Information om ny forskningsplan för SLUs strategiska forskningsområde ”Hållbara Naturresurser” T4F

Bakgrund

Sedan 2009 har SLU ansvar för det strategiska forskningsområdet (SFO:t) ”Hållbart nyttjande av naturresurser”, inom SLU kallat ”Trees and Crops for the Future” (TC4F). Den årliga tilldelningen till TC4F, samt återrapporteringskrav, anges i SLUs Regleringsbrev. Verksamheten inom TC4F sker i samarbete med Umeå universitet och Skogforsk och är utformad i överensstämmelse med intentionen i den beviljade ansökan 2009 samt i enlighet med den utvärdering som genomfördes av Vetenskapsrådet 2015 av samtliga SFO:n, där TC4F var ett av de SFO:n ansågs som så framgångsrikt att det rekommenderades fortsatt finansiering. Totalt finns ett 20-tal SFO:n vid de svenska universiteten.

Övergripande handlar TC4F om växtproduktionsforskning inom skogs- och lantbruk. Inom fakulteten för skogsvetenskap är T4F den viktigaste pågående satsningen på institutionsövergripande forskning med disciplinöverskridande samarbeten. T4F är tvärvetenskapligt mellan grund- och tillämpade ämnesområden och har dessutom hela tiden verkat för att skapa interaktioner och samarbeten mellan stora externforskningssatsningar inom fakulteten, som tidigare till exempel Future Forests, Bio4Energy och för närvarande UPSC Competence Centre for Forest Biotechnology och olika pågående KAW-satsningar. Hitintills har programmet möjliggjort avgörande forskningsgenombrott, unika forskningsinfrastrukturer och innovationer som tillämpas inom praktiskt skogsbruk. Detaljerad årlig rapportering från TC4F publiceras på SLUs webbsida.

På SLU sker arbetet inom programmet huvudsakligen vid två faktulteter: Skogsfakulteten (S, del T, träd) och fakulteten för landskapsarkitektur, trädgårdsvetenskap och växtproduktionsvetenskap (LTV, del -C, crops). Verksamheten sker i stort sett oberoende av varandra, dock tillämpas gemensam planering och rapportering enligt rektorsbeslutet (SLU:id 2018.1.1.1-39). Vid både fakulteten leds arbetet av styrgrupper, där dekanen är ordförande. Varje styrgrupp har utsett programledare som sköter den dagliga verksamheten, ifall av T4F tillsammans med koordinatorer utsedda av varje deltagande institut.

Trots att anslaget tilldelas årsvis har T4F med S-fakultetens godkännande tillämpat planeringsintervall om 5 år. Långa planeringintervaller har varit essentiella för programmets framgång. Trädens långa livslängd och reproduktionstid gör att klimatförändringarnas konsekvenser för skogen blir först mätbara med tiden. Samhällets diskussioner om svikten i skogstillväxten de senaste 10 åren och den nyligen mätta möjliga återhämtningen visar att ännu längre intervaller för utvärdering av fältexperiment kan anses meningsfullt.

Här presenterar T4F sin forskningsplan för de kommande 5 år, 2026-2030.

A preliminary plan for the continuation of the SLU strategic research area Trees and Crops for the Future (TC4F), subprogram Trees for the Future (T4F), for the years 2026-2030

Introduction

Since 2009, SLU in collaboration with Umeå University and Skogforsk, has operated TC4F within one of 20 strategic research areas pointed out as national interests by the government[1]. TC4F was evaluated in 2015 by Vetenskapsrådet[2] and assessed to be a strong research environment with excellent connections to practice, and the forestry and agricultural business sectors. The current program period, 2021 – 2025, allocates an annual funding (26-30 Mkr) via the SLU basic governmental funding to be distributed between SLU (ca. 77 %) Umeå University (ca. 19 %) and Skogforsk (ca. 4 %). Of funding allocated to SLU, it is distributed between the Faculties of Forest Sciences (75 %) and Faculty of Landscape Architecture, Horticulture and Crop Production Science (25 %). The Faculty for Forest Science is the SLU host for TC4F.

Daily operations are split between the SLU faculties in a T4F (Trees for the Future) and C4F (Crops for the Future) part. The T4F has a steering committee at the Faculty of Forest Sciences consisting of Dean Göran Ericsson (chair), Ove Nilsson (faculty representative), Thomas Kraft (Skogforsk representative) and Mikael Elofsson (Umeå University representative).

T4F is devoted to the forest management challenges posed by the emerging bioeconomy, risks associated with climate change, and changing societal values on forests. It encompasses research on the forest from the tree to the landscape level in an interdisciplinary research environment. Knowledge produced by T4F will be applicable for sustainable forest management systems, meeting society's needs for productive and resilient forest ecosystems. Climate change means that the conditions for forest growth are changing, while society's need for forest biomass is increasing. Therefore, our research is directed toward enabling sustainable increases in forest growth in a changing climate.

Societal change challenges today's forest management

In Sweden, conventional forestry operations contribute approximately 185 billion SEK in export value to the Swedish economy, and forests provide a range of ecosystem services that are key to society´s socio-ecological functionality. For example, Swedish forests sequester approximately 60 million tons of carbon dioxide equivalents each year and provide habitat for roughly half of Sweden's endangered species. Globally, the boreal forest, of which includes most of Sweden's forests, accounts for approximately 32% of the terrestrial carbon stock, 30% of global lumber and paper supplies, and provide essential habitat for a diverse range of species.

