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Research paper

Towards a comprehensive development of eco-innovation indicators in forestry sector: an application in the Italian Alps

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ABSTRACT The concept of "eco-innovation" has been increasingly used in environmental policy to analyze an innovation system taking into account social, ecological and economic pillars of sustainability. The aim of this study is to develop a set of eco-innovation indicators suitable to analyze the forest-wood chain at local level. The study was structured in three steps: literature review on eco-innovation indicators; defining a set of eco-innovation indicators suitable for the forestry sector; testing of eco-innovation indicators in a pilot area (Province of Trento, Italy). Eight indicators and sixteen sub-indicators suitable for the forestry sector were identified. The eco-innovation indicators were quantified using official statistics and new data collected by administering a questionnaire to 114 forest-wood chain actors. The results show an average efficiency of the timber processing and a medium-high level of enhancement of the wood residues generated by production process. Conversely, the level of collaboration between actors of forest-wood chain and institutional actors (universities, research institutes, R&D agencies) could be improved with the aim of increasing the diffusion of eco-innovation knowledge and information. The eco-innovation indicators developed by this study emphasize environmental impacts and negative externalities of innovation process in the forestry sector.

KEYWORDS: green innovation, environmental innovation, performance indicators, forest-wood supply chain.

Introduction

At the beginning of the 20th century, the concept of innovation was first introduced by Schumpeter (1911) in his "The Theory of Economic Development" who emphasized that economic growth is a result of new combinations of products, processes, markets, sources of supply, and organizations. According to this evolutionary economics perspective, the innovation requires a successful introduction of novelties based on new technologies or a new organization of production processes (Rogers 1995). The innovation process can be analyzed through two main models (Edquist 1997): the linear model of innovation based on five consequential steps (*i.e.* basic science, technological development, manufacturing, marketing, sales), and the circular model of innovation that recognizes the influence of technological capabilities and market needs within the framework of the innovating enterprise. Recently, the evolutionary economics perspective, more focused on the economic system, has been reworked to include the influence of political and cultural aspects on innovation process (Lundvall 1992). In this new socio-political perspective, social actors – *e.g.*, public institutions, entrepreneurs, development agencies – and their relationships (network) are key aspects to understanding the innovative process the consequent impacts (Kastelle and Steen 2010, Ritala and Huizingh 2014). Concerning the outputs of innovation process, it is important to distinguish between two main categories of innovation (Rennings 2000): (1) product innovations based on changes in the output of an enterprise or organization and (2) process innovations based on technological innovations or innovations in the organization of an enterprise. Both categories of innovation can generate more or less intense environmental impacts and negative externalities based on multiple variables (*e.g.*, production process, technologies, environmental monitoring systems).

In the last decades, the concept of "eco-innovation" – also known as "green innovation" or "environmental innovation" – has become increasingly important in the international scientific literature being considered a key factor to achieve economic, social and environmental objectives (Ekins 2005, Läpple et al. 2015).

In 2010, the European Commission (EU) adopted the Europe 2020 Strategy for a smart, sustainable and inclusive growth in which the role of eco-innovation – defined as all forms of innovation that create business opportunities and benefit the environment by preventing or reducing their impact, or by optimizing the use of resources – was recognized and emphasized. In addition, the European Commission set up the Eco-Innovation Action Plan (EcoAP) as a commitment of the Europe 2020 Innovation Union Flagship Initiative. The main objective of the EcoAP is to increase the rate of eco-innovation and its uptake in Europe and in so doing deliver efficient solutions for environmental problems, and boost the resource efficiency of Europe and its competitiveness (Triguero et al. 2013). According the EU's Eco-Innovation Strategy, the eco-innovation and eco-industry are the paths to a resource and energy efficient economy aimed to reduce the greenhouse gas (GHG) emissions and increase the competitive-

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ness of the EU enterprises (Bleischwitz et al. 2009). Therefore, the European Commission considers eco-innovation as a possible way for economic growth and at the same time to pursue environmental and social sustainability (Cleff and Rennings 1999, del Rio et al. 2010, Tamayo-Orbegozo et al. 2017).

The Eco-Innovation Observatory (EIO) Annual Report (2012) emphasized that eco-innovation in companies leads to reduced costs, improves capacity to capture new growth opportunities as well as strengthens company image in the eyes of customers (EIO 2012). In the EU's vision the diffusion of eco-innovation is a win-to-win strategy both for enterprises in EU member states and for the environment (Rizos et al. 2015).

From the theoretical point of view, eco-innovation can be considered as innovations that consist of new or improved products, processes, practices, and systems which benefit the environment and so contribute to environmental sustainability (Oltra and Saint Jean 2009). In other words, eco-innovation is the process of developing new products, processes or services which provide customer and business value but significantly decrease environmental impacts and negative externalities (Fussler and James 1996, Horbach 2016). From the practical point of view, to understand the concept of eco-innovation it is necessary to analyze the relationship between innovation process and the environmental impacts generated by this process (González-García et al. 2011, 2012). Taking into account these theoretical and practical perspectives, eco-innovation can be analyzed by multiple disciplines such as evolutionary economics and technological change theories, industrial economics, sociology and political sciences, actor-network and communication theories, organizational change, and knowledge management (Kemp and Foxon 2007, Nill and Kemp 2009, del Rio et al. 2010).

To analyze eco-innovation process, the environmental impacts generated by process and the roles and relationships of social actors must be investigated by means of easily measurable criteria and indicators (Davidescu et al. 2015, Tyl et al. 2015). In the international literature, several authors have developed and tested eco-innovation performance indicators to measure the efficiency and sustainability of environmentally-friendly productions (Andersen 2006, OECD 2009, Smol et al. 2015), but performance eco-innovation indicators for the forestry sector have never been developed and implemented. With regard to forestry literature, many authors have studied innovation process through linear and circular model, types of innovation introduced in the forestry sector distinguishing between products, services and organizational innovations, and forest owners' entrepreneurship in many European countries (Rametsteiner and Weiss 2006, Kubeczko et al. 2006, Duduman and Bouriaud 2007, Weiss et al. 2011, Kovalčk 2011, Notaro et al. 2012, Jarský 2015). In addition, few authors have focused on indicators to measure the innovation process and outcomes in forestry (Välimäki et al. 2004, Nybakk and Hansen 2008). Despite these studies, in the current state-of-the-art there is a knowledge gap in the theoretical analysis and practical measurement of eco-innovation in the forestry sector. One of the major gaps is the absence of a set of eco-innovation indicators suitable to the forest-wood supply chain at both national and local level.

