Final project report

Title: Open-field experiments supporting ecologically sustainable forest management
NKFIH identity: K128441
Term: 2018.12.01-2023.11.30 (one year prolongation)
Principal investigator: Péter Ódor

Aims of the project

Forests play an important role in the biodiversity of Europe (Forest Europe 2015), although most of the original forests were converted to agricultural land types (arable lands, meadows, pastures) or secondary forests with altered tree species composition and structure. Recently, beside timber production, other functions of European forests increased considerably, such as biodiversity conservation, ecosystem services and recreation. This resulted in a paradigm shift in forest management from economically sustainable forestry to a more ecologically sustainable, multi-purpose forestry. However, in these areas conservational purposes should harmonize with timber production demands. For planning multifunctional forest management, conservation biological and community ecological researches are necessary, which can explore the requirements of different organism groups that can take into consideration in management plans.

In Hungary, rotation forestry systems (shelterwood system using natural regeneration or clear-cutting system using artificial regeneration) are the dominant management type, resulting in structurally homogenous, monodominant stands. However, conservational requirements led to the expansion of new forestry methods that mimic more the natural disturbance regime of deciduous forests. Continuous cover forestry (CCF) (including group selection and tree selection forestry systems) has been spreading in the last twenty years, but still it is in experimental stage in Hungary, only the Pilis Park Forestry Company use it on landscape scale. It is characterized by often (return time 5-10 yr), low intensity intervention, that maintain the continuous cover of the uneven aged stand, high tree species diversity and heterogeneous vertical and horizontal structure. It would like to mimic the natural disturbance regime of the old-growth forests, and it want to base forest regeneration on natural processes. The most common tool of continuous cover forestry for forest regeneration is the gap-cutting, establishment of small cutting areas usually less than 1000 m^2. The size, shape, orientation and establishment type of the artificial gaps are various depending on the forest type, topography and the preconception of the managers. In oak forests, the regeneration of the target tree species seems to be the most successful in small, elongated gaps, which are later spatially extended, after the colonization of oak seedlings. However, experiences concern mainly the tree regeneration and the growth of the dominant trees, other aspects like forest site conditions and biodiversity are excluded. To explore the effect of forest management on biodiversity, such studies are necessary, which take into account the ecological demands of many organism groups simultaneously. According to these considerations, this project investigated the effects of forestry treatments on biodiversity, using a multi-taxon approach concerning functionally different organism groups. We investigated the forest site (microclimate, soil and litter conditions), tree regeneration (seedlings and saplings), understory, carabid beetle and spiders assemblages, and enchytraeid worms.

The project contained two experiments, both carried out in a sessile oak-hornbeam forest: (1) Pilis Forestry Systems Experiment started in 2014, which we continued in this project from 2018; and (2) Pilis Gap Experiment, which we started within the framework of this project (2018). Both experimental area are managed by the Pilis Park Forestry Company, which implemented the experimental cuttings, and actively participated in the planning and maintenance of the experiments as well as the practical implementations of the results.

The design of Pilis Forestry Systems Experiment is detailed in Fig. 1. It is located on the Hosszú-hill, in a block of a circa 40 ha sized, even-aged, 80 year old sessile oak-hornbeam forest with homogenous forest site conditions (Pilisszántó 24C, 25B, 21A). The main aim of the experiment was to compare the effects of some treatments of the classical rotation forestry system and the recently spreading CCF system on site conditions, regeneration and biodiversity. The investigated treatments are: clear-cutting, preparation cutting, retention tree group, gap-cutting and control (closed mature stand). Clear-cutting and preparation cutting are common elements of the forested landscape managed by rotation forestry system, besides closed stands (control). For conservational purposes a small fraction of the original stands is often left in clear-cut areas after interventions (retention tree group). Canopy gaps are common structural elements of the forested landscape managed by CCF (gap-cutting). The experiment is implemented in a randomized complete block design, using 6 replicates (blocks) and five treatments as:

1. control: closed canopy stand without any treatment;
2. clear-cutting: a 0.5 ha sized circular clear-cut area of 80 m diameter surrounded by closed canopy stand;
3. gap-cutting: an artificial circular gap with 20 m diameter (one gap dimeter/tree height ratio);
4. preparation cutting: 30% of the dominant tree layer in spatially uniform way, and the complete secondary tree- and shrub layer have been removed in a circle of 80 m diameter;
5. retention tree group: a circular group of retained dominant trees (20 m diameter, 8-12 individuals) in the clear-cut areas.

