UNIVERSIDADE FEDERAL DE LAVRAS

LUCIANO CAVALCANTE DE JESUS FRANÇA

SISTEMAS DE APOIO À DECISÃO ESPACIAL APLICADOS AO PLANEJAMENTO FLORESTAL

LAVRAS – MG

2022

LUCIANO CAVALCANTE DE JESUS FRANÇA

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Florestal, área de concentração em Manejo Florestal, para a obtenção do título de Doutor.

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Orientador

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LUCIANO CAVALCANTE DE JESUS FRANÇA

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SPATIAL DECISION SUPPORT SYSTEMS APPLIED TO FOREST PLANNING

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“Mudar o mundo, meu amigo Sancho, não é loucura, não é utopia, é justiça!”

(Dom Quixote de la Mancha)

RESUMO GERAL

Baseado em evidências observadas nas tendências de temáticas atuais em debates nacional e internacionais, sobretudo no contexto da emergência climática, é que esta tese foi estruturada, preponderamentemente, sob duas abordagens de pesquisa. Dois artigos científicos foram desenvolvidos sob pespectiva do planejamento e manejo florestal espacial. No artigo I abordamos a partir de uma revisão crítica, sistemática e bibliométrica, o estado da arte sobre o manejo de paisagens florestais em todo o mundo nas últimas quatro décadas, aproximadamente, partindo do pressuposto de que a estética e aspectos visual da floresta e sua qualidade ambiental como saída combinatória de modelos matemáticos e modelagens espaciais, pode melhorar a aceitação pública das atividades florestais e aumentar a percepção de sustentabilidade dos empreendimentos florestais. Já no artigo II, preconizamos uma abordagem sobre a transição energética para fontes alternativas e renováveis de geração elétrica, com ênfase na biomassa vegetal produzida por empreendimentos de base florestal. A partir de uma perspectiva de inteligência geográfica e planejamento florestal, desenvolvemos um sistema de apoio à decisão baseado em uma modelagem espacial multicritério em ambiente SIG associado a um modelo matemático de programação linear inteira mista para zoneamento da aptidão e disponibilidade de terras para construção de usinas termoelétricas na Bacia Hidrográfica do Rio Grande (Minas Gerais), aliado a identificação e otimização dos melhores locais de abastecimento (novos plantios e áreas já existentes) para alocação de recursos financeiros e suprimento de biomassa florestal para atender a demanda das potenciais usinas candidatas. Nesta etapa, respostas importantes serão obtidas, tais como: a) quantidade de compra de madeira nos 4 primeiros anos; b) contratos de fomento, compra e arredamento de terras para o plantio nos 6 primeiros anos; c) custos detalhados da atividade; d) mapas dos cronogramas de corte das áreas e; e) fornecimento de biomassa para atender a produção energética anual (50 MW). Em ambos os capítulos geramos resultados importantes para compor os mais recentes tópicos de discussões globais, sobretudo proporcionando ao setor de árvores plantadas no Brasil visões multidimensionais sobre a gestão de paisagens florestais e do desenvolvimento de indústrias termoelétricas baseadas em florestas energéticas.

Palavras-chave: Bioeconomia. Planejamento florestal espacial. Manejo de paisagens. Energia renovável. Florestas energéticas.

GENERAL ABSTRACT

Based on evidence observed in current hot topics in national and international debates, especially in the context of the climate emergency, this thesis was structured in two research approaches. Two scientific articles were developed from the perspective of spatial forest planning and management. In article I, from a critical, systematic, and bibliometric review, we approach the state of the art on the management of forest landscapes around the world in the last four decades, approximately, based on the assumption that the aesthetics and visual aspects of the forest and its environmental quality as a combination of mathematical and spatial models can improve public acceptance of forestry activities and increase the perception of sustainability of forestry enterprises. In article II, we advocate an approach on the energy transition to alternative and renewable sources of electricity generation, with emphasis on plant biomass produced by forest-based enterprises. From a geographic intelligence and forest planning perspective, we developed a decision support system based on a multi-criteria spatial modeling in a GIS environment associated with a mixed integer linear programming mathematical model for zoning the suitability and availability of land for constructing plants. thermoelectric plants in the Grande River Hydrographic Basin (Minas Gerais), combined with the identification and optimization of the best supply locations (new plantations and existing areas) for allocating financial resources and supplying forest biomass to meet the demand of potential candidate plants. At this stage, important answers will be obtained, such as a) quantity of wood purchased in the first 4 years; b) contracts for forest outgrower scheme, purchase and lease of land for planting in the first 6 years; c) detailed costs of the activity; d) maps of the cutting schedules of the areas and e) supply of biomass to meet the annual energy production (50 MW). In both chapters we generate important results to compose the most recent topics of global discussions, especially providing the planted tree sector in Brazil with multidimensional views on the management of forest landscapes and the development of thermoelectric industries based on energetic forests.

Keywords: Bioeconomy, spatial forest planning, landscape management, renewable energy, energy forests.

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PRIMEIRA PARTE

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1. INTRODUÇÃO GERAL

Neste século, um dos maiores problemas em escala global está relacionado as formas de manejo, uso, ocupação e alocação de terras para múltiplas finalidades de acordo com a adequação ecológica, econômica e social inerente a determinado local. Estudos globais tem discutido a influência do planejamento do uso da terra para diversos fins, como suporte a formulação de políticas públicas (SUHARDIMAN; KEOVILIGNAVONG; KENNEY-LAZAR, 2019), na legislação florestal (ATHANASIADIS; ANDREOPOULOU, 2019), na compreensão dos efeitos das mudanças de uso e cobertura da terra (ARMENTERAS *et al.*, 2019), elaboração de sistemas de apoio a decisão territorial para fins de manejo florestal (COSTA FREITAS; XAVIER; FRAGOSO, 2019) e, também para a proteção e conservação da biodiversidade (MIKOLÁŠ *et al.*, 2019).

Diante da importância do tema, ferramentas e metodologias para análise de dados e processos de tomadas de decisão no planejamento do uso da terra, foram extensivamente melhoradas pelo desenvolvimento das tecnologias digitais baseadas em computadores, nas últimas décadas (TÜRK; ZWICK, 2019). Além dos avanços significativos dos sistemas de informações geográficas (SIG), as práticas de planejamento ambiental, territorial e florestal, receberam grande aporte das práticas de programação matemática e pesquisa operacional, utilizando-se das ferramentas de suporte à decisão nas estratégias de alocação ótima de uso da terra. Estas ciências unificadas, podem atestar perguntas importantes, tais como: (I) Quais os benefícios diretos e indiretos no planejamento do uso da terra? (II) Quais tipos de uso da terra podem ser indicados para distintas unidades da paisagem? (III) Quais os tamanhos ideais ou necessários de terras a serem alocados para diferentes formas de uso? (IV) Quais são os impactos ambientais, sociais e econômicos de se aumentar ou diminuir o tamanho da terra alocada para diferentes formas de uso? (V) Como as formas de uso da terra afetam a economia de base florestal de uma determinada região? e, (VI) Pode o planejamento do uso do solo influenciar nas tomadas de decisões para fins de desenvolvimento de indústrias de base florestal? Estas questões, demandam de visão holística e escopos multidisciplinares, que perpassem transversalmente por distintas áreas de investigação científica da ciência florestal.

De acordo com relatório da Indústria Brasileira de Árvores (IBÁ, 2021), o setor de árvores cultivadas brasileiro conta atualmente com 9,55 milhões de hectares de áreas plantadas para fins industriais, sendo 78% dessa área composta pelo cultivo de eucalipto (~7,47 milhões de hectares). Os Estados de Minas Gerais, São Paulo, Mato Grosso do Sul, Paraná, Rio Grande do Sul e Santa Catarina seguem como principais produtores de florestas plantadas no país. Minas Gerais apresenta em seu território 2,06 milhões de hectares de eucalipto plantado.

Dado a representatividade e excelência do Brasil no setor de árvores cultivadas, faz-se imprescindível a manutenção e expansão do adequado planejamento do uso do solo como auxílio a gestores públicos e privados em decisões relacionadas ao desenvolvimento sustentável do mercado florestal. Sendo assim, a abordagem desta tese permeia os ideais do uso dos Sistemas de Suporte à Decisão Espacial (SDSS) como união interdisciplinar das tecnologias da informação, geociências, lógica e modelos matemáticos (MORAES; MELO, 2017).

Os SDSS, conceitualmente, são sistemas baseados em computador que combinam recursos de armazenamento, pesquisa, análise e recuperação de sistemas de informações geográficas (SIG), com modelos de decisão e otimização de algoritmos para apoiar a tomada de decisões sobre problemas espaciais. O termo SDSS originou-se com Hopkins e Armstrong (1985). Os problemas de decisão no SDSS são tipicamente caracterizados por uma combinação de características espaciais e não espaciais, com a primeira registrando as coordenadas geográficas e relações espaciais de um local (ou seja, proximidade, sobreposição, contenção, padrão de distribuição). Os tipos de problemas de decisão incluem seleção de sites, alocação de recursos, roteamento de rede, alocação de local e cobertura de serviço (KEENAN; JANCKOWSKI, 2019), redistritamento político, localização de instalações e planejamento do uso da terra (PONTIUS; SI, 2015).

Seguindo a dinâmica global de tendência no avanço das investigações científicas em ordenamento territorial para fins de suporte a decisão florestal, é que, a partir de dois artigos desenvolvidos nesta Tese, buscamos encontrar respostas para auxiliar gestores florestais no planejamento e uso territorial para fins de tomadas de decisões em projetos florestais e implantação de empreendimentos de base florestal.

2. OBJETIVO GERAL

Promover avanços no conhecimento literário científico sobre planejamento e manejo de paisagens florestais (artigo I) e planejamento florestal espacial aplicado a geração de energia elétrica renovável baseada em biomassa de florestas energéticas (artigo II).

3. REVISÃO DE LITERATURA

3.1. A engenharia no planejamento e manejo de paisagens florestais

As áreas florestais comerciais estão aumentando rapidamente em todo o mundo, em decorrência da necessidade em atender à crescente demanda global por madeira, combustível e fibras (HEILMAYR, 2014), o que, em partes, tem aliviado o desmatamento e a degradação das florestas naturais, além de fornecer vários bens e serviços (LIU *et al.,* 2018). Entretanto, a silvicultura intensiva, assim como a agricultura convencional, pode simplificar a estrutura de ecossistemas naturais (BIRD et al. 2000), reforçando a necessidade da busca por práticas de cultivos mais sustentáveis (JACK; LONG, 1996; FONSECA *et al.,* 2009; VIDES-BORRELL *et al.,* 2019). Assim, embora as plantações florestais tenham um objetivo econômico primário, elas podem servir indiretamente à outras funções ecológicas, tais como a conectividade em paisagens (CABARGA-VARONA *et al.,* 2016). A silvicultura tem sido considerada importante atividade no combate às mudanças climáticas aliadas à benefícios econômicos (NAMBIAR, 2019).

O planejamento de recursos florestais se torna cada vez mais complexo à medida que múltiplos critérios econômicos, ambientais e sociais são levados em conta, tais como os impactos das operações de manejo florestal na poluição da água e erosão de solos (FULTON; WEST, 2002), estética da paisagem (PANAGOPOULOS, 2009), fluxo de biodiversidade (CARNUS *et al.,* 2006) e aspectos socioecológicos (FISCHER, 2018). Além destes critérios, a preocupação espacial no planejamento florestal é fundamental (LIU; LIN, 2015), uma vez que a paisagem é uma extensão espacial ideal para o manejo de florestas, sobretudo pois os processos de tomada de decisão no nível da paisagem podem melhorar a eficiência do manejo florestal (FISHER *et al.,* 2019).

As mudanças na paisagem como resultado das plantações silviculturais, é preocupação constante dos cidadãos em países com setor florestal mais desenvolvido, sendo temática de discussão entre ambientalistas e silvicultores (FAO, 2007). Embora pouca pesquisa tenha sido dedicada ao exame de como a avaliação de impacto visual pode melhorar a aceitação pública das atividades florestais e aumentar a sustentabilidade da floresta (PANAGOPOULOS, 2009), estudos estão sendo desenvolvidos sobre esta questão (RIBE, 2009; JENKINS, 2018), tais como a Irlanda, a tratar da participação das comunidades no planejamento das florestas plantadas e suas funções de comodidade e recreação (KEARNEY; O'CONNOR, 1993; DHUBHÁIN; O'CONNOR, 2009) e; nos Estados Unidos, onde foi analisada a percepção social sobre o impacto cênico dos sistemas de desbastes florestais em áreas montanhosas (PALMER, 2008). Nomeadamente, um dos primeiros estudos sobre os impactos cênicos do manejo florestal, foi desenvolvido por Vodak *et al.,* (1985), em que foram quantificadas as percepções de proprietários de terras florestais não industriais privadas sobre a beleza cênica a partir de diferentes regimes de manejo.

Na Finlândia, foi proposto um sistema de pagamentos por serviços ecossistêmicos, denominado de Valor de Paisagem e Recreação (LRVT), onde os proprietários de florestas seriam compensados por melhorar voluntariamente o fornecimento de valores de paisagem e de lazer em suas áreas florestadas. As práticas de governança florestal aplicadas a este sistema, podem ser encontradas em Tyrväinen *et al.,* (2014) e Tikkanen *et al.,* (2017). No contexto dos pagamentos por serviços ecossistêmicos, Mäntymaa *et al.,* (2019), destacam a importância da qualidade da paisagem florestal para empresas que operam em áreas de turismo, onde concluem que a melhoria das práticas de preparação de áreas, manejo florestal e colheita da madeira, por consequência proporciona melhorias à qualidade da paisagem e, beneficiaria o mercado do turismo de natureza, com aumento no número de clientes e receita.

O turismo baseado na natureza, é um setor econômico crescente e de grande importância em diferentes regiões da Europa (TYRVÄINEN *et al.,* 2014; CBI, 2020). Todavia, nas zonas com produção intensiva de madeira, ciclos curtos de rotação e unidades de manejo de grandes tamanhos, são práticas comuns de manejo, o que pode afetar negativamente a qualidade da paisagem e, assim, diminuir a adequação das florestas ao turismo (Mäntymaa et al., 2019). Estudos sobre preferência florestal de turistas realizados no norte da Europa e nos Estados Unidos, concluíram que as pessoas têm preferencias por apreciar florestas maduras com boa visibilidade, alguma vegetação rasteira e uma camada de campo verde, sem fortes sinais visíveis de manejo florestal (Mäntymaa *et al.,* 2018) e, podem ser vistos nos exemplos apresentados por Gundersen e Frivold (2008) e Ribe (2009). No entanto, é importante destacar que em florestas de propriedade privada, faltam incentivos econômicos para que os proprietários produzam estes valores de paisagem e recreação (Mäntymaa *et al.*, 2019). Para maior aprofundamento em aprimoramentos de valores cênicos e recreativos em florestas privadas, recomendamos a leitura de Tyrväinen *et al.,* (2020).

O manejo de paisagens florestais, historicamente, apresenta alguns projetos de destaque, tais como no estado americano do Minnesota, que na década de 90, já desenvolvia programa de qualidade de suas indústrias de base florestal, publicando em 1994 um guia de práticas sustentáveis de manejo florestal (*Visual Quality Best Management Practice*) direcionado a qualidade visual no manejo das suas florestas (USDA, 1994) e, antes mesmo disto, o Serviço Florestal dos Estados Unidos já havia desenvolvido o Programa Nacional de Gerenciamento da Paisagem Florestal (Bacon, 1979), em resposta à crescente preocupação pública pelo recurso visual das florestas plantadas e nativas. Outros aspectos como o aproveitamento dos povoamentos florestais e áreas de preservação permanente para usos como a recreação e melhoria da qualidade estética das rodovias (Magro, 1996), também já eram discutidos no final do século passado.

Na Grã-Bretanha, no final da década de 90, foi publicado a obra de Bell (1999), um importante estudo sobre o manejo das plantações comerciais do país, considerando as grandes preocupações locais com o impacto negativo histórico dos maciços povoamentos florestais na paisagem, que levaram os silvicultores a desenvolver novas abordagens para o estabelecimento de florestas plantadas, nomeadamente com as práticas de redesenhar as florestas existentes à medida que atingiam a idade de corte. Com isto, o país desenvolveu um ambicioso programa de reestruturação das paisagens florestais comerciais.

Outros estudos, nomeadamente na década de 80, demonstraram sobre designações relativas ao uso da terra que afetam percepções de beleza cênica em paisagens florestais (ANDERSON, 1981). No mesmo período foram desenvolvidos modelos estatísticos para análises da beleza cênica de paisagens de florestas de pinheiros, relacionados à dados de inventário florestal para estimativa a partir de equações de regressão, que foram derivadas para combinar medidas das características locais, incluindo número de árvores de diferentes espécies e tamanhos, quantidade de madeira abatida e quantidade de cobertura vegetal do solo, em estimativas da qualidade cênica percebida dos locais (SCHROEDER; DANIEL, 1981). Brown (1987) em estudo aplicado para uma floresta de pinheiro, analisou modelos de beleza cênica para examinar compensações entre qualidade cênica e valor presente líquido dos rendimentos em madeira da floresta. Brush (1979), em Massachusetts, buscou avaliar a atratividade das florestas comerciais sob as percepções de proprietários florestais da região, verificando que a maior parte dos proprietários consideravam a manutenção da qualidade espacial após tratos silviculturais, e que grandes espaços abertos eram de menor atratividade para os proprietários avaliados.

Preocupações semelhantes sobre a estrutura espacial de plantações florestais, também são consideradas para o Mediterrâneo (GONZÁLEZ-MORENO, 2011), onde vários países dessa região têm direcionado esforços para converter plantações de pinus em florestas mistas e mais diversas. Na Espanha, Cabarga-Varona *et al.*, (2016), analisaram a importância das extensas áreas com plantios de *Eucalyptus globulus*, como mecanismo para melhoria da conectividade entre manchas de florestas nativas. Na Suíça, Ewald (2001) destacou a necessidade da melhoria no planejamento paisagístico também relacionados à silvicultura no país. Na silvicultura de outros países da Europa Central (tais como Áustria, República Tcheca, Alemanha, Eslovênia, Suíça), o conceito de manejo florestal multiobjetivo, geralmente referido como silvicultura multifuncional, é utilizado desde o final do século XX (KOCH; SKOVSGAARD, 1999), e se tornou uma das principais ferramentas de política e planejamento de base espacial para a prática do manejo florestal de múltiplos objetivos (BONČINA *et al.*, 2019), com destaque a função das terras florestais para além apenas da produção de madeira.

Na América do Sul, nomeadamente no Brasil, questões ambientais e sociais nos critérios que norteiam o manejo florestal sustentável também têm sido consideradas desde os anos 90, sobretudo em empresas do ramo de papel e celulose (AUGUSTI *et al.*, 2005). A incorporação de restrições ambientais, em especial aquelas envolvendo o manejo do espaço e da paisagem, tem constituído em um dos campos de fronteira do conhecimento da pesquisa internacional na área de otimização do planejamento do manejo sustentado de florestas. O problema abordado mais frequentemente nesses estudos é a limitação da área máxima contínua de corte por período do horizonte de planejamento. Outro ponto é a escolha de áreas para compor corredores de conectividade entre fragmentos da paisagem (MOREIRA; RODRIGUES, 2010). A conectividade da paisagem é um fator chave para a conservação de habitats para biodiversidade, uma vez que garante o intercâmbio genético entre as populações e a disponibilidade de ambientes hábitats (CABARGA-VARONA *et al.*, 2016). Moreira e Rodriguez (2010) utilizaram de uma heurística para incorporação de corredores de conectividade no manejo de florestas comerciais.

As práticas de desenho e paisagem em larga escala tem influenciado no planejamento do uso da terra por muitas décadas. A Comissão Florestal Britânica desenvolveu no início da década de 1960, um programa para encontrar maneiras de superar os padrões regimentados de florestação de plantações não nativas de coníferas, colocadas em linhas retas e quadradas nas colinas declivosas e anteriormente abertas. Tais informações podem ser encontradas na obra clássica de Crowe (1966), desenvolvido à época a partir de estudos das florestas e bosques da Inglaterra, Escócia e País de Gales. Com base nas iniciativas britânicas, o Serviço Florestal dos EUA introduziu um programa formal de paisagismo em 1971, com a publicação de conteúdos científicos sobre diversos temas, como corredores de transmissão de energia elétrica, estradas e montanhas de esqui e recreação. A obra original pode ser vista em USDA (1974).

No Canadá, a British Columbia introduziu as estratégias de manejo da paisagem visual por volta de 1980 (BC MINISTRY OF FORESTS, 1981) e mais tarde, em 1994, enfatizou o design da paisagem nestas estratégias (BC MINISTRY OF FORESTS, 1994). Em meados dos anos 1984, a análise e o planejamento considerando os valores estéticos da floresta na paisagem foram formalizados com a publicação do "Estratégias de Gerenciamento de Paisagens" para a província Canadense de Alberta (ALBERTA FORESTRY, 1988), detalhando regras básicas de planejamento e operação da colheita da madeira em atenção aos recursos visuais.

No Brasil, na década dos anos 1990, um conjunto de justificativas foram apresentadas durante um congresso, que evidenciavam a necessidade do setor florestal do país assimilar a preocupação com o impacto visual das operações de colheita da madeira, reconhecendo que as atividades florestais exercem efeitos positivo ou negativo na qualidade cênica da paisagem, o que é um importante fator para o estabelecimento de programas de melhoria ou manutenção da qualidade paisagística de áreas com florestas plantadas. As obras originais podem ser vistas em Magro (1996) e Seixas e Magro (1998). Para esta região, não encontramos pesquisas mais recentes com foco especificamente neste tema, sendo um importante campo para investigação científica.

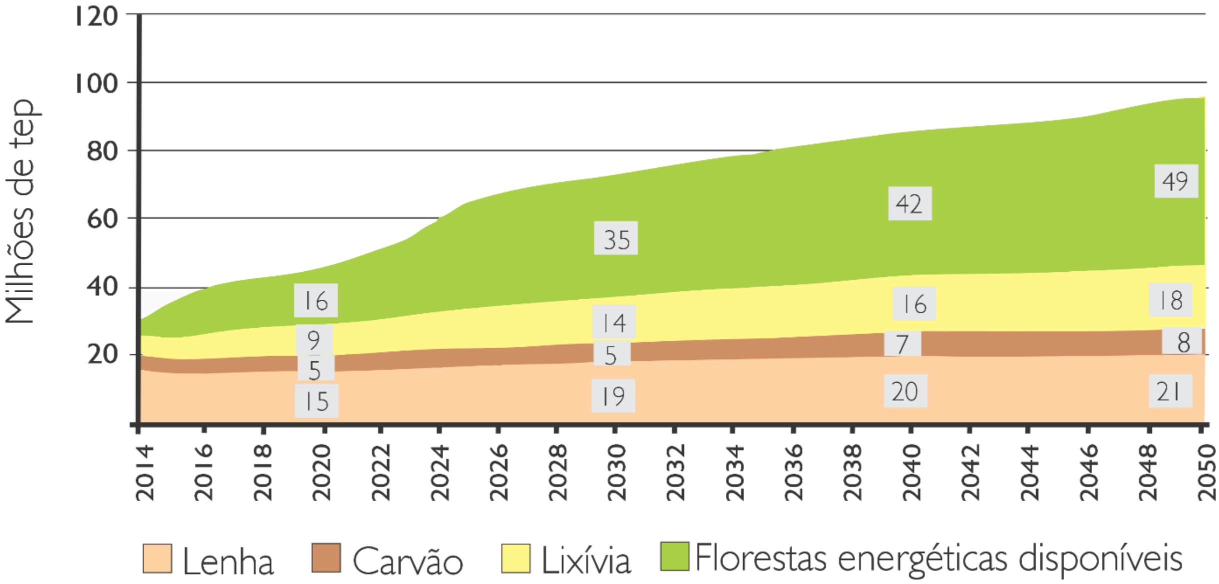
3.2. Por que todo o mundo está falando sobre biomassa?

Nos últimos anos, formuladores de políticas e analistas de todo o mundo deram alta prioridade à expansão da temática de bioeconomia, que cria uma economia social e ambientalmente sustentável, reduz a dependência de recursos fósseis, fornece matérias-primas e energia renováveis, cria empregos em áreas rurais áreas e melhora a competitividade nacional ou regional (LAZORCAKOVA *et al.*, 2022). Conceitualmente, a bioeconomia é o uso sustentável e inovador de biomassa e conhecimento biológico para fornecer alimentos, rações, produtos industriais, bioenergia e outros serviços (LEWANDOWSKI *et al.*, 2018).

A exploração da biomassa florestal para produção de energia é importante na consecução de diferentes objetivos, como a redução da emissão de gases de efeito estufa, a substituição ou coexistência com combustíveis fósseis e a redução do suprimento de energias externas. O desenvolvimento da geração de energia de biomassa atraiu a atenção mundial (ZHAO; LI, 2016). A biomassa é um termo que inclui todo o material orgânico proveniente de plantas, incluindo árvores, culturas e algas. Os resíduos industriais e municipais também foram considerados biomassa devido à sua elevada percentagem de madeira e matéria orgânica (FROMBO *et al.*, 2008). Esse produto nobre representa cerca de 27% da oferta interna de energia primaria utilizada no Brasil, a cana de açúcar com o etanol e o bagaço de cana representam 15,7% do total, a madeira e seus derivados (lenha, carvão vegetal e lixívia) representam 9,9% e, as demais formas de biomassa 0,8% (BALANÇO ENERGÉTICO NACIONAL, 2015).

A geração de energia elétrica no mundo, é baseada principalmente em combustíveis fósseis, como o carvão, óleo e gás natural, seguidos das energias hidráulica e nuclear. Já o Brasil, embora tenha matriz energética baseada em hidroeletricidade, contanto, há grande crescimento das energias eólica e solar (IEA, 2021). Apesar disso, a disponibilidade de biomassa florestal brasileira deve atingir 166% de crescimento para usos energéticos até 2050 (Figura 1). O segmento industrial de Celulose e Papel e a geração termelétrica são os principais responsáveis pela expansão da oferta de energia de base florestal (EPE, 2018; EPE, 2020). O armazenamento de energia através de florestas plantadas até o momento da demanda, potencializa a importância econômica do setor florestal brasileiro na produção de energia elétrica renovável. Ao contrário da energia eólica e solar, os recursos de biomassa podem ser armazenados fisicamente e usados sob demanda. O armazenamento adequado pode garantir a disponibilidade de biomassa ao longo do ano para conversão de energia (van Leeuwen et al., 2021).

Figura 1 – Produção de biomassa florestal para as demandas de lenha, carvão e papel, e celulose, e disponível para florestas energéticas, em milhões de tep (tonelada equivalente de petróleo).



Fonte – adaptada: Ministério de Minas e Energia – Empresa de Pesquisa Energética (EPE).

Novas tecnologias capazes de converter resíduos florestais em bioenergia sustentável e de alta qualidade e produtos biológicos úteis estão surgindo (HAN *et al.*, 2018). Todavia, a localização de uma usina de bioenergia é afetada por uma ampla variedade de fatores, que devem ser considerados, uma vez que a localização de uma usina é altamente influenciada pela localização da matéria-prima de biomassa (DALIVAND *et al.*, 2015). Além disso, um projeto de usina bioenergética à biomassa deve levar em consideração fatores ambientais e sociais para determinar o número, localização e tamanho das instalações dentro da rede de pontos de coleta de matéria-prima, plantas e unidades de armazenamento (BURAK *et al.*, 2011). Por outro lado, o uso da programação matemática tem contribuído significativamente para a gestão de recursos. Um caminho alternativo, caso os modelos tornem-se complexos, é a adoção de métodos meta-heurísticos para a localização de instalações.

A transição energética tem sido um processo contínuo em todo o mundo (CHEN, B. *et al.*, 2019), sendo essa pauta de geração de energia elétrica, juntamente aos problemas inerentes ao aquecimento global, os maiores desafios enfrentados neste século. Esses eventos climáticos extremos e o aumento de temperatura devido às mudanças climáticas, estão tendo impactos drásticos no ambiente natural, enquanto ameaçam o ecossistema e a segurança alimentar (LITTLEFIELD *et al.*, 2017; CHANG; LOU; KO, 2019). Um importante marco destas discussões a nível de acordo global, foi o chamado Acordo de Paris, estabelecido em 2015 para reduzir a escala da economia baseada em combustível fóssil e geração de energia elétrica por fontes renováveis (UNFCCC, 2015). Assim, a substituição das fontes convencionais por modelos bioenergéticos, tem sido o foco em países desenvolvidos.

É verdadeiro o potencial de bioenergia do setor florestal (CHANG; LOU; KO, 2019), sendo a biomassa florestal uma das fontes de energia que possibilitam uma das maiores taxas de geração de emprego por recurso monetário investido (BRITO, 2007). Atualmente no Brasil, um importante exemplo de Temoelétrica à biomassa florestal, é o caso da UTE Onça Pintada (Figura 2), da companhia de celulose Eldorado Brasil, que iniciou em 2021 a operar a maior termoelétrica movida à biomassa do país. O projeto é o primeiro do Brasil a utilizar tocos e raízes para produzir energia renovável. Com capacidade de gerar energia suficiente para abastecer uma cidade de 700 mil habitantes, a usina contou com investimentos da ordem de ~400 milhões de reais, com 50 megawatts de capacidade, a usina tem capacidade para gerar 432 mil megawatts de energia por ano (FORBES, 2021). A usina irá consumir, diariamente, cerca de 1.500 toneladas de biomassa de eucalipto (SANTI, 2021). A energia será entregue ao sistema elétrico nacional, via Ambiente de Contração Regulado (ACR).

Figura 2 – Usina termoelétrica Onça Pintada, Três Lagoas (MS).

Fonte: Correio do Estado e tissue online

4. CONSIDERAÇÃO GERAIS

As revisões de literatura apresentadas contextualizam os capítulos apresentados na Parte II desta Tese, notadamente relacionado aos temas estruturados. Em ambos os artigos desenvolvidos há influência direta dos Sistemas de Apoio à Decisão Espacial, Manejo Florestal, Planejamento e Otimização Florestal. Com os estudos aqui apresentados, espera-se obter descobertas importantes para composição dos mais recentes tópicos de discussões globais, sobretudo espera-se oferecer ao acabouço literário do Brasil e ao setor de árvores cultivadas, visões multidimensionais sobre a gestão de paisagens florestais e do desenvolvimento de indústrias termoelétricas baseadas em florestas energéticas.

5. REFERÊNCIAS BIBLIOGRÁFICAS

ALBERTA FORESTRY, Lands and Wildlife, Forest Service, 1988. **Forest Landscape Management Strategies for Albert**a. Pub. No. T/228. Disponível em:< https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/formain15749/$file/ProvGR94.pdf?OpenElement>. Acesso em: 17/01/2020.

ANDERSON, L. M. Land use Designations Affect Perception of Scenic Beauty in Forest landscapes. **Forest Science**, v. 27, n.2, p. 392-400, 1981. https://doi.org/10.1093/forestscience/27.2.392

AUGUSTI, J.C.; FERRAZ, F.F.; FERRAZ, S.F.; SILVA, J.F.; CAMARGO, S.L. Cultivo integrado com florestas naturais de baixo impacto. **Visão Agrícola**, v.4, p. 62-65, 2005.

Disponível em: https://www.esalq.usp.br/visaoagricola/sites/default/files/va04-florestas-plantadas02.pdf

BACON, WARREN R. 1979. **The visual management system of the Forest Service, USDA**. In: ELSNER, GARY H., and RICHARD C. Smardon, technical coordinators. 1979. Proceedings of our national landscape: a conference on applied techniques for analysis and management of the visual resource [Incline Village, Nev., April 23-25, 1979]. Gen. Tech. Rep. PSW-GTR-35. Berkeley, CA. Pacific Southwest Forest and Range Exp. Stn., Forest Service, U.S. Department of Agriculture: p. 660-665.

BALANÇO ENERGÉTICO NACIONAL. **Relatório Ano base 2014.** Empresa de Pesquisa Energética. 292p.: Rio de Janeiro, 2015. Disponível em: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-127/topico-97/Relat%C3%B3rio%20Final%202015.pdf. Acesso em: 20/02/2021.

BC MINISTRY OF FORESTS. **Forest Landscape Handbook.** 1981. Disponível em:< https://www.for.gov.bc.ca/hfd/library/documents/bib36423.pdf>. Acesso em: 17/01/2020.

BC MINISTRY OF FORESTS. Visual Landscape Design Training Manual. **Rec. Br. Publ.** 1994. Disponível em:<https://www.for.gov.bc.ca/hfd/pubs/docs/mr/Rec023.htm>. Acesso em: 17/01/2020.

BELL, S. Plantation management for landscapes in Britain**. International Forestry Review**, v.1, n.3, 1999. Disponível em: https://www.jstor.org/stable/42609191

BIRD, S.; COULSON, R.N.; CROSSLEY JR, D.A. Impacts of silvicultural practices on soil and litter arthropod diversity in a Texas pine plantation. **Forest Ecology and Management,** v.131, v.3, p.65-80, 2000. https://doi.org/10.1016/S0378-1127(99)00201-7

BONČINA, A.; SIMONČIČ, T.; ROSSET, C. Assessment of the concept of forest functions in Central European forestry. **Environmental Science and Policy**, v. 99, p. 123-135, 2019. https://doi.org/10.1016/j.envsci.2019.05.009

BRITO, J. O. O uso energético da madeira. **Estudos avançados,** v.21, n.59, p. 195-193, 2007. https://doi.org/10.1590/S0103-40142007000100015

BROWN, T. C. Production and Cost of Scenic Beauty: Examples for a Ponderosa Pine Forest. **Forest Science**, v. 33, n.2, p. 394-410, 1987. https://doi.org/10.1093/forestscience/33.2.394

BRUSH, R. O. The Attractiveness of Woodlands: Perceptions of Forest Landowners in Massachusetts. **Forest Science,** v. 25, n.3, p. 495-506, 1979. https://doi.org/10.1093/forestscience/25.3.495

BURAK, A.; CULLINAN, H.; WEBSTER, D.; GUE, K.; SUKUMARAN, S.; EDEN, M.; SAMMONS JR, N. Biomass and mill waste utilization opportunities in alabama: Transportation cost minimization, optimum facility location, economic feasibility, and impact. **Environ. Prog. Sustain. Energy**, v.30, p.720–732, 2011. https://doi.org/10.1002/ep.10501

CABARGA-VARONA, A.; ARROYO, N.L.; NOGUÉS, S. The function of plantation forestry in landscape connectivity. **Applied Ecology and Environmental Research,** v.14, n.1, p.527-542, 2016. http://dx.doi.org/10.15666/aeer/1402_527542

CARNUS, J.M.; PARROTTA, J.; BROCKERHOFF, E.; ARBEZ, M.; JACTEL, H.; KREMER, A.; LAMB, D.; O’HARA, K.; WALTER, B. Planted Forest and Biodiversity. **Forest Ecology**, p. 65-77, 2006.

CBI (Ministry of Foreign Affairs). **The European market potential for nature and ecotourism.** Disponível em:< https://www.cbi.eu/market-information/tourism/nature-tourism/nature-eco-tourism-europe/>. Acesso em:23.01.2020.

CHANG, K.-H.; LOU, K.-R.; KO, C.-H. Potential of bioenergy production from biomass wastes of rice paddies and forest sectors in Taiwan. **Journal of Cleaner Production**, v. 206, p. 460–476, 1 2019. https://doi.org/10.1016/j.jclepro.2018.09.048

CHEN, B. Pathways for sustainable energy transition. **Journal of Cleaner Production,** v. 228, p. 1564–1571, 2019. http://dx.doi.org/10.1016/j.jclepro.2019.04.372

CROWE, S. Forestry in the Landscape. **Forestry Commission Booklet**. n.18, 1966. Disponível em: https://www.forestresearch.gov.uk/documents/6423/FCBK018.pdf. Acesso em: 01/05/2021.

DHUBHÁIN, A. N.; O’CONNOR, D. Stakeholders perceptions of forestry in rural areas - Two case studies in Ireland. Land Use Policy, v. 26, n.3, p. 695-703, 2009. http://dx.doi.org/10.1016/j.landusepol.2008.09.003

EPE – Empresa de Pesquisa Energética. **Brazilian Energy Balance 2020.** Summary Report / Year 2019: Rio de Janeiro, 2020. https://www.epe.gov.br/sites-en/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao217/SUMMARY%20REPORT%202020.pdf

EPE – Empresa de Pesquisa Energética. **Resource Potential Horizon 2050.** Nota Técnica PR 04/18, 2018. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-227/topico416/NT04%20PR_RecursosEnergeticos%202050.pdf

EWALD, K. C. The neglect of aesthetics in landscape planning in Switzerland. **Landscape and urban planning.** v. 54, p. 255-266, 2001. https://doi.org/10.1016/S0169-2046(01)00140-2

FISCHER, A. P. Forest landscapes as social-ecological systems and implications for management. **Landscape and Urban Planning**, v. 177, p. 138-147, 2018. https://doi.org/10.1016/j.landurbplan.2018.05.001

FONSECA, C. R.; GANADE, G.; BALDISSERA, R.; BECKER, C. G. et al. Towards an ecologically sustainable forestry in the Atlantic Forest. **Biological Conservation**, v.142, p.1209-1219, 2009.

FORBES. **Eldorado começa a operar termoelétrica com biomassa de eucalipto**. 2021. Disponível em: https://forbes.com.br/forbesagro/2021/04/eldorado-comeca-a-operar-termoeletrica-com-biomassa-de-eucalipto/. Acesso em: 20/02/2022.

FROMBO, F. *et al.* A decision support system for planning biomass-based energy production. **Energy,** v.34, n.3, p.362-369, 2009.

FULTON, S.; WEST, B. **Forestry Impacts on Water Quality.** Chapter 21. In: WEAR, DAVID N.; GREIS, JOHN G., eds. 2002. Southern forest resource assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 635 p, 2002. Disponível em: < https://www.srs.fs.usda.gov/sustain/report/pdf/chapter_21e.pdf>. Acesso em 28/01/2020.

