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Johanna Johansson & Thomas Ranius

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Biomass outtake and bioenergy development in Sweden: the role of policy and economic presumptions

Johanna Johansson \(^a\) and Thomas Ranius \(^b\)

\(^a\)School of Natural Sciences, Technology and Environmental Studies, Södertörn University Huddinge, Sweden; \(^b\)Department of Ecology, Swedish University of Agricultural Sciences Uppsala, Sweden

ABSTRACT

In this study we review and analyse the policy design of biomass residue outtake in Sweden, focusing in particular on how public authorities specify and motivate rules and guidelines for the extraction of slash and stumps. The results show that the Swedish regulations are built on a mixed approach, including both voluntary, procedural and substantive requirements. The recommendations emphasize many merits of residue extraction, particularly climate change mitigation, new employment opportunities and reduced dependency on energy supplies from abroad. We identify a strong focus on precaution, evident in the risks for undesirable effects on nutritional balance and heavy metals in the soil, on biological diversity and on water quality in lakes and watercourses. The recommendations have remained relatively stable during the last 10 years, but the harvest of forest biomass for energy has varied. The annual harvest rate was positively related with energy prices. Harvest was much more extensive in the south, which is closer to the market. We conclude that economic presumptions have influenced the extent of slash harvest while environmental concerns seem to have limited the extraction of whole stumps. We expect that current levels of residue outtake can quickly change if the energy prices change.

ARTICLE HISTORY

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KEYWORDS

Bioenergy; bioeconomy; forest policy; residue extraction; woody biomass

Introduction

Growing scientific and political concerns over greenhouse gas emissions triggering climate change have spurred the need for energy efficiency and increased use of renewable energy (Söderberg and Eckerberg 2013). At present, the push towards a bio-based economy – a core concept used within the European Union to refer to an economy based on renewable resources – and in particular the transition towards a low-carbon economy, is at the epicenter of the political agenda on climate and energy policy (de Besi and McCormick 2015; Johansson 2018). Numerous intergovernmental initiatives call for efforts to combat climate change and adapt to its effects, such as the Paris Climate Accord and the EU 2030 Climate and Energy Framework, as well as national and sectoral targets for transport, agriculture and forestry (European Commission 2016). The EU strategy includes a milestone target for greenhouse gas emission reduction for domestic EU emissions of 40% in 2030 relative to emissions in 1990, along with at least 27% energy efficiency and 27% share for increased use of renewable energy (European Commission 2014). In addition to such high-level targets, several European level strategies describe needs and possibilities to achieve a forest-based bioeconomy, such as the Bioeconomy Strategy for Europe (European Commission 2012), the EU Forest Strategy (European Commission 2013) and the land-use and forestry proposal for 2021–2030 (LU-LUCF) (European Commission 2016). Forest biomass, used primarily for heating, cooling and electricity, is now the most important source of renewable energy and accounts for around half of the EU’s total renewable energy consumption (European Commission 2013). Various by-products, such as sawdust, bark, slash and stumps, are generated as residues after clear-cutting, thinning and at different stages in the production chain and are increasingly used for energy purposes in plants for district heating and power production (Olsson et al. 2017). The importance of such renewable bio-materials to substitute fossil fuels is particularly acknowledged by the EU (European Commission 2012).

In response to European demand for biofuels, there is increasing interest in utilizing residues from forestry operations in the form of slash (treetops and branches that are left after the extraction of stem wood) and stumps. The boreal forests in northern Europe are often seen as important contributors to the EU renewable targets as they can be used for production of bio-based fuels and materials (Beland Lindahl et al. 2017). Meanwhile, there are notable policy conflicts embedded in the proposed shift to a bio-based, low-carbon economy. One of the most prominent conflicts follows the increased extraction of biomass from forests for energy production, and is between biodiversity protection and production of bio-based fuels and materials (Söderberg and Eckerberg 2013; Beland Lindahl et al. 2017; Pohjanmies...
et al. 2017). In other words, provisioning services, which often have a market value, are potentially in conflict with the less tangible supporting, regulating or cultural services (Makkonen et al. 2015). To mitigate risks for other ecosystem services, the use of biomass for energy production results in a need for cautious trade-offs in policy and practice (Makkonen et al. 2015).

