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A Framework for Addressing Multiple Ecosystem Services in Forest Management Planning

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Abstract

Background: Forest policy and decision makers are challenged by the need to balance the increasing demand for multiple ecosystem services while addressing the impacts of natural disturbances (e.g. wildfires, droughts, wind, insect attacks) and global change scenarios (e.g. climate change) on its potential supply. This challenge provides the motivation for the development of a framework for incorporating concerns with a wide range of ecosystem services in multiple criteria management planning contexts. Thus, the paper focused on both the analysis of the current state-of-the art in forest management planning and the development of a conceptual framework to accommodate various components in a forest ecosystem management planning process.

Results: Based on a thorough recent classification of forest management planning problems and the state-of-the-art research, the key dimensions of that framework and the process were defined. The emphasis is on helping identify how concerns with a wide range of ecosystem services may be analyzed and better understood by forest ecosystem management planning. This research discusses the potential of contemporary management planning approaches to address multiple forest ecosystem services. It highlights the need of a landscape-level perspective and of spatial resolution to integrate multiple ecosystem services. It discusses the importance of methods and tools that may help support the involvement of stakeholders and public participation in hierarchical planning processes.

Conclusions: The research addressed the need of methods and tools that may encapsulate the ecological, economic and social complexity of forest ecosystem management to provide an efficient plan, information about tradeoffs between ecosystem services as well as the sensitivity of the plan to uncertain parameters (e.g. prices, climate change) in a timely manner.

Background

Historically, forest management planning has focused primarily on productive functions of forest ecosystems, mostly overlooking other forest ecosystem values or services. As such, management options such as harvesting and regeneration have often been scheduled in order to address timber and revenue flows concerns. Recent demographic and socioeconomic trends have configured a new forest management planning context characterized by concerns with the provision of a wider range of ecosystem services. Currently, forest managers and practitioners are challenged by the need to develop and implement plans to reduce the risk of any biotic or abiotic disturbances, increase ecosystem resilience, increase water yield, protect soil erosion, conserve biodiversity, improve tree growth and vigor, and provide landscape aesthetics and recreational services.

In order to address this challenge new decision making tools are needed that may overcome the increasing complexity of the forest management planning problem, namely the need to examine tradeoffs among multiple political, economic, ecological, and sociocultural dimensions while guaranteeing efficiency as well as acceptability of forest management plans. The forestry literature reports the development and application of several approaches to address the provision of multiple ecosystem services by forest management plans (Baskent and Jordan, 2002; Bettinger and Chunk, 2004; Kangas and Kangas, 2005; Pukkala and Kurttila, 2005; Diaz-Balteiro and Romero, 2008; Ananda and Herarth, 2009; Nordstrom et al., 2010; Borges et al., 2014, Borges et al., 2017). Some authors have focused on the review of approaches to address a specific ecosystem service, e.g., Ezquerro et al. (2016) developed a comprehensive review of techniques used to address biodiversity concerns. Other authors focused rather on the review of advanced methods that might address a wider range of ecosystem services. For example, Baskent and Keles (2005), Shan et al. (2009) and Llorente et al. (2017) examined management approaches to accommodate spatial aspects of forest planning while Bettinger and Chung (2004) reviewed the application of multiple objective optimization methods in forest management. The potential of multiple criteria methods to support the development and social acceptability of forest management plans, targeting several ecosystem services, has also been addressed by several authors (Mendoza and Martins, 2006; Diaz-Balteiro and Romero, 2008; Ananda and Herath, 2009; Kangas et al., 2016; Borges et al. 2017; Fischer, 2018).

Nevertheless, to our knowledge, no structured framework has been presented that may guide forest managers and practitioners develop plans that may target the provision of several ecosystem services. In this research, we present a framework that addresses the planning processes targeting the provision of multiple ecosystem services as well as the features of tools needed to address them. We build from a survey that characterizes the experience and expertise available world –wide to plan for multiple ecosystem services (Borges et al. 2014). We consider the development and implementation of conceptual approaches to multiple ecosystem services management planning and the use of decision support systems to automate these approaches and provide further information about trade-offs between planning criteria. For clarity, firstly, we outline the framework structure, namely its compositional, spatial, temporal and decision-making context dimensions. Secondly, we examine how the framework components relate to stages of the ecosystem management planning process as well as to policy and governance. Thirdly, we discuss the role of decision systems as a key framework technological enabler.

The Framework

The development of our forest management planning framework builds from a recent survey of models, methods and tools to support forest management planning (Borges et al. 2014). This survey classified forest management planning problems according to a set of dimensions and highlighted the values of the spatial scale, the spatial context, the compositional context, the decision making context and the temporal dimensions that are best suited to address the provision of multiple ecosystem services. Specifically, it emphasized the importance of acknowledging the spatial and temporal interactions of decisions made in neighboring stands (or other areal units), as the provision of several ecosystem services (e.g. water, biodiversity) depends on the spatial conditions generated by the spatial layout of management options. It emphasized further the importance of extending the planning horizons to acknowledge the temporal interactions of management options and address ecosystem services sustainability concerns.

Therefore, the framework is characterized by ***the compositional context*** including broad level and finer level classification of forests (Fig. 1). This context contributes to define the range of ecosystem services that the forest may provide, i.e., the goods and services dimension of forest ecosystem management planning problems (Borges et al. 2014). The forest inventory may focus on a coarse level identification of forest types into vegetation associations, habitat types and age classes depending on management objectives. The inventory can also identify landscape into much smaller details of characterization such as stands or cells. Likewise, the framework is also characterized by ***the spatial scale*** extending from a broad level consideration of forest or landscape-level to a finer level consideration of stands. It underlies the need to develop and regularly update a spatial data base for storing and using spatial data (maps and attribute data). The forested landscape must be classified into stands, e.g., homogeneous land units where management options may be implemented providing a uniform (per hectare) ecosystem service outcome. Characterization of forests into the finer units such as stands effects the size and precision of decision variables in developing better model for landscape projection. As well, on-the-ground identification and effective implementation of management prescriptions highly depends on the precision of forest characterization into the stands. Moreover, stands may be grouped into higher level units (such as stand type, vegetation type or habitat type) where a specific forest value may dominate, mostly because of static attributes/variables such as topography (i.e., slope, aspect, elevation) or legislative mandate such as protected areas for biodiversity conservation or some other political necessities. Alternatively, land allocation and stand management scheduling may be integrated rather than developed sequentially.