GONZÁLEZ-MORENO, P.; QUERO, J.L.; POOTER, L.; BONET, F.J.; ZAMORA, R. Is spatial structure the key to promote plant diversity in Mediterranean forest plantations? **Basic and Applied Ecology**, 12, p. 251-259, 2011.

GUNDERSEN, V.; FRIVOLD, L. Public preferences for forest structures: a review of quantitative surveys from Finland, Norway and Sweden. **Urb. For. Urb. Green.**, 7 (2008), pp. 241-258.

HAN, H.-S.; JACOBSON, A.; BILEK, E.T.; SESSIONS, J. Waste to wisdom: Utilizing forest residues for the production of bioenergy and biobased products. **Am. Soc. Agric. Biol. Eng**. p.5–10. 2018.

HEILMAYR, R. Conservation through intensification? The effects of plantations on natural forests**. Ecological Economics.** v.105, p. 204-210, 2014.

HOPKINS, L.D.; ARMSTRONG, M.P. Analytic and cartographic data storage: a two-tiered approach to spatial decision support systems Proceedings, Seventh International Symposium on Computer-assisted Cartography, American Congress on Surveying and Mapping, Washington, DC, 1985.

IBÁ – Indústria Brasileira de Árvores. **Relatório IBÁ 2021 (Ano base 2020).** São Paulo, 2021. Available in: https://iba.org/datafiles/publicacoes/relatorios/relatorioiba2021-compactado.pdf. Access in: 28-12-2021.

IEA – International Energy Agency. **Global Energy Review 2021.** Available in: https://iea.blob.core.windows.net/assets/d0031107-401d-4a2f-a48b-9eed19457335/GlobalEnergyReview2021.pdf

JACK, S. B.; LONG, J. N. Linkages between silviculture and ecology: an analysis of density management diagrams. **Forest Ecology and Management,** v. 86, p. 105-220, 1996.

JENKINS, J. A ‘deep’ aesthetics of contested landscapes: Visions of land use as competing temporalities. **Geoforum**. V. 95, p. 35-45, 2018.

KEARNEY, B.; O’CONNOR, R. The impact of forestry on Rural Communities. The Forest Service (Department of Agriculture, Food and Forestry), 1993. Disponível em: https://www.esri.ie/system/files/media/file-uploads/2015-07/BKMNEXT75.pdf>. Acesso em: 22/01/2020.

KEENAN, P. B.; JANKOWKSKI, P. Spatial Decision Support System: Three decades on. **Deci. Supp. Syst.** 116, 64-76., 2019. https://doi.org/10.1016/j.dss.2018.10.010

KOCH, N.E.; SKOVSGAARD, J.P. Sustainable management of planted forests: some comparison between Central Europe and the United States. **New. For**, v.17, p. 11-22, 1999.

LAZORCAKOVA, E.; DRIES, L.; PEERLINGS, J.; POKRIVACK, J. Potential of the bioeconomy in Visegrad countries: An input-output approach. **Biomass and Bioenergy,** v.158, 2022. https://doi.org/10.1016/j.biombioe.2022.106366

LITTLEFIELD, J. A. *et al.* Synthesis of recent ground-level methane emission measurements from the U.S. natural gas supply chain. **Journal of Cleaner Production,** v.148, p. 118-126, 2017.

LIU, C. L. C.; KUCHMA, O.; KRUTOVSKY, K. V. Mixed species versus monocultures in plantations forestry: Development, benefits, ecosystem services and perspectives for the future. **Global Ecology and Conservation,** v.15, p.2-13, 2018.

LIU, W.Y.; LIN, C.C. Spatial forest resource planning using a cultural algorithm with problem-specific information. **Environmental Modelling & Software**, v. 71, p. 126–137, set. 2015.

LEWANDOWSKI, I. Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy. V. 356., Springer. https://doi.org/10.1007/978-3-319-68152-8

MAGRO, T.C. Manejo de Paisagens em Áreas Florestadas. **Série Técnica IPEF**, v.10, n.29, p.59-72, 1996.

MÄNTYMAA, E.; JUUTINEN, A.; TYRVÄINEN, L.; KARHU, J.; KURTILLA, M. Participation and compensation claims in voluntary forest landscape conservation: The case of the Ruka-Kuusamo tourism area, Filand. **Journal of Forest Economics**, v. 33, p. 14-24, 2018.

MÄNTYMAA, E.; TYRVÄINEN, L.; JUUTINEN, A.; KURTTILA, M. Importance of forest landscape quality for companies operating in nature tourism areas. **Land Use Policy**. (In Press), 2019.

MOREIRA, J. M. M. A. P.; L.C.E. RODRIGUEZ. A incorporação de corredores de conectividade no manejo de florestas industriais utilizando a heurística da *Razão R*. **Revista de Economia e Sociologia Rural.** v.48, n.2, p.255-282, 2010.

NAMBIAR, E.K.S. Tamm Review: Re-imagining forestry and wood business: pathways to rural development, poverty alleviation and climate change mitigation in the tropics. **Forest Ecology and Management**, v. 448, p.160-173, 2019.

PALMER, J. F. The perceived scenic effects of clearcutting in the White Mountains of New Hampshire, USA. **Journal of Environmental Management.** v. 89, n. 3, p. 167-183, 2008.

PANAGOPOULOS, T. Linking forestry, sustainability and aesthetics. **Ecological Economics**, v. 68, p. 2485-2489, 2009.

RIBE, R. G. In-stand scenic beauty of variable retention harvests and mature forests in the U.S. Pacific Northwest: The effects of basal area, density, retention pattern and down wood. **Journal of Environmental Management**. v. 91, p. 245-260, 2009.

SANTI, T. Eldorado Brasil Inaugura a maior usina de biomassa do país ainda no 1º trimestre. *O Papel*, 6p. (reportagem). 2021. Disponível em: http://www.revistaopapel.org.br/noticia-anexos/1611880103_be609cb1e455d9cad0633914e90bc8e8_1511183091.pdf. Acesso em: 20/02/2022

SCHROEDER, H.; DANIEL, T. C. Progress in Predicting the Perceived Scenic Beauty of Forest Landscapes. **Forest Science.** v. 27, n.1, p. 71-80, 1981.

SEIXAS, F.; MAGRO, T. C. Indicadores ambientais e paisagísticos relacionados às operações florestais. **Série Técnica IPEF**. V. 12, n.31, p. 65-78, 1998.

TIKKANEN, J.; HOKAJÄRVI, R.; HUJALA, T.; KURTTILA, M. Ex ante evaluation of a PES system: safeguarding recreational environments for nature-based tourism. **J. Rural Stud**., 52, pp. 42-55., 2017.

TYRVÄINEN, L.; MÄNTYMAA, E.; JUUTINEN, A.; KURTTILLA, M.; OVASKAINEN, V. Private landowners' preferences for trading forest landscape and recreational values: A choice experiment application in Kuusamo, Finland. **Land Use Policy,** (In Press), 2020.

USDA - Forest Service. **Visual Quality Best Management Practices for Forest Manaqement in Minnesota.** Minnesota, 78 p.,1994. Disponível em:< https://www.leg.state.mn.us/docs/2015/other/155133.pdf>. Acesso em: 09/06/19.

VAN LEEUWEN, L.; CAPPON, H. J.; KEESMAN, K. J. Urban bio-waste as a flexible source of electricity in a fully renewable energy system. **Biomass and Bioenergy**, v. 145, 2021. https://doi.org/10.1016/j.biombioe.2020.105931

VIDES-BORREL, E.; PORTER-BOLLAND, L.; FERGUSON, B. G.; GASSELIN, P.; VACA, R.; VALLE-MORA, J.; VANDAME, R. Polycultures, pastures and monocultures: Effects of land use intensity on wild bee diversity in tropical landscapes of southeastern Mexico. **Biological Conservation**, v.236, p.269-280, 2019.

VODAK, M.C.; ROBERTS, P.L.; WELLMAN, J.D.; BUHYOFF, G.J. Scenic Impacts of Eastern Hardwood Management. **Forest Science**, v. 31, n.2, p.289-301, 1985. https://doi.org/10.1093/forestscience/31.2.289

ZHAO, X.; LI, A. A multi-objective sustainable location model for biomass power plants: Case of China. **Energy**, v. 112, p. 1184–1193, 2016. https://doi.org/10.1016/j.energy.2016.07.011

SEGUNDA PARTE – ARTIGOS

Os artigos foram redigidos conforme às normas dos periódicos científicos alvo de submissão.

ARTIGO 01: Submetido à *Trees, Forests and People Journal*

Forest landscape planning and management: A State-of-the-Art Review

Highlights

- A large systematic bibliographic survey of the state of the art in this theme.
- Identification of the latest research trends (1980 – 2021) in this stream.
- The number of publications has increased, especially in the last decade.
- The spatial forest planning of the landscape is an area of research in expansion.
- Hot topics: forest certification; scenic quality and economic benefits; multi-objective functions and spatial environmental constraints.

Abstract. The visual environmental aesthetics as a combinatorial output of a mathematical model can enhance a better public acceptance of forest activities and increase the perception of sustainability of forest enterprises. This article provides a comprehensive review of the state of the art on landscape management in forest areas around the world. In forest planning, little research has examined how the management of the visual impact on wood production can be compatible with the economic viability of forest enterprises. With this review, we seek to contextualize the problem, listing the challenges, trends, and advances achieved recently. The first part of the review is devoted to considerations about the *i*) management of landscapes in forested areas with a history of the evolution of the theme in important global regions, and *ii*) spatial forest planning, including strategies and techniques for operational research, forest optimization, and GIS to solve problems in a landscape scale. In the second part, we present a bibliometric survey to statistically examine the growth of the theme between 1980 and 2021. The number of studies related to the topic has increased, especially in the last decade. North America and Europe are the global regions with the highest scientific production in forest landscape planning and management. There is still little research dedicated to landscape management in commercially planted forests. The approach in the form of spatial structure, considering the inclusion of multi-objective restrictions and functions, is a desirable evolution in the planning and management of landscape sustainable forest plantations.

Keywords: spatial forest planning, linear programming, spatial support decision system, world forests, landscape management, bibliometric analysis.

Graphical abstract

1 Introduction

According to the Global Forest Resources Assessment (FAO, 2020) and The Global Forest Goals Report (United Nations, 2021), the world forest surface is about 4.06 billion hectares, and the natural forests are 93% or 3.7 billion hectares. The total area of planted forests globally is estimated at 294 million ha, which is 7% of the world's forest area. The commercial area of forest plantations is spreading worldwide to supply the global demand for wood, fuel, and cellulose (Heilmayr, 2014). Unfortunately, the side effect on native forest areas (Liu et al., 2018) and ecosystem services (Paruelo, 2012) are high and may lead to a weakness in their structure (Bird et al., 2000) by converting it into uniform mosaics in texture, color, and shapes. These natural areas also have great importance for ecological functions in landscape connectivity (Cabarga-Varona et al., 2016), carbon sequestration and biodiversity (Vihervaara et al., 2012), and water provision and soil conservation (Dai et al., 2018). However, there are positive examples of forest management operations (Liu et al., 2018) with significant advances in global forestry and species habitat (Begotti et al., 2018; Tavares et al., 2019; Pliscoff et al., 2020), forest fire damaged (Lauer et al., 2017) and landscape conservation (Daniel and Schroeder, 1979; Angelstam et al., 2020). Forest management enables the use of degraded, unproductive, and underused land, usually unsuitable for agriculture (Rode et al., 2014; Guedes et al., 2018). Sustainable silvicultural practices are important to mitigate climate change, soil damage and ecological losses (Jack and Long, 1996; Fonseca et al., 2009; Vides-Borrell et al., 2019). Besides, there are social and economic advantages for landowners and industries (Nambiar, 2019).

The policy and management of land use is a complex issue for government and private landowners due to fact that the forest projects are usually extensive areas across. The monitoring process demands high financial investment to guarantee law compliance. An example of this type of effort is seen in Brazil's Rural Environmental Registry or CAR (in Portuguese), which has a concise database of all rural properties (Jung et al., 2017) for environmental and territorial planning (Roitman et al., 2018). However, the traditional log production focuses on reduced cost and maximum revenue, which is disconnected from the landscape sustainable use context (Ewald, 2001). From the other end of this practice, society and world-key-consumers are looking for eco-friendly products and, as consequence, forest managers are planning considering multi-objective criteria (Bettinger and Sessions, 2003; Baskent and Keles, 2005), e.g., water pollution (Hughes and Quinn, 2019), soil erosion and losses (Fulton and West, 2002), biodiversity (Carnus et al., 2006), connectivity among forest reserves (Augustynczik et al., 2018), socio and ecological aspects (Fischer, 2018), recreational spaces and aesthetic aspect value of the landscape (Panagopoulos, 2009).

Landscape modeling and optimization is a promising area of research (Kaya et al., 2016) and can lead to better production in the timber industry (Liu and Lin, 2015) considering the spatial arrangement of stands. In this sense, selecting species or clones within the site provides improvements in forest management efficiency (Fischer et al., 2019). Monodominance of a single species or clone is undesirable due to its lower resistance to diseases, often in the form of homogeneous mosaics (Martins et al., 2017).

The current paper presents a contextualization of the state of the art on landscape management in forest areas under the perspective of spatial forest planning. The main motivation of our assumes that the aesthetic value as a combinatorial output of a mathematical model can enhance a better public acceptance of forest activities and increase the perception of sustainability of forest enterprises. In this review, we also seek to establish a reflection on the use of more fragile landscapes and less productive sites to maximize landscape values, wood production and strengthen indicators of forest certifications.

Recent studies have raised some important frequent questions about this topic. Rönnqvist et al., (2015) have listed 33 open forest problems in operations research. These include the challenge of modeling and solving spatial problems in harvesting, transport, roads, and wildlife conservation; De Pellegrin Llorente et al., (2017) present a set of spatial considerations in planning forest management with a focus on wildlife habitat, invasive species, and costs of harvesting operations; and Baskent et al. (2020) dedicated a state-of-the-art assessment of ecosystem services applied to forest management planning. We believe that our study answers questions not discussed in these previous researches and contributes to the building of bibliographic knowledge, still scarce, on some points of this theme.

Some spatial forest planning problems are open and still theoretical, especially those that aim to achieve aesthetically pleasing and economically viable forests. In this study, we highlight the gap in the need for real commercial cases that assess the return on profits and economic benefits when investing in landscape and ecosystem attributes for timber production. These issues can be essential to companies and forest managers in the face of forest certification practices. Our study is one of the few in that it compiles a state-of-the-art assessment and bibliometric survey on spatial planning for obtaining aesthetically, environmentally, and economically viable forests at the landscape scale. Bettinger and Chung (2004) report in a bibliographic survey between 1950 and 2001 that timber production and economic objectives still dominated the themes of periodical articles, but that despite this, forest management evolved in the inclusion of non-timber objectives. Shan et al., (2009) also reports that in addition to economic and commodity production objectives, the proportion of ecological and social concerns in the objective functions of mathematical models increased notably. We are, of course, aware that there are many other important and interesting areas and questions that we do not include.

The part 1 of this work present Literature Review aimed to trace a baseline of forest science, industry and sustainability considering the principles of the forest landscape sustainable usage practices. Firstly, we report and contextualize the forest landscape management problem challenges, trends, innovations, and scientific advances in the last decades. The review covers the world statistics of global forest, forest plantations, production, planning, decision support systems, landscape ecology, heuristic, meta-heuristic, and geospatial solutions.

In the second part of this paper the state of the art ranges an extensive review by a qualitative and quantitative bibliometric analysis from world indexers. We are seeking to answer **(1)** What is the history of studies on forest landscape management? and **(2)** What strategies and techniques are being used in different fields of research of forest landscape management. A deep literature research is often applied to understand emerging trends (Huang et al., 2020), differently from the traditional bibliographic research (Merediz-Solà and Bariviera, 2019). The bibliometric method is robust enough due to mathematical and statistical metrics applied (Ball, 2018; Uribe-Toril et al., 2019), offering valuable indicators of global scientific research (Aleixandre-Benavent et al., 2017) and forestry research in recent years (Bonnel, 2012; Bullock and Lawler, 2015; Mourão and Martinho, 2020).

2 Databases and research methods

Several indexers with a set of journals and papers are available online, and they store thousands of millions of information regard scientific advances. The most cited database research engines available are Scopus and Web of Science (WOS) with high quality data and citable references (Mongeon and Paul-Hus, 2016; Guz and Rushchitsky, 2009; Huang et al., 2020). We outline this search to meet the connections among concepts, methods, countries, and authors from the acquired scientific knowledge. The search interval was between 1980 to 2021.

Initially, we conducted a bibliographic search focusing on research paper containing the matched the keywords: (*i*) "world forests"; (*ii*) "forest resource management"; (*iii*) "forest landscape management"; (*iv*) "visual landscape management"; (*v*) "spatial forest planning"; (*vi*) "forest regulation"; (*vii*) "spatial constraints"; (*viii*) "adjacency constraints"; (*ix*) "scenic quality and forest aesthetics"; (*x*) "wildlife conservation"; (*xi*) "green-up"; (*xii*) "geographic information systems" and (*xiii*) "spatial harvest scheduling". Later, we also carried out complementary searches of institutional repositories, conference notes, specialized websites, and government reports.

Given an extensive list of documents, we divided the review into two parts: (1) a review addressing the themes: (a) management of forest landscapes by global region, and (b) spatial forest planning with applications in the management of forest landscapes; and (2) the bibliometric analysis. Zhao and Strotmann (2015) methodology were applied for bibliometric analysis highlighting the most impactful studies and research topics. It integrates *i*) definition of the search keywords; *ii*) cleaning, filtering, and formatting the data; *iii*) initial analysis to verify the compatibility of studies and *iv*) statistical analysis of the data.

Finally, we used bibliometric analysis as a systematic review using the term search rule: TS = *("forest planning"* OR *"spatial forest planning")* AND *("forest landscape management" OR "forest visual landscape management" OR "forest aesthetics")* AND *("spatial* *constraints"* OR *"adjacency constraints"* OR *"green-up"* OR *"gis"* OR *"operational research").* The quotation marks guarantee the accuracy of the records that are managed by the bibliographic services, for the exact expression. The keywords used were included in a non-exclusive way, using the "OR" operator to retrieve all possible articles. We considered as search criteria the period between 1980 and 2021 in the WoS and Scopus database. We also filter searches for data articles and review articles only, in English language only and in the categories: Forestry, Remote Sensing and Computer Science. Our intention with this bibliometric analysis is to recognize studies with a direct focus on spatial planning for landscape-scale management. We do not address keywords associated with more specific themes, in order not to inflate the search result. The documents obtained are unique with no replicas containing an identification number in our database collected using BibTex format for RStudio version 1.2.5033 (2019). The network patterns visualization uses the bibliometrix R package (Aria and Cuccurullo, 2017), the most useful and comprehensive tool for the scientific mapping (Camarasa et al., 2019). Besides, the Biblioshiny web interface application (Aria and Cuccurullo, 2017) used to generate the graphics and tables of the bibliometric survey.

3 Result and Discussion

3.1 An overview of global forests

The world forest surface is about 4.06 billion hectares (FAO, 2020) less than 25 years ago. Natural forests are 3.7 billion hectares and planted forests estimated at 294 million ha (United Nations, 2021) (Figure 1). The planted forests have increased over 123 million hectares since 1990 (FAO, 2020). Despite this, between 2010-2015 there was reduction of the planted areas by 1.2% in East and Southeast Asia, North and South America, and Europe (FAO, 2015; FAO 2018; FAO, 2020). However, this value is less than 2.4% to supply all the demand in the world for wood and fibers (Payn et al., 2015). South America has been increasing the planted forest estimates for 26.7 million hectares in 2050 (McEwan et al., 2019). Trees growth rates and land costs affect their expansion significantly. In general, the mean annual increment is 3-4 times in south Hemisphere than the in North (Siry et al., 2005; McEwan et al., 2019). East Asia and Europe reach the largest areas of planted forests followed by North and South America and Southeast Asia. China has 91.8 million hectares, USA (26.4 million ha), Russian Federation (19.8 million ha) and Canada (15.8 million ha) of planted forest area (Payn et al. 2015). Brazil reached 9.0 million hectares (2019) while 6.97 million hectares *eucalyptus* with 35.3 m³/ha.year (IBÁ, 2020). More detail about tree growth pattern can be seen in Schulze et al. (2019).

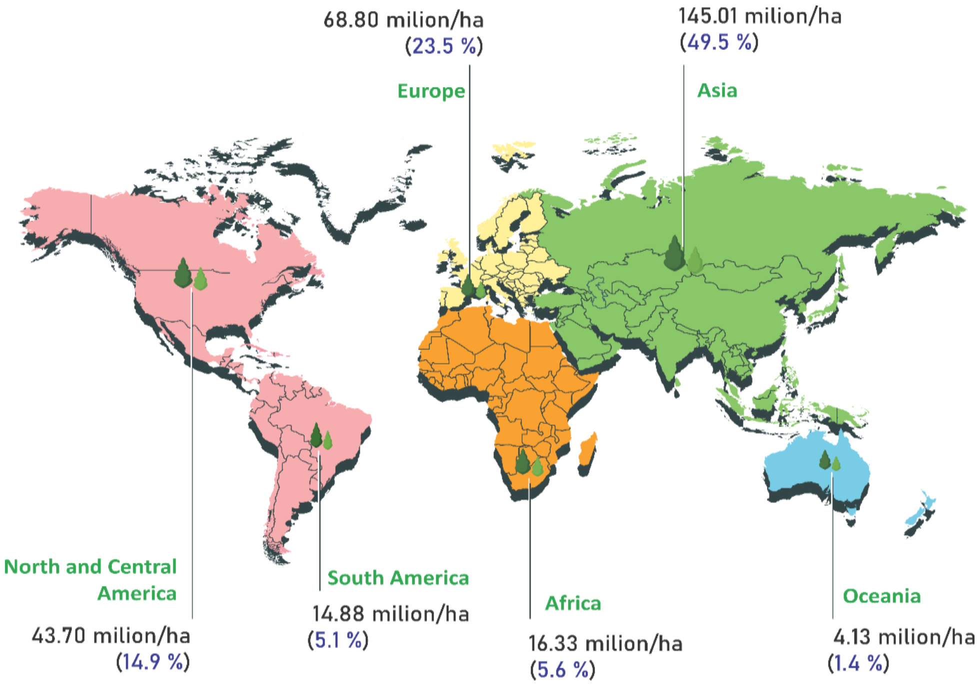


Figure 1. World forest plantation of region and countries (adapted from FAO, 2015; FAO, 2020).

The forestry sector has a relevant contribution for the world trade and economy. Social impacts are also positively for employing directly upper 18.21 million people and indirectly, 45.15 million jobs (Li et al., 2019). Besides, the gross world product (GWP) of the sector was $ 1,298 billion (Li et al., 2019). Recently, the United Nations 2030 Agenda for Sustainable World Development (United Nations, 2015) highlighted the economic growth, quality of social life and environmental sustainability under forest system production in various ways (Li et al., 2019). Concerns about sustainability are increasing, which has incorporated into policymakers' agenda and corporate strategies. The term sustainability itself and its conception have its origins in forestry (Geissdoerfer et al., 2017). Based on forestry principles, the amount of harvested wood must not exceed the growth rate in volume unit. This postulate dates at the beginning of the 18th century from “Sylvicultura Oeconomica” (von Carlowitz, 1713).

Managing forests for multiple objectives proposes is the challenge of the 21st century (Burger, 2009). Several forest products are associated with a range of wood and non-wood services from extensive areas over the landscape (Pretzsch et al., 2015). Generally, these areas affect the pools of carbon storage and balance (Winjum and Schroeder, 1997). Moreover, the forest managers may have to simultaneously work with wood production, energy, recreation, biodiversity, flood control, water quality, and wildlife habitat protection. There are many desirable reasons considering a mixed-species plantation which include ecological benefits (Scherer-Lorenzen et al., 2005), arid and semi-arid soil conservation (Gong et al., 2020) and the increase of soil diversity, structure, and their natural function (Pereira et al., 2019). This system holds many vital ecosystem functions and services been preferred than single-species plantation (Pretzsch and Schutze, 2014). Although, it is not economically viable for global demands within a large production scale.

The challenges for forest management in the world are directly related to new regional demands and integration with technological innovations. Forestry companies have been diversifying and expanding their portfolios through the addition of new non-timber forest products and services (Zivojinovic et al., 2017); The cellulose and paper industries are investing in biorefineries for commercial residual usage (Lynd et al., 2017, Mandeep et al., 2020); Tree clones are pests-resistant and diseases, optimized water uses, and have a high growth rate (Bouvet et al., 2020); Decision support systems and big data for better choices in forest planning (Bettinger et al., 2017) and Currently, automated machines for forest transportation are get involved in especially future works (Rien and Francis, 2021). Forest harvest operations under the restricted area are following the forest management sustainable principles (Marchi et al., 2018, McEwan, 2019). Based on these environmental concerns, Collins (1994) already demonstrated the importance and necessity of the environment as a dominant factor in the technological stimulus of the forest-based industry.

3.2 A whole connection between landscape and forest

Large-scale design and landscape practices have influenced land-use planning for many decades. The British Forestry Commission had a program to overcome the straight and square lines on the sloping in the early 1960s. Previously, the project status of non-native conifer plantations rules for forests and woodlands in England, Scotland, and Wales (Crow, 1966). Building on British initiatives, the US Forest Service introduced a formal landscaping program in 1971 (USDA, 1974). British Columbia/Canada introduced the visual landscape management strategies in 1980, and a decade later, they emphasized the new landscape design (BC Ministry of Forests, 1981 and 1994). The analysis of aesthetic values at the forest planning level was published in “Landscape Management Strategies” for Alberta (Alberta Forestry, 1988). They describe rules for forest harvest planning and visual landscape resources, especially for stand design and layouts forms (line, shape, pattern, size, time, and cutting systems), operations, maintenance, and monitoring. Similar concerns about spatial structure and forest plantations were adopted in Mediterranean area (González-Moreno, 2011).

Since the mid-1980s, the landscape planning and forest harvest operations were connected enough at the spatial level and away from each other principles and goals. At this moment, the sparse published research takes into account the visual impact assessment of forest activities and sustainability (Panagopoulos, 2009, Ribe, 2009; Jenkins, 2018). In Ireland, e.g., the public participation campaign decided the forest decision courses for timber production and recreation proposes (Kearney and O’Connor, 1993; Dhubháin and O’Connor, 2009). The social perception about forest harvest production was evaluated in the United States (Palmer, 2008) and New Zealand (Roche, 2017; Edwards et al., 2018). Generally, all these actions rely on visual quality and sustainable forest operations for rural communities (Brown et al., 2016). The first studies carried out on the scenic impacts of forest management were in Vodak et al. (1985). They measure the private forest landowner’s perceptions about scenic beauty at management regime levels. Brush (1979) also evaluated the attractiveness of commercial forests under the perceptions of forest owners in Massachusetts. Anderson (1981) points out the land use issues and their effects on scenic beauty in forest landscapes.

Naturally, the landscape is straightly related to the recreation and beauty scene (e.g., Europe and North America) and later was absorbed by the multipurpose forest management plans (Panagopoulos and Hatzistathis, 1995; Panagopoulos, 2009). Therefore, the tradeoff production and environmental quality had started as a new forest management version. The document entitled “visual guide for sustainable forest management practices and the landscape quality” (USDA, 1994) proposed by U.S Forest Service and contributors has a program for forest-based industries. These guidelines help ensure that timber harvesting has minimum impact on water quality and natural resources, the so called BMP’s – Best Management Practices (USDA, 1994). BMP’s are mainly developed by individual states in the United States, as guides to forest management activities when state laws are lacking. Even before, the United States Forest Service had already developed the National Forest Landscape Management Program (Bacon, 1979) due to public demands about the forest plantation impacts. Bell (2001) reveals a detailed visual landscape analysis of public participation in forest planning.

The most ambitious works of forest landscapes management are presented at *‘The design of forest landscape – UK’* – Lucas (1991); the guidelines for forest design in British Lowlands landscapes – UK – Forestry Commission (1992); *‘Creating and managing* *woodlands around towns – UK'* – Hodge (1995); '*Visual quality best management practice – USA'* – USDA (1994); '*Designing sustainable forest landscape – COUNTRY'* - Bell and Apostol (2008). Bell (1999) published a protocol study on the commercial plantations' management in Britain. The author revels the great local concerns about the negative impact of the extensive forest on the landscape. The work exposes new challenges for forest managers to develop new compliance and practices of reshaping the commercial stands over cutting age. In Spain, for example, Cabarga-Varona et al. (2016) analyzed the importance of extensive areas with *Eucalyptus globulus* plantations as a mechanism for improving connectivity between patches of native forests. Since the late of 20th century, the commercial forests of Central European countries (e.g., Austria, Czech Republic, Germany, and Slovenia) have multi-objective management goals based on policy and planning tools, emphasis on the role of forest land beyond only wood production (Koch and Skovsgaard, 1999; Bončina et al., 2019). Ewald (2001) highlighted the need for landscape improvement in Switzerland.

In South America, the three countries: Brazil, Chile, and Uruguay; are the only working with landscape issues to guide sustainable forest management. The first country has environmental legislation (Oliveira et al., 2020) for exotic species plantations and recognize the negative landscape impacts after harvest operation. Besides, as an example, there is an experiment called "ecological bands" which preserve native forest strips (25 x 500 m) within eucalyptus plantations (Figure 2). These strips are connected to multiple-proposes as firebreaks, fauna, and species corridors (Zanuncio et al., 2016; Vallourec, 2019). In Chile, the forest plantations certified are around 1.5 million ha and the landscape quality (aesthetics and connectivity) are still incipient (Salas et al., 2016) requesting new forest policy instruments (Mery, 1996). Vihervaara et al. (2012) describing some perceptions between stakeholders (industry and communities in Uruguay) to integrate land uses and ecosystem services.

Figure 2. Ecological bands or corridors between eucalyptus plantations in Brazil. Source: Public Summary of the Forest Management Plan – Vallourec (2020) and Arcgis online satellite imagery.

The Finnish government has a payment system for ecosystem services entitled Landscape and Recreational Values Trading (LRVT). It is a compensatory program for voluntary forest owners that adopt landscape and leisure values in their lands (Tyrväinen et al., 2014; Tikkanen et al., 2017). Mäntymaa et al. (2019) highlight the advances of LRVT applied to tourism in hotspot zones. The program conciliates a range and ambiguous goals for local economy benefits. Today, nature-based tourism is a promissory “green industry” in European economy (Tyrväinen et al., 2014; CBI, 2020) and the forest management practices should mitigate the landscape impacts (Mäntymaa et al., 2019). A detail of practices on scenic and recreational values in private forests can be seen in Tyrväinen et al. (2021). For example, people tend to prefer old-mature forests with high conservation stage them short rotation practices (Gundersen and Frivold, 2008; Ribe, 2009; and Mäntymaa et al., 2018). Therefore, the rotation delays have financial and production effects on forest owners and the government should pay or reduce taxes as a compensatory policy (Mäntymaa et al., 2019). Zabel et al. (2018) suggest a self-sustaining landscape involving a system of taxes resource funds. In such cases, the forest fragmentation and spread habitats may be minimized according to Haines et al. (2019) and Fischer et al. (2019).

Figure 3 describes the common forest landscapes mosaics and their visual impacts. They should be mitigated following some recommendations: i) the establishment of ecological corridors and the permanent protection areas for biodiversity; ii) the spatial stands arrangement and layouts (scale, size, organization, location, shape, pattern, proportion, edge, margin, texture and roads network); iii) forest harvest limits over the relief; iv) heterogeneous stands of trees density, age classes, species, and structure.

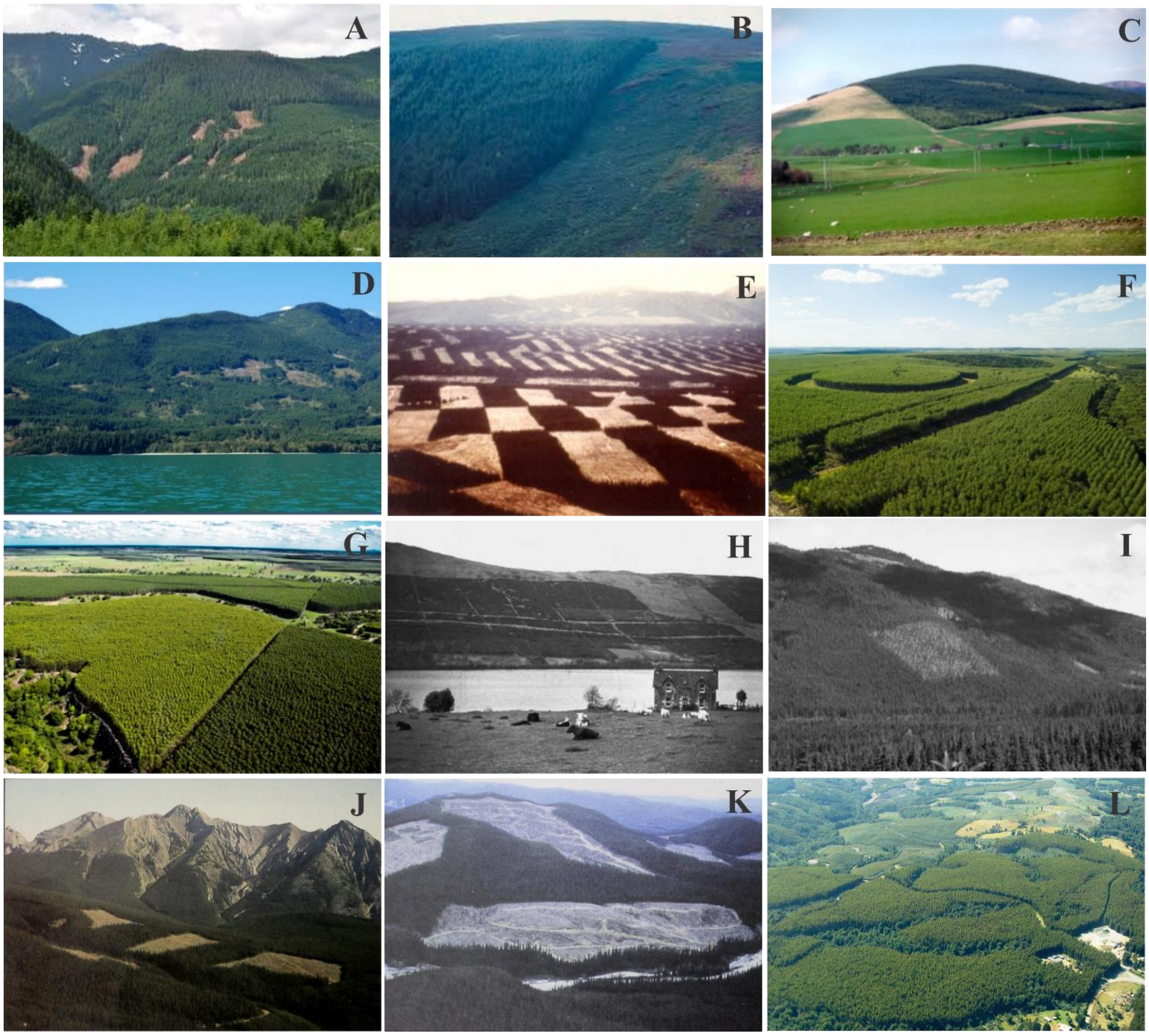


Figure 3. (A) Illustration of the visual impact of forest harvesting in a sloping area; (B) Area with harvested forest cover generating great scenic impact; (C) Forest area also harvested with little regard for local topography compliance - Scotland; (D) Mountainous slope with harvested areas reducing the visual quality of the landscape; (E) Harvesting plots in the shape of a chessboard - Canada; (F) Forested area considering a mosaic with natural forest - Brazil; (G) forestry technique in a mosaic of equine eucalyptus “blocks” interspersed with native vegetation - Brazil; (H) planted and harvested areas with high disagreement and local topography - Great Britain; (I) Harvest in a sloping area, generating a negative visual effect - USA; (J) Visual impact on the harvest pattern in a mountainous forest area - Canada; (K) Significant visual impact of size and harvest on sloping terrain- Canada;

(L) Plots planted in natural forest mosaic - Chile. (*the sources of the images are available in 'supplementary materials').

Currently, the advances of forest landscape management focus on variable retention forestry (VRF) which is an alternative to traditional forest management (Martínez Pastur et al., 2020). According to the author, the method is wide applied over the world integrating environmental, economic, and cultural objectives. Its benefits forest biodiversity and improved harvesting operations (Gustafsson et al., 2012; Gustaffson et al., 2020). The VRF is a practical effort to address global challenges related to the loss of biodiversity in forest areas and compensation for climate change (Shorohova et al., 2019, Franklin and Donato, 2020). In Finland, the Program for the Endorsement of Forest Certification (PEFC) and the Forest Stewardship Council (FSC) require the application of the VRF technique (Kuuluvainen et al., 2019).

Worldwide, forest certification is increasing faster due to customer's demands for sustainability, health, and socioeconomic viability (Garzon et al., 2020). The Green Tag Certified Forestry Certification Programme (American Resources, Inc., 2013) requests an aesthetic quality of planted forests. Further, the FSC certification stimulates forest protection, restoration, and conservation of natural forests, including wildlife corridors, mosaics of ages classes, and rotation to define the plantation layout at large-scales.

The environmental issues of the landscape are the new frontier of knowledge for forest management and planning. The clear-cutting area limits, and the connectivity of vegetation problems are frequently described for landscape management in the literature (Moreira and Rodrigues, 2010). The openings areas have aesthetic negative impacts after harvest operations on a large scale. In certain circumstances, the mathematical formulation with spatial constraints is desirable to solve the forest planning tasks. Chamberlain and Meitner (2009) corroborate an increase the aesthetic design quality and timber production. The authors have modeled a forest harvest scheduling problem aiming at the visual impacts.

