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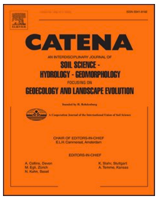

Projecting the impacts of the bioeconomy on Nordic land use and freshwater quality and quantity – An overview

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ABSTRACT

This paper synthesizes a five-year project (BIOWATER) that assessed the effects of a developing bioeconomy on Nordic freshwaters. We used a catchment perspective and combined several approaches: comparative analyses of long-term data sets from well-monitored catchments (agricultural, with forestry, and near pristine) across Fennoscandia, catchment biogeochemical modelling and ecosystem services assessment for integration. Various mitigation measures were also studied. Benchmark Shared Socio-economic Pathways were downscaled and articulated in dialogue with national stakeholder representatives leading to five Nordic Bioeconomy Pathways (NBPs) describing plausible but different trajectories of societal development towards 2050.These were then used for catchment modelling and ecosystem service assessment. Key findings from the work synthesized here are: (a) The monitoring results from 69 catchments demonstrate that agricultural lands exported an order of magnitude more nutrients than natural catchments (medians 44 vs 4 kg P km^{-2} y^{-1} and 1450 vs 139 kg N km^{-2} y^{-1}) whilst forests were intermediate (7 kg P km^{-2} y^{-1} and 200 kg N km^{-2} y^{-1}). (b) Our contrasting scenarios led to substantial differences in land use patterns, which affected river flow as well as nutrient loads in two of the four modelled catchments (Danish Odense Å and Norwegian Skuterud), but not in two others (Swedish catchment C6 and Finnish Simojoki). (c) Strongly contrasting scenarios (NBP1 maximizing resource circularity versus NBP5 maximizing short-term profit) were found to lead to similar monetary estimates of total societal benefits, though for different underlying reasons – a pattern similar across the six studied Nordic catchments. (d) The ecological status of small to medium sized rivers in agricultural landscapes benefitted greatly from an increase in riparian forest cover from 10 % to 60 %. Riparian buffer strips, constructed wetlands, rewetting of ditched peatlands, and similar nature-based solutions optimize natural biogeochemical processes and thus can help in mitigating negative impacts of intensified biomass removal on water quality.

1. Introduction

A consensus exists among Nordic policymakers that the further development of a bioeconomy is desirable and necessary to reduce fossil fuel dependency (Gíslason and Bragadóttir, 2017). However, the specific form of this future bio-economy, the pathways to reach such a societal state and the possible environmental consequences are unclear as yet (Sheppard et al., 2011; Golembiewski et al., 2015; O'Brien et al., 2017; Eyvindson et al., 2018; Sundnes et al., 2020). The BIOWATER Nordic Center of Excellence (https://www.biowater.info) has studied the possible adverse effects of a developing Nordic bio-economy on water quantity and quality. This paper synthesizes the work done in

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BIOWATER, whilst it focuses on the collection of papers in the special issue of Catena entitled ‘Assessing the potential for adverse environmental side-effects of a developing bio-economy in Nordic river basins’. These papers have carried out a common scenario modelling approach to different Nordic catchments in an attempt to chart the effects of such a developing bio-economy. As a useful background for the modelling outputs, we include a summary from a data mining exercise, also carried out within BIOWATER, of currently available longer-term Nordic catchment data sets (De Wit et al., 2020), to see what such observations can teach us about a developing bio-economy. Skarbøvik et al. (2020) provided an earlier mid-term stocktaking of the same issue, and we will start from the tentative conclusions and remaining questions phrased in that assessment.

Skarbøvik et al. (2020) observed that this ‘green shift’ towards a more circular bioeconomy may well have adverse environmental impacts due to an increased competition for land between agriculture, biofuel production and forestry, an increased intensity of land use, and an increased use of marginal lands that have other functions including recreation, biodiversity conservation and flood prevention. The authors argue for a scenario approach such as the one using Nordic Bioeconomy Pathways (NBPs) designed by Rakovic et al. (2020) based on the benchmark Shared Socio-economic Pathways (SSPs) of e.g. O’Neill et al. (2017), but stipulate that a further articulation of e.g. forestry or agricultural attributes is likely necessary for comprehensive catchment and water resources modelling. The current collection of modelling papers answers to this expectation, and we will assess below what type of articulations were particularly necessary.

Skarbøvik et al. (2020) observed a shortage of empirical data on forestry effects on water quantity and quality. Nieminen et al. (2021) a. o. suggest that this is less the case for Finnish forests on peatland. Skarbøvik et al. (2020) further concluded that the ecosystem services framework developed by Vermaat et al. (2020) had sufficient resolution to assess trade-offs among different services occurring as a consequence of the NBP scenarios. These authors also suggest that a better targeting of mitigation measures would be possible as a consequence of the modelling efforts carried out in BIOWATER. We will be able to evaluate their findings from the material presented in the current collection of papers. In doing so, we now have the possibility to project possibly adverse effects of a developing bioeconomy using these NBP scenarios on water quantity and quality via changes in land use and ultimately speculate on the different ways Nordic societies depend on their landscapes.