Furthermore, ***the spatial context*** of management actions is a prevailing consideration within the framework. Among the factors that encourage spatial forest planning are the regulations and voluntary guidelines on the patterns of harvest units and wildlife habitat. Factors that complicate its adoption include technological, financial, and personnel hurdles as well as insufficient data (Bettinger and Sessions, 2003). Nevertheless, international conventions such as biodiversity conservation and sustainable forest management (SFM) initiatives require certain spatial considerations in planning such as interior areas, harvest unit size, riparian buffers and arrangement of patches. These policies acknowledge that some ecosystem services such as water production, wildlife conservation and soil protection depend on the spatial arrangement of management options. For example, the spatial juxtaposition (i.e., neighborhood or adjacency) of management interventions affects parameters such as core area, a proxy indicator for certain target species in wildlife management, calling for a need to address spatial location of harvesting operations.

In fact, characterizing and controlling the spatial configuration, composition and size of patches (i.e., habitats, forest types, stands and age classes) is a major challenge to address in management planning. Specifically; block size, shape, opening size and green-up delay of harvesting units or blocks as well as the core area, edge length, size distribution, and connectivity of forest patches are important spatial indicators. All or some of those indictors are used to account for the provision of several ecosystem services and thus must thus be considered in the framework. Therefore, addressing the spatial dimensions in the framework typically requires the use of exact and/or heuristic spatial optimization approaches (Borges et al. 1999; Falcão and Borges, McDill et al. 2002; Ohman and Lamas 2003; Bettinger and Sessions, 2003; Baskent and Keles, 2005; Constantino et al. 2008; Tóth et al. 2013; Korosuo et al. 2014; Marusak et al., 2015; Llorente et al. 2017).

The framework is characterized further by ***the temporal context*** determined by the long-term strategic to short term operational dimension (Fig. 1). The supply of multiple ecosystem services is achieved predominantly through decisions on how to schedule forest species harvest and regeneration options. The decision alternatives faced by the forest manager are still: when, where, how, and how much to harvest (regenerate and thin). The biological processes involved give particular prominence to medium to long term temporal considerations. Therefore, the framework acknowledges the need to forecast the development of forests over time. Vegetation dynamics models (e.g., forest species growth and yield models) must be used to project over time each stand in the forested landscape. This is key for the simulation of the landscape structure over time and for the generation of the forest management planning problem resource capability models (Borges et al. 2017).

Moreover, when management planning targets multiple ecosystem services, ***the decision-making context*** is often characterized by more than one decision maker and/or other parties with no formal decision-making power and that yet are influenced or may influence the decision (stakeholders) (Borges et al. 2014). Thus the framework is characterized further by a participatory dimension and the need of collaborative planning and consensus building approaches (Fig. 1). Decision-makers and stakeholders have to consider a wide range of often conflicting objectives and to either specify the desired level of achievement or specify the preferences for the various objectives (Martins and Borges 2007, Christensen et al. 2008, Nordström et al. 2009; Ortiz-Urbina et al. 2019). The forestry literature reports several discrete approaches to address multiple decision makers management planning problems (Ananda and Herath, 2003; Nordstrom et al., 2009; Kozat et al., 2009; Kajanus et al., 2012; Khadka and Vacik, 2012; Hujala et al., 2013; Kangas et al, 2016; Nilsson et al., 2016). Nevertheless, the number of management alternatives may require the use of continuous approaches (Borges et al. 2017). Moreover, information regarding the impact of forest management options on objectives and conditions of interest is hardly ever perfect. This has prompted research of management science approaches that may provide additional insights about the resource capability model and the trade-offs between ecosystem services to multiple decision makers and stakeholders (Tóth et al., 2007, Tóth and McDill 2009, Borges et al. 2014, Borges et al. 2017; Marques et al. 2017).

Addressing the decision making context framework’s dimension may require further the analysis of the interests and the power of actors involved. The actor-centered power approach developed by Krott et al., (2014) allows one to evaluate the level of power resources for each actor type and each interest in ecosystem services (e.g., Marques et al. 2020). This may be influential to promote the engagement of decision makers and stakeholders in the planning process and facilitate the development of socially acceptable plans with specific targets for multiple ecosystem services. Having an ultimate authority with all powers and benefits in managing natural assets endangers creativity, sharing and accountability in planning process. Thus, a strong liaison and coordination between the state institutions and civilian stakeholders is necessary, the effective use of technological decision making tools is critically important for effective communication among the stakeholders, willingness as well as enthusiasm of authorities is essential to develop plans targeting the provision of multiple ecosystem services (Baskent et al., 2008). Using quantitative methods, fostering discussion qualities, securing representation and increasing motivation for participation are also necessary components of the structured participation.

Implementing the Framework in Ecosystem Management Planning

Based on the identification of primary processes of contemporary forest management planning, a conceptual flow to encapsulate and harness the framework components may be developed for sustainable provision of multiple ecosystem services (Fig. 2). This conceptual flow starts with the characterization of forest ecosystems through ecosystem inventory and gathering of data from other sources to establish the spatial database (i.e., graphical, attribute and other informal data). Contents, coverage, accuracy and precision of the data are relevant to be able to identify and quantify the ecosystem services. Based on such comprehensive data, planning targets for ecosystem services addressed by national and international conventions, may be formulated to reflect the vision, goals and the strategies of the planning entity. Decision making tools – tailored to address relevant temporal and spatial scales, spatial context and participatory concerns - are used to project future development of forest conditions based on the target and the management strategies. These tools help provide information about trade-offs between ecosystem services as well as about appropriate management schedules and its sensitivity to uncertain parameters (e.g., climate change). The main strategy promises the provision of the appropriate mix of multiples ecosystem services, conforms to the sustainable use of resources, enhances land productivity and accounts for climate change effects. The appropriate schedule is determined on a temporal hierarchy encompassing long term projection to a short term details of operations with or without the involvement of multiple stakeholders. The output of the plan is the proper balance between the sustainable use and conservation of forest ecosystem services in accordance with both national and international regulations and policies.

The flow displays the comprehensive interconnection of components and indicates stepwise process of management planning. The correspondence between the framework components and the ecosystem management planning processes may be summarized as follow;

- **Forest characterization and ecosystem services:** Compositional context, structural characteristics of forest ecosystems and range of goods and services they may provide.
- **Hierarchical planning:** Temporal scale
- **Spatial planning:** Spatial scale and context

- **Participatory planning:** Decision making context with actors, regulations and policies
- **Decision support and knowledge based systems:** Decision support to manage the planning processes.

