Understanding the carbon balance at organ, tree and forest ecosystem level

SFL ScienceDay

Friday, 16th January 2026

08:00 – 17:00

University of Berne
Geografisches Institut (GIUB)
Room: EG-001
Hallerstrasse 12
3012 Bern

Keynote Speaker

Dr. Sebastiaan Luyssaert
Vrije Universiteit Amsterdam

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Content

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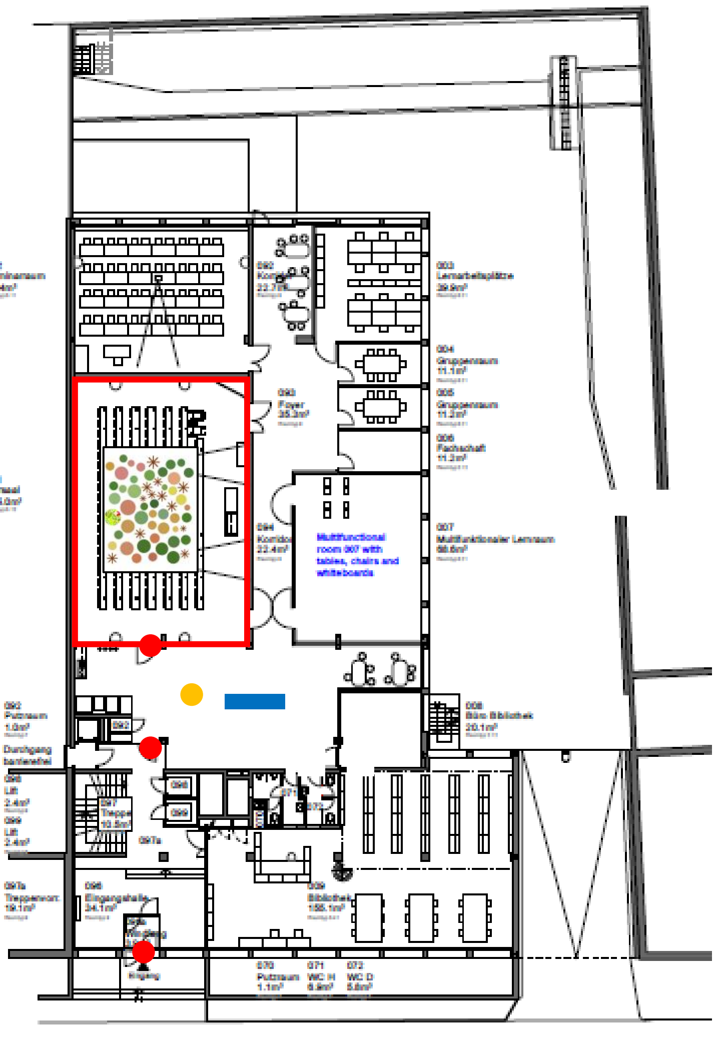

Hallerstrasse 12

- 🟡 Registration / Apèro
- 🔴 Entrances
- 🟦 Poster Sessions

Event Program

08:00 - 09:00	**Registration**		

Session 1 Chair: Bernhard, Fabian

09:00 - 09:05	1.0	Gessler, Arthur	Welcome by the Chairman of SwissForestLab
09:05 - 09:10	1.1	Bernhard, Fabian	Introduction to Geocomputation and Earth Observation (GECO) lab (Inst of Geography, University of Bern)
09:10 - 09:40	1.2	Luyssaert, Sebastiaan	**Keynote:** Continental scale forest management: think global, act local
09:40 - 09:55	1.3	Paul-Limoges, Eugenie	Managing Swiss forests towards net zero in a changing climate
09:55 - 10:10	1.4	Etzold, Sophia	Decreasing water availability reduces productivity in Swiss forests along an altitudinal gradient
10:10 - 10:25	1.5	Zhou, Yu	Atmospheric Deposition Outweighs Dryness in Regulating European Ecosystem Productivity
10:30 - 11:00		**Coffee break**	
11:00 - 11:15	1.6	El-Mejjaouy, Yousra	Detecting physiological drought impacts on ecosystem physiology from multispectral, thermal, and meterological remote sensing data
11:15 - 11:30	1.7	Rog, Ido	Increased belowground tree carbon allocation in a mature mixed forest in a dry vs. a wet year
11:30 - 11:45	1.8	Guidi, Claudia	Drivers of soil organic carbon from temperate to alpine forests: a model-based analysis of the Swiss forest soil inventory
11:45 - 12:00	1.9	de Jong, Philipp	Interactions between earthworm species enhance litter-derived carbon stabilization in the mineral soil
12:00 - 13:45		**Lunch Break**	