In the rising concept of eco-innovation, it is crucial to bear in mind the efforts to develop new value chains also in forest sector and these new value chains must have in the future their own positions. The topic of new value chains is quite new and surely it's fully integrated in the concept of bioeconomy which is fundamental to pursue eco-innovation. Looking to forestry, it is subject of huge if and how energy is part of eco-innovation. It is out of doubt that bio-based energy is a valid alternative for the development of the territory (Zambon et al. 2016, Delfanti et al. 2014, Colantoni et al. 2013a) and with well assessed topics of innovation (Colantoni et al. 2013b), nevertheless it can be considered as part of eco-innovation only when it is part of a cascade-use concept in forestry sector and it is proved a full efficiency in the process.

Starting from these considerations, the main objective of this study is to identify and test a set of eco-innovations indicators suitable for the forestry sector at local scale. The set of eco-innovation indicators was tested in a case study in the Italian Alps (Province of Trento) involved in the Interreg AlpLinkBioEco and in the CirculAlps project (ARPAF EU-Strategy for the Alpine Region – EUSALP). Both the projects are in synergy and they aim to work in a cross-border situation, aimed at promoting circular bioeconomy and innovation in the Alpine timber sector. The Province of Trento was chosen as a pilot area because it is characterized by a high forest area and the forest-wood chain has an important positive impact on the local economy.

Materials and methods

The study aimed to analyze the eco-innovation in the forestry sector at provincial district and local level was structured in three main steps: (1) literature review to identify all potential eco-innovation indicators; (2) defining of a set of eco-innovation indicators suitable for forestry sector and replicable in different contexts; (3) testing of the eco-innovation indicators identified in the Province of Trento (Italy).

Study area

The study area is the Province of Trento (46°04′00″N 11°07′00″E) in North-Eastern Italy characterized by a land area of 621,200 ha and a population of 538,579 inhabitants (density of 0.87 inhabitants per hectare).

In the Province of Trento, the forestry sector plays an important role with 473,133 ha of forest area, 74% of which is managed with Forest Management Unit Plans (FMUPs). Approximately 78% of forest area has a priority productive function (wood production), while the remaining 22% has a priority hydrological protective or recreational function. The growing stock is estimated in 62,000,000 m^3 of which approximately 450,000 m^3 yr^1 are harvested annually (Servizio Foreste e Fauna 2019). The main forest types are Norway spruce (*Picea abies* (L.) H. Karst) with 31.8% of total forest area, European larch (*Larix decidua* Mill.) with 13.0%, European beech (*Fagus sylvatica* L.) with 14.1%, silver fir (*Abies alba* Mill.) with 11.1%, and Scots pine (*Pinus sylvestris* L.) with 8.8%.

The wood processing sector accounts 140 sawmills with more than 1,220 employers (253 owners and 30 family collaborators, 156 employees, 728 workers, 50 between apprentice and seasonal workers). In 2016, the wood processing industries have worked 347,100 m^3 of raw wood materials, 77% coming internally from the Province of Trento, 18% from other Italian regions, and 6% from foreign countries (Delpero and Tell 2017). The amount of wood residues from the wood processing industries is around 908,500 bulk cubic meter (bcm) divided in 410,500 bcm of woodchips, 392,500 bcm of sawdust, 65,500 bcm of bark, and 40,000 bcm of trimmings (Delpero and Tell 2017). Particularly, 94% of woodchips, 34% of bark, 28% of trimming and 9% of sawdust are used in the biomass district heating plants (DHPs) or combined heat and power plants (CHPs). The sawdust is mainly sold to industries for pellet production, instead bark and trimming are generally purchased from other industries for bedding and wood flour production.

Regarding the bioenergy production in the Province of Trento, in 2016, 26 biomass energy plants were operating for a global installed power of 72 MW_{th}, 65% of the installation are below 1,5 MW (small-scale plants), 6 plants are above 10 MW, and 3 among 3-10 MW. Only 7 of 26 biomass energy plants are combined heat and power plants (CHPs). The overall electric power installed is around 5MW_{el}.

Literature review

The literature review was made to analyze the peer-reviewed publications concerning eco-innovation issue and to identify a set of eco-innovation indicators and sub-indicators suitable for the forestry sector.

A time period of 18 years (period 2001-2018) was considered to highlight the trend of eco-innovation publications within the scientific community. Firstly, the peer-reviewed publications on eco-innovation issue published in the above-mentioned period were identified using three main keywords (“eco-innovation”, “green innovation”, and “environmental innovation”) in the Scopus database. Secondly, the peer-reviewed publications identified were analyzed through a textual analysis to understand how many of them were related to the forestry sector. Thirdly, the peer-reviewed publications focused on indicators to quantify and measure eco-innovation process and outcomes were selected and analyzed in depth to identify a set of indicators suitable for the application to forestry sector at local level. The four criteria used to select the eco-innovation indicators were: congruence with the characteristics of the forestry sector; application simplicity; replicability in different geographical contexts; and suitability at local scale.

According to García-Granero et al. (2018) and Goszczyński (2017), the eco-innovation indicators identified through the literature review were classified into four main types: product eco-innovation; process eco-innovation; organizational eco-innovation; and marketing eco-innovation. This classification of eco-innovation indicators is based on the main types of outputs of innovation process so summarized: products innovations (products and services) and process innovations (organizational, technological and marketing).

In the present study, three eco-innovation types – product, process, and organizational-marketing eco-innovation – were considered by aggregating organizational and marketing eco-innovation types into one.

Defining eco-innovation indicators

At the end of the literature review, a preliminary set of eco-innovation indicators suitable for the forestry sector have been identified and described. The preliminary list of eco-innovation indicators has been analyzed to quantify all three eco-innovation types and to implement the set of indicators in the study area. The final list of eco-innovation indicators was formed by eight indicators (Tab. 1): three performance indicators for product eco-innovation; two performance indicators for process eco-innovation; three performance indicators for organizational and marketing eco-innovation. Each indicator was declined by a variable number of sub-indicators (from one to three) based on the degree of complexity of the issue. At this stage bio-based energy was considered an indicator of eco-innovation because it can increase the efficiency in the forest-wood chain and there are many opportunities of innovation in forest-wood process. The aim is to find indicators that in the future could support a compromise between energy requirements and the chance to develop new value chains.

Table 1 - Eco-innovation indicators for the forest-wood chain.

