Emerging technology can guide ecosystem restoration for future water security

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Abstract

Since this is a HP today contribution I understand that it should not have an abstract

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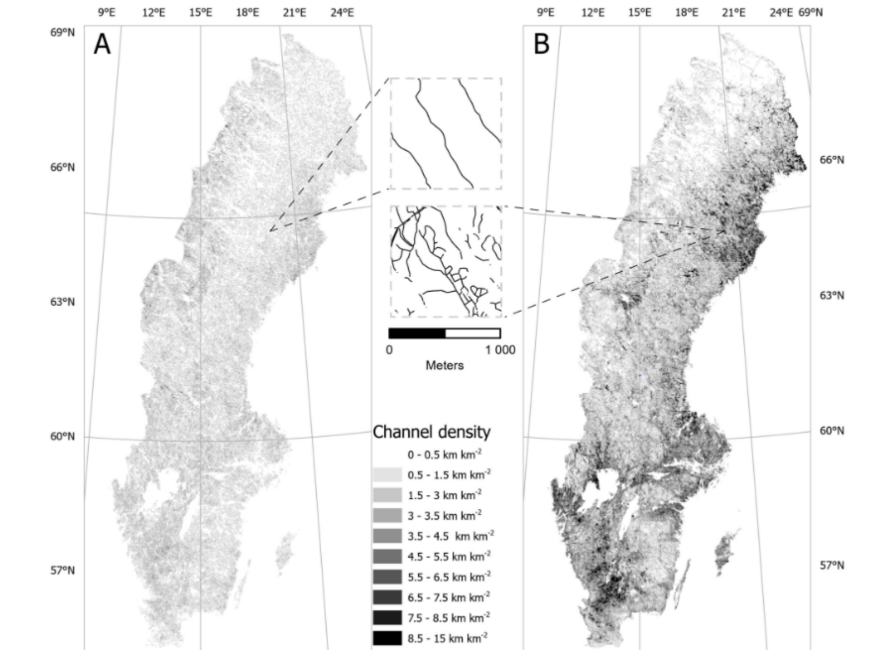
Background

Water is the primary medium through which society will experience the effects of climate change. Altered precipitation patterns, enhanced evapotranspiration rates, loss of snow and ice, declines in groundwater storage, and increased risk of flooding and droughts will all have important implications for our water resources. In fact, we are already experiencing climate-related perturbations to the water cycle, as manifested through increases in temperatures and frequency of weather extremes across the globe (IPCC, 2021). However, a critical but often neglected aspect of predicting future hydrological change is recognizing the implications of historical land-use decisions that can act to either enhance or reduce the resilience of both the quality and quantity of water. Such land use decisions may create 'locked-in' effects reflecting the policies and path dependencies that underpin management inertia (Unruh and Carrillo-Hermosilla, 2006), as well as physical disturbances that caused hydrological changes that are difficult to reverse (Lindenmayer et al. 2011).

While water challenges are global, the water cycle in boreal regions is perhaps uniquely vulnerable due to cumulative effects of land use and climate warming, with the latter proceeding at faster rates at high latitudes (Buntgen et al. 2021). Climate change in the north is predicted to give rise to increasingly snow-free winters and warmer summers in boreal landscapes, which collectively will reduce water storage. Superimposed on these changes are barriers or inertia due to past land-use decisions, that may exacerbate pressures on ground- and surface waters. The most widespread management activity in many boreal countries is the historical ditching of wet soils. Forest ditches are constructed waterways that were dug, often by hand, to remove excess water affecting several million hectares of land, especially in Finland and Sweden, but also in many other northern countries (Strack, 2008; Fig 1). This resulted in improved forest growth and transformed wet soils and peatlands to productive forests, but also came with unwanted environmental consequences.

Drainage ditches are sources of enhanced methane emissions (Peacock et al. 2021) and elevated dissolved organic carbon concentrations (Nieminen et al. 2021). Low water tables also lead to enhanced soil carbon mineralization and increased terrestrial greenhouse gas (GHG) emissions (Evans et al. 2021). The biogeochemical properties of these extensions to the drainage network dramatically alter our understanding of running waters as sources of GHGs to the atmosphere and the overall provisions of ecosystem services. Most importantly, in an era increasingly affected by climate change, we now face conditions that create the opposite obstacle that the ditches aimed to solve – insufficient amounts of water – due to the expected increase in frequency, duration and severity of drought (Spinoni et al. 2021). Historical ditching may thus create enhanced vulnerability to drought in the future, which would require massive efforts to reverse.



Documenting the cumulative effects of such local-scale management activities raises complex challenges that new technologies can help solve. In the case of forest ditching, the full scope of the problem has largely been hidden because existing models fail to map landscape hydrography when natural processes no longer have primacy over channel initiation. Nevertheless, with recent modelling advances, small-scale waterways can now be identified and mapped using high-resolution airborne laser scanning (ALS), combined with tools based on artificial intelligence (AI; Sit et al. 2020).

