests at the time of the fire. Area: TB = Treuenbrietzen, JB = Jüterbog. Abbreviations for time: au = autumn, sp = spring, su= summer, wi = winter.

Tabelle 2. Übersicht über die Behandlung der Untersuchungsflächen des PYROPHOB-Projekts nach dem Feuer. Untersuchungsgebiet: TB = Treuenbrietzen, JB = Jüterbog. Abkürzungen für den Zeitpunkt: au = Herbst, sp = Frühling, su = Sommer, wi = Winter.

location		**Treatment 1: tree removal**			**Treatment 2: soil treatment**				**Treatment 3: Planting**			**other Treatments**				
site	area	tree stock	time of removal	machine for removal	soil tillage	time of tillage	machine for ...	tillage depth	planting	type of planting	species planted	time of planting	fence	hunting	other removals	time of removal
B	TB	no removal			none				yes	seeding		wi 2018/ 2019	no	frequent	stock cutting	wi 2022
C	TB	partial removal (0.5)	au/wi 2019	harvester & forwarder on skidder trails	none				no				no	frequent		
D	TB	partial removal (0.5)	au/wi 2019	harvester & forwarder on skidder trails	none				no				no	frequent		
E	TB	partial removal (0.75)	au/wi 2019	harvester & forwarder on skidder trails	raking	au/wi 2019	forestry boom	10 cm	yes	seeding	red oak (*Q. rubra*)	wi/sp 2020	yes	frequent		
F	TB	partial removal (0.75)	au/wi 2019	harvester & forwarder on skidder trails	plough-ing	au/wi 2019	strip plough	5-8 cm	yes	planting	sessile oak (*Q. petraea*)	wi/sp 2020	yes	frequent		
G	TB	unburned			none				no				no	frequent		
H	TB	clearcut	au/wi 2018	excavator over the entire area	plough-ing	au/wi 2018	strip plough	10-15 cm	yes	planting	sessile oak (*Q. petraea*)	wi/sp 2020	yes	frequent	aspen cutting	su 2020
I	TB	clearcut	au/wi 2018	harvester & forwarder over the entire area	none				no				no	frequent		
J	TB	clearcut	au/wi 2018	excavator over the entire area	plough-ing	au/wi 2018	strip plough	10-15 cm	yes	planting	Scots pine (*P. sylvestris*)	wi/sp 2020	no	frequent		
K	TB	no removal			none				no				no	frequent	stock cutting	wi 2022
L	TB	unburned			none				no				no	frequent		
U	JB	no removal			none				no				no	no		
V	JB	no removal			none				no				no	no		
X	JB	no removal			none				no				no	no		
Y	JB	no removal			none				no				no	no		
Z	JB	unburned			none				no				no	no		

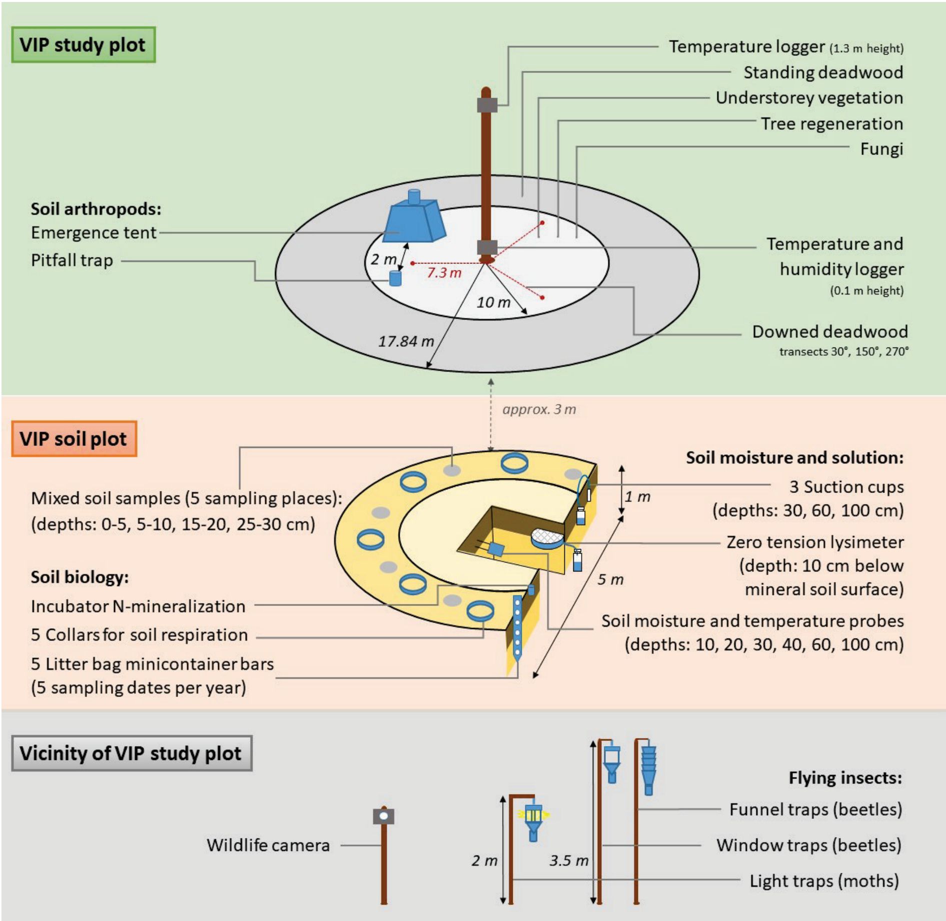

Fig. 4. Scheme of the experimental setup on a VIP ("Very Important Plot") including a VIP soil plot and the instrumentation in the vicinity of the VIP plots of the PYROPHOB research project. The centres of the sample plots are permanently marked with a wooden stake. Deadwood is also recorded along three 7.3 m long transects extending from the centre of the plots. The soil profiles and installations in the soil (only in one of the three VIP plots per study site; "VIP soil plot"), as well as some other equipment are located outside the plot area in order to minimise disturbance to these areas. See Supplement E1 and text for further explanations.

Abb. 4. Schema des Versuchsaufbaus auf einem VIP („Very Important Plot") einschließlich eines VIP-Bodenplots und der Instrumentierung in der Umgebung der VIP-Plots im Forschungsprojekt PYROPHOB. Die Mittelpunkte der Probeflächen sind dauerhaft mit Holzpfählen markiert. Entlang von drei 7,3 m langen Transekten, die sich von der Parzellenmitte aus erstrecken, wird auch Totholz erfasst. Die Bodenprofile und Einbauten im Boden (nur in einem von drei VIP-Plots pro Untersuchungsfläche; „VIP-Bodenplot") sowie einige andere Geräte sind außerhalb des Plots angeordnet, um Störungen auf diesen Flächen zu minimieren. Weitere Erläuterungen siehe Anhang E1 und Text.

2.5 Site inventory and ongoing investigations

For each of the selected study sites, we conducted a soil and a land-use inventory (see Table 1) and collected data on key environmental and biotic variables ('parameters', for details, including the timing of each record, see Supplement E1).