Eco-innovation types	**Eco-innovation performance indicators**	**Description**
Product eco-innovation	I1 - Use of recycled materials	I1.1 Destination of wood residues produced by forest enterprises (high value vs. low value products)
		I1.2 Destination of wood residues produced by wood processing enterprises (high value vs. low value products)
	I2 - Reduce/optimize use of raw materials	I2.1. Efficiency of the production process in the wood processing enterprises
		I2.2 Ratio between real and theoretical energy density of biomass energy plants
	I3 - Product with a longer life cycle	I3.1 Product destination of timber processed by wood processing enterprises (distribution between long, medium and short life cycle products)
Process eco-innovation	I4 Reduce use of energy	I4.1 Quantify of self-consumed thermal energy in the biomass energy plants (% on total thermal energy produced)
		I4.2 Quantify of self-consumed woodchips in the wood processing enterprises to produce thermal energy (% on total woodchips produced)
	I5 R&D	I5.1 Network density between institutional1 and non-institutional2 actors in the R&D initiatives
		I5.2 Freeman centralization of the network between institutional and non-institutional actors in the R&D initiatives
Organizational and marketing eco-innovation	I6 New markets	I6.1 Forest enterprises with a chipper for market allocation of wood residues produced
		I6.2 Wood processing enterprises with a chipper for market allocation of wood residues produced
	I7 Forest certifications	I7.1 Certified forests according to the principles of Sustainable Forest Management (SFM) on total forests
		I7.2 Certified wood processing enterprises on total wood processing enterprises
		I7.3 Certified timber in cubic meters processed by wood processing enterprises on total timber processed
	I8 Environmental certifications	Quality control of raw materials (woodchips) used in biomass energy plants - I8.1 Moisture (%) - I8.2 Certification (A1+, A1, A2, B1)

Source: our elaboration starting the eco-innovation indicators identified by García-Granero et al. (2018).
1 Institutional actors are ministers, regions, province, municipalities, development agencies.
2 Non-institutional actors are all actors of forest-wood chain (forest enterprises, wood processing enterprises, biomass energy plants).

Product eco-innovation

In the category of product eco-innovation, the first Indicator (I_1) – use of recycled materials – was quantified through the destination of wood residues produced by forest enterprises and sawmills during the production process. The two Sub-Indicator ($I_{1.1}$ and $I_{1.2}$) were calculated as percentage (%) distribution of the total wood residues produced by forest enterprises and sawmills considering three main destinations: (1) wood products with a high added value (*e.g.*, packaging, panels, bio-chemicals, bio-textiles); (2) bioenergy production (*e.g.*, woodchips for energy use); and (3) disposed as waste to landfill. From the theoretical point of view, the forest-wood chain can be considered already addressed to develop new value chains if there is a non-negligible percentage of wood residues allocated to produce high added value products. On the opposite, the disposal of wood residues as waste should be avoided assuming that these residues are a resource and not a waste material in accordance with the key principles emphasized by new EU Forest Strategy (2013) and Ministerial Conferences on the Protection of Forests in Europe (MCPFE). From the practical point of view, Figorilli et al. (2018) introduce the use of blockchain technology for the electronic traceability of wood from standing tree to final products in the Calabria region. The main advantage of an electronic traceability on the chain-of-custody of wood products is the potential reduction of illegal cuttings with special regard to the valuable timber (Figorilli et al. 2018).

The second Indicator (I_2) on optimization in the use of raw materials was estimated through two Sub-Indicators: the first one estimated the efficiency of the production process in the sawmills ($I_{2.1}$), while the second one estimated the efficiency of energy production in the biomass energy plants ($I_{2.2}$).

The efficiency of the production process in the sawmills was calculated as quantity of semi-finished wood products produced by processing a cubic meter of roundwood ($I_{2.1}$). The remaining part includes wood residues produced by timber processing (*e.g.*, sawdust, wood shavings, woodchips). Consequently, high values of this Sub-Indicator are expression of an efficient wood-working process and in respect of the assumption of wood cascade-use which can be considered an eco-innovation. The efficiency of wood-working process is also related to the technological innovation introduced (Zhang et al. 2018).

The efficiency of energy production in the biomass energy plants was estimated using the theoretical energy density (kWh bulk m^{-3}) as defined in UNI-EN 17225-4 (eq.2). Considering woodchip with a moisture content of 35%, the theoretical energy density (E_d) was calculated using the following formula (Francescato et al. 2008):

$$E_{dt} = k \cdot q_{p,net,ar} \cdot BD_{ar} \qquad \text{(eq. 1)}$$

Where:

E_d = theoretical energy density of the biofuel (kWh bulk m^{-3});

$q_{p,net,ar}$ = net calorific value (11.2 MJ kg^{-1});

BD_{ar} = bulk density of the biofuel (253 kg bulk m^{-3});

k = conversion factor between kWh and MJ (1/3.6 kWh MJ^{-1}).

The theoretical energy density was equal to 787 kWh bulk m^{-3}. Then, the real energy density (E_{dp}) for the biomass energy plants has been calculated using to the following equation based on the data collected with the questionnaire (Pieratti et al. 2020, Paletto et al. 2019) (eq.3):

$$E_{dp} = \frac{\sum_{n}^{i=1}\left(\frac{E_{iyield}}{W_i}\right)}{n} \qquad \text{(eq. 2)}$$

Where: $E_{i\ yield}$ is the annual energy produced declared by the biomass energy plant i (kWh); W_i is the annual amount of woodchips used as declared by the biomass energy plant i (bulk m^3); n is the number of biomass energy plants involved in the survey (sample).

A conversion efficiency of 80% has been applied indistinctly considering the data provided by Report on conversion efficiency of biomass (BASIS 2015).

The efficiency of energy production in the biomass energy plants involved in the survey ($I_{2.2}$) was estimated as a ratio between the real energy density and the theoretical energy density.

The third product eco-innovation indicator (I_3) estimated the destination of roundwood processed by sawmills distinguishing between products with a long life cycle (*e.g.*, sawn for carpentry and joinery, sawn timber and boards for the building industry, solid wood beams, wooden poles) from products with a medium (*e.g.*, pallets and packaging) and a short life cycle (*e.g.*, fuelwood and woodchips for energy use). The Indicator I_3 was calculated as ratio between long life cycle wood products (m^3) and total wood products (m^3) produced by sawmills ($I_{3.1}$).