Slash and stump harvest may affect a wide range of ecosystem services and organism groups, but most important are the risk for decreased future forest productivity and for loss of species associated with dead wood (see Raniem et al. 2018 for a review). There have also been concerns about water quality. Reduced forest productivity has been observed after slash harvest at thinnings and in Norway spruce forest also at final harvest (Egnell 2017). Water quality may be affected by clearfelling, and since biomass harvest implies an extra disturbance, there have been concerns about increased risks, especially for making mercury more available. However, no increased level of mercury has been observed in runoff water (Raniem et al. 2018). For species associated with sun-exposed dead wood, slash or stumps on clearcuts may constitute their main habitat in today’s landscapes dominated by production forests. Especially for them, extensive slash and stump harvesting imply a decrease in landscape-level habitat amount. To evaluate how much harvesting is possible, without significant increases in long-term extinction risks, is associated with large uncertainties. A theoretical study indicates that certain species may go extinct due to stump harvesting at as low levels as 10–20% (Johansson et al. 2016).

Previous research has paid considerable attention to current and potential future biomass availability (e.g. Blennow et al. 2014; Börjesson et al. 2017; Lauri et al. 2014; Cintas et al. 2017; Lundmark et al. 2015), and private landowners willingness to provide residual biomass (e.g. Leitch et al. 2013; Becker et al. 2013; Joshi et al. 2013; Shivan and Mehmood 2012). Only a handful of studies draw attention to how the policy design of objectives, recommendations and regulations influence current levels of biomass outtake on-the-ground (see, for instance, Stupak et al. 2007; Stupak et al. 2011; Abrams et al. 2017; Becker et al. 2011). One of the most rapid recent changes in forestry is due to the increased demand for bioenergy, and this can be expected to result in conflict with other societal interests, which may call for the development of associated policy. The overall aim of this study is to review and analyse the policy design of biomass residue outtake, focusing in particular on how public authorities specify and motivate rules and guidelines for extraction of slash and stumps. We also relate the annual slash harvest levels in Sweden to economic presumptions. We address the following interrelated questions: (1) what are the main objectives of biomass extraction and how have they developed over time? (2) Which policy tools are mainly used to regulate biomass extraction and which actions and operations guide or regulate residue outtake on-the-ground? (3) To what extent are annual slash harvest levels affected by economic presumptions?

We use Sweden as a case study to provide an illustration of how voluntary recommendations and coercive regulations are enacted in a domestic setting, although the findings are considered in a wider European context of renewable energy targets. As one of the leading countries in contributing to the EU renewable targets, Sweden is considered especially important in providing forest residues to the European bioenergy market (Proskurina et al. 2016). Furthermore, the Swedish government has adopted a climate goal of net zero emissions of greenhouse gases into the atmosphere by 2045, and should thereafter achieve negative emissions (Gov. Bill. 2016/17:146). A national target of 50% renewable energy by 2020 was reached already in 2012 (Swedish Energy Agency 2018). The high percentage is primarily a result of the use of biomass fuels in industry plants and district heating, as well as energy production from hydropower (Swedish Energy Agency 2018). Furthermore, the most recent energy target is 100% renewable electricity production by 2040, including the effective use of existing bioenergy resources (Gov. Bill. 2017/18:228). Over the last decades, a combination of policy instruments has contributed to the reduction of CO₂ emissions and increasing the proportion of renewable energy. At present, bioenergy provides about one-third of Sweden’s total energy use (Swedish Forest Agency 2017).