In our concluding section we will also attempt to answer the specific questions posed by Skarbøvik et al. (2020), here cited literally: ‘(1) How much land will be needed to provide the necessary biomass for the bioeconomy? (2) To which extent will the increased need for biomass change the proportion of forests, agricultural land and more marginal lands (e.g. marginal fields, riparian zones, flood-prone areas)? (3) How much intensification will we see in agriculture and forestry? (4) How will these changes then interfere with water quality (i.e. the Water Framework Directive goals in Europe) and biodiversity conservation policy objectives?’.

On an aggregated Nordic scale, analyses have already shown that it is highly unlikely that the current demand for energy can or has to be met from the biomass produced in Nordic forests. This is because other renewable energy sources become increasingly available (hydropower, solar and wind), and high-quality wood-based products will be more competitive for the raw resource than biofuel (Rytter et al., 2014; Jåstad et al., 2021). This already answers the first of the four questions posed. Still, we have included increasing and more intense forestry exploitation in our scenarios and quantified it with a range of attributes. We did so because we expected that at a local, or catchment scale continuously rising power and fuel demands may still affect Nordic forestry practices the coming years, also because a full-scale electrification of energy-intensive sectors such as transport will likely require decades and markets do not change overnight (Jåstad et al., 2021).

2. Approach: scenarios, stakeholders, models and data compilation

For their different modelling efforts the BIOWATER consortium has used a common set of scenarios that describe contrasting potential trajectories for a developing Nordic bioeconomy, the so-called Nordic Bioeconomy Pathways (NBPs). The development of these NBPs is documented in Rakovic et al. (2020), and Lyche Solheim et al. (2023). Briefly, an elaborate narrative qualification of different aspects (so-called ‘attributes’) of societal development has been deduced from the benchmark SSPs of O’Neill et al. (2017) as NBPs for the Nordic countries. These attributes included demography, social equity, urbanization, economic growth, energy use, bioenergy share, technological development, international trade, globalization and the development of the forestry and agricultural sectors. The time horizon for the use of these scenarios has been set at 2050 (Rakovic et al., 2020). This is a compromise to allow land use change to have some effect accumulating over a few decades whereas it still can be perceived within an imaginable cross-generational scope for policy makers and stakeholder representatives (cf. Berkhout et al., 2002).

The draft narratives and attribute ranges were first discussed in a two-day workshop with the BIOWATER consortium, and then revised (Rakovic et al., 2020) for triangulation in dedicated national workshops with national and regional, institutional and sectoral stakeholder representatives, as is described in Lyche-Solheim et al. (2023). Biogeophysical catchment modelers within the BIOWATER consortium then used these NBPs for their specific cases and adjusted the qualitative narratives into matrices of quantitative input data. Results of these efforts are presented by Carstensen et al. (2023), Farkas et al. (2023), Mårtensson et al. (2023) and Rankinen et al. (2023). Immerzeel et al. (2023) applied the same NBP scenarios in the ecosystem services analytical framework developed by Immerzeel et al. (2021). This framework couples land use categories and publicly available statistical data using simple knowledge rules to provide monetary estimates of final ecosystem service delivery. So, all in all, the modelling efforts used the same set of benchmark scenarios but specifications were adjusted to the characteristics of the catchment in question as well as specific national environmental targets.

Whereas our NBPs are explicitly limited to plausible changes within society and therefore include land use changes, the catchment modelling efforts had the opportunity to also include geophysical scenarios of climate change, the so-called Representative Concentration Pathways (RCPs, Van Vuuren and Carter, 2014). However, the difference in global warming and hydrology among these RCPs is not projected to be very substantial yet for Fennoscandia in 2050 (e.g. IPCC, 2014; Hanssen-Bauer et al., 2015; Aygün et al., 2020; Christensen et al., 2022). Given the currently limited trends in global greenhouse gas emission reductions, it appeared justified to run only RCP 4.5 and 8.5, a middle and a high warming scenario.

3. Learning from the past: Catchment monitoring results

In parallel to the modelling efforts, the substantial volume of data from intensively monitored Nordic catchments has been analysed for trends in the past decades including possible relations to climate change (De Wit et al., 2020). The main findings are summarized here and are also used to verify the position of the catchments selected for intensive bio-geophysical modeling within the broader ranges observed in Nordic catchments.