Forest Characterization and Ecosystem Services

Planning process starts with the inventory and classification of forest landscape into various stand types and use categories based on defined guidelines. Both compositional and configurational characteristics of forest ecosystems are identified to establish a comprehensive forest inventory with a well-developed inventory method. The compositional features include species mix, development stages, crown closure, density and stoking levels while the spatial configuration refers to the size, shape and spatial distribution of stands. The scale or resolution, type and details of stands help identify the quality of the inventory data. The scale ranges from a cell based information to a broader classification of forest types such as hardwood, soft wood or age classes. Given the characteristics of forest ecosystems, the potential forest use categories are then determined, each representing a specific set of values for which the area is aimed to be managed under specific management regimes with certain silvicultural prescriptions. Thus, sound characterization of land use categories and determination of the value-category relationships is highly influential in setting management objectives and conservation targets and developing appropriate prescriptions accordingly for effective decision making process.

At the outset, the classification accommodates ecological, economic and socio-cultural features of forests into a coherent framework providing priorities to the specially designated areas such as statutory areas, legally binding, technically limiting and socially conflicting areas. The quality of ecosystem characterization is associated with the legislative mandate, available resources, technical requirements and societal expectations in addition to the recency, accuracy, consistency and the details of the data. Here, developing a set of criteria and indicators is critical for a scientifically vigorous, socially acceptable and operationally feasible landscape classification. The effectiveness of landscape characterization depends highly on transparent designation criteria, objective oriented management measures, structured participation and the efficient legal and financial instruments.

Ecosystem goods and services (shortly called services) are categorized mainly into ecological, economic and socio-cultural functions, values or benefits according to the SFM initiative. They are the three fundamental pillars of the initiative around which forest management planning is tailored to satisfy the needs of the society. They range from tangible products such as provisioning services of wood and fresh water production to intangible products such as cultural services of recreation and aesthetics (TEEB 2010). Thus, ecosystem services are nowadays identified and classified as provisioning, regulating, cultural, and supporting services according to the classification concept and typology (MEA 2005, TEEB 2010; Castro et al. 2014, Haines-Young and Potschin, 2018). Whatever the ecosystem services are categorized and adopted, the critical point is the characterization (i.e., identification, quantification and valuation) of the ES to be integrated well into the forest management planning process (Costanza et al., 2017; Baskent 2020). In order to integrate ES in management planning and analyze the tradeoffs, they have to be recognized with a developed set of criteria and quantified based on certain parameters. A conceptual framework was well developed and explained to integrate ecosystem services into the multiple use forest management planning process by Baskent (2020).

Hierarchical Planning

Forest ecosystems are naturally developed and organized in a hierarchical structure with larger units at a broader scale (i.e., age class distribution, forest type classification) encapsulating the smaller units (i.e., vegetation types, stands, group of trees) at a finer scale. Decision problems at each level differ in *time horizon*, m*anagement level, spatial coverage, source and detail of information and the risk and uncertainty* associated with the outcome (Gunn 2003). Managing all features of forest ecosystems in a holistic approach may need to address various issues at various scales in hierarchy. Thus, the decision making process involved in planning often encompasses a management hierarchy, ranging from strategic level decisions to operational level ones. The ***strategic level decisions*** relate to the development of broad level policies of land use management and they focus on long-term analysis of resource availability to optimize the performance of the enterprise over time. Long term plans are developed for multiple periods to assess the long term availability of ecosystem services and have to address higher levels of risk and uncertainty that result from its temporal dimension. Specifically, long term resource availability, climate change effects, broad level policy formulations, development of forest composition with limited spatial consideration are tested and determined at strategic level. Thus, broader level allocation of landscape to various forest uses with certain targets and objectives is determined at this level. The output of the upper level models often becomes appropriate constraints for the lower level models due to hierarchical encapsulation of planning features. ***Intermediate or tactical level decisions*** address the most effective use of the resources available to the enterprise in the medium term. Tactical plans try to guarantee long-term wood supply with highest income level. In some cases, the distribution of product types relative to the appropriate assortment categories such as sawlog, veneer, pulp and paper and firewood is determined at this level rather than at the strategic level.   Moreover, the association of silvicultural regimes (e.g., prescriptions) to the land units that result from landscape classification takes into account spatial information that typically is ignored by strategic models. Thus, the spatial details of the implementation of silvicultural interventions as well as of the road network are often taken into consideration at this level to decide where and the products should flow to. Furthermore, available workforce and mechanization, enterprise production plan, seasonal changes in the process of marketing products may also be included at this level. Briefly, the tactical level plans simply involve detailed scheduling of silvicultural interventions on a periodical basis. With the advancement of technology, however, often tactical level decisions are combined into the strategic level ones as large dataset and various management scenarios can be processed and analyzed with various decision making tools. ***Operational level decisions*** consist of scheduling year-around (i.e., monthly, weekly or even daily) silvicultural and transportation activities to make the system function. The operational plans identify the level and the specific time (year, month or week) of harvesting/tending stands, silvicultural plan, forest workforce, logging and transportation means, wood procurement, and assortment, and a number of other processes. In short, the decision-making process at operational level is quite specific, cost effective and detailed for a particular industry or institution, with less risk and uncertainty.

Each model is aimed at a specific level of management and goals and objectives. Indeed, decisions taken at one hierarchical level act as target or constraints on the next lower level decisions. Information feedforward and feedback through the hierarchical plans enables the organizations to function effectively and establish the basis for realization of adaptive management of forest ecosystems (Gadow et al., 2007; Yousefpour et al., 2017; Kaspar et al., 2018). Such hierarchical planning comprehensively covers various levels of information, decisions and requirements so that the whole forest landscape can best be represented for holistic management of ecosystem services.