In all treatment a 6 m×6 m sized fenced plot was established. Air temperature, relative humidity, soil temperature, soil moisture and light conditions were permanently recorded by automatic loggers using 15 min intervals. Soil and litter samples were collected for chemical analyses twice in every growing season. Natural understory vegetation was recorded in 2 m×2 m sized permanent quadrats inside and outside of the fence, two times in a year. Ground beetle and spider assemblages were surveyed twice a year by soil traps. Enchytraeid worms were explored from soil samples collected also twice a year from 2014-2016 (before the start of the project). Five saplings of each of the investigated tree species (*Quercus petraea, Q. cerris, Fagus sylvatica, Carpinus betulus, Fraxinus excelsior*) were planted into the fenced plots. The growth of height, diameter and the total leaf area of the seedlings were measured periodically by a non-destructive method (using portable leaf area meter).

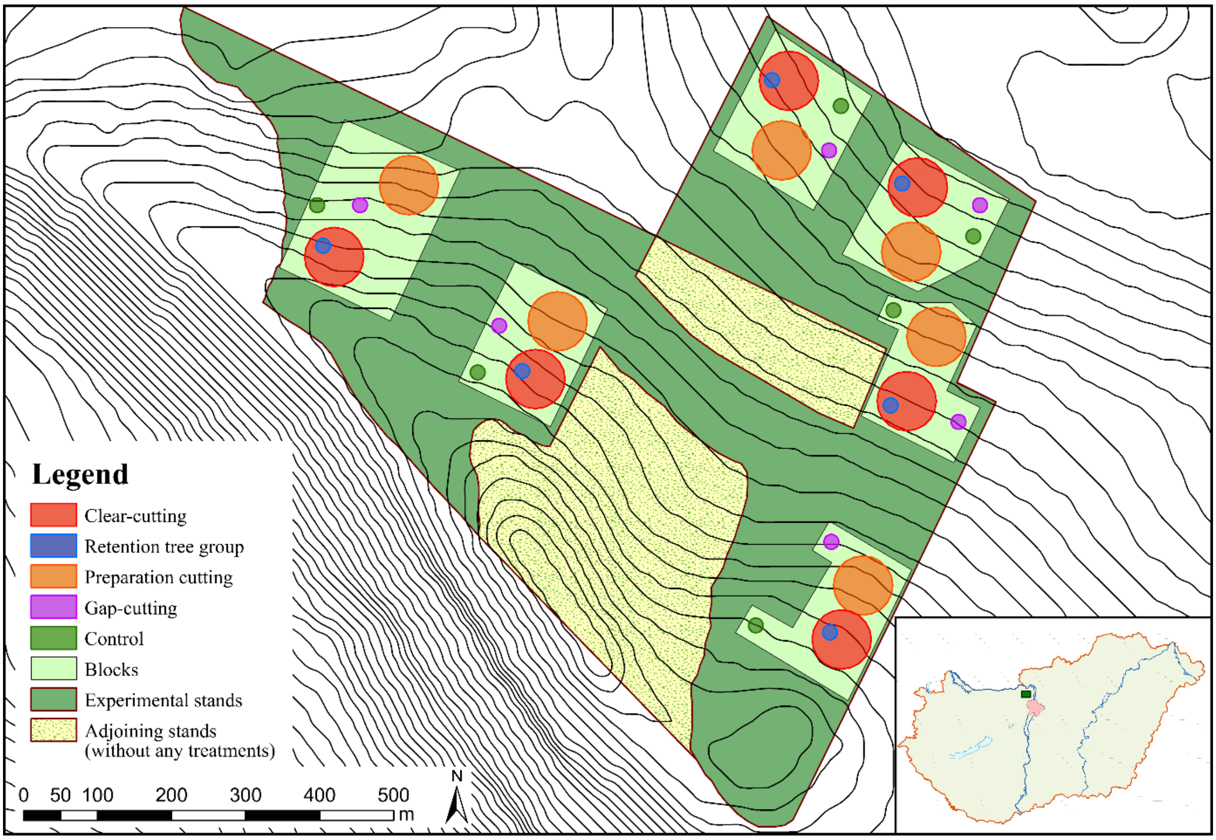

Fig. 1. The design of the Pilis Forestry Systems Experiment.