Following the Paris Climate Agreement, societal expectations are increasingly being placed on forests to deliver biomass that can be used to replace fossil-based materials, including building materials, energy and fuels. In Sweden, forests already play a key role in the political vision of a climate neutral society in 2045. The overarching goal of T4F, ***knowledge to promote sustainable increase of forest growth***, is thus in line with society's current needs. To reach this goal, T4F connects basic and applied science. With interdisciplinary approaches, T4F explores key interactions between tree species and genotypes, management and the changing environment with the aim to develop a knowledge basis for the future of Swedish forestry.

[1] Trees and Crops for the Future | slu.se

[2] https://www.vr.se/download/18.2412c5311624176023d254da/1555426905002/Evaluation-Strategic-Research-Area-Initiative-2010-14_VR_2015.pdf

New Program Plan

As the current TC4F program period is coming to an end in December 2025, work has started to prepare a proposal of a program plan for the upcoming program period from 2026 to 2030. This work is going on in parallel in the T4F and C4F parts. For the T4F part the program, the steering group has appointed a group of researchers to frame a new program plan for the upcoming program period 2026 to 2030. The group is led by Michael Gundale, T4F Program Director, and institute coordinates Kelly Swarts and Vaughan Hurry (Genetics and Physiology, SLU), Urban Nilsson (Southern Swedish Forest Research Institute, SLU), Nat Street (Physiology and Botany, Umeå University) and Mari Suontama (Skogforsk).
This following tentative program plan is according to the original goals and strategy of TC4F building upon T4Fs achievements so far, while strongly promoting renewal and developments of collaborations across departments and infrastructures to enable excellent research on sustainable forest resource use across basic to applied topic areas. Currently, this is the most important strategic program that the faculty has in order to develop a holistic approach to forestry focused experimental plant sciences, connecting genetics and molecular topics to silviculture, forest management and ecosystem science.

Michael Gundale, Professor and T4F Program Director

Introducing a research agenda of T4F for the period 2026-2030

TC4F has been a highly productive research program (Figure 1, 2) that was first established via a government grant, with the forest research component awarded by the government to 3 departments at SLU (Forest Ecology and Management, Southern Sweden Forest Research Centre, and Genetics and Physiology), in collaboration with Umeå University, and Skogforsk. Here we propose a plan for the next phase of the T4F program (2026-2030) that aims to expand on the successes achieved during the first 15 years of the program. The program is designed to generate new knowledge and research connections that are needed to successfully enhance forest productivity and carbon sequestration in Swedish forests into the future, during a period when climate change is predicted to accelerate. This overarching program goal is more relevant than ever, considering that forest growth has decelerated in Sweden during recent decades (Figure 3), which has large implications for Sweden's net carbon emissions targets (Figure 4), and commitments within the EU for achieving climate neutrality by 2045.

Our plan will promote a collaborative research environment between many departments at the Faculty of Forest Sciences (SLU), Umeå University and Skogforsk, and stakeholders. The program will build upon the innovative success of individual research environments across these institutions, where major innovations in areas such as tree genetics and breeding, microbial ecology, ecosystem ecology, silviculture and forest management are today made under the umbrella of T4F. A major aim of the new T4F phase will be to connect high tech research platforms and researchers who work at a wide range of scales, from genes to ecosystems, in order to provide an integrated and holistic knowledge base on sustainable forest production, and forest resistance and resilience to climate change. Our plan for strengthening research connections includes an investment into a new field experiment, maintaining and developing analytical platforms that will be widely available to researchers across all participating institutions, and through supporting research and connecting scientists across all relevant disciplines, and thereby adding value to the wider research communities of each participating institution. We foresee that the continuation of the T4F program will generate a new wave of forest science innovation that will influence how Swedish forest management can be adapted for future climates and continue to meet society's demands for biomass production and carbon sequestration.

Michael Gundale, Department of Forest Ecology and Management, SLU, Program and working group leader.
Vaughan Hurry, Department of Forest Genetics and Plant Physiology, SLU
Kelly Swarts, Department of Forest Genetics and Plant Physiology, SLU
Urban Nilsson, Southern Swedish Forest Research Centre, SLU
Nat Street, Department of Plant Physiology, Umeå University
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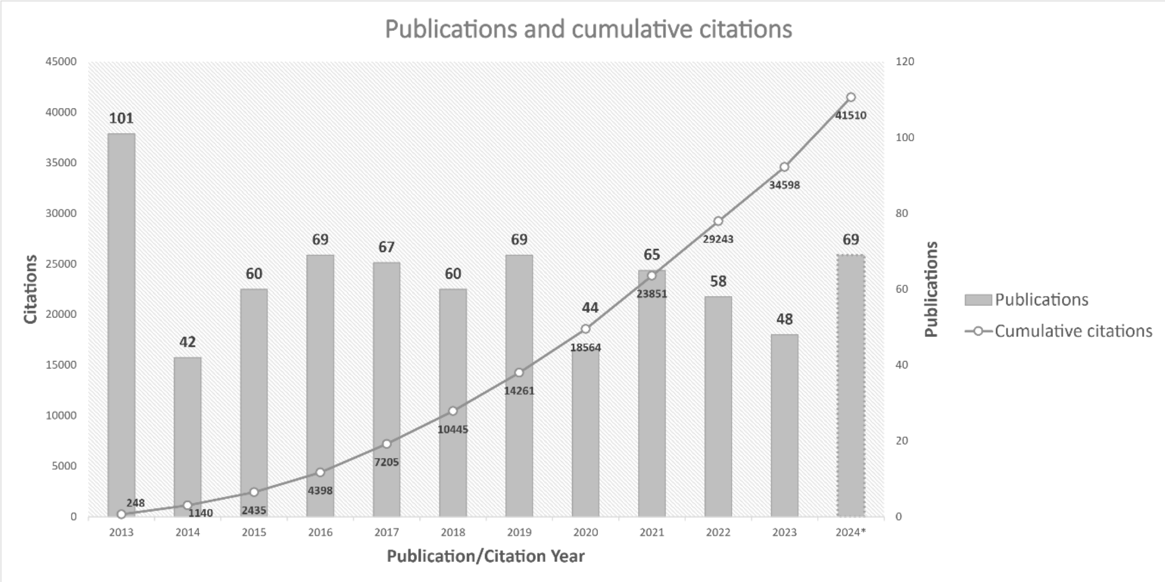