Maximizing the aesthetic environmental quality of the forest landscape is relative action according to criteria and objectives of companies, regions, and socioeconomic realities. These challenges can be discussed from the perspective of spatial forest planning.

3.3 Forest planning and landscape design challenges

In this section, we address what is often applied to forest landscape management correlated with spatial forest planning techniques. Global environmental requirements have driven important changes in forest planning models. They merge spatial forest stands with wildlife habitats, scenic beauty, soil conservation, and water protection (Weintraub and Murray, 2006). These interactions are constrained under a range of problems involving stand shape, management regimes, adjacency, maximum and minimum opening sizes, connectivity to natural ecosystems, landscape fragmentation, and road problems. The spatial or landscape structure refers to the relative spatial arrangement of patches and interconnections between them (Baskent and Keles, 2005), and spatial forest planning is conceptualized as a solid forest modeling approach that accommodates spatial requirements and various management objectives. According to Boyle et al. (2016), the sustainable silviculture conception has disseminated in forest industries motivated by ecological issues. Besides, the new silvicultural practices have incorporated social-ecological aspects within forest management regimes. Changes in forest management prescription quickly outdate the operational level and the landscape impacts reducing. However, the early conception of forest regulation provides a sustainable principle for forest management and planning.

Linear programming can accommodate forest management problems that have wood flow and sustainability concerns, with one of the first works applied to forestry published Curtis (1962). In general, there is a linear programming model for solve the forest regulation problems defining the harvest scheduling and future management practices (Hennes et al. 1971). Therefore, the results are integrated for wood supply and silvicultural tasks. Roth (1914) reinforced the challenge faced by forest regulation is not only to order the work of forestry in time and space with the planting or reform of stands, but also to plan an orderly harvest, road construction and environmental conservation. It requires an appropriate distribution of forest ages, yield, size, and wood quality (Leuschner, 1990). There are two classical models widely applied for solve wood supply chain and described by Johnson and Scheurman (1977). Type I and Type II models, used to portray the forest regulation. Both are widely used in natural resource management planning problems. A Model I linear programming problem uses decision variables that track the history of a field or stratum over the entire planning horizon, regardless of when the area will be cut. It is mostly used at the level of spatial forest planning. A Model II linear programming problem tracks the history of a field, only until a final crop is examined. Model II is best suited for age-matched management regimes (Bettinger et al., 2017).

Table 1 shows several examples of functions and constraints applied in forest planning and landscapes management.

Table 1. A brief description of some forest landscape problems and the mathematical model structure.

Authors	**Description**	***Mathematical formulation**
Barahona et al. (1992)	**Objective:** Model for forest planning that considers habitat dispersion objective.	$Maximize\sum Zc_{ij}x_{ij}$
	Constraints: model subject to constraints related to habitat dispersion.	
Williams (1998)	**Objective:** Network wildlife corridor (NWC) model – A two-objective zero–one programming model is formulated for the problem of selecting land for a system of wildlife corridors that must connect a known set of existing reserves or critical habitat areas. The objectives of minimizing corridor land costs and minimizing the amount of unsuitable land within the corridor system**.**	$MinZ1=\sum_{j\in J}c_j(\sum_{k\in A_j}x_{jk})$ $MinZ2=\sum_{j\in J}a_j(\sum_{k\in A_j}x_{jk})$
	Constraints: model subject to "flow balance" restrictions, related to the delimitation of viable regions to connect habitats and link "islands" of native forest fragments.	
Murray (1999)	**Objective:** models for solving forest harvest planning problems with spatial landscape restrictions. This has meant that analysis incorporate specific objectives and considerations aimed at minimizing the impacts of forest activities.	$MaxZ=\sum_i\sum_t a_{it}x_{it}$
	Constraints: model subject to constraints that limits treatment activity in a unit to occur at most once guarantees a minimum level of treatment activity occurring in each time; ensures that a maximum level of treatment activity results in each time; to provide uniform or non-declining timber supplies; restricts the treatment activity of neighboring units, allowing at most one neighboring unit to be treated and constraints that impose integer requirements on decision variables.	
Öhman (2000)	**Objective:** Planning model designed to maximize the net present value and to create continuous patches of old forest (connectivity problems).	$Max\sum_{i=1}^{I}\sum_{j=1}^{J_i}(D_{ij}+\overline{D_{ij}}Y_i)X_{ij}$ $-\alpha\sum_{p=1}^{P}(\overline{C_p}-\sum_{i=1}^{1}C_{ip})^2_{>0}$ $-\beta\sum_{p=1}^{P}(\sum_{i=1}^{1}G_{ip}-\sum_{i=1}^{1}C_{ip})^2$
	Constraints: model subject to the constraints related to a certain amount of 'core area' in the landscape.	
Graetz (2000)	**Objective:** The SafeD model is a spatially explicit, hybrid simulation/optimization model that allows the achievement of multiple resource goals at both the stand and landscape levels, while recognizing stochastic disturbances, and management behavior. The SafeD model designs planning problems as Model I nonlinear integer problems, where individual stands are tracked through time as they are regenerated or disturbed.	$Maximize\sum_{k=1}^{m}\sum_{j=1}^{q}\sum_{t=1}^{n}r_{k,j,t}x_{k,j,t}$
	Constraints: model subject to constraints related to the landscape scale context.	
McDill et al. (2002)	**Objective:** (MILP ARMS) presented two mixed integer-linear-programming harvest-scheduling formulations that include adjacency constraints in the context of ARM.	

	Constraints: model subject to adjacency constraints, but which allow the simultaneous harvesting of groups of contiguous plots whose combined areas are below the predefined limit.	$Max\sum_{m=1}^{M}\sum_{t=1}^{T} c_{mt}.\mathrm{A}_m.X_{mt}$
Moreira et al., (2013)	**Objective:** a mixed-integer linear programming model that guarantees minimal connectivity among fragmented natural areas while maximizing the profit or the production of the managed industrial forest plantations.	$MaxZ = \sum_{i=1}^{n} A_t \sum_{j=1}^{m} D_{ij}x_{ij}$
	Constraints: model subject to constraints related to field integrity, periodic production (annual volume, minimum and maximum), renovation/replanting, annual budget, the flow of the ecological corridor, and connectivity of existing fragments.	
Almada (2018)	**Objective:** multiobjective model that combines the URM for harvest scheduling and a model for connected and compacted reserves known as RCC-nR, species protection.	$Max\sum_{t\in T}\sum_{i\in L}\ell_{it}x_{it}$ $Min\sum_{i\in L} D_{i\gamma}x_{i\gamma}$
	Constraints: model subject to constraints that requires a position to be harvested at most in one period; guarantee that a certain volume of wood is obtained in each harvest period and the constraint that imposes the adjacency constraint that identifies the URM model, so that no restrictions are repeated.	
Augustynczik et al., (2018)	**Objective:** Optimization model was to maximize forest Net Present Value (NPV) while creating new forest reserve areas, respecting a minimum area requirement, and connecting them through a corridor of extensively managed stands.	$MaxZ = \sum_{i\in S} npv_i x_i +$ $\sum_{i\in S} npvExt_i z_i$ $-\sum_{i\in FR} per_i y_i Dc +$ $\sum_{(i,j)\in E_{FR}} 2edge_{ij}n_{ij}Dc$
	Constraints: model subject to constraints related to ensuring that plots are forest reserves, connecting plots or managed plots; Respect the minimum area; Ensuring a set of restrictions on conservation flows; That meets the total production of wood with the inclusion of forest reserves and connection corridor.	

** For details on the coefficients and variables of the model, access the indicated literature.*

Kaya et al. (2016) published a recent worldwide review of forestry optimization, and they concluded that landscape modeling and optimization is a promissory and new research area. Computational challenges have generated research in two directions for solving harvest scheduling problems accounting for spatial and environmental concerns. One research direction is heuristic solution development. Another direction of research has focused on exact solutions approaches (Rönnqvist et al., 2015). In this context, we highlighted several studies and their connections with forest landscape management. Önal and Briers (2006) formulated a mixed-integer linear programming model for spatial connections between forested areas. Könnyű et al. (2013) applied a similar study to guarantee temporal connectivity within mature forest habitat over time. The edge effects were also investigated using spatial optimization and wood production constraints (Ross and Tóth, 2016). Wei and Hoganson (2007) formulated mixed integer programming (MIP) to describe core area production in a forest management programming model. Augustynczik et al., (2018) developed a model to integrate ecological connection corridors by maximizing the Net Present Value (NPV). They found a 4.2 % reduction rate in NPV and Moreira et al. (2013) only 0.051% in Brazil. Sessions (1992) used a heuristic function for ecological corridors between wildlife areas.

The ecological corridors for species habitats are often found in literature, and it is still a challenge for decision-makers. The main advantage of formulating habitat protection problems such as Integer Programming (IP) models with a array of objectives and constraints, is site specific policy guidance, including habitat protection activities that efficiently achieve wildlife conservation goals and tradeoffs between conservation goals and protection costs (Rönnqvist et al., 2015). Nevertheless, most of the landscape optimization problems considers the harvest scheduling problem at the tactical level (Könnyu and Tóth, 2013; Tóth et al., 2013). Although IP is an important for habitat maintenance and development yet tactical planning is still widely used. Tactical planning is, in fact, the level of planning where these types of problems are recognized.

Generally, the spatial harvest scheduling is associated with environmental, ecological, and social aspects of the managed area while seeking to optimize objectives economically. Nevertheless, it is reasonable to note the negative impact of wood production due to ecological-landscape constraints in most of mathematical models. Landscape changes are easily measured after forest harvest simulation (McGarigal and Marks, 1995; Baskent and Jordan, 1995). Franklin and Forman (1987) presented the ecological consequences of using only a harvest patterns practiced in the western United States. The authors suggest changing the spatial configuration to create an alternative landscape. These changes provide improvements in the lower risk of disturbances, pests and diseases, forest fires, wind destruction. Other spatial ecological aspects can be seen in more detail in Kurttila (2001).

There are two different approaches to harvesting programming, the Unit Restriction Model (URM), which restricts the cutting of adjacent harvest units in the same period, and the Area Restriction Model (ARM), in which the adjacency restriction is controlled by maximum harvest opening sizes (Baskent and Keles, 2005). These two different approaches are for handling clearcut adjacency constraints within a mathematical programming system. That is, it seeks to ensure that the maximum predetermined cut size is not exceeded. These restrictions prevent large contiguous cutting areas from being formed (Kurttila, 2001). URM and ARM were proposed by Murray (1999), who presented a formulation of Integer Linear Programming (ILP) for URM and considered heuristic and dynamic programming to solve ARM. The ARM proposal is the same as the URM, except for expanding the cutting area in the landscape in the neighboring units. They are two models for solving crop planning problems with spatial landscape restrictions. There are still some computational obstacles to the effective use of exact methods for these problems. Constantino et al. (2008) proposed a Mixed-Integer Programming Model for harvest-scheduling subject to maximum area restrictions with stand-clear-cut variables (ARMSC). The approach uses a polynomial number of variables and constraints to better obtain solutions in short computational time.

Adjacency constraints require organizing crops in space and time to achieve a landscape goal, assessing the problem mathematically before activities are implemented on the ground (Bettinger and Sessions, 2003). For example, clear cut plots can increase erosion, visual impacts, and habitat disturbance (Church et al., 1998). The basic mathematical representation of adjacency constraints (Murray, 1999) applied to spatial harvest planning problems, includes (i) restrictions on the period of adjacency and exclusion, which restrict the harvest of adjacent stands during a specified period of exclusion and (ii) restrictions of whole variables and other restrictions related to sustainability and the uniform flow of removals (Kurttila, 2001). Essentially, two main approaches to optimization techniques are used, namely (i) integer linear programming and mixed-integer linear programming and, (ii) heuristics.

Studies on adjacency constraints are important for forest harvest planning in line with aspects of environmental quality (Weintraub et al., 1994; Kurtilla, 2001; Baskent and Keles, 2005). Weintraub and Murray (2002) show for this purpose that heuristic approaches have been widely used, such as tabu search and simulated annealing algorithms.

The spatial restriction requires that the harvested areas not be larger than a certain size, where it seeks to neutralize the harvest patterns similar to a chessboard (e.g., Figure 3-E), the regulation of the spatial impacts of the harvesting activity promotes higher quality forests and long-term sustainability (Weintraub and Murray, 2006). Könnyu and Tóth (2013) emphasize that restrictions on the size of the opening in the forest harvest are even requirements for forest certification standards such as the Forest Stewardship Council (FSC) and Sustainable Forestry Initiative (SFI). The impacts generated on the landscape after forest harvest in reforestation are visible and may contain extensive areas with soil exposure, breaking of the continuity and shredding of the landscape and increased risks caused by gales (Gomide et al., 2013). The forest certification is designed to guarantee consumers that the wood products they buy come from managed forests that maximize aspects of environmental quality in forest management (Van Deusen et al., 2010).

In the models of spatial harvest planning that incorporate maximum restrictions on the size of the harvest opening (URM or ARM) (Murray, 1999; Könnyu and Tóth, 2013), the period of greening or exclusion period is also inherent. This is the period generally expressed in years, which must pass before harvesting activities are allowed in adjacent areas (Bettinger et al., 2017). Also, restrictions that prohibit final harvesting in areas before the regeneration of harvested areas are known in forest planning as green-up constraints (Borges et al., 2015).

In North America, where adjacency constraints are particularly common, green-up constraints regulate the simultaneous harvesting of neighboring plots (Murray and Weintraub, 2002; Tóth et al., 2012). Adjacency and green-up restrictions address the juxtaposition of crops and habitat and are perhaps the most widely used spatial restrictions in forest planning today (Kadioğullari et al., 2015). In addition to the adjacency restrictions and restrictions for green-up problems (Boston and Bettinger, 2001), there are also restrictions designated for the maintenance of ecological corridors (Fischer and Church, 2003), some linked to landscape indexes (Heinonen, 2007), block restrictions to facilitate the harvest (Nelson, 2001) among others (Gomide et al., 2010).

The block cutting restrictions are widely used in countries with fast-growing forests. These restrictions, depending on the size of the harvest blocks in large areas, can have a significant impact on the landscape, which, considering the scenic value and environmental quality, can cause a negative impact, despite the proportions, despite generating greater positive economic effects for forest owners. Classic approaches to optimized forest planning to model harvest scheduling problems with block size constraints can be seen in Lockwood and Moore (1993), Clements et al., (1990), and Augustynczik et al. (2017).

In Figure 4, we present an illustration of spatial dynamics of the influence of adjacency restrictions (Fig. 4a) in an illustrative forest area, with a demonstration of valid and viable harvest units for cutting according to established maximum sizes and harvest scheduling scenarios in a planning horizon. Scenarios related to restrictions in blocks with green-up requirements (Fig. 4b) and an ecological corridor between the stands (Fig. 4c) are also illustrated. In the harvest schedule, it is common to protect wildlife and its habitat to ensure a connected nature reserve whose stand has a minimum time before being harvested (Almada, 2018).

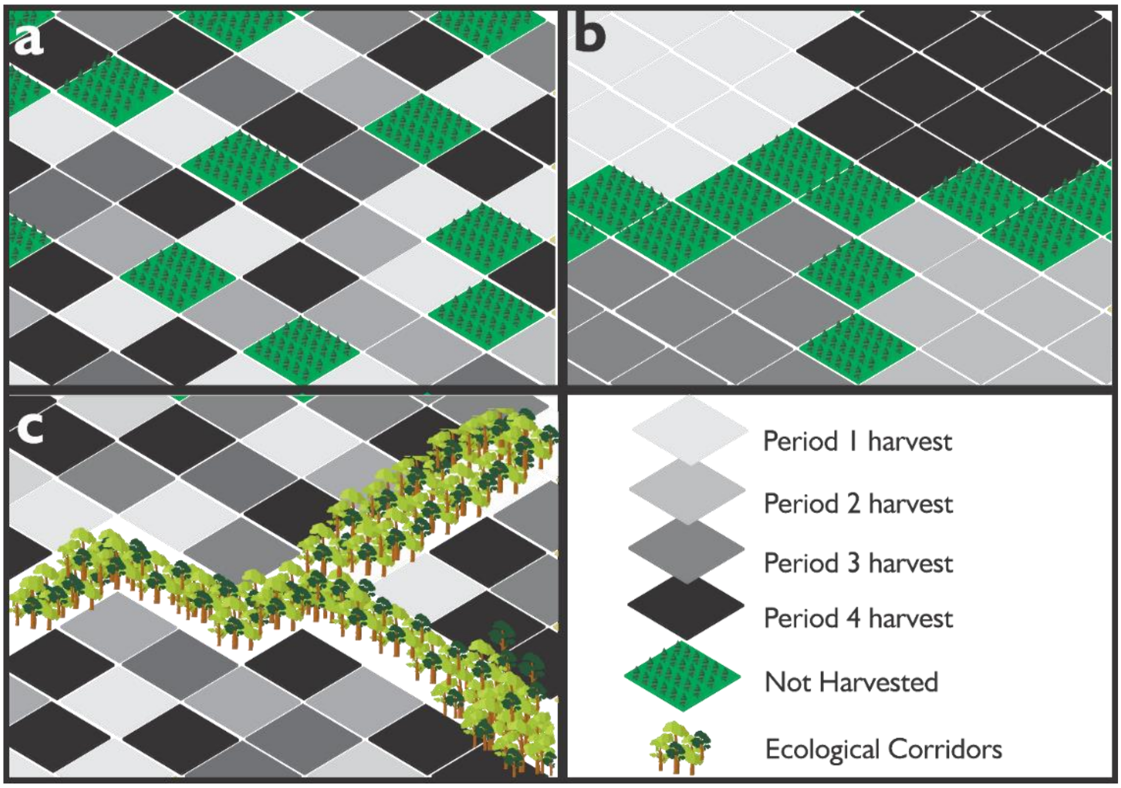


Figure 4. Hypothetical illustration of ideal / alternative forest harvesting programs in the context of forest regulation and landscape quality, in which: (**a**) harvesting for periods with the imposition of adjacent restrictions on spatial dynamics; (**b**) block harvesting modeled to comply with green-up requirements and (**c**) harvest condition integrating the ecological corridor environmental restriction. Source: the authors, 2021.

There have been progress in the use of heuristic techniques to solve spatial forest planning problems. A fraction of the solving problem is associated with integer variables and exact algorithms that have high computational time demands. Therefore, it doesn´t make sense of using traditional techniques of mathematical programming and a range of successful methods such as heuristic and meta-heuristics are suitable (Bettinger and Kim, 2008; Gadow and Pukkala, 2008). In contrast, a given landscape-level planning model has single or multiple objective functions and traditional or advanced techniques to solve it (Bettinger and Kim, 2008). They have been widely used in forestry and territorial planning policies and studies (Hayes et al., 2004). The search for better management of environmental aspects, resources and economic benefits was what led to the concept of managing the forest landscape (Baskent and Jordan, 1996). There is still a lot to be done in this area of research, as most of the spatial problems and environmental processes presented in this section are stochastic, with significant economic, mathematical, and computational challenges.

Generally, it is necessary to convince and engage within the companies to implement one more restriction on harvesting and transport planning, which will divide the harvest blocks and probably make the operation difficult. The cultural issue of companies that only aim at short-term profit is one of the main challenges. Developing this shift in mindset can be a problem in the case of developing or underdeveloped countries. Certifications value landscape planning actions, but do not oblige them to do so, so it is up to the company to implement it or not.

3.4. Support Decision Systems for Spatial (SDSS) analysis

Spatial forest planning is causally related to geovisualization and processing of geographic data. What is frequently applied to forest landscape management and correlated with SDSS techniques?

The Geographic Information Systems (GIS) is another important research field in forest science and maps are essential for data visualization. The spatial structure of trees, stands, roads, and forest are essential for wood supply chain control (Bettinger and Sessions, 2003). The idea behind forest planning and GIS melting over decades (Kyem, 2002; Gomide, 2009). The authors Baskent and Jordan (1991), Jordan and Baskent (1992), Baskent and Jordan (1996), Jamnick and Walters (1993), and Pukkala et al. (1995) emphasize the benefits of this technology for forest management. In addition, the resource provides valuable information for spatial analysis (Baskent and Keles, 2005).

Spatial Decision Support Systems (SDSS) combine spatial and non-spatial data within GIS technology for problem management and solution. Besides, the SDSS has many advantages to evaluate the trade-offs goals (Keenan and Jankowski, 2019) which include landscape management and spatial forest planning. One of the most complete publications is the FORSYS report (Borges et al., 2014) ‘Forest Management Decision Support Systems’, which brought together almost a hundred authors and approaches related to twenty-six countries in Europe, North and South America, Africa and Asia. The authors present an overview of computational tools for forest management planning in several countries. They also describe methods and technologies based on the multicriteria and objective function, GIS, computer programming, as well as communication tools, and spatial visualization. In general, SDSS are essential tools for solving complex forest decision-making problems (Segura et al., 2014). Bettinger and Sessions (2003) point out a robust database to extract correct spatial information. This critical alert affects the final decision and landscape responses. Forest management companies need to create management plans that balance environmental, social, economic, and operational aspects in their harvesting plans (Walters et al., 1999).

The 3D visualization is often used for architectural modeling systems, realistic simulators, virtual computer reality, and other applications (Favorskaya and Tkacheva, 2013). The real-time rendering of forest landscape scenes is also possible for better aesthetic management in large forest plantations (Bao et al., 2012). A 2D and 3D visualization model applied to landscape harvest plans can be seen in Chamberlain and Maitner (2009). Falcão et al. (2006) developed a real-time 3D visualization module for forest landscapes, based on heuristics, mathematical programming techniques and GIS. The construction of virtual landscapes allows real-time navigation through the forest in each period of the planning horizon of a scenario. The technology explores a range of views to support forest activities and certification programs (Domingo-Santos et al., 2011). Today, rendering technology has been made easier at Light Detection and Ranging - Lidar (Wulder et al., 2012) for the land surface with high-resolution detailed (Pierzchała et al., 2018; Ozkan et al., 2020). The dataset cost is still high but should decrease over time (Bettinger et al., 2017).

Forest landscape-planning include economic, ecological, and social aspects to guide the decisions. These virtual results may concern stakeholders' views and goals. Some examples can be observed in Meo et al. (2013) with GIS of public participation (PPGIS) in forest landscape planning; Vopěnka et al. (2015) with a developed GIS extension for forest harvest scheduling problems with spatial and temporal design aspects; An GIS-based model to have impacts on recreation areas caused by harvesting activities in a commercial forest (Harshaw and Sheppard, 2013); Ezzati et al. (2016) based on a Multicriteria Decision Analysis (MCDA) methodology found optimal locations of viable harvest zones in mountainous areas. In MCDA and spatial forest planning the use of the AHP (Analytic Hierarchy Process) methodology (Saaty, 1980) has been a tool widely used to model problems of assessing preferences of multiple criteria (Alho et al., 2002; Kangas and Kangas, 2002; França et al., 2020; Morandi et al., 2020).

Meta-heuristic techniques associated with SDSS and developed in multiple programming languages should also be explored for spatial forest planning. In the microplanning and optimization of stands, an important current challenge for forestry companies is to achieve greater homogeneity of their stands. The forest plot definition can be explored via the 'Nesting Problem' method (Bennel and Oliveira, 2008), which performs ordering and better arrangement of geometric pieces (Lo Valvo, 2017), in this case at the level of the forest landscape.

In 1996, with the possibility of using ESRI Shapefiles (Environmental Systems Research Institute) in forestry decision support systems with resources for spatial planning, the Canadian company Remsoft Inc. launched the Stanley software (Spatial Optimizer), which uses sets of heuristics for the automatic insertion of spatial constraints in strategic forest-planning models with multi-objective linear programming (Goals programming). It was an important step in dealing with the inclusion of new sustainability criteria in the planning of forest management. Heuristics-based shapefiles applying the imposition of adjacent and green-up constraints on spatial parameters help the planner to better control the minimum, average and maximum size of the cutting units and the green-up period between adjacent areas.

Finally, statistical models have also been developed to analyze the scenic beauty of plantations in forest landscapes. The model inputs are associated with tree density, species, harvested volume, and vegetation cover (Schroeder and Daniel, 1981). Brown (1987) also analyzed a statistical model including scenic quality and net present value. Generally, most models developed predicted the perceived scenic quality of the sites.

Therefore, statistical or mathematical models and geospatial support of SDSS provide the management of forest landscapes in a more comprehensive way, creating an effective link between strategic and operational levels.

3.5. Bibliometric results

Scientific production related to the approach of spatial forest planning and landscape management aimed at the scenic and environmental quality forest is not yet a much-researched area compared to other areas in forest engineering (e.g. forest carbon stock, ecosystem services). Nevertheless, these studies have a great impact on society and the environment because they involve extensive production areas. The bibliometric analysis allowed the identification of trends observed in the topics, terms, and sub-fields of the analyzed theme. The overall of the spatial forest planning and landscapes management articles are present was obtained.

We summarized 2022 articles from 129 sources (Journals) over the timeline (1980-2021). 1959 are data articles and 63 literature reviews. The average of calculated collaboration rate was 2.77 authors which, configuring a high degree of predominance of collaborative research. A collaboration network between authors is strategic to increase the impact on scientific production, especially international collaborations (Koseoglu, 2016). Publications with a single authorship represent only 7.96% (161 single-authored documents) of the 5245 authors involved in the survey. 5084 documents are from authors in multiple authorship, confirming the high collaboration among researchers in this line of study. Demonstrating that, although the theme is still not much studied in comparison to other themes, there are many people involved and interconnected in these studies. We also found a total of 5942 different keywords used by these authors to provide the central idea of their manuscripts. There is scientific production related to the theme before 1980 in different parts of the world. However, according to our methodological rules for searching for keywords and production time scale, these works were not examined in bibliometrics. Despite this, a large part of these records before that decade were included in the critical review of the state of the art of the subject. Most were books, technical reports, guides, or local production.

The bibliographic review indicates an increase rate of the publishing number (Figure 5). In this regard, the temporal evolution confirms the relevance of the theme over the last two decades. Besides, the dataset records suggest a strong correlation between our research theme and global sustainable agendas, also including forest certification, land use, and climate change (Sánchez and Croal, 2012; Leemans and Vellinga, 2017; COP 21, 2015; COP 25, 2019; Maamoun, 2019). The most relevant journals are Forest Ecology and Management (237 articles), Forests (155 articles), International Journal of Applied Earth Observation and Geoinformation (150 articles), Spatial Information Research (117 articles) and Forest Science (99 articles) of global publishing (Figure 6A). The maximum point observed is between 2017-2021, reinforcing that the topic has more focus more recently, and this line tendency suggests a hot topic study for the next years (Figure 5). The regression analysis supports our findings from coefficient of determination (0.76%).

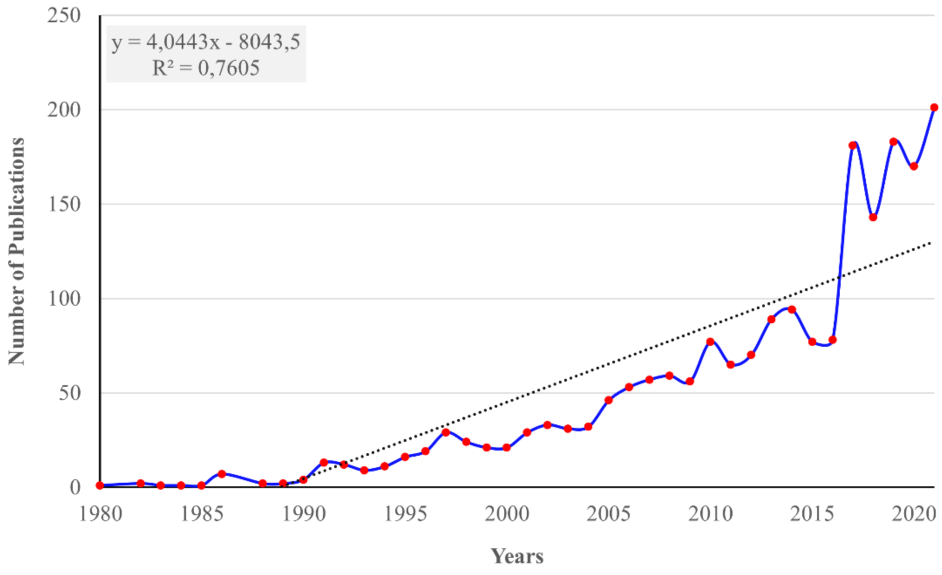


Figure 5. Annual publishing production of articles from Web of Science (WOS) and Scopus.

The most relevant affiliations were Swedish University of Agricultural Sciences (Sweden), Finnish Forest Research Institute (Finland) and Oregon State University (USA). In terms of the countries that produce the most, the United States (1145 articles), China (521), Finland (449) and Canada (415) stand out. In them are the main author's affiliation origin that has been working with the themes (Figure 6C). Considering the ratio of citation and published articles, the most relevant country is United States, Canada, and Finland, with average article citations of 19,56 and total citations of 7102 (USA), Canada 3121 citations and Finland 2938. This may be because these countries have large forest areas and a long tradition in the use of forest resources. For example, Finnish forest-based companies are among the most concerned with sustainable growth and are precursors to the circular bioeconomy (Näyhä, 2019) and forest certification with advanced strategies for sustainable forest management (Kuuluvainen et al., 2019).

Çağlayan et al. (2018) define the United States and Finland as a leader countries of forest management optimization. They have commercial systems, spreadsheet applications and tools based on linear programming, heuristic techniques for spatial forest planning (Bettinger and Sessions, 2003). The forest certification processes are the internal factor to encourage this researches. 48% (207 million hectares) of the certified forest area globally is in North America, 25% (107 million hectares) is in western Europe (UNECE, 2015). In the collaboration map between countries (Figure 6D) we observe a great flow of interaction between North America and Europe.

The high article publication relevance is dominated by Pukkala T. (43 articles) and Bettinger P. (36 articles). Although these authors present the highest productivity according to our bibliometric search rules, they are also seen in our state-of-the-art survey as the authors with the main works related to forest landscape management and spatial forest planning, with a hundred other studies with broader approaches on the subject. Timo Pukkala and Pete Bettinger are associated with universities in Finland and USA, respectively. We also observed a high citation of these authors within other articles. Besides, the second important group of authors are Kangas, A. (22 articles), Kurttila, M. (18 articles), Kangas J. (16 articles) and Ohwan K (16 articles), among others (Figure 6B).

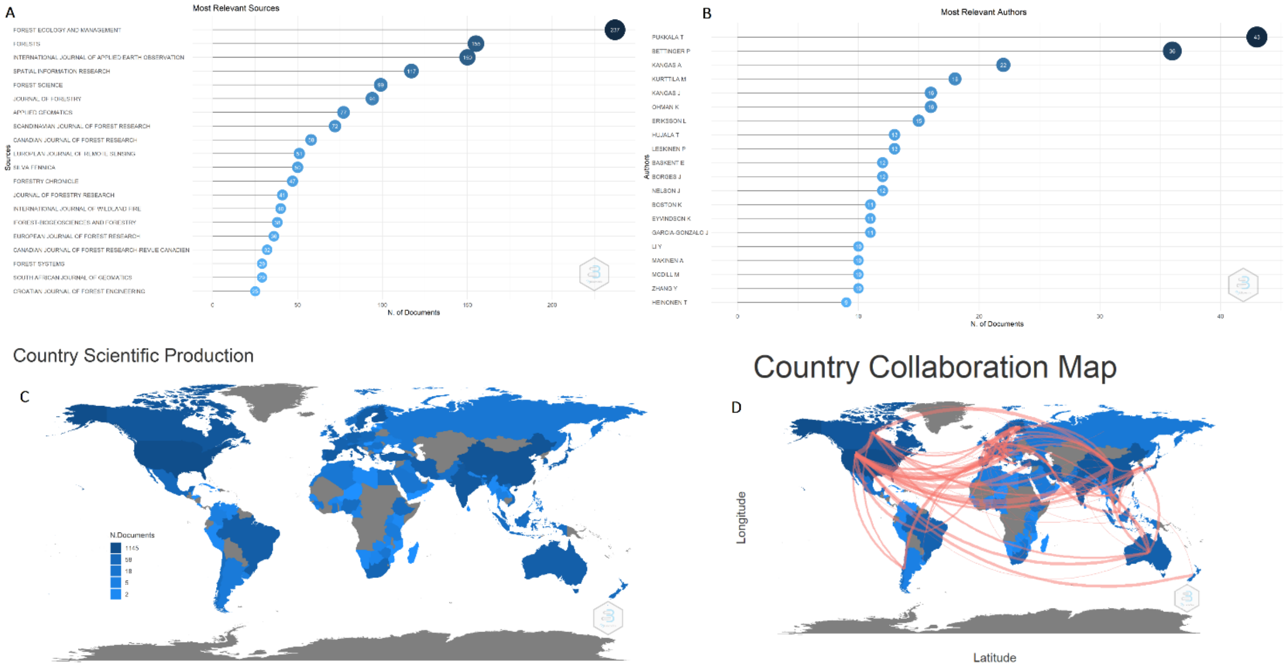


Figure 6. (A) Most relevant sources; (B) Most relevant authors; (C) Country scientific production and (D) Country collaboration map.

According to our selected keywords for the search procedure, the most researchable terms or most relevant words were "gis", "remote sensing", "forest planning", "forest management" and "optimization" at this sequence order (Figure 7A). The dendrogram (Figure 7B) shows the similarity groups highlighting the formation of two main clusters, one related to optimization (group in blue color) and another to management of landscape and forest resources (group in red color).

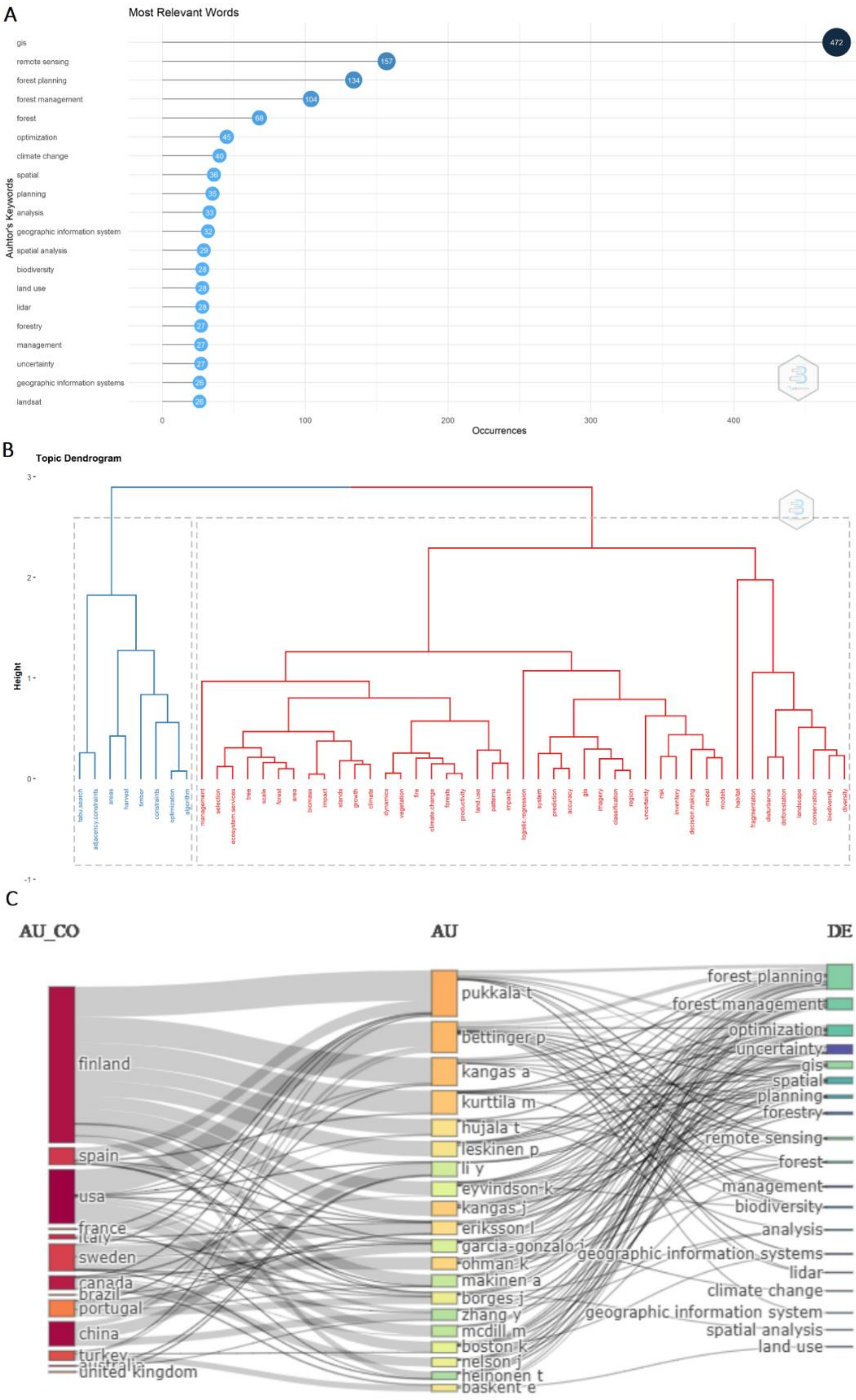


Figure 7. (A) Most relevant words; (B) Topic Dendrogram and (C) Sankey diagram, the interaction map between countries, authors, and keywords.

Finally, the sankey diagram (Figure 7C) match three objects (countries – authors – keywords) according to their relevance and frequency in a longitudinal data structure. The output describes an interactive flux of information and inferences within levels. It has been widely used to visualize and compare flow patterns of simultaneous topics (Davis et al., 2018) and multidimensional data dimension (Lupton and Allwood, 2017). Our findings suggest a plural pattern of actors and researches. With this result, we observe that the central theme is in essence multidisciplinary and broad. It is important to note the rectangles size at any given level (Fig. 7C) which reflects the weight of the element proportionality of occurrence (Chao et al., 2020) and the lines is proportional to the index inclusion between connected themes/level. Today, the scenic quality continues a hard task for the wood supply chain on a large scale. The case studies take into account the simulation approach and mathematical modeling are crucial for landscape management and their effects. These proposals model is usually complex to solve due to the combinatorial complexity (Weintraub and Murray, 2006).