Process eco-innovation

The process eco-innovation was estimated through two main indicators: (1) reduced use of energy in the sawmills (Sub-Indicator $I_{4.1}$) and in the biomass energy plants (Sub-Indicator $I_{4.2}$), and (2) collaboration between institutional and non-institutional actors of forest-wood chain in Research and Development (R&D) initiatives (Sub-Indicator $I_{5.1}$ and $I_{5.2}$).

The first Sub-Indicator $I_{4.1}$ was calculated based on quantify of self-consumed woodchips in the sawmills (bulk m^3) to produce thermal energy on total quantify of woodchips produced in the sawmills.

Regarding the reduce use of energy in the production process, the second Sub-Indicator $I_{4.2}$ was quantified considering the quantify of self-consumed thermal energy in the biomass energy plants (i.e. District Heating Plants-DHPs and Combined Heat and power Plants-CHPs) as a percentage of total thermal energy produced in the biomass energy plants.

The Indicator I_5 considered the collaboration among institutional actors (*e.g.*, ministries, governmental agencies, regions and other local public administrations) and actors of the forest-wood chain (*e.g.*, forest enterprise, sawmills, DHPs and CHPs) in Research and Development (R&D) initiatives. The data collected with the questionnaires was processed using social network analysis (SNA) approach to quantify the level of collaboration between institutional and non-institutional actors in R&D initiatives.

The first Sub-Indicator ($I_{5.1}$) considered the centralization of network in the R&D initiatives in the Province of Trento (vertical ties between institutional and non-institutional actors). In particular, the initiatives of R&D considered by this Sub-Indicator were the following two: test of technologies and updates on latest innovations.

The centralization of the network is high when certain actors are more "popular" in the network than others, meaning they send and receive more ties. This variability can translate into some actors having more access to network resources than others (Moolenaar et al. 2011). Therefore, a highly centralized network is one in which all ties run through one or a few actors, thus decreasing the distance between any pair of actors (Wasserman and Faust 1994). The centralization ranges from 1 (centralized network) to 0 (decentralized network). In the centralized network, more knowledge and advice spreads from a single or a few influential sources to the rest of the network. Conversely, in the decentralized network, knowledge and advice are much more evenly shared among all actors. The centralization of the network – based on the ties between institutional and non-institutional actors – was calculated using the following equation:

$$I_{5.1} = \frac{\sum_{i=1}^{N} C_x(p_*) - C_x(p_i)}{\max \sum_{i=1}^{N} C_x(p_*) - C_x(p_i)} \quad \text{(eq. 3)}$$

Where:

$C_x(p_i)$ = any centrality measure of actor i

$C_x(p_*)$ = the largest such measure in the network

The Sub-Indicator $I_{5.2}$ estimated the network density between institutional and non-institutional actors of the forest-wood chain using the SNA approach. In the SNA, network density is the proportion among the ties which are effectively present within the network and the possible ties calculated on the basis of the number of actors. Density is a structural property of the network, and can vary from 0, if ties are completely absent, to 1 if ties are strongly present (Scott 1991). The network density is directly proportional to the facility of information transmission within the network itself (Paletto et al. 2015). According to Granovetter (2005) into the dense social network the individuals are subordinate to social need and it can be a deterrent to the diffusion of new ideas and innovations (Campos 1996). The density of the network in forest-wood chain activities – Sub-Indicator $I_{5.2}$ – was estimated using the following equation:

$$I_{5.2} = \frac{L}{t(t-1)} \quad \text{(eq. 4)}$$

Where:

L = number of ties effectively present in the network between actors of forest-wood chain

t = number of actors in the network (sample of sawmills and biomass energy plants)

Organizational and marketing eco-innovation

The organizational and marketing eco-innovation considers the innovation process aimed to reduce environmental impacts and to increase the efficiency of forest-wood chain in long-term period. The organizational and marketing eco-innovation can be pursued through an internal reorganization of the production and communication process and an external marketing campaign and identification of new markets.

The first Indicator (I_6) focused on the valorization of wood residues produced by forest enterprises and sawmills during the production process. The availability of wood-chippers by the forest enterprises and sawmills was used as a proxy of internal ability to enhance the wood residues produced. The Sub-Indicator $I_{6.1}$ was calculated as the percentage of forest enterprises with a wood chipper owned or rented on total forest enterprises, while the Sub-Indicator $I_{6.2}$ was calculated as percentage of sawmills with a wood chipper owned or rented on total sawmills.

The second Indicator is related to "Forest certifications" (I_7) that emerged to address the management of forests according to the principles of sustainability. In the present study, the development of forest certification was estimated though three main sub-indicators able to quantify the diffusion of certification systems along the entire forest-wood chain in the Province of Trento. The first two sub-indicators were estimated using the official statistics and database ($I_{7.1}$ and $I_{7.2}$), while the third sub-indicator was quantified based on the data collected with the questionnaires ($I_{7.3}$).

The first Sub-Indicator ($I_{7.1}$) estimated the diffusion of the SFM certified forests – considering both Forest Stewardship Council (FSC) and the Program for the Endorsement of Forest Certification (PEFC) schemes – on total forest area of the Province of Trento (ha). The second Sub-Indicator ($I_{7.2}$) calculated the percentage of Chain-of-Custody (CoC) certified sawmills on total sawmills registered by the Autonomous Province of Trento. The third Sub-Indicator ($I_{7.3}$) estimated the quantity of certified timber processed by sawmills on total timber processed. This Sub-Indicator was quantified using the data collected through the questionnaire administered to the sample of enterprises.

The last Indicator (I_8 "Environmental certifications") of the organizational and marketing eco-innovation was estimated through two sub-indicators calculated based on data collected with questionnaires. The first Sub-Indicator ($I_{8.1}$) considered the diffusion of the practice of moisture control of the raw materials (woodchips) purchased used in biomass energy plants of the Province of Trento. The second Sub-Indicator ($I_{8.2}$) focused on the diffusion of purchasing certified woodchips by the biomass energy plants.

The woodchips classes considered in this study are those established by the ISO 17225-4:2014 "Solid biofuels – Fuel specifications and classes – Part 4: Graded wood chips". The Sub-Indicators $I_{8.1}$ was quantified as percentage of biomass energy plants that control woodchips moisture during the purchase on total biomass energy plants, while the Sub-Indicators $I_{8.2}$ was calculated as percentage biomass energy plants that buy only certified woodchips on total biomass energy plants.