Session 2 Chair: Lachat, Thibault

13:45 - 13:50	2.0	Lachat, Thibault	Introduction to Forest Ecology lab (Bern University of Applied Sciences BFH)
13:50 - 14:05	2.1	Buchmann, Nina	Soil, below-canopy and ecosystem CO2 and CH4 fluxes and their drivers in a subalpine spruce forest
14:05 - 14:20	2.2	Ehming, Merten	Four Decades of Forest Development in the Context of Nitrogen Eutrophication and Climate Change
14:20 - 14:35	2.3	Chen, Liangzhi	Multiyear droughts and ecosystem responses – A global look
14:35 - 15:00		**Coffee break**	
15:00 - 15:15	2.4	Gessler, Arthur	What if we could reconstruct tree metabolism and explore how environmental factors influence it through tree rings?
15:15 – 15:30	2.5	Lukovic, Mirko	Point dendrometer and climate data processing with temporal convolution networks

Poster Pitches

15:30 - 15:35	2.6	Wright-Osment, Nicholas	Measuring Carbonyl Sulfide Fluxes for Enhanced Insight into Carbon Dynamics in a Mixed Forest
15:35 - 15:40	2.7	Bernhard, Fabian	Model-data fusion of daily ecosystem fluxes and forest inventories with a dynamic vegetation model
15:40 - 15:45	2.8	Haoyu, Diao	Contrasting photosynthetic, stomatal, and mesophyll mechanisms drive common reductions in leaf water-use efficiency under blue light
15:45 - 15:50	2.9	Schneider, Pascal	Early Warning Signals for Tree Mortality: A Review of Indicators, Limitations, and Emerging Opportunities
15:50 - 17:00		**Poster Session & Apéro**	

Oral Presentations

Continental scale forest management: think global, act local

Sebastiaan Luyssaert[1)]

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The common denominator of my work is the two-way interaction between forest management and climate change for which I contribute to data synthesis, literature review, and the development of the land surface model of the IPSL climate model.

Managing Swiss forests towards net zero in a changing climate

Paul-Limoges Eugenie[1)], Mauri Achille[1)], Rigling Andreas[2) 1)], Bugmann Harald[4)], Schulz Tobias[5)], Griess Verena[3)], Portier Jeanne[6)], Heubel Sina[3)], Krumm Frank[1)]

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Switzerland has an ambitious goal to achieve net zero CO2 emissions by 2050. In particular, the construction sector has an immense potential by substituting CO2-intense material (e.g. concrete and steel) with biomaterials such as wood. However, to investigate the availability of domestic wood to sustain this transition, an assessment of future forest biomass availability as well as tree species composition is needed. As part of the multidisciplinary project, MainWood, which is aimed at leveraging the transition to a construction bioeconomy across the wood supply chain in Switzerland, we simulate future forest development under anticipated climate scenarios and for various stakeholders' informed management strategies. We selected five case study regions representing the most important production regions of Switzerland. To assess tree species' climate suitability and growth dynamics, we employ the dynamic process-based ForClim model at the stand scale. Our simulations are based on different types of forest management scenarios: a "Business-As-Usual" scenario (Swiss close-to-nature and multi-purpose forestry) and alternative stakeholder-informed scenarios, including segregated management approaches (e.g., short-rotation plantations) to meet the expected future demand in construction wood production. We also evaluate how alternative forest management scenarios affect biodiversity, which require a balance between wood extraction and biodiversity related measures (for e.g. deadwood, habitat trees, old growth islands). In some regions, we found an increase in forest productivity at higher elevations, which however might not benefit the bioeconomy transition due to the difficult and costly harvesting operations in mountainous regions. At lower elevations, forest productivity will decrease, in some regions quite drastically. Assisted migration might help in some cases to remedy this forest productivity loss, resulting sometimes in a shift towards a higher proportion of deciduous tree species. This will require the development of new technologies capable of implementing cost-effective construction processes that use new timber engineering products based on a mix of softwood and hardwood species.