The rest of the paper is organized into six sections, including this one. The next section provides analytical considerations on how policy choices can be understood and categorized, with a particular focus on policies related to biomass extraction and socio-ecological challenges that influence the level of biomass outtake. The third section presents the contextual and regulatory background for the case whereas the fourth section describes the methods and sources used. The fifth section presents the results; the current policy design on slash and stump harvest in Swedish forestry, including national energy and climate targets and on-site implementation regulations and guidelines as specified by the Swedish Forest Agency. We also analyse statistically the annual slash harvest levels in Sweden in relation to economic presumptions. The sixth and concluding section discusses how existing policies, practices and economic presumptions influence current harvest levels, and potential implications for the future.

**Biomass extraction, policy design and socio-ecological challenges**

From a governance perspective, there are several ways to achieve implementation, from voluntary commitments to mandatory law enforcement. Drawing on Böcher (2012) four types of policy instruments has be distinguished in the scientific literature: (1) *Informal instruments*, which attempt to influence collective action by providing information, (2) *Cooperative instruments* that use the coordination mechanism of negotiations, e.g. between non-state actors and/or public agencies, to establish voluntary agreements (e.g. forest certification schemes), (3) *Regulatory instruments* that require the largest amount of direct state control as they rely on the principle of hierarchy by “command-and-control” to influence actors’ behaviour, and, (4) *Economic instruments* that use the market-based coordination mechanism of prices to influence actors’ behaviour (e.g. eco-taxes or subsidies to stimulate environmentally friendly behaviour). Policy instruments may thereby vary in scope, strength and purpose, including command-and-control regulations, energy or CO₂ taxes, fiscal incentives
or voluntary codes of conduct (Rogge et al. 2017). Regulatory instruments have been used since the onset of environmental policy in industrialized countries in the 1970s. However, alternatives to command-and-control regulations (e.g. market-based or voluntary forms of governance) have been successively implemented, yet, with considerable variation among countries and sectors (Jordan et al. 2005; Böcher 2012; Ring et al. 2017). Since the end of the 1980s, governments frequently require flexible instruments that can handle long-term environmental dangers and for which regulatory instruments alone are insufficient (Böcher 2012). In recent years, a growing body of studies has suggested that a multiplicity of policy instruments are needed to foster low-carbon energy transitions (Purkus et al. 2017; Rogge et al. 2017; Flanagan et al. 2011; Purkus et al. 2018; Makkonen et al. 2015). Such policy mixes are often considered to include a broad range of policy instruments with a preference for less coercive measures, regulatory flexibility and opportunities for win-win outcomes by providing incentives for actors going beyond compliance (Van Gossum et al. 2009).

Understanding the prescriptiveness of policy instruments or whether they are mutually conflicting can advance policy development and on-site implementation (Abrams et al. 2017). As regards biomass outtake, prescriptiveness can be defined as “the degree to which they [policies] prescribe the precise nature and extent of acceptable harvesting practices” (McDermott et al. 2009, p. 220). The degree of prescriptiveness can be assessed based on whether a policy is (1) voluntary or mandatory and (2) emphasizes procedures or performance (referred to as “procedural” and “substantive”, respectively) (McDermott et al. 2009). A procedural policy is a regulation, voluntary or mandatory, that does not specify the on-the-ground management in detail. Thus, a procedural policy leaves room for individual interpretation and variation in management. On the other hand, a performance-based policy prescribes the precise on-the-ground management, while a mixed approach requires certain action, but does not specify exactly how to undertake a certain course of action (Ring et al. 2017). McDermott et al. (2009) have argued that the level of prescriptiveness can result from scientific consensus about the existence of an ecological problem, a country’s level of economic development and the level of expectation that policies will be consistently enforced.