Spatial Planning

Spatial planning principally refers to the geographic arrangements of both patches such as forest types, stands and habitats and management intervention units such as harvest blocks across a landscape (Borges and Hoganson 2000; Öhman and Lamas 2003; Bettinger and Sessions 2003; Baskent and Keles 2005; Llorente et al., 2017; Yoshimoto and Patrick, 2019). Typically, it is associated to tactical and operational planning levels. Nevertheless, spatial planning features may also be considered over longer planning horizons. Moreover, this is the process that addresses the spatial scale of the management planning problem, namely whether its focus is on stand, landscape or regional scales. Spatial planning accommodates quantitative decision making techniques to incorporate both ecosystem goods and services with spatial features into a forest management plan easily applicable on the ground (Bettinger and Sessions 2003; Kaspar et al., 2016). It is further addressed by planning methods that target the solution of logistics and transportation problems (Karlsson et al. 2004, D'Amours et al. 2008). Policies and regulations of forest management planning in different jurisdictions require certain patterns of treatment units and remaining habitats for either economic of ecological necessities. For example, economics of forest operations calls for appropriate cluster of harvesting operations on spatial locations to minimize the harvesting costs. Wildlife management necessitates un-fragmented landscape focusing on the certain size, adjacency, shape and configuration or arrangement of both harvesting units and habitat patches across a forest landscape (Marušák et al., 2015; Heinonen et al., 2018). Due to combinatorial nature of spatial problem, decision methods used in forest planning have often resorted to heuristic techniques such as simulated annealing, tabu search, genetic algorithm and cellular automata (Baskent and Jordan 2002; Falcão and Borges, 2002; Bettinger et al. 2002; Heinonen and Pukkala, 2007; Shan et al., 2009; Borges et al., 2002;; Pukkala and Heinonen 2006; Dong et al., 2016; Bettinger and Boston 2017). These techniques may use either an area-based or unit-based restriction model to control the size and adjacency of harvesting areas or units (Murray, 1999; Borges et al., 2002; Boston and Bettinger 2002; McDill et al.,2002). The successful use of these techniques depends highly on the architectural design of the spatial model and in the case of heuristics is quite sensitive to the parameters used within the model. For example, the quality of solution is sensitive to the existence of various optional moves in tabu search (Boston and Bettinger 2002; Bettinger et al., 2002) and cooling schedules in simulated annealing (Baskent and Jordan 2002). Since they are inexact techniques, the advantages of various techniques can well be combined to develop hybrid models to generate better solution (Boston and Bettinger 2002). However, there are certain areas to improve the efficiency of metaheuristics in forest planning. These include hybridization with exact models, process improvements, reversion strategies, destruction and reconstruction strategies, intelligent or dynamic parameterization approaches, intelligent termination or transitioning approaches, and seeding strategies (Bettinger and Boston, 2017). Nevertheless, new model formulations have demonstrated the potential of using exact approaches to represent and solve spatial planning problems (e.g. McDill et al. 2002; Constantino et al. 2008; Goycoolea et al. 2009, Tóth et al. 2013).

Aside from harvest scheduling and accessibility; fire, pest, soil and watershed management require certain spatial features or have additional important aspects that call for spatial arrangement of management operations on the ground. For example, spatial juxtaposition of various stand types such as hardwood and softwood stands and topography are crucial elements for fire prevention and effective fuel management (Marques et al., 2017; Moreira et al., 2011). Rainfall runoff models require identification of geographic arrangement of vegetation cover and topography of a watershed (Mirchi et al., 2009). Integration soil erosion into harvest scheduling effectively requires handling of “maximum harvest area” constraints calculated for each stand based on the topographic features and hydrological connectivity (i.e., water flow and LS factor) (Gimenez et al., 2019). Other ecosystem services such as air quality, pollination, water production and wildfire prevention may also have certain level of spatial indications that should be considered by spatial planning. Indeed, global conventions on conservation and management of natural resources require certain spatial considerations in planning such as creation of core areas, limits in harvest unit size, maintenance of riparian buffers and conservation of certain habitats with certain spatial configuration. Besides, connectivity among forest patches is another important spatial feature to be considered in spatial planning (Könnyű et al. 2014). In brief, recognizing the specific geographic location of management interventions can help planners and practitioners better realize the provisions of various ecosystems services requiring spatial restrictions and thus allow them to make appropriate decisions (Baskent 2018).

Participatory Planning

Decision making in forest management planning with multiple objectives is more challenging than ever as decisions have to be made according to economic, ecologic and social perspectives. Such planning process often involves various stakeholders, experts, or decision makers in addition to the forest owners, all of whom may have to use tools to address problems that are characterized by multiple and often conflicting objectives creating a complex decision making environment. To ease and overcome the complexity of management planning with multiple objectives, both technological tools and participatory approaches need to be applied. Participation is generally employed in (i) classifying land base for various forest use categories, ii) setting up management objectives and listing the ecosystem services to provide ii) helping evaluate trade-offs between these services under different management scenarios and iv) selecting to the plan to implement. Informed decisions are in fact taken with structured participation as indicated in Fig. 3.

The first stage of participation is the identification of stakeholders (Martins and Borges 1997). Actors include local and county agencies, forest industries and associations, scientists, local politicians and several other local forest-related organizations. The second stage is to create awareness among the stakeholders on the status of forest ecosystems. The contribution of natural resources to the quality of human life is highlighted for the actors to appreciate the significance of sustainable use of ecosystem services. Information is generated and knowledge base is built to initiate informed discussions for better decision making. In the third stage, various opinions arising on the issues are discussed and the decisions result from a negotiation process. Ecological attributes, quality of life, global warming, and economic considerations are some contemporary issues for discussion. Using quantitative methods in the participatory situation, fostering discussion qualities and securing representation and increasing motivation for participation are necessary for the participatory process of management planning. The ownership history, the present and future management goals, ecosystem services produced, opinion on forest management activities, the forest management tradition, forest legislation, actors in the forest landscape, local conflicts, cooperation and networking are important factors to be considered in the participatory process. One of the most important, yet neglected stage of the participatory process is the sharing of the rights and responsibilities among the key stakeholders towards the co-management or governance of ecosystems. Roles or rights and responsibilities of the stakeholders are to be defined clearly so that the selection of ecosystem services target levels as well as the plan that may provide them is made transparently. It would be quite difficult to see the positive effect of participation on the management of ecosystem services unless this stage is performed. Finally, those who hold the rights to manage the ecosystem services need to be accountable for the results of executing forest management activities to the public in order to build the trust among the public.

Undoubtedly, some forest values may be in conflict with others due to the ecological-economic (e.g. production and conservation functions) and socio-political (e.g., strong coercion, incentives, and dominant information as power resources of stakeholders involved) contexts (Krott et al., 2014; Marques et al. 2020). The actor-centered power approach developed by Krott et al., (2014) allows one to evaluate the level of power resources, for each actor type and each interest in multiple forest values. Such approach can also help identify the conflicts that need to be dealt with in management planning process (Marques et al. 2020).