Decreasing water availability reduces productivity in Swiss forests along an altitudinal gradient

Sophia Etzold[1)], Arun K. Bose[1)], Arthur Gessler[1)], Frank Krumm[1)], Katrin Meusburger[1)], Marcus Schaub[1)], Anne Thimonier[1)], Peter Waldner[1)], Roman Zweifel[1)]

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Forests are under increasing pressure since recent decades due to climate change, increasing frequency of extreme events such as heat waves and storms, and air pollution. On the other hand, our forests are the most important terrestrial CO_2 sinks, and provide important ecosystem services , such as avalanche and erosion protection, cleaning water and air, recreation, as well as a huge economic value. Therefore, it is important to know how the sink capacity and health of forests is developing under the changing conditions. To assess the variability of tree and forest growth of various Swiss forest ecosystems, we analysed 25 years (1995-2020) of growth data, measured at 18 forest sites of the Swiss monitoring network "long-term forest ecosystem research" (LWF), spanning a wide range of altitude and climatic conditions. We found a decreasing trend of forest productivity (basal area index, and net carbon uptake by growth), particularly pronounced since 2015 across all altitudinal ranges, age classes and species, which could not solely be attributed to stand density and ageing of the forest, but also to soil water availability. The growth rate of trees, as well as the ingrowth rate were hereby the most important factors explaining the overall forest productivity. At a given stand density, forest productivity was lower in recent years compared to earlier decades. This 30-years declining growth trend could partly be attributed to water and nutrient limitations, and points to a decreasing growth capacity of the forest sites, that is the long-term potential of a site to sustain tree growth.

Atmospheric Deposition Outweighs Dryness in Regulating European Ecosystem Productivity

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Ecosystem productivity across Europe is widely assumed to be constrained primarily by dryness level in recent decades. Yet the influence of atmospheric deposition remains poorly quantified, even as Europe undergoes rapid changes in nutrient cycles and experiences the world's fastest decline in nitrogen and sulfur inputs. Here, combining satellite observations and atmospheric deposition data from 2000 to 2023 with explainable machine-learning models, we show that atmospheric deposition exerts a stronger influence than both atmospheric and soil dryness on gross primary productivity (GPP) by regulating maximum carbon uptake capacity (GPP_{max}) and the carbon uptake period (CUP). Declining nitrogen deposition consistently reduced GPP_{max} and shortened CUP across large regions, whereas declining sulfur deposition enhanced both metrics, reflecting ecosystem recovery from historical acidification. In contrast, recent changes in atmospheric and soil dryness were spatially limited, affecting roughly three times fewer areas than deposition, although atmospheric dryness remains an important driver of GPP_{max} and CUP at the ecosystem functional level. Together, these results indicate that shifts in atmospheric nutrient deposition can rival climatic drying in shaping ecosystem carbon uptake and provide early insight into how declining nutrient inputs may influence future productivity as other regions undergo similar transitions.

Detecting physiological drought impacts on ecosystem physiology from multispectral, thermal, and meteorological remote sensing data

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Satellite remote sensing of surface reflectance is widely used to assess vegetation structure, green foliage and to quantify vegetation indices such as the normalized difference vegetation index (NDVI). However, abiotic stress (e.g., drought) and physiological responses are often not directly measured or are insufficiently captured by these indices. In this study, we combine a large volume of eddy covariance flux data with satellite remote sensing and machine learning to develop a multispectral Earth observation (EO) model that captures the drought physiological response, separated from the structural response. Using MODIS full spectral and thermal data (TIR) and ERA5-Land meteorological data and derived potential cumulative water deficit (PCWD), we predict the reduction in light use efficiency due to soil moisture drought (fLUE), derived from eddy covariance flux measurements and given at several sites across a wide environmental gradient and different vegetation types. Using spatial cross-validation, our model predicted fLUE with a coefficient of determination (R^2) of 0.64 and a root mean square error (RMSE) of 0.112. To further evaluate the robustness of the full multispectral reflectance, TIR data, and meteo data in detecting physiological responses, we compare it to vegetation indices, mainly NDVI, across central Europe during two summer drought conditions. Our results show that under drought conditions, the physiological response can be partly estimated from the combination of spectral, thermal, and meteorological data. While the effect is partly correlated with NDVI and the structural response, the correlation breaks down in evergreen ecosystems. Under these conditions, our remote sensing data-driven model captures a larger portion and an earlier onset. Our results demonstrate that integrating a pigment-sensitive spectral index (GRVI) with key meteorological drought drivers (PCWD and LST) enables partial detection of vegetation physiological stress. This combined approach captures pigment, thermal, and atmospheric drought responses that is untapped traditional vegetation indices and can be used for a more complete estimation of drought impacts from EO.