Emerging hydrological technology

We mapped small channels across all of Sweden with a deep neural network. The deep learning model was based on ALS data and 1607 km of manually digitized ditches (Ågren et al. 2021). The ALS point cloud had a last return density of 0.5-1 points m^{-2} and a surface model with 1 m resolution was created by the Swedish land use and cadastral registration authority. A high pass median filter (HPMF) was applied to the surface model to emphasize short-range variability in the topography. The HPMF-algorithm was implemented in Whitebox tools (Lindsay, 2014) and operates by subtracting the value at the grid cell at the center of the window from the median value in the surrounding neighbourhood with a kernel of 5 cells. Negative values indicate depressions while positive values indicate ridges. The digitized vector lines have no width so we utilized average ditch width from a field inventory where 2188 ditch channels were surveyed across Sweden. The average ditch width was 2 m with a standard deviation of 1.3 m. Instead of flagging all pixels within ˜3 m of a vector line as ditch, we utilized the HPMF to create more natural ditch labels. Pixels within three meters of a vector line and with a HPMF value less than -0.075 were flagged as ditch pixels.

TensorFlow 2.6 was used to build an encoder-decoder style deep neural network, to transform the filtered HPMF images into images highlighting the detected ditches. On the encoding path, the network learns a series of filters, organized in layers, which express larger and larger neighbourhoods of pixels in fewer and fewer vectors of features. After encoding the ALS image into a spatially more compact representation, it was again decoded by a series of learned filters performing transposed convolutions into the final classification map. This map contains, for every pixel in the input image, the probability that the pixel belongs to a ditch. In order to separate channels from local depressions, we used a conditional random field layer which learns to penalize undue label discontinuities. This neural network model was trained using weighted cross-entropy loss to deal with the large class imbalance between ditch and non-ditch pixels.he model was trained on 80%

of the dataset and evaluated on 20 % of the data that were set aside for testing. The model correctly mapped 82 % of all ditches in the test data with a Matthew's correlation coefficient of 0.72. The final model was implemented using Microsoft Azure to map ditch channels across all of Sweden in collaboration with the Swedish Forest Agency. The deep learning method with the trained model and a reproducible example is available from GitHub (Lidberg et al. 2021). Finally, the national ditch map is available as open data from the Swedish Forest Agency (*https://www.skogsstyrelsen.se*).

Implications and conclusions

Our results suggest that while the best available maps for Sweden include 0.4 million km of waterways, they only identify 22% of the channels. Automatic detection using our deep learning methods increases this estimated network length to approximately 1.2 million km (Fig 2), equivalent to 28 times around the world. The average channel density is 2.5 km/km^2, but can be up to 15 km/km^2 in the most affected areas. Of all channels in Sweden, 67% are human-made. The anthropogenic channel network has affected almost the entire land area of Sweden, except for the mountain region in the northwest. In Finland, similar drainage has, on average, reduced water storage capacity of affected areas by over 200 mm (Menberu et al. 2016), while also representing a significant source of sediment and nutrients to downstream waterbodies (Finér et al. 2021).

When ditches age, some of their hydrological function decrease due to peat decomposition, vegetation ingrowth, and sediment deposition. Thus, ditch-cleaning has been established as a standard practice, with the aim of promoting tree regeneration following clear-cutting. Since many of the forest areas drained a century ago now are reaching the end of their rotation period, the decision of whether or not to clean ditches following harvest is now a matter of debate. Should we follow the forest industry's recommendation to increase ditch-cleaning to maintain high forest biomass production, restore them by blocking the artificial channels, use alternative continuous cover forestry techniques to manage water tables, or leave ditches to develop freely? Despite a scientific discussion about evaluating the need for artificial drainage to stimulate forest growth as early as the 1930's (Malmström, 1931), the science and policy debate about ditching did not resurface until the last decade. Except for a few isolated studies addressing the drainage effects on hydrology, research in Sweden has essentially been absent. In this context, path dependency (Pierson, 2000), in terms of institutionalized management practices to increase productivity in forestry, appears to have been locked-in as an industry standard, and could thus be resistant to new scientific findings for the current forest land-use policy (Löfmarck, et al. 2017).

Whatever management actions are taken today will have century-long implications for the hydrology of northern forests. Increasing the resilience of water and forest resources in a future climate requires improved knowledge and better communication about the implications of different management options. The AI technology presented here (see concluding section) can help us identify the exact location and extension of ditches in the boreal forest, which is a first step towards more science-based management decisions on this massive landscape alteration occurring during the last century. Given the prospects of a drier future, the plan to continue to clean ditches seems risky from a water storage context, yet the efficacy and consequences of other management options are also highly uncertain (Kreyling et al. 2021). Either way, the story of historical ditching in Sweden serves as a cautionary tale about making widespread landscape changes to address a perceived problem without carefully considering the long-term implications. To avoid repeating short-term fixes that may cause new locked-in effects, it is critical to evaluate what management and policy options exist to meet the demands for freshwater resources in a future climate while also continuing to improve our knowledge base for policy development.

As we enter the beginning of the UN Decade on Ecosystem Restoration, mechanistic insights into restoration targets, land-use management policies, and improved decision-support tools hold the key to successful implementation. As the number of ALS datasets are increasing worldwide, applying deep learning methods to detect both natural and anthropogenic stream networks can become standard practice across many landscapes. Based on this, we can then begin to understand how past land-use contributes to hydrological alteration under contemporary and future climatic scenarios. Using such landscape scale information will allow improved identification of areas most vulnerable to climate change and therefore those that most effectively should be targeted for different ecosystem restoration actions. With this information we can then develop functional restoration methods, which can be tested and applied to solve the challenge of securing water resources in managed boreal forest landscape in the decades to come.

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