Soils and hydrology

For the standardised **soil inventory**, the soil profile at the VIP soil plot was characterised in terms of field pedology according to the German soil classification system (KA5: Ad-Hoc-Arbeitsgruppe Boden 2005) and the World Reference Base of Soil Resources (IUSS Working Group WRB 2022). The soil profiles are presented in Supplement E2. They have been mainly classified (according to IUSS Working Group WRB 2022) as Dystric Cambisols (Arenic), partly showing podzolisation processes of varying intensity. Signs of podzolisation are more pronounced at the JB sites. Soil samples were taken from all soil horizons in all soil profile pits in 2020 and 2021. In addition, humus layer samples and mixed mineral soil samples were taken at each soil plot from four depths (0–5 cm, 5–10 cm, 15–20 cm, and 25–30 cm) at five individual sampling points on each soil plot. The parameters pH, electrical conductivity (EC), organic matter, soil texture (i.e., sand, silt and clay content) and nutrient content were determined. Humus stocks were calculated from the total content of soil organic carbon (Corg).

Three methods are used for the **soil biological characterisation** of the study sites: To determine the **nitrogen mineralisation** in situ, cylindrical stainless steel incubator was initially installed on each of all the soil plots vertically at a depth of 0–10 cm in the mineral soil (Kwak et al. 2016) and in the references (G and Z) also in the organic layer. Later, in 2023, cylinders were installed only at selected sites (TB: B, K, I, J, L; JB: U, X and Z). Cylinders were initially sampled regularly, with one sample taken per month throughout the growing season (May to October). From 2023 onwards, this was generally adapted to the sampling scheme of the litter decomposition tests, as detailed below. The **Litter decomposition** tests (Eisenbeis 1999) were initially performed on seven selected soil plots in TB (C, F, I, G) and JB (U, X, Z), but have since been carried out on exactly the same study sites selected for the nitrogen mineralisation tests in TB and JB including the two reference sites L and Z, respectively. For this purpose, mini-containers (~ 1 cm^3) of dried birch and pine litter were placed in the soil at five depths (0–2 cm, 2–4 cm, 4–8 cm, 8–12 cm and 12–16 cm). These were removed after 14, 28, 70, 112 and 168 days, and the litter loss was determined by weighing. In addition, soil biological activity is measured on all main soil VIPs by measuring carbon dioxide emissions (as a result of **soil respiration**). Five PVC collars were installed on each soil VIP for the duration of the project. Using a portable IRGA, soil CO_2 efflux is measured roughly every week from March to November. Using an additional probe (Hydra Probe) soil moisture and temperature are also recorded locally at a depth of 5 cm.

The **seepage water composition in the topsoil** and thus the discharge of substances is monitored in different depths. Free-draining zero tension lysimeters were installed at a depth of 10 cm in all soil plots. Additional lysimeters were installed just below the organic layer at all soil plots of the reference sites. Leachate samples are collected at monthly intervals and analysed for the following parameters when sufficient solution volume is available: Quantity in ml, pH value, electrical conductivity (EC), calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), phosphate (PO_4), chloride (Cl), ammonium (NH_4), nitrate (NO_3), sulphate (SO_4), total carbon (TC), total organic carbon (TOC), dissolved organic carbon (DOC), total nitrogen (TN) and dissolved organic nitrogen (DON). By offsetting the measured concentrations with the observed solution quantities, discharge quantities from the upper soil for the measured substances are estimated. On the VIP soil plots, additional suction cups were set up under negative pressure at depths of 30, 60 and 100 cm to take soil solution samples from the **subsoil**. These are examined for the same parameters as the topsoil lysimeters. In order to investigate the dynamics of nutrient discharge from wildfire soils immediately after the fire event, laboratory leaching tests are carried out on undisturbed soil columns from the two reference sites: A forest fire is simulated on the organic and adjacent mineral layers, and the columns treated in this way as well as untreated control columns are eluted.

Hydrological measurements to assess soil hydrological processes include six rain gauges (three in TB, three in JB) and one station for multi-depth monitoring of **soil moisture and temperature** on each study site, located at the soil VIP plots in coordination with the soil chemical instrumentation (see Fig. 4). Soil moisture and temperature are measured every 20 minutes on two replicate profiles at six depths each (10, 20, 30, 40, 60, 100 cm) using dielectric sensors (SMT-100, Truebner, Germany). Additionally, two extra profiles were set up at sites F and H each in order to compare the soil moisture dynamics of the top and furrow of the plough structures. In addition, three profile probes with nine measurement depths (SoilVUE, Campbel Scientific, UK) were installed in study site J in TB to investigate the small-scale variability. The **soil water balance, seepage water movement and groundwater recharge** are reconstructed using 1D hydrological modelling.

Weather and climate

Two **meteo stations** were set up, one in TB and one in JB. The meteo station in TB was installed in study site H, and the one in JB was installed in the open field but in immediate vicinity of the study area. The weather stations consist of an approximately 2 m high mast, which is equipped with a total of seven different, continuously operating sensors: leaf wetness, light intensity (photo/light – PAR), barometric pressure, precipitation, solar radiation (Silicon Pyranometer), temperature and relative air humidity, and wind speed. All measurements are recorded every 10 minutes.

Microclimate data is collected using temperature data loggers (Hobo pendant) on the ten plots of each study site. The data loggers are attached to a wooden pole at a height of 1.3 m in the centre of the plot (Fig. 4) and protected from direct sunlight by a white plastic protective casing. All records are stored as synchronised measurements at 10 minute intervals. In addition, temperature and relative humidity (Hobo pro V2) are recorded at 10 cm above the ground in the three main sample plots (VIPs) of the study sites and allow the calculation of water vapour pressure deficit (VPD). The data collection of the **degree of canopy closure** takes place together with the microclimatic data logger readout several times per year during and outside the vegetation period using a densiometer on all sample plots. The equipment and methodological design have been tested at numerous forest sites (Blumröder et al. 2019, 2021a, 2022).

Land Surface Temperature (LST) Analyses are based on Landsat 8 and 9 imagery. The Landsat 8 satellite revisit the area approximately every 16 days between 10:30 and 11:30 a.m., providing 100 m spatial resolution for Thermal Infrared Sensor (TIRS). The dataset acquisition and pre-processing steps were conducted in the Google Earth Engine Code Editor. The study period comprised the vegetation periods (April–September) of 2019, 2020, 2021 and 2022. The cloud cover percentages were taken according to the data availability.