De Wit et al. (2020) present a comparative trend analysis of nutrient loads from 69 Nordic headwater catchments over the past two decades. Catchments were categorized in three groups based on predominant land cover: agricultural, forestry and so called ‘natural’ cover, which may be unexploited woodland, bogs, mountainous uplands or extensive grazing land. With the exception of Denmark, the patterns were comparable: agricultural land exported about an order of magnitude higher loads than natural catchments (overall medians: 44 vs 4 kg P km^{-2} y^{-1} and 1450 vs 139 kg N km^{-2} y^{-1}, whereas forested land was intermediate (7 kg P km^{-2} y^{-1} and 200 kg N km^{-2} y^{-1}). In Denmark, the fragments of natural catchments are embedded within an agricultural landscape, leading to higher exports. Given the large contrast in land use, soil types, bedrock conditions, and relatively short time series of two decades, it is not surprising that De Wit et al. (2020) concluded that land use overridingly controls nutrient export compared to climate change. Indeed, Kyllmar et al. (2023) observed major differences in N and P export between arable (higher exports) and grass-covered (lower exports) among 34 agricultural catchments in the Nordic-Baltic region. Over time, declines in nitrogen concentrations were detected in Denmark and Sweden which is linked to the implementation of nitrogen leaching reduction programs. However, the last 10 years this trend faded. This may be due to more strongly variable weather but also reflects the need for more measures that are also better targeted. Kyllmar et al. (2023) found little evidence for changes in annual water discharge over time from 1990 to 2020, whereas significant seasonal changes were identified by Wenng et al. (2021a) who studied several small agricultural catchments in Norway in more detail over about the same period. These authors also found that climate change effects became visible, but these were dependent on the importance of snow in the water balance. These changes in precipitation and frost cycles however have already led to adaptive responses in agricultural practice, combating for example topsoil loss with cover crops (Wenng et al., 2020).

Clearly, underlying the heterogeneity in land use among Nordic catchments is a major latitudinal gradient affecting growing season day length, but there are also important contrasts in underlying geology. Prevalence of bedrock with very limited infiltration capacity is particularly apparent in Norway and leads to limited retention and high proportions of rainfall converted into run-off and river flow (Fig. 1). The contrast with for example Denmark is stark. The studied Nordic catchments show considerable variation in annual water and particle retention (e.g. Kyllmar et al., 2023; Skarbøvik et al., 2023), and hence also in the potential for nutrient retention – a concern to be taken into consideration when mitigating measures are designed or more intensive forest exploitation is considered.

The widespread peatlands in Finland have been drained during 1970ies to enable forestry and improve timber production. The effects of this drainage can be considered similar to those of more intense forestry management that is conducive to increased biomass outtake (e.g. Laudon et al., 2016; Parc & Thiffault, 2016; Eyvindsson et al., 2018). Drainage led to short-term flushes of humic substances, increased mineralization and hence increased discharge of carbon and nutrients (Finer et al., 2021). Results are a water quality burden to the receiving waters, and a net increase in carbon emission, both undesired consequences. Closure of such drainage ditches has been shown an effective measure, rapidly restoring mire hydrology and reducing exports (Menberu et al., 2018). Cost-effectiveness of such a management option, however is strongly depending on whether market or non-market goods and services are preferred and included in the assessment (Juutinen et al. 2020; Miettinen et al., 2020).

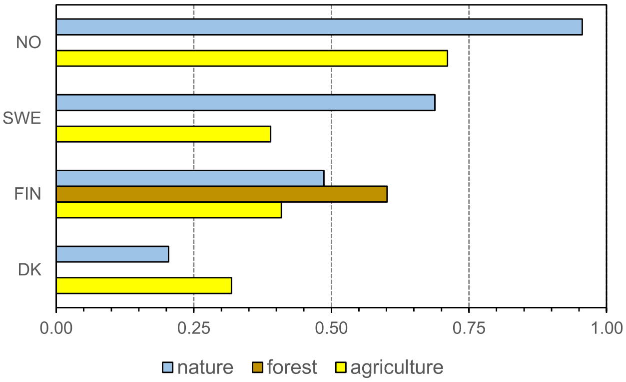

Fig. 1. Proportion of precipitation that leaves Nordic catchments as river flow, estimated as mean annual flow / mean annual precipitation. Presented are ratios of countrywide medians from De Wit et al (2020). Only from Finland the number of forested catchments was sufficient for statistical analysis (cf De Wit et al. 2020). Note that the category ‘nature’ pools different categories, such as mires in low-slope terrain, undisturbed pristine boreal forest as well as uplands with little or no soil covering bedrock.