Figure 1: Number of publications each year, and cumulative citation counts of T4F supported research from 2013 onward.

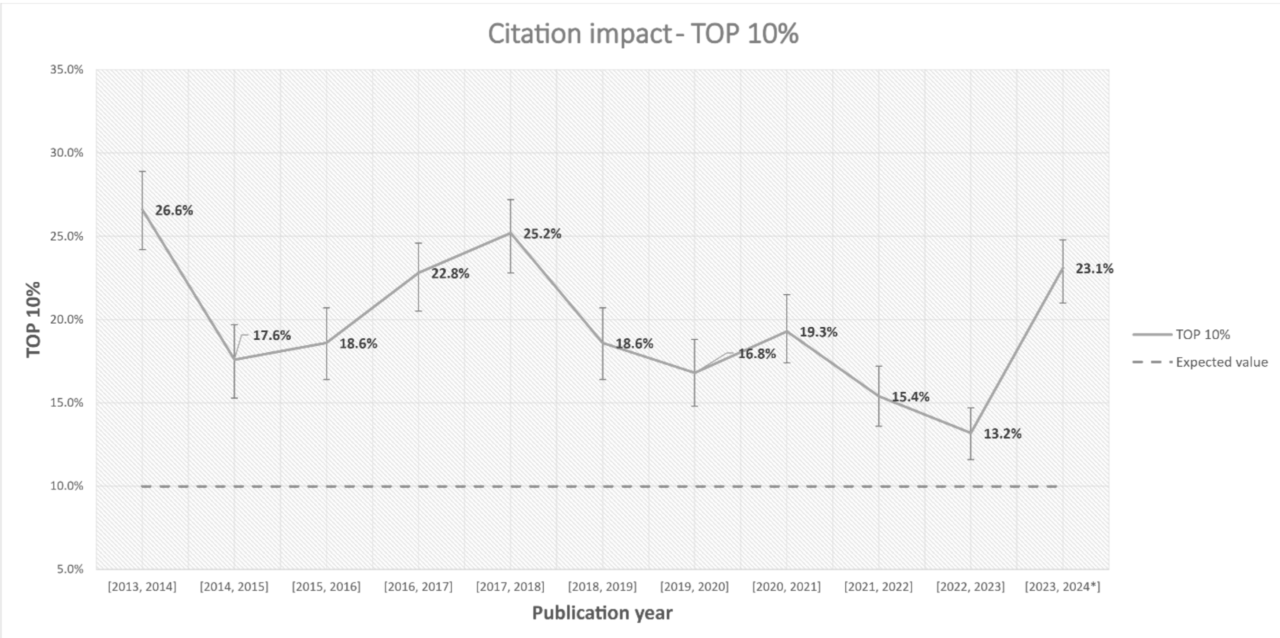

Figure 2: Proportion of T4F publication in the tope 10% of most cited publications in the field. A value >10% indicates a higher rate than expected.

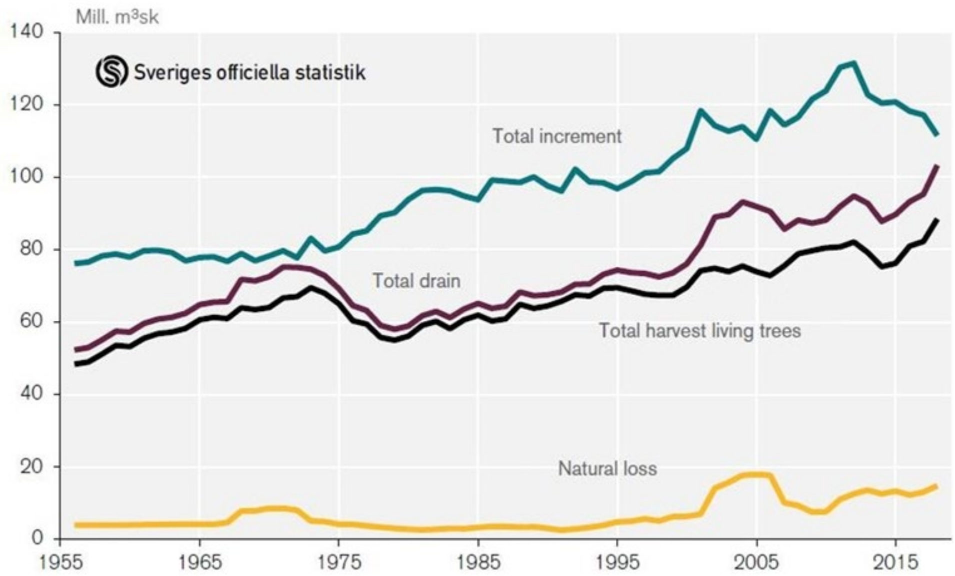

Figure 3: Trends in Swedish volume growth (Blue line), and loss from natural damage (yellow line), harvest (black line), and total production removal (purple line). The data show a sharp decrease in forest growth beginning around 2013, which is speculated to be a symptom of climate change factors, which are addressed in the Phase 4 program plan.