Vegetation and stand structure

In order to obtain a comprehensive picture of the development of the **forest stand structure** over time (see examples in Fig. 5), various complementary survey methods have been established during the course of the project. These include the recording of standing and lying deadwood, tree regeneration and the degree of canopy cover as well as surveying the conditions of the tree regeneration. In addition to conventional manual recording in the field, terrestrial laser scanning (TLS) and remote sensing techniques such as drone (UAV) flights and satellite image analysis are used. Surviving trees, **standing deadwood** and stumps, from 7 cm in breast height diameter (DBH), are recorded in the radius of 17.8 m ($A = 1000\ m^2$) on the three VIP plots of the study sites every six months. This will be supplemented and compared with the results of annual TLS measurement in the leafless season. TLS also allows to assess the tree volume and tree architecture based on geometric features of the wood structures. To record the volume and condition of the **lying deadwood,** the line intersect method of the US forest inventory (van Wagner 1968, Woodall et al. 2019) is used. Lying deadwood is recorded in a radius of 7.3 m ($A = 167.42\ m^2$) on three transects on all plots.

To record **tree regeneration** as a key indicator for the success of forestry treatments, all trees up to a DBH of 7 cm on the three VIP plots of the study sites within a radius of 10 m ($A = 314.16\ m^2$) are documented once per year after the growing season. The type of regeneration is distinguished by naturally established, planted or sown. Tree status is differentiated by alive, cut, bent over or dead. Damages of the leading shoot are classified in the categories browsed, broken or else (e.g. desiccated, fungi). Leaf damage is recorded when more than 30% of the leaves show significant damage. In order to be able to monitor individual tree growth as well, each tree is marked with an individual number on the remaining seven sample plots (non-VIP plots) within a radius of 2 m ($A = 12.57\ m^2$). All trees taller than 10 cm height and smaller than 7 cm in DBH are recorded every winter. Side shoot damages are additionally recorded.

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Fig. 5. Vegetation development on study sites of the PYROPHOB project; example plots from the scientific photo monitoring from the same perspective over time (2020–2023). Left: Plot U7, Jüterbog (no forest management): Nearly all burned Scots pine trees fall to the ground within a few years and contribute to the structural diversity on the areas; regeneration of deciduous trees is significantly lower in this study area than in TB. Right: Plot J2 Treuenbrietzen (salvage logging, ploughing, pine plantation) with very strong growth of European aspen (*Populus tremula*) (Photos: T. Geisel).

Abb. 5. Vegetationsentwicklung auf Untersuchungsflächen des PYROPHOB-Projekts; Beispielflächen im wissenschaftlichen Fotomonitoring aus der gleichen Perspektive im Zeitverlauf (2020–2023) aufgenommen. Links: Plot U7, Jüterbog (kein forstliches Management): Die verbrannten Wald-Kiefern fallen innerhalb weniger Jahre vollständig zu Boden und tragen zur Strukturvielfalt auf den Flächen bei; die Verjüngung von Laubbäumen ist in diesem Untersuchungsgebiet deutlich geringer als in TB. Rechts: Plot J2 Treuenbrietzen (Kahlschlag, Pflügen, Kiefernpflanzung) mit sehr starkem Aufwuchs der Zitter-Pappel (*Populus tremula*) (Fotos: T. Geisel).

2020
2020
2021
U 9
04.07.21
2021
J 2
04.07.21
2022
U 9
15.07.22
2022
J 2
15.07.22
2023
U 9
16.07.2023
2023
J 2
16.07.2023

The **understorey vegetation** (vascular plants, bryophytes, lichens) is recorded annually on all 10 sample plots per site including the unburned reference sites (r = 10 m, A = 314.16 m^2) by vegetation surveys including a detailed estimation of plant cover. Strategies for the recolonization of the burned areas are analysed. The **above- and below-ground biomass** of the vegetation is calculated by allometric models on the plots. For this purpose, the PhytoCalc and a single tree model (Bolte et al. 2006, Wolff et al. 2009) were adapted for post-fire vegetation by destructive sampling of dominant plant and moss species outside of the plots (Schüle & Heinken 2024). Carbon stocks and nutrient element pools of the samples were determined. In combination with the calculated biomass, this allows the estimation of carbon and further element pools of the plants on the plots.

For a better understanding of spatial relationships, the data on vegetation and forest structure collected in the field are supplemented by **remote sensing**. Unmanned aerial vehicles (UAVs) were used in TB in 2019–2023 to collect RGB imagery (DJI Mavic Pro) with sub-decimeter ground resolution. A workflow for mosaicing of the images was developed based on USGS recommendations (USGS 2017) and adapted to site-specific needs. The resulting imagery is used to derive the status of the tree population (tree vitality and population structure). **Burn severity** (Keeley 2009) was determined using the Difference Normalized Burn Ratio Index (dNBR; Key & Benson 2005) for both study areas based on multispectral satellite data (Sentinel2 data with 10–20 m spatial resolution). As this spatial scale provides only limited information on the plot scale, two additional indices were applied, using only bands with 10 m spatial resolution to classify the data into "**fire type**", distinguishing between unburned, surface fire and crown fire areas: the NIR/green ratio (Daughtry et al. 2000) in JB and the MCARI1 (Haboudane et al. 2004) in TB.

Funga

To record the **fruit body-forming fungi and phytoparasites**, five sampling campaigns are carried out annually when the weather conditions are suitable for fructification. Volunteers from the *Pilzkundliche Arbeitsgemeinschaft Berlin-Brandenburg e. V.* (www.pabb.de) are involved in the data collection, visiting each study site and taking samples individually from the three VIP plots (radius = 10–15 m) and additionally randomly from the remaining study site. Identification of fungal species is supported by the sequencing of marker genes in all samples. In order to examine **ectomycorrhizal fungi** directly on the root tips of trees different sampling strategies are followed. Soil cores (40 cm deep, 3 cm diameter) containing root tips are taken on each of the seven non-VIP plots using a root auger, either 15 cores in 15 m distance around the centre (old tree stands on V and Z) or five cores in close vicinity to young trees (oaks on E, F and H, aspen and birch on J and V). Otherwise, young trees are completely excavated outside the plot areas (r = 10 m) and root tips are sampled directly (pine on V, J; aspen and birch on H, I, J; oaks on E, F, H; and occasionally willow). Root tips are morphologically categorized and identified by sequencing fungal marker genes. Identification of host tree species (root tips from drilling cores only) is supported by comparison of their restriction fragment length polymorphism (RFLP) with authentic tree samples.

Fauna

To record the diversity of **predatory soil arthropods** and their potential to contribute to the control of moth larvae in relation to the management of the sites is carried out using a paired design of emergence tents (ET) measuring 60 cm × 60 cm at the base, and pitfall traps (PT) in each plot. ETs are used to capture all individuals that emerge from the soil. Each ET has a pitfall trap inside and a catch bottle on top to collect both flying and non-flying arthropods that emerge from the ground. Outside the tents, PTs are also used to estimate the local activity density of ground-dwelling arthropods. A full year period of sampling the emergence and activity density of spiders and ground beetles was covered. Six plots were sampled in each study area (three VIP plots and three additional, randomly selected sampling plots). In addition, predator attack rates on artificial caterpillars and soil fauna feeding activity were estimated together with the activity density of the respective arthropod groups. **Saproxylic beetles** are caught close to two VIP plots of all study sites by means of a flight-interception trap (window trap) and a funnel trap (Lindgren Funnel Trap; Lindgren 1983) at a height of approximately 3 m from mid-April to the end of August. In addition, hand catches are carried out. Using automated window cross light traps, **moths** are caught next to all VIPs from mid-March to early November. Up to 15 traps can operate in parallel per trap night. Depending on atmospheric conditions and moonlight, a maximum of up to 15 trapping periods per VIP is intended. Each trap can operate for up to six hours per night.