The second part of the project was the establishment of the Pilis Gap Experiment. It was established in a 90 year old sessile oak-hornbeam forest stand (Pilisszántó 26A and 27A), near the Pilis Forestry Systems Experiment (Fig. 2). We analyzed the effect of gap size (small versus large), shape (circular vs. elongated) and type (promptly created vs. delayed extended). All combinations of the size and shape (small circular, large circular, small elongated, large elongated) were implemented into the experimental setup, while small elongated gaps were created twice, from that one will be extended to large cicular gap. For the regeneration of oaks, forestry practice often establish small elongated gaps, but after the regeneration of the seedlings they are extended to large circular gaps for the acceleration of vertical growth of the seedlings. This extension will be implemented in 2024 (after the project), so the results of this treatment is not included in this report. The different gap-cuttings are compared to the untreated closed mature stand as control. The main questions of the Pilis Gap Experiment were: how the applied treatments changed (1) the forest site conditions (microclimate, soil and litter properties); (2) the understory vegetation and natural regeneration; (3) the community structure of different animal groups (ground beetles and spiders,); (4) the regeneration of sessile oak seedlings. The experiment followed a complete block design using 6 blocks as replicates and 5 treatments within each block (30 plot). The size of the small gaps is 150 m^2 (14 m diameter for circular, 7 m × 21 m for elongated gap), while it is ~300 m^2 for large gaps (20 m diameter for circular and 10 m × 30 m for elongated gaps). The whole area was fenced; the browsing effect was studied only in Pilis Forestry Systems experiment. The treatments was implemented in the winter of 2018-2019. For all investigated variables the pre-treatment conditions was measured in 2018, which made possible the BACI analyses. The same microclimate variables (air temperature, air humidity, soil temperature, light) as well as soil water content was measured as at Pilis Forestry Systems Experiment. The permanent soil moisture measurements was extended by regular systematic sampling with Fieldscout TDR 350 (Spectrum Technologies, Aurora US-IL). Light conditions was measured by LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, US-NE) and by fish-eye photograps. Soil and litter chemical variables were studied in similar way as in Pilis Forestry Systems experiment. Understory (herbs and arboreal plants) was recorded in 2 m × 2 m sized quadrats in each plot based on cover estimation in spring and summer. The regular survey was extended in certain years with a more intensive, systematic sampling of smaller (0.25 m^2 sized) quadrates, which allow to describe the spatial pattern of vegetation within the gaps. The studied animal groups (ground beetles, spiders) was surveyed in the same way as in Pilis Forestry Systems Experiment. The effect of the treatments on sessile oak regeneration was studied based on the long-term survey of individual seedlings.