The group of words "forest planning", "forest management" and "optimization" together with the group of words "gis", "remote sensing" and "spatial analysis" represent the motor themes or themes of greater relevance and centrality in this subject. Other word combinations are organized in the graph of degree of development and degree of relevance (Figure 8).

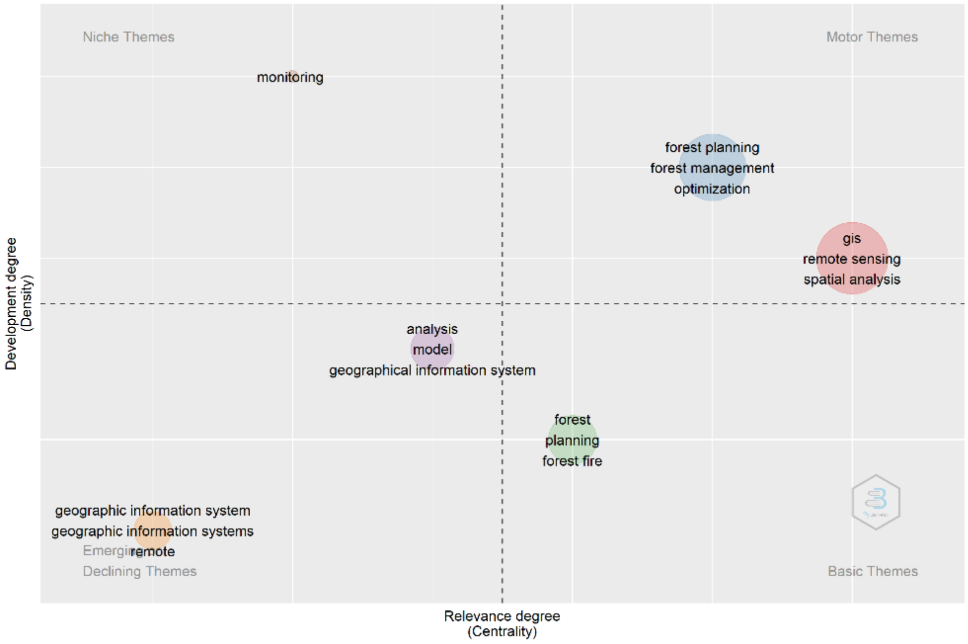


Figure 8. Thematic map of degree of relevance and development of themes.

We set a network of keyword interaction and the co-occurrence analysis (Figure 9). The network linkage between nodes (keywords) associates the frequency and correlation of pairwise terms. Generally, this connected graph defines the relationship of keywords used within articles (Chen et al., 2016). The networks represent the interrelationship of countries working together (Figure 9A), the groups of researchers (Figure 9B) and the group of keywords in their respective niches (Figure 9C).

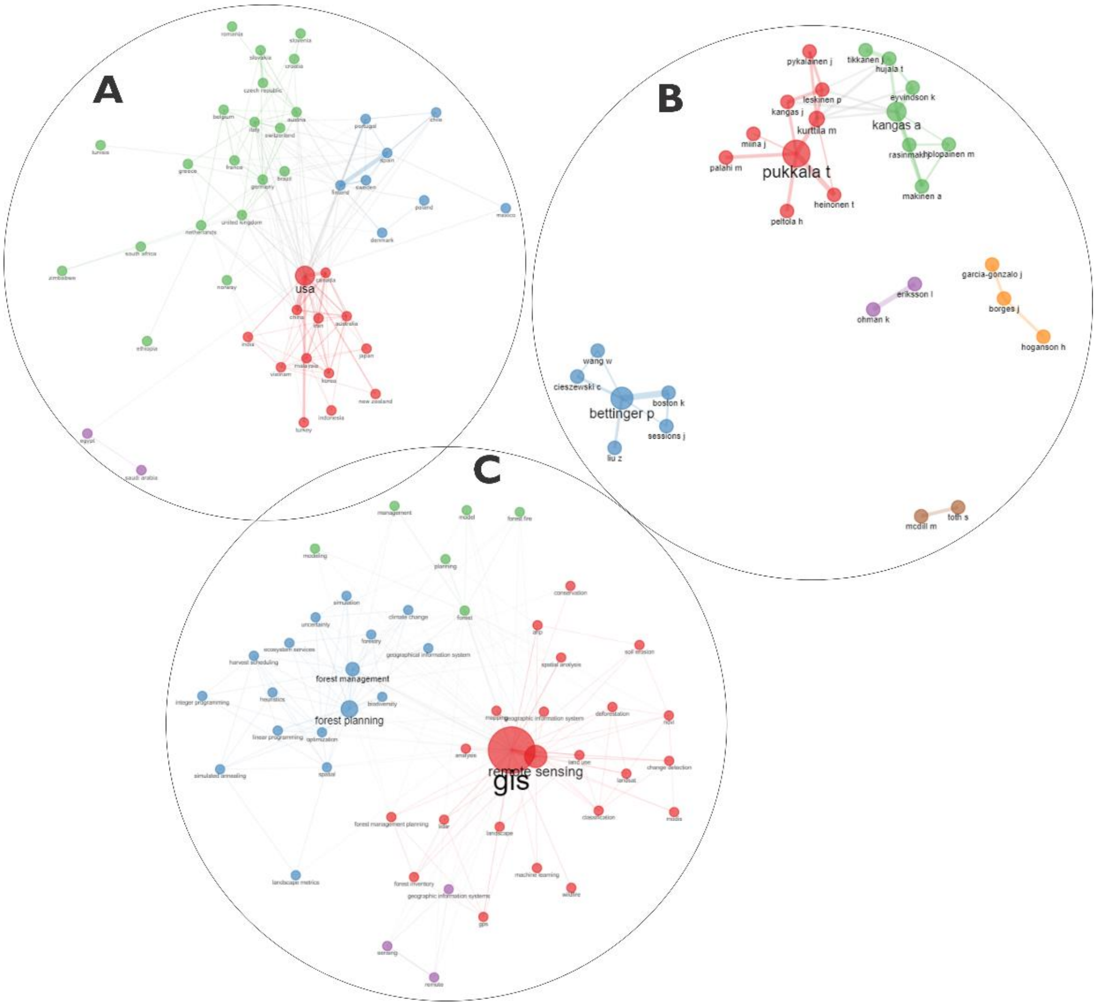


Figure 9. (A) Interrelationship of countries working together; (B) The groups of researchers and (C) the group of keywords in their respective niches.

In contrast, the keywords that are close to each other influence the next keywords quickly and so on. This analysis (Figure 9A) combined four-color groups by theme (red, green, blue, and purple subnet). The grouping of countries in the red subgroup is dominated by the United States of America. Particularly, there is connection between all clusters. In Figure 9B the authors are seen in their networks of collaboration and scientific production together. We observed that there is a collaboration network between the groups dominated by the authors Pukkala T. and Kangas A (red and green cluster, respectively). The same happens for the connection network between the keywords (Figure 9C), where "gis" and "remote sensing" dominate the largest cluster of words (red cluster) and "forest planning" and "forest management" dominate another large cluster. of words (blue cluster). Among all clusters there is a direct relationship.

These results confirm a link with what was observed in the state of the art seen in the previous topics. The clusters and connection network between the keywords call attention to the relation with the temporal chronology of the studies developed on the central theme. The spatial forest planning has increasingly considered issues related to the maintenance and improvement of scenic and landscape aspects of forest areas. The aesthetic value of the landscape as a combined result of a mathematical model can increase the perception of sustainability of forest enterprises and improve the landscape structure conditions for biodiversity.

Despite the challenges, forest industries are faced with the problem of spending much time and resources to achieve better strategies. In fact, we expected high interest in research institutions, companies, and governments considering the subject. Our findings suggest that environmental issues are already incorporated into industry production guiding international trade agreements. The positive rate indicates that North America and Europe concentrate the majority of scientific publications. Although the aesthetic and environmental merit is increasingly demanding the attention of forest planners, more research needs to be encouraged for other regions with forest production on the rise in the world, such as South America.

4. Conclusions and key recommendations

- We contextualize the spatial forest planning and landscape correlation at a global scale. The challenges, trends, and advances were pointed out as an important theoretical framework for further discussion. This review links the sustainable, aesthetically pleasing, and economically viable productive forests under forest certification purposes and global demands for ecological services.
- We identified research trends on the topic from 1980 to 2021 and observed clear evidence of an increase in publications, especially in the last decade. Highlighting the spatial forest management of the landscape as a research area in full expansion.
- The scientific advances of spatial forest planning consider multi-objective functions and environmental constraints to support decision making. These mathematical models should also integrate transportation route and road investments (maintenance, adequacy, and/or construction) according to technical, economic, environmental, and social criteria at the three hierarchical levels (operational, tactical, and strategical). Currently,

this research area has been associated with remote sensing, GIS database, and computer programming.

- There are differences in public perception and landscape importance around the world. The high suitability of commercial forest is found in Europe and North America. In this sense, the long rotation of these forests has a high possibility of exploring the visual resource for tourism. Moreover, wildlife corridors, multiple species and age mosaics of forests should be easily adopted in commercial plantations.
- The integration of forest planning and landscape management is encouraged to join after the spreading of forest certification programs in the last three decades. These forests for biomass, timber, charcoal, and cellulose production has improved their protocols to mitigate the socio-environmental impacts after their operation.
- Business cases and applied researches are needs to analyze the economic benefits of keeping the landscape attributes and ecosystem services over timber production. Besides, fragile landscape areas should be taken with more caution for damages by applying simulation techniques to minimize them.

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References

Alberta Forestry, Lands and Wildlife, Forest Service. Forest Landscape Management Strategies for Alberta. Pub. 228. 1988. Available in: https://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/formain15749/$file/ProvGR94.pdf?OpenElement. Access in: 17/01/2020.

Aleixandre-Benavent, R., Aleixandre-Tudó, J.L., Castelló-Cogollos, L., Aleixandre, J.L. 2017. Trends in scientific research on climate change in agriculture and forestry subject areas (2005-2014). J. of Clean. Produc. 147, 406-418. https://doi.org/10.1016/j.jclepro.2017.01.112

Alho, J. M., Korhonen, P., Leskiken, P. 2002. Measurement of preferences in multiple criteria evaluations. In: Pukkala, T. Multi-objective Forest Planning. SPRINGER-SCIENCE+BUSINESS MEDIA, B.V. 213p. Available in: https://link.springer.com/chapter/10.1007/978-94-015-9906-1_2. Access in: 19/05/2020.

Almada, A. J. C. Optimization Algorithms in Forest Planning. MEIC-T, Extended Abstract. 8p. 2018. Available in: :< https://pdfs.semanticscholar.org/6f59/63814c0d88d2f3ce508fe4583e37d7df36bc.pdf?_ga=2.195406380.142446173.1589896887-1599166387.1589896887>. Access in: 19/05/2020.

American Resources, Inc. Green Tag Certified Forestry. American Resources, Inc., Vienna, VA. 2013. Available in:< http://www. greentag.org/default.asp>. Access in: 15/05/2020.

Anderson, L. M. 1981. Land use Designations Affect Perception of Scenic Beauty in Forest landscapes. Forest Science, 27, 392-400. https://doi.org/10.1093/forestscience/27.2.392

Angelstam, P., Manton, M., Yamelynets, T., Sorensen, O. J., Stepanova, S. V. K. 2020. Landscape Approach towards Integrated Conservation and Use of Primeval Forests: The Transboundary Kovda River Catchment in Russia and Finland. Land. 9, 1-27. http://dx.doi.org/10.3390/land9050144

Aria, C., Cuccurullo, M. 2017. Bibliometrix: An R-tool for comprehensive science mapping analysis. J. Informetr. 11, 959-975. https://doi.org/10.1016/j.joi.2017.08.007

Augustynczik, A. L. D., Arce, J. E., Silva, A. C. L. 2017. Implementing minimum area harvesting blocks in an optimized forest planning model. Revista Árvore. 41, 2-8. https://doi.org/10.1590/1806-90882017000100018

Augustynczik, A. L. D., Yousefpour, R., Rodriguez, L. C. E., Hanewinkel, M. 2018. Conservation Costs of Retention Forestry and Optimal Habitat Network Selection in Southwestern Germany. Ecological Economics. 148, 92-102. https://doi.org/10.1016/j.ecolecon.2018.02.013

Bacon, W.R. 1979. The visual management system of the Forest Service, USDA. In: Elsner, Gary H., and Richard C. Smardon, technical coordinators. Proceedings of our national landscape: a conference on applied techniques for analysis and management of the visual resource [Incline Village, Nev., April 23-25, 1979]. Gen. Tech. Rep. PSW-GTR-35. Berkeley, CA. Pacific Southwest Forest and Range Exp. Stn., Forest Service, U.S. Department of Agriculture: p. 660-665.

Ball, R. 2018. An Introduction to Bibliometrics: New Development and Trends; Chandos Publishing: Cambridge, MA, USA, 15–53.

Bao, G., Li, H., Zhang, X., Dong, W. 2012. Large-scale forest rendering: Real-time, realistic, and progressive. Computers & Graphics. 36, 140-151. https://doi.org/10.1016/j.cag.2012.01.005

Barahona, F., Weintraub, A., Epstein, R. 1992. Habitat Dispersion in Forest Planning, and the Stable Set Problem. Operations Research. 40, Supplement 1: Optimization, 14-21. https://doi.org/10.1287/opre.40.1.S14

Baskent, E. Z., Borges, J. G., Kašpar, J., Tahri, M. A Design for Addressing Multiple Ecosystem Services in Forest Management Planning. Forests, 11, 1 – 24, 2020. http://dx.doi.org/10.3390/f11101108

Baskent, E. Z., Keles, S. 2005. Spatial forest planning: A review. Ecological Modelling. 188, 145-173. https://doi.org/10.1016/j.ecolmodel.2005.01.059

Baskent, E.Z., Jordan, G.A. 1991. Spatial wood supply simulation modeling. Forestry Chronicle, 67, 610-621. https://doi.org/10.5558/tfc67610-6

Baskent, E.Z., Jordan, G.A. 1995. Characterizing spatial structure of forest landscapes. Can. J. For. Res. 25, 1830-1849. https://doi.org/10.1139/x95-198

Baskent, E.Z., Jordan, G.A. 1996. Designing forest management to control spatial structure of landscapes. Landsc. Urban Plan., 34, 55-74. https://doi.org/10.1016/0169-2046(95)00200-6

BC Ministry of Forests. 1981. Forest Landscape Handbook. Available in:< https://www.for.gov.bc.ca/hfd/library/documents/bib36423.pdf>. Access in: 17/01/2020.

BC Ministry of Forests. 1994. Visual Landscape Design Training Manual. Rec. Br. Publ. Available in:<https://www.for.gov.bc.ca/hfd/pubs/docs/mr/Rec023.htm>. Access in: 17/01/2020.

Begotti, R. A., Pacífico, E. S., Ferraz, S. F. B., Galetti, M. 2018. Landscape context of plantation forests in the conservation of tropical mammals. J. for Nat. Cons. 41, 97-105. https://doi.org/10.1016/j.jnc.2017.11.009

Bell, S. 1999. Plantation management for landscapes in Britain. Inter. For. Rev. 1, 177-181. www.jstor.org/stable/42609191

Bell, S. 2001. Landscape pattern, perception, and visualization in the visual management of forests. Land. and Urb. Plan. 54, 201-211. https://doi.org/10.1016/S0169-2046(01)00136-0

Bell, S., Apostol, D. 2008. Designing sustainable forest landscapes. Taylor & Francis, Ed. 1, London, 368p.

Bennell, J. A., Oliveira, J. F. 2008. The geometry of nesting problems: A tutorial. Europ. J. of Operat. Res. 184, 397-415. https://doi.org/10.1016/j.ejor.2006.11.038

Bettinger, P., Boston, K., Siry, J. P.; Grebner, D. L. 2017. Forest Management and Planning. Academic Press: Elsevier, 362p. ISBN: 9780128097069. https://www.sciencedirect.com/book/9780128094761/forest-management-and-planning

Bettinger, P., Kim, Y.H. 2008. Spatial Optimization – Computational Methods. In: Gadow, K.; Pukkala, T. Designing Green Landscapes. Springer Science & Business Media, 290p. Access in: 16/05/2020.

Bettinger, P., Sessions, J. 2003. Spatial Forest Planning: To Adopt, or Not to Adopt? Journal of Forestry. 101, 24-29. https://doi.org/10.1093/jof/101.2.24

Bird, S., Coulson, R.N., Crossley JR, D.A. 2000. Impacts of silvicultural practices on soil and litter arthropod diversity in a Texas pine plantation. For. Ecol. and Manag. 131, 65-80. https://doi.org/10.1016/S0378-1127(99)00201-7

Bončina, A., Simončič, T., Rosset, C. 2019. Assessment of the concept of forest functions in Central European forestry. Envir. Sci. and Pol. 99, 123-135. https://doi.org/10.1016/j.envsci.2019.05.009

Bonnell, B. 2012. Trends in research and collaboration in the Canadian Model Forest Network, 1993–2010. For. Chron. 88, 274-282. https://doi.org/10.5558/tfc2012-054

Borges P., Bergseng, E., Eid, T., Gobakken, T. 2015. Impact of maximum opening area constraints on profitability and biomass availability in forestry – a large, real world case. Silva Fennica. 49, 2-21. https://doi.org/10.14214/sf.1347

Borges, J. G., Nordstrom, E. M., Garcia-Gonzalo, J., Hujala, T., Trasobares, A. 2014. Computer-based tools for supporting forest management. The experience and the expertise world-wide. Report of Cost Action FP 0804 – Forest Management Decision Support Systems (FORSYS). 507 p. Available in:< https://pub.epsilon.slu.se/11417/>. Access in: 14/08/2020.

Boston, K.; Bettinger, P. 2001. The economic impact of green-up constraints in the southeastern United States. For. Ecol. and Manag. 145, 191-202. https://doi.org/10.1016/S0378-1127(00)00417-5

Bouvet, J. M., Ekomono, C. G. M., Brendel, O., Laclau, J. P., Bouillet, J. P., Epron, D. 2020. Selecting for water use efficiency, wood chemical traits and biomass with genomic selection in a Eucalyptus breeding program. For. Ecol. and Manag. 465, 2-10. https://doi.org/10.1016/j.foreco.2020.118092

Boyle, J. R., Tappeiner II, J. C., Waring, R. H., Tattersall Smith, C. 2016. Sustainable Forestry: Ecology and Silviculture for Resilient Forests. Reference Module in Earth Systems and Environmental Sciences. https://doi.org/10.1016/B978-0-12-409548-9.09761-X

Brown, P., Probstl-Haider, U., Koch, N.E. 2016. Social and Political Aspects of Sustainable Forestry. Reference Module in Earth Systems and Environmental Sciences. https://doi.org/10.1016/B978-0-12-409548-9.09483-5

Brown, T. C. 1987. Production and Cost of Scenic Beauty: Examples for a Ponderosa Pine Forest. Forest Science. 33, 394-410. https://doi.org/10.1093/forestscience/33.2.394

Brush, R. O. 1979. The Attractiveness of Woodlands: Perceptions of Forest Landowners in Massachusetts. Forest Science. 25, 495-506. https://doi.org/10.1093/forestscience/25.3.495

Bullock, R., Lawler, J. 2015. Community forestry research in Canada: A bibliometric perspective. For. Pol. and Econ. 59, 47-55. https://doi.org/10.1016/j.forpol.2015.05.009

Burger, J.A. 2009. Management effects on growth, production and sustainability of managed forest ecosystems: past trends and future directions. For. Ecol. Manag. 258, 2335–2346. https://doi.org/10.1016/j.foreco.2009.03.015

Cabarga-Varona, A., Arroyo, N.L., Nogués, S. 2016. The function of plantation forestry in landscape connectivity. App. Ecol. and Env. Res. 14, 527-542. http://dx.doi.org/10.15666/aeer/1402_527542

Çağlayan, I., Yeşil, A., Çınar, D., Cieszewski, C. 2018. Taxonomy for the optimization in forest management: a review and assessment. Forestist. 68, 122-135. https://doi.org/10.26650/forestist.2018.354789

Camarasa, C., Nageli, C., Ostermeyer, Y., Klippel, M., Botzler, S. 2019. Diffusion of energy efficiency technologies in European residential buildings: A bibliometric analysis. Energy and Buildings, 202. https://doi.org/10.1016/j.enbuild.2019.109339

Carnus, J.M., Parrotta, J., Brockerhoff, E., Arbez, M., Jactel, H., Kremer, A., Lamb, D., O'Hara, K., Walter, B. 2006. Planted Forest and Biodiversity. Forest Ecology, 65-77.

CBI (Ministry of Foreign Affairs). The European market potential for nature and ecotourism. Available in:< https://www.cbi.eu/market-information/tourism/nature-tourism/nature-eco-tourism-europe/>. Access in :23/01/2020.

Chamberlain, B. C., Meitner, M. J. 2009. Automating the visual resource management and harvest design process. Land. and Urb. Plan. 90, 86-94. https://doi.org/10.1016/j.landurbplan.2008.10.015

Chao, W., Ming K, L., Longfeng, Z., Ming-Lang, T., Chen-Fu, C., Lev, B. 2020. The evolution of Omega-The International Journal of Management Science over the past 40 years: A bibliometric overview. Omega. 90, 2-21, https://doi.org/10.1016/j.omega.2019.08.005

Chen, X., Cheng, J., Wu, D., Xie, Y., Li, J. 2016. Mapping the research trends by co-word analysis based on keywords from funded project. Procedia Computer Science. 91, 547-555. https://doi.org/10.1016/j.procs.2016.07.140

Church, R. L., Murray, A. T., Weintraub, A. 1998. Locational issues in forest management. Location Science. 6, 137-153, https://doi.org/10.1016/S0966-8349(98)00051-5.

Clements, S. E., Dallain, P. L., Jamnick, M. S. 1990. An operational, spatially constrained harvest scheduling model. Canadian Journal of Forest Research. 20, 1438-1447. https://doi.org/10.1139/x90-190

Constantino, M., Martins, I., Borges, J. G. A New Mixed-Integer Programming Model for Harvest Scheduling Subject to Maximum Area Restrictions. Operations Research, 56, 3, 542 – 551, 2008. https://doi.org/10.1287/opre.1070.0472

COP 21 - 21st. Conference of the parties to the United Nations framework convention on climate change. 2015. Available in: <https://s3.sa-east-1.amazonaws.com/cop25.cl/documents/esp/ACUERDO%20DE%20PARIS.pdf>. Access in: 28/01/2020.

COP 25 - 25 st. Conference of the parties to the United Nations framework convention on climate change. 2019. Available in: https://www.cop25.cl/#/. Access in: 28/01/2020.

Crow, S. 1966. Forestry in the Landscape. Forestry Commission, Booklet, n. 18. Available in:< https://www.forestresearch.gov.uk/research/archive-forestry-in-the-landscape/>. Access in:17/01/2020.

Curtis, F.H. 1962. Linear programming the management of a forest property. Journal of Forestry. 60(9): 611-616. https://doi.org/10.1093/jof/60.9.611

Dai, E., Zhu, J., Wang, X., Xi, W. 2018. Multiple ecosystem services of monoculture and mixed plantations: A case study of the Huitong experimental forest of Southern China. Land Use Policy. 79, 717-724. https://doi.org/10.1016/j.landusepol.2018.08.014

Daniel, T. C., Schroeder, H. 1979. Scenic beauty estimation model: predicting perceived beauty of forest landscapes. In: Elsner, Gary H., and Richard C. Smardon, technical coordinators. Proceedings of our national landscape: a conference on applied techniques for analysis and management of the visual resource [Incline Village, Nev., April 23-25, 1979]. Gen. Tech. Rep. PSW-GTR-35. Berkeley, CA. Pacific Southwest Forest and Range Exp. Stn., Forest Service, U.S. Department of Agriculture: p. 514-523.

Davis, M., Ahiduzzaman, Md., Kumar, A. 2018. How will Canada's greenhouse gas emissions change by 2050? A disaggregated analysis of past and future greenhouse gas emissions using bottom-up energy modelling and Sankey diagrams. Applied Energy. 220, 754-786. https://doi.org/10.1016/j.apenergy.2018.03.064

De Pellegrin Llorente, I., Hoganson, H.M., Carson, M.T., Windmuller-Campione, M. 2017. Recognizing Spatial Considerations in Forest Management Planning. Curr Forestry. 3, 308 – 316. https://doi.org/10.1007/s40725-017-0068-x

Dhubháin, A. N., O'Connor, D. 2009. Stakeholders' perceptions of forestry in rural areas - Two case studies in Ireland. Land Use Policy. 26, 695-703. https://doi.org/10.1016/j.landusepol.2008.09.003.

Domingo-Santos, J. M., Villarán, R. F., Rapp-Arrarás, I., Provens, E. C.P. 2011. The visual exposure in forest and rural landscapes: An algorithm and a GIS tool. Land. and Urb. Plan. 101, 52-58. https://doi.org/10.1016/j.landurbplan.2010.11.018

Edwards, P., Velarde, S. J., Sharma-Wallace, L., Barnard, T., Pohatu, P., Warmenhoven, T., Porou, T., Harrison, D., Dunningham, A. 2018. Forest scholars empowering communities: A case study from the East Coast of New Zealand. For. Pol. and Econ. 91, 46-53. https://doi.org/10.1016/j.forpol.2017.09.001

Ewald, K. C. 2001.The neglect of aesthetics in landscape planning in Switzerland. Land. and Urb. Plan. 54, 255-266. https://doi.org/10.1016/S0169-2046(01)00140-2

Ezzati, S., Najafi, A., Bettinger, P. 2016. Finding feasible harvest zones in mountainous areas using integrated spatial multi-criteria decision analysis. Land Use Policy, 59, 478-491. https://doi.org/10.1016/j.landusepol.2016.09.020

Falcão, A, O., Santos, M. P., Borges, J. G. A. real-time visualization tool for forest ecosystem management decision support. Computers and Elecronics in Agriculture, 53, 3-12, 2006. https://doi.org/10.1016/j.compag.2006.03.003

FAO - Food and Agriculture Organization. Global Forest Resources Assessment 2020 – Key findings. Rome, 2020. Available at: http://www.fao.org/3/CA8753EN/CA8753EN.pdf

FAO - Food and Agriculture Organization. Global Forest Resources Assessment 2015: How are the world's forests changing? Second Edition. Rome. 2015. Available at: http:// www.fao.org/3/a-i4793e.pdf

FAO - Food and Agriculture Organization. State of the World's forests, 2018. FAO of the United Nations, Rome. 181p, 2018. Available at: http://www.fao.org/3/I9535EN/i9535en.pdf

Favorskaya, M., Tkacheva, A. 2013. Rendering of wind effects in 3D landscape scenes. Procedia Computer Science. 22, 1229-1238. https://doi.org/10.1016/j.procs.2013.09.210

Fischer, A. P. 2018. Forest landscapes as social-ecological systems and implications for management. Land. and Urb. Plan. 177, 138-147. https://doi.org/10.1016/j.landurbplan.2018.05.001

Fischer, A.P., Klooster, A., Cirhigiri, L. 2019. Cross-boundary cooperation for landscape management: Collective action and social exchange among individual private forest landowners. Land. and Urb. Plan. 188, 151-162. https://doi.org/10.1016/j.landurbplan.2018.02.004

Fischer, D. T., Church, R. L. 2003. Clustering, and compactness in reserve site selection: an extension of the biodiversity management area selection model. Forest Science. 49, 555–565. https://doi.org/10.1093/forestscience/49.4.555

Fonseca, C. R.; Ganade, G.; Baldissera, R.; Becker, C. G. et al. 2009. Towards an ecologically sustainable forestry in the Atlantic Forest. Biol. Cons. 142, 1209-1219. https://doi.org/10.1016/j.biocon.2009.02.017

Forest Stewardship Council (FSC). 2010. Swedish FSC Standard for Forest Certification Including SLIMF Indicators. FSC Sweden, Uppsala.

Forestry Commission Lowland Landscape Design Guidelines. 1992. HMSO, London.

França, L.C.J., Mucida, D. P., Santana, E. C., Morais, M. S., Gomide, L. R., Bateira, C. V. M. 2020. AHP approach applied to multi-criteria decisions in environmental fragility mapping. Floresta, 50, 1623-1632. http://dx.doi.org/10.5380/rf.v50i3.65146

Franklin, J. F., Donato, D. C. 2020. Variable retention harvesting in the Douglas-fir region. Ecol. Proc. 9, 1-10. https://doi.org/10.1186/s13717-019-0205-5

Franklin, J.F., Forman, R.T.T. 1987. Creating landscape patterns by forest cutting: ecological consequences and principles. Landscape Ecology, 1, 5-18. https://doi.org/10.1007/BF02275261

Fulton, S., West, B. 2002. Forestry Impacts on Water Quality. Chapter 21. In: Wear, David N.; Greis, John G., eds. Southern forest resource assessment. Gen. Tech. Rep. SRS-53. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 635 p, 2002. Available at: < https://www.srs.fs.usda.gov/sustain/report/pdf/chapter_21e.pdf>. Access in 28/01/2020.

Gadow, K., Pukkala, T. 2008. Designing Green Landscapes. Springer Science & Business Media: 290p. https://doi.org/10.1007/978-1-4020-6759-4

Garzon, A. R. G., Bettinger, P., Siry, J., Abrams, J., Cieszewski, C., Boston, K., Mei, B., Zengin, H., Yesil, A. 2020. A comparative Analysis of Five Certifications Programs. Forests, 11, 1-21. https://doi.org/10.3390/f11080863

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E. J. 2017. The Circular Economy – A new sustainability paradigm? J. of Clea. Prod. 143, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

Gomide, L. R. 2009. Planejamento Florestal Espacial. Thesis presented to the postgraduate program in forestry engineering, Federal University of Paraná (Brazil). 256p. Available in: < https://acervodigital.ufpr.br/bitstream/handle/1884/21401/t264_0326-D.pdf?sequence=1&isAllowed=y>. Access in: 28/01/2020.

Gomide, L. R., Arce, J. E., Silva, A. C. L. 2013. Comparison the metaheuristic simulated annealing and integer linear programming for solving the forest harvest scheduling with adjacency constraints. Ciência Florestal, 23, 449-460. https://doi.org/10.5902/198050989289

Gomide, L. R., Arce, J. E., Silva, A. L. 2010. Spatial adjacency constraints effect in optimized forest planning. Floresta. 40, 573-584. http://dx.doi.org/10.5380/rf.v40i3.18919

Gong, C., Tan, Q., Xu, M., Liu, G. 2020. Mixed-species plantations can alleviate water stress on the Loess Plateau. For. Ecol. and Manag. 458. https://doi.org/10.1016/j.foreco.2019.117767

González-Moreno, P., Quero, J.L., Pooter, L., Bonet, F.J., Zamora, R. 2011. Is spatial structure the key to promote plant diversity in Mediterranean forest plantations? Basic and Appl. Eco. 12, 251-259. https://doi.org/10.1016/j.baae.2011.02.012

Graetz, D.H. 2000. The SafeD model: incorporating episodic disturbances and heuristic programming into forest management planning for the Applegate River watershed, southwestern Oregon. Corvallis, OR: Department of Forest Resources, Oregon State University. 127 p. M.S. thesis.

Guedes, B. S., Olsson, B. A., Egnell, G., Sitoe, A. A., Karltun, E. 2018. Plantations of Pinus and Eucalyptus replacing degraded mountain miombo woodlands in Mozambique significantly increase carbon sequestration. Glob. Eco. and Cons. 14. https://doi.org/10.1016/j.gecco.2018.e00401

Gundersen, V., Frivold, L. 2008. Public preferences for forest structures: a review of quantitative surveys from Finland, Norway, and Sweden. Urb. For. Urb. Green. 7, 241-258. https://doi.org/10.1016/j.ufug.2008.05.001

Gustafsson, L., Baker, S.C., Bauhus, J., Beese, W.J., Brodie, A., Kouki, J., Lindenmayer, D.B., Lõhmus, A., Martínez Pastur, G., Messier, C., Neyland, M., Palik, B., Sverdrup-Thygeson, A., Volney, J.A., Wayne, A., Franklin, J.F. 2012. Retention forestry to maintain multifunctional forests: A World Perspective. BioScience. 62, 633–645. https://doi.org/10.1525/bio.2012.62.7.6

Gustafsson, L., Hannerz, M., Koivula, M., Shorohova, E., Vanha-Majamaa, I., Weslien, J. Research on retention forestry in Northern Europe. Ecol. Proc. 9, 1-13, 2020. https://doi.org/10.1186/s13717-019-0208-2

Guz, A.N., Rushchitsky, J.J. 2009. Scopus: a system for the evaluation of scientific journals. Inter. Appl. Mech. 45, 351-362. https://doi.org/10.1007/s10778-009-0189-4

Haines, A., Thompson, A. W., McFarlane, D., Sharp, A. K. 2019. Local policy and landowner attitudes: A case study of forest fragmentation. Land. and Urb. Plan. 188, 97-109. https://doi.org/10.1016/j.landurbplan.2018.08.026

Harshaw, H. W., Sheppard, S.R.J. 2013. Using the recreation opportunity spectrum to evaluate the temporal impacts of timber harvesting on outdoor recreation settings. J. of Out. Recr. and Tour. 40-50. https://doi.org/10.1016/j.jort.2013.03.001

Hayes, J. L., Ager, A. A., Barbour, J. R. 2004. Methods for Integrated Modeling of Landscape Change: Interior Northwest Landscape Analysis System. Gen. Tech. Rep. PNW-GTR-610. Portland, OR: U.S. Department of

Agriculture, Forest Service, Pacific Northwest Research Station. 218p. Available in: <https://www.fs.fed.us/pnw/pubs/pnw_gtr610.pdf>. Access in: 16/05/2020.

Heilmayr, R. 2014. Conservation through intensification? The effects of plantations on natural forests. Eco. Econ. 105, 204-210. https://doi.org/10.1016/j.ecolecon.2014.06.008

Heinonen, T. 2007. Developing spatial optimization in forest planning. Dissertation. University of Joensuu, Joensuu. 48 p.

Hennes, L. C., Irving, M. J., Navon, D. 1971. Forest control and regulation: a comparison of traditional methods and alternatives. Res. Note PSW-RN-231. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 11 p.

Hodge, S.J. 1995. Creating and Managing Woodlands Around Towns. Forestry Commission, Handbook 11 HMSO Publications Center, London.

Huang, L., Zhou, Mi., Lv, J., Chen, K. 2020. Trends in global research in forest carbon sequestration: A bibliometric analysis. J. of Clea. Prod. 252, 2-17 . https://doi.org/10.1016/j.jclepro.2019.119908

Hughes, A. O., Quinn, J. M. 2019. The effect of forestry management activities on stream water quality within a headwater plantation Pinus radiata forest. For. Eco. and Man. 439, 41-54, https://doi.org/10.1016/j.foreco.2019.02.035

IBÁ – Industria Brasileira de Árvores. Relatório IBÁ 2020 (Ano base 2019). São Paulo, 2020. Available in: < https://iba.org/datafiles/publicacoes/relatorios/relatorio-iba-2020.pdf>. Access in: 09-10-2020.

Jack, S. B., Long, J. N. 1996. Linkages between silviculture and ecology: an analysis of density management diagrams. For. Eco. and Man. 86, 105-220, https://doi.org/10.1016/S0378-1127(96)03770-X

Jamnick, M.S., Walters, K.R. 1993. Spatial and temporal allocation of stratum-based harvest schedules. Can. J. For. Res. 23, 402-413. https://doi.org/10.1139/x93-058

Jenkins, J. 2018. A 'deep' aesthetics of contested landscapes: Visions of land use as competing temporalities. Geoforum. 95, 35-45. https://doi.org/10.1016/j.geoforum.2018.07.003

Johnson, K.N., Scheurman, H. L. 1977. Techniques for Prescribing Optimal Timber Harvest and Investment Under Different Objectives - Discussion and Synthesis. Forest Science. 18, 1-31. https://doi.org/10.1093/forestscience/23.s1.a0001

Jordan, G.A., Baskent, E.Z. 1992. A case study in spatial wood supply analysis. Forestry Chronicle, 68, 503-516. https://doi.org/10.5558/tfc68503-4

Jung, S., Rasmussen, L. V., Watkins, C., Newton, P., Agrawal, A. 2017. Brazil's National Environmental Registry of Rural Properties: Implications for Livelihoods. Eco. Econ. 136, 53-61. https://doi.org/10.1016/j.ecolecon.2017.02.004

Kadioğullari, A. I., Keles, S., Baskent, E. Z., Bingöl, Ö. 2015. Controlling Spatial Forest Structure with Spatial Simulation in Forest Management Planning: A Case Study from Turkey. Sains Malaysiana. 44, 325-336. http://journalarticle.ukm.my/8474/1/03_Ali_Ihsan.pdf

Kangas, J., Kangas, A. 2002. Multiple criteria decision support methods in forest management: An overview and comparative analyses. In: Pukkala, T. Multi-objective Forest Planning. Springer-Science+Business Media, B.V. 213p. https://doi.org/10.1007/978-94-015-9906-1_3

Kaya, A., Bettinger, P., Boston, K., Akbulut, R., Ucar, Z., Siry, J., Merry, K., Cieszewski, C. 2016. Optimization in Forest Management. Forest Management, 2, 1-17. https://doi.org/10.1007/s40725-016-0027-y

Kearney, B., O'Connor, R. 1993. The impact of forestry on Rural Communities. The Forest Service (Department of Agriculture, Food and Forestry). Available in: https://www.esri.ie/system/files/media/file-uploads/2015-07/BKMNEXT75.pdf>. Access in: 22/01/2020.

