

# Ecosystem services in the Swedish water-energy-food-land-climate nexus: Anthropogenic pressures and physical interactions



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## ABSTRACT

Traditionally, challenges of natural resource management have been addressed with a sectoral policy approach. However, it is increasingly recognised that different sectors are interconnected in a complex and mutually interacting system. A nexus approach is proposed to identify synergies and trade-offs between sectors and to foster the sustainable and efficient use of resources, particularly in light of climate change. The nexus approach has led to studies identifying interactions between policy objectives across nexus sectors, but the physical interactions between nexus sectors that can be the result of policy interactions, have received less attention. Nevertheless, such interactions can have severe consequences for the environment, affecting ecosystems and the services they provide. Integrating the nexus approach and the ecosystem service concept may help to better understand pressures and impacts related to a resource nexus and to address trade-offs. In this study, literature and expert assessment are used to analyse the water-energy-food-land-climate nexus in Sweden through the lens of the ecosystem services concept to gain insights into interactions between the nexus sectors. By demonstrating how anthropogenic pressures originating from the nexus sectors affect ecosystem functions and services, this paper serves as a foundation to further inform policy making (within and outside Sweden) when considering the water-energy-food-land-climate nexus.

## 1. Introduction

Global change is a growing problem, governed by demographic, economic and climatological drivers. Such developments are leading to an increasing demand for natural resources, putting increasing stress on ecosystems (Nelson et al., 2006; IPBES, 2019). The water, energy, and food sectors help fulfil many of society's demand for products and services. They are increasingly recognised as being interconnected in a complex and mutually interacting system. Traditionally, challenges regarding natural resource management have often been addressed with a sectoral policy approach (siloes), in which impacts on one sector as a result of policy or resource changes in another were largely overlooked. This approach often failed and there is growing evidence that there are complex interlinkages between the water, energy, and food sectors that should be considered in decision-making processes (FAO, 2014; WEF, 2016; Al-Saidi and Elagib, 2017). A novel way to address this complexity is the 'nexus approach', which attempts to identify

synergies and trade-offs between sectors (Albrecht et al., 2018). Such an approach fosters sustainable and efficient use of resources that is needed to deal with challenges related to climate change, global development and resource scarcity (Hoff, 2011). Several adaptations of the water-energy-food nexus have been discussed in the literature: two-sector nexus models ('water-food' or 'water-energy') have been presented (Ringler et al., 2013; Endo et al., 2017) and the nexus has been expanded to incorporate the effects of climate (change) and/or land use as well (e.g. Laspidou et al., 2018; Sušnik, 2018; Sušnik et al., 2018). The climate (C) and land (L) sectors are more crosscutting and less straightforward than the traditional water-energy-food (WEF) sectors, since their policies are to some extent integrated into those of the other sectors. However, including climate and land use in the nexus analysis as separate sectors allows for a better understanding of the large potential influence of these sectors on water, energy and food.

The multi-sectoral nexus approach adopted in this study is defined as "a systematic process of scientific investigation and design of

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coherent policy goals and instruments that focuses on synergies, conflicts and related trade-offs emerging in the interactions between water, land, energy, food and climate at bio-physical, socio-economic, and governance level” (Munaretto and Witmer, 2017). The novelty of this approach lies in its ability to offer opportunities to consider holistic policy integration and the nexus-wide impacts of adopted policies, thereby highlighting potentially important feedbacks and connections. This approach separates itself from other multi-sectoral approaches, including ecosystem service analysis, by providing a structure for interdisciplinary knowledge generation and cross-sectoral governance, while giving equal weight to all sectors involved (Munaretto and Witmer, 2017). A unique quality of the nexus approach is that it helps identify interactions between policy goals across nexus sectors, which occur when policy introduced in one sector inhibits or promotes goal achievement in another sector (Nilsson et al., 2012). Therefore, the nexus approach not only assesses pressures on ecosystems from a wide number of sources, but also considers how policy can be reformulated to best address these pressures in the most coherent and efficient way possible, providing multiple benefits across sectors while minimising detrimental (policy-related) ecosystem impacts. It is through this extension to traditional ecosystem service analysis that this approach adds most value.

The physical interactions between nexus sectors resulting from policy interactions typically receive little attention (Bekchanov et al., 2015), but such interactions can have significant consequences for the environment, affecting ecosystems and the services they provide (Karabulut et al., 2018). Ecosystem services have a major influence on human well-being and are crucial in the implementation of the Sustainable Development Goals (Constanza et al., 2016; Wood et al., 2018). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) states that both the global environmental and societal goals can be met through cross-sectoral cooperation and planning (IPBES, 2019). The integration of the nexus approach and the ecosystem service concept may aid this process, as it can increase our understanding of specific pressures and impacts related to each nexus sector (Bell et al., 2016). Some scholars even argue that ecosystems and their services should have a separate domain in the nexus (Hülsmann et al., 2019; Karabulut et al., 2015). Through socio-demographic changes, the demand for provisioning ecosystem services has risen, leading to the intensification of anthropogenic pressures on ecosystem structures, processes, functions and consequently on services (Rounsevell et al., 2010). The water, energy, food, land, and climate sectors are responsible for driving these pressures, but cross-sectoral effects on the physical environment are poorly understood (Liu et al., 2017). Moreover, the potential feedback of changes to ecosystem services and their interactions in the nexus require further analyses.

While society’s attention and appreciation for regulating and cultural ecosystem services are increasing (Castro et al., 2014; Lamothe et al., 2019), industries often favour provisioning services such as food, drinking water, raw materials, and energy products over other services whose benefit to human society is not always immediately visible, especially in agricultural settings (Deng et al., 2016). This prioritization has potentially far-reaching consequences, since ecosystem services are known to interact with one another, i.e. the delivery of one service can affect the provision of other services (Bennet et al., 2009). These effects can be either positive (synergy) or negative (trade-off). Ecosystem service trade-offs commonly impact regulating ecosystem services, especially water-related ones (Turkelboom et al., 2018). These services play a central role in the provision of other ecosystem services (e.g. maintaining water quality which in turn increases recreational value), suggesting that problems might arise if trade-offs are not addressed (Carpenter et al., 2009). Positive interactions, or synergies, between ecosystem services can be achieved by turning trade-offs into opportunities through appropriate ecosystem management (Maes et al., 2012). Adequate understanding of the trade-offs, their causes and their impacts is helpful to make this transformation (Howe et al., 2014), and

may benefit from a nexus approach. This is even more important in a changing climate, which poses an additional challenge as it is driven largely by emissions from human activities and simultaneously affects the actions in all nexus sectors.

Sweden is known for its progressive and ambitious approach towards tackling climate change, represented in the current climate and energy plan, which aims at a 63% decrease in greenhouse gas (GHG) emissions by 2030 (compared to 1990), and reaching zero net emissions by 2045 (GOS, 2018). Sweden is also recognised as a leading country in environmental policy formulation (Juhola et al., 2011). Nonetheless, Sweden is facing environmental problems, such as decreases in water quality, biodiversity decline and more frequent extreme weather events (OECD, 2014). In 2012, ecosystem services and biodiversity were incorporated into Sweden’s environmental quality objectives as some of the important considerations to improve decision making with regard to natural resources (SEPA, 2012a). However, the ecosystem service concept has still not been fully integrated into practical decision making (Beery et al., 2016; Blicharska and Hilding-Rydevik, 2018). The importance of ‘interdisciplinary and cross-sector knowledge’ in Swedish ecosystem service research and policy has been acknowledged (SGI, 2013), but cross-sectoral interactions and their causes and consequences are largely unknown. To gain insight into these interactions, this study focuses on the anthropogenic pressures and the physical interactions between the water-energy-food-land-climate nexus sectors in Sweden, through an ecosystem service lens and using the nexus approach to assess the interactions. By demonstrating how different elements of the ecosystem service cascade (De Groot et al., 2010) are affected by anthropogenic pressures originating from activities in the nexus sectors, this paper serves as a foundation to further inform policy making (within and outside Sweden) when considering impacts throughout the water-energy-food-land-climate nexus.