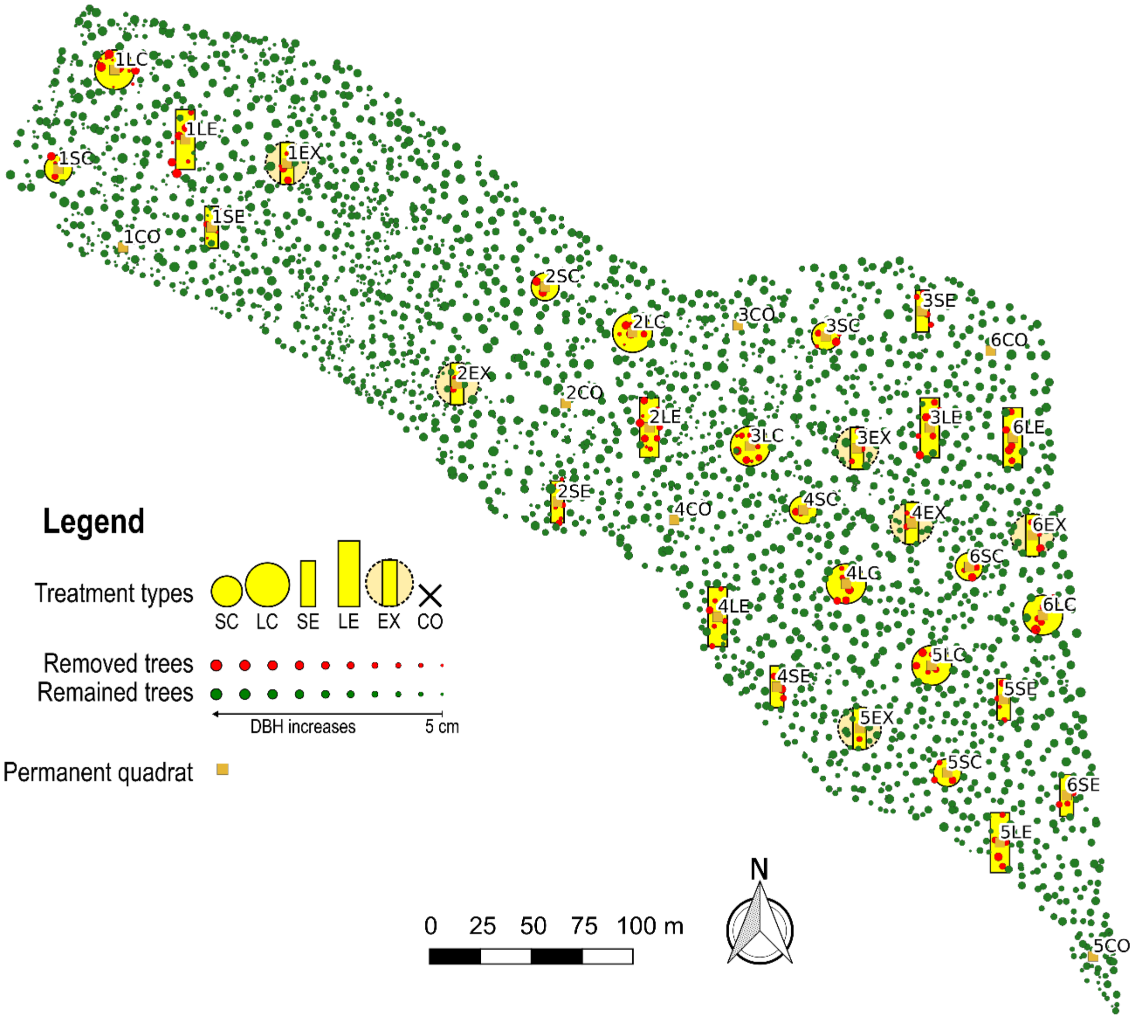

Fig. 2. Experimental design of the Pilis Gap Experiment. Numbers mean the blocks, letters the treatments: SC (small circular), LC (large circular), SE (small elongated), LE (large elongated), EX (extended), CO (control). Dots represent the locations of the trees (dot size are related to trunk diameter).

Personal and institutional background

Péter Ódor was the principal investigator of the project from the Centre for Ecological Research, Institute of Ecology and Botany, Forest Ecology Research Group. Participant researchers in the project from the same institute were Réka Aszalós (understory in Pilis Forestry System Experiment), Gergely Boros (enchytraeid worms), Bence Kovács (microclimate), Zoltán Soltész (dipterans), Flóra Tinya (regeneration, understory in Pilis Gap Experiment). Participant researchers from external institutes were András Bidló (University of Sopron, soil and litter characteristics), Zoltán Elek (MTA-ELTE-MTM Ecology Research

Group, ground beetles), Ferenc Samu (HUN-REN Centre for Agricultural Research, spiders). During the project a non-researcher employee (Csaba Németh) and two PhD student joined. Csenge Veronika Horváth studied the understory and microclimate and Eszter Lilla Szabó investigated the browsing effect in Pilis forestry Systems Experiment. Zoltán Soltész quited from the project, he had too high summed FTE values because of his starting PD project.

Scientific results

Publication summary

We published 17 scientific papers from the project, their cumulative impact factor is 60. According to the SCIMAGO qualification, 10 were published in D1, 3 in Q1, 2 in Q3 journals and 2 without rank or impact factor (in Hungarian forestry journal "Erdészettudományi Közlemények"). We published three informative papers in the Hungarian forestry journal Erdészeti Lapok. 18 of the 20 publication were connected directly to the two experiments, mainly the project participants were the first and principal investigator was the last author. The two exceptions are Bölöni et al. 2021 (Forest Ecology and Management) and Tinya et al. 2021 (Scince of the Total Environment). The first one is a review; the second one is a generalization of an earlier study, both connected to the research topic. Three MSc thesis were published from the project, we expect the defense of two PhD thesis in the near future. We kept 18 conference presentation (with abstracts) connected to the project. All publications and additional information from the research are available in the website https://piliskiserlet.ecolres.hu/ .

Pilis Forestry Systems Experiment

Although the experiment started in 2014, most of the publication connected to the experiment were published in the period of the project (2018-2023) because of the slow responses of the forest ecological functions after the treatments.