Keenan, P. B., Jankowkski, P. 2019. Spatial Decision Support System: Three decades on. Deci. Supp. Syst. 116, 64-76. https://doi.org/10.1016/j.dss.2018.10.010

Koch, N.E., Skovsgaard, J.P. 1999. Sustainable management of planted forests: some comparison between Central Europe and the United States. New. For.17, 11-22. https://doi.org/10.1023/A:1006520809425

Könnyű, N., Tóth, S. F. 2013. A cutting plane method for solving harvest scheduling models with area restrictions. Europ. J. of Operat. Rese. 228, 236-248. https://doi.org/10.1016/j.ejor.2013.01.020

Könnyű, N., Toth, S. F., McDill M. E., Rajasekaran, B. 2015. Temporal Connectivity of Mature Patches in Forest Planning Models. For. Sci. 60, 1089-1099. https://doi.org/10.5849/forsci.12-112

Koseoglu, M. A. 2016. Mapping the institutional collaboration network of strategic management research: 1980-2014. Scientometrics. 109, 203-226. https://doi.org/10.1007/s11192-016-1894-5

Kurttila, M. 2001. The spatial structure of forests in the optimization calculations of forest planning – a landscape ecological perspective. For. Eco. and Manag. 142, 129- 142. https://doi.org/10.1016/S0378-1127(00)00343-1

Kuuluvainen, T., Lindberg, H., Vanha-Majamaa, I., Keto-Tokoi, P., Punttila P. 2019. Low-level retention forestry, certification, and biodiversity: case Finland. Eco. Proc. 8, 1-13. https://doi.org/10.1186/s13717-019-0198-0

Kyem, P. A. K. 2002. Using GIS to support multi-objective decision making in forest management. In: Pukkala, T. Multi-objective Forest Planning. SPRINGER-SCIENCE+BUSINESS MEDIA, B.V. 213p., Available in:< https://link.springer.com/chapter/10.1007/978-94-015-9906-1_2>. Access in: 12/08/2020.

Lauer, C. J., Montgomery, C. A., Dietterich, T. G. 2017. Spatial interactions and optimal forest management on a fire-threatened landscape. For. Pol. and Econ. 83, 107-120, http://dx.doi.org/10.1016/j.forpol.2017.07.006

Leemans, R., Vellinga, P. 2017. The scientific motivation of the internationally agreed 'well below 2 °C' climate protection target: a historical perspective. Cur. Opi. in Envi. Sust. 134-142. http://dx.doi.org/10.1016/j.cosust.2017.07.010

Leuschner, W. A. 1990. Forest Regulation, Harvest Scheduling, and Planning Techniques. Wil. Inter. Publ. 21, 304 p.

Li, Y., Linhares-Juvenal, T. 2019. The economic contribution of the world's forest sector. For. Pol. and Econ. 100, 236-256. https://doi.org/10.1016/j.forpol.2019.01.004

Liu, C. L. C., Kuchma, O., Krutovsky, K. V. 2018. Mixed species versus monocultures in plantations forestry: Development, benefits, ecosystem services and perspectives for the future. Glob. Ecol. and Cons. 15, 2-13. https://doi.org/10.1016/j.gecco.2018.e00419

Liu, W.Y., Lin, C.C. 2015. Spatial forest resource planning using a cultural algorithm with problem-specific information. Envir. Model. & Soft. 71, 126–137. https://doi.org/10.1016/j.envsoft.2015.06.002

Lo Volvo, E. 2017. Meta-heuristic Algorithms for Nesting Problem of Rectangular Pieces. Proced. Engin. 183, 291-296. https://doi.org/10.1016/j.proeng.2017.04.041

Lockwood, C.; Moore, T. 1993. Harvest scheduling with spatial constraints: a simulated annealing approach. Can. J. of For. Rese. 23, 468-478. https://doi.org/10.1139/x93-065

Lucas, O.W.R. 1991. The Design of Forest Landscapes. Oxford University Press, New York.

Lupton, R.C., Allwood, J.M. 2017. Hybrid Sankey diagrams: Visual analysis of multidimensional data for understanding resource use. Resour. Conser. and Recy. 124, 141-151. https://doi.org/10.1016/j.resconrec.2017.05.002

Lynd, L. R., Liang, X., Biddy, M. J., Allee, A., Cai, H., Foust, T., Himmel, M. E., Laser, M. S., Wang, M., Wyman, C. E. 2017. Cellulosic ethanol: status and innovation. Cur. Opin. in Biot. 45, 202-211. https://doi.org/10.1016/j.copbio.2017.03.008

Maamoun, N. 2019. The Kyoto protocol: Empirical evidence of a hidden success. J. of Env. Econ. and Manag. 95, 227-256. https://doi.org/10.1016/j.jeem.2019.04.001

Mandeep, D., Gupta, G. K., Shukla, P. 2020. Insights into the resources generation from pulp and paper industry wastes: Challenges, perspectives, and innovations. Bio. Tec. 297. https://doi.org/10.1016/j.biortech.2019.122496

Mäntymaa, E., Juutinen, A., Tyrväinen, L., Karhu, J., Kurtilla, M. 2018. Participation and compensation claims in voluntary forest landscape conservation: The case of the Ruka-Kuusamo tourism area, Finland. J. of For. Econ. 33, 14-24. https://doi.org/10.1016/j.jfe.2018.09.003

Mäntymaa, E., Tyrväinen, L., Juutinen, A., Kurttila, M. Importance of forest landscape quality for companies operating in nature tourism areas. Land Use Pol. 18, 2019. https://doi.org/10.1016/j.landusepol.2019.104095

Marchi, E., Chung, W., Visser, R., Abbas, D., Nordfjell, T., Mederski, P.S., McEwan, A., Brink, M., Laschi, A. 2018. Sustainable Forest Operations (SFO): a new paradigm in a changing world and climate. Sci. Tot. Env. 634, 1385–1397. https://doi.org/10.1016/j.scitotenv.2018.04.084

Martínez Pastur, G. J. M., Vanha-Majamaa, I., Franklin, J. F. 2020. Ecological perspectives on variable retention forestry. Eco. Proc. 9, 1-6. https://doi.org/10.1186/s13717-020-0215-3

Martins, T. V., Gomide, L. R., Ferraz Filho, A. C., Silva, P. R., Melo, L. A. 2017. Eucalyptus clonal mosaics in forest planning and their effects on wood production and economy. Sci. For. 45, 727-737.

McDill, M. E., Rebain, S. A., Braze, J. 2002. Harvest Scheduling with Area-Based Adjacency Constraints. For. Sci. 48. https://doi.org/10.1093/forestscience/48.4.631

McEwan, A., Marchi, E., Spinelli, R., Brink, M. 2019. Past, present and future of industrial plantation forestry and implication on future timber harvesting technology. J. of For. Rese., 1-13. https://doi.org/10.1007/s11676-019-01019-3

McGarigal, K., Marks, B.J. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. U.S.D.A. Forest Service, PNW, General Technical Report, p. 351, 1995.

Meo I., Ferretti, F., Frattegiani, M., Lora, C., Paletto, A. 2013. Public participation GIS to support a bottom-up approach in forest landscape planning. iForest. 6, 347-352. https://doi.org/10.3832/ifor0917-006

Merezis-Solà, I., Bariviera, A.F. 2019. A bibliometric analysis of bitcoin scientific production. Res. in Inter. Bus. and Fin. 50, 294-305. https://doi.org/10.1016/j.ribaf.2019.06.008

Mery, G. 1996. Sustainable Management of Forest Plantations and Natural Forests in Chile. Environmental Science and Technology Library, 249-274. Available in:< https://link.springer.com/chapter/10.1007/978-94-009-1588-6_14>. Access in: 14/05/2020.

Mongeon, P., Paul-Hus, A. 2016. The journal coverage of Web of Science and Scopus: a comparative analysis. Scientometrics, 106, 213-228. https://doi.org/10.1007/s11192-015-1765-5

Morandi, D. T., Franca, L.C. J., Menezes, E. S., Machado, E. L. M., Silva, M. D., Mucida, D. P. 2020. Delimitation of ecological corridors between conservation units in the Brazilian Cerrado using a GIS and AHP approach. Eco. Indic. 115, 2-10.https://doi.org/10.1016/j.ecolind.2020.106440

Moreira, F., Viedma, O., Arianoustsou, M., Curt, T., Koutsias, N., Rigolot, E., Barbati, A., Corona, P., Vaz, P., Xanthopoulos, G., Mouillot, F., Bilgili, E. 2011. Landscape – wildfire interactions in southern Europe: Implications for landscape management. J. of Env. Manag. 92, 2389-2402. https://doi.org/10.1016/j.jenvman.2011.06.028

Moreira, J. M. M. A. P., Rodriguez, L.C.E. 2010.A incorporação de corredores de conectividade no manejo de florestas industriais utilizando a heurística da Razão R. Rev. de Econ. e Socio. Rur. 48, 255-282. https://doi.org/10.1590/S0103-20032010000200001

Moreira, J. M. M.A. P., Rodrigues, L. C. E., Caixeta-Filho, J. V. 2013. An Optimization Model to Integrate Forest Plantations and Connecting Corridors. For. Sci. 59, 661-669. https://doi.org/10.5849/forsci.12-051

Mourão, P. R., Martinho, V. D. Forest entrepreneurship: A bibliometric analysis and a discussion about the co-authorship networks of an emerging scientific field. J. of Clea. Produc. 256, 2020. https://doi.org/10.1016/j.jclepro.2020.120413

Murray, A.T. 1999. Spatial restrictions in harvest scheduling. For. Sci., 45, 45–52. https://doi.org/10.1093/forestscience/45.1.45

Murray, A.T., Weintraub, A. 2002. Scale and unit specification influences in harvest scheduling with maximum area restrictions. For. Sci., 48, 779-789. https://doi.org/10.1093/forestscience/48.4.779

Nambiar, E.K.S. 2019. Tamm Review: Re-imagining forestry and wood business: pathways to rural development, poverty alleviation and climate change mitigation in the tropics. For. Eco. and Manag. 448, 160-173. https://doi.org/10.1016/j.foreco.2019.06.014

Näyhä, A. 2019 Transition in the Finnish forest-based sector: Company perspectives on the bioeconomy, circular economy and sustainability. J. of Clea. Produc. 209, 1294-1306. https://doi.org/10.1016/j.jclepro.2018.10.260

Nelson, J. D. 2001. Assessment of forest harvest blocks generated from operational polygons and forest-cover polygons in tactical and strategic planning. Can. J. of For. Res. 31, 682-693. https://doi.org/10.1139/x00-205

Oliveira, A. L., Borges, L. A. C., Coelho Júnior, M. G., Barros, D. A., Coelho Júnior, L. M. 2020. Forest Replacement in Brazil: A Fundamental Policy for Forestry. Floresta e Ambiente, 27 (4). https://doi.org/10.1590/2179-8087.002118

Öhman, k. 2000. Creating continuous areas of old forest in long-term forest planning. Can. J. F. For. Res. 30, 1817-1823. https://doi.org/10.1139/x00-103

Önal H., Briers R.A. Optimal selection of a connected reserve network. Operat. Resear. 54, 402–403, 2006. https://doi.org/10.1287/opre.1060.0272

Ozkan, U. Y., Damirel, T., Ozdemir, I., Saglam, S., Mert, A. 2020. Examining LiDAR – WorldView-3 data synergy to generate a detailed stand map in a mixed forest in the north-west of Turkey. Adv. in Space Rese. 65, 2608-2621. https://doi.org/10.1016/j.asr.2020.02.020

Palmer, J. F. 2008. The perceived scenic effects of clearcutting in the White Mountains of New Hampshire, USA. J. of Env. Manag. 89, 167-183. https://doi.org/10.1016/j.jenvman.2007.01.064

Panagopoulos T., Hatzistathis A. 1995. Early growth of *Pinus nigra* and *Robinia pseudacacia* stands; contributions to soil genesis and landscape improvement on lignite spoils in Ptolemaida. Land. and Urb. Plan. 32, 19-29. https://doi.org/10.1016/0169-2046(94)00186-7.

Panagopoulos, T. 2009. Linking forestry, sustainability, and aesthetics. Eco. Econ. 68, 2485-2489. https://doi.org/10.1016/j.ecolecon.2009.05.006

Paruelo, J. M. 2012. Ecosystem services and tree plantations in Uruguay: A reply to Vihervaara et al (2012). For. Pol. and Econ. 22, 85-88. https://doi.org/10.1016/j.forpol.2012.04.005

Payn, T., Carnus, J-M., Freer-Smith, P., Kimberley, M., Kollert, W., Liu, S., Orazio, C., Rodriguez, L., Silva, L. N., Wingfield, M. J. 2015. Changes in planted forests and future global implications. For. Eco. and Manag. 352, 57-67. https://doi.org/10.1016/j.foreco.2015.06.021

Pereira, A. P. A., Durrer, A., Gumiere, T., Gonçalves, J. L. M., Robin, A., Bouillet, J.P., Wang, J., Verma, J. P., Singh, B. K., Cardoso, E. J.B.N. 2019. Mixed Eucalyptus plantations induce changes in microbial communities and increase biological functions in the soil and litter layers. For. Eco. and Manag. 433, 332-342. https://doi.org/10.1016/j.foreco.2018.11.018

Pierzchała, M., Giguère, P., Astrup, R. 2018. Mapping forests using an unmanned ground vehicle with 3D LiDAR and graph-SLAM. Comp. and Elect. in Agric. 145, 217-225. https://doi.org/10.1016/j.compag.2017.12.034

Pliscoff P., Simonetti, J. A., Grez, A. A., Vergara, P. M., Barahona-Segovia, R. M. 2020. Defining corridors for movement of multiple species in forest-plantation landscape. Glob. Ecol. and Cons. 23. https://doi.org/10.1016/j.gecco.2020.e01108

Pretzsch, H., Forrester, D. I.; Rotzer, T. 2015. Representation of species mixing in forest growth models. A review and perspective. Eco. Model. 312, 276-292. https://doi.org/10.1016/j.ecolmodel.2015.06.044

Pretzsch, H., Schutze, G. 2014. Size-structure dynamics of mixed versus pure forest stands. For. Syst., 23, 560-572. http://dx.doi.org/10.5424/fs/2014233-06112

Pukkala, T., Nuutinen, T., Kangas, J. 1995. Integrating scenic and recreational amenities into numerical forest planning. Land. and Urb. Plan. 32, 85-195. https://doi.org/10.1016/0169-2046(94)00195-9

Ribe, R. G. 2009. In-stand scenic beauty of variable retention harvests and mature forests in the U.S. Pacific Northwest: The effects of basal area, density, retention pattern and down wood. Journal of Env. Manag. 91, 245-260. https://doi.org/10.1016/j.jenvman.2009.08.014

Rien, V., Francis, O. O. 2021. Automation and Robotics in Forest Harvesting Operations: Identifying Near-Term Opportunities. Croat. J. of For. Eng. 42. 13-24. https://doi.org/10.5552/crojfe.2021.739

Roche, M. 2017. Forest governance and sustainability pathways in the absence of a comprehensive national forest policy – The case of New Zealand. For. Pol. and Econ. 77, 33-42. https://doi.org/10.1016/j.forpol.2015.12.007

Rode, R., Leite, H. G., Silva, M. L., Ribeiro, C. A. A. S., Binoti, D. H. B. 2014. The economics and optimal management regimes of eucalyptus plantations: A case study of forestry outgrower schemes in Brazil. For. Pol. and Econ. 44, 26-33. https://doi.org/10.1016/j.forpol.2014.05.001

Roitman, I., Vieira, L. C. G., Jacobson, T. K. B., Bustamante, M. M. C., Marcondes, N. J. S., Cury, K., Estevam, L. S., Ribeiro, R. J. C., Ribeiro, V., Stabile, M. C.C., Filho, R. J. M., Avila, M. L. 2018. Rural Environmental Registry: An innovate model for land-use and environmental policies. Land Use Policy. 76, 95-102. https://doi.org/10.1016/j.landusepol.2018.04.037

Rönnqvist, M., D'Amours, S., Weintraub, A., Jofre, A., Gunn, E., Haight, R. G., Martell, D., Murray, A. T., Romero, C. 2015. Operations Research challenges in forestry: 33 open problems. Annals of Operations Research. https://doi.org/10.1007/s10479-015-1907-4

Ross, K. L.; Tóth, S. F. 2016. A model for managing edge effects in harvest scheduling using spatial optimization. Scand. J. of For. Res. 31, 646-654. https://doi.org/10.1080/02827581.2016.1213877

Roth, F. 1914. Forest Regulation, or the Preparation and Development of Forest Working Plans. Publisher by th author. Ann Arbo, Michigan. Available in: < https://babel.hathitrust.org/cgi/pt?id=mdp.39015071242575&view=1up&seq=7>. Access in: 18/05/2020.

RStudio Team. 2019. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA URL http://www.rstudio.com/.

Saaty, T. L. 1980. The Analytic Hierarchy Process. McGraw-Hill, New York. 287 p.

Salas, C., Donoso, P. J., Vargas, R., Arriagada, C. A., Pedraza, R., Soto, D. P. 2016. The Forest Sector in Chile: Na Overview and Current Challenges. J. of For. 114, 562-571. https://doi.org/10.5849/jof.14-062

Sánchez, L. E., Croal, P. 2012. Environmental impact assessment, from Rio-92 to Rio+20 and Beyond. Amb. & Soc. 3, 41-54. https://doi.org/10.1590/S1414-753X2012000300004

Scherer-Lorenzen, M., Körner, C., Schulze, E.D. 2005. Forest diversity and function. Ecol. Studies 176, Springer, Berlin, Heidelberg, p. 399.

Schroeder, H., Daniel, T. C. 1981. Progress in Predicting the Perceived Scenic Beauty of Forest Landscapes. For. Sci. 27, 71-80. https://doi.org/10.1093/forestscience/27.1.71

Schulze, K., Malek, Ž., Verburg, P. H. 2019. Towards better mapping of forest management patterns: A global allocation approach. For. Eco. and Manag. 432, 776–785. https://doi.org/10.1016/j.foreco.2018.10.001

Segura, M., Ray, D., Maroto, C. 2014. Decision support systems for forest management: A comparative analysis and assessment. Comp. and Elec. in Agric. 101, 55-67. https://doi.org/10.1016/j.compag.2013.12.005

Sessions, J. 1992. Solving for habitat connections as a Steiner network problem. For. Sci. 38, 203-207. https://doi.org/10.1093/forestscience/38.1.203

Shorohova, E., Sinkevich, S., Kryshen, A., Vanha-Majamaa, I. 2019. Variable retention forestry in Europe boreal forests in Russia. Ecol. Proces. 8, 1-11. https://doi.org/10.1186/s13717-019-0183-7

Siry, J. P., Cubbage, F. W., Ahmed, M. R. 2005. Sustainable forest management: global trends and opportunities. For. Pol. and Econ. 7, 551-561. https://doi.org/10.1016/j.forpol.2003.09.003

Tavares, A., Beiroz, W., Fialho, A., Frazão, F., Macedo, R., Louzada, J., Audino, L. 2019. Eucalyptus plantations as hybrid ecosystems: Implications for species conservation in the Brazilian Atlantic Forest. For. Eco. and Manag. 433, 131-139. https://doi.org/10.1016/j.foreco.2018.10.063

Tikkanen, J., Hokajärvi, R., Hujala, T., Kurttila, M. 2017. Ex ante evaluation of a PES system: safeguarding recreational environments for nature-based tourism. J. Rural Stud. 52, 42-55. https://doi.org/10.1016/j.jrurstud.2017.03.011

Tóth, S. F., McDill, M. E., Konnyu, N., George, S. 2012. A strengthening procedure for the path formulation of the area-based adjacency problem in harvest scheduling models. Math. Comput. For. Nat.-Res. Sci. 4, 16–38. http://mcfns.net/index.php/Journal/article/view/MCFNS.4%3A27/MCFNS.4%3A27

Tóth, S. F., McDill, M. E., Könnyu, N., George, S. 2013. Testing the Use of Lazy Constraints in Solving Area-Based Adjacency Formulations of Harvest Scheduling Models. For. Sci. 59, 157-176. https://doi.org/10.5849/forsci.11-040

Tyrväinen, L., Mäntymaa, E., Juutinen, A., Kurttilla, M., Ovaskainen, V. 2021. Private landowners' preferences for trading forest landscape and recreational values: A choice experiment application in Kuusamo, Finland. Land Use Policy. v.7, 1-11. https://doi.org/10.1016/j.landusepol.2020.104478

Tyrväinen, L., Mäntymaa, E., Ovaskainen, V. 2014. Demand for enhanced forest amenities in private lands: the case of Ruka-Kuusamo tourism area Finland. For. Pol. and Econ. 47, 4-13. https://doi.org/10.1016/j.forpol.2013.05.007

United Nations Economics Commission for Europe, 2015. ECE/FAO Forest Products Annual Market Review, 2014-2015. Geneva Timber and Forest Study Paper 29, ECE/TIM/SP/39. United Nations Economic Commission for Europe, Timber Section, Geneva. 120 p.

United Nations. Transforming our World: The 2030 agenda for sustainable development. 2015. Available in: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf. Access in: 22/01/2020.

United Nations. The Global Forest Goals Report. United Nations Department of Economic and Social Affairs, United Nations Forum on Forests Secretariat, 2021. Available in: https://www.un.org/esa/forests/wp-content/uploads/2021/08/Global-Forest-Goals-Report-2021.pdf

Uribe-Toril, J., Ruiz-Leal, J.L., Haba-Osca, J., Valenciano, J. P. 2019. Forests' First Década: A Bibliometric Analysis Overview. Forests. 10, 2-17. https://doi.org/10.3390/f10010072

USDA - Forest Service. 1974. Visual Management System. National Forest Landscape Management, Volume 2, Chapter 1; and subsequent chapters. Available in: < https://www.nrc.gov/docs/ML1224/ML12241A372.pdf>. Access in: 24/03/2022.

USDA - Forest Service. 1994. Visual Quality Best Management Practices for Forest Management in Minnesota. Minnesota, 78p. Available in: https://www.leg.state.mn.us/docs/2015/other/155133.pdf. Access in: 24/03/2022.

Vallourec. 2019. Public Summary the Plan Forest management. Available in:< https://www.vallourec.com/-/media/Corporate_WebSite/BR_Documents/Plano_Manejo_Florestal_VFL.ashx>. Access in: 06/08/2020.

Van Deusen, P. C., Wigley, T. B., Lucier, A. A. 2010. Some indirect costs of forest certification. Forestry. 83, 389-394. https://doi.org/10.1093/forestry/cpq021

Vides-Borrel, E., Porter-Bolland, L., Ferguson, B. G., Gasselin, P., Vaca, R., Valle-Mora, J., Vandame, R. 2019. Polycultures, pastures and monocultures: Effects of land use intensity on wild bee diversity in tropical landscapes of southeastern Mexico. Biol. Cons. 236, 269-280. https://doi.org/10.1016/j.biocon.2019.04.025

Vihervaara, P., Marjokorpi, A., Kumpula, T., Walls, M., Kamppinen, M. 2012. Ecosystem services of fast-growing tree plantations: A case study on integrating social valuations with land-use changes in Uruguay. For. Pol. and Econ. 14, 58-68. https://doi.org/10.1016/j.forpol.2011.08.008

Vodak, M.C., Roberts, P.L., Wellman, J.D., Buhyoff, G.J. 1985. Scenic Impacts of Eastern Hardwood Management. For. Sci. 31, 289-301. https://doi.org/10.1093/forestscience/31.2.289

von Carlowitz, H.C. Sylvicultura Oeconomica: Hausswirthliche Nachricht und Naturmäßige Anweisung zur Wilden Baum-Zucht. Johann Friedrich Braun, Leipzig, 1713. https://www.digitale-sammlungen.de/en/view/bsb10214444?page=,1

Vopěnka, P., Kašpar, J., Marušák, R. 2015. GIS tool for optimization of forest harvest-scheduling. Comp. and Elec. in Agric. 113, 254-259. https://doi.org/10.1016/j.compag.2015.03.001

Walters, K. R., Feunekes, U., Cogswell, A., Cox, E. 1999. A forest planning system for solving spatial harvest scheduling problems. CORS National Conference, Canada.

Wei, Y., Hoganson, H. M. 2007. Scheduling forest core area production using mixed integer programming.Canadian Journal of Forest Research, 37, 10, 1924 – 1932. https://doi.org/10.1139/X07-033

Weintraub A., Barahona F., Epstein R., 1994. A column generation algorithm for solving general forest planning problems with adjacency constraints. For. Sci. 40, 142-161. https://doi.org/10.1093/forestscience/40.1.142

Weintraub, A., Murray, A. T. 2006. Review of combinatorial problems induced by spatial forest harvesting planning. Disc. App. Math.154, 867-879. https://doi.org/10.1016/j.dam.2005.05.025

Williams, J. C. 1998. Delineating protected wildlife corridors with multi-objective programming. Env. Mod. and Ass. 3, 77-86. https://doi.org/10.1023/A:1019006721277

Winjum, J.K., Schroeder, P. E. 1997. Forest plantations of the world: their extent, ecological attributes, and carbon storage. Agric. and For. Meteo. 84, 53-167. https://doi.org/10.1016/S0168-1923(96)02383-0

Wulder, M. A., White, J. C., Nelson, R. F., Naesset, E., Orka, H. O., Coops, N. C., Hilker, T., Bater, C. W., Gobakken, T. 2012. Lidar sampling for large-area forest characterization: A review. Rem. Sens. of Env.121, 196-209. https://doi.org/10.1016/j.rse.2012.02.001

Zabel, A., Bostedt, G., Ekval, H. 2018. Policies for forest landscape management - A conceptual approach with an empirical application for Swedish conditions. For. Pol. and Econ. 86, 13-21. https://doi.org/10.1016/j.forpol.2017.10.008

Zanuncio, J. C., Tavares, W. S., Ramalho, F. S., Leite, G. L. D., Serrão, J. E. 2016. Sarsina violascens spatial and temporal distributions affected by native vegetation strips in Eucalyptus plantations. Pesq. Agropec. Bras. 51, 703-709. https://doi.org/10.1590/S0100-204X2016000600001

Zhao, D., Strotmann, A. 2015. Analysis and Visualization of Citation Networks. Morgan & Claypool, San Rafael, 207p. https://doi.org/10.2200/S00624ED1V01Y201501ICR039

Živojinović, I., Nedeljković, J., Stojanovski, V., Japelj, A., Nonić, D., Weiss, G., Ludvig, A. 2017. Non-timber forest products in transition economies: Innovation cases in selected SEE countries. For. Pol. and Econ. 81,18-29. https://doi.org/10.1016/j.forpol.2017.04.003

ARTIGO 02: Manuscrito adaptado à revista *Science of the Total Environment.*

Towards a renewable energy project under sustainable watershed principles for forest biomass supply

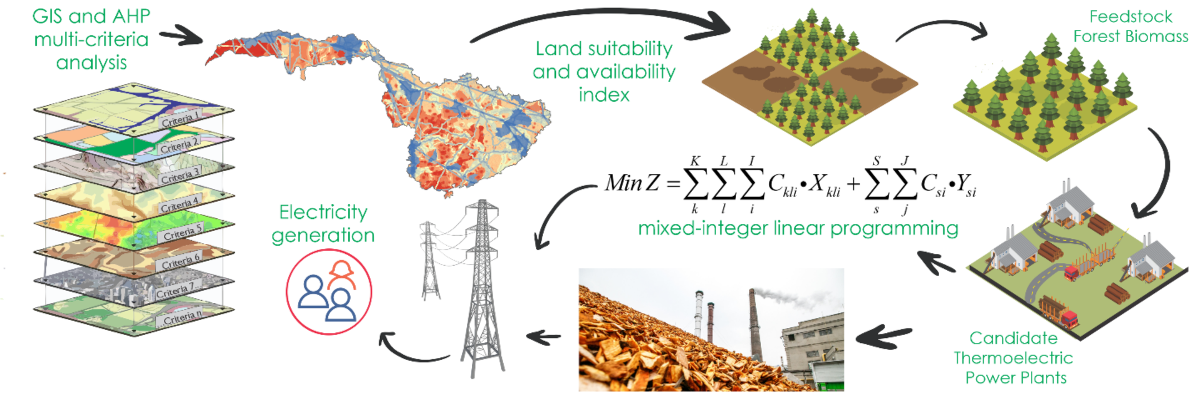
Highlights

- The land use planning is crucial for forest biomass projects at large-scale.
- A multi-criteria method has supported the spatial optimization model and decisions.
- The triad of environmental, economic, and social constraints may reduce the project risks and impacts.
- A mixed-integer linear programming model is desirable for decision-making.
- The optimal solution suggests an overall investment of around USD 103 million over 27,234 hectares.
- The spatial strategies and optimal solution are welcome at green industry development view.

Abstract. The transition in the global energy matrix to sources of renewable electric generation has been the main demand of countries in the face of a state of climatic emergency. Forest biomass is a potential alternative to meet the growing demand. The expansion of thermoelectric projects based on forest residues highlights the need to assess the availability of raw materials and the suitability of land. This is usually a problem of spatial decision and geographic intelligence under a holistic perspective since in the planning of these projects it is essential to understand the economic, environmental, and social feasibility. In this article, we propose a decision support system based on multicriteria modeling on a GIS structure associated with a mathematical optimization model for zoning the suitability and availability of land for constructing thermoelectric power plants. Various environmental, social, and economic criteria and constraints have been integrated into the geospatial model for determining priority sites. The AHP method was used to weight and estimate the relative importance weights of the criteria for modeling territorial aptitude. The results of the GIS stage formed the basis of a mixed-integer linear programming model that incorporated technical and economic aspects for a better allocation of financial resources. The minimized cost function included transport costs, harvesting, forestry, purchase of land/leasing land/forest outgrower schemes, and purchase of wood from the market to supply the biomass. We used a large hydrographic basin in southeastern Brazil as a case study for the demonstration. Mapping of suitability and constrained zones was produced to identify the classes of preference and availability of land. The proposed mathematical model identified sets of supply locations (new plantations or existing areas) and minimized the final cost of the project to supply biomass to meet the demand of potential thermoelectric plants that are candidates for implementation. Despite the large scale of the problem and the large set of data, our findings indicated that we could provide a broad and multidimensional view on the potential of developing electrical generation systems based on forest biomass. The methodology and the model proposed in this study can be replicated in other global regions and can be modified to assess other resources from different biomasses and bioenergy systems.

Keywords: forest planning; land-use planning; green industry; renewable energy; multi-criteria decision analysis; mixed-integer linear programming, bioeconomy.

Graphical abstract



1. Introduction

The anthropogenic CO_2 emissions have increased globally at a level of ~30 Gt over 2019-2020 (Abdallah and El-Shennawy, 2020). Half of them were significantly related to the power generation and industrial processes at least (IEA, 2021a). The electricity sector achieved 12.3 Gt of CO_2 or 36% of all energy-related emissions, which is more than any other sector in 2020 (IEA, 2021b). Furthermore, serious consequences are altering important environmental factors such as species extinction, famine, and the emergence of diseases considered sensitive to climate change (Grobush and Grobush, 2022). Even whether the maximum global warming thresholds as established by the Paris Agreement (1.5 and 2 °C relatives to pre-industrial levels) are not exceeded, part of the climate system impacts resulting from this warming will be unavoidable (Martins et al., 2022).

The race to reduce carbon emission has started early and the world depends on sustainable projects to reduce social and environmental risks. Furthermore, governmental, and non-governmental initiatives are widely reported in agreements, protocols, and certificates that consider the greenhouse gas emissions (GHG). Several principles have been driving the mitigation of these negative impacts on climate changes. Fortunately, they bring together some highlighted themes which include economic growth and energy security (generation/cogeneration of electricity) from renewable sources (Liebensteiner and Wrienz, 2020; Pablo-Romero et al., 2021).

Bioenergy systems have a high potential to phase out the use of fossil fuels (Zhang *et al*., 2017; Briones-Hidrovo et al., 2021), and are an important renewable resource for low carbon economies in the energy transition (Gabrielle et al., 2014; Acuna et al., 2019). The forestry sector is the largest stakeholder with more than 85% of all biomasses for the energy proposes (WBA, 2019; Briones-Hidrovo et al., 2021). Currently, a total of 6,890 TWh of renewable electricity is worldwide produced yearly (WBA, 2020), and hydropower has the largest renewable electricity generating source (62%) followed by wind (19%) and Bioenergy (9.25%). In Brazil, the power/energy matrix has high dependence of hydroelectric plants (64.1%) and fossil fuels (15.4%), followed by eolic (9.0%), biomass (8.8%), solar (1.5%), and nuclear (1.2%) (Brazilian Energy Balance, 2020). Unfortunately, the warm/cool phases of oceans have changed the precipitation distribution and temperature of Brazil. The current hydrological condition has a negative effect on reservoirs' level and the hydroelectric energy offer. Further, there are several social and environmental impacts associated with large dams (Oliveira et al., 2022; Botelho et al., 2022), and other questions about technical viability or enterprise life cycle.

The energy generation projects of biomass sources have been observed over the years in Brazil. For instance, the installed capacity of electric generation is 14,978 MW (2019). The primary growth projections (2050) of forest biomass suggest an increased scenario of 166% for energy uses in Brazil. These values are boosted by Pulp-Paper industries, which are also expanding their forest domain for energy proposes (EPE, 2018; EPE, 2020). Given that condition, the raw material is almost processed vertically integrated with industrial scope. Moreover, residuals or secondary forest products are usually detected in industrial processing/forest harvesting. Annually, they export around 41 million tons of wood residues (Ferreira et al., 2018) or the equivalent of 1.7 GW for energy proposes in Brazil. They should be more explored for energy resources and economic profits (Ferreira-Leitão et al., 2010).

Brazil's forest-based production chain has encouraged the diversification of its economy to generate jobs, income and consolidate sustainable development policies. The country has extensive planted areas with shorter rotations and the highest productivity in the world, which may support the production of renewable electric energy. Brazil has 9.55 million hectares of planted trees within 78.21% of *eucalyptus* genus with the an average growth rate of 36.8 m^3/ha.year (IBÁ, 2021). The biomass stock and flexible harvest scheduling lead to the "storage of energy" at the time of consumption reducing the risks (van Leeuwen et al., 2021). Conversely, wind and solar energy have technical constraints of operational stock or high costs so far.

Challenges facing countries for energy production are associated with mono-dependencies/limitation of primary sources, efficient generation system and transmission, increasing the diversification within the energy matrix, investments, international price volatility and global demands. The shortage of energy across the world is real, facing the global commercial dependence on fossil fuels coming from great energy powers. The European Union imports around 82% of its oil and 57% of its gas from Russia. Other large energy orders are seen in populous countries like China and India. The demand for energy will expand by 45% by 2030 globally, and it will increase by more than 300% by the end of the century (Hao et al., 2016). It may reflect the economic downturn and recovery time after the last two pandemic years.

Thermoelectric projects with forest biomass sources must deal with several assumptions at large-scale units. The success of the operational licenses and land use planning depends on how they join efficiently the stakeholders. For instance, there is a large amount of land within a wide conservation status, ecological biomes rules and uses for agriculture/pasture/other, and government compliance (Rural Environmental Registry or CAR, in Portuguese) to achieve the return performance of the investment in Brazil. As expected, spatial planning and land use management under multiple constraints of any social, ecological and productive indicators may be desired in a sustainable wood supply chain. In fact, this optimization problem combines the minimization of project implementation costs with suitable zones according to the selection criteria. Although financial outlay is the key point, within private enterprises or any political constrained, the landscape analysis matters to reduce the enterprise risks. Fortunately, the industry supply chain and location also affect the final decision and should be fitted perfectly into the landscape view. Even investment has promoted the development of the country inside areas, the large-scale project has much association with social-ecological patterns. The glace of management does not focus only on the land cost or site quality to grow, but the holistic view between multi-factorial variables. Under these circumstances, the spatial decision problem faces a wide range of constraints. The perception of industrial growth limits or zoning may reduce the pressure on the landscape, which means traditional communities, endemic species of fauna and flora, hydrology, beauty scene, hotspot of diversity, and any other industrial side effects. Perhaps an accurate sustainable land management enhances the efficiency of its uses for economic purposes (Fei et al., 2017; Oakleaf et al., 2019). The forest biomass enterprise requires a substantial amount of land within a region. The land size of the investment depends on the wood demand, site quality, labor allocation, technical progress, capital formation, political stability, the possibility of different options for land use and bioproducts, among others (McEwan et al., 2020).

Multi-Criteria Decision Analysis (MCDA) is an analytical method with criteria and parameters to support the decision-making (Kougkoulos et al. 2017) in many application fields, including natural resource management (Kangas et al., 2008). Usually, this sub-field of operational research relies on matrixes and rules for solving complex problems with opposite goals (Kougkoulos et al. 2017). The outlined method integrated with geographical information systems (GIS) has been applied for locations facilities management (Ma et al., 2005; Latinopoulos and Kechagia, 2015; Delivand et al., 2015; Sánchez-Lozano et al., 2015; Azevêdo et al., 2017; Jeong and Ramírez-Gómez, 2017; Hanssen, 2018; Woo et al., 2018; Costa et al., 2020) over the last decades. This association may include economic, environmental, and social criteria for suitable and desirable zones of use at the spatial view (Holsbeeck and Srivastava, 2020). The overlapping of matrix operations eliminates inappropriate areas highlighting a set of favours lands without severe restrictions.

Despite all positive assumptions, rather few studies have attempted to relate territorial zoning and linear programming modeling for thermoelectric power plants supplied by forest biomass. Furthermore, several researches have focused on agriculture waste or industrial/city residuous (Sultana and Kumar, 2012; Costa et al., 2020; Cuong et al., 2021). In this context, the hypothesis that guides the present study is that through the application of MCDA-GIS techniques and a linear programming model, it is possible to assist in decision-making with geographic intelligence for the purchase of wood, leasing land, forest outgrower schemes, and purchase of land for implementation and supply of thermoelectric projects based on residues from planted forests. Therefore, this research analyzed available and priority areas for the implementation of thermoelectric power plants e developed a resource allocation model via mixed integer linear programming to define the best land use strategies at a hydrographic basin scale, with a case study applied to Brazil. The main contributions of our study are related to the urgent need for diversification of the Brazilian energy matrix. We explored the use of new criteria and constraints not used in other previous studies, to better represent the real complexity of spatial analysis. And from the mapped potential areas, we developed a mathematical model of resource allocation through mixed-integer linear programming, involving forest business modalities within realistic scenarios.