Wild mammal monitoring is carried out to observe the recolonisation of the burned sites by mammalian wildlife, the distribution of animals, their activity patterns and habitat preferences. One camera trap is randomly installed at each study site, monitoring the area for 15 days and nights resulting in 11–16 active cameras (two cameras at site F). After this period, due to heterogeneous patterns and shapes of the sites, the camera is installed at a second point within the site for another 15 days and nights. These studies are carried out four times a year across all seasons. Camera trap data is complemented by standardised aerial wildlife surveys. For these, predesigned transects are flown over the study areas. The microlight aircraft is equipped with a combination of a thermal infrared (IR) camera and a high resolution visual (VIS) camera, looking vertically downwards. The infrared data is being used for detection and the visual data for verification and species identification. As a result, the density of animals per 100 ha for a certain date and time can be estimated.

Bird territory monitoring to assess the habitat selection of individual species and species communities following rapid habitat change took place with at least six inspections at all study sites from March to July in 2021–2023. Inspections were carried out almost exclusively under optimal weather conditions (Oelke 1974, Südbeck et al. 2005). Due to the relatively small overall size of the study sites, birds were also recorded in the border area of the sites in order to be able to assign them more precisely to the study sites when later assigning the paper territories. Population densities refer to 10 ha as a standard reference size (Südbeck et al. 2005).

2.6 Data management and data analysis

A central data management system was developed in advance to synthesise the individual results. For this purpose, the data exchange platform EUDAT.eu, in particular its service “B2Drop”, was selected. In addition to the field data, information and documents relevant to the project as a whole are made available to all researchers of the project. They upload their collected data, measurements, etc. annually for subsequent synthesis.

Various analyses have been initiated, including multivariate tools (e.g. PCA) and mixed effects models. The different forest management treatments (salvage logging, soil disturbance, planting, fencing) are combined into one forest management variable for some analyses. Given the lack of replication for most treatments and some data gaps due to technical issues a comparison of all plots over the full time period will not be the main focus of data analysis. Rather, the data offer many opportunities for smaller-scale analyses, including changes over time at particular sites, which will not always use all datasets (and all plots).

2.7 Education and public outreach

As part of the overall project, numerous excursions are carried out with students of environmentally relevant courses and guest scientists from the participating universities and institutions as well as with politicians, or conservation and forestry actors. In addition, bachelor's and master's theses in connection with the PYROPHOB project are supervised in various study programs, some of which have already resulted in scientific publications (see Schüle et al. 2023a).

The public relations work is aimed at forestry experts, the nature conservation sector, the local population, and the general public, e.g. school classes. The project's framework and preliminary findings have been disseminated through articles (e.g., Blumröder et al. 2021b, Clerc et al. 2023, Schüle et al. 2023b, Heinken et al. 2024), local, national, and international press as well as online media, radio and television. The results of PYROPHOB are communicated to experts at various specialist and public conferences. Outreach activities also include excursions to the study area with scientists, journalists, etc. as well as project presenting at local environmental markets and festivals. The numerous publications and activities have greatly increased the visibility of PYROPHOB at a regional, national and international level and raised awareness of the forest fire problem (e.g., over 150 media reports since the start of the project).

3. Concluding remarks

The PYROPHOB project is the first to record and analyse a wide range of abiotic and biotic parameters at a post-fire site in Germany, including rarely studied ones such as fungi. This will allow a comprehensive study of their interactions and their relationship to ecosystem processes. Although five years is a short time for forest establishment and final evaluation of fire impacts and silvicultural treatments, it is a relatively long time for a project investigating post-fire ecosystems. While many studies in forest fire areas cover only one year (de Chantal & Granström 2007, Beghin et al. 2010, Vacchiano et al. 2015, Orczewska et al. 2016), were conducted at intervals of several years (Stähr 2012, Kwiatkowska-Falińska et al. 2014, Dittrich et al. 2016, Wohlgemuth & Moser 2018), or used space-time substitution (Marozas et al. 2007, Adámek et al. 2016) which must ignore the influence of the different conditions of each fire event, we systematically examine temporal shifts of parameters and will be able to capture the main trends in ecosystem development in the early years. Of course, a longer study period would be more than desirable for a good understanding of medium-term processes and also for an economic evaluation of forest treatments. It would also be desirable to return to the areas after a few years and record the same parameters or at least some of them. In this context, the disadvantage of privately owned and used land is that it is not easy to rule out further interventions in subsequent years. The project even had to accept discontinuity in this respect on some plots during the project period, as the owner changed and decided to cancel the research collaboration. This meant that further research on most of the TB sites, including the CleverForst sites, had to be terminated following a decision by the new landowner (C, D, E, F and G at the end of 2022; B and K at the end of 2023). However, some of our project partners are endeavouring to continue the research on at least some plots (JB and H, I, J in TB) and selected key parameters such as tree regeneration, plant species composition and soil conditions at longer time intervals within their institutional research frameworks.

Working in a real landscape with ongoing environmental change and silvicultural intervention raises many issues for experimental design, data analysis and interpretation (see Fischer et al. 2010). The drivers of ecosystem development, such as forest management and soil conditions, are rarely completely independent or perfectly balanced, as would be desirable in a planned experiment. Spatial autocorrelation in a plot-based sampling design needs to be taken into account for some organisms, but not for others, depending on their mobility. In addition, study plots need to be large enough to ensure that measurements do not interfere with each other (and some instruments need to be spatially separated for the same reason), but still spatially homogeneous enough to allow integration of different results from the same plot. The lack of replication is virtually unavoidable, as different fires have a very individual signature, e.g. in terms of intensity and impact (Regos & Díaz-Raviña 2023); and (post-)fire treatments by firefighters and forest owners may also vary from region to region or even from stand to stand. In addition, the pre-fire history and legacy of land use would also be fundamentally different between regions and perhaps even site-specific. The wider landscape characteristics, such as surrounding forest cover, may also influence specific site characteristics. Finally, forest development on post-fire sites, especially from different years, will experience a very individual combination of local weather conditions, e.g. with (extreme) precipitation events. It must also be taken into account that the workload varies considerably between environmental parameters and different taxa, requiring some flexibility in the design in terms of temporal and spatial replication. Thus, a fundamental goal of such an interdisciplinary project is to integrate the divergent requirements of individual disciplines and to promote their optimal cooperation.