Woody biomass passes through a number of stages in a production cycle. Regulations or recommendations may directly or indirectly influence how trees and logging residues are harvested, the proportion used for sawn timber, pulp, and renewable energy, infrastructure options, and conversion technology used (Becker et al. 2011). This also includes policies that actively integrate bio-based production with objectives of climate mitigation, biodiversity conservation and societal goals (Söderberg 2011). National polices not specific to forest biomass outtake, such as energy and environmental policies, also influence the amount of raw material available for extraction (Abrams et al. 2017). Becker et al. (2011) suggest that biomass policies may invoke both motivational, informative and coercive structure, yet, they need to provide private landowners with adequate incentives (Becker et al. 2011). In order to foster synergies between energy, forest and climate policy, several biomass promotion polices and strategies have been enacted globally, yet their effectiveness at various scales remains unclear (c.f. Abrams et al. 2017; Becker et al. 2011). For instance, at the EU level, the EU Bioeconomy strategy draws attention to the need to foster innovation and optimize the use of woody biomass. However, the need to increase policy interactions and compatibility with market regulation and environmental and social regulation across sectors is recognized (European Commission 2012). At a local scale, on-site criteria and indicators specified in nationally adopted forest certification schemes or guidelines, which specify levels and how the outtake of slash and stump harvest should be extracted, vary depending on institutional context and habitat and landscape structure (Johansson and Lidestav 2011).

As a result of the multi-actor, financial and environmental reality involved in the outtake of biomass residues, careful attention should likewise be drawn to institutional as well as socio-ecological challenges (Becker et al. 2011). For instance, ecological challenges related to the typical structures of a certain landscape, economic challenges related to expected profit, prices, market access and logistical challenges such as infrastructure, affect available levels for outtake (Puettmann et al. 2015). Access to raw material may also be challenged by a diverse set of landowner objectives, which may not prioritize residue outtake (Abrams et al. 2017; Becker et al. 2013). Previous research has confirmed that the payment level offered to harvest biomass plays a significant role in private forest owners’ decisions (Becker et al. 2013; Joshi et al. 2013). However, non-monetary factors, including soil impacts, aesthetics, distance of landowners’ residence from the forest, previous harvesting experience and social norms are also important (Becker et al. 2013; Shivan and Mehmood 2012; Joshi et al. 2013). Yet, in the absence of a well-defined market, it is difficult to predict the willingness of landowners for supplying biomass from their forests (Shivan and Mehmood 2012).

Background and sectorial overview: Swedish forestry and forest policy

Sweden is one of the most extensively forested countries in Europe, with 23 million hectares of productive forest land (or about 60% of its total land area). More than 90% of the productive forest land is used for forestry, with the majority consisting of even-aged stands managed by clearfelling and thinnings (Swedish Forest Agency 2014). Mainly two indigenous tree species are harvested (Scots pine *Pinus sylvestris* L. and Norway spruce *Picea abies* (L.) Karst.). Sweden has a relatively high percentage of privately owned forests: approximately 50% of the country’s forest lands are owned by non-industrial private forest owners; private corporations own 25%; the state (including state-owned corporations) owns 17%; and other private and public bodies own the remaining 8%. Partly due to this diverse ownership structure, the Government has traditionally relied on providing forest owners with education, information and advice rather than command-and-control instruments to implement forest policy. The current Swedish forest policy underwent major
changes when the de-regulation of the Forest Act came into force on January 1st 1994. In order to strengthen environmental consideration in forest management, the Forestry Act raised the prioritization of biodiversity conservation to equal that of timber production. However, the Act only prescribes minimum criteria related to both goals, and does not stipulate detailed practices for meeting them. Instead, Swedish forest policy affirms the importance of freedom with responsibility, granting Swedish forest owners substantial scope to decide how to include environmental protection in management of their forests (Gov. Bill. 2007/08:108). Swedish forestry is, still today, guided by management-by-objectives and a policy instrument mix, with a focus on voluntary, non-coercive, and incentive-based instruments such as market-driven forest certification schemes, information and advice (Beland Lindahl et al. 2017; Johansson 2018).

Methods and materials

Policy analysis

We compared the policy design as described in our conceptual framework to documents related to residue outtake in Swedish forestry (see Table 1 for an overview). We drew our review upon the following types of documents: (1) legal acts issued by the Swedish parliament, (2) statutory instruments or delegated legislation issued by the Swedish government, (3) national strategies often specified in Government Bills, i.e. a long-term plan issued by the government, which sets the direction of a policy for a sector, such as forestry, (4) recommendations and advice from the Swedish Forest Agency, and (5) market-based forest certification standards, the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification Schemes (PEFC 2017).

