Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate

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Review

Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate

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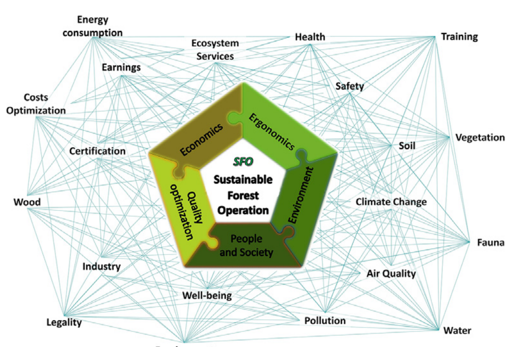
HIGHLIGHTS

- A broader focus and scales for a new concept of Sustainable Forest Operations
- Adaptation to a changing world and climate
- Reconciling bioeconomy, environmental ecology, and human factors and society
- Sustainable Forest Operations includes five performance areas.
- Environment; ergonomics; economics; quality optimization; people and the society

GRAPHICAL ABSTRACT



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ABSTRACT

The effective implementation of sustainable forest management depends largely on carrying out forest operations in a sustainable manner. Climate change, as well as the increasing demand for forest products, requires a re-thinking of forest operations in terms of sustainability. In this context, it is important to understand the major driving factors for the future development of forest operations that promote economic, environmental and social well-being. The main objective of this paper is to identify important issues concerning forest operations and to propose a new paradigm towards sustainability in a changing climate, work and environmental conditions. Previously developed concepts of forest operations are reviewed, and a newly developed concept – Sustainable Forest Operations (SFO), is presented. Five key performance areas to ensure the sustainability of forest operations include: (i) environment; (ii) ergonomics; (iii) economics; (iv) quality optimization of products and production; and (v) people and society. Practical field examples are presented to demonstrate how these five interconnected principles are relevant to achieving sustainability, namely profit and wood quality maximization, ecological benefits, climate change mitigation, carbon sequestration, and forest workers' health and safety. The new concept of SFO provides integrated perspectives and approaches to effectively address ongoing

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and foreseeable challenges the global forest communities face, while balancing forest operations performance across economic, environmental and social sustainability. In this new concept, we emphasize the role of wood as a renewable and environmentally friendly material, and forest workers' safety and utilization efficiency and waste management as additional key elements of sustainability.

Contents

1. Introduction

Wood, as a renewable and environmentally-friendly raw material, has played a major role throughout human history (Rowell, 2013). With the unprecedented rate in population growth further aggravated by climate change, resource shortages and the critical need for environmental protection, wood products have been receiving attention from scientists, policymakers and the public as key resources for the development of a sustainable bio-economy and the future. In fact, sequestering carbon itself is an important role of wood that helps mitigate and abate greenhouse gas emissions.

The use of renewable resources is one of the most important sustainability topics. Non-renewable resources are incompatible with sustainability perspectives and practices. Practices that enable the use of renewable resources are directly related to the well-being of society, both in the short and long term; offsetting the negative effects of pollution on human health and climate. Earth Day in Rio de Janeiro, Brazil, in 1992 (United Nations, 1992) ensured that using renewable energy is recognized worldwide. The utilization and interest in supplying and producing woody biomass as a renewable raw material for energy is rising (Suttles et al., 2014).

In the last decades, the term “sustainability” has become very common in the description of resource utilization intentions (Hahn and Knoke, 2010). The most common definition and meaning of the term “sustainability” is defined within the context of development in the World Commission on Environment and Development report (WCED, 1987 – The Brundtland Report), as ‘*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*’. This concept has changed the perspective of economic development, and affected consumption, policies and production practices as it attempts to encompass the entire range of human values (Ascher, 2007). In practice, sustainability aims to achieve social well-being, without compromising the environmental resources, through a fair economic well-being (Koehler and Hecht, 2006) that is related to three pillars – the economy, the environment and society (Kastenhofer and Rammel, 2005). In 1994, John Elkington further detailed this concept as the “triple bottom line”. He defined the sustainability of 3Ps (profit, people and planet) with the aim to measure the financial, social and environmental performance of corporates over a period of time. Sustainability in this sense accounts for the true cost involved in doing business (Elkington, 1994, 2004).

The complexity of sustainable management practices is particularly evident in the forestry sector because of the multiple benefits, interests and uses that uniquely characterize forested areas worldwide. This includes ecosystem services such as clean drinking water, recreation, hunting, and more recently climate mitigation functions (Mederski et al., 2009; De Meo et al., 2011; Sacchelli et al., 2014). Sustainable forest management practices have been extensively studied within the forest science community under a variety of definitions and terms (e.g. sustainable forestry, sustainable forest management, ecosystem approach, best management practices, etc.) (Ducey and Larson, 1999; Hahn and Knoke, 2010; Wilkie et al., 2003).

Effective implementation of sustainable forest management practice depends on carrying out forest operations in a sustainable manner. In fact, the silvicultural practices of forest operations may also have a strong effect on environmental, economic and social performances, and hence sustainability. Continuous research and development efforts in the field of forest operations (i.e. the activities of extracting wood products from a forested area) seek to investigate present and potentially future practices to help sustain forests, forest resources and forest management. The field of “forest operations” is defined as a scientific and problem-oriented discipline that helps provide solutions for technological problems in forestry (Heinimann, 2007).

In this context, it is important to understand the major driving factors for the future development of forest operations that promote economic, environmental and social well-being in light of changing social demands, climate, and work conditions.

The main objective of this paper is to propose a paradigm shift in forest operations by redefining Sustainable Forest Operations (SFO) based on the historical evolution of the concept of forest operations sustainability and the efforts to address the main challenges forest operations are currently facing worldwide. It is vital to draw attention to the sustainability issues in forest operations in order to raise awareness and stimulate healthy debate. This paper focuses on three areas: (i) the evolution of forest operations sustainability and a proposal for a new SFO concept; (ii) a global understanding of SFO addressing the ongoing challenges of achieving sustainability; and (iii) the improvement of harvesting systems and technologies in order to fulfill the requirements of the newly-defined SFO concept.