Indeed, it is specific to our project that a fully balanced experimental design of research sites in terms of management types, as in the case of the Biodiversity Exploratories (Fischer et al. 2010), was not possible due to the specific fire events and forest treatments, which were largely determined by the landowners. The two fires did not occur in the same year and season (late summer 2018 vs. early summer 2019). As a result, the starting conditions for the colonisation of the burned areas by the different groups of organisms were different, and the succession in the two areas is not fully synchronised. The project could only be planned and funded after the fires, so there are no data for the TB site from the first year after the fire, apart from small preliminary studies (Blumröder et al. 2022, Neumann 2022). Further delays and data gaps were caused by the fact that four study sites (two in TB: B, K, and two in JB: X, Y) had to undergo an in-ground survey and clearance of unexploded ordnance before equipment installation and surveys could commence.

Finally, and perhaps most importantly, a large proportion of the study sites in TB, including all forest treatments other than natural succession and complete salvage logging (B, C, D, E, F, G and K), were affected by a second wildfire between 17 and 20 June 2022 (Fig. 3h). The reburn allowed some very valuable observations, but of course interrupted the continuous vegetation development on the site and destroyed the direct comparability with the other sites that had not reburned. To replace the burned reference site G, a new reference site L was established (see Table 2, Fig. 1), but the forest treatments of the burned sites could not be replaced. For all the reasons mentioned above, in some cases no or only very short time series of parameters are available and conclusions about the effect of specific treatments will be limited.

Despite all these difficulties, valuable observations have already been made in the first few years. Even if a comprehensive synthesis with analyses of all data across all years will not be as complete as envisaged, many issues can be addressed that are not only of scientific interest, but can also inform practical and policy advice.

Erweiterte deutsche Zusammenfassung

Hintergrund und Projektziel – PYROPHOB bedeutet feuerabweisend und ist Namensgeber für ein interdisziplinäres Forschungsprojekt mit dem Untertitel „Strategien zur Entwicklung pyrophober und klimaresilienter Wälder auf Waldbrandflächen“, das seit Mai 2020 über einen Zeitraum von fünf Jahren durchgeführt wird. Das Projekt untersucht mit acht beteiligten Institutionen in brandenburgischen Kiefernforsten die ökologischen Auswirkungen von Waldbrandereignissen und anschließende waldbauliche Behandlungsstrategien, um letztlich Handlungsempfehlungen für den Umgang mit Waldbrandflächen für die Praxis zu formulieren. In Nordostdeutschland ist in den letzten Jahren, die überdurchschnittlich trocken und warm waren, eine deutliche Zunahme von zum Teil großflächigen Waldbränden zu verzeichnen und auch zukünftig besteht eine steigende Waldbrandgefahr aufgrund des Klimawandels. Von Waldbränden sind hier vor allem Kiefernforsten betroffen, in denen sich viel brennbares Material akkumuliert. Eine effektive Wiederbewaldung nach Waldbränden sowie eine ökosystembasierte Anpassung der Wälder an den Klimawandel stellen große Herausforderungen an das Management und die Bewirtschaftung dar. Die Verringerung des Brandrisikos zukünftiger Wälder ist dabei von besonderer Bedeutung.

Da Waldbrände in Mitteleuropa lange Zeit nicht als relevant angesehen wurden, ist das ökologische Wissen über ihre Effekte noch begrenzt. Waldbrände führen in den heimischen Kiefernwäldern zu einem weitgehenden Absterben der Bäume und zu einer drastischen Reduktion der Bodenvegetation und der Humusschicht. Asche erhöht den pH-Wert und düngt den Boden zunächst; Nährstoffe können jedoch später ausgewaschen werden (Vacchiano et al. 2014, Dzwonko et al. 2015, Bartsch & Röhrig 2016). Das Mikroklima nach einem Brandereignis ist durch Temperaturextreme und verringerte Bodenfeuchtigkeit gekennzeichnet (Marcolin et al. 2019, Blumröder et al. 2022). Die Vegetation regeneriert sich vor allem durch windausgebreitete Arten und über die Samenbank (Dzwonko et al. 2018, Wohlgemuth & Moser 2018) und ist vorübergehend artenreicher als vor dem Waldbrand (Marozas et al. 2007, Beghin et al. 2010, Adámek et al. 2016, Wohlgemuth & Moser 2018). An Gehölzen etablieren sich vor allem Pionierbaumarten wie Birken, Zitter-Pappel und Weiden, allerdings in stark wechselnden Anteilen und unterschiedlichen Gesamtzahlen (Jahn 1980, Moser et al. 2010, Stähr 2012, Dzwonko et al. 2015). Die offene Pioniervegetation wird dann zunehmend durch waldtypische Vegetation ersetzt (Adámek et al. 2016, Bartsch & Röhrig 2016). Die Pilzdiversität ist nach Waldbränden reduziert (Dove & Hart 2017), aber sehr spezifisch (Butin & Kappich 1980), und Arthropoden reagieren sehr unterschiedlich auf Brände (Moretti et al. 2004, 2006). Kaum bekannt ist dagegen, wie sich diese und andere abiotische und biotische Parameter gegenseitig beeinflussen und wie die verschiedenen Komponenten der Biodiversität in Waldbrandfolgeökosystemen zusammenhängen.

In der Regel werden Waldbrandflächen in Mitteleuropa rasch forstwirtschaftlich behandelt. Kahlschlag oder ein Pflügen der Flächen verändern die Standorte drastisch und können sich negativ auf die natürliche Regeneration auswirken, gleichzeitig kann belassenes Totholz die Etablierung von Bäumen fördern (Parro et al. 2015, Marcolin et al. 2019, Béland et al. 2000). Auch die Nährstoff- und Kohlenstoffvorräte im Boden scheinen sich ohne solche forstlichen Maßnahmen schneller zu regenerieren (Sewerniak et al. 2023). Allerdings ist die Funktion des gesamten Waldökosystems nach einem Waldbrand im Hinblick auf die Waldbewirtschaftungspraxis bisher kaum bekannt und es ist nicht untersucht, wie sie dazu beitragen kann, Waldökosysteme in Zukunft feuerresistenter und besser an den Klimawandel angepasst zu gestalten. Mit dem Projekt PYROPHOB wollen wir die Grundlagen für die erfolgreiche Durchführung eines anwendungsorientierten Ökosystemforschungsprojektes in Waldbrandgebieten veranschaulichen. Dabei ist das Untersuchungsdesign für die Bearbeitung interdisziplinärer Fragestellungen sowie für die quantitative Synthese der Forschungsergebnisse äußerst relevant und soll auch Anregung für zukünftige Projekte sein.

Grundprinzipien des Projektaufbaus – Wir untersuchen relevante Ökosystemkomponenten auf Waldbrandflächen, die in vielfältigen Wechselwirkungen stehen (Abb. 1): Nach dem Brand bleiben Asche und Totholz zurück. Während letzteres durch pyrophile Pilze und Arthropoden abgebaut wird, sind die anorganischen Bodennährstoffe wichtig für die Wiederbesiedlung durch die Vegetation. Neu gebildeter Humus wird bei der Zersetzung durch Mikroben und Invertebraten in den Nährstoffkreislauf integriert. Das Mikroklima, das zunächst stark von ggf. verbliebenden Bäumen abhängt, reguliert die genannten Prozesse. Wie wirken sich unterschiedliche waldbauliche Behandlungen auf die Entwicklung der Ökosystemkomponenten aus? Vor allem Totholz, Mikroklima, anorganische Bodenkomponenten und die Vegetation werden direkt beeinflusst, wobei der Biodiversität in unseren Untersuchungen eine besondere Bedeutung zukommt.