Similarly, increased forest exploitation has been shown to have adverse effects on in-stream biodiversity in the drainage network (Rajakallio et al., 2021). Also here, setting aside the wooded riparian zone from timber harvesting has strong mitigation potential (Rajakallio et al., 2021), just as the preservation or restoration of wooded riparian buffer strips has in agricultural landscapes (e.g. Blankenberg and Skarbøvik 2020, Vermaat et al., 2021; Tolkkinen et al., 2021; Turunen et al., 2021). Krzeminska et al. (2023) demonstrated the potential of constructed wetlands in the landscape over a longer time span, supporting the review on a range of near-stream mitigation measures by Carstensen et al. (2023).

4. Modelling outcomes of bio-economy scenarios: Contrasts and similarities

The different biogeochemical modelling groups selected only a limited number of catchments for their detailed analyses, for logistical reasons (Table 1). Similarly, a number of catchments was selected for ecosystem services assessments, but here other criteria were important, such as a sufficiently numerous human population to allow for questionnaire surveys (Immerzeel et al. 2021). Therefore these catchments do not overlap well. A relevant question is how well the modelled catchments represent the broader range reported in De Wit et al. (2020) from the BIOWATER catchment database. For total P, all four models produced concentrations that are well within the middle quartiles (Fig. 2), for total N this is only the case for the Finnish model, whereas model outcomes for the other three are still near the lower 25% quartile bound and well within the full range (partly unpublished data from Bhattacharjee, Farkas, Carstensen and Mårtensson, not shown here). Note that all models were calibrated and validated and performed well for the specifically modelled catchment – it is only that these selected catchments happen to be in the lower half of the full range observed in monitored catchments with respect to total nitrogen export. This may have several reasons. One may be that all modeled catchments are larger in area than the monitored catchments reported in De Wit et al. (2020; 4.5–3160 km^2 vs. 0.04–5.6 km^2) and thus may have a higher cumulative internal retention (De Klein and Koelmans, 2011). We concluded that the model work in these selected catchments is sufficiently representative for our purpose of exploring the potential effects of a developing bio-economy in Nordic catchments.

Since the modelled catchments differ in geography and land use, also different scenario attributes have been selected for modelling (Table 1). In the Danish case focus was on agricultural attributes, whereas the Finnish case had a focus on forestry attributes (see Lyche Solheim et al., 2023).

Overall, the most obvious difference in N and P exports is rather among the four catchments than among the NBP scenarios (Fig. 3): Simojoki had substantially lower N and P exports than the other catchments, and also showed little response to the modelled scenarios in SWAT (Bhattacharjee, 2022). The other three modelled catchments were more responsive, although the greenest NBP1 did not always lead to the lowest nutrient exports. NBP1 led to the clearly lowest export of N for the Danish Odense Å model and of P for the Norwegian Skuterud (modelled P-results as yet unpublished, but correlated satisfactorily with suspended solids patterns): respectively, 68% less and 56% less than the scenarios with the highest exports (Fig. 3). In the Swedish model, in contrast, the exports were relatively high compared to the other catchments, but the differences among the scenarios were not substantial

Table 1
Overview of catchment modelling efforts using the nbp scenarios (cf.Rakovic et al., 2020 and Lyche Solheim et al., 2023) and their main outcomes. RCPs = Radiative Forcing Pathways, a set of geophysical climate change scenarios (cf. Van Vuuren and Carter, 2014). NBP scenario attributes are only briefly labelled here (Agr = agriculture, For = forestry, for a full explanation cf. Lyche Solheim et al., 2023).