## 2. Methods

### 2.1. The five nexus sectors: water, energy, food, land and climate

The water-energy-food-land-climate nexus (hereafter ‘the nexus’) formed the starting point of this study (Fig. 1). The nexus consists of five interconnected domains that each represent either a natural phenomenon and its physical properties (water, land and climate) or a socio-economic construct (energy, food) (Lapidou et al., 2017). Human activities related to these domains are organized into sectors, which are the main focus of this study, and are defined in the context of this study as “distinct parts or divisions of a regional, national, continental or global economy” (SIM4NEXUS, 2018).

The **water sector** is concerned with regulating water quantity and maintaining water quality, allowing people to use the water as a resource for e.g. drinking water, irrigation or energy generation. The **energy sector** deals with the generation and consumption of energy

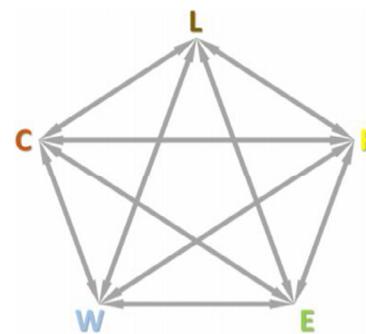


Fig. 1. Simplified representation of the interconnections between the nexus domains (Lapidou et al., 2017). Clockwise, starting from the top: L = land; F = food; E = energy; W = water; C = climate.

from different sources. The challenge is to develop sustainable, renewable alternatives to the burning of fossil fuels (e.g. wind/solar power, hydropower, bioenergy from biomass). The **food sector** strives to provide society with sufficient food of sufficient nutritional quality, using arable and grazing land for crop and livestock production. Energy and food products can either be produced within the land (forestry and agriculture) or water (hydropower and fishing) domain. The **land sector** is regarded as a policy area that influences all other sectors. Land use policy determines where, how and how much land can be used for specific purposes and is strongly influenced by climatological processes that enable or disable certain land use types (Dale et al., 2011). The effect of the land sector on ecosystem services is mostly indirect through policy measures implemented in other sectors (e.g. agricultural land use policy in the food sector). The **climate sector** is responsible for policy that deals with two main issues: mitigation of climate change (i.e., decreasing greenhouse gas emissions) and adaptation to climate change effects (i.e., dealing with consequences of a changing climate). As the climate is omnipresent and drives environmental conditions that affect land and water resources, this type of policy influences the human activities and decisions in the other four sectors.

## 2.2. Study area

This study focuses on Sweden, a country characterised by countless lakes and streams, significant forest cover, and relatively low emissions from energy production as compared to most other countries (IEA, 2013; Fig. 2). Although historically a region abound with water, Sweden faces several challenges regarding water quantity and quality. In particular, drinking water supply has been threatened during drought periods on several occasions in recent years (SAMWM, 2018).

With a share of 26% of the total amount of TWh produced, biofuels are the second most used source for energy production after nuclear power (30%) and they are the largest renewable energy source in Sweden (SEA, 2017). Sweden's extensive river network provides

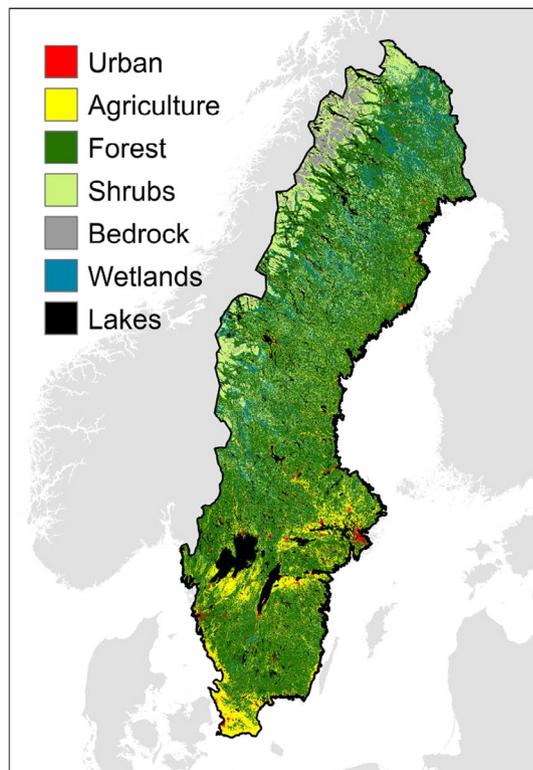


Fig. 2. Land cover classes in Sweden according to the CORINE Land Cover CLC2006 dataset (Büttner, 2014).

hydropower, which generated 14% of Sweden's total energy in 2017 (SEA, 2017). As the nexus approach was developed as a tool to facilitate the sustainable integrated management of resources, this Swedish case study includes renewable energy resources (biomass and hydropower) only.

Sweden's primary food production takes place on approximately 63,000 farms, with an average farm size of 0.41 km<sup>2</sup> (SBA, 2017). About 18% of the farmed land is used for organic production, giving Sweden the second largest share of organic farm land within the EU member states (SBA, 2017). A national food strategy aligns the food sector with environmental objectives and promotes the efficient use of resources (GOS, 2017).

Land cover (Fig. 2) revolves around two main industries, namely forestry and agriculture. Approximately 69% of the 410,000 km<sup>2</sup> of the Swedish surface area consists of forests, 8% is agricultural land (arable and grazing) and 3% is built-up (Statistics Sweden, 2019). The remaining 20% consists of heathland and herb meadows, open mires and bare rock (Statistics Sweden, 2019). National laws and regulations guide land allocation and land use practices, but actual land use planning is done by municipalities on a local level.

Since 2018, the national Climate Act aims to achieve zero net carbon emissions by 2045. The government is obliged to develop comprehensive climate policy, which is reviewed by an independent council (SCPC, 2018). Sweden's efforts to reduce greenhouse gas emissions are strongly connected to the energy sector, but climate adaptation strategies are being made throughout all nexus sectors.

## 2.3. Ecosystem service approach

Physical interactions between nexus sectors were studied through the lens of the ecosystem services concept. Ecosystem services are defined as 'the contributions that ecosystems make to human well-being' (TEEB, 2010) and are divided into three main categories according to the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2018): (1) provisioning, (2) regulation and maintenance (referred to as 'regulating services'), and (3) cultural services. They originate from a diverse set of ecosystem structures, processes and functions (De Groot et al., 2010). The basis of this ecosystem service approach was the ecosystem service cascade (e.g. De Groot et al., 2010) which is used to analyse how biophysical structures and processes harbour ecosystem functions that support ecosystem service provision, thereby contributing to human well-being. The study focused on the anthropogenic influences originating from the nexus sectors and their effects on elements of the ecosystem service cascade, which were studied in a five-step procedure (Fig. 3) further explained below.

The role of biodiversity in ecosystem service provision is still under debate. Constanza et al. (2017) treat biodiversity as an ecosystem function, like primary production and biogeochemical cycling. In contrast, Bennett et al. (2015) state that biodiversity is an important factor that supports ecosystem functions. In this study, biodiversity is regarded as an essential element that shapes ecosystems and their functions and functional traits (Díaz et al., 2006), but it is not included as an ecosystem service or function, which is in accordance with the Common International Classification of Ecosystem Services, CICES, v5.1 (Haines-Young and Potschin, 2018).

