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Swedish forest growth decline: A consequence of climate warming?

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ABSTRACT

Following an almost century-long increase, forest growth in Sweden has abruptly decreased during the last decade. Lower than expected forest biomass trajectories threaten national targets for carbon sequestration and bioeconomy. While climate-related drought is the most likely cause, the critical question is whether this recent growth decline is transient, or the beginning of a new normal where conventional management actions may risk further losses of resilience to water stress. We argue that improved mechanistic insights through better integrated research are urgently needed to avoid worsening the situation and further delaying necessary actions.

The decline in annual forest growth during the last decade follows an unprecedented acceleration in growth rate between 1996 and 2013, superimposed on a general increase throughout much of the 20th century (Fig. 1a). The doubling of the annual growth rate since the Swedish National Forest Inventory (NFI) measurements started in 1923 can primarily be attributed to altered management driven by an improved scientific understanding and increasing economic value of forest resources, combined with more favourable environmental conditions (Elfving and Tegnhammar, 1996). Management activities, such as drainage to remove excess water and replacement of low-stocked old stands with improved genetic material, combined with enhanced atmospheric nitrogen deposition, CO_2 fertilization and increased air temperature have likely contributed to the long-term increase. However, it remains unclear to what extent past management and environmental change can explain the accelerated increase in annual growth beginning in the late 1990s, and if this has any bearing on the rapid decline the last decade (Fig. 1b). Addressing these unanswered questions could help forecast how the Swedish growth trend will unfold in the future.

The growth rate decline across Sweden parallels trends in both Norway (Breidenbach et al., 2024) and Finland (Henttonen et al., 2024) and may be part of a wider, pan-European, pattern of drought-related forest die-back (Senf et al., 2020). While the observed increase and subsequent decline in forest growth over the last 25 years is most pronounced in southern Sweden, this pattern is evident across the entire country. The long-term increases in growth rate are observed for both the two dominant and most commercially valuable tree species in Sweden: Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) (Aldea et al., 2024). Both species have shown declined growth rates over the past decade, with Norway spruce exhibiting greater decreases than Scots pine (Mensah et al., 2023). Both Norway spruce and Scots pine are native to the region, but Norway spruce dominates under wetter growing conditions, whereas Scots pine primarily grows on drier soils.

Following the gradual long-term rise in productivity, the accelerating increase in growth rate in the early 2000s came as a positive surprise. Both the forest industry and politicians effectively used this rapid upsurge in forest biomass production for large national bioeconomic investments and international carbon sequestration assurances. However, the need to investigate and understand the underlying mechanisms of this acceleration in growth rates never seemed critically important. Instead, more favorable climatic conditions were believed to be the main driver, which led to even more ambitious plans for forest production and use. Most climate warming scenarios also supported this optimistic view, with forecasts of increased tree growth rates across Sweden, where short growing seasons and excess water historically have been limiting factors for forest productivity (Bergqvist et al., 2022). These model predictions are, however, in sharp contrast to empirical observations by the NFI based on almost 100,000 annually surveyed trees (see methods), establishing that annual tree growth has been decreasing substantially over the last decade (Fig. 1b).

Studies point to water limitation being a key underlying cause of the recent tree growth decline (Lim et al., 2015; Mensah et al., 2023), but the mechanistic processes underpinning this decrease remain largely elusive. Although annual precipitation is generally increasing across Sweden, the seasonal precipitation distribution is also changing, as wet seasons are getting wetter and dry seasons are getting drier (Schimanke et al., 2022). While attribution of the decreasing tree growth to soil water limitation seems likely, an increasing trend in atmospheric

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evaporative demand (Shekhar et al., 2024), measured as *Vapor Pressure Deficit* (VPD), may have aggravated the soil drought effect.

Understanding the consequences of water limitation for long-term tree growth requires improved mechanistic insights. Water transport through the xylem to the leaves or needles is driven by the gradient in water potential between the soil and atmosphere and is regulated through a series of variable resistances in the tree, the most important being leaf stomata. If soil water availability is limited, trees will close their stomata, which leads to reduced photosynthesis and associated short-term reduction in tree growth rate (McDowell et al., 2008). If the gradient becomes too steep because of too high atmospheric VPD in relation to the water transport capacity, this will result in xylem embolisms, where the internal 'water plumbing' in the tree cavitate. Ultimately, this can cause hydraulic failure resulting in long-lasting declines in tree growth and even mortality (Gessler et al., 2018). Hence, disentangling the independent- and combined effects of soil water supply *vs*. atmospheric evaporative demand is key to understanding current and future climate impacts on forest productivity and tree water requirements.