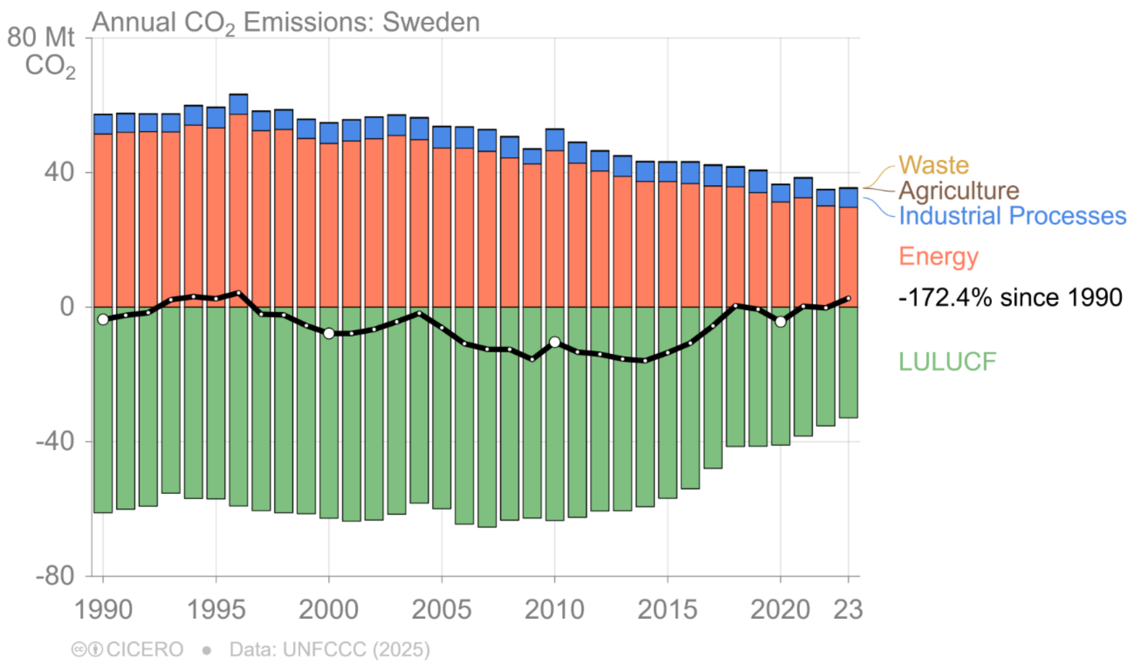

Figure 4: Swedish sources and sinks for CO2 (Million Tonnes of CO2), and net annual emissions. Green bars refer to CO2 uptake, as influenced by Land Use, Land-Use Change, and Forestry (LULUCF), for which forest growth is the dominant driver. Pink and blue bars refer to CO2 emission sources. The black line is the net CO2 emissions, which is the balance between sources (pink and blue bars) and sinks (green bars). The graph shows that while CO2 emission sources have declines over the past 3 decades, the CO2 sink strength of Swedish land has declined over the past decade, leading to a recent net positive emission. Data source CICERO (Center for International Climate and Environmental Research, Oslo Norway) and UNFCC (United Nations Framework Convention on Climate Change.

Background to the proposed research

Swedish forests are experiencing a wide range of global change factors. Firstly, global emissions of CO2 are steadily increasingly, reaching above 35000 million tonnes annual CO2 emission globally in the 2020s. Increasing CO2 emissions globally has led to a 50% increase in atmospheric CO2 concentrations compared to the pre-industrial era, which can have a direct positive effect on forest growth. However, higher atmospheric CO2 can impair forest growth through multiple indirect pathways. First, CO2 emissions are the dominant driver of global warming. Global temperatures have been rising by about 0.13°C per decade for the last 75 years. Future warming is predicted to accelerate, by about 0.2°C per decade. This warming is not evenly distributed globally, with the highest degree of warming occurring at the highest latitudes, with some boreal environments predicted to warm by as much as 6°C by 2100 according to the recent intergovernmental panel on climate change (IPCC) report. While warming can promote forest growth by promoting a higher rate of photosynthesis, and longer growing seasons, the increasing frequency of extreme temperature events above forest tolerance limits can result in photosystem damage, and cause increasing wildfire activity, which results in increased tree mortality. Another symptom of CO2 induced warming is that drought events are becoming more frequent and intense. In Sweden, severe drought of 2014 and 2018 stand out as notable anomalies, which coincide with a period of forest growth decline in Sweden. Forest drought stress is likely intensifying, as a warmer and drier atmosphere increases forest water demand via evapotranspiration, while at the same time, rainfall events are becoming less frequent but more intense, which can limit forest water storage. In addition to temperature and drought stress, rising atmospheric CO2 is increasing the nitrogen demand of forests, and this intensification of nitrogen limitation is likely to become a stronger constraint on future forest growth. Stress caused by extreme temperatures, drought, and intensified nitrogen limitation can further lead to greater vulnerability of trees to insect and pathogen damage. These ongoing environmental change factors serve as a backdrop for Swedish forestry, where decisions made today will play out under different environmental conditions that continue to develop into the future.