2. Evolution of the concept of Sustainable Forest Operations

In 1992, the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro strengthened the relevance of social values towards sustainable forest management (SFM) (Wang, 2004). Sound forest management strategies that considered social, economic and environmental objectives had been implemented in various countries prior to SFM (Wilkie et al., 2003; Hahn and Knoke, 2010). Due to the unavoidable link between forest management and forest operations, the debate on the value and concepts of implementing Sustainable Forest Operations has increased. Three especially prominent approaches that have advanced the understandings of sustainability in forest operations are: (i) "Environmentally Sound Forest Harvesting" (ESFH) (Dykstra and Heinrich, 1992; Heinrich, 1999; Vanclay, 1993), (ii) "Reduced-Impact Logging" (RIL) (Putz and Pinard, 1993; Putz et al., 2008), and (iii) "Forest Operations Ecology" (FOE) (Heinimann, 2007) (Fig. 1).

First, the ESFH understanding was developed and promoted by the FAO Forestry Department at the beginning of the 90's (Dykstra and Heinrich, 1992). The ESFH is defined as a comprehensive pre-harvest planning, appropriate monitoring and execution of operations as well as post-harvest evaluations, with the purpose of increasing the production of goods and services, particularly in diversifying forest products outputs, i.e. timber and non-timber forest products. This approach aimed to generate more income and employment, and enhance the life of rural populations without compromising the regenerative capacity of the forests and their continued contribution to human welfare, while satisfying the requirements of goods and services for future generations. Second, in the 90's, the concept of RIL was also developed and proved to be "*more broadly acceptable than environmentally sound timber harvesting*" (Dykstra, 2002). Research on RIL has flourished over the past decades with more than 200 publications on the topic (FAO, 2004) and both its importance and role in SFM have been stated by Dykstra (2012). The FAO (2004) report summarized the work of several authors, and offered a comprehensive definition of RIL as follows: "*intensively planned and carefully controlled implementation of harvesting operations to minimize the impact on forest stands and soils, usually in individual tree selection cutting*". Both the RIL and ESFH approaches differ in focus and scale, from local to regional, respectively (Fig. 1). Third, Heinimann (2007), introduced the concept of FOE and stressed the issue of environmental ecology within Sustainable Forest Operations and changed the approach from the local and regional to the global scale. The FOE concept aimed "*to develop and deploy environmentally sound forest operations technologies, to use resources efficiently, to minimize the overall production of waste and emissions, and to minimize impacts to structures and functions of environmental spheres (atmosphere, biosphere, hydrosphere, and lithosphere)*" (Heinimann, 2007). All of three forest operations approaches and concepts (EFSH, RIL, FOE) with their unique and specific foci and scale, broadened the perspective towards forest operations and the understanding of forest systems and products that go beyond wood production. However, no formal integration of the "anthroposphere" had emerged in these approaches, i.e. the human-based social needs. Moreover, the increasing demand for forest products, the new values given to forests by the society (i.e. changing perception on the relevance of forests for social well-being; supplied ecosystem services) and the problems related to climate change require the re-thinking of forest operations within the realm of sustainability social criteria.

3. Sustainable Forest Operations as a new approach for healthy forest practices

This study proposes a contemporary approach to Sustainable Forest Operations (SFO) which is based on a broader focus and different scales that reconcile bioeconomy, environmental ecology, human factors and society (Fig. 1). In addition to the three pillars of sustainable development (economy, environment and society), SFO considers two further aspects, i.e. ergonomics and quality optimization (Fig. 2). Both of these aspects are a key component that sustains value-based and healthy forest operations practices and have not been integrated into previous forest operations sustainability understandings and help formulate our contribution to this SFO understanding.

The concept of SFO is defined herewith as: a complex system of relationships that encompasses a set of technologies, methods, systems and practices applied in forest operations planning, implementation, monitoring and improvement with the consideration of five performance areas including: (i) **environment**; (ii) **ergonomics**; (iii) **economics**; (iv) **quality optimization**; (v) **people and the society**. This new approach of SFO seeks to apply an effective and practical concept of sustainability to forest operations while considering the anthroposphere ("mankind's sphere of life, a complex technical system of energy, material, and information flows" - Baccini and Brunner, 1991) as an interactive sphere in the system. In this sense, SFO concepts encompass a holistic approach to setting key indicators for the five performance areas defined above. The level reached in each performance area in terms of "quality and quantity" may affect many aspects of life and the environment (Fig. 2) strongly linked with each other and influenced

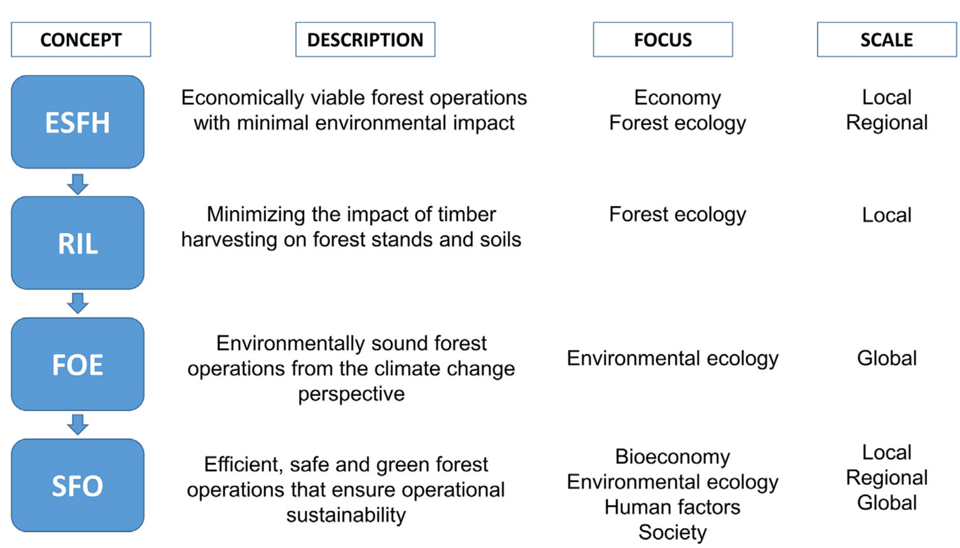

Fig. 1. Evolution of the concept of forest operation sustainability. ESFH – Environmentally Sound Forest Harvesting; RIL – Reduced Impact Logging; FOE – Forest Operation Ecology; SFO – Sustainable Forest Operation.