In Sweden, like in many other industrialized countries affected by drought-induced tree growth decline, there are human induced environmental stressors that may have exacerbate the climate change effects. In the Swedish context, with strongly nitrogen limited forests, anthropogenic nitrogen deposition has had large positive effects on tree growth, especially in the south where deposition has been highest (Binkley and Högberg, 2016). This nitrogen loading, in combination with decades of more favorable weather conditions and increasing atmospheric CO_2 concentrations, may have further intensified the growth acceleration trend that began around the end of the last millennia. However, this positive influence of nitrogen loading on forest growth in the past may now potentially contribute to the recent growth decline as a result of reduced resilience to water stress. Increasing the nutrient status of soils can result in a reallocation of biomass growth from roots to canopy, which reduces fine root production and lessens the plant water uptake potential (Lim et al., 2015). Also, the anatomy of the water conducting tissues in roots, stems and branches become modified by increased nitrogen deposition rates, negatively affecting the hydraulic safety margin of trees (Gessler et al., 2017). Hence, the extensive nitrogen deposition that previously boosted above-ground biomass production may have reduced tree drought tolerance and aggravated the declining growth trends in more recent years. An additional human dimension that could have made the Swedish forest even more drought sensitive is the one million kms of forest ditches dug during the early 20th century (Laudon et al., 2022). These ditches have affected almost every forest stand in the country and have generally had positive effects on the forest growth potential in the past when excess water was limiting growth. The large density of artificial drainage networks may now be causing additional problems by reducing the water holding capacity of soils. This reduction in soil water storage, in combination with more frequent warm and dry conditions, may have strong negative impacts on tree growth.

The recent decreasing trend in forest growth rates now threatens a forest sector that largely has operated on the assumption of a continuous growth increase in biomass production, but the decline also jeopardizes EU targets for fulfilling national contributions to annual carbon sequestration and climate change mitigation. Given the large economic and political investments, there is now greater pressure than ever to increase forest management activities such as forest fertilization and clean human-made ditches to meet expected forest growth targets. Although the consequences of such activities require improved understanding, both could potentially make the Swedish forest even more vulnerable to drought-related stressors if implemented at large scale.

To avoid potential pitfalls related to business as usual in forest management, the recent rise and decline in forest growth should serve as a wake-up call to seek improved, mechanistic insights into what regulates the growth of northern forest and its sensitivity to water limitation under new climatic conditions. To reach such insights we need concerted studies that combine the use of long-term forest monitoring, large scale experiments and improved modeling. Failure to do so may result in a shortage of national based raw materials for the Swedish forest industry and an over-committed political system unable to meet international climate mitigation targets and policies.

1. Method

The NFI is based on probability sampling with a stratified systematic cluster design based on permanent, 10 m radius plots (with a five-year return time), and temporary plots, measured once (Fridman and Westerlund, 2016). Annually, over 10,000 plots including over 100,000 sample trees are surveyed by a team of 60 experienced field staff. Growth rate is estimated at an individual tree level, and thereafter scaled up to plot, region and finally to all of Sweden. Rate estimates are based on two basic approaches where trees on permanent plots are used to estimate the difference between volume predictions from two consecutive inventories by using tree species, diameter at breast height, tree height and crown height. Trees on the temporary plots are used to make direct regression model estimates including microscope-measured radial increment and age on sub-sample trees as additional independent variables. The estimated growth rate for the two different samples, permanent and temporary, are then combined to a weighted mean (Fridman et al. 2014). The relative uncertainty for the estimated growth has been estimated to be approximately one percent over time.

Author information

This commentary is the result from 10 months of discussion about

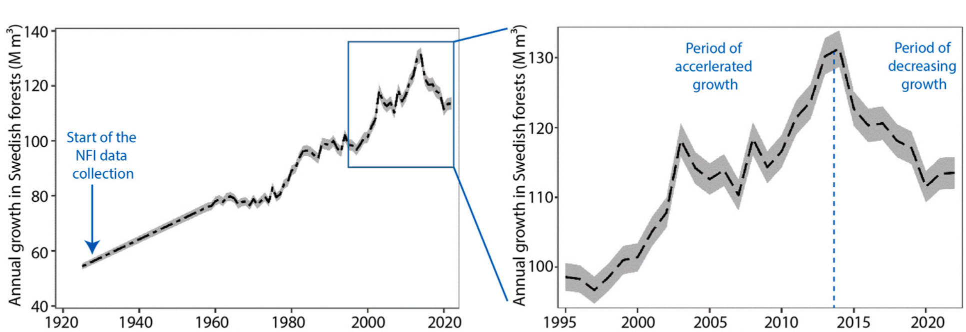

Fig. 1. Trends in annual incremental growth since the beginning of the Swedish National Forest Inventory (NFI) data collection in 1920 (left), as well as an enlarged view from 1995 to the present (right). Each annual data estimate is based on over 100,000 annually inventoried sample trees, which are aggregated into 5-year running averages. Data between 1925 and 1958 are linearly interpolated, thereafter running five-year averages. The grey area denotes the uncertainty band of the annual growth estimates.

the long-term trend among the co-authors commissioned by the Swedish University of Agricultural Science. HL lead the writing, wrote the first draft, which was commented, improved and agreed on by all co-authors.

CRediT authorship contribution statement

Hjalmar Laudon: Writing – original draft, Visualization, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Sandra Jämtgård:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization. **Torgny Näsholm:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Jonas Fridman:** Writing – review & editing, Project administration, Formal analysis, Data curation. **Alex Appiah Mensah:** Writing – review & editing, Formal analysis, Data curation.

Declaration of Competing Interest

This is a declaration that there is no competing interest in the manuscript Swedish forest growth decline: a consequence of climate warming?

Data availability

Data will be made available on request.

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