Sampling and data collection

The data used to test the set of above-mentioned eco-innovation indicators were collected through two sources: official statistics and database at provincial district and administration of a semi-structured questionnaire to a sample of actors of the forest-wood chain in the Province of Trento (*i.e.* forest enterprises, sawmills, biomass energy plants).

The sample of forest-wood chain actors was randomly selected starting from the official data (year 2017) provided by Chamber of Commerce, Industry, Crafts and Agriculture (CCIAA) and Energy Service of the Autonomous Province of Trento. At the end of sampling phase, 17 forest enterprises, 75 sawmills (53.6% of population), and 22 biomass energy plants (85.6% of population) were involved in the survey.

In March 2018, a preliminary version of the semi-structured questionnaire was developed and pre-tested with six privileged forest-wood chain actors according to the method developed by Paletto et al. (2019). The final version of questionnaires was face-to-face administered to the sample of forest-wood chain actors in the Province of Trento (from April to August 2018).

The questionnaire for the forest enterprises was divided in two sections: general information on forest enterprises and timber and woodchips destination. This questionnaire focused on quantity and location of tree species harvested annually (m^3 per year for each species), quantity of woodchip produced annually (m^3 per year), destination of wood harvested.

The questionnaire for the sawmills was divided in three sections so named: general information on the sawmill; timber processed per year; wood residues produced per year and working process efficiency. The data about origin of timber and destination of wood resides produced (bark, woodchips, sawdust, trimming) by sawmill was used to estimate the environmental impacts of transport phase.

Lastly, the questionnaire for the biomass energy plants was structured in three sections so named: general information on the biomass energy plant; energy and emission data; and feedstock characteristics. Therefore, each biomass-based plant has provided the feedstock supplier (name and location of the sawmills and/or forest enterprises) and woodchip characteristics (quantity used annually and type distinguishing between bark, sawmill woodchips and forest woodchips).

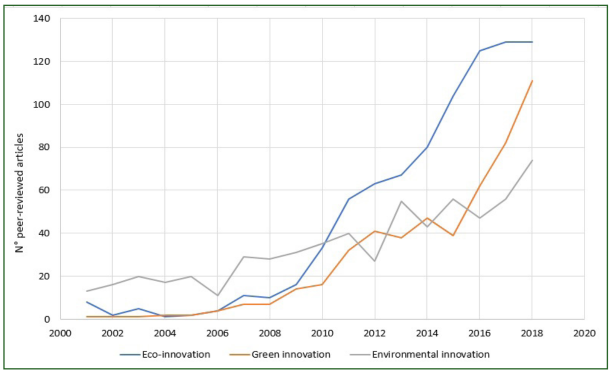
In the last thematic section of all questionnaires, the respondents indicate the name of other actors with whom they have collaborations in R&D (Research and Development) initiatives such as: test of technologies and updates on latest innovations. The data collected with this thematic section were processed using the SNA approach to develop and analyze the R&D network between institutional and non-institutional actors of forest-wood chain.

Results

Literature review

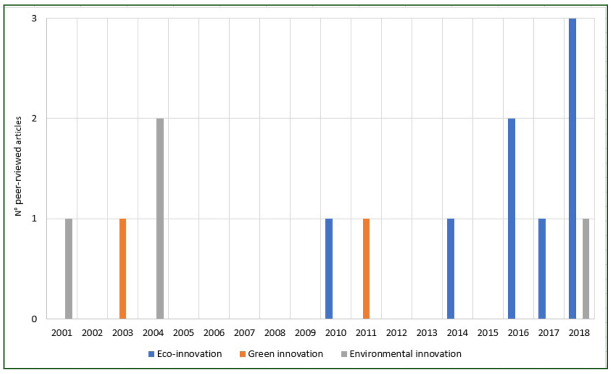
The results of literature review show that in the period 2001-2018 a continuous and constant growth in the number of peer-reviewed articles on eco-innovation issue (Fig. 1). From a terminological point of view, the first term used in the scientific literature was "environmental innovation" by Van Es and Pampel (1976) that emphasizing the need to induce farmers to voluntarily change their farming operation to reduce environmental hazard. Until 2010, environmental innovation – defined as innovation that serves to prevent or reduce anthropogenic burdens on the environment, clean up damage already caused or diagnose and monitor environmental problems (VINNOVA 2001) – is the term most used in international literature with an average number of 20 publications per year. After 2010, "eco-innovation" becomes the most used term in the scientific literature with a constant growth in the number of annual publications (from 33 peer-reviewed articles in 2010 to 129 peer-reviewed articles in 2018). The term "green innovation" – defined as the innovation that is related to green products or processes, including the innovation in technologies that are involved in energy-saving, pollution-prevention, waste recycling, green product designs, or corporate environmental management (Chen et al. 2006) – has grown in popularity since 2008 as also highlighted by Schiederig et al. (2011).

Figure 1 - Trend of eco-innovation ("green innovation" and "environmental innovation") publication by years (period 2001-2018).



Concerning the eco-innovation in the forestry sector, the results show a low number of peer-reviewed publications per year (less than 1 peer-reviewed article by year). In the last three years (period 2016-2018), the number of publications on eco-innovation (green innovation, environmental innovation) in the forestry sector has quickly grown with shown in Figure 2 (three-year average of 2.33).

Figure 2 - Eco-innovation publication in the forestry sector by years (period 2001-2018).



Eco-innovation indicators in the case study

Product eco-innovation

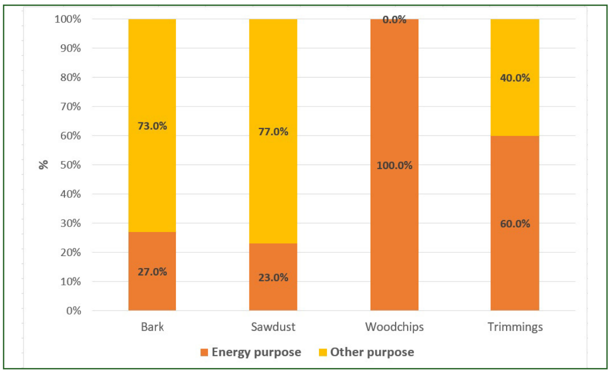
The results of Sub-Indicator $I_{1.1}$ show that in accordance with the data provided by the sample of forest enterprises (n=17) 44.0% of wood residues produced during the forestry operations is transformed in woodchips used for energy to the local biomass energy plants or private buyers, while the remaining 56.0% of wood residues remain in the forest for ecological or technical-logistical reasons. Conversely, the wood residues produced by sawmills (n=75) during timber processing are allocated in the following way: 60.4% for energy purposes to the biomass energy plants, and 39.6% for other purposes such as panels production ($I_{1.2}$=39.6%). The results show that bark and sawdust are the two main types of wood residues intended for alternative purposes, while trimmings are mainly used for energy purpose and minimally intended to carpentries (Fig. 3).