Authors	Catchment; predominant land use, modelling tool*	What was modelled?	NBP attributes used	Main outcomes
Carstensen et al. (2023)	Odense Å upstream Kratholm ($486\ km^2$, 70% agriculture); SWAT	Water quantity (discharge patterns) and quality (N and P)	Agr3, artificial fertilizer use; Agr4, animal husbandry expressed as manure; Agr6, set aside land for buffer strips and wetlands; Agr8, catchment management strategies, here variable forest cover	(a) Changes in land use (attribute Agr6 and Agr8) were far more important than the others. (b) Small but significant changes in flow occurred: lower winter and higher summer flow in NBP1 due to less tile drainage and more groundwater recharge and flow. (c) Including RCPs had limited effect compared to the NBPs (d) Considerable reduction in N load was realised in NBP1 whereas in NBP5 the load increased; only NBP1 would meet the Water Framework Directive target for the downstream estuary of Odense Fjord.
Farkas et al. (2023; also unpublished results)	Skuterud ($4.5\ km^2$, 61% agriculture); INCA	Water quantity (discharge patterns), sediment loss and water quality (P)	Agr1, land use change; Agr2 conservation efforts in tillage; Agr3, artificial fertilizer use; Agr4, animal manure; Agr6 buffer strips	(a) NBP1, but also NBP 4 and 5, led to distinctly lower annual flow and export of suspended solids compared to current, NBP2 and 3 (b) NBP1 had a lower occurrence of extreme flow events (99-percentile), and it is these events that explain most variation in sediment export (c) Both RCPs led to a similar change in flow regime compared to current: more discharge in winter and less in spring and autumn. (d) As yet unpublished results on P loads suggest a substantial decline due to changes in land use and fertilizer practice in NBP1 and NBP3, whereas NBP2 and 4 led to increased loads relative to the current situation. The effect of increased winter flow in both RCPs aggravated catchment P-losses most in NBP2, 4 and 5.
Mårtensson et al. (2023)	Catchment C6 ($33\ km^2$, 56% agriculture), nested within the larger Leaching Region 6 (~$5000\ km^2$); NLeCSS	N and P export	Agr1, crop mixture; Agr2, tillage system; Agr6 buffer strips (18 m width); Agr7, catch crops	(a) crop mixture (Agr1) had the most profound effect. (b) In NBP1, a shift from animal husbandry to grain production was assumed, which is a contrast with the other modelling studies. This led to increased leaching of N and (to a lesser extent) of P. Mitigation measures (Agr6 and 7) could not fully counteract this.
Rankinen et al. (2023); Bhattacharjee (2022)	Simojoki ($3160\ km^2$, 2% agriculture, 57% drained peatland); INCA, PERSIST, SWAT	Water quantity (discharge patterns), sediment loss and water quality (N and P)	For2 and For3, stand management and biomass harvesting; For4, catchment management strategies; For5, fertilizer use; Rankinen et al. (2023) combined RCP4.5 with NBP1, 4 and 5, ad RCP8.5 with NBP2 and 3.	(a) Implementing NBP1 and 2 led to different outcomes than NBP3 to 5: flow and therefore export of suspended solids increased in the former with decreased evapotranspiration, whereas reduced stand management and biomass removal in the latter led to lower flow, as well as export of suspended solids and nutrients. The percentage changes were systematic but low (~1%). (b) The two different RCP scenarios had little effect on exported loads, but spring melt peak flow was earlier in the warmer scenarios (c) Varying fertilizer use had no measurable effect on modelled response variables. (d) Rankinen et al. (2023) observed that different scenario combinations could lead to the same resulting water quality. NBP1 would most likely safeguard water quality best.
Immerzeel et al. (2023)	Six different Nordic catchments: Halden (N), Orre (N), Sävjåan (S), Vindelälven (S), Odense (DK) and part of Simojoki (F); 102–1200 km^2, 2–80% agriculture; 'Mononen-cascade' spreadsheets	Delivery of a suite of 21 different final ecosystem services including their estimated monetary value.	6 animal husbandry attributes, 5 attributes for crops, 4 for forestry, 9 for population, geography and economics, and 4 for energy production.	(a) The different scenarios led to profoundly different relative importance of the different final services. (b) Overall, recreation by residents and visitors was found to provide the highest estimated economic value per unit land. Experiencing nature through recreational

(continued on next page)

Table 1 (*continued*)

Authors	Catchment; predominant land use, modelling tool*	What was modelled?	NBP attributes used	Main outcomes
				visits contributes a high and likely undervalued benefit to society. This recreation is tightly linked to water and scenic 'Nordic vista's' in the landscape – wholesale forest harvesting may reduce this value. (c) NBP1 and NBP5 led to the highest summed total economic value, but with a very different mix of services. A Nordic green shift can generate greater benefits to society for all stakeholders. (d) The distribution of benefit over stakeholder categories is most responsive to the NBPs for recreating visitors. (e) The distribution of value over society and the risk of conflicts will depend on the shape of the green shift, the NBPs indicate possible trajectories only.

*Each modelling tool is explained in the cited paper and all have been used in previous publications and have been carefully calibrated and validated for the work reviewed here.