### 2.3.1. Step I: identification of anthropogenic pressures

The first step was to identify the anthropogenic influences originating from the five nexus sectors. This identification was based on Swedish governmental and research reports reviewing ecosystem services in general (SEPA, 2012b), in the water sector (SAMWM, 2017) and in the land sector (SFA, 2017; TRIS, 2016), as well as on expert judgement of the authors. Relevant scientific literature about ecosystem services in Sweden was consulted to fill gaps. Information on climate change effects was obtained from all the listed documents.

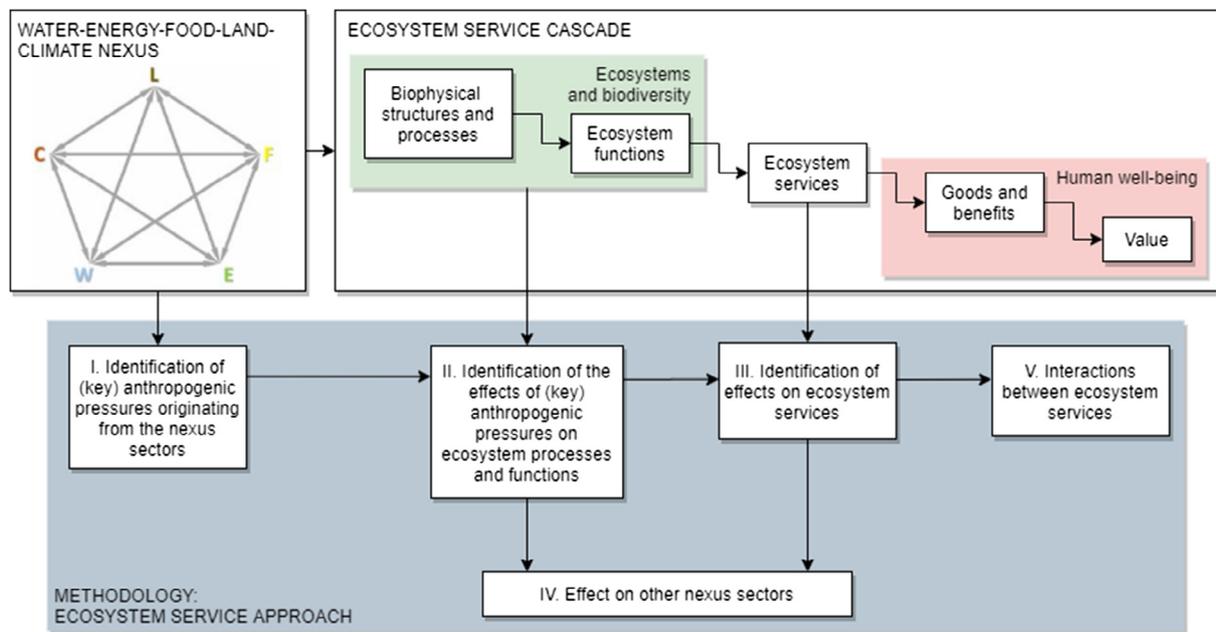


Fig. 3. Schematic overview of the ecosystem service approach methodology (grey block) used in this study, and its relations to the two core elements of the study: the water (W)-energy (E)-food (F)-land (L)-climate (C) nexus (Laspidou et al., 2017) and the ecosystem service cascade (based on De Groot et al., 2010).

Anthropogenic influences can have positive and negative effects on the environment. Generally, negative effects are ascribed to industries and consumption, but there are also positive effects in the form of conservation and restoration measures, which are being taken by governments and industries. An example is the use of retention forestry methods as a way to minimise negative effects of harvesting for forestry products (Fedrowitz et al., 2014). Such measures often aim at ecosystems that have been disturbed by human interventions (e.g. traditional harvesting regimes) and their main objective is usually to conserve or restore biodiversity, while indirectly contributing to ecosystem service provision. However, this study focusses on negative anthropogenic influences, i.e. pressures, because of their potential negative consequences to ecosystem service provision and thus to human well-being.

### 2.3.2. Step II: effects on ecosystem processes and functions

The capacity of ecosystems to deliver ecosystem services is determined by the processes and functions within them (Haines-Young and Potschin, 2018). In the second step, the impacts of the anthropogenic pressures found in step I on ecosystem processes and functions linked to the five nexus sectors were identified. The Swedish Environmental Protection Agency identified six main ecosystem processes and functions in Swedish ecosystems (SEPA, 2012b), following the latest CICES classification (v5.1, Haines-Young and Potschin, 2018):

- (1) primary production (i.e., production of chemical energy and synthesis of organic compounds by plants, algae and bacteria)
- (2) biogeochemical cycling (i.e., the contribution to maintain nutrient and water cycles)
- (3) soil formation/fertility (i.e., weathering, deposition and biogeochemical processes within soils)
- (4) habitat provision (i.e., supply of food, shelter and protection for a species)
- (5) stability and resilience (linked to provision of high biodiversity)
- (6) ecological interactions (i.e., maintaining food-webs)

Given that the last item was not addressed in any of the other Swedish reports analysed, we excluded 'ecological interactions' from further analysis.

The anthropogenic pressures from each sector and the affected

ecosystem processes and functions were gathered into a database (Appendix A). The pressures originating from land- or water-based energy and food production were listed under the land and water sector, respectively, since they are the result of allocation decisions in the land and water sector. For simplification purposes, the *individual pressures* were gathered in *pressure groups* if they contributed to the same overarching goal (e.g. 'drainage' and 'irrigation' were grouped under 'water regulation', as they both aim to regulate water quantity). To highlight pressures with the largest impact on ecosystem functions, key pressures, i.e. pressure groups that simultaneously affected three or more ecosystem functions, were additionally identified.

### 2.3.3. Step III: effects on ecosystem services

The third step of the study focused on ecosystem services in the nexus. The effects of the anthropogenic pressures on ecosystem services, either directly or via effects on ecosystem functions, were assessed. This was done using our expert judgement, and based on the information derived from the above-mentioned Swedish reports on ecosystem services. The results were documented into a database (Appendix B). This database followed the same structure as Appendix A, meaning that effects from the energy and food production were listed under the land and water sectors. Ecosystem service classification was based on CICES v5.1 (Haines-Young and Potschin, 2018). The effects of anthropogenic pressures on ecosystem functions (Appendix A) were accounted for in this database to demonstrate the relationships between functions and services.

### 2.3.4. Step IV: effects on other nexus sectors

In some cases, the Swedish reports mentioned that pressures originating from one sector affected other nexus sectors through their effects on ecosystem functions and services. Such cases were documented in the databases (Appendix A and B). The assessment was based on the question "Is this pressure directly affecting components of another nexus sector?" This was interpreted either as a direct effect on the physical water, land or climatic conditions or as a direct effect on the energy and food production processes.

### 2.3.5. Step V: ecosystem service interactions

The Swedish reports discussed several synergies and trade-offs

between different ecosystem services, meaning that the provision of one service was deemed to be related to the provision of another. These interactions were regarded as indirect effects that the different anthropogenic pressures have on ecosystem services, thus they were added to the database (Appendix B). While we acknowledge that this step is unable to capture the full complexity of ecosystem service interactions in Sweden, as it derives from a limited number of available reports, we believe that it provides a first step towards a better understanding of these interactions.

### 3. Results

The identified anthropogenic pressures from the nexus sectors and their effects on ecosystem processes and functions (steps I and II) are discussed in Section 3.1. The effects of these pressures on ecosystem services (step III) and on the other sectors (step IV) are discussed in Section 3.2. The interactions between ecosystem services (step V) are discussed in Section 3.3.