The results of the Sub-Indicator $I_{2.1}$ show that the average percentage of wood residues produced during the timber processing by sawmills (n=75) is 33% with a standard deviation of 12.5%. The average efficiency of the production process in sawmills is 67% ($I_{2.1}$=67.0%). This value can be considered in line with the literature that estimated an average working process efficiency between 65% and 70% (Sacchelli et al. 2014, Pieratti et al. 2020).

The results on energy density ($I_{2.2}$) collected on 12 on 22 biomass energy plants (46.1% of total biomass energy plants of the Province of Trento) show a ranges from a minimum of 512 kWh bulk m^{-3} to a maximum of 1000 kWh bulk m^{-3}, with an average value of 754.6 kWh bulk m^{-3} ($I_{2.2}$=95.9%).

Concerning the wood product destination, the results show that 76.0% of total wood products produced by sawmills (n=75) are long life cycle products (*i.e.* sawn for carpentry and joinery, sawn timber and tables for the building industry, solid wood beams, wooden poles), while 23.0% are medium life cycle products (*i.e.* pallets and packaging) and 2.0% short life cycle products (*i.e.* fuelwood). Consequently, the Sub-Indicator $I_{3.1}$ is equal to 99.0% (medium and long-life cycle products) of total wood products by sawmills in the Province of Trento.

Figure 3 -Destination of wood residues produced by sample of wood processing enterprises in the Province of Trento.



Process eco-innovation

The results show that 30 of 75 sawmills involved in the survey (40%) use wood residues to produce thermal energy corresponding to 9.4% of total wood residues produced ($I_{4.1}$=9.4%). The main wood residues re-used within the enterprises are: 54.6% woodchips, 39.4% sawdust, and the remaining 6.0% trimmings.

Regarding the bioenergy production, the results of process eco-innovation show that for the sample of biomass energy plants involved in the survey (n=22) 6.0% of total thermal energy produced is re-used within biomass-based energy plant, while the remaining 94.0% of total thermal energy produced is sold to end consumers ($I_{4.2}$=6.0%).

The network between institutional and non-institutional actors of forest-wood chain in the Province of Trento (Fig. 4) is formed by 70 non-institutional actors (48 sawmills and 22 biomass energy plants) and 9 groups of institutional actors (universities, technical training schools, research institutes, wood clusters, provincial and local public administrations, certification agencies, R&D agencies, trade associations). The network is characterized by a density of 0.01168 (Sub-Indicator $I_{5.1}$) with 32 actors of forest-wood chain that collaborate with institutional actors (22 sawmills and 10 biomass energy plants) in R&D initiatives. Consequently, approximately 54% of both sawmills and biomass energy plants have no collaboration with institutional actors in R&D initiatives. The centralization of the network (Sub-Indicator $I_{5.2}$) is 0.39185 with four institutional actors playing a more key role in the dissemination of knowledge and information related to the innovations. However, the network has a medium-low level of centralization.

In addition, the results show that the biomass energy plants (DHPs and CHPs) collaborate with two main institutional actors: public administrations (Energy Service of the Autonomous Province of Trento) and technical training schools specialized in the wood processing. The relationship with the Energy Service, is due to data collection on energy efficiency of biomass energy plants and technical support, while the relationship with technical training schools is due to educational visits to the biomass energy plants and training internships related to the dissemination of knowledge on innovations. Conversely, many sawmills actively collaborate with universities – mainly Padua and Trento universities –, public administrations (Forest and Wildlife Service of the Autonomous Province of Trento), and provincial association of craftsmen.

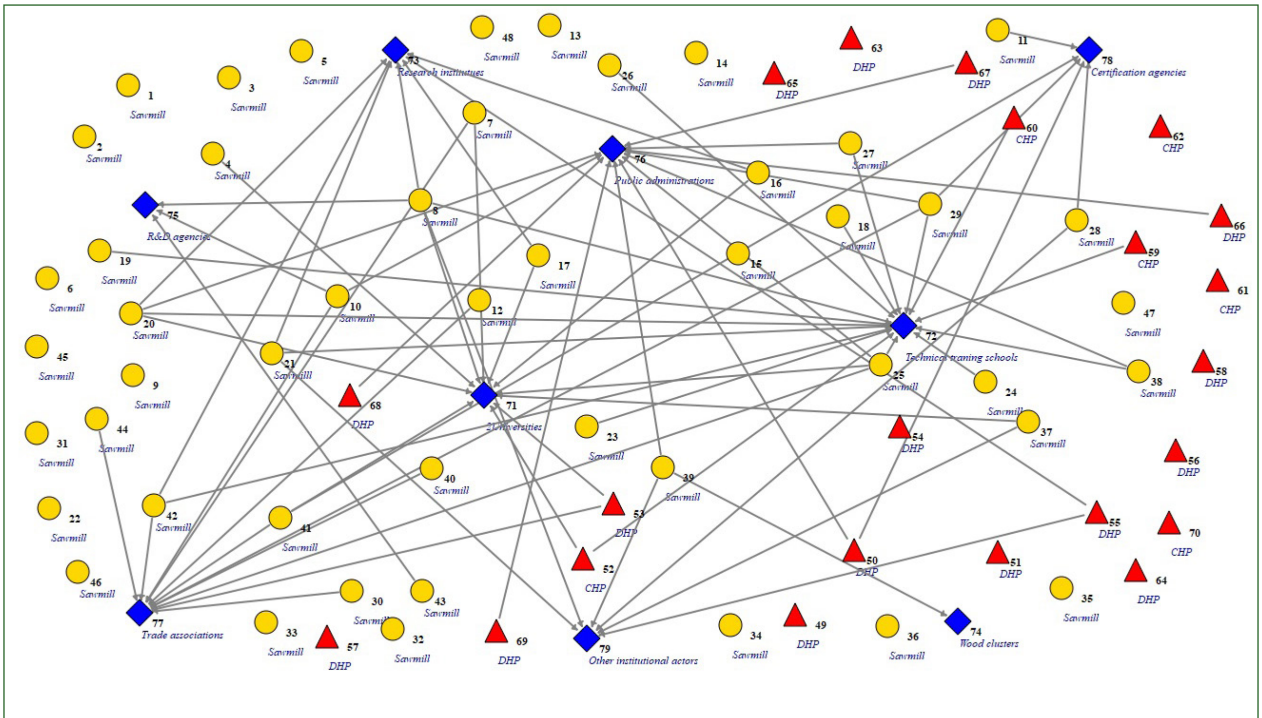
Organizational and marketing eco-innovation