Increased belowground tree carbon allocation in a mature mixed forest in a dry vs. a wet year

Ido Rog[1)], Boaz Hilman[2), 3)], Hagar Fox[1)], David Yalin[4)], Rafat Qubaja[4)], Tamir Klein[1)]

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Tree species differ in their carbon (C) allocation strategies during environmental change. Disentangling species-specific strategies and contribution to the C balance of mixed forests requires observations at the individual tree level. We measured a complete set of C pools and fluxes at the tree level in five tree species, conifers and broadleaves, co-existing in a mature evergreen mixed Mediterranean forest. Our study period included a drought year followed by an above-average wet year, offering an opportunity to test the effect of water availability on tree C allocation. We found that in comparison to the wet year, C uptake was lower in the dry year, C use was the same, and allocation to belowground sinks was higher. Among the five major C sinks, respiration was the largest (~60%), while root exudation (~10%) and reproduction (~2%) were those that increased the most in the dry year. Most trees relied on stored starch for maintaining a stable soluble sugars balance, but no significant differences were detected in aboveground storage between dry and wet years. The detailed tree-level analysis of nonstructural carbohydrates and $\delta^{13}C$ dynamics suggest interspecific differences in C allocation among fluxes and tissues. To quantify the exact timing and spatial distribution of belowground C allocation, we additionally applied $^{13}CO_2$ pulse labelling on one of the tree species. C allocated belowground in two main time-lags: after 3-5 days and 15-20 days. Overall, our findings shed light on mixed forest physiological responses to drought, an increasing phenomenon under the ongoing climate change.

Drivers of soil organic carbon from temperate to alpine forests: a model-based analysis of the Swiss forest soil inventory

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Predicting soil organic carbon (SOC) stocks in forest ecosystems is crucial for assessing forest C balance, but the relative importance of key drivers - litter inputs, climate, and soil properties - remains uncertain. Here, we linked SOC stocks at 556 old-growth Swiss forest sites from 350 to 2000 m a.s.l. to climate variables (mean annual precipitation, MAP: 700-2100 mm, mean annual temperature, MAT: 0-12°C), soil properties, net primary production (NPP), and forest type. We compared measured SOC stocks to Yasso20-simulated stocks. Since Yasso20 is driven by litter inputs and climate, deviations between modelled and measured stocks can reveal the significance of organo-mineral interactions that we hypothesize to be crucial for SOC stocks.

SOC stocks exhibited distinct regional patterns, with highest values in the Southern Alps, characterized by soils rich in Fe and Al oxides. On average, SOC stocks simulated by Yasso20 aligned with measured SOC stocks (13.7 vs 13.2 kg C m^{-2}). However, the model did not capture regional SOC variability. Model deviations were largely driven by exchangeable Fe at pH ≤ 5, and by exchangeable Ca at pH > 5. Beyond soil properties, MAP was a key driver of total SOC stocks, with Yasso20 underestimating stocks for MAP > 1400 mm.

Our study indicates that mineral-driven SOC stabilization and precipitation are the primary drivers of SOC stocks, while NPP remained unrelated to SOC stocks. Incorporating mineral-driven SOM stabilization can improve predictions of SOC stocks, and possibly, of SOC stock changes, the primary application of Yasso in greenhouse gas inventories.

Interactions between earthworm species enhance litter-derived carbon stabilization in the mineral soil

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Earthworms may act as double-edged swords for soil organic matter. While they may enhance mineralization via increased microbial activity, they can also elevate organic matter stabilization. This study examined their role in beech-dominated limestone forests. Endogeic and anecic earthworm species were kept in mesocosms with soil from two beech-dominated forests in the Swiss Jura mountains. Highly labelled beech litter (^{13}C, ^{15}N, ^{2}H) was applied. Carbon fluxes were repeatedly measured. After 12 months, bulk soil, casts, and soil fractions were analyzed for isotope enrichment. All treatments showed similar total CO^2 respiration. Likewise, total soil organic carbon stocks did not differ. Earthworm effects became apparent in litter decomposition. Less litter-derived CO^2 was released with the anecic earthworm present. In the mineral soil we found 27% litter-derived C with only the anecic species present but up to 40% when both species where present. A spatial sampling within the mesocosm showed contrastingly distributed hotspots of litter-derived C enrichment depending on species composition.