#### 3.1. Anthropogenic pressures on ecosystem processes and functions

In the first step, 66 pressures originating from the water, energy, food, land and climate sectors were found to affect the five main ecosystem processes and functions (i.e., primary production, biogeochemical cycling, soil formation/fertility, habitat provision and stability/resilience). Results indicate that the energy and food sectors were responsible for most of these pressures (52), and that there was a clear distinction between land-based production (mainly forestry and agriculture) and water-based production (mainly hydropower generation and fishing).

In the second step, the individual pressures were categorised into 17 pressure groups, each containing from one to seven pressures (Table 1;

Fig. 4). Nine of the pressure groups affected three or more different key ecosystem functions and were thus labelled ‘key pressure groups’ (Table 1). ‘Construction of dams for hydropower’ affected only ‘biogeochemical cycling’ and ‘habitat’, but because of the large scale of hydropower production in Sweden and the attention it received in the reviewed reports it was also regarded as a key pressure group. Pressures related to acid rain and its effect on water quality were discussed in Swedish reports, but were not explicitly accounted for because the biggest sources causing acid rain are fossil fuel-burning energy production, industry, and transport, none of which are considered in the Swedish nexus.

In general, the ecosystem function that was reported to be impacted by the largest amount of pressures (30, coming from all sectors) was ‘Biogeochemical cycling’ (Fig. 4). For example, nutrient dynamics are disturbed as a consequence of biomass removal, which removes nutrients from the environment. Especially the northern half of Sweden suffers from nutrient depletion through whole-tree harvesting, which cannot be restored by atmospheric deposition (Akselsson et al., 2007).

Two anthropogenic pressure groups affected all five considered ecosystem functions: ‘withdrawal of biomass’ and ‘species selection’, both originating from land-based energy and food production. Swedish reports mentioned seven individual pressures under ‘withdrawal of biomass’ that mainly originate from the felling of trees and harvest of agricultural crops. The six individual pressures in the group of ‘species selection’ were caused by the introduction of foreign species and the use of monocultures.

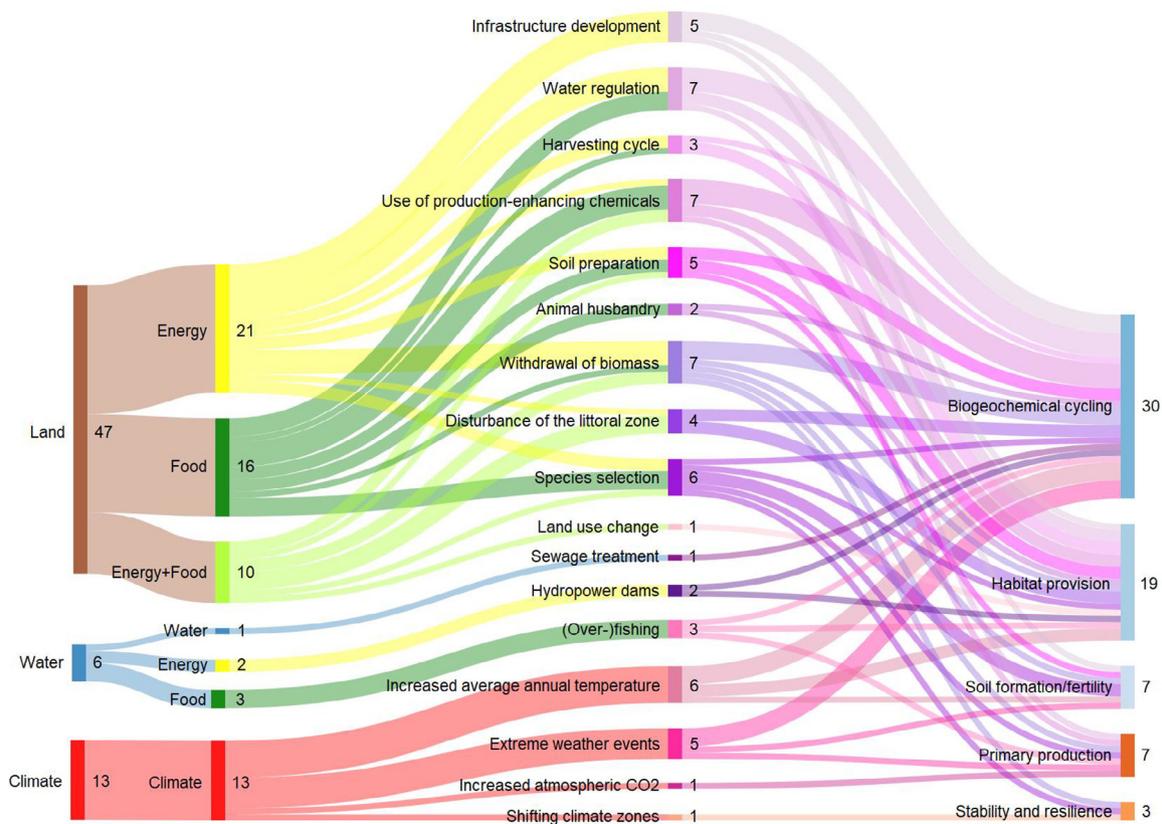
The largest anthropogenic pressure group originating from water-based production was (over-) fishing (food sector), which was reported to affect three strongly connected ecosystem functions. Nutrient dynamics between trophic levels are altered by fishing that targets specific species (groups), which can lead to changes in biogeochemical cycling and primary production (Chislock et al., 2013). Changes in species

**Table 1**

Groups of anthropogenic pressures identified in the study. Key anthropogenic pressure groups in **bold**.

Origin (sector)	Sectors	Groups of anthropogenic pressures	Biophysical processes affected	Ecosystem functions affected
Land-based production (Land)	Energy, Food	Disturbance of the littoral zone	Habitat availability/diversity	Biogeochemical cycling
		Forest regeneration	Mediation of hazardous substances	Habitat
		Land use change	Nutrient cycling	Primary production
		<b>Soil preparation</b>	Physical soil condition	Soil fertility
		<b>Species selection</b>	Physical water condition	Stability and resilience
		<b>Use of production enhancing chemicals</b>	Photosynthesis	
		<b>Water regulation</b>	Species composition	
		<b>Withdrawal of biomass</b>	Water cycling	
	Energy	<b>Infrastructure development</b>	Mediation of hazardous substances	Biogeochemical cycling
			Nutrient cycling	Habitat
			Physical soil condition	Soil fertility
			Physical water condition	
			Water cycling	
	Food	Animal husbandry	Habitat availability/diversity	Biogeochemical cycling
			Nutrient cycling	Habitat
Water-based production (Water)	Water	Sewage treatment	Mediation of hazardous substances	Biogeochemical cycling
	Food	<b>(Over-)Fishing</b>	Nutrient cycling	Biogeochemical cycling
			Photosynthesis	Habitat
			Species composition	Primary production
		Water cycling		
	Energy	<b>Construction of hydropower dams</b>	Mediation of hazardous substances	Biogeochemical cycling
			Nutrient cycling	Habitat
			Physical water condition	
			Water cycling	
Climate change effects (Climate)	Climate	<b>Extreme weather events</b>	Mediation of hazardous substances	Biogeochemical cycling
		<b>Increasing annual temperature</b>	Nutrient cycling	Habitat
		Increasing atmospheric greenhouse gas concentration	Physical soil condition	Primary production
		Shifting climate zones	Photosynthesis	Soil fertility
			Species composition	Stability and resilience
		Water cycling		

Note: Contents of this table are ordered alphabetically. We acknowledge that there are many connections between the anthropogenic influences, biophysical processes, and ecosystem functions, as described in Section 3.1.