2. Material and Methods

2.1. Large-scale study area

The study location is a fraction of Brazilian's territory delimitated by the Rio Grande watershed (86,086.4 km²) in Minas Gerais state (Figure 1.A). The region has high economic expansion been an important frontier of agribusiness, industries, tourism, and hydroelectric production (Camargos, Itutinga, Funil, and Furnas dams). For instance, there are approximately 255,000 ha of *Eucalyptus* spp. trees planted for commercial purposes (MapBiomas, 2020), and productivity estimates (Mean Annual Increment) varying between 37.55 and 50.35 m^3 ha^{-1}. year $^{-1}$ at 6 years old of final rotation (Binkley et al., 2020). The population is around 6 million within 287 municipalities (IGAM, 2020). According to the Köppen classification system (Figure 1.B), the region has clearly three types of climates over the watershed: a) western portion: Tropical climate (*Aw*), b) middle point: Humid subtropical zone (*Cwa*), and c) south and southeast region: Humid subtropical zone (*Cwb*). The average annual precipitation is ranging between 1,300 - 1,900 mm. However, the western portion is relatively dry with high temperatures. The average temperature around 14 - 24 °C (Alvares et al. 2013; Carvalho et al., 2010) and altitudinal gradient (302 – 2,778m).

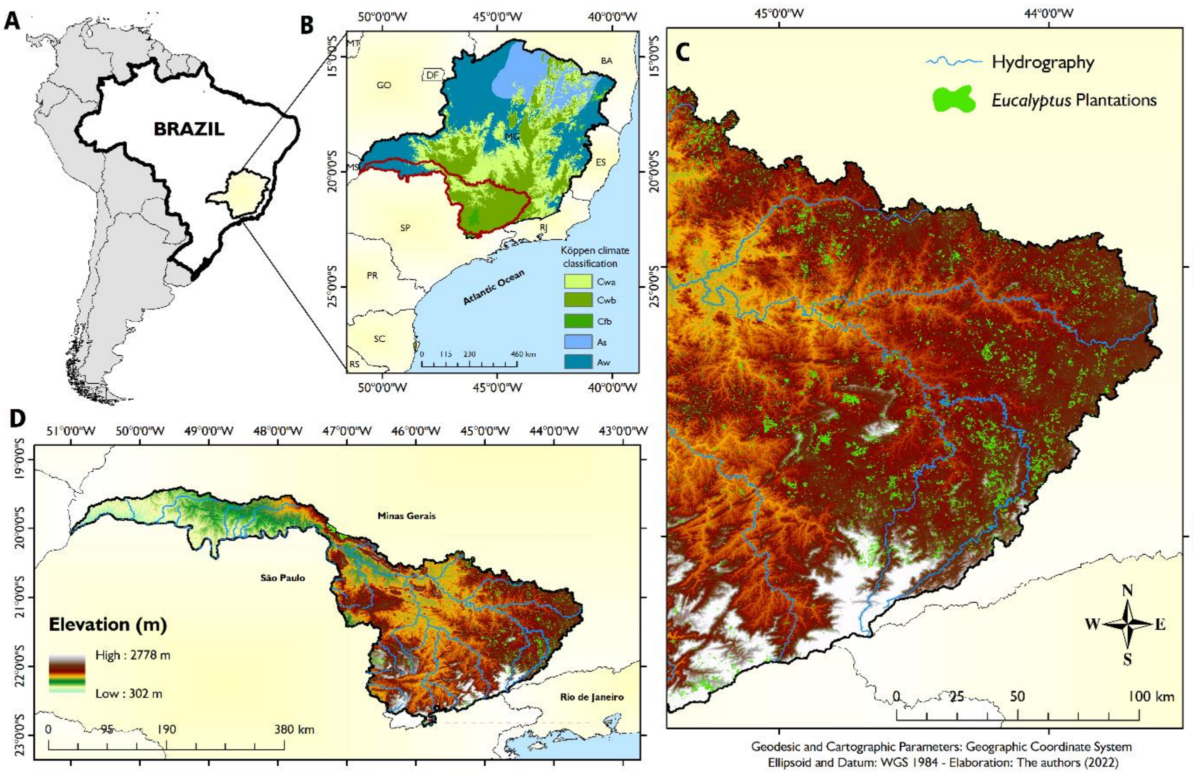


Figure 1. The Grande River drainage basin in the Minas Gerais state – Brazil (**A**), climate classification types (**B**), the spatial distribution of *eucalyptus* plantations (**C**), and elevation gradient (**D**).

2.2. Wood supply chain and land management problem

The problem portrayed in this study involves the appropriate use of land for the installation of large thermoelectric projects, involving the consumption of forest biomass. Vegetable biomass has become a key and strategic raw material to not only drive the economy in various sectors, such as pulp, paper, panels and sawmills, but also its use in generating thermoelectric energy. The idea in question has been consolidated for decades in Brazil and in the world, but only recently has it begun gaining strength and form due to the recurring crises of energy generation that the country and world have been going through. If, on the one hand, there is a ready-to-use raw material, on the other hand, it is possible to perceive the existence of land available for the expansion of commercial eucalyptus plantations, as well as favorable climatic conditions for silviculture and facilities for the success of the operation.

The target region of this study allows facilities for electrical connection to the national grid, which reduces operating costs. However, the real sustainability of the enterprise in question depends on its own plantations, so as not to depend on market prices in relation to wood price variations/adjustments. In this sense, we seek to answer a series of questions: (i) Is it possible to identify in high detail the most appropriate locations for the installation of this forest cluster based on robust spatial zoning? and (ii) Can the development of a mathematical programming model provide guidelines to support decision-making for forestry and thermoelectric investments? The feasibility of implementing thermoelectric industries in this region will directly reflect on the possibility of creating jobs, collecting taxes from the government, better land use practices, greater control in forest protection, respect for legislation and maintenance of areas with preserved native forests, less dependence the level of water reservoirs, and contribution to the debate on the global climate emergency.

2.3.Part I: Territorial Sustainability Index (TSI)

2.3.1. Multi-Criteria Decision Analysis (MCDA)

We have applied a set of 17 input layers to guide the restricted/unrestricted areas over the watershed. The entire spatial data is open access and an official from Brazilian institutions (Table 1 – *Anexo – Supplementary material*). The constraint rules of the land uses have been defined according to the legal information of government and industrial facilities. The available zoning without constraints for the forest biomass project was designed considering the environmental, social, and economic factors. Finally, the Territorial Sustainability Index (TSI) was calculated to define the priority lands for the implementation of thermoelectric plants and their silvicultural projects. The ArcGIS 10.8 (ESRI, 2016) and free web based AHP solution called AHP-OS package (Goepel, 2018) softwares were used to map and run the AHP method, respectively.

2.3.2. Account the constrained and sustainability areas

An exclusion analysis was conducted to define the areas considered unsuitable for constructing thermoelectric plants. Topological constraints related to artificial, natural, and environmental elements were considered and are summarized in Table 2. The social, environmental, and legal acceptability of establishing thermoelectric industries based on forest biomass, largely depends on the appropriate treatment given to these three elements (Sultana and Kumar, 2012). In the analysis of constrained areas, we implemented an extension (buffer zone) for each restriction, selected based on the characteristics of the study region and based on guidelines obtained from the literature and legislation.

Table 2. Thecnical constraints of land use to delimit spatial buffer zones.

Theme	Technical values of constrained areas	Reference sources
Urban areas	Radius (≤ 1 km)	Sultana and Kumar (2012); Teixeira *et al.,* (2018); Costa *et al.,* (2020).
Archaeological sites	Distance (≤ 200 m)	Perpiñá *et al.,* (2013).
Airfields (Public and Private)	Buffer zone (≤ 13 km or ≤ 20 km) [a]	Brasil (1986); Brasil (1987); Brasil (1995); Dong (2008); Teixeira *et al.,* (2018); Costa *et al.,* (2020).
Hydrography (rivers, lakes, and other water bodies)	Buffer zone (≤ 200 m[c]) [b]	Brasil (1980); Sultana and Kumar (2012); Brasil (2012); Costa *et al.,* (2020); Perpiñá *et al.,* (2013).
Environmentally sensitive areas (Veredas)	Distance (≤ 50 m)	Brasil (2012); Minas Gerais (2013); Costa *et al.,* (2020).
Conservation unit (Integral protection)	Buffer zone (≤ 10.000 m)	SNUC (2000); Sultana and Kumar (2012); Costa *et al.,* (2020).
Conservation unit (Sustainable use)	Polygons (área)	
Highways and Railways	Buffer zone (≤ 30 m)	Teixeira *et al.,* (2018); Costa *et al.,* (2020); Sultana and Kumar (2012); Perpiñá *et al*. (2009; 2013).
Power transmission lines	Buffer zone (≤ 30 m)	Costa *et al.,* (2020); Teixeira *et al.,* (2018).
Surface inclination	hillslopes (>25% or >15º)	Ramos (2000); Dong (2008); Perpiñá *et al.,* (2013); Teixeira *et al.,* (2018); Costa *et al.,* (2020).
Indigenous lands	Polygons (area)	Teixeira *et al.,* (2018).
Rural settlements	Polygons (área)	Teixeira *et al.,* (2018); Costa *et al.,* (2020).

[a] 20 km radius for airports that operate according to the instrument flight rules (IFR) and 13 km radius for other airfields - Law N°. 7,565/1986 (BRASIL, 1986); [b] MINTER ordinance Nº.124, of August 20, 1980, established rules for the location of potentially polluting industries in water collections (BRASIL, 1980).

From the manipulation of geospatial data, a raster map (90 m) was generated for each constraint element. The image data were transformed into a binary image by reclassifying cells within the restriction area by "0" and cells outside the area by "1", that is, cells with a value of "1" indicated the potentially favorable locations for the construction of the thermoelectric plants, and the value “0” indicated that the cell was not suitable. The final binary restriction map was produced by multiplying the data layers (Equation 1), where $C_{E,i}$ is the value of the cell *i* of the boolean value (0,1) assigned to *i* ésimo cell value in *j* ésima restricted grid layer; *n* is the number of constraints considered in the analysis.

$$C_{E,i} = \prod_{j=1}^{n} C_{i,j}$$

Eq.1

We examined the factors that most influence the selection and sustainability of potentially priority sites for the installation of thermoelectric plants. In this step, we used 12 criterias/themes (Table 3) in spatially defined data to map suitable or preferred areas. The choice of criteria and definition of preference classes was established based on technical aspects observed in an extensive bibliographic survey (Richardson et al., 2002; Pohekar and Ramachandran, 2004; Dong, 2008; Sultana and Kumar, 2012; Perpinã et al., 2013; Recanatesi et al., 2014; Teixeira et al., 2018, Energy Answer Arecibo, 2010; Zhang et al., 2017; Sánchez-García et al., 2017; Woo et al., 2018; Costa et al., 2020), especially for those criteria in which their distances/buffer zones are not specified by government regulations or regional environmental legislation. For the analysis of suitability, buffers were generated around the physical elements of the landscape and influence. Each buffer zone was reclassified by assigning a score representing the relative influence of each individual zone. For criteria where establishing a Euclidean distance did not apply (e.g., Land Cost), the values of the raster cells were reclassified directly by assigning the relative scores. In contrast to the exclusion criteria, the analysis of priority areas is used to quantify the degree of suitability of the land for the installation of thermoelectric plants. For all layers, a uniform scoring range from 1 to 3 was established, being: Low Suitability (Score 1), Medium Suitability (Score 2), and High Suitability (Score 3). The sub-criteria that positively influence aptitude received higher scores, while those that have some limitation or greater distance from sources of influence, received lower relative scores (Table 3).

Table 3. The selected criteria (factors) for suitability evaluation preferable to the installation of thermoelectric plants to forest biomass and references.

Criteria	Information	Gradient	Subcriteria/scores	Reference sources
Comercial forest plantations	Distance of immediate wood supply offering (km)	Nearby	> 80 (1) 40 – 80 (2) 0 – 40 (3)	Asikainen et al., (2002); Teixeira et al., (2018).
Urban Areas	Distance of urban areas (km)	Farly	1 – 3 (1) 3 – 5 (2) ≥ 5 (3)	Apawootichai (2001); Dong (2008); Teixeira et al., (2018).
Hydrography	Distance of water bodies (m)	Nearby	200 – 1000 (3) 1000 – 5000 (2) >5000 (1)	Apawootichai (2001); Teixeira et al., (2018).
Thermoelectrics	Indication of the existing distance to other thermoelectric power plants (The closer the better)	Nearby	1 – 5 km (3) > 5 km (2)	Sharma et al. (2017)
Overhead power line	Proximity to the electricity transmission lines (The closer the better)	Nearby	30 – 1600 m (3) > 1600 m (1)	Apawootichai (2001); Koikai (2008); Teixeira et al., (2018).

Roads	Indication of the existing distance to the main roads (The closer the better)	Nearby	30 – 750 m (3) 750 – 1500m (3) > 1500m (3)	Koikai (2008); Sharma et al., (2017)
Railways	Indication of the existing distance to the railways (The closer the better)	Nearby	30 – 5000 m (3) > 5000 m (2)	Koikai (2008).
Power stations	Indication of the distance to the existing substations (the closer, the better)	Nearby	2 – 5 km (3) 5 – 10 km (2) > 10 km (1)	Dong (2008); Energy Answer Arecibo (2010).
Surface inclination	Land slope indication for industrial installations (The flatter the better).	lower slope	0 – 10 % (3) 10 – 20% (2) 20 – 25% (1)	Dong (2008); Ramos (2000); Teixeira et al., (2018); Costa et al., (2020).
Woodstock volume (m^3)	The amount of wood produced	Large volume	51,930 – 206,600 (3) 13,500 – 51,930 (2) 0 – 13,500 (1)	***
[a]Mean Annual Increment (MAI)	Indicates the average growth of the forest until age *n* (The higher the IMA, the better)	Large increment	> 40 $m^3\ ha^{-1}\ ano^{-1}$ (3) 37.55 – 40 $m^3\ ha^{-1}\ ano^{-1}$ (2)	Teixeira et al., (2018); IBÁ (2020)
[b] Bare Land Value (BLV) **(**$/ha)	Indicates the price of land (The lower the cost, the more attractiveness)	Lowest price	274.38 – 1317.04 (3) 1317.04 – 2497.44 (2) 2497.44 – 5291.03 (1)	***

[a] the spatialization of the *Eucalyptus* MAI was carried out using the geostatistical procedure of ordinary kriging; [b] BLV or land cost: monetary values converted to US Dollar.

2.3.3. AHP weights

We use the AHP method of multicriteria decision-making aid, a technique of decision analysis and planning of multiple indicators, in which its application reduces the study of complex systems to a sequence of comparisons to pairs of components appropriately identified (Saaty, 1980). Through a pairwise comparison matrix, the AHP calculates the weight value for each criterion (w_i) by taking the eigenvector corresponding to the largest eigenvalue of the matrix, and then normalizing the sum of the components to a unity (Quinta-Nova *et al.*, 2017). Some conditions are necessary for the correct application of the method (Saaty, 2008): (*i*) Definition of the problem and objective to be achieved; (*ii*) Structuring the indicators in the form of hierarchy; (*iii*) Construction of a square matrix for comparing pairs and; (*iv*) Assigning weight to each of the indicators, on a scale of 1 to 9 (Table 4 – *Anexo – supplementary material*), according to the basic scale referring to the comparison of the criteria.

The method must respect 3 mathematical assumptions: (*i*) Reciprocity (If $a_{ij} = x$, then $a_{ji} = 1 / x$, with $1/9 \leq x \leq 9$); (*ii*) Homogeneity (If the elements *i* and *j* are considered equally important, then $a_{ij} = a_{ji} = 1$, in addition $a_i = 1$ for all *i*; and (*iii*) Consistency (Index and Consistency Ratio must be ≤ 0.10 or 10%) (Saaty, 1980). We checked the consistency rate of the AHP assessment performed in the study. The consistency check aims to verify reliability of the weightings. Thus, the calculation of the consistency index (Saaty, 2008) is given by Equation 2, where CI = Consistency Index; n = number of indicators evaluated; λ_{Max} = Eigen main number. A Consistency Ratio (CR) is determined by the ratio of the value of the Consistency Index (CI) to the Random Index (RI). The matrix is considered consistent if the ratio is ≤ 0.1 or 10% (Saaty, 1980; 2008). Equation 3 describes the relationship is demonstrated by, where RI is a constant value and depends on the dimension of the matrix being compared, that is, on the number of criteria (n) evaluated. The RI values should be checked according to the size (n) of the matrix (Saaty, 1980; 1990) (Table 5 – *Anexo – supplementary material*).

$$\text{CI} = \frac{(\lambda_{Max} - n)}{(n-1)} \qquad \text{Eq.2}$$

$$\text{CR}=\frac{\text{CI}}{\text{RI}} \qquad \text{Eq.3}$$

When the CR value is greater than 0.1 (10%), it is necessary to review the weights established in the main matrix AHP. The results will also be validated as consistent if the main paired comparison matrix shows $\lambda_{\max} \geq n$ (Saaty, 1991). These statistics indicate that the comparisons of the characteristics were adequately consistent and that the relative weights are feasible for later use in multicriteria spatial modeling (Feizizadeh and Blaschke, 2013). The eigenvector or main vector of Eigen (λ_{Max}) comprises the sum of the product of each element of the comparison matrix by the priority vector (Eigen) of each criterion, dividing the result of this expression by the priority vector from which it calculates the arithmetic mean (Santos and Cruz, 2013; Morandi et al., 2020) (Equation 4). Where $\{\text{A}w\}i$ corresponds to the resulting matrix from the product of paired comparison matrix by calculated weights (w).

$$\lambda_{\max} = \frac{1}{n}\sum_{i=0}^{n}\frac{\{Aw\}i}{w} \qquad \text{Eq.4}$$

2.3.4. Raster overlay operations for suitable lands (TSI)

The weighted overlay analysis was conducted to combine the maps referring to the criteria and to identify the preferred zones. The MCDA approach used was the Weighted Linear Combination (WLC), considered one of the most used methods due to its practicality and efficiency (Voogd, 1983; Nzeyimana et al., 2014; Rodríguez-Merino et al., 2020). The WLC has the advantage of assigning different weights to the themes, which indicates its relative importance (Costa et al., 2021). To run the WLC and obtain the final map of suitable land, each normalized layer was multiplied by its respective weights obtained from the AHP model and then summed (pixel-by-pixel operations), obtaining a single output information plan (Raster Calculator), classified in the three aptitude classes (scale from 1 to 3) (*Natural Breaks – Jenks method*). Subsequently, the result was multiplied by exclusion zones, which produced the fitness model (Equation 5), where: *S* is the final preference value of the fitness zone, w_i the weight of the vector to the *i*-ésimo criteria, x_i the normalized cell value of the *i*-ésimo criteria; C_{ij} the boolean value (0,1) attributed to *i*-ésima cell of the *j*-ésima exclusion zone; *k* is the number of criteria considered in the analysis of the suitability zone and; *n* the number of constraints considered in the analysis of the exclusion zone.

$$S = \sum_{i=1}^{n} w_i \times x_i * \prod_{j=1}^{k} C_{i,j} \qquad \text{Eq.5}$$

2.4.Part II: Wood supply planning for the first thermoelectric life cycle

2.4.1. Mathematical formulation of the optimization problem

In this phase, a mathematical programming model was developed to meet the initial premises that guarantee the operation of a thermoelectric plant for a life cycle. Due to the large scale of the problem, it has been subdivided to allow processing efficiency. Generally, matrices similar to the problem of this study can present more than 5 million lines (decision variables) and make the model processing unfeasible. Based on this technical evidence, in this proposal we individually tested each *n* thermoelectric installation sites and later compared the results. In the proposed model, each thermoelectric project was dimensioned with a capacity to generate and export electricity of 50 MWh, according to the regulatory limit for the enterprise to be considered special incentivized energy. In addition to biomass thermoelectric plants, other renewable sources receive tax incentives. Solar power plants, small hydro and wind power plants also include a special incentive classification. These incentivized sources have a subsidy that guarantees a discount to the generator in the Tariffs for Use of Distribution and Transmission Systems (TUSD/TUST) (BRASIL, 2015).

Thus, the model proposed in this study identified sets of supply locations (plantings/existing areas) that minimize the final cost of the project and manage to supply biomass to meet the demand of potential thermoelectric plants that are candidates for implementation. The minimization cost function includes costs of transport, harvesting, forestry, land purchase/lease/outgrower scheme and purchase of wood from the market to supply the biomass. The costs used for the modeling were approximate values and determined based on scientific literature, companies and weighted by experts (Table 6 – *Anexo – supplementary material*). The first six years for constructing the thermoelectric plant (1th and 2th year) and purchase of wood from the market already established in the area (3th to 6th year). The remaining years are considered the period of effective forestry production, using the plant's own funding and wood (7th to 12th year). The costs were discounted to their present value using an annual rate of 8%.

We have established 100 ha (1 km²) grids (*Create fishnet function*) to support possible silvicultural projects. Each grid unit represents a portion of the feasible lease and contract land. Only grids with an effective area above 80 ha were considered in the analysis. In these units, the three contract options were simulated throughout the initial years of project development. A spatial distribution of thermoelectric plants was prepared based on the result of the zoning and sustainability index defined in the previous item. We systematically allocated 10 plants in locations with the highest suitability index values (medium to high suitability locations, above the average value obtained in the index = 1.82, considered preferred land). With the establishment of these potential points, a Euclidean distance matrix was generated combining the production units/grids with the respective thermoelectric candidates. A Euclidean distance matrix was generated by combining all ten plants with all grids, mutually, from the centroids of each cell. The other data referring to the available planted area, productivity ($m^3. ha^{-1}$) at 6 years and land price and land suitability index were obtained and weighted by grid.

Due to the magnitude of the scale of the problem for the purposes of analysis, it was necessary to establish radio of 150 km of feasible supply zone around each thermoelectric plant. This distance is important for compositing costs in the objective function, allowing even better spatial control of the responses, since at this point locations *x* distance are combined. Alternatively, the eucalyptus plantations already existing in the study area (wood from the market) make up the model to support the supply of wood, until the beginning of the first cuts/harvest in the project, which will occur from the sixth year onwards. Due to the large number of plantations that already exist in the area, only polygons above ≥20 ha were used. This filtering action was implemented to reduce efforts in areas reduced by logistics, in addition to improving computational performance due to the combinatorial nature of the problem.

The calculation of the conversion of potential biomass stock to thermoelectric energy was carried out from equation 6 (CENBIO, 2009; Teixeira et al., 2018). Was required the conversion of wood volume unit for ton, 1 m^3 equal to 0.68 t of logs (wood for energy) (SBS, 2008; CENBIO, 2009). The Lower Calorific Value (LCV) was of 2,000 kcal / kg (Teixeira et al., 2018). The wood conversion efficiency in thermoelectric power was 33% (Carneiro and Oliveira, 2013; Goldemberg, 2009; Teixeira et al., 2018) and the conversion factor of kcal/kg to kWh/kg 860 (Coelho et a*l.*, 2000; CEMIG, 2017).

$$Potential\left(\frac{MW}{year}\right) = \frac{\left[\left(m^3 wood \ * \ 0.68\right) \ * \ LCV\,\frac{kcal}{kg} \ * \ 0.33\right]}{860 \ * \ 8{,}322/year} \qquad \text{(Eq. 6)}$$

The proposed model aimed to minimize the global cost of the thermoelectric project (Equation 7), being the decision variable X_{glt} as the area (ha) to be used from grid g {1, ..., 43643} in land use modality l {1 – purchase, 2 – lease, 3 – outgrower scheme), considering annual contract t {1, ... ,6}, and 12 years of planning horizon (Figure 2). The variable Y_{sj} being binary {0,1}, when identifying the existing stands s {1, ... ,2403} that will supply wood in period j of the planning horizon. As each thermoelectric will be analyzed individually, there is no need for a sub-index that directs the activation of a given thermoelectric, with the values of C^1 as the cost (US$.ha^{-1}) of the discounted enterprise to year zero and distributed by its occurrence over the 12 years, with the same reasoning for C^2 but involving the range of 3 to 6 years and market wood. A_g is the maximum area available on the grid g. T is the year of contracting the land for the enterprise that will take place until the 6th year. Once active its fixed 6-year rotation cycle ($t+6$) and all the silvicultural activities for its management. C^3 represents the electrical generation cost of 50 MW. Equations (8), (9), (10.1 and 10.2), represent the set of technical constraints for the problem. Eq. 8 controls the use of the existing forest stock or the purchase of wood in the initial years of the thermoelectric plant, namely the supply of wood from the third to the sixth year (T = {3,4,5,6}). In this restriction, an existing stand can only be used once during the 4 years of purchase of the wood. The variable Y_{sj} is binary {0,1} indicating the purchase of wood in stand s for period j and providing the raw material for the thermoelectric plant. The restriction established in Eq. 9 establishes the maximum limit of area used per grid/unit, in which it is not possible to hire more than what is available in the grids l = {own, lease, outgrower scheme}. Regarding the restrictions on the type of contract, we consider the assumptions established in the model that 60% must be allocated to purchase, 30% to leasing and 10% to the outgrower scheme. Eq. 10 controls the maximum annual energy generation capacity of each thermoelectric plant between the 3rd and 12th year. It is divided in two, to represent, at first, dependence on wood from the market (Eq. 10.1) and then considering only wood/areas belonging to the project (Eq. 10.2). b_{glt} corresponds to the biomass demanded according to the contract period. P_e = {60% = purchase, 30% = leasing, 10% = outgrower scheme}. Due to the nature of the objective function, there is no requirement to establish an upper limit as the model will seek to minimize the total cost. Equations 11 and 12 are non-negativity decision variable. The mathematical problem was solved by a mixed integer linear programming (MLP) model in the R environment (R CORE TEAM, 2021). The models were built in the lpSolveAPI package (Lp_solve et al., 2020), to generate the file in the MPS (Mathematical Programming System) extension, and their resolution will be in the Gurobi package (Gurobi Optimization LLC, 2020) - version 9.0.2. Data processing was performed on a computer with an Intel® Core ™ i3–2100 CPU @ 3.10 GHz processor and 8 GB RAM.

Objective Function*:*

$$MinZ = \sum_{g}^{G}\sum_{l}^{L}\sum_{t}^{T} C^{1}{}_{gl(t-\mathrm{HP})} \bullet X_{glt} + \sum_{s}^{S}\sum_{j}^{J} C^{2}{}_{sj} \bullet Y_{sj} + C^{3} \qquad \text{(Eq.7)}$$

Subject to

$$\sum_{j}^{j} Y_{sj} \le 1; \forall_{s} \qquad \text{(Eq.8)}$$

$$\sum_{l}^{L}\sum_{t}^{T} X_{glt} \le A_{g}; \forall_{g} \qquad \text{(Eq.9)}$$

$$\sum_{s}^{S} V_{s} \bullet Y_{sj} \ge V_{j} \qquad \text{(Eq.10.1)}$$

$$\sum_{g}^{G} b_{glt} \bullet X_{glt} = P_{e} \bullet B_{t}; \forall_{l}; \forall_{t}; t \le HP; \qquad \text{(Eq.10.2)}$$

$$X \ge 0 \qquad \text{(Eq.11)}$$

$$Y \in \{0,1\} \qquad \text{(Eq.12)}$$

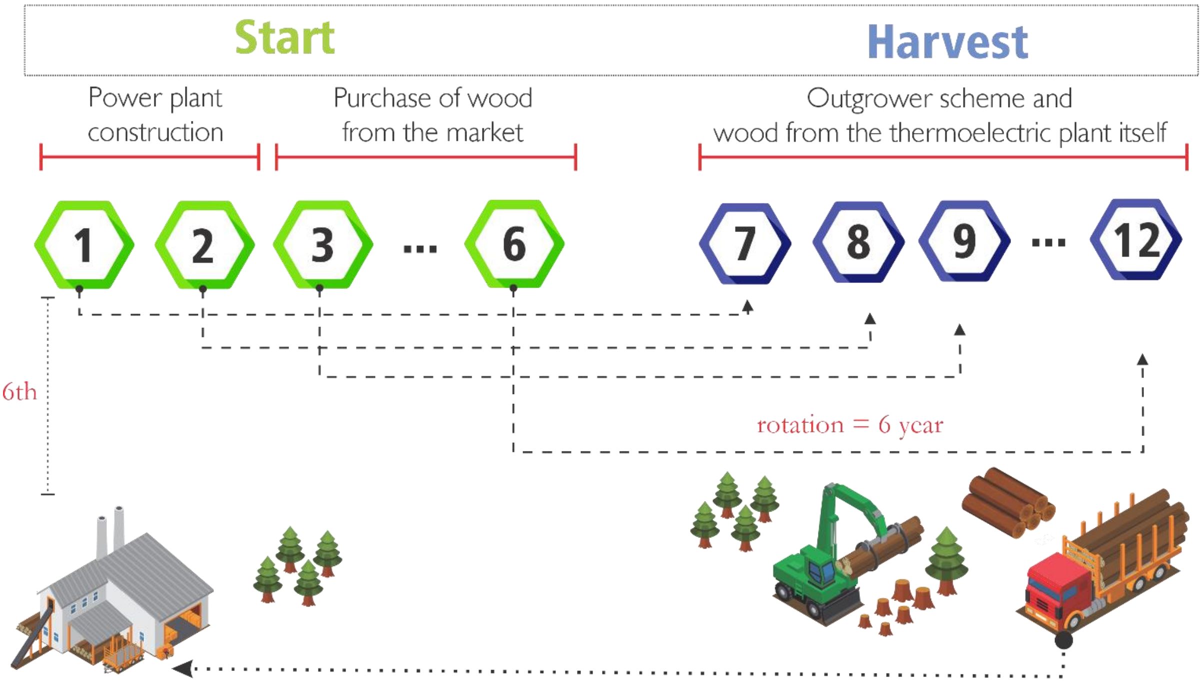


Figure 2. Scheme of the planning horizon considering 12 years, the initial six years being related to the construction of the plant, prospecting for areas and purchasing wood from available forests and the remainder defined as years of effective volumetric production with harvesting of the raw material. Source: The authors (2021) - freepik vectors.

A geostatistical analysis was used to interpolate the results of costs minimized by the objective function corresponding to the best thermoelectric scenario. For comparative analysis, we generate a map of total cost, cost of buying wood from the market and the cost of producing own wood. The geostatistical method used was Ordinary Kriging (Wackernagel, 1995). The findings obtained in this study were evaluated under two aspects: (*i*) the interpretation of the spatial mapping of the suitability index and availability of land and (*ii*) the result generated by the mathematical model. In the first item, potential sites were identified, describing their advantages and disadvantages regarding their selection. This analysis is descriptive and quantitative at the spatial level, observing the interactions with the forest massifs existing in the GRHB. In the second moment, the answers of the mathematical model were confronted with the technical and economic aspects for its interpretation. As all the analysis were individualized among the possible installation points of the thermoelectric plants, the values of the objective function and area used were of great value for this purpose. All criteria used in this study are deterministic in decision making. Finally, the methodological procedures of the study are briefly described in Figure 3.

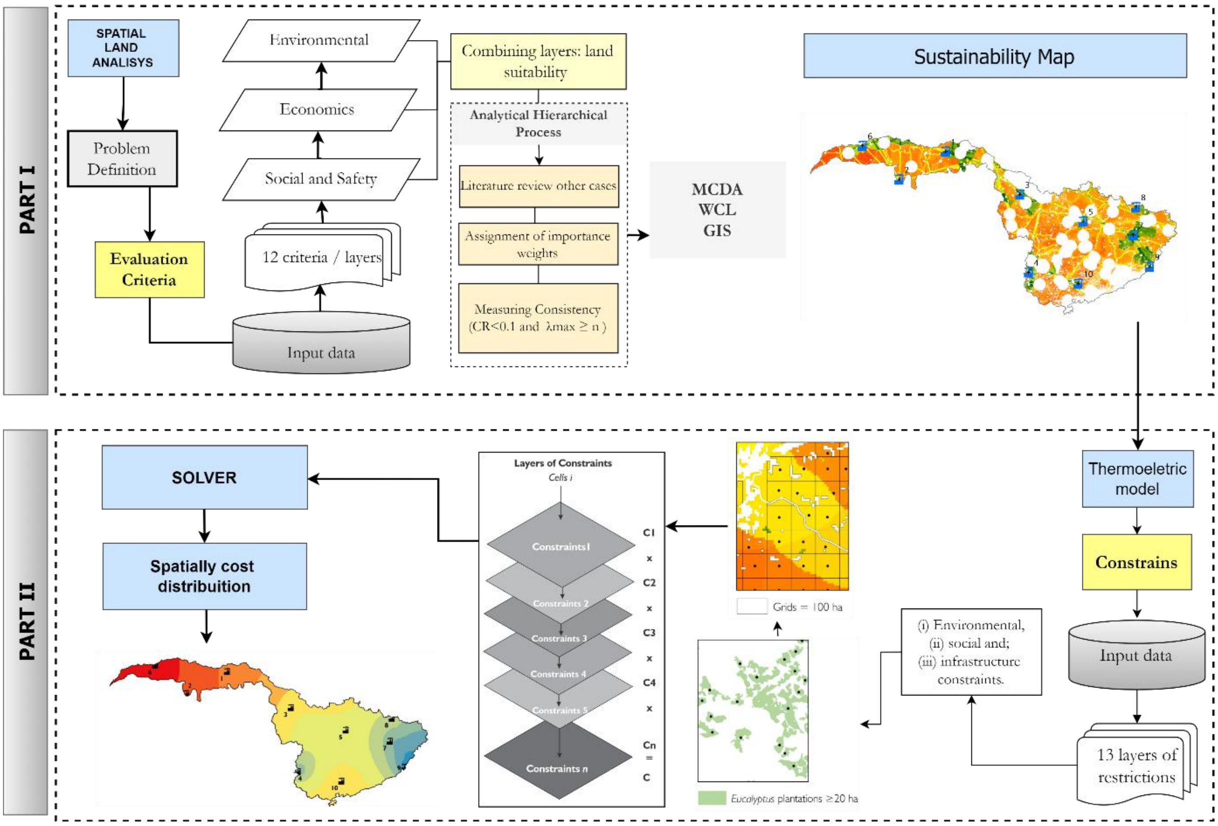


Figure 3. Flowchart of the methodological procedures to drive suitable investment areas for thermoelectric power plants based on forest biomass.

3. Results

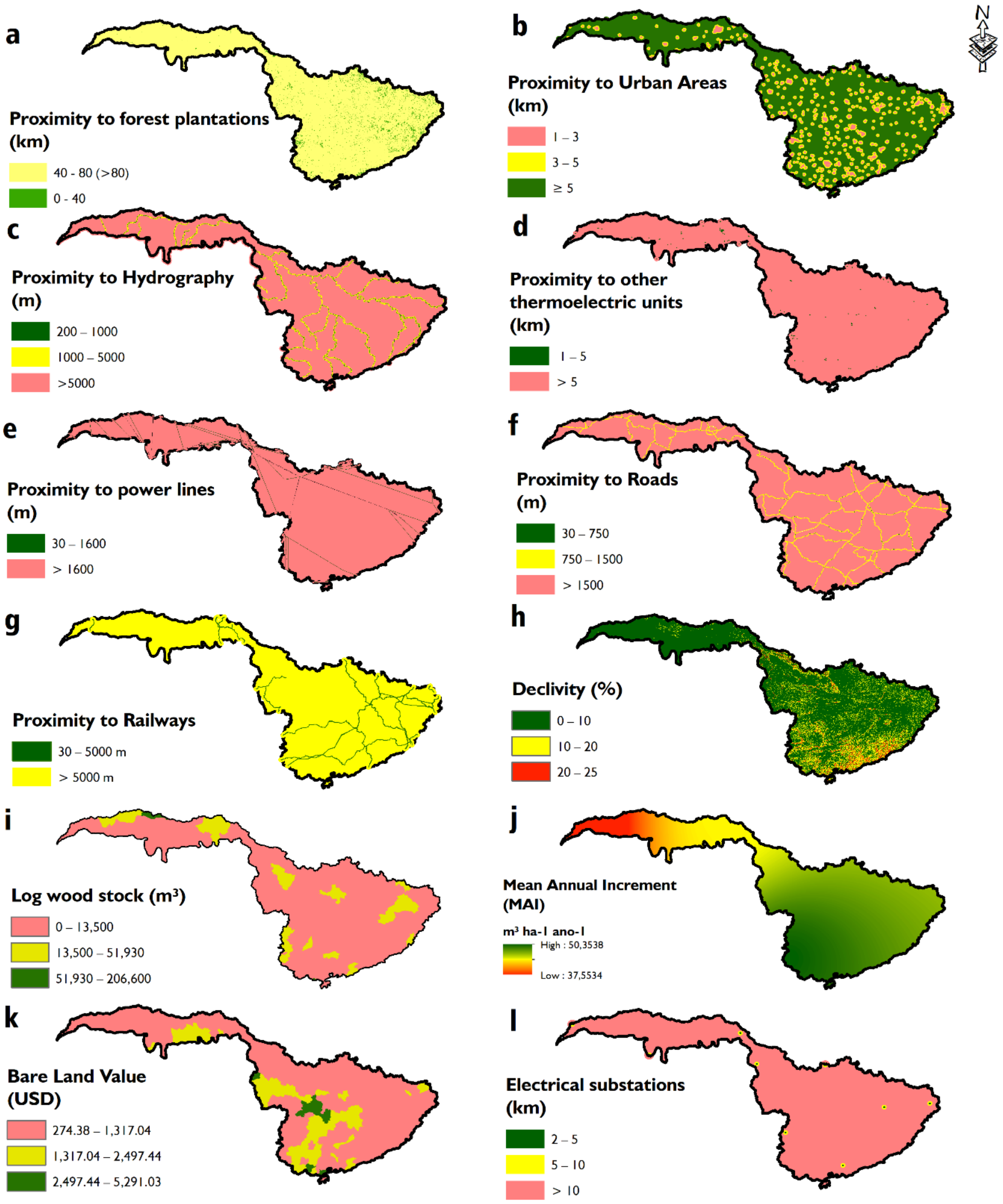
3.1. Part I: Territorial Sustainability Index

3.1.1. Importance of layers obtained via AHP model

A hierarchy of priority for the importance of the criteria was obtained using the AHP model. The result of the paired matrix is shown in Table 7 (*Anexo – supplementary material*). The criteria 'proximity to forest plantations' showed the greatest relevance in the context of zoning of areas suitable for installation of thermoelectric plants based on forest biomass, representing 23.7% of importance in the composition of the multicriteria evaluation model (MCDA). In the sequence of importance, the criteria ‘log wood stock (m^3)’, ‘proximity to roads’ and ‘proximity to power lines’ presented the highest weights, respectively, 17.1%, 13.9% and, 10.9%. The other criteria and their weights in the order of importance are presented in Table 8 (*Anexo – supplementary material*).