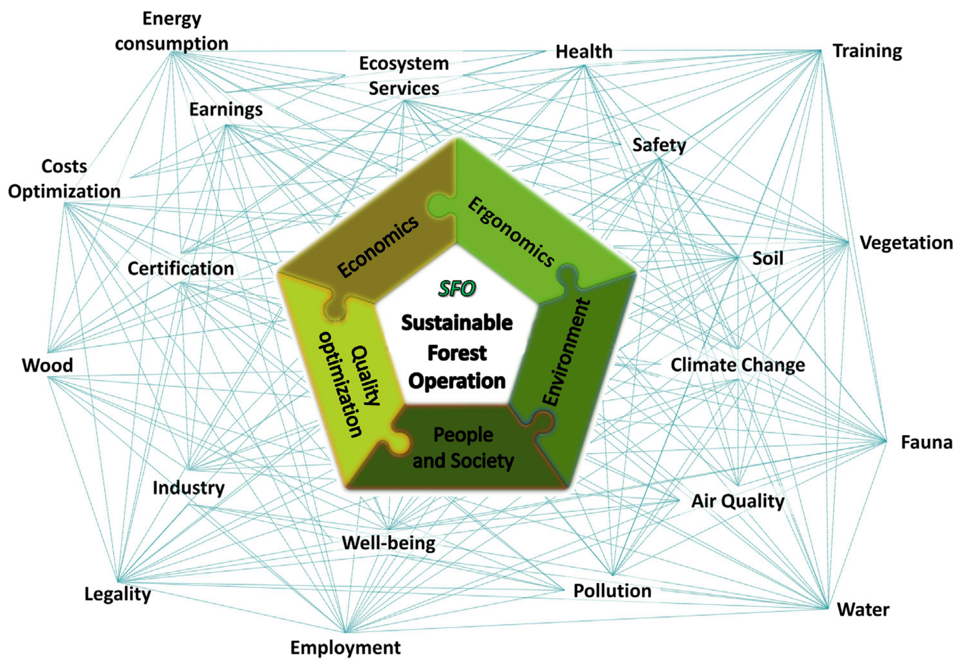

Fig. 2. The complex system of relationships involved in the SFO concept and its five performance areas including: Economics; ergonomics; environment; quality optimization; and people and society.

by the "quality and quantity" level reached in the other areas. Moreover, each performance area may be affected by local, regional or national and international legal frameworks, certification and stakeholder policy. For each performance area that contributes to the success of SFO, the key aspects to be considered are:

- Environment: The environmental impacts due to forest operations at the local, regional and global scale should be minimized. Environmental considerations are offered via solutions that limit impacts of forest operations on:
  - o *Energy consumption*: Energy, oils and lubricant consumed and the proportion of renewable energy in relation to the output of wood volume.
  - o *Soil*: Compaction, rutting, erosion, pollution, and modifications on chemical, physical and biological properties.
  - o *Air*: Direct and indirect pollutant emissions due to the use of forest machineries (e.g. fossil fuels, oil and lubricant leakage, and emissions from modifications in gas exchanges between the soil and the atmosphere) in relation to the output of wood volume.
  - o *Water*: Effects on quality and quantity (sedimentation, pollution, temperature change) and hydro-geological modifications due to the changes in water flows.
  - o *Remaining stand and regeneration capacity*: Damage to residual trees and their reproduction capacity (re-sprouting and seed germinability) after harvesting.
  - o *Biodiversity*: Disturbance of flora and fauna causing negative effects to forest populations and communities.

- Economics: Forest operations should be profitable in order to maintain a healthy forest sector and improve the entire forest management process. In this context, the applicable indicators are:
  - o *Productivity* measured as output divided by input. The classical example is the quantity and quality of timber produced per hour worked.
  - o *Costs* measured as input divided by output (e.g. cost of harvesting per 1 m^3 of harvested timber).
  - o *Added value* measured by the extra worth that comes from a process or added features to a wood product. An example is willingness to pay (WTP) price premiums for environmentally certified wood products. Recent market studies highlighted the rise in market outlets for environmentally friendly wood products. At present the literature reported a WTP for certified wood products over non-certified options ranging from 1.0% to 39.3% (Veisten, 2002; Aguilar and Cai, 2010). Moreover, these values of WTP estimates have increased in recent years (Cai and Aguilar, 2013).

- Ergonomics: Forest operations cannot be considered sustainable if forest workers are not safeguarded and protected from undue risks. According to Jafry and O'Neill (2000), ergonomics in forest operations includes the comfort of operations through the application of modern means and techniques, adapted to the specific contexts, but it also pursues the health and safety of forest workers. Awareness raising of ergonomics among forest workers is very important to improve their health and safety. The key aspects include:
  - o *Risk assessment*: This needs to be calibrated for local work conditions (machines, tools, and terrain and vegetation characteristics).
  - o *Accountability awareness* (me, us, others): ME - each employee is responsible for his/her own safety in the first place; US - each employee is responsible for the safety of team members in the workplace; OTHERS - each employee is responsible for the safety of outside persons entering the workplace.
  - o *Physical and mental workload*: This must be calibrated based on the capacities of individual workers.
  - o *Quality of work environment*: Physical work environment that surrounds forest workers (working posture, operators seat and armrests, cabin space and access, visibility, noise and vibrations, gases and particulates, lighting and climate control) and how it contributes to health, competence, job satisfaction and performance (Becker, 1985; Gellerstedt et al., 2006).
  - o *Updated technology*: Preference needs to be given to modern, state of the art technology. Appropriate mechanization level, equipment type and necessary tools should be calibrated according to work conditions (not only those related with the physical work environment (e.g., terrain conditions), but also those in respect to the socio-economic environment of the region), and provided for forest workers.
  - o *System perspective on work environment*: Studies about forest work environments generally focus on individual aspects of work conditions,

but forest work environment should be analyzed as a whole. Although a hindrance to applying a system perspective exists as it demands transdisciplinary research, diverse aspects of sustainability should be applied to work environment assessment (Häggström, 2015).

- Quality optimization: Attention should be given towards improving utilization rates of harvested trees, reducing waste materials, and enhancing product quality and profitability during in-forest operations. The fundamental elements taken into account in SFO for quality optimization include:
  - o *Utilization rate*: Maximizing biomass extraction by applying the best harvesting system in relation to local conditions. The extraction of logging residues should be carefully assessed in relation to local environmental conditions, considering nutrient recycling and protection of soil and water resources.
  - o *Waste reduction*: Minimizing damage to timber during harvesting and extraction.
  - o *Quality and value*: Optimizing product quality and value through wood quality assessment, optimal bucking and consideration of the timber market.
  - o *Future products*: Avoiding damage to residual trees and reduction in regeneration capacity of the forest for future sustained wood production.