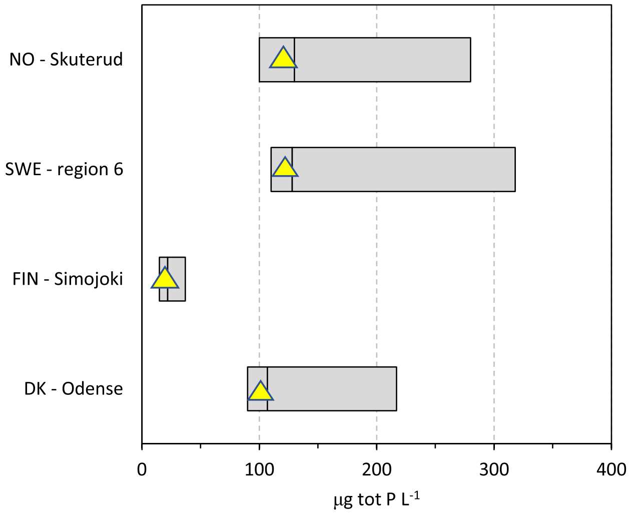

Fig. 2. Quartile (25%-50%-75%, grey bars) plots of annual outflow total P concentration for the modelled agricultural catchments in Denmark, Sweden and Norway as well as the forestry catchments from Finland from De Wit et al. (2020) versus modelled outflow concentrations of total P (yellow triangles) for, respectively Odense Å (DK), Leaching region 6 (SWE), Skuterudfeltet (NO, modelled P as yet unpublished) and the Simojoki catchment (FIN). Data from De Wit et al. (2020) and partly unpublished modelling output courtesy Mette Vodder-Carstensen, Csilla Farkas, Joy Bhattacharjee, Katri Rankinen and Kristina Mårtensson.

(1.0–1.2 kg ha^{-1} y^{-1}), and the specific articulation of NBP1 in Mårtensson et al. (2023) with increased cropland for locally produced protein-rich crops led to the highest P- export in this scenario (Fig. 3). These contrasting responses suggest that the context-specificity of the modelled catchments should not be ignored. Current land use and agricultural policy measures in Norway and Denmark target on a reduction in nutrient export (Carstensen et al. 2023; Farkas et al., 2023). For Norway, high P exports are usually associated with high suspended sediment exports (Wenng et al., 2021b), as these have been considered most problematic for the receiving waters. Both Carstensen (2023) and Rankinen (2023) compared nutrient loads with the water quality targets set by the European Water Framework Directive. Carstensen et al (2023) deployed an additional roll-out of wetlands on-top of their extensively 'green' NBP1-articulation to meet these requirements. Rankinen et al. (2023), however, suggest that the currently low nutrient export from the Simojoki catchment would not cause a violation of the current water quality targets, but still conclude that overall, the river ecosystem of the Simojoki would be best safeguarded under NBP1.

The scenario modelling of Simojoki, Skuterud and Odense Å included two RCPs. Overall, the effect of these geophysical warming scenarios was limited compared to that of the socio-economic NBPs (Table 1). An important reason for this is likely the time horizon of 2050. The full effect of warming will most likely be felt only towards the end of the century, as IPCC's assessment shows divergence among RCPs to increase markedly in the second half of the century (e.g. IPCC, 2014). Carstensen et al. (2023), Rankinen et al. (2023) and Farkas et al. (2023) found changes in flow seasonality coupled to the RCPs. This involved an earlier discharge peak due to earlier snow melt (Norway, Finland), or higher winter discharges (Denmark). The effects on annual nutrient and sediment exports, however, were limited compared to the effects due to differences in land use coupled to the societal NBPs.

The assessment of the effect of the NBPs on a suite of ecosystem services provided by Nordic catchments (Immerzeel et al., 2023) included nutrient retention as it contributes to a final service of good surface water quality for drinking water (cf. Immerzeel et al., 2021). Two of the six modelled catchments were also included in Immerzeel et al. (2023): Simojoki and Odense Å. Immerzeel quantified P export based on land use type and median export rates for cropland, grassland, forest and mires from the Nordic *meta*-analysis of De Wit et al. (2020, see above), hence changes in areas of land use type governed mean export rate estimates from the studied catchments. Thus, the variation in P export estimates among scenarios of Immerzeel et al. (2023) is due to changes in land use. Land use also varied considerably with NBP in the modelling studies (Carstensen et al., 2023; Rankinen et al, 2023; Bhattacharjee, 2022 and unpublished) but P export showed only limited variation. Odense Å may serve as an example: Carstensen et al. (2023) had a range among scenarios of 0.35–0.43 kg ha^{-1} y^{-1}, whereas Immerzeel et al. (2023) estimated 0.08–0.38 kg ha^{-1} y^{-1}, with a much stronger reduction in NBP1. It appears plausible that the geophysical models have a better grasp of the soil processes involved, although they may not be able to grasp all types of mitigation measures well.