Our findings indicate that earthworms did not enhance overall mineralization but affected litter-derived C stabilization. When both species were present, more litter-C was incorporated into mineral soil than by single species, suggesting enhanced organic matter stabilization on mineral surfaces.

Soil, below-canopy and ecosystem CO2 and CH4 fluxes and their drivers in a subalpine spruce forest

Nina Buchmann[1)], Iris Feigenwinter[1)], Mana Gharun[2)], Lukas Hörtnagl[1)], Luana Krebs[3)], Philip Meier[1)], Liliana Scapucci[1)]

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Forest ecosystems play an important role in the global carbon (C) budget by exchanging large amounts of carbon dioxide (CO_2) and methane (CH_4). However, flux magnitudes as well as forest C sink or source behaviour are affected by ever changing environmental and biotic drivers. In the past, disentangling these drivers was limited by their complex interactions; now-a-days, machine learning (ML) approaches offer unprecedented insights into their temporal contributions driving CO_2 and CH_4 fluxes across scales.

We measured soil/forest floor CO_2 and CH_4 fluxes with automatic opaque chambers (six years), below-canopy CH_4 fluxes (one year) and net ecosystem CO_2 (26 years) and CH_4 (five years) fluxes with eddy-covariance, complemented by climatic variables, in the subalpine spruce forest Davos-Seehornwald. Using the ML approaches XGBoost and SHAP, we identified the environmental drivers, their contributions and changes over time.

The spruce forest was typically a CO_2 sink during the last 26 years, with annual sink strengths decreasing in the last years. As expected, the soil was always a CO_2 source. While the forest was a small CH_4 source, the forest floor and the soil were small CH_4 sinks. Soil temperature was always the major driver of soil/forest floor CO2 fluxes, while snow depth was driving soil CH_4 fluxes. Annual net ecosystem CO_2 fluxes (NEE) were strongly related to start, end and length of the C uptake period, but no trend in phenology was detected during the last 26 years, suggesting ecophysiological acclimation. Daylength, incoming shortwave radiation, soil water content and minimum air temperature were driving daily NEE. Thus, the spruce forest benefited from higher temperature between autumn and spring. However, high summer temperatures increasingly limited NEE during the last 26 years, suggesting adverse effects for this subalpine spruce forest in the future.

Four Decades of Forest Development in the Context of Nitrogen Eutrophication and Climate Change

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Four decades of intercantonal forest monitoring across 247 sites in Switzerland reveal the escalating impact of combined environmental stressors on forest health. While air pollution and nitrogen (N) deposition remain primary drivers of soil acidification and nutrient imbalances—evidenced by declining BC/Al ratios—climate change has emerged as the predominant threat.
Analysis of Fagus sylvatica, Picea abies, and Quercus species shows that cumulative drought years (2015–2022) have triggered unprecedented vitality shifts. The hot summer of 2018 acted as a tipping point; for European beech, the proportion of severely damaged trees increased by a factor of 6.9 and mortality by 4.2 compared to pre-2018 levels. Norway spruce exhibited a 9.9-fold increase in mortality during recent drought years (2018–2022), particularly under high N deposition. While oaks showed greater resilience, even Q. pubescens faced significant damage on dry sites.
Recent data indicate a universal decrease in stem volume increment across all species, driven by increased mortality and wind damage. These rapid, climate-driven changes, exacerbated by eutrophication and pathogens, underscore the critical necessity for continued, cause-related intensive monitoring to inform adaptive forest management.

Multiyear droughts and ecosystem responses – A global look

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With more regions projected to experience an increase in drought frequency and intensity, the chances that single droughts cumulate into multiyear droughts – events lasting years to decades – increase. We applied a novel method to identify the morphologically contiguous droughts over space and time, thus forming a multi-year droughts inventory at a global scale. In addition, we use the vegetation greenness indicator to proxy ecosystem responses to such multiyear droughts during the satellite era. We found that multiyear droughts have become drier and hotter and led to increasingly diminished vegetation greenness, but such patterns vary across ecosystems around the globe.

What if we could reconstruct tree metabolism and explore how environmental factors influence it through tree rings?