The calculated Consistency Index (CI) and Consistency Ratio (CR) were 0.09 and 0.06, respectively. These values are in accordance with the scale of coherence and reliability (≤0.10

or 10%) (Saaty, 1980). The value obtained from $\lambda_{max} = 12.97$ ($n = 12$) also confirmed the adequacy of the ponderations performed, where $\lambda_{max} \geq n$ (Saaty, 1991). The composite map in Figure 4 presents the data from Table 3 in spatialized layers.



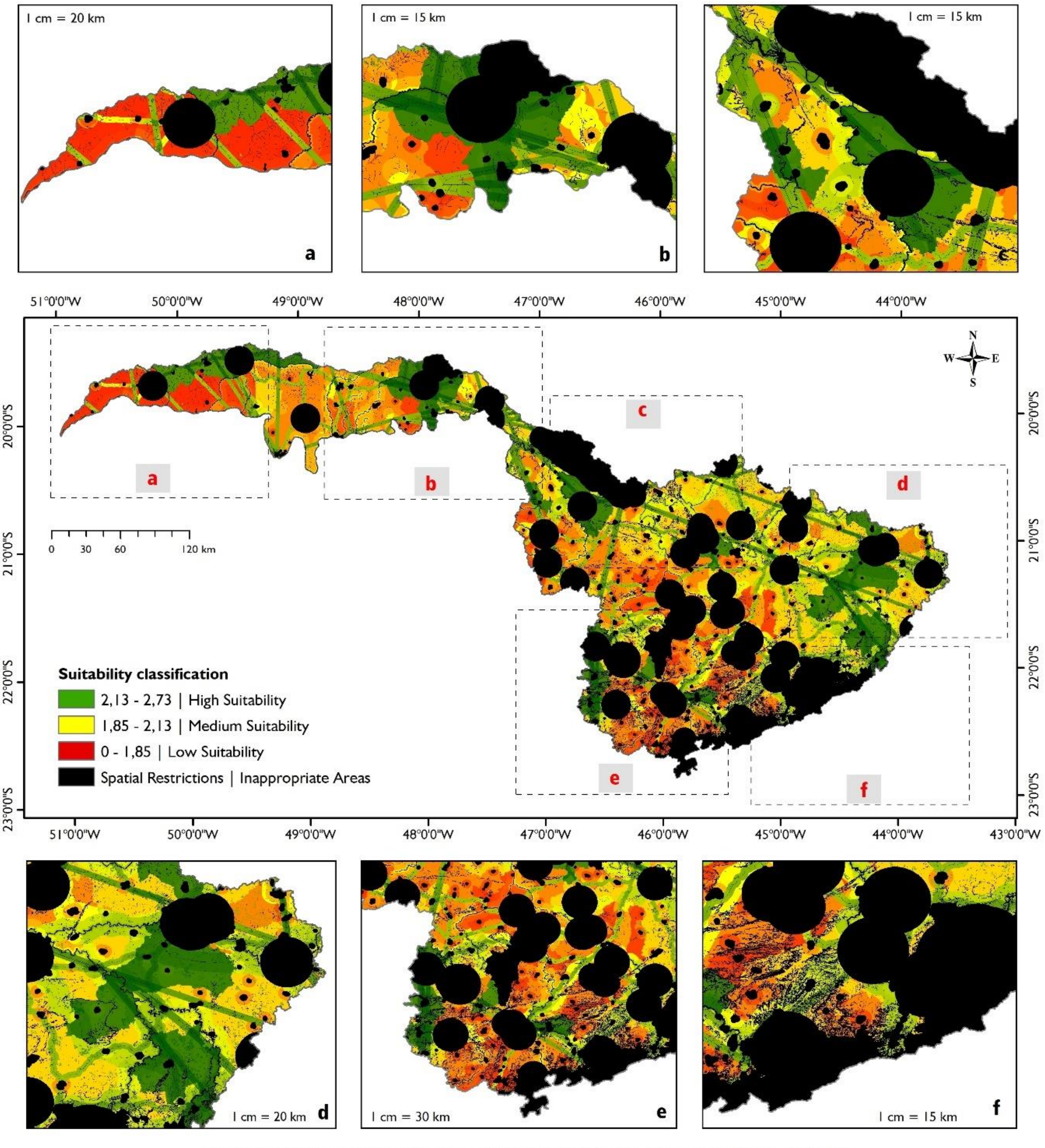
Geodesic and Cartographic Parameters: Geographic Coordinate System | Ellipsoid and Datum - WGS 1984

Figure 4. Normalized criteria used in the composition of the spatial model for zoning of territorial suitability for the implementation of forest biomass-based thermoelectric plants in the GRHB, Brazil.

3.1.2. Constraint areas and land suitability maps

The analysis of the restricted areas or exclusion zones identified the areas inadequate or permanently inappropriate for the location of thermoelectric plants based on forest biomass.

Approximately 39.06% of the study area has some constraints (Table 11 – *Anexo – supplementary material*). The constraints related to the conservation units, airfield zones, and surface inclination, represented about 87% of the total area of the exclusion zones. The total restricted area represented 44,459.47 km² considering each theme individually. Calculating the overlaps between the restriction themes, we obtained the effective value of exclusion areas of 33,620.66 km² (Table 11). Finally, the multi-criteria map and constraints were multiplied to create the final suitability and fitness map. This operation is equivalent to cutting the restricted areas of the multicriteria map. The value of the model suitability index ranged from 1.56 to 2.73 (Figure 5), with a mean ($\bar{x}$) of 1.82 and a standard deviation (σ) of 0.17. Sites with high index values indicate the greatest territorial suitability. These areas are more suitable for developing thermoelectric projects based on forest biomass. No fully suitable areas meet all variables simultaneously, that is, no cell resulted from an aptitude equal to 3 (maximum value), nor were there any areas with entirely low aptitude equal to 1 (minimum value).



Geodesic and Cartographic Parameters: Geographic Coordinate System | Ellipsoid and Datum - WGS 1984

Figure 5. Suitability and availability zoning of land for the installation of thermoelectric power plants based on forest biomass in the GRHB, Minas Gerais State, Brazil.

According to the suitability model applied, 42.6% (36,682.04 km²) of the GRHB has areas of low or little suitability for the installation of thermoelectric plants and, 15.26% (13,135.91 km²) and 3.07% (2,640.04 km²) are areas of medium and high suitability, respectively (Table 11 – *Anexo – supplementary material*). Discounting permanently unsuitable areas, approximately 52,456.98 km² of the GRHB is available for developing these forestry projects.

3.2. Part II: Proposed model for supplying thermoelectric plants with wood

Among the 10 candidate plants, the model presented between 178,758 and 354,384 decision variables, varying due to the differences in the areas involved, with an average processing run-time of 8hrs. The first decision to be taken after the multi-criteria mapping of the suitability of the soil and available areas is to obtain the regions where the thermoelectric plant will conduct the prospection of land for acquisition/lease/outgrower scheme and purchase of wood. The allocation of the location of the 10 candidate thermoelectric plants from the points with the highest soil suitability index is presented in Figure 6. From this result, the deterministic mathematical model developed identified sets of supply locations (plantings/existing areas) that minimized the final cost of projects to offer biomass to meet the demand of potential plants. The result of the model can eventually be used by organizations to efficiently evaluate different decision-making scenarios.

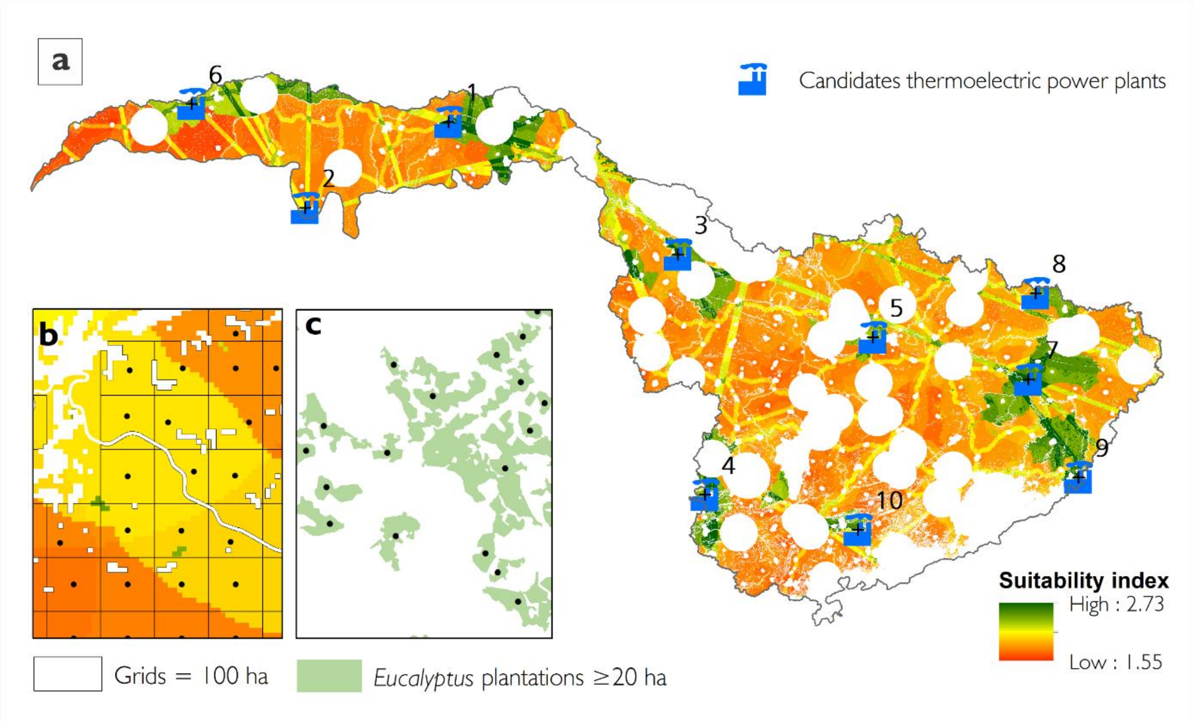


Figure 6. The spatial distribution of candidate's thermoelectric plants. (**a**) Land suitability and availability map with the optimal allocation of candidate thermoelectric power plants; (**b**)

Illustration of the 100 ha grids established in the study area and summarized those above 80 ha; (**c**) Illustration of eucalyptus plantations filtered for stands/polygons ≥ 20 ha.

Our findings indicated a total cost of implementing the thermoelectric projects between USD 103,479,779.34 (lower cost) to USD 139,218,170.10 (higher cost). Respectively, the lowest cost was observed for the thermoelectric T7, located in the micro-region of the municipality of São João del Rey, Upper Grande River, Minas Gerais. The highest cost was for the thermoelectric T6, found in the region of Campina Verde (Lower Grande River/Triângulo Mineiro, Minas Gerais). From the perspective of total investment costs, other locations may also be attractive to investors, such as thermoelectric plants T3 (Passos, central region of the Grande River Basin) and T8 (Resende Costa, Upper Grande River), USD 103,705,448.27 and USD 104,771,948.28, respectively. In Table 12 we present the optimization results in terms of the objective function value. The table indicates the number of areas in hectares required/enabled in the context of the solutions obtained in the model for each candidate thermoelectric plant (T_n) with an electric generation potential of 50 MW/h. The total costs of implementing the projects, purchase of wood, purchase of land, leasing, and forest outgrower scheme are also described. The costs presented are a summary of the model's operations according to the planning horizon (Fig. 2).

Table 12. Spatial and economic results obtained by the model.

Candidate power plants (T_n)	**Total area required (ha)**	**Project costs distribution (USD)**				
		Log market	**Own land unit**	**Leasing land**	**Outgrower scheme**	**Total**
T1	30,190.64	49,043,607.40	40,926,248.66	21,417,534.02	7,098,800.57	118,486,190.65
T2	30,104.64	58,404,985.61	44,081,565.00	22,183,979.93	7,091,244.35	131,761,774.89
T3	26,916.31	40,925,759.16	36,631,040.19	19,254,459.77	6,894,189.15	103,705,448.27
T4	26,375.46	38,758,366.88	40,665,056.20	20,170,420.65	7,016,735.21	106,610,578.94
T5	27,202.31	40,345,045.20	37,960,891.15	19,900,452.13	7,012,742.06	105,219,130.54
T6	31,591.86	65,953,544.10	43,435,688.63	22,561,081.90	7,267,855.47	139,218,170.10
T7	27,234.76	38,497,977.81	38,031,765.00	19,933,551.32	7,016,485.21	103,479,779.34
T8	27,553.00	39,035,904.90	38,519,483.16	20,172,503.79	7,044,056.43	104,771,948.28
T9	27,270.97	38,069,044.77	41,708,796.61	20,715,839.88	7,051,572.91	107,545,254.17
T10	26,846.09	41,673,843.69	40,941,464.56	20,242,085.10	7,020,851.04	109,878,244.39

Regarding the cost of purchasing wood from the market, the best result was observed for T9 (Andrelândia Microregion) (USD 38,069,044.77) and T7 (Resende Costa) (USD 38,497,977.81). The lowest costs in terms of land purchase (Own land unit), leasing land and outgrower scheme were observed for T3 (Passos), respectively, USD 36,631,040.19; USD 19,254,459.77 and; USD 6,894,189.15. In terms of the area required to meet the thermoelectric project, T4 (Poços de Caldas Microregion) required the smallest area, approximately 26,375.46 hectares. T6 had the largest area, 31,591.86 ha needed. The other areas are shown in Table 12. For the solution (T7) with the lowest total cost, the total area demanded and allocated by the mathematical model for its supply was 27,234.76 ha. Of this area, 10,594.43 ha was allocated to what the plant needs to purchase wood from the existing plantations in the first 4 years after the plant was built. 16,640.34 ha the equivalent of land available for purchase, lease and forest outgrower scheme. Regarding the restrictions by type of contract, this result met the assumptions established in the model (60% should be destined for purchase, 30% for leasing and 10% for outgrower scheme). Notably, the areas intended for purchase, lease and outgrower scheme were 9,968.45 ha, 4,999.71 ha and 1,672,17 ha, respectively.

A map with the spatialization of the economic results and the optimal solution of the model (T7 plant), is presented in Figure 7. The map shows the areas enabled for land purchase (Fig 7.A), leasing land (Fig. 7.B), forest outgrower scheme (Fig 7.C) and purchase of wood already on the market (Fig. 7.D) according to their respective periods. For better visualization and interpretation of these results, the maps are presented in scales according to the spatial solutions obtained in the model within the radius/feasible search area (150 km).

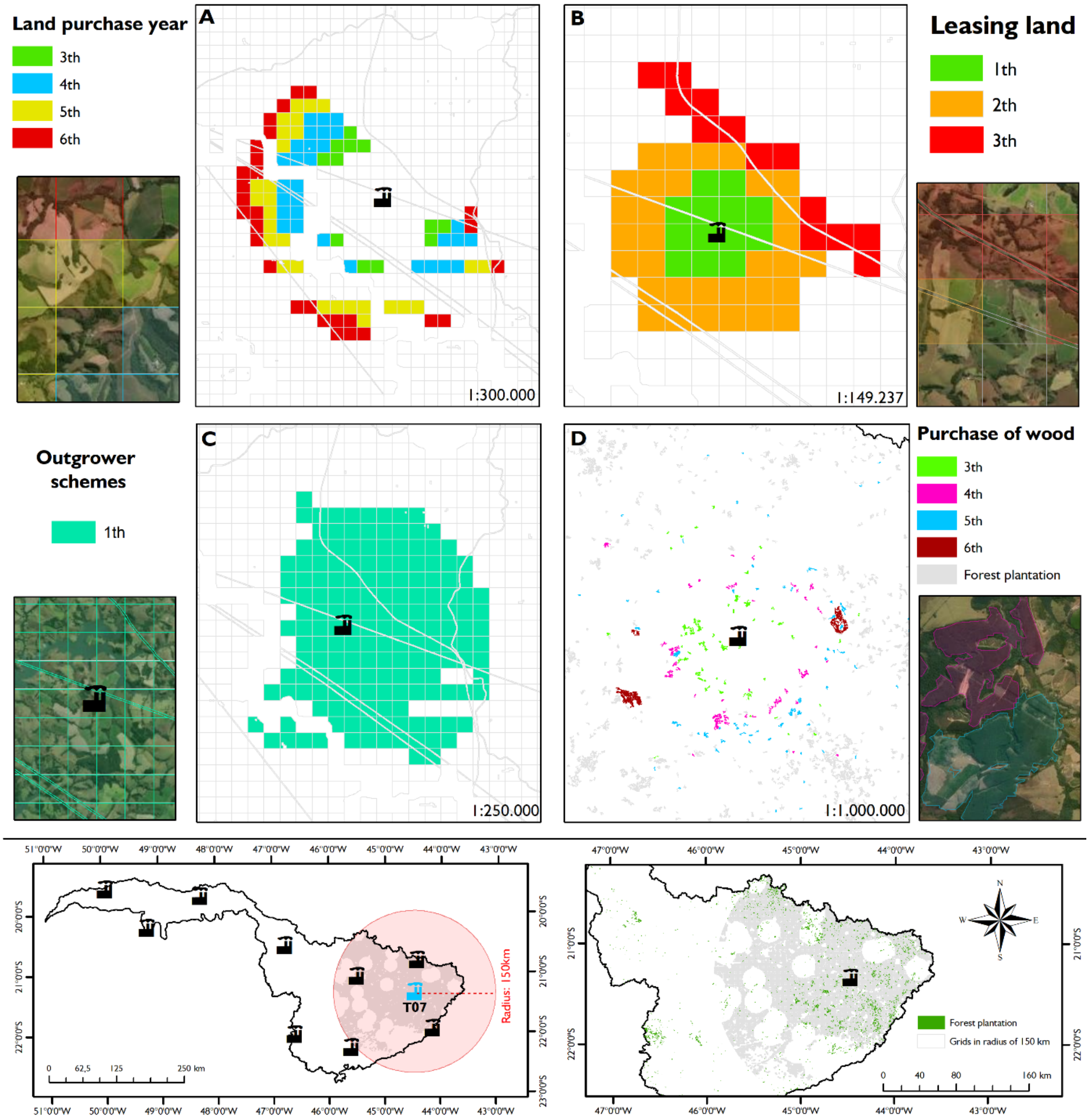


Figure 7. Spatialization maps of the economic results and the optimal solution of the model for Thermoelectric 7 (T7) and their respective cut/use schedules. (**A**) Purchase of land; (**B**) Leasing land; (**C**) Forest outgrower schemes and; (**D**) Purchase of wood.

In the map in Figure 8, we present the result of the geostatistical interpolation of the minimized economic costs in the proposed mathematical model. The maps represent the total costs of implementing the thermoelectric plants (Fig 8.a), indicating the lowest estimated costs around the best T7 solution (solução de menor custo total); wood purchase costs from the market (Fig. 8.d), and the costs of own wood production, land purchase (Fig. 8.a), lease (Fig. 8.b) and forest outgrower schemes (Fig 8.c).

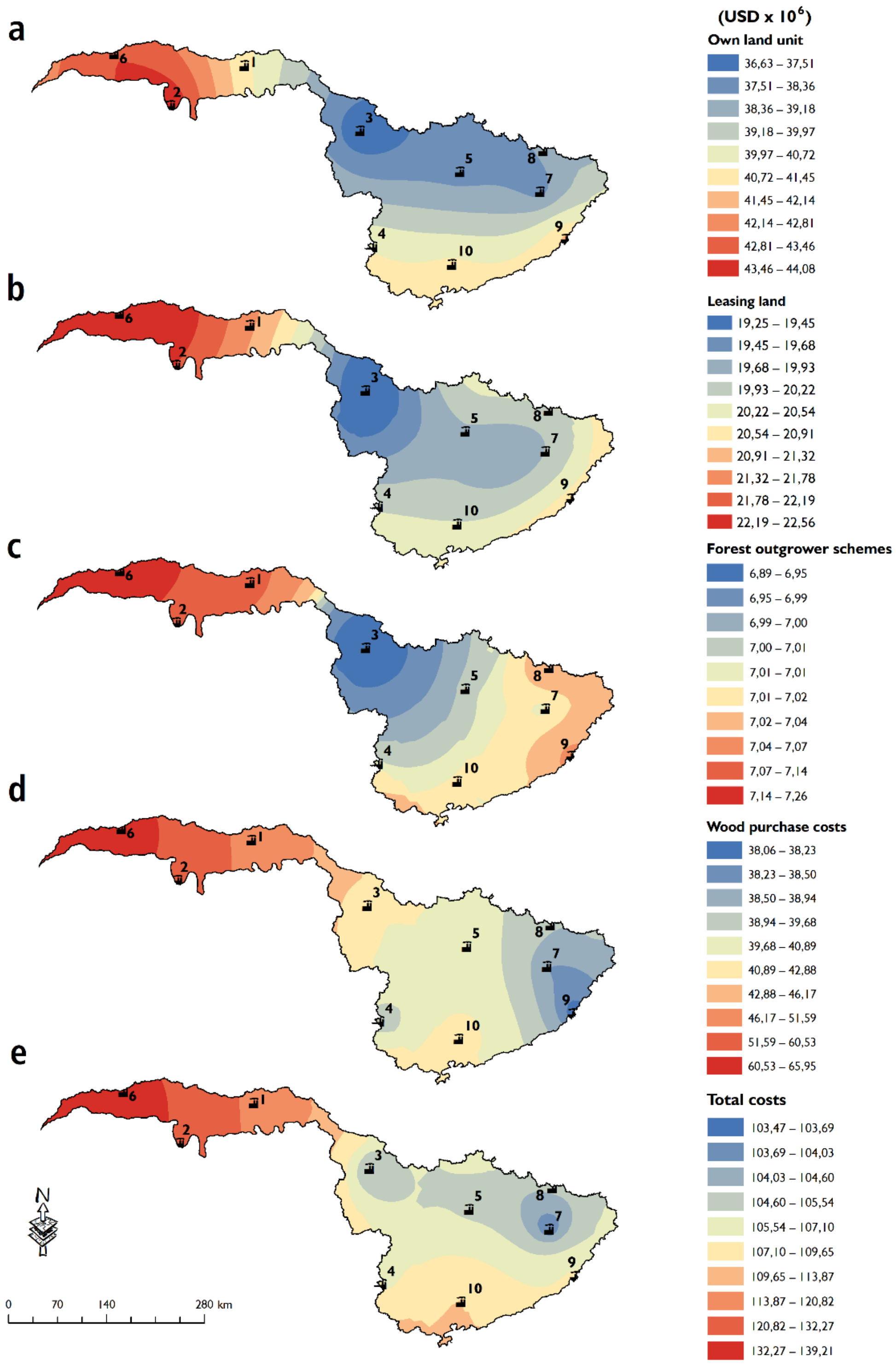


Figure 8. Result of geostatistical interpolation of economic costs minimized in the proposed mathematical model. Costs (USD x 10^6) of (**a**) purchase and (**b**) lease of land for planting and (**c**) forestry outgrower scheme; (**d**) Wood purchase costs from the market and; (**e**) Map of total costs of implementing the thermoelectric plants.

With these spatialized results (Figure 8), we observed that despite the T7 plant having the lowest total cost (Fig. 8.e and Table 12) and the lowest cost of purchase wood from the market (Fig. 8d and Table 12), however, we observed that T3 plant has the lowest costs of own wood production (land purchase, lease and forestry outgrower scheme).

4. Discussion

4.1.Part I: Territorial Sustainability Index

4.1.1. AHP and multicriteria analysis

The criteria of the first part of the study represent qualitative and spatial relevance for developing the plants. Notably technical, economic, environmental, and social aspects (Cambero and Sowlati, 2014) (Table 8). For example, the criterion of proximity to urban areas, which involves direct social and environmental importance, is due to the risks related to air quality in the proximity of human dwellings. Despite this, Brazilian environmental legislation establishes emission limits for thermoelectric generation and measures to reduce the impact of atmospheric emissions on air quality and public health. The country has a specific resolution applied to wood derivatives and their pollutants from heat generation processes from combustion in the generation of electricity (CONAMA, 2006). Brazilian Law Nº. 6,938/1981, on the National Environmental Policy (BRASIL, 1981), classifies thermoelectric industries as "utility services" with medium potential for pollution. Despite these factors, biomass from a sustainably managed forest can be considered a carbon-neutral energy source. The carbon emitted during the energy conversion process is relatively quickly fixed during subsequent photosynthesis and forest growth (Holsbeeck *et al.*, 2020).

The proximity of forest plantations (Priority = 23.70%) (Fig 4.a), Log wood stock (m³) (Priority = 17.10%) (Fig. 4.i) and Mean Annual Increment (MAI) (Priority = 8.70%) (Fig 5.j) make up a crucial decision element for thermoelectric industrial development. The greater proximity to commercial eucalyptus plantations and the municipalities with the largest stock of available wood provide a greater probability of supply of forest biomass. The favorable geographic distribution is attractive to the electricity sector. The energy industry seeks to obtain sufficient quantities of biomass to satisfy demand at the lowest cost (Chalmers et al., 2003). The cost of raw materials can represent a significant part of total production costs (Zhan et al. 2005).

Biomass to energy projects is highly geographically dependent and the plant's profitability can be strongly influenced by its location (Noon Daly, 1996; Panichelli and Gnansounoun, 2008). The criteria related to roads (Fig 4.f) and railroad lines (Fig. 4.g) also represented relevant weights in the AHP model (13.90 % and 5.10 %, respectively). Biomass transport accounts for a significant part of the total costs of bioenergy (Zhan et al. 2005). Usually, more than half the cost of waste delivered to heating plants is incurred by transportation (Richardson et al., 2002). The criteria for proximity to transmission lines (10.90%) (Fig 4.e) and power substations (9.30%) (Fig. 5.i) are also fundamental elements of high decision-making value for the thermoelectric development of the region. We also considered the Bare Land Value criterion (Priority = 3.50%) in the study. Data related to land costs were not always considered in previous studies, generally because it is a database not always publicly available in all regions. We consider this layer because it is fundamental information in decision making for developing thermoelectric plants. As well as the multi-criteria analysis, also in part II of this study, land cost information was fundamental to obtain robust results.

The criteria proximity to the hydrography, proximity to other thermoelectric units, proximity to urban areas and terrain slope showed the lowest percentages of importance in the AHP model. Being, 2.70%, 2.50%, 2.20% and 1.20%, respectively. Despite this, it does not mean low importance in real-world instances. These variables are essential for decision-makers in planning the construction of thermoelectric plants and forest supply projects. All the criteria used in this study are decisive in decision making by investors in the electricity and forestry sector. Logistics is often expensive and involves complex acquisition, transport and use of biomass. This underscores the need for an economic design of the forest biomass supply chain to overcome existing challenges. Cambero and Sowlati (2014) also reinforce that in the decision-making process in bioenergy projects, there is also a need to increase public awareness of sustainability issues. Understanding the economic, environmental and social impacts of forest biomass supply chains is necessary to mitigate undesirable impacts and ensure the sustainability of new projects with attractiveness, interest and support from populations, governments and investors.

4.2.2. Restricted areas and land suitability: practical implications

The map of exclusion zones is essential for greater precision in spatial modeling of territorial suitability. We use a broad set of restrictive layers data to suppress inappropriate areas as closely as possible to real-world instances. The identification of these areas must precede the other stages of geospatial analysis, as they reduce the volume of data analyzed and, consequently, the time to obtain a solution (Sultana and Kumar, 2012; Costa et al., 2020). The restricted areas related to the Airfields influence zones, Conservation units and high surface inclination, together represented a large part of the permanently unsuitable areas excluded from the study. This result is a reflection of the legal rigor that governs these variables. In Brazil governed by legislation related to safety, social and environmental applied to industrial development near airports and conservation units. We also detected a high value of the total exclusion area (39.06% of the study area). This value corroborates the high proportions of restricted zones also found in other similar models (Lovett et al., 2009; Sultana and Kumar, 2012; Costa et al., 2020). We understand that the more robust and detailed the dataset of overlapping restrictions, the greater the percentage of areas unsuitable for these investments.

The final suitability and available land map is a fundamental basis for future decision-making processes for land use and optimization at GRHB. The fitness index obtained was the result of the compensation effect between the values categorized as less or more acceptable according to the categories from low to high aptitude. The calculated aptitude index (Figure 5) showed that no totally suitable areas meet all criteria simultaneously. This means that no cell resulted in the highest fitness class equal to 3 (maximum value), as well as areas with entirely low fitness equal to 1 (minimum value) were not found. This characteristic is common in real-world instances, as it is generally impossible to achieve an absolutely high fitness value for all themes in their entirety (Sultana and Kumar, 2012; Costa et al., 2020).

We also found a high value of land with low suitability (42.6%) for developing thermoelectric projects. This low aptitude is mainly influenced by the greater distance observed between features of criteria of high importance in the spatial model. The approach seen in Figure 5.b, west of the GHRB (Triângulo Mineiro), presents large continuous extensions of areas with low to medium suitability. This is a reflection of the trade-off between greater distance from large players from existing forest plantations (Fig 4.a), lower MAI observed (Fig 4.j) and lower occurrence of railroads (Fig. 4.g). Nevertheless, when looking at the fitness map in Figure 5. a, we can see a part of this region with high fitness. This area is related to the greater region of Uberlândia, which has been receiving large investment in new players for the Brazilian forestry sector. In terms of proximity to large forestry companies, this area becomes strategic for thermoelectric plants. Some portions of areas with low suitability disposed in the south central region of the GRHB (Fig 5.f) are also a reflection of the combination of long distances from power transmission lines (Fig 4.e) and higher land costs (Fig 4.k), in addition to land with many inappropriate areas due to environmental and social restrictions.

The analysis of the results considering the criteria used in the modeling concludes that the most suitable locations were mainly influenced by the proximity component of raw material and infrastructure in the study area. The economic viability of using solid biomass fuel for thermoelectric generation is highly influenced by proximity to the source of production, transport and handling costs, moisture contents and processing systems and preparation for more efficient technologies (MME, 2007). The use of spatial modeling to assess the suitability and availability of land is complex and requires a careful assessment of the different local characteristics and the final destination of these areas. This part of the study allowed showing potential locations for the production of electricity from forest biomass. An MCA analysis prioritizes land with some potential quality indicators. Despite this, we recommend that decision-making for developing thermoelectric and forestry projects also consider the interests of the economic and social development of less priority regions. We hope that areas of low suitability will not be completely disregarded in eventual real interventions. Brazil still cannot meet the energy needs of its entire population (Lucon et al., 2015), especially in rural, isolated and difficult to access areas. This deficiency in energy service is directly related to the physical or economic challenges encountered in extending the electrical grid. Additionally, it is recommended to invest, especially, in rail transport to maximize the efficiency of the production and distribution logistics of forest raw materials in a more efficient, accessible and safe way (Teixeira et al., 2018).

4.2.Part II: Feeding thermoelectric plants with wood

Based on the results of the model developed, it is possible to notice an economic effect on its outputs. At first, the model uses the alternative of the outgrower scheme in the first year, reflecting the costs, given the effect of the discounted rate. We observed that there was only indication of land purchase recently (from the 9th to the 12th year in the planning horizon) (Fig 7.d), in which the mill would only start producing wood from the 9th year onwards based on own areas already purchased, the time required for the formation of the plant's own forests. In order of priority of the most interesting cost options, the model indicated outgrower scheme, lease and purchase of land, respectively. Activating only outgrower scheme and lease initially in the first years. This information is crucial for investor decision making, as the model allocates the use of the largest financial capital only from the third year onwards to purchase land. Notably, the model intelligently distributed the costs temporally. In terms of area demanded by T9, the model also directed the purchase of the largest number of areas in hectares for the last years (from the tenth year onwards), focusing on the purchase of more productive areas.

Despite the benefits of using forest biomass, technical and economic challenges still make its intensified use difficult. Forest residues are spread over large regions, which increases the collection, handling and transport costs. Additionally, there is variability in the quantity and quality of forest biomass due to the accessibility of the forest throughout the year, climatic conditions, pre-processing, transport and storage conditions, and competition from other end-users (Wood and Layzell, 2006; Cambero and Sowlati, 2014). Additionally, there is also a need for further studies to better recognize the real stock of raw material (eucalyptus waste) available for the production of energy from forest biomass in this region.

Regarding the energy potential (MWh) of *eucalyptus* forests, it is important to highlight that the basic density of wood directly influences the lower or higher generation capacity. Density values vary according to species or genetic materials. The efficiency of different biomass energy systems depends largely on their mass densities (Zalk and Behrens, 2018). It is important to note that investors in GRHB can also seek raw materials and other resources in the surroundings and in other regions of the state of Minas Gerais or neighboring states. When a region's raw materials are in short supply, power plants must compete for biomass resources to meet their own demand. These are important improvement issues to be considered in future studies.

Despite all these scientific challenges, there are still those of an external and political nature. Planning and operational decisions for the implementation of thermoelectric plants are generally influenced by uncertainty about future policies and market conditions (Galik et al., 2021). We believe our results provide useful context to support future research and policy deliberations in this and other regions of Brazil. We confirm the hypothesis of our study that by building a GIS framework based on MCDA-AHP and a linear programming model, it is possible to assist in decision-making with geographic intelligence for the purchase of wood, leasing land, forest outgrower schemes, and purchase of land for implementation and supply of thermoelectric projects based on residues from planted forests.

5. Conclusions and final remarks

- The optimal model's solutions indicate investment costs of around US$ 103 million over 27,234 hectares of supply areas. The optimal results of the spatial strategies obtained in this study are important for Brazil, as we simulate scenarios based on the consolidation of real mega industrial projects. Our results are an advance in relation to studies already published on the subject.
- A GIS model was developed to zone the suitability and availability of land for the implementation of forest-based thermoelectric projects in a hydrographic basin in southeastern Brazil. We generated a mapping of zones with legal constraints and modeling of preferred sites based on a range of suitability.
- The combination of MCDA and GIS methods can therefore be seen as an essential tool for solving power planning problems, such as territorial suitability for locating biomass plants.
- Although the motivation has been the proposition of a GIS framework and a linear programming model for thermoelectric projects based on forest biomass, the multicriteria, multidimensional and multiobjective context are relevant for any other form of biomass for electricity generation.
- The zoning presented in our study does not imply that the areas are fully available, but it does present essential foundations for decision-makers. Other’s parameters can be tested and adjusted according to the characteristics of each region.
- The methodological approach of this study is flexible and replicable at different scales and regions. And it is available to investors, local and state governments, electricity utilities, forestry producers and stakeholders interested in the potential for expansion and diversification of the forest-based energy matrix. Our study can serve as a guide for land and forest planning.
- The development of thermoelectric industries based on forest biomass can help Brazil face the challenges of ensuring energy security; achieving climate goals on the global stage and; generating jobs and forest-based economic development.