Ein zentrales Element von PYROPHOB ist ein System von standardisierten, Daueruntersuchungsflächen nach dem Vorbild der DFG Biodiversitäts-Exploratorien (Fischer et al. 2010), die von allen beteiligten Forschungsgruppen gemeinsam genutzt werden und statistische Vergleiche zwischen Umweltfaktoren, Taxa und Bewirtschaftungstypen bzw. -intensitäten ermöglichen. Diese befinden sich auf zwei 334 bzw. 744 ha großen Waldbrandflächen auf sandigen Böden bei Treuenbrietzen (TB) und Jüterbog (JB) in Brandenburg.

Auswahl und Einrichtung der Untersuchungsstandorte und -plots – Im Jahr 2020, zwei Jahre nach dem Brand in TB und ein Jahr nach dem Brand in JB, wurden 15 Untersuchungsstandorte (US) in den beiden Untersuchungsgebieten (UGs) (zehn in TB und fünf in JB) mit verschiedenen Waldbewirtschaftungsoptionen eingerichtet (Tab. 2). Zwei Referenz-US befinden sich jeweils im benachbarten, nicht verbrannten Kiefernforst. Die 13 Standorte auf den Brandflächen deckten sieben verschiedene Bewirtschaftungsvarianten (Behandlungen) mit unterschiedlichen Kombinationen von Holzeinschlag, Bodenbearbeitung, Pflanzung und Einzäunung ab (Tab. 2, Abb. 3c–f). Die Behandlungsvariante ohne forstwirtschaftliche Eingriffe wurde durch sechs US repräsentiert. Pro US wurden zehn Probekreise (Plots) als Replikate ausgewählt (Abb. 2), von denen jeweils drei als Hauptprobekreis (VIPs; Abb. 4) definiert wurden. Eine Liste mit den erhobenen Parametern ist in Anhang E1 nachzulesen. Ein Holzpfahl in der Mitte jedes Plots ist der Ausgangspunkt für die Datenerhebung (Abb. 4, s. u.). Am äußeren Rand der VIPs werden Bodenuntersuchungen durchgeführt.

Standortinventur und laufende Untersuchungen – Für jeden US wurden eine Boden- und Landnutzungsinventur durchgeführt (Tab. 1, Einzelheiten im Anhang E1). In den Jahren 2020 und 2021 wurden in allen Profilgruben Bodenproben aus allen Horizonten entnommen und pH-Wert, elektrische Leitfähigkeit (EC), organische Substanz, Bodentextur und Gesamt-Nährstoffgehalt bestimmt. Zur bodenbiologischen Charakterisierung werden vier Methoden eingesetzt: Stickstoffmineralisierung in situ, Streuzersetzungstests mittels Minibehältern mit getrockneter Streu, Ködersteifen zur Erfassung der Fraßaktivität und Erfassung der bodenbiologischen Aktivität durch Messung der aus der Bodenatmung resultierenden Kohlendioxidemissionen.

Zwei Wetterstationen messen u. a. Niederschlag, Sonneneinstrahlung und Temperatur in unmittelbarer Nähe der UGs. Mikroklimadaten werden mithilfe von Temperaturdatenloggern auf den zehn Plots jedes US in 1,3 m Höhe erfasst; die Messung von Temperatur und relativer Luftfeuchte in Bodennähe ermöglicht die Berechnung des Wasserdampfdruckdefizits (VPD). Dazu wird auf allen Plots der Kronenschlussgrad mittels Densiometer bestimmt. Flächendeckende Analysen der Landoberflächentemperatur (LST) basieren auf Landsat 8-Aufnahmen während der Vegetationsperioden.

Um ein umfassendes Bild der zeitlichen Entwicklung der Waldbestandsstruktur zu erhalten (Abb. 5), wurden verschiedene sich ergänzende Erhebungsmethoden etabliert. Im Feld werden v.a. das stehende und liegende Totholz nach der Linientransekt-Methode (van Wagner 1968, Woodall et al. 2019) und die Baumverjüngung als Schlüsselindikator für den Erfolg forstwirtschaftlicher Behandlungen detailliert erfasst. Daneben kommen terrestrisches Laserscanning (TLS) und Fernerkundungstechniken wie Drohnenflüge (UAVs) und Satellitenbildanalyse für die Erfassung der Vitalität und Waldbestandsstruktur zum Einsatz. Die Brandschwere wurde mithilfe des differenziellen Normalized Burn Ratio Index (dNBR) für die gesamten UGs basierend auf multispektralen Sentinel2-Satellitendaten bestimmt. Die Bodenvegetation (Gefäßpflanzen, Moose und Flechten) wird jährlich auf allen 10 Plots (r = 10 m) pro US durch Vegetationsaufnahmen mit detaillierter Deckungsgradschätzung erfasst. Die ober- und unterirdische Biomasse der Vegetation und damit die Abschätzung der Kohlenstoffvorräte wird durch allometrische Modelle auf den Plots berechnet. Zu diesem Zweck werden bestehende Modelle (Bolte et al. 2006, Wolff et al. 2009) an die Vegetation nach Brand angepasst, indem die dominanten Pflanzenarten außerhalb der Plots beprobt werden.

Zur Erfassung der fruchtkörperbildenden Pilze und Phytoparasiten werden jährlich fünf Probenahmekampagnen mit ehrenamtlichen Helfern durchgeführt. Die Identifizierung der Pilzarten wird durch die Sequenzierung von Markergenen in allen Proben unterstützt. Verschiedene Probenahmestrategien werden angewendet, um Ektomykorrhizapilze direkt an den Wurzelspitzen von Bäumen zu untersuchen; die Wurzelspitzen werden morphologisch kategorisiert und die Arten durch Sequenzierung von Pilzmarkergenen identifiziert.

Die Erfassung der Diversität der räuberischen Bodenarthropoden (Spinnen und Laufkäfer) erfolgte über ein Jahr durch paarweise Anordnung von Emergenzzelten und Bodenfallen in jedem Plot (Abb. 4). Mit den Emergenzzelten werden alle aus dem Boden schlüpfenden Individuen erfasst. Außerhalb der Zelte werden Bodenfallen eingesetzt, um die lokale Aktivitätsdichte laufaktiver Arthropoden abzuschätzen. Holzbewohnende (xylobionte) Käfer werden während der Vegetationsperioden in der Nähe von zwei VIPs aller US mit einer Kreuzfensterfalle und einer Trichterfalle (Lindgren Funnel Trap) gefangen (Abb. 4). Nachtfalter werden während der Vegetationsperioden in bis zu 15 Fangzeiträumen neben allen VIPs mit automatisierten Kreuzfensterlichtfallen gefangen. Für das Monitoring wildlebender Säugetiere wurde in jedem US eine Kamerafalle installiert, die das Gebiet viermal im Jahr an zwei Punkten für jeweils 15 Tage überwacht. Diese Daten werden durch Aufnahmen von Wildtieren aus der Luft ergänzt. Hierzu werden mit einem Ultraleichtflugzeug, das mit einer thermischen Infrarotkamera und einer hochauflösenden visuellen Kamera ausgestattet ist, Transekte über die UGs geflogen. In den Jahren 2021–2023 wurden auf allen US ein Vogelrevier-Monitoring zur Erfassung der Siedlungsdichte der Brutvögel nach Südbeck et al. (2005) durchgeführt.