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The climate crisis is pushing forests to a limit. Modern forest management aims to help forests maintain viability and ecosystem functions and services. However, making appropriate management decisions is difficult since our understanding of the connections between climate variations and detailed tree physiological and phenotypic responses is not well interlinked or well represented in current models. We need to open the black box of physiological and metabolic processes that provide the missing link between environmental and phenotypically observable changes. Once achieved, we can refine and test hypotheses about which processes must be better represented and incorporated into models.

New high-resolution bioanalytical mass spectrometers offer high-throughput metabolite identification and compound- and intramolecular position-specific isotope analysis in the natural isotope abundance range. Changes in the commitment of substrates to metabolic pathways and the activation or deactivation of others alter enzyme-specific isotope effects. This leads to differences in reaction products' intra-molecular and compound-specific isotope compositions. Substantial intramolecular position-specific isotope information of intermediates of metabolic pathways is integrated into the tree ring chemical compounds, allowing to inversely model metabolic fluxes and pathway commitments. By combining disciplines, such as metabolomics, stable isotope ecology and tree ring research, we can use this "multidimensional isotopic fingerprint" in the tree ring archive to unveil the mechanisms of metabolism-environment interaction on scales ranging from cellular regulation to whole plant resource allocation. This will allow retrospective testing of whether processes such as sink control and stomatal growth optimisation respond to selected environmental drivers and affect tree functioning and whether they are correctly incorporated into models. Hence, deciphering past processes will allow us to reveal insights into the future trajectories of forests..

Point dendrometer and climate data processing with temporal convolution networks

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TreeNet is a growing network of forest monitoring sites designed primarily to measure tree stem radius changes using high-resolution point dendrometers. These measurements, taken every 10 minutes with micrometer precision, are complemented by other critical environmental data streams, such as temperature and relative humidity, recorded by thermometers and hygrometers. All data are transmitted via LoRaWAN without local logging, making them vulnerable to gaps caused by transmission disturbances. As the network expands, ensuring data integrity through automated gap-filling and cleaning becomes essential—not only for dendrometer signals but for all channels. We present a temporal convolutional network (TCN) approach to address this challenge by leveraging cross-correlation among locally available data streams and meteorological products. Our method constructs an 11-channel time series per site and trains the model to correct three key variables—stem radius, temperature, and relative humidity—while exploiting inter-channel relationships to reconstruct missing segments and remove artifacts such as drift and misalignment. Preliminary results indicate that TCNs outperform traditional imputation techniques in accuracy and robustness, offering a scalable solution for maintaining high-quality datasets across TreeNet's infrastructure. This approach will enable reliable downstream analyses of tree physiology and ecosystem responses to environmental variability. Future work will refine the architecture, incorporate uncertainty estimates, and validate performance across diverse sites and species..

Poster Presentations

Measuring Carbonyl Sulfide Fluxes for Enhanced Insight into Carbon Dynamics in a Mixed Forest

Nicholas Wright-Osment[1)], Kukka-Maria Kohonen[1)], Lilliana Scapucci[1)], Philip Meier[1)], Thomas Baur[1)], Nina Buchmann[1)]

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Understanding forest carbon dynamics is crucial under current climate change scenarios. The net ecosystem exchange of CO2 (NEE) is the result of two major CO_2 fluxes: gross primary production (GPP; i.e., photosynthesis) and ecosystem respiration (Reco). Currently, the partitioning of NEE into GPP and Reco is based on modeled quantities which assume both that Reco displays the same magnitude, and the same relationship with temperature at night and daytime and that photorespiration is negligible. Despite decades of ecosystem-scale measurements of NEE, there is no agreed-upon method to directly assess GPP in situ. As such, there is still substantial uncertainty in estimates of forest carbon uptake. Eddy covariance measurements of carbonyl sulfide (COS) fluxes have been proposed as one potential approach to constrain GPP, as COS is taken up along a nearly identical pathway to CO_2 but is not emitted back to the atmosphere. However, there are still very few multi-year studies of ecosystem COS fluxes and even fewer which parse its individual components. Over 3 years, the ABACOS project will measure CO2, H2O, and COS fluxes at multiple scales, using eddy covariance in a mixed deciduous forest ecosystem (Lägeren; CH-Lae). To assess the status of the entire ecosystem and evaluate component fluxes we will use above and below-canopy eddy covariance measurements together with branch/leaf and soil gas exchange measurements. The data will then be used to develop an empirical relationship between CO2 and COS uptake and will, in turn, be used to constrain GPP and evaluate the traditional partitioning methods.