**Fig. 4.** Schematic overview showing the pathways through which the 17 pressure groups (tallest centre column) originating from the nexus sectors (second column from left) affect ecosystem functions (right-most column). The nexus sectors of water, food and energy have been grouped into land-based production, and water-based production (left-most column). Numbers indicate the number of individual pressures coming from a particular sector. For simplicity, processes contributing to particular functions (see Table 1), are not included. Note however that one function can be derived from different processes. The pathways indicate the extraordinary complexity of the nexus. Figure was created using an open source tool on sankeymatic.com.

composition and chemical conditions alter aquatic habitat characteristics (e.g. light and nutrient availability).

These examples illustrate that there are many interactions between and among the different processes and functions, and that particular processes may contribute to various functions. For example, the process of ‘water cycling’ contributes to the ecosystem function ‘biogeochemical cycling’, but can also contribute to the ‘habitat provision’ function when water cycling physically shapes the environment. Functions such as ‘soil fertility’ and ‘primary production’ are highly dependent on the amount of nutrients in the soil/water, meaning they are closely connected to biogeochemical cycles. In the case of eutrophication, primary production increases the turbidity of the water, thus altering habitat conditions (e.g. low/absent oxygen levels, low light availability).

The climate sector was reported to affect ecosystem processes and functions via 13 individual pressures related to climate change, divided in four pressures groups (Fig. 4). Climate change effects are different from the other pressure groups because climate change is a globally created issue. Increasing average annual temperature and more frequent extreme weather events (e.g. heavy rainfall, drought periods) counted as key pressure groups. The nutrient and (global) water cycles were affected by most of the individual pressures from each group, causing alterations to the biogeochemical cycling function of ecosystems. Teutschbein et al. (2017) demonstrated that the most important consequences of a changing climate manifest themselves in a longer growing season (+5–7 weeks) and more freshwater (+13%) flowing into the Baltic Sea, especially during winter. Both of these shifts directly influence the total amount and the seasonal patterns of biogeochemical elements (e.g., carbon, phosphorus or nitrogen) being exported from Sweden into the Baltic Sea (Teutschbein et al., 2017). Increased precipitation is connected to higher nitrogen and phosphorus loadings in

lake catchments around Stockholm (Wu and Malmström, 2015).

### 3.2. Ecosystem services in the nexus context

Section 3.2.1 discusses the effects of the land-based food and energy production on ecosystem services and the other nexus sectors that were revealed during the study (Appendix C, Fig. C.1). Section 3.2.2 discusses the effects originating from the water-based food and energy production (Appendix C, Fig. C.2). Results regarding the climate sector are presented in Section 3.2.3.

#### 3.2.1. Land-based energy and food

The prioritization of provisioning ecosystem services (such as energy and food products) over the other services, driven by a growing societal demand, has led to the intensification of forestry and agriculture, resulting in increasing pressures of land-based energy and food production on ecosystem functions and services (e.g. Björklund et al., 1999; Pohjannies et al., 2017). The Swedish reports discussed 85 anthropogenic pressures on ecosystem services originating from land-based energy and food production, which included 38 direct pressures and 47 indirect pressures (affecting ecosystem services via an effect on ecosystem functions).

All key ecosystem functions were reported to be affected by pressures coming from land-based food and energy production. Apart from the effects of biomass withdrawal and species selection discussed in Section 3.1, problems were also found relating to the physical and chemical properties of the soil as a consequence of ground packing (infrastructure development), fertilization (use of production-enhancing chemicals) and drainage (water regulation), among others. These anthropogenic pressures affect biogeochemical cycles and primary

production processes through artificial additions to or extractions from the system. Moreover, they affect soil fertility and habitat provision by altering the physical condition of the soil and the species that live in/on it. Stability and resilience suffer most from low-diversity species composition (e.g. monocultures).

A direct effect of an anthropogenic pressure on an ecosystem service is the effect of biomass withdrawal and soil preparation on the regulating service of erosion control. Both pressures affect underground root structures that are important for soil retention. If roots are broken and their joining ability is compromised, the soil will become more vulnerable to erosion (SEPA, 2012b; SFA, 2017). However, most of the effects on ecosystem services were indirect, caused by the anthropogenic pressures' effects on ecosystem functions. For example, air quality regulation strongly depends on biogeochemical cycling and primary production, and outdoor recreation opportunities rely on physical habitat features and species composition. The arrow representing this relationship is double pointed (Appendix C, Fig. C.1), since Swedish reports also discussed some effects of affected ecosystem services on ecosystem functions. For example, the Swedish Forest Agency (SFA, 2017) reported that a loss of erosion control capacity (service) can cause problems with water and nutrient cycles in the soil (function).

Out of 85 reported individual anthropogenic pressures from land-based food and energy production on ecosystem functions and services, 25 affected water conditions. Most of these pressures acted on water and nutrient cycling abilities, affecting water quality and quantity through the function of biogeochemical cycling (15 pressures). Erosion control and flow regulation were the water-related regulating services affected by the largest amount of pressures (two pressures each). The climate was affected by 13 anthropogenic pressures, most of which were related to the uptake of CO<sub>2</sub> by plants, resulting in effects on primary production and biogeochemical cycling (both four pressures). The regulating service affected by the largest amount of pressures (three pressures) was the regulation of air quality, which is strongly related to the primary production function.

The water and climate sectors, through their activities and policies respectively, determine the physical properties of an ecosystem, shape its structures and processes, and thus affect the ecosystem's functions and regulating services. The provisioning services targeted with land-based food and energy production are dependent on many functions and services that are affected by changes in environmental conditions, caused by the anthropogenic pressures originating from the same production processes. In other words, the food and energy sectors have the potential to hamper their own production via a complex network of feedback interconnections, further demonstrating the complexity of the nexus.

### 3.2.2. Water-based energy and food, and water treatment

The Swedish reports addressed 10 anthropogenic pressures originating from water-based energy and food production, and drinking water production (supported by sewage treatment). Four pressures affected ecosystem services directly, whereas the other six pressures acted through the pressures' impacts on ecosystem functions. Two key pressure groups were identified: 'construction of hydropower dams' and '(over-) fishing'.

The removal of specific species (groups) from the ecosystem through fishing affects interactions between trophic levels, leading to changes in primary production, biogeochemical cycling and habitat. Most problems arise when piscivorous fish are targeted, because then planktivorous fish numbers tend to increase. These fish mostly feed on zooplankton, thereby removing organisms that consume phytoplankton and thus regulate primary production (Eriksson et al., 2009; Chislock et al., 2013). With primary production increasing, the risk of toxic algal blooms and hypoxic conditions increases, which affects all aquatic organisms and the services they provide. Thus, the fishing industry (both commercial and recreational) has the potential to damage the natural

resource it relies on, (arrow from box II/III back to box I in Appendix C, Fig. C.2) in a way other than merely depleting fish stocks. The effect of hydropower dam construction lies in the physical barriers these dams form, which obstruct water flows, thereby affecting biogeochemical cycling and habitat. The largest problem is that migratory routes for aquatic organisms are blocked, leading to disturbance in migratory fish reproductive cycles. In Sweden, hydropower dams were found to be responsible for 20%–60% of the decline in silver eel, compared to the 20%–30% caused by fisheries (Dekker et al., 2018). Other, non-migratory, species can also be affected by poorer habitat quality and lack of fish refuges that are caused by hydropower dams (Benejam et al., 2014).