Analyzing the microclimatic changes of first three years after the treatment we found that clear-cuts differed the most from the uncut control due to the increased irradiance and heat load (Kovács et al. 2020, Ecological Applications). Means and variability of air and soil temperature increased, air became dryer along with higher soil moisture levels. Retention tree groups could effectively ameliorate the extreme temperatures but not the mean values. Preparation cutting induced slight changes from the original buffered and humid forest microclimate. Despite the substantially more incoming light, gap-cutting could keep the cool and humid air conditions and showed the highest increase in soil moisture after the interventions. For most microclimate variables, we could not observe any obvious trend within three years. Based on multivariate analyses, the treatments separated significantly based mainly on the temperature maxima and variability. We found that (i) microclimate responds immediately after the harvests; (ii) the effect sizes among treatment levels were consistent throughout the years; (iii) the climatic recovery time for variables appears to be far more than three years and (iv) the applied silvicultural methods diverged mainly among the temperature maxima. Based on our study, the spatially heterogeneous and fine-scaled treatments of continuous cover forestry (gap-cutting, selection systems) are recommended. By applying these practices, the essential structural elements creating buffered microclimate could be more successfully maintained. Thus, forestry interventions could induce less pronounced alterations in environmental conditions for forest-dwelling organism groups.

The effect of the treatments on litter conditions during the four-year period was published in Sass et al. 2021 (Erdészettudományi Közlemények). The average litter features of the closed control forest area remained unchanged, however, the treatments significantly influenced all the studied litter-variable (quantity, moisture, pH). Litter quantity was the highest in retention tree groups, although this area was the driest. The lowest quantity of litter was measured in clear-cutting. The treatments had the highest effect on the acidity/alkalinity: pH increased in case of clear-cuttings and a less extent gap-cuttings, caused by the increased herbaceous understory cover. We can conclude that moderate partial cutting (preparation cutting) did not change the litter conditions, retention tree groups can buffer the extreme effect of clear-cuttings, and gaps only slightly modify the litter conditions compared to the clear-cuts. These results show that continuous cover forestry maintain more favorable litter conditions than rotation forestry systems.

The short-term changes of the understory vegetation after the treatments were published by Tinya et al. 2019 (European Journal of Forest Research), Horváth et al. 2019 (MSc Thesis), and Horváth et al. 2021 (Erdészettudományi Közlemények), while the mid-term changes by Aszalós et al. 2023 (Forest Ecology and Management). We found a large temporal variability in the understory variables over the study period. In all cases, the interventions led to an initial increase in species richness, often followed by a decline later, as the regeneration layer started to close. At the end of the study, retention tree group had the highest average species richness, comprising a heterogeneous group of perennial forb species. The interventions all resulted in a rapid increase in total herb layer cover, mainly in favour of graminoid and perennial species. The extent of the cover increase depended primarily on the intensity of the intervention, reflecting the amount of additional light received (clear-cutting > gap-cutting > preparation cutting > retention tree group > control). Turnover values, i.e. the rate of compositional change, also decreased in the same order. The effect of game exclusion was especially pronounced in the case of the clear-cutting and gap-cutting, where game browsing significantly slowed downed the regeneration outside the fences. The most significant changes in almost all variables were in the clear-cutting. It had the highest number of indicator species, many of them annual, ruderal, and invasive. Gap preserved the forest character of the vegetation better and proved to be less susceptible to the mass appearance of disturbance-related and invasive herbaceous species. Increasing the share of continuous cover forestry methods is crucial to preserve the forest herb layer at the landscape scale. Rotation forestry with large cutting areas is not recommended or should be kept at low landscape rates, as these areas are highly exposed to disturbance-related and invasive species. Leaving retention tree groups can be key to the survival of numerous forest plant species.

The regeneration after the treatments was published by Tinya et al. 2020 (Forest Ecology and Management). We found that the acorns production of oak was high in closed forest, intermediate in preparation cutting and retention tree group, low in gaps, and zero in clear-cutting. It means that in gaps and clear-cuts the oak regeneration is limited by the acorn dispersal. Four years after the interventions, there was no detectable treatment effect on the species number of regeneration. Survival increased in every treatment compared to control, but there was no significant difference in this measure between the differently treated sites. Height growth was highest in the gaps and clear-cuts, intermediate in preparation cuts, and lowest in retention tree groups and controls. Species with different seed dispersal mechanisms responded differently to treatments: oaks were dispersal-limited in the gaps and clear-cuts, while anemochorous species (e.g., hornbeam and manna ash) were present in every treatment. The survival and growth pattern of the particular species proved to be similar, but the intensity of the response differed: shade-tolerants (hornbeam, beech, and ash) showed better survival than oaks in most treatments, and their height growth was larger. According to our results, oak regeneration establishes successfully in oak-hornbeam forests not only in the case of rotation forestry, but also during continuous cover forestry (gap-cutting). The survival and growth of the saplings are similar in cutting areas and gaps, but keeping in mind other considerations (such as preserving forest continuity, balanced site conditions, and forest biodiversity), continuous cover forestry should be preferred.