There are various approaches to address participation in forest management planning. They include multi attribute and multiple criteria decision making techniques such as AHP, ANP, TOPSIS, VIKOR,fuzzy logic, goal programming and Pareto frontier methods . They help elicit the preferences of stakeholders and decision makers (Martins and Borges, 2007; Diaz-Balteiro and Romero 2008; Vacik, 2012; Nilsson et al. 2016; Ortiz-Urbina 2019). They are utilized further to quantify the relative values of ecosystem services, incorporate stakeholder preferences in economic, environmental and social values and increase the transparency and the credibility of management planning process. They have been proven as a useful tool for the analysis of preferences of stakeholders, the negotiation of ecosystem services target levels and to help build consensus, thus contributing to improve the decision-making process. Moreover, they also contribute to the effectiveness of the communication among the stakeholders and provide information to internalize the sustainable management and governance of ecosystem services as common assets (Baskent et al., 2008). Furthermore, setting up legal, institutional and policy frameworks to create an enabling environment for planning involves strengthening institutional capacities as well as collaboration and networking. Participatory planning brings together all interest groups and planners for co-management of a forest landscape and helps to create strong coordination, collaboration, and communication among multiple stakeholders for effective execution of the planning process.

Decision support and knowledge based systems

The development of the forest ecosystem management planning processes (Fig. 2) requires the use of information and communication technology (ICT) so that all components of the framework (Fig. 1) may be adequately addressed. The characterization of the forest and ecosystem services relies on remote sensing as well as on information systems and databases to automate data acquisition and management. Moreover, the efficiency and the effectiveness of hierarchical, spatial and participatory planning depend on the automation of the simulation of the future development of ecosystems and the corresponding resource capability models that detail how each management alternative may contribute to the provision of each ecosystem service. They depend further on the automation of the generation of the decision space as well of the selection of plan proposals. The former brings together resource capability and policy models while the latter encapsulates techniques to search for the plan that approximates most the objectives of the decision makers.

Reynolds et al. (2005) listed the drivers behind the adoption of ICT and the growth of ICT innovations in forest management, namely the advances in scientific understanding of forest systems, public pressure for involvement in resource management decisions, and organizational needs for enhanced competitiveness. Typically, these ICT tools are combined within modular structures such as decision support systems (DSS) and knowledge based systems (KBS). DSS encompass four main modules. The first consists of the database management system, it addresses the compositional and ecosystem services context of our framework. The second consists of a model base that encapsulates the vegetation dynamics model as well as the ecosystem services models (e.g. Bugman et al. 2010; Calama et al. 2010; Botequim et al. 2017; Rodrigues et al. 2020). It is used to generate the resource capability models needed to address the temporal context as well as the spatial context and spatial scale components of our framework. The third consists of a methods base that encapsulates decision-making methods, e.g., as linear programming, mixed integer programming (McDill et al. 2002; Constantino et al. 2008, Tóth et al. 2013), goal programming (Diaz-Balteiro and Romero, 2008; Aldea et al., 2014), stochastic programming (Lohmander, 2000; Kabli et al. 2015), Pareto frontier methods (Borges et al. 2014, 2017; Marques et al. 2017), heuristic techniques (Borges et al 1999, Falcão and Borges 2002; Borges et al., 2002; Bettinger et al., 2002; Borges et al., 2002; Baskent and Jordan 2002; Pukkala and Kurttila, 2005; Pukkala and Heinonen 2006; Dong et al., 2016; Bettinger and Boston 2017). The methods base integrates the resource capability model with the policy model to reflect the ecosystem services targets by the decision makers. It addresses thus the decision-making context of our framework. The fourth consists of the graphical user interface developed so that decision makers or decision analysist may interact with the data, the models and the methods. Typical KBS include three main modules where the first consists of an interface to capture knowledge from experts, the second consists of the knowledge base and its logical models and the third is the explanation interface that builds from logical and inference models to provide information to the decision maker (Mallach 1994). These three modules may help address any of our framework components. As pointed out by Reynolds et al. (2004), hybrid systems that combine functionalities of KBS and DSS, e.g., by KBS symbolic processing of information provided by DSS modules may further improve both the efficiency and effectiveness of forest ecosystem management. Furthermore, simulation and scenario analysis, behavior models, agent frameworks, social networks and multiple criteria methods are additional decision support tools to help analyze and discusses their use to support policy analysis (Garcia-Gonzalo and Borges, 2019).

Reynolds et al. (2008) reviewed some of the more important issues in the development of DSS and KBS for forest ecosystem management and included a synopsis of computer-based tools (Pyatt et al., 2001; Borges et al., 2003; Gardiner et al, 2003; Reynolds et al., 2003; Garcia-Quijano et al. 2005; Lexer et al. 2005¸ Shao et al., 2005; Twery et al., 2005; Remsoft, 2005) that highlights how the availability of these tools may contribute to address concerns with the provision of ecosystem services. Vacik and Lexer (2014) showed further that the design of DSS architectures and the selection of models and methods to encapsulate in its modules have been driven both by forest ecosystem management needs – namely by the range of ecosystem services to consider - as well as by the availability of decision support technologies. The report of the experience of using DSS worldwide does highlight the pervasiveness of its use to address the provision of ecosystem services (Borges et al. 2014). Moreover, recent developments show how these computerized tools have been tailored to address the components of our framework and support the corresponding planning processes. For example, Marto et al. (2018) report the first application of a system that combines knowledge based logical modeling and DSS simulation models as well as decision-making methods to help stakeholders select baskets of ecosystem services and the corresponding management plans. Moreover web-based systems have been presented by Marto el al. (2019) and Rammer et al. (2014) to facilitate the involvement of stakeholders in planning processes and to address adaptive management, respectively, while Nordström et al. (2019) discuss the application of several DSS to address the provision of a wide range of ecosystem services under scenarios of global change.

Socioeconomic and environmental trends impact forest ecosystem management settings and are thus key factors for DSS development (Vacik et al. 2016). Namely, different expectations on future DSS may cause several dilemmas (Vacik et al., 2016):

- Various user groups require complex forest models which might lead to overwhelm decision makers and DSS users.
- Users expect easy to use and smart tools similar apps running on their Smartphone.
- The demand for meaningful cases of forest DSS is increasing, meaning that more emphasis will have to be put on the way in which and how information is presented.
- Emphasis may have to be given to the consideration of the "*joy and play*" factor in the design to decrease the barrier for general use of DSS.