Four regulating ecosystem services were reported to be affected by either the anthropogenic pressures or the change in ecosystem functions as a result of these pressures. Primary production was linked to the maintenance of water quality service, as photosynthesis transforms CO<sub>2</sub> into oxygen, influencing the chemical conditions of the water. Primary production can also be a threat to water quality when nutrient concentrations are high and increased primary production leads to eutrophication. The habitat function showed interactions with water flow regulation, as many organisms require a specific (or lack of) flow rate, substrate and stream width (Trigal and Degerman, 2015). Biogeochemical cycling was connected to both of the aforementioned services, and to the maintenance of air quality because they depend on the availability and cycling of water and nutrients. The effect on disease control originated from fish farms, which grow fish for food and restocking purposes in high densities. These were reported to potentially become sources of pathogens if treated inadequately (SAMWM, 2017).

Similarly to the feedbacks described at the end of Section 3.2.1, the sectors of land and climate shape ecosystem conditions through their policies, and they can be affected by changes in ecosystem functions and services caused by the anthropogenic pressures from the water sector in return. Out of 10 individual pressures coming from water-related human activities, none were reported to directly affect the land or climatic conditions. However, such effects were reported for several of the ecosystem functions. For example, the nutrient content of the water affects the carbon cycle (biogeochemical cycling), which has consequences for primary production (function) and the regulation of air quality (service) (SAMWM, 2017).

### 3.2.3. Climate

The climate determines the environmental preconditions for the ecological structures and processes that underpin ecosystem service provision in other sectors. Swedish reports mention 11 individual pressures related to climate change that directly influence ecosystem services, and 13 pressures that indirectly influence ecosystem services through impacting different functions (Fig. 4), resulting in 24 pressures in total. Two key pressure groups were identified: 'Increased average annual temperatures' and 'Extreme weather events'.

Out of the 24 individual climate change pressures reported, 11 affect water-related sectors. Seven of these pressures were related to evaporation and precipitation effects, which mainly affect the water cycle (biogeochemical cycling, two pressures), and erosion control (two pressures). Climate change projections for Sweden show an increase in snow-driven floods in spring (as a result of increased temperatures) and in rain-driven floods in autumn (as a result of increased precipitation) (Arheimer and Lindström, 2015).

The food and energy sectors were affected by 17 (out of 24) climate change pressures, which included changes to the growing period for crops and trees (temperature increase), and effects on the water cycle (evaporation and precipitation) that influence water availability for hydropower and plant growth. The most affected ecosystem functions were biogeochemical cycling (two pressures) and soil fertility (two pressures), which is possible due to the fact that increased temperature and precipitation are expected to have a positive effect on evapotranspiration (and thus, the water cycle) through increased tree growth

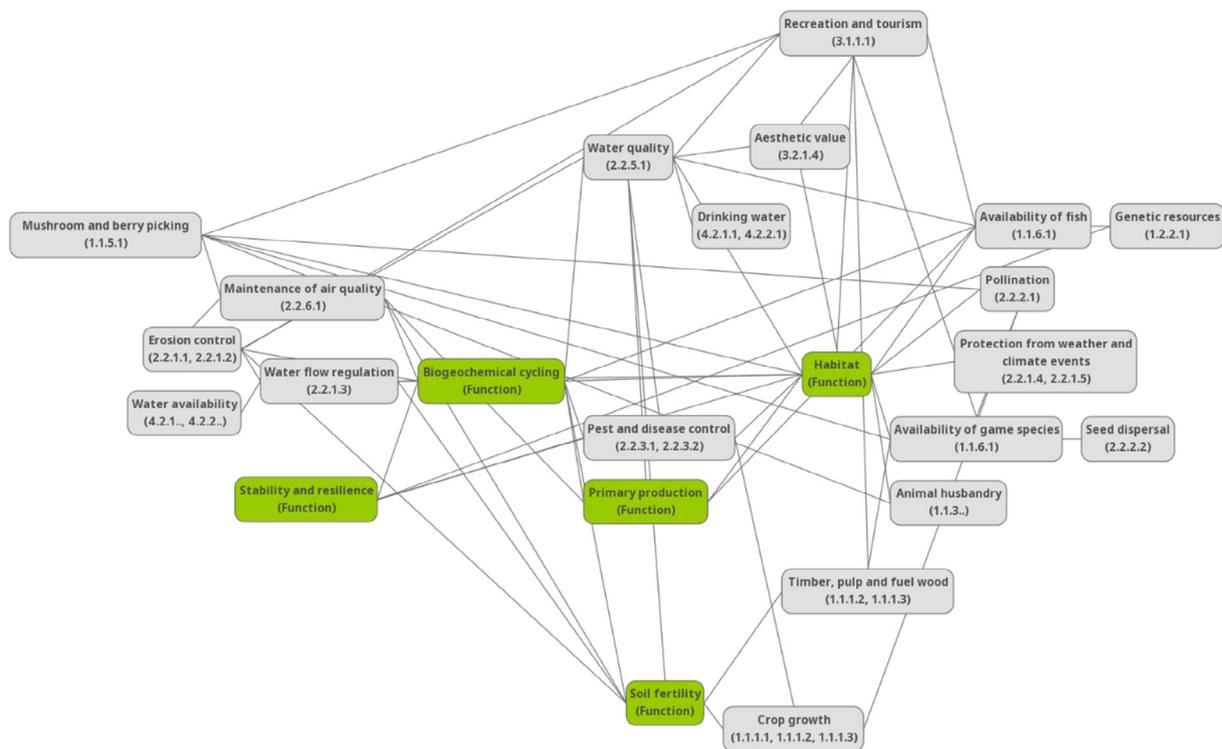


Fig. 5. Reported interactions between ecosystem functions (green boxes) and services (grey boxes) in the water, energy, and food sectors. Numbers based on CICES classification v5.1 (Haines-Young and Potschin, 2018).

(Hasper et al., 2016).

### 3.3. Ecosystem service interactions

The Swedish reports mentioned 72 interactions between ecosystem functions and services, and among ecosystem services, suggesting that the effect of an anthropogenic pressure on an ecosystem function or service can have indirect effects on many other functions and services through different connections (Fig. 5). Many of the connections in Fig. 5 were reported to work in both directions, meaning that the functions/services can affect each other (and themselves) in different ways, depending on which function/service is affected by the pressure.

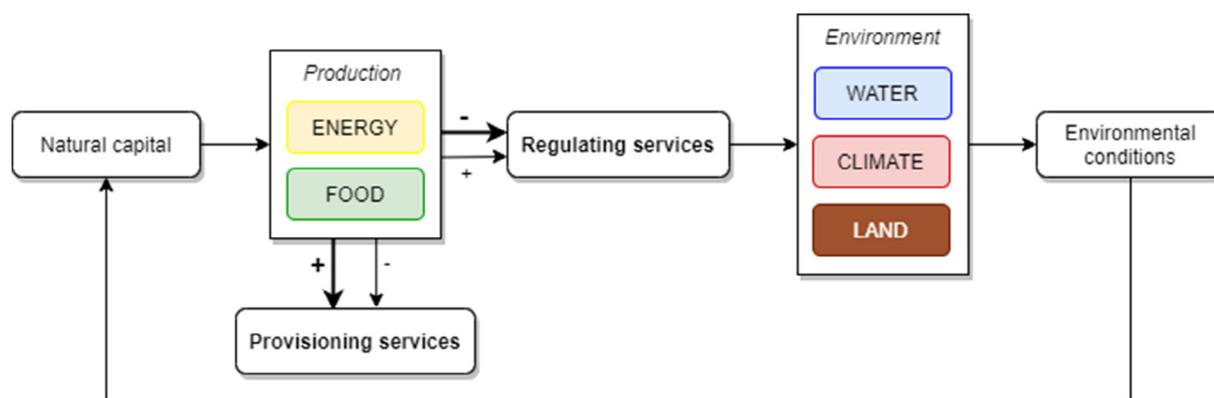
One example of the complex interactions between ecosystem services is the indirect effect of the pressure ‘Use of production-enhancing chemicals’. The overuse of fertilizers can lead to the leakage of nutrients to ground and surface water, which causes alterations in the biogeochemical cycles (function). Excess nutrients can stimulate primary production (function) and lead to the eutrophication of a water body. In such a water body, the maintenance of water quality (regulating service) is thus impeded. A decrease in water quality causes problems to aquatic organisms, such as fish (provisioning service), and has consequences for the potential to serve as a source for drinking water (provisioning service). Moreover, the decline in fish availability affects the opportunities for recreational fishing (cultural service and economic impact). Throughout history, there have been several accounts of fish mortality caused by eutrophication in Sweden’s four largest lakes (Degerman et al., 2001). And although water quality in the Swedish lakes has improved since the 1970’s, the effects of eutrophication are still visible in species compositions (Tammi et al., 2003).