- People and society: Services and functions provided by forests include a wide range of ecological, political, economic, social and cultural systems and processes that are necessary for people and society (La Notte et al., 2017). Forest operations should be planned and implemented to sustain or enhance forest services and functions. The main aspects include:
  - o *Provisioning services and functions*: To ensure the sustainability of future yields of wood and non-wood forest products (e.g. food, fibers, fuel, genetic resources).
  - o *Regulating and maintenance services and functions*: To regulate and maintain the interactions among biotic and abiotic elements of the ecosystems (e.g., water quality and regulation, climate regulation, extreme weather events and disease mitigation, etc.).
  - o *Cultural services and functions*: To maintain cultural services and functions that affect livelihoods and wellbeing of local community (e.g., eco-tourism and recreation, aesthetic, physiological relaxation, cultural experience, etc.) and the rights of native people, while avoiding reduction of landscape amenity and value.
  - o *Employment service and functions*: To support local economy and help reduce poverty. Sustainable forest management activities for maximizing ecosystem services and supporting the green economy potentially have positive impacts on local employment and economy. The development of steady job opportunities in rural areas with fair pay and earnings will help reduce the migration of a young workforce to urban areas.

In general, SFO should promote socially acceptable and responsible forest operations to support community values and wellness, maximize ecosystem services and enhance public understanding of well managed forests. Important components include the involvement and participation of various stakeholders in forest operations decisions, and the practices that comply with existing laws and regulations, and the continuous improvement and monitoring through certifications or other existing auditing techniques.

4. Five major challenges that SFO will address

4.1. More wood removal from less available forest land base

The total global forest area including primary forest, modified natural forest, semi-natural forest, and forest plantation (cf. FAO, 2005 for definitions), decreased by about 129 million ha from 1990 to 2015 (Fig. 3). Deforestation has been the main cause of the decline especially in the tropics and the regions in the low- and middle-income categories (Keenan et al., 2015). Primary forests and modified natural forests also have declined globally (FAO, 2005). As the human population continues to rise, land use conversion from forests to agriculture or urban areas would likely continue.

In the same period, a net gain of forested areas has occurred in East Asia, Europe and North America (i.e. in temperate climate and high-income countries) (Keenan et al., 2015; FAO, 2016b). The net gain was caused by expansion of natural forests and increased afforestation. Plantation forest areas have increased in all climatic domains, as well as in some specific countries, such as China, but the expansion has slowed down in the last years, especially in Europe, North America and Asia (FAO, 2016b) (Fig. 3).

Wood removal in the last five decades has increased, reaching about 3.7 billion m^3 in 2015 (FAO, 2016d). More than half of all wood removal was used for energy purposes (FAO, 2016c). However, it is foreseen that the use of woodfuel in high-income countries will also grow mainly in the form of energy feedstock like logging residues and small diameter trees, according to the “utilization rate” improvement included in “Quality optimization” defined in SFO.

It is estimated that more than 100 million m^3 of wood is illegally harvested each year globally, although there was a significant reduction in the last decade (Lawson and MacFaul, 2010) due to large scale endeavors from the industry to comply with moratoriums on supplied commodities that involve deforestation in the tropics.

In the tropical and subtropical regions, a rising interest in managed and plantation forests has led to the development of good practices. It is expected that wood harvesting from these regions will replace or strongly reduce wood supply coming from natural forests across the globe (FAO, 2016a). However, wood supply from plantation forests will not be enough to meet the growing industrial roundwood demand. It is expected that natural and semi-natural forests in boreal and temperate zones would remain as the major source of wood products without a foreseen increase in the timber land base around the world (Barua et al., 2014).

In this context, waste reduction and bucking optimization in forest operation become important concepts and practices. Applying the concepts of SFO will be a good solution in this circumstance; a “quality optimization” approach may help to maximize wood quantity and quality, enhancing product and value recovery of harvested trees while minimizing costs to the environment, economy and society at large.

4.2. Promoting wood as a renewable and ecologically friendly raw material

Harvested wood products (HWPs) are increasingly recognized as a means of carbon storage. Three primary wood products (i.e. sawn wood, wood-based panels as well as paper and paperboards) were estimated to store 73, 21 and 6% of carbon, respectively, with a trend of increasing share of the two latter products (FAO, 2016a; Palma et al., 2016). In 2013, the total amount of carbon stored in the three products was estimated as approximately 5360 Tg C (19,671 Gt CO_2e) (FAO, 2016a; Miner and Gaudreault, 2016).

The following three activities have been recognized as crucial to our endeavor to increase forest carbon stocks: afforestation or reforestation, improved forest management, and green building and furnishing (Nabuurs et al., 2007). Wood products, as well as green building and furnishing materials have great potential for carbon storage (Julin et al., 2010). Wood is being more recognized as green and advanced material in the architecture, engineering and construction communities because of its environmental advantages over other building materials. It is known that the use of plastics, steel and aluminum results in relatively high GHG emissions in comparison with wood production and processing (González-García et al., 2011).

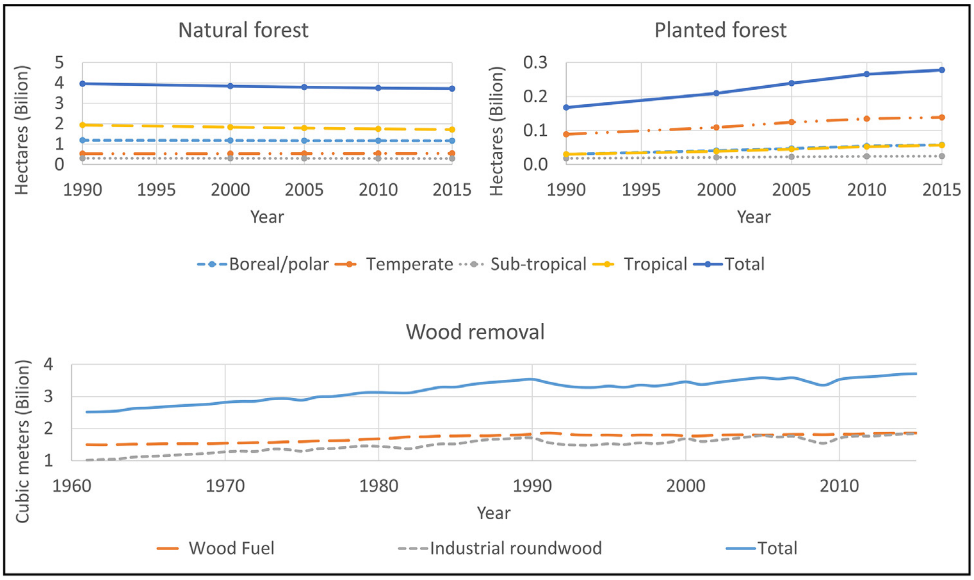

Fig. 3. Natural forest area, planted forest area and global wood removal trends in the last decades.
(Data from Keenan et al. (2015) and FAO (2016d))