DSS architecture approaches (e.g., Marques et al. 2011) with its emphasis on the involvement of stakeholders on the development of the tools may contribute to usefulness of the DSS (Pastorella, 2016)and thus address these dilemmas. Another possible future development that could help to dilemmas address them is the use of serious games, i.e., "*games that do not have entertainment, enjoyment, or fun as their primary purpose*" (Michael and Chen, 2005). Their use for planning and problem solving grew exponentially in recent years (Laamarti et al., 2014). Rodela et al. (2019) explore further the possibility of using them to support forest ecosystem management planning processes.

Discussions

In this paper, a framework is presented that accommodates various components of forest management planning and a flow of planning process in which those components are integrated. Based on this framework, five components such as decision making context, compositional context, temporal context, spatial context and spatial scale have been defined along a gradient of planning process. *Decision making context* of today's forest management planning needs to take into account multiple actors with multiple criteria decision analysis in a *spatial context* considering geographic configurations of stands/habitats and harvesting units. Most of the ecosystem services require certain level of spatial consideration that should be accounted for in the planning at various *spatial scales*. As well, an accurate stand base forest inventory data is required to represent and characterize landscape with various *compositional context* such as habitat, stand type and stand depending on the detail of the information required. In terms of *temporal context*, management planning is a hierarchical planning process covering the strategic decisions to ascertain long term availability of ecosystem services as well as the details of stand level decisions to develop an on-the-ground applicable management plan.

A set of literature can be found to focus on the review of multiple use forest management planning, particularly models and methods used to address concerns with the provision of ecosystem services in forest management planning. The methods and tools covered in this paper were compiled and evaluated with respect to several schools of thought. For example, Ananda and Herarth (2008) reviewed some apparent MCDM and their implications in forestry, emphasizing the proliferation of hybrid methods as opposed to goal programming to maximize the synergy. It appears that there is still vagueness in decision criteria that should be refined and the value judgement should be promoted through innovative approaches that use schematic diagrams with visualization and animation techniques. A review by

Duncker et al. (2012) developed a framework focusing on five management approaches resulting completely from the intensity of various silvicultural systems spanning from intensive management to close-to-nature approach. In fact, both Bauhus et al. (2013) and Boncina (2011) highlighted the importance of nature-based (close-to-nature) silvicultural system referring to the stand level compositional context (e.g., respecting local site conditions) in integrating nature conservation to ecosystem management framework developed in this study. Another review by Orazio et al. (2017) emphasized the landscape level approach to promote sustainably and vulnerability in forest management planning. Baskent (2018) reviewed the advancements in multiple use forest management planning concept, exploring some components of planning, highlighting the need for improved stand projection models to account for climate changes, upgraded functionality of DSS to accommodate various ecosystem services, use of expert knowledge, better communication with the stakeholders and opportunity to analyze trade-offs. Development and transparent use of analytical tools with additional functionality to integrate multiple objectives accommodating risks and uncertainties are stated as the future challenges in developing a sound management framework. This study report on the aspects of the frameworks to characterize forest management in a planning context, indicating how the methods and tools should be tailored to address the components of our framework and support the corresponding planning processes. The framework developed here has been built upon the evolving ideas, visions and understanding of recent developments in forest management planning and designed to contribute to the advancement of both understanding of forest dynamics and creating knowledge in better conceptualization of management planning framework. Furthermore, this paper can also stimulate a discussion to conceptualize the design of forest management planning by motivating and leading the readers towards a holistic view of planning, just before preparing and implementing a management plan.

Rather than a plain literature review, this paper focused on the conceptual aspects highlighting the theoretical underpinnings, the nature of planning problems, abstract design of management planning and particularly the methods and tools used in the application of the concept. The planning framework and the process developed here can contribute to improve understanding of the spatially oriented multiple use forest management planning concept. The paper highlighted emerging trends in the vision and the use of methods and tools in forest planning. First of all, planning has moved towards characterizing and accommodating multiple ecosystem services to address increasing and varying needs of society. The challenge identified is the quantitative characterization of intangible ecosystem services and integration of them into the planning process for an optimal output. A similar conclusion was drawn in the review of Baskent (2020), providing a conceptual framework to identify, quantify and accommodate ecosystem services in forest management planning.

Spatial planning has become an important component of forest management. Specifically, there is a high trend of tendency concerning the use of spatial panning to address spatial requirements, integrate spatially oriented ecosystem services (e.g., biodiversity conservation and erosion control) and enhance applicability of the plan on the ground. For example, Llorente et al., (2017) recently addressed the spatial facets including adjacency and harvest area limitations, habitat connectivity, edge impacts and proximity considerations for restructuring stand shapes and sizes in management planning. They concluded that operation research techniques can help explore the complex combinatorial nature of the situation, integrate multiple objectives over large landscapes, and make tradeoff analyses for decision makers to better understand forest-wide opportunities, suggesting the use of parallel processing to help increase the practicality of model applications. Recent studies show a shift towards development and using combinatorial optimizations techniques with various exploration and exploitation options, as highlighted by Bettinger and Boston (2017) so that the capabilities and effectiveness of heuristic approaches when applied to spatial problems can be enhanced. It appears that algorithmic advancement can definitely accelerate and proliferate the use of heuristics in spatial planning.

Development and utilization of decision making tools help motivate individuals to easily identify the untested gaps in management planning and design tests that address important hypotheses. Unless, wider planning options are created and tested virtually (i.e., modeling exercise based on scenario analysis), it is impossible to claim a successful design of management framework and its implementing process. Kaya et al. (2016) reviewed the use and evolution of optimization based decision making tools in forest management planning at various spatial levels and revealed that exact methods for optimising systems mainly continue to be used at forest/landscape level, and at the stand level, optimisation seems to now involve exploration of a variety of analytical methods. They noted that realistic approaches such as non-linear programming, multi-criteria approach, scenario analysis and mixing optimization (heuristics) are explored to accommodate multiple ecosystem services. Particularly, integration of multiple ecosystem services with a DSS under climate change effect has been regarded as a contemporary challenge in ecosystem management (Vacik and Lexer, 2014). Based on the review, developing a modular structures of decision tools into a coherent DSS supported by knowledge based systems (i.e., a hybrid system) helps to address the components of our framework, support the corresponding planning processes and thus improve the efficiency and effectiveness of forest ecosystem management. However, perception of using models as panacea (i.e., blind applications of decision techniques) in the case of increasing complex problems and risk and uncertainties may overwhelm decision makers using DSS as noted by Vacik et al., (2016) and Ananda and Herarth (2008). Realizing the use of models as "*a support and game tool*" may better implement our framework components and the associated process in the future.