The boreal forest, which dominates Sweden's landscape, accounts for 1/3 of the world's forests and global terrestrial carbon stocks. Forestry in the boreal region is also a major source of economic activity, including in Sweden, where it is a major contributor to the national economy. Climate change-induced shifts in the functioning of this ecosystem may therefore have immense consequences for global carbon cycling and storage, as well as on the national economy. Economics and environmental sustainability can often appear to be competing goals; however, the goal to increase productivity in Sweden's forests can be hugely beneficial for the economy and the stability of the global environment. While increasing forest productivity clearly provides economic benefits for forest owners and for the national economy, increased productivity is also beneficial for environmental sustainability because enhanced forest production can promote CO_2 sequestration. Yet a major challenge facing the Swedish forest industry is to maintain a stable and strengthening forest carbon sink (see Figure 3 and 4 for a clear view of this current challenge), as these global change factors continue to develop, which requires consideration of forest growth and soil carbon dynamics. **To accomplish this, we need to better understand the physical and biological processes that have result in declining forest productivity, and test a range of tools (e.g. genetics and silviculture) that will better adapt Swedish forests to tolerate and mitigate ongoing climate change.**

Genetics, breeding, and new silvicultural strategies will be key tools in preparing for this uncertain and changing future. However, the net effect of these tools on stand productivity and stand level carbon sequestration remains unclear, especially in regards to key global change factors (rising CO2, temperature, drought stress, and intensified N limitation). Genetic composition or silvicultural strategies that are poorly adapted to future climates may increase the frequency of suboptimal growth conditions. Conversely, carefully selected forest management treatments may reduce damage, enhance productivity, and maximize carbon storage in both trees and soils. To prepare for the future, we must also confront the aspect of the forestry sector that sets it apart from other sectors: its long-term planning horizon. In practice, a full forest management rotation spans in the order of 60-120 yr in boreal regions, so today's management decisions need to be done in anticipation of future climates. Our limited knowledge of how forests will respond to future atmospheric CO_2 concentrations, temperature stress, water stress, and intensifying nitrogen limitation results in great uncertainty for forest managers and the forest industry, that must be addressed through a carefully targeted research program.

Main challenges targeted by T4F – Forest Management Tools for a Changing Climate

Mitigating the combined threats of environmental change and increasing demand for biomass production will require a knowledge-based approach to understand and utilize the interactions between genotypes, species, silviculture, and the environment. Forest owners, managers and breeders need quantitative predictive tools put in place today that will be successful in the future, to complement the experience-based, practical knowledge that often drives management decisions. Experience-based decisions alone will be insufficient to meet the challenges posed by future climates, particularly under the long stand rotation age that is common in Swedish forests. These forest management challenges will be targeted in an organisation ensuring an interdisciplinary research environment and a continuous dialogue with stakeholders from the forest sector.

T4F research has, since the start of the programme in 2009, addressed a broad range of issues related to this overarching forest management challenge. Over this period researchers within T4F have built new and complementary knowledge bases, and it is now natural to engage in a joint efforts to combine the disciplines of conifer and broadleaved genomics and molecular biology, ecophysiology, silviculture, and ecosystem science in order to directly address the challenges facing the forest sector. In the future T4F research funding framework, we will organize research on three main themes related to sustain forest production and enhancing carbon sequestration under a changing climate. We will further invest in some core common competences and infrastructure.

An organizational framework for the 4th phase of T4F

We suggest that in the 4th phase (2026-2030) T4F should continue to broadly address the objectives of the first three phases of the program – ***to build a knowledge base for the sustainable use and management of the Swedish forest landscape. In Phase four, we will increase the focus on sustainable forest management within the context of ongoing climate change***. The program will be operated by core institutes, including Forest Ecology and Management (FEM), Forest Genetics and Plant Physiology (GenFys), Southern Swedish Forest Research Centre (SSFRC) at SLU, Plant Physiology (FysBot) and Ecology and Environmental Sciences (EMG) at Umeå University, and Skogforsk (SF). Below we highlight the main research themes for T4F Phase 4, and planned investments into competencies and infrastructure that will be widely beneficial to a wider community of forest researchers.

1. Suggested research themes

Here we highlight three major themes that are essential for understanding and adapting Swedish forests to environmental change, including shifting the genetic composition of future forests

(Heritable Adaptive Responses), developing new silvicultural knowledge related to tree species, tree species mixtures, new silvicultural systems (e.g. continuous cover forestry), and regeneration (Adaptive Silviculture), and understanding how tree interactions with micro-organisms influence their nutrient acquisition and soil C cycling dynamics under environmental change (Dynamic Forest Microbiomes).