Analysis of annual slash harvest data

To understand the economic presumptions behind the amount of biomass harvest (RQ 3), we used statistics from the Swedish Forest Agency on the annual slash harvest in Sweden for 13 years (2006–2018; earlier statistics are not available). At this period of time, the stump harvest in Sweden remained negligible. The statistics are based on reports

Table 1. Overview of the policy design of bioenergy outtake from forests in Sweden. Framework adopted from Howlett and Rayner (2013).

<table>
<thead>
<tr>
<th>Policy ends or aims</th>
<th>Policy means or tools</th>
<th>Objectives</th>
<th>National policy design for bioenergy residue extraction</th>
<th>On-the-ground requirements, recommendations and example of use: slash harvest and whole stump removal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-level goals</strong></td>
<td><strong>Instrument logic</strong></td>
<td><strong>Drivers</strong></td>
<td><strong>Mechanisms</strong></td>
<td><strong>Settings</strong></td>
</tr>
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</table>
from the manager for every clearfelling and indicate whether the harvest will be conducted or not. During this period, only minor modifications of the regulations were done, while the energy price varied. We obtained energy prices from the Swedish Energy Agency; we used the price (taxes excluded) from wood chips at industries in Sweden, taking into account inflation (i.e. annual change of consumer prices from Statistics Sweden). We related the proportion of the total clear-felled area where slash harvest was reported with energy prices, using linear regression. To control for a trend over time, one model also included year as an explanatory variable. The proportion that was slash harvested was arcsine square root transformed before analysis.

Results

Policy goals, regulations and recommendations on biomass extraction in Swedish forestry

What are the main objectives of biomass extraction and how have they developed over time?

The extraction of logging residues in Sweden after harvesting has been implemented to varying degrees during the last four decades (Edwards and Lacey 2014). The Forest Agency issued general advice on restrictions on the withdrawal of tree parts in addition to stem wood for the first time in 1985. In 1998, a regulation was added on the notification of withdrawal of biomass as well as an addition that specified, among other things, that damages to land and water courses should be avoided or limited. With these restrictions in mind, the Agency’s recommendations concerning slash harvest were formed. In 2001, they were supplemented with doses, quality requirements, and quality control of ash products used in compensation for nutrition removal. Since 2001, additional knowledge has been taken into consideration, which made the Forest Agency update the recommendations in 2008 (Swedish Forest Agency 2008).

During the 1970s and 1980s, stump removal was used to provide biomass material for the pulp and paper industry (Swe: called Mackmyrapérioden), but the practice was withdrawn in the late 1980s/early 1990s due to environmental concerns. Stump harvest was re-introduced as an experimental programme in 2004 by the Forest Agency, primarily for bioenergy use and climate change mitigation (Swedish Forest Agency 2009). It is foreseen to become more accepted due to climate change mitigation strategies (Edwards and Lacey 2014), however, the Swedish FSC standard (Forest Stewardship Council 2010) states that stump harvest is only allowed on certain trial plots. As a result, stump harvest has only been undertaken to a limited extent in Swedish forestry. Yet, stump harvest is indicated as an appropriate method for increasing the outtake of biomass from the forest (Gov. Bill. 2007/08:108). The Forest Agency considers that if the recommendations are followed, stump harvest has the potential to contribute to climate mitigation (Swedish Forest Agency 2009). In general, Swedish authorities remain positive towards residue extraction if the Forest Agency’s (voluntary) recommendations are followed (Swedish Forest Agency 2008). Furthermore, the recommendations emphasize many benefits of residue extraction, particularly climate change mitigation, new employment opportunities and reduced dependency on energy supplies from abroad. Further, it is stressed that negative environmental impacts must be counteracted or limited to ensure that residue outtake can be considered in accordance with sustainable forestry (Swedish Forest Agency 2008).

Which policy tools are mainly used to regulate biomass extraction and which actions and operations guide or regulate residue outtake on-the-ground?