Current studies on reviewing and developing forest management planning concept indicted certain improvements in solving contemporary forest problems including characterization and integration of multiple ecosystem services, explicit recognition of spatial facets of planning, certain management planning approaches, special silvicultural systems, combination of OR techniques (hybrid systems), behavioral models and trade-off analysis tailored to various facets of forestry problems. Our study analysis the current achievements and envisages future challenges by providing a comprehensive framework with through coverage of planning components and the planning process where those components are integrated into it. In fact, the framework improves upon the contemporary vision of forest management, identifies and characterizes the primary planning components from a broader perspective towards a finer details and assembles them into the planning process. Each component was conceptualized and explored in a way to capture real essence of planning process required in developing a functionally operating DSS based forest management planning model.

Conclusions

Forest management planning is a decision making process involving multiple ecosystem services, planning approaches, methods and tools and multiple stakeholders in addition to the vision, intuition and wisdom of planners. Decision making is greatly challenged by the need to develop a working framework to incorporate various dimensions of planning process and balance between utilization and conservation, considering natural disturbances such as forest fire and climate changes. Key dimensions of the planning framework, defined based on the state-of-the-art research, include spatial scale, compositional context, temporal context, decision making context and spatial context. Thus, the quality of decision highly depends on the consideration of spatial features, multiple stakeholders, stand level inventory data and the hierarchical structure of planning at various scales.

In reality, forest management is dynamic and primarily an initiative to design a comprehensive planning framework with the essential components to achieve evolving objectives based on vision, policy and limitations. In fact, management planning can only be executed successfully with the plethora of accurate data and information at the right scale, regularly obtained from the field and readily accessible with the advanced technologies such as remote sensing and GIS. Up-to-date spatial database base (graphical and attribute) covering the details of landscape structure (composition and configuration) and the knowledge-base gathered from the experts and traditions directly link to the successful preparation of forest management plan. Third, development of a rigorous set of management strategies based on broader/deep understanding of forest dynamics (biological and technological principles) over time and space is an important aspect of successfully management planning. Understanding the cause and effect relationship provides fundamental baseline information to manage the forest ecosystems without jeopardizing ecological integrity and foreclosing the future management options. Such exercises provide an opportunity for adoptive management to improve the effectiveness of planning on the ground. Finally, planning is ultimately limited to quality of the ideas and perception of planning experts in association with the key stakeholders. Structured participation with appropriate role playing and sharing of rights and responsibilities help improve the successful integration of the framework components.

Based on the principle dimensions of the framework, the main components of the planning process were identified and described. The research highlighted the need of a *landscape-level perspective* and of *spatial resolution* to integrate multiple ecosystem services. It strives for heterogeneous matrix of landscape, multifunctionality with a few values, operates at a range of different spatial and temporal scales and deliberately engage the social system with the natural system through various forms of stakeholder participation in decision making. Spatial resolution is critical in developing on-the-ground plans as many ecosystem services connote spatial features and require true spatial representation of objects. *Methods and tools* are the key components to help choose appropriate planning options and support the *involvement of stakeholders* and public participation in hierarchical planning processes to prepare an efficient plan. They enable the test of theoretical visons or hypothesis before implementing them on the ground and understand forest dynamics by virtually exercising various planning options in the future. They encapsulate the ecological-economic-social complexity of forest ecosystem management, information about tradeoffs between ecosystem services as well as the sensitivity of the plan to uncertain parameters in a timely manner. Critical aspects of a comprehensive DSS include generality, user-friendliness, transparency, simplification, abstraction and functionality, besides consideration of the spatial features of planning problem. It is then only possible to realize *adoptive management* approach through circular linking of the theoretical thoughts to the results of management interventions in reality on the ground through decision making tools.

Based on the analysis of related reviews in forest management planning by the prominent researchers, we envisage few emerging challenges of forest management planning that scientists and specifically foresters face today and likely in the future. Acquisition of high resolution forest inventory data, effective handing of large spatial database, quantification of all ecosystem services, developing hybrid decision making tools, three dimensional animated management planning in virtual environment, accommodation of risks and uncertainties, conflict resolution exercises with multiple stakeholders in virtual environment, integrated management of various land uses in a holistic management concept, forecasting and integrating the effects of climate changes on forest landscape dynamics and fast computing opportunities with mega computers using parallel processing features are the prevailing challenges. New generation growth and yield modelling concept is essential to characterize the dynamics of landscape productivity for multiple ecosystem services under natural disturbances such as climate changes. An adoptive management considering integration of stochastic events such as forest fires and insects into the planning is critical in holistic management of ecosystems. A behavioral model is also an emerging challenge to abstract the socio-economic features of forest management problem. A mixture of management regimes and silvicultural operations such as two-stage harvesting and large-scale shelter-wood system other than clear-cut are necessary both to help achieve and balance multiple often conflicting objectives in ecosystem management. Furthermore, benchmarking and assessing *"forest naturalness"* particularly for degraded forest areas is a big challenge for developing appropriate silvicultural prescriptions (i.e., rehabilitation and planting options) and conservation decisions in practical forestry.

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The authors declare no conflict of interest

Authors' contributions

Conceptualization, Emin Zeki Başkent and Jose Guilherme Borges; Writing – original draft, Emin Zeki Başkent; Writing – review and editing, Emin Zeki Başkent, Jose Guilherme Borges and Jan Kaspar.