The effect of treatments on ground beetle assemblages was analyzed in Elek et al. 2022 (Ecological Applications). The species composition was only slightly influenced by the treatments; on the ordination biplot, the control, retention tree group and clear-cutting treatments formed relatively homogeneous groups, well separated from each other, while the others were scattered randomly in the ordination space. Over time, the species richness decreased in all treatments, but it was higher in the retention tree group treatment than in others in 2016 and 2017. The activity density also declined between years, but an immediate mass effect was revealed after the implementation of treatment types especially in the control, gap and preparation cuts. We found that assemblages in the clear-cutting and retention tree group had similar characteristics: high functional diversity, more open-habitat, generalist and omnivore species and fewer carnivore species; while those in the control, gap and preparation cutting ones had the opposite: lower functional diversity, more forest species and carnivorous. Beside community level analysis the individual movements of *Carabus scheidleri* and *C. coriaceus* were studied in Ruzickova et al. 2021 (Acta Zool. Acad. Sci. Hung.). They found that activity density, mean walking speed and the proportion of active time were significantly higher in preparation cutting and clear-cutting than in control plots. However, the individual movement revealed only temporal use of these treatments. The movements of *C. coriaceus* was studied by radio-transmitters (Elek et al. 2021, Biologia). They revealed that the proportion of the random walk and the directional movement in a particular trajectory was influenced by the forestry treatments. In the core zone of preparation cuts, the random walk and the directional movement were equally distributed in the trajectory. A clear directional movement was observed in the clear-cuts suggesting the beetles moved directly toward the adjacent (control) forest interior. These results suggest that forest specialist ground beetles can avoid the forestry treatments especially clear-cuts, however edge habitats and (the studied) preparation cuts can mitigate the migration constraints due to their more favorable environmental conditions compared to clear-cuts. The predation of carabids was studied by 3D printed decoys in the experiment (Ruzickova and Elek 2021, Diversity). Their results revealed significantly higher predation risk on carabids in both clear-cutting and preparation cutting than in the control. Moreover, it was also higher in nighttime than daytime. Contrarily, no effects of season and microhabitat features were found. These clues revealed that habitats modified by forestry practices may act as an ecological trap for carabids.

The spider assemblages of the treatments were followed by Samu et al. 2021 (Scientific Reports). They found that in the treatment plots spider abundance and species richness increased marginally. Species composition changes were more pronounced and treatment specific, initially diverging from the control plots, but becoming more similar again by the fifth year. These changes were correlated mostly to treatment-related light intensity and humidity gradients. The patchy implementation of the treatments induced modest increase in both gamma and beta diversity of spiders in the stand. Overall, spiders gave a prompt and species specific response to treatments that was by the fifth year showing signs of relatively quick recovery to pre-treatment state. At the present fine scale of implementation the magnitude of changes was not different among forestry treatments, irrespective of their severity.

Soil-dwelling organisms e.g. enchytraeid assemblages, had fast and drastic responses to the treatments (Boros et al. 2019, Applied Soil Ecology). Two years after the treatments, a strong response was observed in clear-cutting and even more in retention tree group: in both treatments the abundance and the species richness of enchytraeids were reduced. Species did not show vertical movements into deeper layers and were not able to tolerate the altered soil conditions caused by changed microclimate. Gap-cutting and preparation cutting did not differ significantly from control plots. Our study showed that right after the interventions tree retention at the size of one tree height in diameter had no sheltering effect on this important soil decomposer animal community. These results are in contrast with earlier findings in boreal zones, where soil organic layer is considered a well buffered habitat against environmental changes. Oppositely, enchytraeid assemblages in a temperate deciduous forest are more diverse but seem more vulnerable to management-related alterations in soil conditions (soil temperate increment, reduced soil moisture).