Carbon neutrality of energy from wood is a controversial issue due to CO_2 release to the atmosphere, as well as particulate matter, methane (CH_4) and nitrous oxide (N_2O) (Klein et al., 2015). Wood energy can be considered carbon neutral if the source forest is sustainably managed and sequesters at least the same amount of CO_2 released during the production process of energy from the wood (FAO, 2016c). Wood for energy harvested according the SFO approach will meet the demands for carbon neutrality. All sources of wood energy including forest residues may significantly reduce GHG emission per unit of produced energy (Baral and Malins, 2014; Wihersaari, 2005; Zhang et al., 2009).

SFO approach aims to minimize pollutant emission per unit volume of wood during timber logging, thus increasing wood carbon storage efficiency.

4.3. Improving forest operations under climate change

Changes in climate affect all forested ecosystems. Although impacts associated with climate change vary across regions, they commonly include increases in temperature, changes in precipitation patterns, more extreme weather events, and rising sea level (IPCC, 2014). These impacts directly and indirectly change forest ecosystems, soil, and the work environment conditions of forest operations and the duration of operating seasons. This can affect resource accessibility, and climate change may also result in altering forest locations, composition and productivity (Sedjo, 2010; Dumroese et al., 2015). Migration of tree species to higher altitude might expand production forest land areas, but require advanced harvesting techniques for steep ground operations.

Changes in forest type and tree species composition are anticipated in some regions, including North America and Europe (Shugart et al., 2003; Lindner et al., 2008). More frequent and severe forest disturbances such as the spread of pests and pathogens, storm damage and wildfires, also affect forest structure and function, and therefore forest operations (USDA Forest Service, 2015; Westerling et al., 2006; Kilpeläinen et al., 2010). Widespread damage from extreme weather events, insects and wildfires can increase the occurrence and amount of salvage harvest and a shift in management focus from timber management to forest restoration might affect the sustainability and profitability of forest industries. Individual nations, local governments and forest management agencies in many parts of the world have devised forest management strategies and policies for climate change mitigation and adaptation (FAO, 2013; Kolström et al., 2011; USDA Forest Service, 2014). Different strategies have been planned to answer to these challenges, such as increasing the adaptive capacity of managed forests, reducing impacts of extreme weather, insect epidemics and wildfires, and improving carbon sequestration and production of both wood and socio-economic benefits. Evolving tree species, stand composition and environmental concerns may offer production opportunities for a different set of timber products and services (Kirilenko and Sedjo, 2007), yet there could be important challenges involved in forest operations.

Forest growth is expected to increase in response to higher temperature and atmospheric CO_2 levels (Boisvenue and Running, 2006); but, weather-induced tree mortality is also expected to rise in many parts of the world (van Mantgem and Stephenson, 2007; Brando et al., 2014; Garfin et al., 2014; Lindner et al., 2010).

Forest operations may contribute to climate change due to increasing greenhouse gas (GHG) emissions into the atmosphere. Current research has found that most of the impacts connected to GHG emissions were found to be in the harvesting stage due to fuel use for machine operations, as opposed to machine fabrication or repair (Athanassiadis, 2000a; Handler et al., 2014; Abbas and Handler, 2018). In fact, the release of GHG during harvesting operations is mainly related to the manufacture, distribution, and combustion of fossil fuels in the machines for harvesting and extraction (Berg and Karjalainen, 2003; Athanassiadis, 2000a, 2000b; Laschi et al., 2016a, 2016b). The CO_2 released may vary depending on the product being harvested, local conditions, machines used, and extraction and hauling distances (Korpilahtia, 1998; Klvač and Skoupý, 2009; Klvač et al., 2012; Devlin et al., 2013). This means that fuel efficiency (i.e. the amount of fossil fuel consumed for the extraction of a cubic meter of wood) is a key factor for reducing the environmental impacts in logging. Several studies investigated fuel consumption and CO_2 emissions related with different phases of forest operations for different wood products. CO_2 emission ranges from 5 to 12 kg m^{-3} according to logging methods and local conditions (Manner et al., 2013, 2016; Korpilahtia, 1998; Klvač and Skoupý, 2009; Klvač et al., 2012; Fuente et al., 2017). On the basis of these data we can roughly estimate a total emission from forest operation ranging from 18 and 44 Tg of carbon dioxide per year at a global level. Some studies also recorded an increase of methane and nitrous dioxide emission originating from soil compaction induced by machine passes (Cambi et al., 2015). From a SFO perspective, Life-Cycle Analysis methodology according to the ISO standard 14040 (2006) can be used as an important tool for evaluating harvesting systems (Fuente, 2017; Laschi et al., 2016a) and moving towards a reduction of fossil fuel consumption.

Changes in climate on local and regional scales may result in more seasonal constraints on forest operations and site entry. Shorter and warmer winters that reduce snow precipitation and soil frost could shorten operating seasons in the regions where snow cover is required to protect the sensitive soils from disturbance (Rittenhouse and Rissman, 2015; Gregow, 2013). Longer wet seasons and more frequent storms could also mean shorter operating seasons and additional road maintenance costs in more temperate regions. In addition, changes in the intensity and pattern of precipitation could increase potential soil erosion and landslides (Nearing et al., 2004). Increased seasonal restrictions on forest operations may require higher operational efficiency in order to maintain the previous production level in a shorter amount of time without compromising workers' safety.

Forest roads play a key role in forest management and the recreational functions of forests but in many parts of the world are known as a significant source of erosion (Grace and Clinton, 2007; Laschi et al., 2016d). Substantial adaptations in road design and use need to be made to avoid increases in erosion, particularly in regions where more intense rainfall events are anticipated (Rackely and Chung, 2008).

While the shifts in climate can present challenges for many forest practitioners around the world, well-planned adaptation efforts based on the concepts of SFO are opportunities in forest management (Table 1).