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6. Bibliographic References

Abdallah, L.; El-Shennawy, T. Evaluation of CO2 emission from Egypt's future power plants. *Euro-Mediterranean Journal for Environmental Integration*, v. 5, n.49, 2020. https://doi.org/10.1007/s41207-020-00184-w

Acuna, M.; Sessions, J.; Zamora, R.; Boston, K.; Brown, M.; Ghaffariyan, M. R. Methods to Manage and Optimize Forest Biomass Supply Chains: a Review. *Curr Forestry Rep* **5,** 124–141 (2019). https://doi.org/10.1007/s40725-019-00093-4

Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M.; Sparovek, G. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, 22, 6, p. 711-728, 2013. https://doi.org/10.1127/0941-2948/2013/0507

Asikainen, A.; Björheden, R.; Nousiainen, I. Cost of wood energy. In: Richardson, J., Björheden, R., Hakkila, P., Lowe, A.T. and Smith, C.T. (eds.). Bioenergy from Sustainable Forestry: Guiding Principles and Practice. Kluwer Academic Publishers, The Netherlands. 2002
Azevêdo, V. Q. B.; Candeias, A. L. B.; Tiba, C. Location Study of Solar Thermal Power Plant in the State of Pernambuco Using Geoprocessing Technologies and Multiple-Criteria Analysis. *Energies*, v. 10, n. 1042, p.1-23, 2017. https://doi.org/10.3390/en10071042

Binkley, D.; Campoe, O. C.; Alvares, C. A.; Carneiro, R. L.; Stape, J. L. Variation in whole-rotation yield among Eucalyptus genotypes in response to water and heat stresses: The TECHS project. *Forest Ecology and Management*, v.462, 2020. https://doi.org/10.1016/j.foreco.2020.117953

Botelho, D. F.; Oliveira, L. W.; Dias, B.H.; Soares, T. A.; Moraes, C. A. Prosumer integration into the Brazilian energy sector: An overview of innovative business models and regulatory challenges. *Energy Policy*, 161, 2022. https://doi.org/10.1016/j.enpol.2021.112735

br

BRASIL - Conama Resolution N°. 4 of October 9, 1995 - Establishes the Airport Security Areas – ASAs. Available at: http://www2.cprh.pe.gov.br/wp-content/uploads/2021/02/4de9deoutubrode1995.pdf

BRASIL – Law N° 7.565, of December 19, 1986. Available at: http://www.planalto.gov.br/ccivil_03/Leis/L7565.html

BRASIL - Law N°. 12.651, of May 25, 2012. Available at: http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm

BRASIL – Law Nº 13.097, of January 19, 2015. Available at: http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2015/lei/l13097.htm

BRASIL - Minter Ordinance Nº. 124, of 08/20/1980 - Establishes norms for the location of potentially polluting industries near water collections polluting industries close to hydric collections. Available at: http://www.oads.org.br/leis/3426.pdf

BRASIL - Ordinance N° 1.141/GM5, of December 8, 1987. Available at: https://www.anac.gov.br/assuntos/legislacao/legislacao-1/portarias/portarias-1987/portaria-no-1141-gm5-de-08-12-1987

BRASIL. Laws and decrees, etc. Presidency of the Republic. Law No. 6.938, of August 31, 1981. Provides on the National Environmental Policy, its purposes and formulation and application mechanisms, and other provisions. Official Diary of the Federative Republic of Brazil. Brasília, DF: Civil House. Available at: http://www.planalto.gov.br/ccivil_03/leis/l6938.htm

Brazilian Energy Balance. Final Report year 2019. Empresa de Pesquisa Energética. Rio de Janeiro: EPE, 291p., 2020. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-479/topico-528/BEN2020_sp.pdf

Briones-Hidrovo, A.; Copa, J.; Tarelho, L. A. C.; Gonçalves, C.; Costa, T. P.; Dias, A. C. Environmental and energy performance of residual forest biomass for electricity generation: Gasification vs. Combustion. *Journal of Cleaner Production*, v.289, 2021. https://doi.org/10.1016/j.jclepro.2020.125680

Cambero, C.; Sowlati, T. Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives – A review of literature. *Renewable and Sustainable Energy Reviews*, v. 36, 62-73, 2014. http://dx.doi.org/10.1016/j.rser.2014.04.041

Cambero, C.; Sowlati, T. Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives – A review of literature. *Renewable and Sustainable Energy Reviews*, 36, p.62-73, 2014. http://dx.doi.org/10.1016/j.rser.2014.04.041

Carneiro, A. C. O.; Oliveira, A. C. Produção sustentável de carvão vegetal. Viçosa, SIF, 2013. 39p.

Carvalho, L. G.; Alves, M. C.; Oliveira, M. S.; Vianello, R. L.; Sediyama, G. C.; Carvalho, L. M. T. Multivariate geostatistical application for climate characterization of Minas Gerais State, Brazil. *Theoretical and Applied Climatology volume*. V. 102, p. 417-428, 2010. https://doi.org/10.1007/s00704-010-0273-z

CEMIG - Minas Gerais Energy Company. Minas Gerais Biomass Atlas. Belo Horizonte: Rona Gráfica e Editora, 100p. Available in: https://www.cemig.com.br/wp-content/uploads/2021/03/atlas-biomassa-mg.pdf

CENBIO – Centro Nacional de Referência em Biomassa. Atlas da Bioenergia do Brasil. Projeto Fortalecimento Institucional do CENBIO, Convênio 721606/2009 – MME. São Paulo, 2009.

Chalmers S, Hartsough B, De Lasaux M. Develop a GIS-based tool for estimating supply curves for forest thinning and residues to biomass facilities in California. Final report. Department of Biological & Agricultural Engineering, University of California, Davis, 2003. 39pp.

Coelho, S. T; Paletta, C. E. M; Freitas, M. A. V. Medidas Mitigadoras para a Redução de Emissões de Gases de Efeito Estufa na Geração Termelétrica. Brasília: Dupligráfica, 2000.

CONAMA – Conselho Nacional do Meio Ambiente. Resolução CONAMA nº 382, de 26 de dezembro de 2006. Disponível em: http://www2.mma.gov.br/port/conama/legiabre.cfm?codlegi=520

Costa, F. R.; Ribeiro, C. A. A. S.; Marcatti, G. E.; Lorezon, A. S.; Teixeira, T. R.; Domingues, G. F.; Castro, N. L. M.; Santos, A. R.; Soares, V. P.; Menezes, S. J. M. C.; Mota, P. H. S.; Telles, L. A. A.; Carvalho, J. R. GIS applied to location of bioenergy plants in tropical agricultural areas. *Renewable Energy*, v. 153, p. 911-918, 2020. https://doi.org/10.1016/j.renene.2020.01.050

Cuong, T. T.; Le, H. A.; Khai, N. M.; Hung, P. A.; Linh, L. T.; Thanh, N. V.; Tri, N. D.; Huan, N. X. Renewable energy from biomass surplus resource: potential of power generation from rice straw inVietnam. *Nature*, 11:792, 2021. https://doi.org/10.1038/s41598-020-80678-3

Delivand, M. K.; Cammerino, A. R. B.; Garofalo, P.; Monteleone, M. Optimal locations of bioenergy facilities, biomass spatial availability, logistics costs and GHG (greenhouse gas) emissions: a case study on electricity productions in South Italy. *Journal of Cleaner Production*, v.99, p.129-139, 2015. http://dx.doi.org/10.1016/j.jclepro.2015.03.018

Diaz-Balteiro, L.; Romero, C. Multiple Criteria Decision-Making in Forest Planning: Recent Results and Current Challenges. In Weintraub, A.; Romero, C.; Bjørndal, T.; Epstein, R. Handbook of Operations Research in Natural Resources, Springer, 624p, 2007. https://doi.org/10.1007/978-0-387-71815-6

Dong, J. GIS and Location Theory Based Bioenergy Systems Planning. A thesis presented to the University of Waterloo. Ontorio, Canada, 138p., 2008. Available in: https://uwspace.uwaterloo.ca/bitstream/handle/10012/3805/GIS_and_Location_Theory_Based_Bioenergy_Systems_Planning.pdf?sequence=1&isAllowed=y

EPE – Empresa de Pesquisa Energética. Brazilian Energy Balance 2020. Summary Report / Year 2019: Rio de Janeiro, 2020. https://www.epe.gov.br/sites-en/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao217/SUMMARY%20REPORT%202020.pdf

EPE – Empresa de Pesquisa Energética. Resource Potential Horizon 2050. Nota Técnica PR 04/18, 2018. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-227/topico416/NT04%20PR_RecursosEnergeticos%202050.pdf

ESRI - Environmental Systems Research Institute. ArcGIS Desktop: Version 10.8. Redlands, CA, 2020.

Ezzati, S. Geospatial Multicriteria Decision Analysis in Forest Operational Planning. Spatial Modeling in GIS and R for Earth and Environmental Sciences, 85–116, 2019. https://doi.org/10.1016/B978-0-12-815226-3.00004-1

Fei, D.; Cheng, Q.; Mao, X.; Liu, F.; Zhou, Q. Land use zoning using a coupled gridding-self-organizing feature maps method: A case study in China. *Journal of Cleaner Production*, v. 161, p. 1162-1170, 2017. https://doi.org/10.1016/j.jclepro.2017.05.028

Feizizadeh, B.; Blaschke, T. GIS-multicriteria decision analysis for landslide susceptibility mapping: comparing three methods for the Urmia lake basin, Iran. *Natural Hazards*, v. 65, p.2105-2128, 2013. https://doi.org/10.1007/s11069-012-0463-3

Ferreira, L. R. A.; Otto, R. B.; Silva, F. P.; De Souza, S. N. M.; De Souza, S.S.; Ando Junior, O. H. Review of the energy potential of the residual biomass for the distributed generation in Brazil. *Renewable and Sustainable Energy Reviews*, v.94, p.440-455, 2018, https://doi.org/10.1016/j.rser.2018.06.034

Ferreira-Leitão, V.; Gottscharlk, L. M. F.; Ferrara, M. A.; Nepomuceno, A. L.; Molinari, H. B. C.; Bom, E. P. S. Biomass Residues in Brazil: Availability and Potential Uses. Waste Biomass Valor, v.1, p. 65-76, 2010. http://dx.doi.org/10.1007/s12649-010-9008-8

Gabrielle, B.; Bamière, L.; Caldes, N.; De Cara, S.; Decocq, G.; Ferchaud, F.; Loyce, C.; Pelzer, E.; Perez, Y.; Wohlfahrt, J.; Richard, G. Paving the way for sustainable bioenergy in Europe: Technological options and research avenues for large-scale biomass feedstock supply. *Renewable and Sustainable Energy Reviews*, v. 33, p. 11-25, 2014. http://dx.doi.org/10.1016/j.rser.2014.01.050

Galik, C. S.; Benedum, M. E.; Kauffman, M.; Becker, D. R. Opportunities and barriers to forest biomass energy: A case study of four U.S. states. *Biomass and Bioenergy*, 148, 2021. https://doi.org/10.1016/j.biombioe.2021.106035

Goepel, K.D. Implementation of an Online Software Tool for the Analytic Hierarchy Process (AHP-OS). *International Journal of the Analytic Hierarchy Process*, 10, 3, p 469-487, 2018, https://doi.org/10.13033/ijahp.v10i3.590

Goldemberg, J. Biomassa e energia. Química Nova. v. 32, n. 3, São Paulo, 2009.

Grobush, L. C.; Grobush, M. P. A hot topic at the environment–health nexus: investigating the impact of climate change on infectious diseases. International Journal of Infectious Diseases. 116, 7-9. 2022. https://doi.org/10.1016/j.ijid.2021.12.350

Guedes, B. S.; Olsson, B. A.; Egnell, G.; Sitoe, A. A.; Karltun, E. Plantations of *Pinus* and *Eucalyptus* replacing degraded mountain miombo woodlands in Mozambique significantly increase carbon sequestration. *Global Ecology and Conservation*, v. 14, 2018. https://doi.org/10.1016/j.gecco.2018.e00401

Guilhermino, A.; Lourinho, G.; Brito, P.; Almeida, N. Assessment of the Use of Forest Biomass Residues for Bioenergy in Alto Alentejo, Portugal: Logistics, Economic and Financial Perspectives. *Waste Biomass Valor*, v.9, p. 739-753, 2018. https://doi.org/10.1007/s12649-017-9830-3

Guimarães, D. P.; Reis, R. J.; Landau, E. C. Rainfall Indices in Minas Gerais. Boletim de Pesquisa e Desenvolvimento. Embrapa Milho e Sorgo, 88 p., 2010. Available in: https://www.infoteca.cnptia.embrapa.br/handle/doc/879085

Hanssen, F., May, R., Van Dijk, J., Stokke, B.G., De Stefano, M. Spatial Multi-Criteria Decision Analysis (SMCDA) toolbox for Consensus-based Siting of Powerlines and Wind-power plants (Con-Site). NINA Report 1455. Norwegian Institute for Nature Research, 2018. https://tethys.pnnl.gov/sites/default/files/publications/Hanssenetal2018.pdf

Hao, X.; An, H.; Qi, H.; Gao, X. Evolution of the exergy flow network embodied in the global fossil energy trade: Based on complex network. *Applied Energy*, 162, 1515-1522. 2016. http://dx.doi.org/10.1016/j.apenergy.2015.04.032

Holsbeeck, S. V.; Brown, M.; Srivastava, S. K.; Ghaffariyan, M. R. A Review on the Potential of Forest Biomass for Bioenergy in Australia. *Energies*, 13, 2020. http://dx.doi.org/10.3390/en13051147

Holsbeeck, S. V.; Srivastava, S. K. Feasibility of locating biomass-to-bioenergy conversion facilities using spatial information technologies: A case study on forest biomass in Queensland, Australia. *Biomass and Bioenergy*, v. 139, 2020. https://doi.org/10.1016/j.biombioe.2020.105620

IBÁ – Indústria Brasileira de Árvores. Relatório IBÁ 2020 (Ano base 2019). São Paulo, 2020. Available in: https://iba.org/datafiles/publicacoes/relatorios/relatorio-iba-2020.pdf.Access in: 09-10-2020.

IBÁ – Indústria Brasileira de Árvores. Relatório IBÁ 2021 (Ano base 2020). São Paulo, 2021. Available in: https://iba.org/datafiles/publicacoes/relatorios/relatorioiba2021-compactado.pdf. Access in: 28-12-2021.

IEA – International Energy Agency. Global Energy Review 2021. Available in: https://iea.blob.core.windows.net/assets/d0031107-401d-4a2f-a48b-9eed19457335/GlobalEnergyReview2021.pdf

IEA – International Energy Agency. Workd Energy Outlook 2021. Available in: https://iea.blob.core.windows.net/assets/88dec0c7-3a11-4d3b-99dc-8323ebfb388b/WorldEnergyOutlook2021.pdf

IGAM – Instituto Mineiro de Gestão das Águas. Federal hydrographic basins of Minas Gerais. 2020. Access in: 10/02/2021. Available in: https://www.mg.gov.br/conteudo/conheca-minas/geografia/bacias-hidrograficas

Ioannou, K.; Tsantopoulos, G.; Arabatzis, G.; Andreopoulou, Z.; Zafeiriou, E. A Spatial Decision Support System Framework for the Evaluation of Biomass Energy Production Locations: Case Study in the Regional Unit of Drama, Greece. Sustainability, 10, 531, 2018. http://dx.doi.org/10.3390/su10020531

Jeong, J. S.; Ramírez-Gomes, A. A Multicriteria GIS-Based Assessment to Optimize Biomass Facility Sites with Parallel Environment - A Case Study in Spain. *Energies*, v.10, 2095, p.1-14, 2017. https://doi.org/10.3390/en10122095

Kangas, A.; Kangas, J.; Kurttila, M. Decision Support for Forest Management. Springer Sciences + Business Media B.V., 221p., 2008. https://doi.org/10.1007/978-1-4020-6787-7

Kangas, J.; Kangas, A. Multiple criteria decision support methods in forest management: An overview and comparative analyses. In: Pukkala, T. Multi-objective Forest Planning. Springer Science + Business Media B.V. 213p, 2002.

Koikai, J. S. Utilizing GIS-Based Suitability Modeling to Assess the Physical Potential of Bioethanol Processing Plants in Western Kenya. 10, Papers in Resource Analysis. 12 pp. Saint

Mary’s University of Minnesota University Central Services Press. Winona, MN. 2008, Available at: http://www.gis.smumn.edu

Kougkoulos, I.; Cook, S.J.; Jomelli, V.; Clarke, L.; Symeonakis, E.; Dortch, J.M.; Edwards, L.A.; Merad, M. Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes. Sci. Total Environ, 621, p.1453-1466, 2017. https://doi.org/10.1016/j.scitotenv.2017.10.083

LAPIG – Laboratório de Processamento de Imagens e Geoprocessamento. Atlas Digital das Pastagens Brasileiras. Universidade Federal de Goiás (UFG). Available in: https://pastagem.org/map. Access: 28-12-2021.

Latinopoulos, D.; Kechagia, K. A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece. *Renewable Energy*, 78, 550-560, 2015. http://dx.doi.org/10.1016/j.renene.2015.01.041

Liebensteiner, M.; Wrienz, M. Do Intermittent Renewables Threaten the Electricity Supply Security? *Energy Economics*, v.87, 2020. https://doi.org/10.1016/j.eneco.2019.104499

Lovett, A.A.; Sünnenberg, G.M.; Richter, G.M.; Dailey, A.G.; Riche, A.B.; Karp, A. Land use implications of increased biomass production identified by GIS-based suitability and yield mapping for miscanthus in England. BioEnergy Res., 2, 17-28, 2009. https://doi.org/10.1007/s12155-008-9030-x

Lucon, O.; Romeiro, V.; Fransen, T. Bridging the gap between energy and climate policies in Brazil. IEE-USP: Environmental Energy Institute of São Paulo University. 92p., 2015. Available in: https://www.wribrasil.org.br/sites/default/files/bridging-the-gap-energy-climate-brazil.pdf

Ma, J.; Scott, N. R; DeGloria, S. D.; Lembo, A. J. Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. *Biomass & Bioenergy*, v. 28, 591-600, 2005. https://doi.org/10.1016/j.biombioe.2004.12.003

Martins, F. B.; Benassi, R. B.; Torres, R. T.; Brito Neto, F. A. Impacts of 1.5 °C and 2 °C global warming on *Eucalyptus* plantations in South America. *Science of the Total Environment.* (In Press), 2022. https://doi.org/10.1016/j.scitotenv.2022.153820

McEwan, A.; Marchi, E.; Spinelli, R.; Brink, M. Past, present and future of industrial plantation forestry and implication on future timber harvesting technology. *J. For. Res.* 31 (2), 2020 *https://doi.org/10.1007/s11676-019-01019-3*.

MINAS GERAIS - Law Nº. 20.922 of October 16, 2013. Provides for forestry and biodiversity protection policies in the state. Available at: http://www.siam.mg.gov.br/sla/download.pdf?idNorma=30375

MME – Ministério de Minas e Energia. Plano Nacional de Energia 2030. MME – Empresa de Pesquisa Energética. Brasília: MME:EPE, 2007. Disponível em: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-165/topico173/PNE%202030%20%20Gera%C3%A7%C3%A3o%20Termel%C3%A9trica%20(Biomassa).pdf

Morandi, D. T.; França, L. C. J.; Menezes, E. S.; Machado, E. L. M.; Silva, M. D.; Mucida, D. P. Delimitation of ecological corridors between conservation units in the Brazilian Cerrado using a GIS and AHP approach. Ecological Indicators, v. 115, 2020. https://doi.org/10.1016/j.ecolind.2020.106440

Mota, P. H. S.; Rocha, S. J. S.; Castro, N. L. M.; Marcatti, G. E.; França, L. C. J.; Schettini, B. L. S.; Villanova, P. H.; Santos, H. T.; Santos, A. R. Forest fire hazard zoning in Mato Grosso State, Brazil. Land Use Policy, v. 88, 2019. https://doi.org/10.1016/j.landusepol.2019.104206

Noon, C. E.; Daly, M. GIS-based biomass resource assessment with BRAVO. *Biomass and Bioenergy*, 101-109, 1996. https://doi.org/10.1016/0961-9534(95)00065-8

Oakleaf, J. R.; Kennedy, C. M.; Baruch-Mordo, S.; Gerber, J. S.; West, P. C.; Johnson, J. A.; Kiesecker, J. Mapping global development potential for renewable energy, fossil fuels, mining and agriculture sectors. *Nature, Scientific Data*, v. 6, n.101, 2019. https://doi.org/10.1038/s41597-019-0084-8

Oliveira, L. L.; Ribeiro, C. O.; Qadrdan, M. Analysis of electricity supply and demand intra-annual dynamics in Brazil: A multi-period and multi-regional generation expansion planning model. *International Journal of Electrical Power and Energy Systems.* 137, 2022. https://doi.org/10.1016/j.ijepes.2021.107886

Pablo-Romero, M. P.; Sánchez-Braza, A.; Galyan, A. Renewable energy use for electricity generation in transition economies: Evolution, targets and promotion policies. *Renewable and Sustainable Energy Reviews*, 138, 2021. https://doi.org/10.1016/j.rser.2020.110481

Panichelli, L.; Gnansounou, E. GIS-based approach for defining bioenergy facilities location: A case study in Northern Spain based on marginal delivery costs and resources competition between facilities. *Biomass & Bioenergy*, 32, 289 – 300, 2008. https://doi.org/10.1016/j.biombioe.2007.10.008

Perpiñá, C.; Alfonso, D.; Pérez-Navarro, A.; Peñalvo, E.; Vargas, C.; Cárdenas, R. Methodology based on Geographic Information Systems forbiomass logistics and transport optimization. *Renewable Energy*, 34, p. 555 – 565, 2009. https://doi.org/10.1016/j.renene.2008.05.047

Perpiñá, C.; Martínez-Llario, J. C.; Pérez-Navarro, Á. Multicriteria assessment in GIS environments for siting biomass plants. *Land Use Policy*, v.31, p.326-335, 2013. http://dx.doi.org/10.1016/j.landusepol.2012.07.014

Pohekar, S. D.; Ramachandran, M. Application of multi-criteria decision making to sustainable energy planning—A review. *Renewable and Sustainable Energy Reviews*, v. 8, p. 365-381, 2004. https://doi.org/doi:10.1016/j.rser.2003.12.007

Pukkala T. The Use of Multi-Criteria Decision Analysis and Multi-Objective Optimization in Forest Planning. 2006 In: Hasenauer H. (eds) Sustainable Forest Management. Springer, Berlim, Heidelberg. https://doi.org/10.1007/3-540-31304-4_17

Quinta-Nova, L., Fernandez, P., Pedro, N. GIS-Based Suitability Model for Assessment of Forest Biomass Energy Potential in a Region of Portugal. World Multidisciplinary Earth Sciences Symposium (WMESS 2017), IOP Conf. Series: Earth and Environmental Science, 95, 2017. https://doi.org/10.1088/1755-1315/95/4/042059

Recanatesi, F.; Tolli, M.; Lord, R. Multi Criteria Analysis to Evaluate the Best Location of Plants for Renewable Energy by Forest Biomass: A Case Study in Central Italy. *Applied Mathematical Sciences*, v.8, n.129, p. 6447-6458, 2018. http://dx.doi.org/10.12988/ams.2014.46451

Richardson, J.; Björheden, R.; Hakkila, P.; Lowe, A. T.; Smith, C. T. Bioenergy from Sustainable Forestry: Guiding Principles and Practice. Kluwer Academic Publishers, New York, Boston, Dordrecht, London, Moscow. 344p., 2002.

Rikalovic, A.; Cosic, I.; Lazarevic, D. GIS Based Multi-Criteria Analysis for Industrial Site Selection. *Procedia Engineering,* 69, 1054 – 1063, 2014. http://dx.doi.org/10.1016/j.proeng.2014.03.090

Rode, R.; Leite, H. G.; Silva, M. L.; Ribeiro, C. A. A. S.; Binoti, D. H. B. The economics and optimal management regimes of eucalyptus plantations: A case study of forestry out grower schemes in Brazil. *Forest Policy and Economics.* v. 44, p. 26-33, 2014. https://doi.org/10.1016/j.forpol.2014.05.001

Saaty, T. L. How to make a decision: The Analytic Hierarchy Process. *European Journal of Operational Research*, v.48, p. 9 – 26, 1990, https://doi.org/10.1016/0377-2217(90)90057-I

Saaty, T. L. Some mathematical concepts of the Analytic Hierarchy Process. *Behaviormetrika*, v. 18, 29, 1–9, 1991. https://doi.org/10.2333/bhmk.18.29_1

Saaty, T. L. Theory and Applications of the Analytic Network Process: Decision Making with Benefits, Opportunities, Costs, and Risks. Pittsburgh: RWS Publications, 2005.

Saaty, T.L. The Analytic Hierarchy Process. McGraw Hill International, New York, 1980.

Saaty, T.S. Decision making with the analytic hierarchy process. *International Journal of Services Sciences*,1,1,2008.Available in: http://www.rafikulislam.com/uploads/resourses/197245512559a37aadea6d.pdf

Sánchez-García, S.; Athanassiadis, D.; Martínez-Alonso, C.; Tolosana, E.; Majada, J.; Canga, E. A GIS methodology for optimal location of a wood-fired power plant: Quantification of available woodfuel, supply chain costs and GHG emissions. *Journal of Cleaner Production,* v. 157, p. 201-212, 2017. https://doi.org/10.1016/j.jclepro.2017.04.058

Sánchez-Lozano, J. M.; García-Cascales, M.S.; Lamata, MT. Evaluation of suitable locations for the installation of solar thermoelectric power plants. *Computers & Industrial Engineering*. 87, p. 3430355, 2015. https://doi.org/10.1016/j.cie.2015.05.028

SBS – Brazilian Society of Forestry. Brazil Forest Facts and Figures. São Paulo, 1 – 92, 2008. Available in: http://www.celsofoelkel.com.br/artigos/outros/09_2008_FatoseNumerosdoBrasilFlorestal.pdf. Accessed in: 24/07/21.

Sharma, B.; Birrel, S.; Miguez, F.E. Spatial modeling framework for bioethanol plant siting and biofuel production potential in the U.S *Applied Energy*, 191, p.75-86, 2017. https://doi.org/10.1016/j.apenergy.2017.01.015

SNUC – National System of Nature Conservation Units. Law N° 9.985, of July 18, 2000. http://www.planalto.gov.br/ccivil_03/leis/l9985.htm

Souza, V. S. S.; Junior, R. T.; Berger, R.; Silva, J. C. G. L.; Delacote, P. Rentabilidade Econômica do Arrendamento de Terra para Cultivo de Eucalipto em São Paulo. Floresta e Ambiente, 22, p. 345-354, 2015. http://dx.doi.org/10.1590/2179-8087.033113

Sultana, A.; Kumar, A. Optimal siting and size of bioenergy facilities using geographic information system. Applied Energy, 94, p. 192-201, 2012. https://doi.org/10.1016/j.apenergy.2012.01.052

Teixeira, T. R.; Ribeiro, C. A. A. S.; Santos, A. R.; Marcatti, G. E.; Lorezon, A. S.; Castro, N. L. M.; Domingues, G. F.; Leite, H. G.; Menezes, S. J. M. C.; Mota, P. H. S.; Telles, L. A. A.; Vieira, R. S. Forest biomass power plant installation scenarios. *Biomass and Bioenergy.* 108, p. 35-47, 2018. https://doi.org/10.1016/j.biombioe.2017.10.006

Van Leeuwen, L.; Cappon, H. J.; Keesman, K. J. Urban bio-waste as a flexible source of electricity in a fully renewable energy system. *Biomass and Bioenergy*, v. 145, 2021. https://doi.org/10.1016/j.biombioe.2020.105931

Vettorazzi, C. A.; Valente, R. A. Priority areas for forest restoration aiming at the conservation of water resources. *Ecological Engineering*, v. 94, p. 255-267, 2016. https://doi.org/10.1016/j.ecoleng.2016.05.069

Wackernagel, H. Ordinary Kriging. In: Multivariate Geostatistics. Springer, Berlin, Heidelberg, 1995. https://doi.org/10.1007/978-3-662-03098-1_11

Wang, W.; Fan, L.W.; Zhou, P. Evolution of global fossil fuel trade dependencies. Energy, 238, 2022. https://doi.org/10.1016/j.energy.2021.121924

WBA – World Bioenergy Association. Global Bioenergy Statistics 2019. https://worldbioenergy.org/uploads/191129%20WBA%20GBS%202019_HQ.pdf

WBA – World Bioenergy Association. Global Bioenergy Statistics 2020. https://worldbioenergy.org/uploads/201210%20WBA%20GBS%202020.pdf

Woo, H.; Acuna, M.; Moroni, M.; Taskhiri, M. S.; Turner, P. Optimizing the Location of Energy Facilities by Integrating Multi-Criteria Analysis (MCA) and Geographical Information Systems (GIS). *Forests*, v.9, 585, 2018. https://doi.org/10.3390/f9100585

Wood SM, Layzell DB. A Canadian biomass inventory: feedstocks for a bio-based economy. Final report; 2006.

Zalk, J.v.; Behrens, P. The spatial extent of renewable and non-renewable power Generation: A review and meta-analysis of power densities and their applicaton in the U. S. Energy Policy, v.123, 83-91, 2018. https://doi.org/10.1016/j.enpol.2018.08.023

Zhan, F. B.; Chen, X.; Noon, C. E.; Wu, G. A GIS-enabled comparison o ffixed and discriminatory pricingstrategies for potential switchgrass-to-ethanol conversionfacilities in Alabama. *Biomass & Bioenergy*, 28, 295-306, 2005. https://doi.org/10.1016/j.biombioe.2004.06.006

Zhang, F.; Wang, J.; Liu, S.; Zhang, S.; Sutherland, J. W. Integrating GIS with optimization method for a biofuel feedstock supply chain. *Biomass and Bioenergy*, v.98, p.194-205, 2017. http://dx.doi.org/10.1016/j.biombioe.2017.01.004

ANEXO

(Supplementary material)

Table 01. Acquisition sources and summary of input layers used in the analysis.

Data		Primary Source
1	Hydrography	National Water Agency (ANA) (https://www.gov.br/ana/en)
2	Airfields	National Civil Aviation Agency (ANAC) (https://www.anac.gov.br/en)
3	Archaeological sites	National Register of Archaeological Sites (CNSA / SGPA - IPHAN) (http://portal.iphan.gov.br/cna/pagina/detalhes/1227)
4	Indigenous lands	National Institute of Colonization and Agrarian Reform (INCRA) (http://acervofundiario.incra.gov.br/acervo/acv.php)
5	Rural settlements	National Institute of Colonization and Agrarian Reform (INCRA) (http://acervofundiario.incra.gov.br/acervo/acv.php)
6	Veredas (Environmentally sensitive áreas)	Geoenvironment Digital Atlas (Instituto Pristino) (https://institutopristino.org.br/)
7	Thermoelectric Power Plants	Electric Sector Georeferenced Information System (SIGEL), National Electric Energy Agency (ANEEL) (https://sigel.aneel.gov.br/Down/)
8	Highways and Railways	Ministry of Infrastructure / Spatial Data Infrastructure of the State System of Environment and Water Resources (IDE-Sisema) (http://idesisema.meioambiente.mg.gov.br/)
9	Power transmission lines	National Electric Energy Agency (ANEEL) (https://www.aneel.gov.br/)
10	Conservation units	Spatial Data Infrastructure of the State System of Environment and Water Resources (IDE-Sisema) (http://idesisema.meioambiente.mg.gov.br/)
11	Forest plantations	MAPBIOMAS Collection 5.0 (Google Earth Engine Data Catalog) (https://mapbiomas.org/)
12	Surface inclination	DEM-SRTM, Earth Explorer (USGS) (https://earthexplorer.usgs.gov/) and Ecological-Economic Zoning of Minas Gerais (ZEE-MG) (SEMAD-UFLA) (http://idesisema.meioambiente.mg.gov.br/)
13	Mean Annual Increment (MAI)	TECHS-IPEF project (Binkley *et al.*, 2020)
14	Quantity of roundwood produced in silviculture (m^3)	IBGE Automatic Recovery System (SIDRA-IBGE): Production of Vegetable Extraction and Silviculture (PEVS-2018). (https://sidra.ibge.gov.br/pesquisa/pevs/quadros/brasil/2018)
15	Bare Land Value (BLV)*	Minas Gerais State Technical Assistance and Rural Extension Company (EMATER) (http://www.emater.mg.gov.br/)
16	Electric Power Substations	National Electric System Operator (ONS) (http://sindat.ons.org.br)

*Average price in 2020.

Table 4. The fundamental scale preferences in the pair-wise comparison process according to Saaty (1980; 2008). Verbal judgments of preferences between alternative *i* and alternative *j*.

a_{ij} value	Definition	Explanation
1	A_i is equally important to A_j	Objectives *i* and *j* are of equal importance.
3	A_i is slightly more important than A_j	Objective *i* is weakly more important than objective *j*.
5	A_i is strongly more important than A_j	Experience and judgments indicate that objective *i* is strongly more important than objective *j*.
7	A_i is very strongly more important than A_j	Objective *i* is very strongly or demonstrably more important than objective *j*.
9	A_i is extremely more important than A_j	Objective *i* is absolutely more important than objective *j*
2,4,6,8	Intermediate values	Intermediate values, for example, a value of 8 means that objective *i* is midway between strongly and absolutely more important than objective *j*.
*Reciprocals of above numbers	If an activity has one of the above numbers (e.g., 3) compared with a second activity, then the second activity has reciprocal value (e.g., 1/3) when compared to the first.	

Table 5. RI values *(Random Index)* for square matrices of order *n* (Saaty, 1980; 2005).

n	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56

Table 6. Summary of planning data involving forestry costs and annual periods that composed the objective function coefficients of the mathematical model.

[1]Costs (US$)			**Period**
***Thermoelectrical**			**Year**
Average cost 50 megawatt power plant (MW)	62,014,954.5	US$	1th to 2th
***Purchase of Land + Lease of Land**			**Year**
Land purchase	**	US$/ha	0
Planting	851.2	US$/ha	0
Others	95.5	US$/ha	1th to 6th
Transport	0.041	US$/m^3/km	6th
Harvest	8.3	US$/m^3	6th
Coppicing	70.9	US$/ha	6th
Land annual cost (annual) * interest	**	US$/ha	1th to 6th
Land lease (annual) * 15%	**	US$/ha	1th to 6th

*** Outgrower scheme**			**Year**
Planting	124.1	US$/ha	0
Others	***	US$/ha	1th to 6th
Transport	0.041	US$/m³/km	6th
Harvest	8.3	US$/m³	6th
Coppicing	62.1	US$/ha	6th
Wood purchase	10.2	US$/m³	6th
*** Purchase of Wood from the Market**			**Year**
Purchase	26.5778	US$/m³	indifferent
Transport	0.041	US$/m³/km	indifferent
discount rate	8	(% a.a)	

[1] The values were converted from Brazilian Real to US Dollar according to the 2021 exchange rate, based on the currency converter of the Central Bank of Brazil; * The technical foundation of the values was based and adapted from the regional literature (Ferreira et al., 2019; Silva, 2019; Rode et al., 2015; Souza *et al.,* 2015); ** Value varies by location; *** Amount on behalf of outgrowers.

Table 7. Pairwise comparison matrix between the study parameters.

*	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**	**AUTO VETOR**	**A.N.V.**
C1	1	1/2	1/4	1/5	1/5	1/4	1/8	1/7	1/7	1/9	1/7	1/9	0,21	1,2%
C2	2	1	1/2	1/4	1/3	3	1/6	1/6	1/4	1/7	1/3	1/9	0,38	2,2%
C3	4	2	1	1/3	1/5	2	1/5	1/5	1/4	1/7	1/4	1/8	0,44	2,5%
C4	5	4	3	1	1/3	2	1/5	1/3	1/5	1/5	1/6	1/7	0,61	3,5%
C5	5	3	5	3	1	3	1/3	1/4	1/2	1/5	1/3	1/7	0,90	5,1%
C6	4	3	1/2	1/2	1/3	1	1/6	1/3	1/3	1/6	1/3	1/8	0,47	2,7%
C7	8	6	5	5	3	6	1	2	2	1/2	2	1/2	2,43	13,9%
C8	7	6	5	3	4	3	1/2	1	1/2	1/2	1/2	1/3	1,52	8,7%
C9	7	4	4	5	2	3	1/2	2	1	1/2	2	1/3	1,80	10,2%
C10	9	7	7	5	5	6	2	2	2	1	2	1/2	3,00	17,1%
C11	7	3	4	6	3	3	1/2	2	1/2	1/2	1	1/3	1,64	9,3%
C12	9	9	8	7	7	8	2	3	3	2	3	1	4,17	23,7%
	68	**48,50**	**43,25**	**36,28**	**26,40**	**40,25**	**7,69**	**13,43**	**10,68**	**5,96**	**12,06**	**3,76**	**17,56**	**100%**

(**i**) Number of comparisons = 66; (**ii**) Consistency Ratio CR = 5.9%; (**iii**) Principal Eigen Value = 12.97; (**iv**) Eigenvector solution: 6 iterations, delta = 1.4E-8; (**v**) *****Criteria – **C1:** Surface inclination; **C2:** Proximity Urban Areas; **C3:** Proximity other thermoelectric units; **C4:** Bare Land Value (BLV) (Land cost - US$ /ha); **C5:** Proximity to Railways; **C6:** Proximity to Hydrography; **C7:** Proximity to Roads; **C8:** Mean Annual Increment (MAI); **C9:** Proximity to power lines; **C10:** Log wood stock (m³); **C11:** Electric Power Substations; **C12**: Proximity to forest plantations. (A.N.V = Auto Normalized Vector / Weights of importance).

Table 8. Criteria (*n*) and weight coefficients in priority hierarchy obtained after the implementations of AHP.

Order of importance	Criteria (*n*)	Weight w_{ij}	Priority (%) Importance scale
1	Proximity to forest plantations	0.237	23.7%
2	Log wood stock (m^3)	0.171	17.1%
3	Proximity to Roads	0.139	13.9%
4	Proximity to power lines	0.109	10.9%
5	Electric Power Substations	0.093	9.3%
6	Mean Annual Increment (MAI)	0.087	8.7%
7	Proximity to Railways	0.051	5.1%
8	Bare Land Value (BLV)	0.035	3.5%
9	Proximity to Hydrography	0.027	2.7%
10	Proximity other thermoelectric units	0.025	2.5%
11	Proximity Urban Areas	0.022	2.2%
12	Surface inclination	0.012	1.2%

Table 10. Calculation of the proportion of restricted or permanently unsuitable areas for constructing thermoelectric plants based on forest biomass in the GRHB.

	Constraints	Area (km^2)	Area (%)
1	Urban areas	1,192.76	2.68
2	Archaeological sites	0.18	0.00
3	Airfields	14,990.67	33.72
4	Hydrography	1,714.26	3.86
5	Environmentally sensitive areas (Veredas)	383.97	0.86
6	Conservation unit[1]	10,788.74	24.27
7	Conservation unit[2]	5,800.60	13.05
8	Highways	244.74	0.55
9	Railways	143.38	0.32
10	Power transmission lines	282.59	0.64
11	Surface inclination	7,133.87	16.05
12	Indigenous lands	1,581.87	3.56
13	Rural settlements	201.78	0.45
	Total (∑)	44,459.47*	100

[1] Integral protection; [2] Sustainable use; *area without overlap.

Table 11. Suitability and availability areas classes for the implementation of thermoelectric plants based on forest biomass.

Suitability Classes	**Area (km²)**	**Percentage (%)**
Low Suitability (I)	36,681.04	42.61
Medium Suitability (II)	13,135.91	15.26
High Suitability (III)	2,640.04	3.07
Inappropriate Areas (IV)	33,620.66	39.06
Total (∑)	86,077.65	100
Effective available areas	52,456.99	60.94