In short, the most apparent similarity among these four modelling efforts is the limited effect of the RCPs toward 2050. The most striking contrast is the difference in responsiveness to the NBPs among the catchments: Odense had a range of 68% among scenarios for N and Skuterud of 56% for P, whereas Simojoki had maximally 7% for P and the Swedish C6 17% for P. Then NBP1, the scenario that was designed to

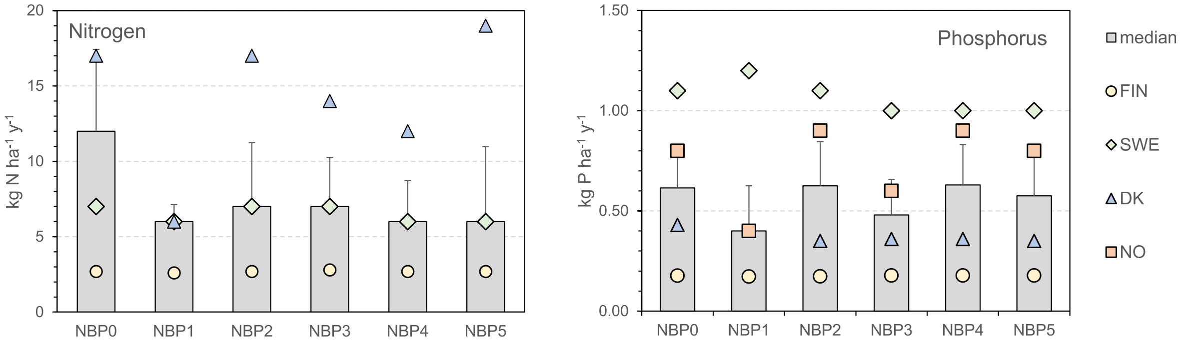

Fig. 3. Effect of modelled NBP scenarios on estimated nutrient export rates from four intensively studied Nordic catchments: Simojoki (FIN), catchment C6 (SWE), Odense Å (DK) and Skuterud (NO). Presented are medians plus 1 standard error. Data courtesy Mette Vodder-Carstensen, Katri Rankinen, Joy Bhattacharjee, Kristina Mårtensson and Csilla Farkas.

be most green and circular in its attributes, was lowest or amongst the lowest in its N export for all catchments, but not for P in Sweden and Denmark despite a generally high P export in these catchments. This is most likely due to a slow response of the soil P pools in these low-slope catchments with a comparatively high P sorption capacity (e.g. Ige et al., 2007). For the Swedish case (Mårtensson et al., 2023), a second reason may be the field- and crop-scale interpretation of the NBPs. Finally, if Nordic societies develop along the lines of the less precautionary or 'green' scenarios, such as NBP 3 or NBP4, then particularly N-loads from the Odense Å catchment and sediment and thus P-loads from Skuterud to the receiving waters would be high and will likely not meet the environmental targets set by the European Water Framework Directive already for 2027, a time horizon much earlier than the modelled 2050 (e.g. Carvalho et al., 2019).

5. Comparing empirical trends with modelling outcomes

First, it should be kept in mind that all modelling efforts involved calibration and verification against historical empirical data. Hence, they have been compared with empirical data and their trends for these specific target catchments. Second, an important conclusion we have already drawn above is that the modelled catchments fall well within the middle quartiles of the large dataset compiled by De Wit et al. (2020). Third, in two of the four modelled catchments a marked shift in land use practice towards circularity as modelled in NBP1 indeed would suggest that a further reduction in nutrient export is possible (Table 1). Immerzeel et al. (2023) suggest that this shift according to NBP1 may not have to occur at the expense of the total suite of societal benefits, which is only determined partially by the revenues gained from forestry and agriculture, but much more from cultural services, notably recreation, and regulating services such as flood prevention and carbon sequestration. Remarkably, Immerzeel et al. (2023) also showed that local landowners would only loose little benefit in NBP1 compared to the current situation of NBP0.

In concordance with the empirical observations compiled for 2010–2018 by De Wit et al. (2020) that land use rather than climate change controlled nutrient export, the modelled effect of the geophysical RCPs was comparatively limited towards 2050 (Bhattacharjee, 2022; Carstensen et al., Farkas et al., Rankinen et al., 2023). However, we must also be aware of the fact that already now landowners in agriculture and forestry adjust their practices to what these actors perceive as climate change, also following advice of agricultural extension services on for example cover crops (Wenng et al., 2020) or by planting drought-resistant tree varieties (e.g. Schueler et al., 2021).

6. Caution: Limitations and remaining knowledge gaps

We discuss here, respectively, the consequence of the adoption of the family of SSP scenarios, our iterative dialogue with stakeholder representatives to further articulate these scenarios, the parallel workflow within the BIOWATER project, the absence of any interaction between climate change and land use in our modelling approaches, and our limitation to classical water quality parameters as main indicators of effect.