A) Heritable Adaptive Responses

Heritable genetic variation is the basis for tree breeding and improvement. Natural populations of tree species used for forestry in Sweden contain high genetic variation and one challenge is to identify which components of genetic variation increase growth and productivity and those that result in improved ability to tolerate stress conditions while remaining high yield. Identifying the basis of this variation involves basic research to uncover the molecular regulatory mechanisms linking genes to phenotype while also identifying individual molecular markers (genetic variants) that can be used in breeding programs. The focus of this topic is to develop the genetic and genomic resources and tools needed to select the most vigorous trees for future environmental conditions, while being able to withstand pests and diseases. Here we will unite operational tree breeding with fundamental research in genomics, which will include close interaction between Skogforsk and Umeå Plant Sciences Center (SLU and Umeå University). The following research questions and topics will take a central focus in Phase 4:

- Can we identify genotypes from natural forests that are already adapted to future climates? Using longitudinal measurements of tree growth from tree rings, we can isolate growth variation associated with genetics and climate, using statistical tools paired with data from weather stations, satellites or historical data. Removing the growth response due to local environment, this approach can identify adapted germplasm from *any* forest tree, with improved genomic prediction into new populations and environments. This approach will be applied to Swedish forests, and will identify compatible new genetic variation under changing environments for Swedish forestry or in a conservation ecological context.
- What tree genotypes and traits are optimal for specific climate conditions? This research question will focus on developing advanced methods and tools for selecting trees in various environments and climatic conditions. Traits important for tree resilience and overall production both in quantity and quality are in focus. More effective phenotyping methods and use of genomic markers in tree improvement are necessary research topics to speed up the breeding to respond to the challenges of climate change.
- Forest genetics suffers from a lack of common genomic resources. Provenance typically explains less than 5% of the variation between individuals and without a common, range-wide repository for genetic variation, every new study, trial, or experiment relies on new collections leading to a lack of replicability. While these resources would be invaluable for all tree systems, we will start in spruce to develop a clonal archive from range-wide material that will be deployed in trials across Sweden and Europe in collaboration with partner institutions. Critically, the clonal archives will be maintained by skogforsk and made available for downstream physiological, developmental or genetic studies that can leverage the real-world phenotypic data derived from the trials.
- How important is phenotypic plasticity for environmental resilience, and what is the genetic basis of plasticity? We will utilize the NordAsp (Nordic Aspen) collection established during the previous phase to link genetic variation to the control of phenotypic plasticity, and to determine whether plasticity is beneficial for maintaining growth under environmental stress. This work will benefit from the extensive genetic resources available for aspen, which will enable functional testing of identified candidate genetic markers

underlying phenotypic plasticity. These results will form a framework to direct similar studies in commercial forestry species.

- Developing genomics resources for future forestry species. Siberian larch and silver birch are both important species with future potential for forestry in Sweden. However, both species lack extensive, high quality genomic resources. We will address this by generating such resources to enable subsequent development of markers for use in breeding and to link genes and genetic variation to target phenotypes relevant to growth and resilience under future climate conditions
- Advancing resources and methodology for profiling tree-microbiome interactions. In the previous phase we established a pipeline to analyze the interaction of Norway spruce root associated ectomycorrhizal species and how this interaction is altered by nutrient enrichment. We will extend this approach to additional species, develop new genomic resources to support this, and will establish the use of spatial and single cell metatranscriptomics to substantially enhance the resolution to which we can link specific molecular responses of the host trees and associated fungi to alternations in community function and the ecological impact of these changes.
- What is the role of genetic variation beyond the focus on protein coding genes? Recent advances in biology have revealed the importance on non-protein coding transcripts and epigenetics for development, stress response and ecological interactions. We will establish reference datasets to serve as a general resource for projects aiming to link genetic components and associated genetic variation to their function role on determining phenotype.

These topics will build on the common investment in Bioinformatics, and will also utilize new and past field experiments. The theme will also broaden the focus to a variety of tree species relevant to current and future Swedish forestry, and will utilize existing and new clonal tests/field experiments consisting of natural ecotypes, which will lead to new breeding materials.

B) Adaptive Silviculture

Forestry needs to consider which tree species, tree species combinations, and silvicultural tools used to initiate stand regeneration can be deployed to achieve maximum growth and stability under future environmental conditions. For this, preparation for the use of exotic tree species and increased use of underused native trees are an obvious path to follow. Here, we will deploy a range of tools, such as already existing long term field trials, Swedish National Forest Inventory databases, the Swedish National Forest Inventory tree core archives, and Heureka modelling. Key research questions and topics include:

- How do different tree species respond to spatial and temporal variation in climate, and can this be used as a tool to predict growth under predicted future climates? Tree species differ in their growth rates, but characteristics that support high growth rates may have disadvantages when it comes to resistance and resilience to extreme climate events. Here we will evaluate tree species growth responses to latitudinal and temporal change in climate, using tools such as national forest inventory data, new data derived from the national forest inventory tree core archive, and field trials that exist throughout Sweden.
- Are there advantages to using exotic tree species for maximizing forest growth, soil carbon accumulation, and resilience as the environment is changing? Carefully selecting and evaluating tree species from current environmental conditions that we expect will occur in Sweden in the future, is an approach that may allow the Swedish forest industry to rapidly transition forests for the future. However, many aspects need to be studied before such a

transition can be made, such as the tolerance of potential species to the range of Swedish environmental conditions (e.g. soils and climate variability), or assessing the risk of non-native species to spread and cause ecological degradation. We will investigate these relationships for a range of candidate species.