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Figures

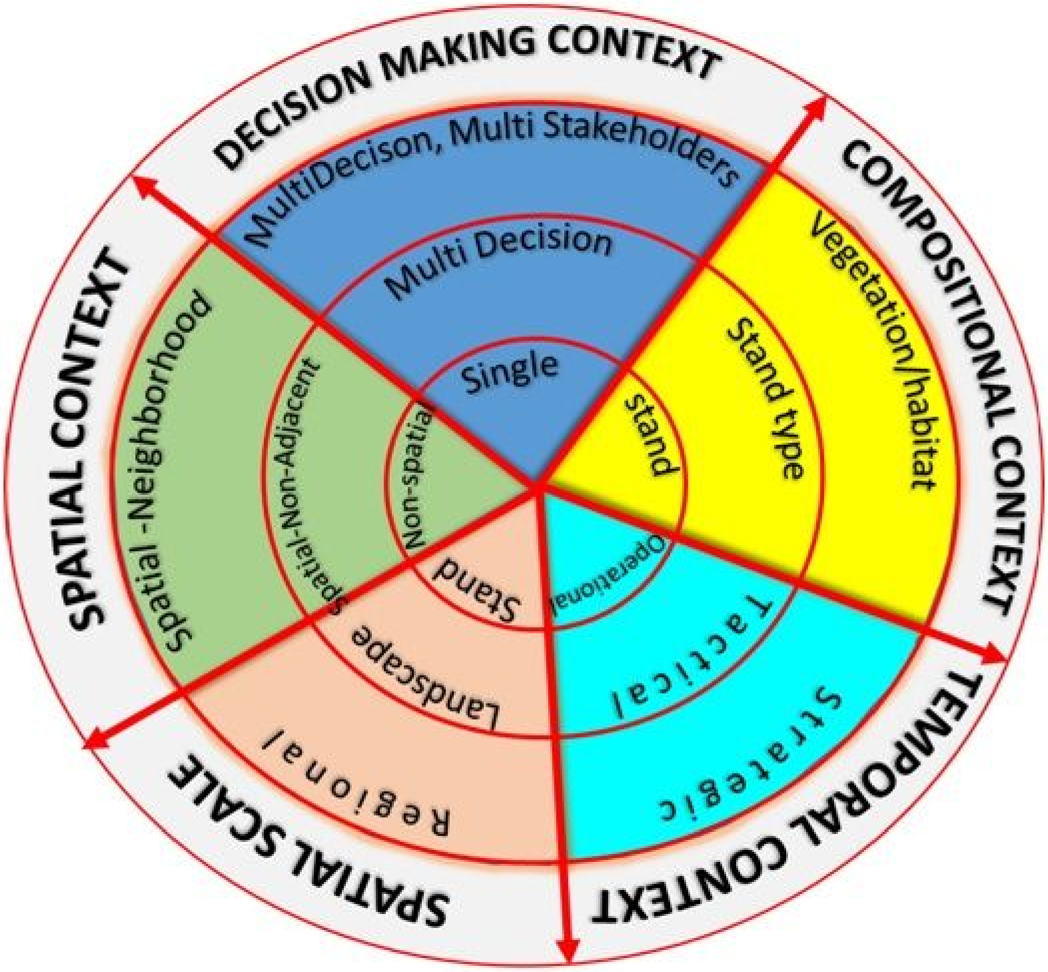

Figure 1

A contextual organization of basic components of the framework for addressing multiple ecosystem services in forest management planning

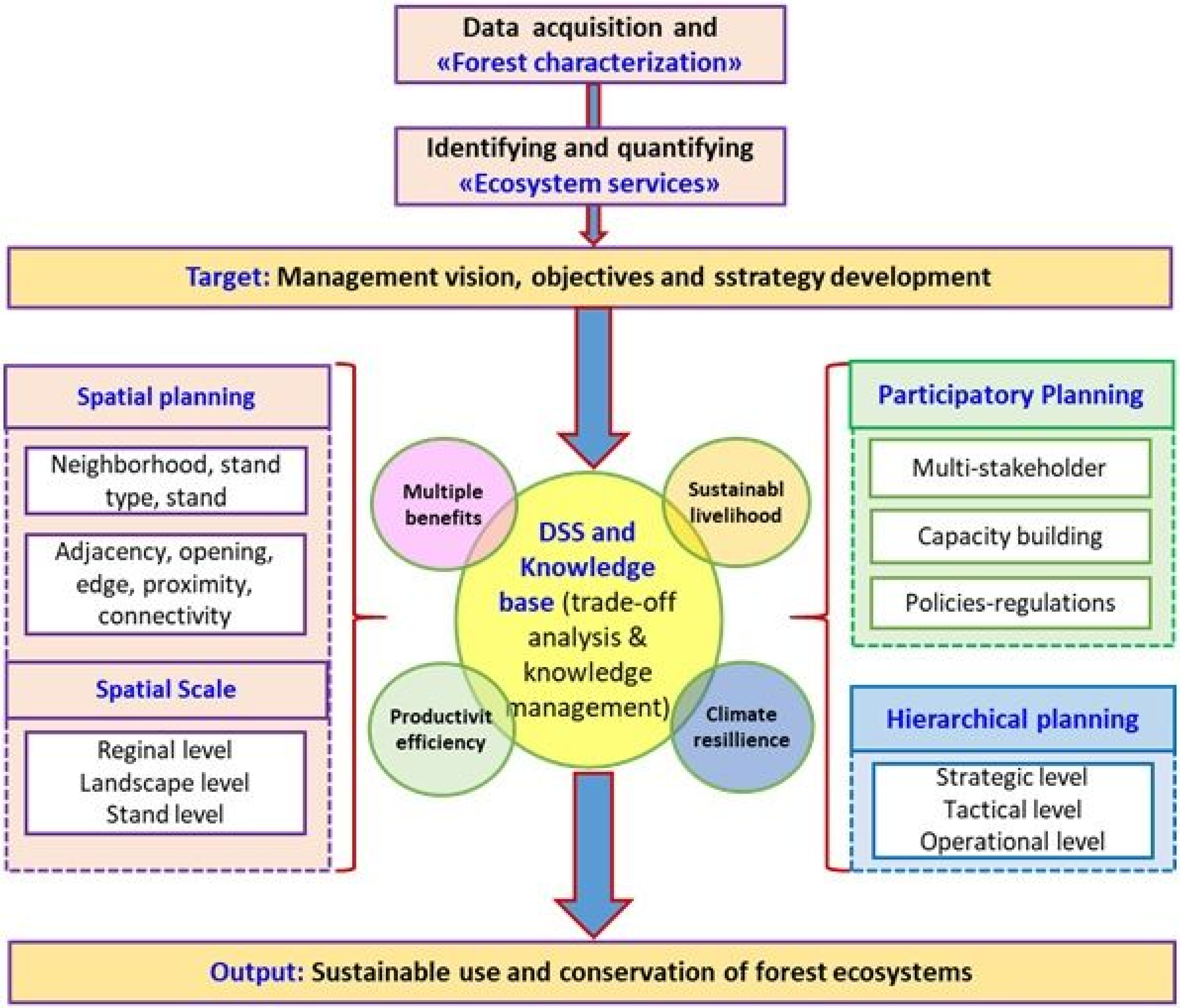

Figure 2

The conceptual framework components indicating the organization and connections to forest ecosystem management planning processes.

Figure 3