The early response to the treatments on different organism groups (plants, ground beetles, spiders, enchytraeids) were compared in a multi-taxon paper (Elek et al. 2018, Scientific Reports). They showed that the effect of treatments on the different facets of assemblage structure was taxon-specific. Clear-cutting and retention tree group strongly impoverished enchytraeids assemblages. Even if the species richness and cover of plants increased in clear-cutting and gap-cutting, their species composition moderately changed after treatments. For spiders only their species composition was influenced by the treatments, while the response of ground beetles was slightly affected. Short-term effect of forest management interventions on biodiversity might be compensated by the dispersal (spiders, ground beetles) and resilience (plants) of organism groups, however sedentary soil organism showed high sensitivity.

Based on the results of the Pilis Forestry Systems Experiment we can conclude that cutting areas created by the rotation forestry system result in strongly unfavourable abiotic conditions for the conservation of forest biodiversity. The composition of forest communities changes due to the large daily temperature range, the low air humidity, and the substantially increased light. The proportion and abundance of non-forest species increases, while forest species are forced back. Contrary to this, in the gaps created by continuous cover forestry, despite the increased light, the microclimate preserves its balanced, forest characteristic. The increased water content in the upper soil layer results in favourable conditions for plants and soil-dwelling organisms. The composition of the forest organism groups changes, but basically it keeps its forest character. For the tree regeneration, conditions of gaps are similarly proper than that of clear-cuts, but in order to ensure the adequate development of oaks, the control of fast-growing shade-tolerant species is necessary in both treatments. Game browsing has a strong effect in both treatments, but it is more pronounced on the admixing tree and shrub species than on the main tree species. In the preparation cutting, both microclimate and forest taxa preserve their forest characteristics. The slight decrease of canopy closure does not change the forest conditions. Retention tree groups can compensate the unfavourable effects of clear-cuts for certain organism groups (e.g., for the understory vegetation), but for the soil-dwelling taxa the dry and warm soil offer poor conditions. Regarding the temperature, retention tree groups buffer the daily variation, but do not compensate the changes of the mean values. In order to preserve forest biodiversity during the rotation forestry system, we suggest to retain larger tree groups than our 300-m^2 sized ones, especially at dry forest sites. As a summary, we can conclude that treatments of continuous cover forestry ensure better the protection functions of forests than rotation forestry system.

<u>Pilis Gap Experiment</u>

From the Pilis Gap experiment we published the short-term microclimatic responses (Horváth et al. 2023, Science of the Total Environment). In all gaps diffuse light had a central maximum and a concentric pattern. Direct light was distributed along a north-south gradient, with maxima in northern gap parts. Soil moisture was determined by gap shape: it increased significantly in the centre of circular gaps, with multiple local maxima in the southern-central parts of large circular gaps. Its pattern was negatively related to direct light, and larger spatial variability was present in circular than in elongated gaps. The daily mean air temperatures at 1.3 m increased in all, especially in large gaps. Soil and ground-level temperatures remained largely unchanged, reflecting light and soil moisture conditions affecting evaporative cooling. Relative humidity remained unaltered. Even though the opening of experimental gaps changed microclimatic conditions immediately, effect sizes remained moderate. Gap size and gap shape were both important determinants of microclimate responses: gap size markedly affected irradiation increase, gap shape determined soil moisture surplus, while soil and air temperatures, and air humidity depended on both components of the gap design. We conclude that 150-300 m^2 sized management-created gaps can essentially maintain forest microclimate while theoretically providing enough light for oak regeneration; and that the manipulation of gap shape and gap size within this range are effective tools of adaptive management.

The response of spider assemblages to the treatments were published by Samu et al. 2023 (Diversity). Pitfall samples of ~4600 spiders indicated that spider species richness was moderately higher in the gaps than in control stands. Spider assemblages did not respond in a specific way to the different gap implementations, but their variation in species composition was considerably higher in gaps than in the control plots. The excess spider abundance and species number in gaps, as compared to control, increased over the observation period, as did the dissimilarity of gap assemblages to control. Species responses imply that gaps create a variation in microhabitats and microclimatic conditions, resulting in spiders' diversification. The overall effect of gaps on spider assemblages suggests that gap-cutting is a suitable management option that preserves forest spider assemblages.