Model-data fusion of daily ecosystem fluxes and forest inventories with a dynamic vegetation model

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The structure of forest stands strongly influences resource availability to individual trees and determines tree and ecosystem carbon balances. Aggregating this heterogeneity into an ‘apparent’ parametrisation e.g. with a big-leaf model can work for short-term predictions of the net ecosystem carbon exchange but gives potentially inaccurate results on longer time scales with altered forest structures.

Dynamic (global) vegetation models (DGVM) resolve and track this heterogeneity. They are used to simulate growth, mortality, competition, and carbon allocation strategies. Thereby they propagate changes in environmental conditions into changes in structure of forest ecosystems. For reliable predictions these models need to be calibrated to observations of forest structure.

Here, we use ecosystem flux measurements of gross primary production (GPP) and multi-annual forest inventories (DBH) as observational constraints to calibrate BiomeE (Weng et al., 2015), a process-based DGVM grounded in optimality principles. We aim to reproduce observed GPP and DBH distributions, enabling site specific inference of physiological traits (e.g., photosynthetic capacity acclimation via P-model; Stocker et al., 2020) and population dynamics (e.g., carbon allocation, height structured competition for light; Strigul et al., 2008).

Contrasting photosynthetic, stomatal, and mesophyll mechanisms drive common reductions in leaf water-use efficiency under blue light

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Forests experience complex light environments, but the detailed roles of photosynthetic, stomatal, mesophyll, and biochemical responses to dynamic blue light remain unclear in tree species. We measured the blue-light responses of leaf gas exchange, online isotope discrimination, photorespiration, and chlorophyll fluorescence in grey alder (*Alnus incana*) and holm oak (*Quercus ilex*), and investigated the underlying biochemical and physiological mechanisms. With increasing blue light, differing photosynthetic and stomatal responses consistently led to a decrease in intrinsic water-use efficiency (iWUE) in the two species. For alder, the decline in iWUE was primarily due to a reduced photosynthesis rate (A_n); for oak, although A_n also decreased, blue-light-stimulated stomatal opening played a major role. Although the reduction in A_n was linked to blue-light-induced photoprotective processes in alder, it was coordinated with mesophyll conductance (g_m) in both species. The maximum carboxylation rate of Rubisco and g_m imposed considerable photosynthetic limitations, especially at high blue-light levels. However, the component of g_m that responded to blue light and coordinated with A_n was the chloroplast membrane in alder whereas it was the cell wall and plasma membrane in oak. Our findings highlight species-specific physiological strategies in the response to blue light and underscore the importance of considering spectral composition when assessing carbon–water trade-offs in forest trees.

Early Warning Signals for Tree Mortality: A Review of Indicators, Limitations, and Emerging Opportunities

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2) ETH Zurich (Swiss Federal Institute of Technology), Institute of Terrestrial Ecosystems, Zurich, Switzerland

Tree mortality is increasing worldwide, intensifying the need for forest monitoring systems that can detect vulnerability before irreversible damage occurs. Predicting mortality remains difficult because tree death results from interacting predisposing conditions, inciting disturbances, and contributing agents that unfold over time. These drivers interact with recovery processes in highly non-linear ways, creating cascading stress trajectories in which trees may cross tipping points beyond which recovery becomes impossible.

This review synthesizes the literature on resilience indicators and early warning signals for assessing tree mortality risk. Existing approaches span a broad range, from threshold-based indicators and model-based risk predictions to disturbance-focused recovery metrics and indicators derived from changes in time-series dynamics. Despite their conceptual diversity, most approaches share two key limitations. First, many overlook the tree-level physiological stress history, such that similar drought events may lead to minimal or catastrophic damage depending on prior stress exposure. Second, many indicators are often too late for operational resilience monitoring, relying on retrospective data or signals that typically emerge only after substantial structural damage has already occurred.

Physiological theory and empirical evidence indicate that stress responses relevant to mortality risk arise at the level of hormonal regulation and stomatal control, affecting photosynthesis, transpiration, and leaf reflectance well before structural damage occurs. Recent advances in sensor technology now enable high-frequency observation of these processes through a growing range of in-situ and remote measurements. Yet few frameworks exist to interpret such time series as early warning signals. While resilience theory offers promising concepts for understanding critical transitions, it has rarely been applied to real-time forest monitoring. We highlight this gap and emphasize the role of controlled experiments in validating which physiological signals reliably precede mortality, enabling the translation of high-frequency measurements into actionable early warning indicators.