The adaptation of benchmark SSPs appears well justified, but it also allowed us to remain unspecific about what a developing bio-economy might mean. A distinct choice for a single trajectory would likely have allowed for a more quantitative description and led to clearer modelling outcomes. This can be considered a limitation of our studies. A further issue is the iterative design of the NBP scenarios in dialogue with stakeholder representatives (cf. Lyche Solheim et al., 2023). This approach is advocated in the literature (e.g. Kok et al., 2006; Mitter et al., 2019), but it does necessarily lead to contrasting interpretations of the more general narratives, both within local stakeholder panels and among countries. Thirdly, the project's life span and the logistical needs for the different exercises dictated that the geophysical modelling and ecosystem services assessment were carried out in parallel and quite independently. Estimations of cultural service values in specific catchments by means of surveys had to be carried out in the field where and when sufficient respondents were present (Immerzeel et al., 2022), whereas catchment modelers necessarily require well-monitored catchments. A closer coordination of these two exercises would likely have been beneficial for matched cross-comparisons. Fourthly, geophysical climate change and land use cover as well as exploitation practices interact continuously. As for example Wenng et al. (2020) demonstrate, climate adaptation is an on-going process, also in Nordic countries. Such a dynamic interaction is difficult to incorporate in an input matrix of NBPs and RCPs. The ecosystem services assessment, in contrast, could not include dynamic change at all, obviously, here only a one-step projection from current to 2050 was feasible. Finally, our modelling focus for water quality and quantity has been on 'classical' nutrients and suspended solids, whereas other aspects of the catchment and its drainage system may have been equally important to the multiple dimensions of stream water quality, such as the presence of wooded riparian buffer strips (Tolkkinen et al., 2021; Vermaat et al., 2021), artificial interruptions of the drainage network (e.g. Carstensen et al., 2020) or regulation of discharge for hydropower generation (e.g. Grizetti et al., 2017; Ashraf et al., 2018).

7. No-regret plausible projections for policy

First, from the ecosystem services assessment it appears that a 'green' trajectory corresponding to NBP1 would not necessarily lead to major income declines among local land-owners, whereas it would lead to a summed Total Economic Value that is similar to that of the highly growth-oriented NBP5. Importantly, this NBP1 would enhance the value generated by recreation of local residents as well as tourists, aspects not necessarily included extensively in (local) spatial planning. As

Immerzeel et al. (2021, 2022) show, such recreation benefits are closely related to the presence of rivers and lakes, and the esthetic landscape quality as well as water quality are both appreciated highly by the respondents.

With other words, a policy focus on safe-guarding natural river corridors could be effective and should be considered alongside measures to reduce nutrient losses from agricultural fields, certainly in Nordic catchments where agriculture is comparatively extensive. This appears in correspondence with the importance of natural floodplains next to nitrogen loading in affecting water quality in the overall Europe-wide assessment by Grizetti et al. (2017). In addition, 'dynamic' and functional floodplains (Olde Venterink et al., 2003; Gilvear et al., 2013) will serve in flood risk reduction, may lead to increased carbon sequestration and will most likely serve as network conduits that enhance biodiversity conservation (e.g. Jansson et al., 2007; Sethi et al., 2017; Vermaat et al., 2021). The increasing risk of high-damage floods (e.g. Dottori et al., 2018) suggests that a clear longer-term 'no regret' advice to policy is the safe-guarding or restoration of floodplains and natural flow regimes of rivers. Furthermore, it may well be wise to do so already along the lower order streams higher up in the catchment, as it is these that together accumulate most of the diffuse nutrient load as well as the flow that's builds up to cause flooding in the lower reaches.

8. Conclusions

We now attempt to phrase overall answers to the main questions phrased in our introduction and return to the three that were not answered yet.

- To which extent will the need for biomass change the proportion of forests, agricultural land and more marginal lands? We conclude that this will depend on the trajectory along which Nordic societies develop towards 2050 whether the proportional distribution of land will change greatly. In the green NBP1 scenario shifts in land use type were often the most pronounced (Immerzeel et al., 2023; Carstensen et al., 2023; Rankinen et al. 2023).
- How much intensification will we see in agriculture and forestry? We show that this will depend on the scenario, but also on the local interpretation of it. Lyche Solheim et al. (2023) reflect on the importance of local context and local interpretation. Particularly a societal trajectory with limited environmental awareness, similar to NBP3 or NBP5, will likely involve increased intensification in both sectors.
- How will these changes then interfere with WFD goals and biodiversity conservation policy objectives?' It is likely that increased intensity of land use, notably in NBP 3 and NBP5, will have impacts on hydrology, water quality and stream biodiversity. Therefore, particularly along the lines of these two latter scenarios the WFD goals will be difficult to achieve.

In conclusion, we would like to reiterate that our NBP scenarios are only projections, attempts to sketch a set of contrasting, but internally consistent trajectories of global to local societal change. They are never intended to be predictions – and thus will not grasp current or future political crises, even though it is tempting to see realistic real-world analogies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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