The first Indicator (I_6) of organizational and marketing eco-innovation shows a low diffusion of technological innovation systems to enhance wood residues produced by forest-wood chain. The results show that only one forest enterprise own a wood chipper, while none of forest enterprise rent a wood chipper to produce woodchips for energy purpose ($I_{6.1}$=5.9%). Generally, many forest enterprises involve external companies specialized in the woodchips production. Regarding the sawmills, 18.7% of the sample own at least one wood chipper with two companies that own more than one wood chippers ($I_{6.2}$=18.7%).

The results on forest certification (Indicator I_7) show that in the Province of Trento 271,184 ha of forest area is certified by the Program for the Endorsement of Forest Certification (PEFC) scheme (RaF Italia 2017-2018), while the Forest Stewardship Council (FSC) scheme covers around 20,000 ha of forest area. It is important highlight that there is an overlap between FSC and PEFC certified forests. Consequently, PEFC and FSC certified forests cover 57.3% of total forest area ($I_{7.1}$).

Regarding the second Sub-Indicator ($I_{7.2}$), in the PEFC database, 55 sawmills are certified for the Chain-of-Custody (CoC) – 48 enterprises are PEFC certified and 7 enterprises are FSC certified (Delpero and Tell 2017) – corresponding to 39.2% of total sawmills registered in the Province of Trento, while in the FSC database the CoC certified sawmills are seven (5.0%). All six sawmills certified FSC also have PEFC certification ($I_{7.2}$=39.2%).

Figure 4 -Network between institutional and non-institutional actors of forest wood chain in the Province of Trento in R&D initiatives. In blue = institutional actors; in yellow = wood processing enterprises; in red = biomass energy plants (DHPs and CHPs).



The results of questionnaire show that the sample of sawmills (*n*=75) work on average each year 74.4% ($I_{7.3}$) of PEFC and FSC certified timber and 25.6% of non-certified timber. The PEFC and FSC certified timber mainly comes from the Province of Trento or from neighboring countries (*e.g.*, Austria and Slovenia).

Regarding the quality control of woodchips used for energy production (Indicator I_8), the results show that 54.5% of the biomass energy plants involved in the survey not control the moisture of woodchips, while the remaining 45.5% of the biomass energy plants check regularly this quality parameter using portable hygrometer ($I_{8.1}$=45.5%). The average moisture of woodchips checked by sample of biomass energy plants is approximately 35% with a range between a minimum value of 17% and a maximum value of 50%.

In addition, approximately 41.0% of biomass energy plants buy only certified woodchips: one biomass-based energy plant buys A1+ woodchips, six biomass energy plants buy A1 woodchips, one buys A2 woodchips, and one buys B1 woodchips. Conversely, the remaining 59.0% of biomass energy plants do not require certified woodchips.

Discussion

Summarizing the results, it can be asserted that the forest-wood chain in the Province of Trento is characterized by a medium-high level of eco-innovation based on the aspects considered in this study (Tab. 2). However, some aspects can be further improved. The indicators of product eco-innovation show a balanced distribution of wood residues produced during the forestry operations between part intended for energy production and part released in the forest for ecological reasons (44.0% vs. 56.0%). The percentage of wood residues not to be removed from forest depends to site and stand characteristics, and harvesting method adopted by forest enterprises. Regarding wood residues, fine woody debris with a diameter below 10 cm is an important structural and multifunctional component of forest ecosystem (Harmon et al. 1986), but if its amount is too high the risk of forest fires and biotic attacks increases (Hegetschweiler et al. 2009, Pieratti et al. 2019). Wood residues produced by forest enterprises and sawmills – estimated in 270,000 bulk m^3 of forest woodchip and 410,500 bulk m^3 of sawmill woodchip (Delpero and Tell 2017, Servizio Foreste e Fauna 2019) – is able to satisfy the demand of DHPs and CHPs located in the Province of Trento.

During the timber processing, the sample of enterprises show an average efficiency of the production process (67.0%) with a good percentage of long life cycle products on total products (76.0%). Currently, the forest-wood chain in the Province of Trento is characterized by a high number of enterprises with a diversified production ranging from packaging to wooden buildings. Approximately 1,200 employees are involved in wood processing sector, a third of whom work in the sawmills (Delpero and Tell 2017). About three quarters of raw material processed in the sawmills are local roundwood of Norway spruce and European larch, while the main wood products produced by sawmills are high-value products for construction and furniture. Conversely, wood residues produced by wood processing are marginally valued for the production of high added value products (39.6%). These wood residues characterized by a low moisture content and size could be more valued for the production of innovative wood products – *e.g.*, bio-chemicals and bio-textiles – in accordance with the principles by the Updated EU Bioeconomy Strategies (Hetemäki and Hurmekoski 2014). These bio-products compared to the synthetic oil-based materials have the advantage to reduce environmental impacts and water consumption (Antikainen et al. 2017, Hämmerle 2011).

Regarding the process eco-innovation related to bio-based energy, the self-consumed thermal energy in the biomass energy plants and sawmills is congruent with internal energy needs, while the collaboration between institutional and no-institutional actors in R&D initiatives is still quite low. The process in the Province of Trento can be considered efficient and innovation has been introduced also in some processes (pre-extraction of essential oils from residual biomass before using for energy process). To increase the diffusion of eco-innovations a more "dense" network with close collaborations with universities/research institutes and enterprises would be desirable. Collaboration network may encompass information exchange, knowledge transfer, and advice increasing the diffusion of innovation among operators in the forestry sector (Moolenaar et al. 2011).

With regard to the organizational and marketing eco-innovation, a greater diffusion of the technological innovations for enhancing wood residues between forest enterprises and sawmills could have positive impacts on eco-innovation in the medium-long term. In the last years, some enterprises have started to equip themselves with new equipment including wood chippers thanks to measures of the regional Rural Development Programme (RDP) of the Autonomous Province of Trento. However, a greater diffusion of technological innovations would be further desirable to increase the efficiency of regional forest-wood chain and reduce the environmental impacts, but the renewing of equipment to develop new value chains cannot be restricted to chippers or harvesting machines.