There are several regulations and recommendations that form the responsibilities for residue outtake in Swedish forestry. The Environmental Code (1998:808) (regulating activities that may significantly alter the natural environment, Chapter 12, §6) and the Forestry Act (1979:429) are the main back-ground regulations on which the Forest Agency’s recommendations are based. Further, the recommendations are based on research on residue outtake, compensation fertilizing and nutritional balance in the soil. Many of the Swedish Environmental Quality Objectives set by the Swedish Riksdag have also provided guidance, although they are not formally binding (for instance, Reduced Climate Impact, Natural Acidification Only, Flourishing Lakes and Streams, Sustainable Forests and A Rich Diversity of Plant and Animal Life).

In the Forestry Act, the extraction of forest residues and compensation fertilizing is mainly regulated in Regulations and general recommendations to §30 (consideration to nature), §14 (notification of forest fuel extraction) and with regard to storage §29 (forest protection). Since ashes are considered to be waste under Swedish law, the Environmental Code §15 is also of importance (Swedish Forest Agency 2008).

The Forest Agency’s recommendations, which complement the coercive regulations stated above, outline how the extraction of forest residues should be conducted in order to minimize undesirable effects on the nutritional balance in the soil, on biological diversity and water quality in lakes and water courses and also to avoid any net flow of heavy metals into the soil. The recommendations have four objectives: to preserve biological diversity, to prevent acidification and impoverishment of forest land, to limit the damage caused by vehicles to the ground and to prevent damage caused by insects, and, finally, documentation, regulations and contacts with authorities (Swedish Forest Agency 2008). For instance, the Agency recommends that damage of trees and bushes retained at stem harvesting should be avoided at slash extraction. Furthermore, wet forest land and other forests with high biodiversity values should be exempt from extraction operations if these values would be negatively affected, i.e. extraction should only include the most common tree species in the landscape. Further, at least one-fifth of the residues should be left behind, preferably in sun-exposed conditions, and especially dead wood, tops and large-dimension branches from deciduous forests. It is stressed that an intensive outtake of biomass may lead to acidification and nitrogen leaching. Therefore, the Agency recommends compensation fertilizing through the provision of ashes to limit damage to the soil. The ashes should originate from the combustion of forest fuel and the desired
quality and recommendation of doses of ashes are specified in an Appendix to the recommendations (Swedish Forest Agency 2008).

There are several recommendations on how stump harvest should be carried out in order to minimize adverse effects on the environment. However, there are knowledge gaps in several areas that affect the impact of stump harvest on environment and production. In view of this uncertainty, the Forestry Agency’s recommendations have been based on a precautionary approach, taking into account, on the one hand, the proportion between the risk and size of a possible negative effect, and on the other hand the extent of the restrictions. Particularly, concerns should be taken to biodiversity conservation and cultural heritage (§30 of the Forestry Act. See also SKSFS 2011:7). Furthermore, the conditions for recreation and outdoor life should not be deteriorated to any significant extent. The Forest Agency estimates that stump harvest in the coming years will affect a relatively limited area, up to 10,000–20,000 ha (5–10%) of the annual clear-felled area. With a geographically dispersed distribution of the stump harvest, the impact on biodiversity is estimated to be limited if the recommendations are followed (Swedish Forest Agency 2009; Swedish Forest Agency 2011). Where it is done, stump harvest should be concentrated on forest stands where it does not adversely affect the environment or other general interests. Examples of such stands are: (1) those that do not have high biodiversity values, valuable cultural environments or high social values, and where the soil conditions are such that stumps can be harvested without any obvious risk of soil damage with subsequent negative effects on production or the environment, (2) damaged stands, where stump harvest has a potential to reduce the risk of root rot in the future tree generation and (3) spruce plantations on abandoned farmland, which usually have low environmental values. At the same time, some stands may be unsuitable for stump removal due to high risk of adverse effects on the natural and cultural environment as well as on social values (Swedish Forest Agency 2009).