## 4. Discussion

### 4.1. Physical interactions in the nexus and the potential for effective policy making

Policy coherence studies from several countries and sectors have unveiled multiple conflicts and synergies between policy objectives in the nexus (Martinez et al., 2018; Munaretto et al., 2019). Following from these findings, this study has assessed the physical interactions between nexus sectors in Sweden through an ecosystem services lens. There are a large number of anthropogenic pressures originating from each nexus sector that affect different ecosystem functions and services, and thereby (in-)directly also other nexus sectors and domains. It is shown that land- and water-based production processes in the energy and food sectors are affecting the land, water and climate and vice-versa. There are direct impacts on ecosystem services, as well as indirect effects through interactions between functions and services, which cannot be foreseen through a silo-thinking approach. A whole systems nexus perspective is required to better understand and anticipate some of these complex indirect effects, leading to more effective policy making.

Capturing all elements of the water-energy-food-land-climate nexus in one study is a complicated task. Therefore, in this study the analysis of the land sector was limited to agriculture and forestry (with energy and food production regarded as the only purpose) and the analysis of the energy sector was limited to biomass and hydropower. Naturally, this is not a comprehensive representation of reality, but it does capture the most important nexus sector elements and their connections in Sweden (Fig. 6). Fig. 6 is a simplified representation of the nexus and is meant to show the major connections that underpin the key anthropogenic pressures and subsequent impacts on ecosystem services. Natural capital, or “the living and non-living components of ecosystems – other than people and what they manufacture – that contribute to the generation of goods and services of value for people” (quoted from Guerry et al., 2015), is transformed into energy and food products



**Fig. 6.** General connections between the sectors of the water-energy-food-land-climate nexus and the role of ecosystem services. This figure is not intended as comprehensive, but rather aims to show the general connections and feedbacks between the nexus and ecosystem services that should be considered in the context of policy making. See text for details.

(provisioning services) through production processes, usually having an environmental and energy cost, and thus having wider ecosystem impacts. These processes (e.g. tree and crop production, hydropower generation) are dependent on the environmental preconditions that determine the plant's growing conditions and water availability. Energy and food production alter the natural environment through the use of the natural resources that ecosystems provide, often at the expense of other, non-provisioning, services (Rodríguez et al., 2006). As a result of socio-demographic changes, the demand for energy and food has risen and production has intensified, leading to a stronger pressure on non-provisioning services (bold arrows in Fig. 6). Regulating services play a crucial role in the regulation and maintenance of processes related to water and air quality, and soil conditions. Thus, a decrease in these services affects components of the land, water and the climate, resulting in altered environmental conditions, which in turn affects energy and food production, closing the circle of nexus interactions. Despite many efforts to promote environmentally sustainable practices in energy and food production, non-provisioning services and the environment are still under pressure.

The physical effects of energy and food production on the environment and vice versa are shaped through policies from each sector. Guidelines on land use, water use and climate adaptation are increasingly being incorporated in energy and food policies to mitigate the effects of production processes on the environment. Conversely, policies that influence environmental conditions influence production. For example, land use policy influences the natural capital that is allocated for production. Consequently, land use policies indirectly influence the regulating services through their effect on energy and food production, leading to changes along the whole chain. One of the difficulties in dealing with land use planning and environmental policy in Sweden is that spatial plans are largely the responsibility of local authorities (i.e. municipalities), which can lead to problems when (inter)national policies (e.g. global environmental targets such as the Paris Climate Agreement) are translated to the local level (e.g. Söderholm et al., 2007). Ecosystem and nexus interactions do not abide by geographical boundaries, complicating effective management in ecosystems that cross these limits. Therefore, the land sector (and potentially other sectors) should acknowledge the administrative context when adopting the nexus approach and assessing ecosystem services, underlining the need for both horizontal (sectoral) and vertical (cross-scale) coordination in nexus policy making.

Cultural ecosystem services (CES) were only briefly discussed in most of the Swedish reports considered, which is probably due to the fact that assessment of CES is a complicated task (Blicharska et al., 2017). Satz et al. (2013) identified some challenges with accounting for CES in environmental assessments, such as: a) comparing cultural values to other (monetary) values is not always possible; b) cultural value

construction and deliberation might change value over time; and c) cultural values are often personally motivated and it is not always clear whose values should be considered. There is a rapidly growing body of literature on CES that addresses these challenges and proposes indicators to measure the value of CES in monetary and non-monetary terms (e.g. Cheng et al., 2019; Hernández-Morcillo et al., 2013). In the Swedish reports on CES, information regarding responses to anthropogenic influences and interactions with other ecosystem services was mostly unavailable. In some cases (e.g. recreation and tourism), the service was expressed in terms of human activity or markets (e.g. outdoor recreation companies or ecotourism accommodations), but for most CES no such indicators were used. Nevertheless, one report argued that most of the CES are always dependent on other ecosystem services, so a general decline in services is likely to affect CES as well (TRIS, 2016). As a result of the insufficient information, CES were not included in Fig. 6, but we do acknowledge that they should in general be included in the considerations of anthropogenic pressures on ecosystem services. Research is needed to further clarify the effect of anthropogenic pressures that drive ecosystem service loss on CES and determine the mechanisms related to such relationships. Moreover, there is a need for a future research on CES indicators to help assess these services and their interactions.

#### 4.2. Implications for future research and policy

One of the most striking conclusions of this study is that, despite the increased attention in policy making, there is still a significant scientific information gap on ecosystem services and their interaction with human activities in Swedish reports. While there is a growing body of research on this topic, it seems not to be reflected well in the governmental reports, which suggests a lag between academic knowledge and its implementation in policy. This issue was, for example, evident in the use of the concept of biodiversity in the Swedish reports. While biodiversity was included as a supporting ecosystem service in some reports, most scholars do not refer to biodiversity as an ecosystem service (e.g. Haines-Young and Potschin, 2010) and, in general, do not support the notion of "supporting ecosystem services", but rather refer to ecosystem functions (e.g. Potschin-Young et al., 2017). A lack of understanding of the role of biodiversity in ecosystem service provision and interactions could complicate the creation and adoption of coherent policies within the nexus (Mace et al., 2012).

In addition, many connections between human activities and ecosystem services were overlooked in the literature analysed, there was no clear distinction between functions and services, and, in most cases, there was no mention of any guiding ecosystem service classification scheme. This may pose challenges because effectively dealing with ecosystem service trade-offs requires a good understanding of such

interactions and underlying mechanisms and their presentation in a clear theoretical framework (Howe et al., 2014). While the qualitative nature of the complexity has been exemplified in this work (Figs. 5 and 6), better description and clarity of some of the issues stated would help improve holistic policy implementation. Lack of definition and clarity on ecosystem services in the nexus could hamper effective policy uptake (De Groot et al., 2010). In addition to ongoing efforts to develop a large variety of tools to assess ecosystem services (Bagstad et al., 2013) and provide information to policy makers at a range of different levels, sectors, metrics, methods, participatory processes (e.g. CICES, IPBES), there is also a need for tools that focus on the simultaneous, cross-sectoral assessment of ecosystem services in the nexus. Moreover, special attention should be paid to spatial and temporal scale effects, the distinctions between ecosystem service supply and demand, and the consideration of winners and losers in ecosystem service interactions (Cord et al., 2017).