- Can mixture of tree species achieve overyielding of growth and greater resistance and resilience in response to extreme climate events, compared to mono-cultures? Here we will utilize a range of approaches, including evaluation of National Forest Inventory growth data in mixed versus mono-culture forests, as well as a new experimental infrastructure implemented in phase 3. These tools will help us understand if Swedish forestry relies too heavily on even-aged monocultures, and whether mixed forests, which are already desired by society for their aesthetics and biodiversity benefits, may also be able to increase forest production and carbon storage.
- How can current forest management be updated to achieve sustainable forest growth in a changing climate? A major change of tree-species and genetics can only be done at the time of regeneration but many interventions such as pre-commercial and commercial thinnings are done during the rotation. About 600-800 thousand hectares are either pre-commercially or commercially thinned annually. We will use long-term experiments in both monocultures and mixed species stands to investigate novel thinning regimes for better adaptation to a changing climate. Thinning regimes include density, stand structure and tree-species composition after thinning.
- How do continuous cover forestry (CCF) perform compared to rotation forestry with respect to volume production, economy and carbon sequestration? On which sites is CCF a sustainable system with adequate ingrowth of new trees? CCF is becoming increasingly popular among forest owners and scientific results and experience are slowly building up. CCF will be an important complement to rotation forestry. However, reliable models for ingrowth and volume-growth are needed for guidance on how to select sites for CCF, to plan for future interventions, and for prognosis of future production and economic value. In the last phase of T4F, current models have been validated and the work on constructing new models has started. This will continue in phase four, and we will use data from old and new long-term experiments as well as data from the national forest inventory to estimate new ingrowth- and growth functions that can be implemented in Heureka.
- How can we adapt forests to climate change, both in stand and landscape scale? We will together with Sveaskog establish a thematic forest on one of their estates near Asa, Småland, to make targeted management testing suggested climate change adapted silviculture (CCA). The estate is close geographically to the other two themed Sveaskog estates; the Asa Experimental forest (AEF) and the High yield growth forest in Asa (CCM) in Swedish called "Tillväxtparken". The combination of the three themes will give us experimental data on tree and stand level (AEF), climate change mitigation landscape solutions (CCM) and climate change adapted silviculture (CCA). By concentrating on the three themes, we will be able to provide a center for forest and climate change research that can be of interest for scientists from the whole of Europe. In the CCA forest we will create the parallel of the existing CCM, but here focus is on landscape-scale adaptations, by e.g. choice of tree species and forest management systems and health monitoring. We will also make adaptations in the forest plans not only for the forests but also concerning road infrastructure, water catchment areas and nature and wildlife management. At the start of T4F phase four, a climate change adapted forest management plan will be developed for the CCA-landscape. In parallel to operational management that will continue for decades, future development of the CCA-landscape will be simulated with Heureka.

C) Dynamic Forest Microbiomes

Fungi and bacteria (i.e. the microbiome) are key components of forests that can greatly influence tree growth, and soil carbon turnover. Bacteria and fungi occur on all plant organs, but most notably, the microbiome associated with roots and bulk soils are critically important for regulating nutrient and water uptake by trees, and in controlling the rate of soil C accumulation. Boreal forests have more than twice as much carbon stored in the soil than is found in the living tree biomass. Soil carbon represents the balance between carbon inputs from forest vegetation, which can vary in quantity and quality; and carbon outputs, which are driven by the action of the soil microbiome. The soil microbiome can vary in biomass, composition and function, and understanding how these properties respond to environmental change and forest management practices is therefore critical for understanding how forest growth and soil C develops through time. We aim to address a variety of research frontiers within this theme:

- How do forest microbiomes respond to spatial and temporal changes in nutrient availability, for example in response to rising CO2 concentrations or forest management practices, and what are the consequences of microbiome for regulating growth or soil carbon turnover? Changing N limitation due to rising CO2, or in response to forest management practices (e.g. fertilization, thinning, or tree species choices) may change the dominant microbial taxa trees associate with. We will explore how these community level shifts alter key ecosystem processes, such as nutrient acquisition and forest C dynamics.
- How does the soil microbiome influence the flow of carbon through the atmosphere-tree-soil carbon continuum? We have developed tools for studying communication between the host tree and the linked fungal microbiome to demonstrate how and why fungal community composition changes dynamically as tree nutrient (primarily nitrogen) status changes. This generates insights into how microbial community assemblages form host tree roots. However, we lack insight into the mechanisms of control of the formation of these assemblages as conditions, such as nutrient availability, soil water status or forest tree species composition change with changing environmental or management conditions. To establish the control mechanisms, fine resolution tools will be developed, such as in situ or single cell transcriptomics in the developing roots of the trees in the field, to study not only how the associations form between the tree root and the linked fungal microbiome – but why they change with changing environmental conditions.
- What are the dominant sources of biological nitrogen fixation in Swedish forests. Decades of research on forest nitrogen fixation has focused on cyanobacteria associated with feather mosses as the key source. However, recent research indicates a large portion of accumulating N in forests is unaccounted for. Thus, it is imperative to identify and quantify the dominant N2-fixation niches (e.g. root rhizosphere, decomposing litter, deadwood, etc.), and understand how their N2-fixation activity responds to climate change factors, in order to understand how N limitation develops in future climates.
- What role do root bacterial assemblages, and specifically plant growth promoting bacteria, play in the establishment of plant-fungal association? Plant growth promoting bacteria are known to be important facilitators during the formation of mycorrhizal symbioses. However, at present very little is known about the role played by the bacteria assemblages on the roots of boreal forest trees. In the previous program phase, T4F researchers have identified the bacterial assemblages on the roots of boreal forest trees and shown how they change in concert with altered fungal colonization due to changing soil nutrient status. From these we have identified potential mycorrhizal partners (e.g. *Burkhalderia* sp.) and these will be cultured from the soil for experimental testing to identify those that do play a role of fungal endosymbionts or otherwise promote root mycorrhization.