The understory response on the treatments are analysed, but it is still on manuscript stage, before submission (Tinya et al., manuscript), preliminary results were published as an MSc Thesis (Locatelli 2020). Our results indicate an increase in light in all gap types. However, light decreased in large circular gaps over the years, while remaining more stable in other gap types. Species richness experienced a temporary increase in large circular gaps, whereas total cover increased in all gap types. The height of the understory and the shrub cover also increased in large circular gaps. Annual and perennial forb cover remained unchanged in all studied gap types, although graminoid cover showed transient growth in large elongated gaps. Small gaps had the highest cover of woody regeneration, whereas blackberry (*Rubus fruticosus agg.*) cover increased in large circular gaps. Species composition exhibited the most significant changes in large circular gaps, and the least in small elongated ones. Vegetation changes proved to be most prominent in large circular gaps. While these gaps can be considered favorable from conservational aspect, as they may enhance the structural diversity of the stand, their dense coverage of blackberry and shrubs hinders the effective regeneration of sessile oak (*Quercus petraea*). Smaller gaps slightly increase the heterogeneity of the forest understory, and provide ample light to initiate regeneration. If regenerating oak using larger gaps, competition from blackberry can be mitigated by applying an elongated shape.

For the final analysis of the regeneration success of oak, we plan to use the data of 2023 and 2024, we published the preliminary results as an MSc Thesis (Gitau 2023). The results revealed that gap cuttings significantly affected the acorn supply, the height increment and the abundance of the *Quercus petraea* saplings. However, initial survival was driven by other factors independent of the gap type. Abiotic conditions (light and soil moisture) proved the most favourable for oak regeneration in the large circular gaps. However, these circumstances also promoted the competing vegetation (perennial forbs and some woody species such as *Carpinus betulus* and *Cornus sanguinea*). Large elongated and small circular gaps offered only slightly lower resources (light and soil moisture), with lower competition effect. Thus, in these gap types, more oak saplings could reach the larger size categories, with a slightly smaller but considerable growth. The height increment of oak saplings was the weakest in small elongated gaps, but it also ensured their survival, while acorn production was the highest in this gap type. Our findings imply that oaks can be regenerated in small-scaled gaps. However, the competing perennial species must be controlled for successful regeneration in sites with suitable abiotic factors (soil moisture and light), or regeneration should be favored using smaller or narrower gaps.

Contribution to the education, to forest management and conservation as well as to the society

The project directly contribute to the development of sustainable forest management by the investigation of CCF, which is in an experimental stage in the Hungarian forestry, only our project partner, the Pilis Park Forestry Company applies it on landscape scale. The project compared the ecological effects of the treatments of CCF as well as the traditional rotation forestry (Pilis Forestry Systems Experiment) and contributed to the development of gap-based regeneration applied by CCF (Pilis Gap Experiment). The CCF provide effectively the conservational functions and ecosystem services of the forests resulting similar (or higher) economic utilization of the timber. The results of the project is widely communicated to practical professionals (foresters, nature conservationists), decision makers and for the general public. We published three information papers in the Hungarian forestry journal (Erdészeti Lapok) describing the aims, main results and forestry relevancies of the project (Ódor et al. 2020, Horváth et al. 2021, 2023). We maintain a website about the two experiments including documents for the general public, maps, pictures, as well as all scientific publications and presentations (https://piliskiserlet.ecolres.hu/en). The principle investigator active in the professional life of the forestry and conservation sector (board member of the CCF section and the Professional Core Group of the Hungarian Forestry Association, the Pro Silva Hungaria Association), he keeps many presentations and postgraduate lectures for foresters involving the results of the project. The project was actively communicated to the general public, circa 10 media appearances connected to the project yearly (printed articles and interviews, radio and TV presentations, podcast etc.). The project is also incorporated to the university education, two PhD and three MSc student worked in the experiments during the project period, it is a field practice place of the PhD curse in Eötvös University and Sopron University. The principal investigator teaches ecology and CCF in Sopron University, the project is incorporated to the lecture curses as a practice and example.

Correspondence between the research plan and the implementation of the project

The planned field inventories of the two experiments were completely realized (establishment of the Pilis Gap Experiment, inventory of microclimate, soil, understory plants, regeneration, ground beetles, spiders, enchytraieids etc.). We made additional field sampling in the experiments not planed in the project as fungi and collembola inventory, detailed terrestrial lidar inventory in the Pilis Gap Experiment, functional investigation of the soil microbiome community, fine-scaled understory and light inventory. We postponed the establishment of the gap extension in Pilis Gap Experiment, because it depends on the stage of the regeneration. The planed publication are mainly realized, for some organism groups (eg. ground beetles) we published more papers than it was originally planned. Some planned publications of the Pilis Forestry Systems Experiment will be realized later as the changes of the soil conditions (the responses were very slow) and the effect of browsing (fencing) on the regeneration. For the Pilis Gap Experiment we can publish the results of the understory and the regeneration only after the project (probably in 2024), because the regeneration responses were very slow after the intervention.