Despite the lack of detailed information, this study has revealed a multitude of physical ecosystem services interactions between nexus sectors in Sweden, which suggests that conflicting policy objectives (even if well intentioned) may affect ecosystems and the services they provide, threatening human well-being. Policy coherence studies have been undertaken in several European countries, including Sweden (Munaretto and Witmer, 2017, 2019), highlighting potential consequences for ecosystem service provision. For example, Sweden's goal of creating a competitive food supply chain may potentially conflict with Swedish Environmental Quality Objectives (SEPA, 2012a) related to water quality (Munaretto et al., 2019), since the Swedish reports linked the use of production-enhancing chemicals in the food sector to alterations in biogeochemical cycles that affect water quality. While the key focus of the present study was on physical interactions and not on analysing the conflicts between the policy objectives that may lead to trade-offs on the ground, future research on interactions between the nexus sectors should account for both the teleological base of ecosystem service interactions and their physical consequences.

Most of the interactions identified in this study were trade-offs, meaning that the provision of one service negatively affected the provision of another. Many such trade-offs were not known a-priori, even in a qualitative way, due to nexus complexity. This study has helped to begin elucidate some of that complexity, allowing policy makers to be able to 'trace' potential trade-offs across the nexus, offering the opportunity to minimise detrimental impacts. Trade-offs can be detected at an early stage by looking at specific indicators, such as the potential competition between provisioning and non-provisioning services (Howe et al., 2014). Conversely, synergistic opportunities and policy measures with benefits in multiple nexus sectors as well as on ecosystem services can be identified and their mutual impact maximised.

There are many studies that discuss multi-sectoral approaches, such as integrated environmental assessment (Howells et al., 2013), life cycle assessment (de Souza et al., 2018) and systems thinking (Bleischwitz et al., 2018). Moreover, ecosystem accounting tools have been developed to better understand the value of ecosystem services in different sectors by analyzing ecosystem services in a national accounting format (Hein et al., 2015). Consequently, some scholars are sceptical about the novelty of the nexus concept and its usefulness in policy making. Wichelns (2017) questions the added value of the nexus concept, claiming that an integration of different sectors is already achieved through programs like Integrated Water Resources Management. Smajgl et al. (2016) argue that most nexus frameworks focus strongly on water, thereby providing only a partial image of the nexus. Albrecht et al. (2018) criticise the lack of a coherent and consistent modelling approach/framework to solving nexus issues, although the vast diversity of scales, nexus sectors, and nexus interactions arguably prohibits such a common approach (Brouwer et al., 2018). Despite the validity of the criticism addressed, recent developments in nexus research emphasize giving equal weights to each sector, while aiming to create a coherent framework that can be applied in a variety of cases/

countries (e.g. Munaretto and Witmer, 2017). The combination of the nexus approach and the ecosystem service concept, while maintaining the integrity of both, creates opportunities for qualitative (and potentially quantitative) assessment of i) ecosystem wide impacts resulting from numerous pressures and; ii) options for nexus-wide coherent policy reformulation aiming to address the pressures to maximise benefits while minimising trade-offs across sectors. This can be accomplished without forcing the information into prescriptive frameworks that may fail to address the complexity of the myriad interacting nexus sectors, and therefore the diversity (and unexpectedness) of ecosystems impacts resulting from the pressures. In the same way, unanticipated multiple benefits from policy reformulation may be uncovered that were not previously considered.

Many scholars see great potential in the nexus approach, especially when dealing with complex issues like climate change (Bleischwitz et al., 2018; Rasul and Sharma, 2016). Climate change is driven by human activities in the nexus sectors, but it also affects these same sectors (Hoff, 2011). Many studies focus on connections between the water, energy and food sectors, but the addition of climate to the nexus is relatively new (Endo et al., 2017), and the extension to include ecosystem services and ecosystem functioning is in its infancy. The increased attention for climate in the nexus fits with the global trend in environmental research and is crucial for understanding of the interactions between climate change, water, and energy and food production, creating opportunities for sustainable solutions in all sectors (Rasul and Sharma, 2016). The ecosystem service approach adopted in this study can add specific information on which climate-related functions and services (e.g. primary production function and regulation of air quality services) are connected to human activities in the nexus sectors. Based on this discussion, and the potential to improve understanding of nexus interactions within the policy making community, climate mitigation and adaptation options and pathways can be better prioritised. There is the potential to achieve climate mitigation and/or adaptation through indirect nexus pathways to ecosystem service provision, opening the possibility of 'multiple win' policy scenarios that create many mutual co-benefits across the nexus and ecosystems.

This Swedish case study, while unique in specific aspects, is far from unique in complexity, and similar conclusions could be drawn for many locations, widening the impact of these findings. Fig. 5 (specifically) and Fig. 6 (more generally), while being strong simplifications of the actual situation, aim to demonstrate the complexity of the nexus and the interactions with ecosystem services. Fig. 6 can be used as a conceptual framework to inform policy makers from different sectors about the general relationships between the nexus sectors and ecosystem services. Conceptual frameworks have been found to support collaboration on complex biodiversity-related issues in groups with mixed expertise (Potschin-Young et al., 2018), and they could have a similar effect in a nexus context. Subsequently, the framework can be adapted and expanded to other situations after appropriate analysis such as that performed here has been carried out in the specific context.

There is considerable complexity within the nexus, and even with recent analytical advances (e.g. Laspidou et al., 2017, 2018), there are knowledge gaps, especially when it comes to quantification. This study focused on a qualitative analysis of nexus complexity, but quantifying even some direct impacts is still ongoing and with much uncertainty, while assessment of indirect impacts is rarely, if ever, done. Nevertheless, even the mere awareness of nexus complexity in policy makers, to which this study aims to contribute, is valuable in supporting more effective policies (Pahl-Wostl, 2007). Adopting a nexus approach provides opportunities for collaboration and the co-production of knowledge about interactions and complexity (Howarth and Monasterolo, 2017). In addition, the link to ecosystem services, how they are impacted by (in-)direct changes in the nexus sectors and how they can themselves change the nexus sectors (cf. Fig. 6) contributes to these opportunities as well. Some of the feedbacks have been explored in the context of this study specifically (Appendix C) and generalised to be

more widely applicable (Fig. 6). Such generalisations of nexus complexity and the link with ecosystem services could prove useful in the ongoing outreach attempts for policy integration and coherence (cf. Munaretto et al., 2019). By gaining at least a qualitative understanding of the potential (in-)direct impacts of a given policy measure in one nexus sector on other sectors, policy makers can better account for such impacts, anticipating and mitigating detrimental impacts that may not have been foreseen using a silo approach. Moreover, with research on ecosystem service quantification expanding quickly (Czúcz et al., 2018), quantitative assessments of physical interactions in the nexus could be facilitated in the near future. In essence, policy making can aim to become more coherent across sectors, accounting for feedback from ecosystem services to the nexus sectors. Further work is required to embed the concepts from this research into policy practice, focusing on better definition of cross-sectoral impacts on ecosystem services, and highlighting the trade-offs and potential synergies that can be derived from them.

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## 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

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecoser.2020.101141>.

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