- How do mycorrhizal fungi communities change through stand development, and how do they influence the activity of soil decomposer organisms (i.e. saprotrophs). There has been much recent debate about the magnitude to which forestry causes soil C losses or accumulation. Mycorrhizal composition and abundance are likely a very strong control on this. While the loss of mycorrhizal communities following harvest may allow decomposer activity to accelerate, their re-establishment may suppress decomposers, and lead to rapid soil C accumulation. The link between mycorrhizal composition and abundance and decomposer activity is a research frontier that requires further exploration, and which may solve outstanding debates.

2) Suggested investments into common competencies and infrastructures

Here we describe six areas for investments in competencies or infrastructure. New recruitment of researchers will be allocated to ensure cutting-edge developments within these areas that are all spanning several disciplines and are already well established within T4F. The new long-term field infrastructures will be designed as hubs for investigations by researchers from a wide array of disciplines, also bridging basic to applied science.

A) Bioinformatics

T4F has been crucial for establishing the Tree bioinformatics competences in Umeå, which in turn has been crucial for genetics, genomics, breeding and metagenomics activities. There is now an established Bioinformatics platform at UPSC, T4F will continue support to ensure that the needs of these activities will also be met in the future. Here we also aim to strengthen connections with Sci-Life Lab, another strategic research area, which can provide great synergy for our platforms in Umeå, and will serve as a genomic resource for many relevant taxa (trees and microbiomes).

B) Tree breeding

Skogforsk will continue as main provider of resources in tree breeding and quantitative genetics. Breeding applications will be developed in relation to developments in forest management and in addition to Norway spruce and Scots pine, also for other species such as birch, larch and lodgepole pine.

C) Modeling

The modeling will focus on implementing new process-based functionalities in the Heureka forestry decision support system in close cooperation with the team of specialists at the unit for Forest Sustainability Analysis. The new functionalities will be brought in from ecosystem models that use physio-chemical inputs to simulate forest growth, e.g. models like 3PG or BIOMASS and the overarching aim is to allow for Heureka, which is the tool used for forestry planning in Swedish forestry, to better capture the effect of climate change in long-term simulations of stand-, estate- and landscape forest development.

D) Genotyping Platform

While genotyping arrays are easy to use and appropriate for closed breeding programs, ascertainment bias in resulting genotypes is not appropriate for genomics in diverse populations. To support the genomic activities outlined above, T4F will support a technician trained in DNA extraction and library preparation of MULTI-GBS libraries, using the restriction enzyme based approach adapted to tree systems. Libraries can be generated for ~10 SEK per sample and they are massively parallel, enabling the efficient use of new sequencing platforms and resulting in a couple million variants in conifers at the sequencing cost of approximately 50 SEK/sample.

E) Drought Experiment

How is Norway spruce production affected by drought and what are the consequences on tree vitality and carbon sequestration? Are provenances from different regions affected differently by drought? How do other symbiotic- and pathogenic organisms respond to drought and stressed trees? A rain exclusion experiment will be installed in a Norway spruce provenance experiment near to Tönnersjöheden in southern Sweden, and near Vindeln in Northern Sweden. The rain exclusion will remove 50% of annual precipitation reaching ground level for four years. Exclusions will be replicated and large enough to effectively affect trees in the central part of the exclusion zone. Spatial position of all trees in the exclusion zones and control plots will be recorded before the experiment commences, and they will be individually measured for height, diameter and damage before the experiment starts, and after every growing season. Diameter-growth of sample trees will be measured with dendrometers, and transpiration will be measured with stem flow sensors during the growing seasons. During drought-events, shoot water potential will be measured in 24-hour campaigns. Soil moisture content will be monitored using probes installed before the start of the experiment. Other ecosystem level responses will be implemented to provide a holistic view of drought impacts on Swedish Spruce forests.

F) Clonal Archive

We will initiate a clonal archive from range-wide material, maintained by Skogforsk, that will be made available long-term for physiological, genetic and developmental studies. In parallel, this material will be deployed across Sweden and Europe in collaboration with partner institutions as replicated clonal trials. While both of these types of resources are already available, they are not currently paired and this will be the first resource of its kind. When the trials are established, this new resource will allow researchers to measure real-world phenotypic data derived from the trials and generate follow-up studies to ascertain the functional basis of trait variation relevant for traits critical to future forestry including growth, disease and adaptation to diverse environments.

Conclusion

Environmental change is a major threat to Swedish forests, and very likely will influence the degree to which forests can be relied upon to produce biomass, and as a carbon sink that offsets societies' fossil fuel emissions. This has enormous implications for the Swedish economy, and carbon emissions agreements within the EU. Our program, T4F, will continue to deliver high quality and excellent research that will inform the forest industry in how to adapt forests to environmental change, and maximize carbon sequestration. We will do this by setting a high priority research agenda, and investing in new and ongoing competencies and infrastructure, that will help solve this problem. Phase 4 of T4F will lead to major innovations in genetics, silviculture, and microbial ecology, which is needed to address one of Sweden's most important challenges, to develop a carbon neutral and sustainable bioeconomy.