Bildungs- und Öffentlichkeitsarbeit – Im Rahmen des Projektes werden zahlreiche Exkursionen mit Studierenden umweltrelevanter Studiengänge der beteiligten Universitäten und Institutionen, Politikern, Naturschutz- und Forstakteuren, Wissenschaftlern und Journalisten durchgeführt sowie Bachelor- und Masterarbeiten betreut. Die Öffentlichkeitsarbeit richtet sich an Forstexperten, den Naturschutz, die lokale Bevölkerung und die breite Öffentlichkeit. Die zahlreichen Veröffentlichungen in Artikeln (z. B. Blumröder et al. 2021b, Clerc et al. 2023, Schüle et al. 2023b), in der Presse sowie in Online-Medien, Radio und Fernsehen haben ebenfalls die Sichtbarkeit von PYROPHOB auf regionaler, nationaler und internationaler Ebene deutlich erhöht und das Bewusstsein für die Waldbrandproblematik geschärft.

Abschließende Bemerkungen – PYROPHOB ist das erste Forschungsprojekt, das eine Vielzahl von abiotischen und biotischen Parametern an Waldbrandstandorten in Deutschland untersucht. Dies ermöglicht eine umfassende Analyse ihrer Wechselwirkungen zu Ökosystemprozessen und den Dynamiken in den ersten fünf Jahren der Waldentwicklung. Die Forschung in einer realen Landschaft mit kontinuierlichen Umweltveränderungen und waldbaulichen Eingriffen bringt zahlreiche Probleme für das experimentelle Design, die Datenanalyse und die Interpretation mit sich (vgl. Fischer et al. 2010). Die Treiber der Ökosystementwicklung, wie z. B. die Bodenbedingungen und die Bewirtschaftung, sind selten völlig unabhängig oder perfekt ausbalanciert wie in einem gut geplanten

Experiment. Fehlende Replikation ist teilweise unvermeidlich, insbesondere da verschiedene Brände eine sehr individuelle Signatur haben und die Waldentwicklung nach Bränden durch eine sehr individuelle Kombination jährlicher und lokaler Witterungsbedingungen beeinflusst wird. Schließlich können weitere Eingriffe auf Privatflächen in den Folgejahren nicht ausgeschlossen werden. So war es in PYROPHOB nicht möglich, ein vollständig balanciertes experimentelles Design der US hinsichtlich der Bewirtschaftungstypen wie im Fall der Biodiversitäts-Exploratorien zu realisieren: Die beiden Brände fanden nicht im selben Jahr und in derselben Jahreszeit statt (Spätsommer 2018 vs. Frühsommer 2019). Dadurch waren die Ausgangsbedingungen für die Besiedlung der Brandflächen unterschiedlich (Abb. 5) und die Sukzessionsabfolge in den beiden UGs ist nicht vollständig synchron. Vielleicht am wichtigsten ist, dass ein großer Teil der US in TB, einschließlich aller Waldbehandlungen außer natürlicher Sukzession und vollständiger Abholzung, im Juni 2022 von einem zweiten Brand betroffen war (Abb. 3h). Dieser Brand unterbrach die kontinuierliche Vegetationsentwicklung und machte die direkte Vergleichbarkeit mit den anderen nicht erneut abgebrannten Standorten zunichte. Auf einigen US musste das Projekt während der Projektlaufzeit sogar ab 2023 abgebrochen werden, da der neue Eigentümer eines Teils der Flächen in TB die Forschungskooperation aufkündigte. Auch wenn eine umfassende Synthese mit Analysen aller Daten aus allen Jahren nicht möglich ist und Aussagen über die Wirkung bestimmter Behandlungen begrenzt sein werden, können wir viele Fragen beantworten, die nicht nur von wissenschaftlichem Interesse sind, sondern auch in die praktische Beratung einfließen können.

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Author contributions

PLI, JB and TH conceived the overall project idea and formulated the overarching research aims. Funding acquisition was obtained by PLI and JB with contributions from specific research group leaders, PLI and JB supervised the project, and project administration was carried out by JB and SR. – TH wrote the original draft of the manuscript with contributions from PLI, JB and specific research group leaders and subject matter experts. TH, PLI, JB and specific subject matter experts were involved in reviewing and editing of the original draft, with significant contributions from WG, TW, KB, JS, DC and MS (UP). The visualization was carried out by TH, WG, MS (UP), DC and MS (LFE). All authors contributed critically to the draft and gave final approval for publication.

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Supplements

Additional supporting information may be found in the online version of this article.

Zusätzliche unterstützende Information ist in der Online-Version dieses Artikels zu finden.

Supplement E1. Overview of the parameters collected in the PYROPHOB project and the responsible project partners.

Anhang E1. Übersicht über die im PYROPHOB-Projekt erhobenen Parameter mit den verantwortlichen Projektpartnern.

Supplement E2. Soil profiles of the studied VIP soil plots.

Anhang E2. Bodenprofile der untersuchten VIP-Bodenplots.

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Supplement E1. Overview of the parameters collected in the PYROPHOB project and the responsible project partners. aerosense = wildlifemonitoring by aerosense, BTU = Brandenburg Technical University Cottbus, GEI = Senckenberg German Entomological Institute, HNEE: Eberswalde University for Sustainable Development, LFE: Landeskompetenzzentrum Forst Eberswalde, NWA = Naturwald Akademie gGmbH, PABB = Pilzkundliche Arbeitsgemeinschaft Berlin-Brandenburg e.V., UmLand = Umland Büro für Umwelt- und Landschaftsplanung, Thünen: Thünen Institute of Forest Genetcs, UP: University of Potsdam.

Supplement E1. Übersicht über die im PYROPHOB-Projekt erhobenen Parameter mit den verantwortlichen Projektpartnern. aerosense = Wildtiermonitoring by aerosense, BTU = Brandenburgische Technische Universität Cottbus, GEI = Senckenberg Deutsches Entomologisches Institut, HNEE: Hochschule für nachhaltige Entwicklung Eberswalde, LFE: Landeskompetenzzentrum Forst Eberswalde, NWA = Naturwald Akademie gGmbH, ABB = Pilzkundliche Arbeitsgemeinschaft Berlin-Brandenburg e.V., UmLand = Umland Büro für Umwelt- und Landschaftsplanung, Thünen: Thünen Institute für Forstgenetik, UP: Universität Potsdam.