4.4. Minimizing ecological impacts of harvesting

One of the main goals of SFO is to comply with forest operations ecology (Heinimann, 2007; Marchi et al., 2014). Each harvesting method, from the simplest (e.g. animal logging) to the most sophisticated (e.g. highly mechanized), has the potential to cause environmental impacts (Cambi et al., 2015). Environmental issues and concerns have been increasing as quickly as the development of mechanization of forest operations in the last 50 years in most of the world (Riala et al., 2015). In tandem, research on damage caused by forest operations has been also rising (Cambi et al., 2015; Sakai et al., 2008; Vasiliauskas, 2001).

Heavy and powerful machines have the potential to cause severe impacts on residual trees, forest stand regeneration capacity, soil, water and pollutants emitted to the atmosphere. The severity of such environmental impacts highly varies with logging equipment and methods. For example, machine traffic on forest ground may cause a higher impact on soil than winch logging, while winch logging may cause higher mechanical injury to trees, soil and regeneration than cable yarding (Cambi et al., 2015; Marchi et al., 2014; Picchio et al., 2012). A careful use of machines and tools, a mindful choice of operating season and meteorological conditions, well thought out logging planning and practices, and training and skills of forest operators can mitigate negative environmental impacts of forest operations (Chamen et al., 2003; Horn et al., 2007; Labelle and Jaeger, 2011; Marchi et al., 2014; Page-Dumroese, 1993; Picchio et al., 2012; Vanclay, 1993).

Negative consequences of ground-based operations include soil compaction, rutting, puddling, and displacement (Agherkakli et al., 2010; Cambi et al., 2015; Eliasson, 2005; Sakai et al., 2008). Soil compaction affects fluids movement, and decreases soil porosity, particularly macroporosity, and soil hydraulic conductivity (Ballard, 2000), thus reducing gas exchange and water drainage (Williamson and Neilsen, 2000). On steep terrain, increased runoff is an outcome of compaction, which can lead to erosion, mudflow and soil loss (Ballard, 2000). Soil degradation also affects soil chemical and biological properties (Busse et al., 2006; Cambi et al., 2017a; Hartmann et al., 2014, 2013; Kleibl et al., 2014; Magagnotti et al., 2012; Worrell and Hampson, 1997) and may result in reduced plant growth and/or regeneration difficulties (Adams and Froehlich, 1981; Cambi et al., 2017b; Cambi et al., 2018; Pinard et al., 2000; Williamson and Neilsen, 2000). Logging can also impact soil by decreasing CH_4 consumption (Topp and Pattey, 1997) or even converting CH_4 sinks into sources, thus increasing the emission of the greenhouse gases CH_4 and N_2O (Ball et al., 2000) and potentially contributing to global warming (Yashiro et al., 2008, Teepe et al., 2004). Soil compaction also reduces aerobic microbial activity, root respiration and gas diffusivity (Conlin and van den Driessche, 2000; Goutal et al., 2012; Hartmann et al., 2014).

Several studies investigated the damage caused to regeneration and remaining trees in forest stands during forest operations. Crown, stem or root damage may lead to serious economic losses due to growth reduction (Isomäki and Kallio, 1974; Tavankar et al., 2015), wound pathogens and decay formation in trees (Dimitri, 1983; Pechmann, 1974; Shigo, 1966), thus leading to wood losses and quality degradation of damaged trees (Karaszewski et al., 2013; Tavankar et al., 2017). Other

Table 1
Adaptation measures for Sustainable Forest Operations and their potential benefits.

Issue	Adaptation measure	Potential benefit
Management strategies and product markets	• Assess the current and foreseeable changes in forest characteristics, tree species, silvicultural practices and market trends. • Understand the characteristics of damaged trees for conducting forest operations in plantation and wildland management. • Assess immediate and potential long-term socio-economic and environmental impacts of salvage harvests (i.e., harvesting and site rehabilitation).	Increase socio-economic benefits
Operational efficiency	• Select harvesting system and forest management equipment that are versatile for a variety of trees and work area conditions. • Design site- and task-specific harvesting systems and operations to improve operator safety, machine-to-machine coordination, and system productivity. • Plan and implement transportation systems to improve access for management of high risk areas. • Train forest operators and machine operators for safety and efficiency of forest operations under a variety of work conditions.	Improve the safety and productivity of forest operations
Soil and water conservation	• Understand negative soil impacts of forest operations including the interaction between rainfall (snow) events and soil changes associated with harvesting activities. • Minimize soil disturbance, including compaction, rutting and displacement. • Locate, design and maintain forest roads and stream crossings to minimize soil erosion and sediment runoff. • Evaluate and improve the current road network system (i.e., upgrading, maintaining, decommissioning, and relocating). • Restrict harvesting activities and the use of forest roads during adverse weather and soil conditions.	Minimize negative environmental impacts
Climate change mitigation	• Select equipment and techniques that can potentially reduce carbon footprints and negative environmental impacts. • Use forest residues for bioenergy and bio-based products to substitute for fossil-based energy and products.	Mitigate climate change

forest ecosystem services, such as carbon sequestration, soil protection, and water control may be degraded by residual stand damages, as well (Picchio et al., 2011). Several influencing factors for stand damage are known as: silvicultural treatment and amount of timber removed from harvest (Bettinger et al., 1998; Fjeld and Granhus, 1998; Gullison and Hardner, 1993); logging methods and harvesting system (Bembenek et al., 2013a, 2013b; Bragg et al., 1994; Fjeld and Granhus, 1998; Han and Kellogg, 2000; Spinelli et al., 2010; Marchi et al., 2014); design of extraction trails and skill of machine operators (Gullison and Hardner, 1993; Nikooy et al., 2010); logging season, site characteristics and tree species (Bettinger and Kellogg, 1993; Limbeck-Lilienau, 2003; Sist et al., 2003; Vasiliauskas, 2001).

The SFO approach, in particular "environment" and "quality optimization" performance areas, requires minimizing the level of damage, in terms of both quantity of damaged trees and extent of damage, to assure the highest quality of future harvested timber and ecosystem services. From a SFO perspective, forest operational planning must consider all possible factors and their interactions affecting environmental impacts.