**Figure 1.** Percent of harvested area with slash extracted for southern (Götaland and Svealand) and northern (Norrland) Sweden. Statistics from the Swedish Forest Agency based on reports from landowners made before the harvesting.

**Figure 2.** Relationships between slash extraction (% of total harvested area reported by the landowners before the extraction) and average price of wood chips (excl. taxes, with inflation considered). The positive relationship is statistically significant in linear regression, both when Year is included in the model (Price: \( p = 0.000272 \)) and when excluded (Price: \( p = 0.0141 \)). Data from the Swedish Forest Agency (slash harvest) and Swedish Energy Agency (energy prices).

**To what extent are annual slash harvest levels affected by changes in economic presumptions?**

We found that the proportion of clearcut area where the slash harvest was conducted was higher in southern than in northern Sweden. In the latter region, transport distances are longer and the harvestable volume per hectare lower. Further, the proportion of area harvested varied among the years (Figure 1) and the annual proportion of area harvested increased with the energy price (Figure 2).

**Discussion**

In this study, we drew particular attention to how Swedish public authorities specify and motivate rules and guidelines for the extraction of slash and stumps. We also analysed the relationship between annual slash harvest levels in Sweden in relation to economic presumptions. The results show that the Swedish regulations and recommendations on slash and stump harvest emphasize many merits of residue extraction,
particularly climate change mitigation, new employment opportunities and reduced dependency on energy supplies from abroad. The policy design is built on a mixed approach, including both voluntary, procedural and substantive requirements. This includes a mix of motivational as well as coercive structures to stimulate biomass utilization (c.f. Becker et al. 2011). Current recommendations and the reliance on voluntary schemes fit well into the underlying principle – freedom with responsibility – of the Swedish forest policy. However, given the voluntary scope of current policy, few binding regulations and sanctions exist. Further, current bioenergy policy has a strong focus on increasing the extraction of biomass for energy purposes. However, the recommendations on slash harvest specify priority objectives for extraction as well as performance-based actions on e.g. compensation fertilizing. We identify a strong focus on precaution, evident in the risks for undesirable effects on nutritional balance and heavy metals in the soil, on biological diversity and on water quality in lakes and watercourses. These recommendations are overall consistent with the outcome from international research on the consequences of forest biomass harvest (Ranius et al. 2018). For instance, the recommendations give priority to biodiversity, soil nutrients, and water quality that are important issues also according to scientific literature. Further, the recommendations to be more restrictive to stump harvesting than to slash harvesting, to compensate nutrient loss by ash recycling, and to avoid biomass harvesting of rare tree species are in line with recommendations in the scientific literature (Ranius et al. 2018).

Although the recommendations have remained relatively stable during the last 10 years, the harvest of forest bioenergy has varied. We found that these fluctuations are correlated with energy prices. Furthermore, the harvest is much more extensive in the south of Sweden, where transport distances are shorter and the amount of residues to harvest higher due to higher forest productivity in comparison to the north. The demand for residues to use as renewable energy is likely to increase in the coming years. As a result, there is a strong incentive for forest owners to increase the outtake of harvested residues. It has been estimated that the use of slash can potentially increase three times during the next decade. This is especially the case in northern Sweden, but currently slash harvest is often not profitable (Swedish Forest Agency 2015). We confirm the predictions made by the Forest Agency that the future development of the level of slash harvest is mainly due to future energy prices and where it is extracted depends on the distance of road transportation (Swedish Forest Agency 2017). According to Swedish authorities, improved and promoted policy instruments can increase the demand for alternatives to fossil fuels (Swedish Forest Agency 2017). Further, it has been suggested that relevant policy instruments should have a long-term perspective and be technology-neutral to support market development for bioenergy and other renewable energy sources (Swedish Forest Agency 2017). We conclude that economic presumptions have influenced the extent of slash harvest while environmental concerns seem to have limited the extraction of whole stumps. We expect that current levels of residue outtake can quickly change if the energy prices change.

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ORCID
Johanna Johansson http://orcid.org/0000-0001-6823-3503

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