Parameter group	Parameter	Measurement data	Number & type of measuring points	Sampled plots	Frequency of survey	Responsible institution
Remote sensing	Burn severity	dNBR via satellite-based multispectral data	Areawide	All plots	Once, 2018/19	UP
		Classification of fire type	Areawide	All plots	Once, 2018/19	UP
	Vegetation structure	Optical drone images	Areawide south of main road, TB	Plots B-G	Annually (late spring) 2019-2023	UP
Soil inventory	Soil classification	Parent material, horizon sequence and thickness, soil type, soil texture, soil fabric, soil colour	1 soil profile per site	VIP soil plots	Once, beginning	BTU
Soil & soil water	Humus layer	Horizon sequence and thickness	15 humus profiles per site	VIP plots	2 sampling campaigns: 2020/21 and 2024	BTU
	Soil chemistry	C_{org}, pyrogenic C, total C stock, N content, C/N ratio, total nutrient stocks, exchangeable nutrient cations, pH	15 humus profiles per site	VIP plots	2 sampling campaigns: 2020/21 and 2024 (partly)	BTU
	Biological soil activity	N mineralization	1 plot per site; incubator	VIP plots	Annually, May - Oct	BTU
		Litter decomposition	1 plot per site; containers with litter	VIP plots	Annually, May - Oct	BTU
		Soil respiration (CO_2 emission)	1 plot per site, PVC collars	VIP plots	Weekly, Mar-Nov	HNEE
	Solution chemistry of seepage water top soil	pH, electric conductivity, cations & anions, DOC, TIC, DON	1 soil profile per site; litter & topsoil passive lysimeters	VIP plots	Continuous, collected monthly	BTU
	Solution chemistry of seepage water subsoil	pH, electric conductivity, cations & anions, Elements, DOC	1 soil profile per site, 1 suction cups at each 30,60,100cm depth	VIP soil plots	Bimonthly, Mar-Nov	BTU
	Soil water dynamics	Seepage water amount	1 soil profile per site; suction cups	VIP soil plots	Monthly	UP
		Soil moisture	1 soil profile per site; sensors	VIP soil plots	Every 20 min	UP
		Soil temperature	1 soil profile per site; sensors	VIP soil plots	Every 20 min	UP
		Water balance, seepage water movement & groundwater recharge	1D hydological modeling with data collected above	VIP soil plots		UP
Stand stucture	Standing deadwood	Tree species, length, diameter, degree of decomposition, position (conventional measurements)	3 plots per site; r=17.84m	VIP plots	Every 6 months	LFE
		Height, diameter, volume, basal area (terrestrial laser scanning)	All plots or 3 per site; r=17.84m	All plots (2020/21), VIP plots (2022ff)	Annually (winter)	NWA
	Lying deadwood	Volume, position (terrestrial laser scanning)	All plots or 3 per site; r=17.84m	All plots (2020/21), VIP plots (2022ff)	Annually (winter)	NWA
		Volume, condition (conventional measurements)	3 transects; l=7.3m	all plots	Annually (winter)	LFE
	Tree regeneration	Tree species (number), height, root collar diameter, vitality, damage	3 plots per site; r=10m	VIP plots	Annually (after growing season)	LFE / HNEE
		Tree species (individual position), height, root collar diameter, vitality, damage	7 plots; r=2m	7 non-VIP plots	Annually (after growing season)	LFE / HNEE
Microclimate	Canopy closure	Percentage densiometer	All plots	All plots	Twice a year (growing season and winter)	HNEE
	Microclimate	Temperature (130 cm)	All plots	All plots	continuous (10min interval)	HNEE
		Temperature, relative air humidity (10 cm)	3 plots per site	VIP plots	continuous (10min interval)	HNEE
Understorey vegetation including tree regeneration	Vascular plants	Cover/abundance of individual species, height, tree regeneration: also number	All plots; r=10m	All plots	Annually	UP
	Bryophytes and lichens	Cover/abundance of individual species	All plots; r=10m	All plots	Annually	UP
	Aboveground & belowground biomass	Dry weight per area	All plots; r=10m; based on adapted allometric models	All plots	Annually	UP
	Storage of carbon and nutrients in biomass	Total C, N, nutrient cations (K^+, Ca^{2+}, $Mg^{2+)}$)	All plots r=10m; calculated from content in biomass	All plots	Annually	UP
Fungi	Fruit-body forming fungi	Species identity and number (morphology & marker genes)	3 plots r=10-15m per site	VIPs	Annually, 5 campaigns Mar-Nov	Thünen / PABB
	Phytoparasites	Species identity and number (morphology & marker genes)	3 plots r=10-15m per site	VIPs	Annually, 5 campaigns Mar-Nov	Thünen
	Ectomycorrhiza	Species identity and number (morphology & marker genes)	7 plots r=10-15m per site, root tips from soil cores and excavated trees	non-VIPs	5 times per year, 2022-2024	Thünen
Arthropods	Predatory soil arthropodes: spiders and ground beetles	Species identity and number & abundance	6 plots per site (emergence tents & ground traps	VIP plots plus 3 other plots	Every 4 weeks, Mar 2021-Mar 2022	BTU
	Predator attack rates	Attack marks artificial caterpillars	6 plots (2 height levels & on the ground, emergence tents & outside pitfall traps with and without cages)	VIP plots plus 3 other plots	1-2 weeks in 2022, 2023 and 2024	BTU
	Feeding activity of soil animals	Bait Lamina strips	6 plots (inside and outside the emergence tent)	VIP plots plus 3 other plots	3 months May - Juli 2022 and 2024	BTU
	Seed predation	Removal of plant seeds	6 plots per site (inside emergence tents & outside pitfall traps with and without cages)	VIP plots plus 3 other plots	1-2 weeks in 2022, 2023 and 2024	BTU
	Saproxylic beetles	Species identity and number & abundance	2 plots per site, window & funnel traps	near VIPs	Continuously, Apr-Aug, 2021-2023	UmLand
	Moths	Species identity and number & abundance, size	3 plots per site, window cross light traps	near VIPs	Continuously Mar-Nov 2021-2023, up to 15 per year	Senckenberg GEI
Vertebrates	Large mammals	Species identity and number & abundance	1(-2) per site, 2x 15 days	Randomly on the study site	4 monitoring periods per year	NWA
			Aerial wildlife surveys, microlight airplane with (infrared) camera	transects over the whole study area	1 flight per year (early spring, 2021-2023)	NWA / aerosense
	Brds	Species identity and number & abundance	1 per site; territory mapping of breeding birds	whole study areas	6 inspections (March to July, 2021-2023)	NWA
Macroclimate	Macroclimate	Leaf wetness, light intensity (PAR), air pressure, precipitation, solar radiation, temperature & humidity, wind speed	1 wheather station per study area	Outside treatments	Continuous (10min interval)	UP

Heinken et al.: PYROPHOB – A post-fire ecosystem research project to inform management for resilient forest development. – Tuexenia 44 (2024).

Supplement E2. Soil profiles of the studied VIP soil plots.

Anhang E2. Bodenprofile der untersuchten VIP-Bodenplots