4.5. Improving safety and ergonomics of forest operators

Ergonomics, which is simply put "the study of the safety and efficiency of persons in their working environment" has been historically underrepresented in the field of forest operations in several regions around the world (FAO, 1992). However, occupational health and safety in forestry have recently emerged as an important topic in both research and practices (Gandaseca and Yoshimura, 2001; Brachetti Montorselli et al., 2010; Stampfer et al., 2010; Albizu-Urionabarrenetxea et al., 2013; Garland, 2013; Laschi et al., 2016c; Magagnotti et al., 2016). Logging has long been the most dangerous civilian job in many countries (Sygnatur, 1998; Laschi et al., 2016c; U.S. BLS, 2015), and mechanization of logging has helped decrease the rate of accidents (Axelsson, 1998; Bell, 2002). As an example, due to highly mechanized forest operations in Sweden, the number of accidents resulting in sick-leave of forest workers is about 5 per year out of 1000 employees, which is lower than the average for all work business in the country (Arbetsmiljöverket, 2012).

Other issues related to workers' safety in many countries include aging forest workers, use of old, outdated equipment, terrain topography, underdeveloped road networks, and lack of training programs for forest workers (Abbas et al., 2014; Abbas and Clatterbuck, 2015; Abbas et al., 2017; Enache et al., 2016; Lindroos and Burström, 2010; Owende et al., 2002). Further, as demand increases for forest products, accessing more remote and difficult to reach areas are expected to increase adding a higher level of difficulty to operations (Hakkila, 2004). Shortage of training can result in lower productivity and further endanger the safety of operators.

Although forest workers' health and safety have a significant impact on the sustainability of the supply chain of forest products, and has seen a growing interest, workforce equipment and ergonomics training in several European and North American areas still remains short in the implementation of local best management practices and forestry certification schemes (Abbas et al., 2017). The SFO approach highlights the importance of workers' safety, community values and wellness, and promotes development of practice guidelines and certification schemes that can help improve forest workers' health and safety in the forestry workplace. Moreover, the improvement of health and safety levels, increasing skills and capacities of forest operators, should improve recognition of the profession of forest operator as a complex and qualified figure, with positive consequences on both work quality and remuneration.

5. Moving towards SFO: improving work systems and technologies

Improving forest work systems in a forest-based bio-economy should be based on the balance of economic, environmental and social well-being, although given the industrial nature of timber production systems, the emphasis is often on improving economic performance. An unbalanced emphasis may lead to an improvement in the short term, but will eventually result in a failure of sustainability. For example, traditional chainsaw operations for tree cutting are normally high cost, low productivity operations, which are becoming more and more financially unsustainable in many places around the world (Schweier et al., 2015). On the contrary, mechanization of tree cutting may improve both productivity and safety (Bell, 2002), but at the expense of potentially higher negative impacts on forest soils (Cambi et al., 2015). Another example can be found in steep terrain operations (Abbas et al., 2017). Cable logging systems have long been recognized as a relatively low impact harvesting method as they can reduce ground contact of heavy equipment (Samset, 1985). However, cable logging is considerably more expensive than ground-based harvesting (Spinelli et al., 2016; Visser and Stampfer, 2015) and also more dangerous with much higher accident and injury rates. New cable-assisted ground-based harvesting systems have been implemented to improve both productivity and safety of steep terrain operations, but little is known of the soil damage risks associated with these systems (Visser and Stampfer, 2015).

SFO can provide guidelines for selecting the most suitable forest operations machines and systems. The five performance areas of SFO need to be balanced based on local society's needs and available knowledge, experience and resources. In principle, the best possible forest harvesting system would minimize environmental impacts, maximize productivity and social acceptance with consideration of ergonomics and workers' safety, and optimize products quality.

For selection of a timber extraction system as an example, two mechanized harvesting methods dominate; full-tree and cut-to-length (Uusitalo, 2010). Over the past years both methods have been compared with respect to fuel consumption (Sambo, 1997), damage to soils and residual trees during felling and terrain transport (MacDonell and Groot, 1997), as well as harvesting costs and machine system production rates (Lanford and Stokes, 1996; Hartsough et al., 1997; Plamondon and Page, 1997; Favreau and Gingras, 1998; Spinelli et al., 2014). In general, cut-to-length systems tend to have less soil impacts and residual tree damages (Bembenek et al., 2013a, 2013b; Han et al., 2006, 2009), as well as consume less fuels than full-tree harvesting (Ghaffariyan et al., 2015; Fuente et al., 2017; Athanassiadis et al., 1999; Greene et al., 2014). For economic efficiency, Uusitalo (2010) concludes that no general differences exist between the two methods, and the differences tend to be marginal and stand-dependent; full-tree system is in general more efficient on large-sized stands at short extraction distances (Uusitalo, 2010).

With regard to "Environment" performance area of SFO, there have been a number of harvesting techniques and machinery options developed to reduce certain environmental impacts. For example, the use of wide tires or slash mats may reduce soil compaction (Spinelli and Magagnotti, 2011; Horn et al., 2007). Soil compaction can be further limited when CTL is combined with a chainsaw method on midfield, leading to fewer strip roads in the harvest stand (Mederski, 2006). Additionally, using larger machines (forwarders or skidders) can reduce the number of passes required to complete the timber extraction. Most countries, where active forest management is practiced will have pragmatic harvesting guidelines and best management practices that can help minimize negative impacts of forest operations and comply with the related laws (e.g. VDOF, 2014; Sessions, 2007).

The SFO approach is not just for selection of machines or harvesting systems, but also for a detailed operational planning to reduce potential negative impacts and improve their economic efficiency and safety (Contreras et al., 2016; Chung et al., 2008; Chung et al., 2004). For example, wet soil is a limiting factor for logging, but the majority of small streams are not typically mapped, and soil conditions also vary throughout the year (Ågren et al., 2015). Detailed operational planning using technologies such as real-time mapping, sensors, and machine route optimization may help the machine avoid wet areas and thus reduce potential damages to soil and stand's regeneration capacity, while also reducing total driven distance and fuel consumption (Mohtashami et al., 2012; Jundén, 2012; Lindroos et al., 2017).

One clear link to climate change for timber harvesting is the consumption of fossil fuels that drive the forest machines. In general, the way to reduce the CO_2 release per m^3 wood utilized is to consume less fuel during harvesting. Despite the prevalence of accurate fuel consumption gauges in modern harvesting equipment, accurate information about actual fuel use during harvesting is somewhat difficult to find (Athanassiadis et al., 1999). The use of on-board electronic control units or on-site delivery systems makes it possible to collect detailed fuel consumption data (Manner et al., 2016; Kenney et al., 2014). However, some comprehensive studies provide insight into total fuel consumption. These studies highlight that fuel consumption for ground based and cable systems ranges from 2 to 4 l m^{-3} (Oyier and Visser, 2016; Greene et al., 2014; Holzleitner et al., 2011).