In the late 90s, the forest certification was recognized as a key tool to protect natural and semi-natural forests and to satisfy consumers' environmen-

Table 2 - Eco-innovation indicators applied to forest-wood chain of the Province of Trento.

Eco-innovation types	Eco-innovation performance indicators	Sub-Indicators
Product eco-innovation		
Use of recycled materials	Destination of wood residues produced by forest enterprises (% of high value products)	I1.1 = 44.0%
	Destination of wood residues produced by wood processing enterprises (% of high value products)	I1.2 = 39.6%
Reduce/optimize use of raw materials	Efficiency of the production process in the wood processing enterprises	I2.1 = 67.0%
	Energy density of biomass energy plants compared to theoretical energy density	I2.2 = 95.9%
Product with a longer life cycle	Destination in long life cycle product of wood volume processed by wood processing enterprises (% of medium and high life cycle products	I3.1 = 99.0%
Process eco-innovation		
Reduce use of energy	% of self-consumed woodchips on total woodchips produced in the wood processing enterprises	I4.1 = 9.4%
	% of self-consumed thermal energy on total thermal energy produced in the biomass energy plants	I4.2 = 6.0%
R&D	Network density in R&D initiatives	I5.1 = 0.01168
	Centralization of the network in R&D initiatives	I5.2 = 0.39185
Organizational and marketing eco-innovation		
New markets	% of forest enterprises with a wood chippers owned or rented	I6.1 = 5.9%
	% of forest enterprises with a wood chippers owned or rented	I6.2 = 18.7%
Forest certifications	% of SFM certified forests on total forest area	I7.1 = 57.3%
	% of CoC certified wood processing enterprises on total wood processing enterprises	I7.2 = 39.2%
	% of certified timber processed by wood processing enterprises on total wood processing enterprises	I7.3 = 74.4%
Environmental certifications	% of biomass energy plants that control raw material (woodchips) moisture	I8.1 = 45.5%
	% of biomass energy plants that purchase raw material (woodchips) certified	I8.2 = 40.9%

tally-friendly products request by the Autonomous Province of Trento. This fact has increased the level of knowledge and interest of local forest operators regarding benefits provided by forest certification. The results of this study confirm the high level of diffusion of forest certification between the actors of forest-wood chain. Over half of the provincial forests are certified in accordance with the principles of Sustainable Forest Management (SFM) thanks to the active role of the public authority in the initial implementation of PEFC scheme in Italy. In addition, the high percentage of public forests compared to private forests in the Province of Trento (76.4% vs. 23.6%) facilitated the certification process.

Concerning the environmental certifications, the purchase of certified woodchips can be considered a good practice for the following reasons: improving the environmental performance of wood biomass appliances; decreasing pollutants emission; and reducing use of raw material from illegal loggings in accordance with the EU Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan (2003).

In the Province of Trento, the quality of raw materials (woodchips and other wood residues) used to produce energy is checked in less than half of the biomass energy plants involved in the survey: approximately 46% of biomass energy plants carry out regular checks on the moisture of the woodchips and 41% of them buy certified woodchips. Several studies highlighted that the quality of raw material – mainly moisture, size and amount of foreign incombustible matter (*e.g.*, mould, loam, stones) – used for energy production has a direct influence on combustion process (Gruduls et al. 2013, Rimár et al. 2016). The raw material with a low moisture content (less than 30%), small size (less than 3 cm), and free of foreign matter improves combustion efficiency and decreases pollutants emission in accordance with the EU standards. Therefore, concerning these eco-innovation indicators it would be appropriate to encourage the biomass energy plants of the Province of Trento to buy woodchips certified more regularly. This can be considered a crucial step to make a compromise between the eco-innovation efficiency if a bio-based energy chain with the chance to develop new value chains.

As already pointed out, in the forestry literature criteria and indicators to measure eco-innovation have not been developed and implemented. Existing studies have focused on innovativeness indicators such as enterprise personnel dedicated to R&D initiatives, R&D expenditures, number of development projects, cooperative development work with other enterprises (horizontal ties in the network analysis), cooperation with universities and other public research institutes (vertical ties in the network analysis), number of new products to the market, number of product improvements, number of implemented changes and internal reorganizations (Välimäki et al. 2004, Nybakk and Hansen 2008). All these studies consider marginally the environmental impacts and negative externalities generated by forestry production process. Conversely, the present study sought to emphasize on those indicators related to environmental impacts and natural resources consumption with special regard to forest-wood chain at local level. Therefore, the indicators developed by this study should be considered complementary to those developed by previous studies on innovativeness and enterprises competitiveness.

Conclusions

The eco-innovation indicators and indexes can be considered useful tools to focus the attention of policy makers to some of the key challenges that need to be resolved. To improve the efficiency and sustainability of forest-wood chain at regional and local level in accordance with the principles of EU Updated Bioeconomy Strategy (2018), measurement tools and techniques must be developed to facilitate the decision-making process for solving complex situations. In the international literature, some sets of eco-innovation indicators have been developed and tested to measure the efficiency and sustainability of several environmentally-friendly productions, but performance indicators for forestry sector have never been developed and implemented. In this context, the present study provided a preliminary set of eco-innovation indicators and sub-indicators to be applied to the forest-wood chain at local level to overcome the current knowledge gap.

The main advantage of the proposed set of eco-innovation indicators is the ease of application and replicability in other contexts. Another advantage of the set of eco-innovation indicators developed by this study is the flexibility. The preliminary list of indicators and sub-indicators can be expanded by introducing additional indicators or reduced based on available data. To be calculated, some sub-indicators need information available in official statistics and database with low procurement costs, while for other sub-indicators it is necessary to collect data on a sample of the forest-wood chain actors. A different degree of depth can be adopted in the implementation of the set of indicators and sub-indicators based on the study objectives and available resources and information.

Conversely, the main disadvantage of the proposed method is due to the details required by some sub-indicators limiting the application only to a local scale. To extend the application on a national scale, it would be necessary to identify indicators and sub-indicators measurable through official statistics available at national level. The eco-innovation indicators at national scale should need less detailed information, but mandatory data should be easily accessible and available for the whole national territory.

The future steps of the study will identify a set of eco-innovation indicators to be implemented at national forestry sector. The combination of large-scale indicators (national level) with those at local level will provide an exhaustive and detailed picture of the eco-innovation process and outputs of forestry sector in a certain context.

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