Machine manufacturers typically focus on integrating energy efficient engines, transmissions and hydraulic systems because fuel is also a major cost component of timber harvesting. Previous studies indicate that on average fuel contributes 12.8% (Baker et al., 2013) and 18.5% (Baker and Greene, 2012) of total harvesting costs in the south-eastern USA; and constitutes 10% and 20% of total harvesting cost in Canada and Sweden, respectively (Nordfjell et al., 2003). New machine developments that use hybrid electric power systems can significantly reduce fuel use, i.e. corresponding costs and CO_2 emissions. However, in general, manufacturing of forestry machines lags behind other industries in terms of fuel efficiency because they are produced in a relatively few numbers (Drushka and Konttinen, 1997).

For non-renewable energy consumed during forest operations, some have argued that animal logging would have benefits over mechanization, especially in the areas where the use of machines is environmentally and economically unsustainable (Cerutti et al., 2014). Rydberg and Jansén (2002) reported that 60% of the energy used by horse for traction was renewable whereas that of a tractor was only 9%. Engel et al. (2012) calculated the environmental performance of draught horses for forest operations using LCA and reported that horses are more climate-friendly than large-scale machines; per hectare of forest logged, a mixed animal-mechanized system had almost 45% lower GHG emissions than a fully mechanized system. Opponents to this argument are of the view that tractor work involves lower consumption of fuel than that needed to produce the feed consumed by animals to carry out the same amount of work (Cerutti et al., 2014). This is supported by Spinelli and Magagnotti (2011) who concluded in their study about that the introduction of modern machinery does not result in a higher consumption of fossil energy per unit of product in comparison with animals; suggesting a slight energy saving.

Illegal logging has long been recognized as a significant global problem that harms the sustainability of forest operations. A technological innovation, such as wood tracking information systems, could be a solution to confront illegal logging and reinforce regulations. Several tools and instruments have been developed to trace wood products along the supply chain (e.g., visual marking, barcodes, radio-frequency identification tags, etc.), and thus to prevent and control the trade of illegally logged timber products (Tzoulis et al., 2014; Picchi et al., 2015). These systems may support or in some cases substitute the current document-based certification designed for log tracking and forest protection. Development and implementation of new technologies that can help reduce or eliminate any irresponsible forest operations will certainly help achieve the goals of SFO.

Special consideration in SFO is given to improving the operating environment for forest workers. There are several measures that can help improve work conditions. Regular training, PPE, locally calibrated safety procedures and fair contractual conditions are some of the fundamental measures for safety improvement. From a machine design and manufacturing perspective, it is important to use the latest standards for safety and ergonomics (Gellerstedt et al., 2006). The workers' health and safety is found to be improved by using partial to fully mechanized felling and extraction operations (Enache et al., 2016; Tsioras et al., 2014; Alam et al., 2012; Lindroos and Burström, 2010). There have been efforts to develop semi-automated or automated machines that are expected to further improve workers' health and safety, but the machine and system design needs to be done through a holistic approach considering interactions between human-machine, human-environment and machine-environment (Häggström, 2015; Lindroos et al., 2017).

The “quality optimization” performance area of SFO requires the development of methods, systems and techniques for assessing wood quality and optimizing tree bucking, allowing to reduce wood waste and optimize product quality and value. An increasing number of studies have been investigating or developing new methods and techniques to produce larger quantity, higher quality wood from the same or less harvest area. Quality optimization may help increase logging profitability while effectively meeting the society's demands for wood products (Andersson et al., 2016; Labelle et al., 2017; Nakahata et al., 2014). For example, a harvester head equipped with load cells and a near infrared spectrometer has been recently developed as part of a European Union research project called “SLOPE” (http://www.slopeproject.eu). This harvester head is able to assess wood quality and incorporate the information into log assortment decisions in real-time.

New harvesting techniques are continuously developed due to technology development. The main enablers behind any significant technological changes are the availability of new technology; demand for new wood-based products; and the need for changes in current operations due to new regulations (Lindroos et al., 2017). Automation and robotization are examples of new technology that will soon dominate in forest operations (Parker et al., 2016; Visser and Harrill, 2017).

6. Conclusions

The concept of sustainability is important in planning and practice of forest operations, and should encompass different aspects. This paper has described the evolving views of sustainability in forest operations, as well as the evolving challenges the field of forest operations has been facing. We suggest in this study that the proposed concept of SFO provides integrated perspectives and approaches to effectively address ongoing and foreseeable challenges while balancing forest operations performance across economic, environmental and social sustainability objectives. In this new concept, we emphasize that the forest workers' ergonomics, health and safety, and utilization efficiency and waste management are additional key elements that enrich the understanding of the sustainability in SFO. In addition, through the promotion of afforestation and reforestation, improved forest management, and green building and furnishing, the SFO concept further emphasizes the role of wood as a renewable and environmentally friendly material.

The balanced view of SFO should be continuously reflected on the best forest practices developed to meet local, regional and global needs of forests and people. The concept of SFO is not intended to provide any specific performance standards, but rather it provides an overarching framework in which individual performance and evaluation criteria can be developed for appropriate scales and purposes. Development of region-specific, practically relevant performance criteria are highly desirable that meet local needs and maintain flexibility to evolve and be capable of incorporating ever-changing work environments and challenges.

For the practicality of SFO, it is essential to: (i) promote operationally safe, environmentally responsible, locally acceptable and economically viable forest mechanization; (ii) invest in workforce training that improve not only operational skills but also awareness of health and safety issues and quality operations that are sensitive to changing work conditions; (iii) develop certification programs to meet and enforce operator and performance efficiency standards; (iv) encourage forest professionals to improve their management skills and sustainable business strategies; (v) improve the forest workers' health and safety without compromising the profitability, viability and economic competitiveness of forest business and practices; and (vi) encourage renovation and innovation of forest machinery in order to improve the efficiency and reduce the negative ecological impact of forest operations. It is crucial for local, regional and global markets to recognize the important role of wood products and their sustainability in the bio-economy, and therefore provide their fair values in order to fulfill or further expand the sustainability of forest operations.

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