Economic and environmental assessment of regional development measures of an economic sector at multiple scales : the case of the forest and wood sector in the French region Grand Est

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THESE

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Évaluation économique et environnementale du développement régional d'une filière en interaction multi-secteur et multi-échelle : le cas de la filière forêt-bois du Grand Est

par

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Résumé de la Thèse

Développement de la bioéconomie et critères de durabilité

Un pan significatif de la transition écologique repose sur le développement des activités liées à l'utilisation de ressources naturelles renouvelables, dans une perspective de gestion durable, en remplacement des ressources fossiles et minérales. Dans ce cadre, le concept de bioéconomie est mobilisé par diverses institutions supranationales et nationales pour mettre en avant les perspectives de développement de ces activités fondées sur les secteurs agricoles, forestiers, de la pêche et l'aquaculture. L'OCDE propose une définition large du terme bioéconomie comprenant tous les secteurs et activités économiques liés à la production et à la transformation de biens et de services basés sur des ressources biologiques, ainsi qu'à la production de services écosystémiques (OECD, 2009).

Dans le but de développer ces secteurs, des initiatives ont été lancées dans différentes instances, i.e. le programme d'action de l'OCDE (OECD, 2018), la stratégie bioéconomie de la Commission Européenne (European Commission, 2018) ou la National Bioeconomy Blueprint aux États-Unis (The White House, 2012). Neuf pays européens ont formulé des stratégies nationales spécifiques déclinant les modalités de mise en œuvre locales de la bioéconomie (European Commission, 2020).

En France, la stratégie nationale de bioéconomie est orientée notamment sur la biomasse forestière destinée à des usages énergétiques et matériaux (Ministère de l'Agriculture et de l'Alimentation, 2018). Dès les années 90, les politiques publiques orientées vers le secteur forestier ont mis en avant les perspectives environnementales favorables, soit à travers la séquestration de carbone ou les bénéfices en termes de conservation des habitats soit, plus récemment, à travers la substitution carbone liée à l'utilisation du bois pour l'énergie ou les matériaux (Lenglet and Caurla, 2020). Depuis les années 2000, les politiques se sont focalisées sur les utilisations énergétiques du bois par le biais de diverses mesures d'incitation à la demande de bois-énergie, complétées par des mesures directes ou indirectes de soutien à l'offre. Dans cette thèse, nous étudions plus particulièrement ces politiques orientées vers les usages énergies du bois, auxquels est destinée plus de la moitié de la biomasse forestière, aussi bien en France que pour l'UE. Par ailleurs, la production de bioénergie repose à plus de 60% sur la biomasse forestière (Scarlat *et al.*, 2019).

Les orientations des stratégies de développement de la bioéconomie forestière soulèvent toutefois des questions en matière de durabilité : une politique sectorielle, a priori vertueuse, est-elle vraiment durable ? Cette question s'est notamment posée pour les agro-carburants de première génération, promus sans analyse environnementale approfondie, alors que les impacts environnementaux se sont avérés notables (Koh and Ghazoul, 2008). Des critères de durabilité ont été établis au niveau de l'Union européenne (European Union Law, 2018), basés sur le risque d'émissions indirectes liées à des changements d'utilisation des terres, en fonction du type de biomasse utilisée et des catégories d'utilisations des terres susceptibles d'être mobilisées pour la produire. En ce qui concerne la biomasse forestière, des recommandations existent, mais sont inégalement mises en œuvre parmi les États membres (Banja *et al.*, 2019). De manière générale, l'élaboration de ces cadres légaux se heurte aux difficultés de l'évaluation de la performance face à l'hétérogénéité des systèmes techniques, des conditions locales, et du poids du choix des méthodes (Finkbeiner, 2014; Ter-Mikaelian, Colombo and Chen, 2015; Brandão *et al.*, 2019). De plus, le secteur forestier cristallise des enjeux et des attentes parfois contradictoires, souvent évalués séparément, pour lesquels des synergies ou des arbitrages peuvent exister : sur les enjeux économiques – bioénergie, bois d'œuvre, commerce – ou environnementaux – carbone, biodiversité, pollutions. L'existence de ces arbitrages doit être explicitée grâce à des évaluations multicritères sur les différents piliers de la durabilité. Néanmoins, si les outils d'évaluation des critères environnementaux et économiques sont à un stade de maturité avancé, les mesures du critère social sont moins abouties et font encore l'objet de recherches à part entière (Chhipi-Shrestha, Hewage and Sadiq, 2015; Kühnen and Hahn, 2017).

Enjeux et spécificités de l'échelle régionale

Une caractéristique notable des plans de développement de la bioéconomie réside dans l'importance accordée à ses déclinaisons régionales. L'approche française met l'accent sur le développement des marchés locaux de la biomasse et des chaînes régionales d'approvisionnement en bois énergie, notamment en fixant des objectifs régionaux de production de biomasse (Ministère de la Transition Ecologique et Solidaire, 2020). Par ailleurs, en vis-à-vis des politiques développées par l'angle de la bioéconomie, des innovations sociotechniques dans le secteur forestier émergent également à partir des territoires. Des acteurs locaux développent des innovations techniques et organisationnelles dans une logique intégrant tant le développement économique territorial que la durabilité des pratiques (Lenglet, 2018).

Qu'il s'agisse de politiques institutionnelles ou d'initiatives locales, l'intérêt pour l'approche locale provient notamment de la possibilité d'articuler des enjeux spécifiques liés à la gestion durable de la ressource avec des dynamiques économiques régionales. La pertinence de cette échelle peut néanmoins être interrogée à l'aune des nombreuses interactions susceptibles de peser sur l'évaluation de la durabilité du système étudié, i.e., effets économiques directs et indirects entre différentes entités géographiques, impacts environnementaux à différentes échelles, changement globaux de long terme.

Question de recherche et démarche générale

Notre objectif est de contribuer à développer une méthode scientifiquement robuste pour estimer les impacts économiques et environnementaux de la mise en œuvre d'une stratégie de développement de la bioéconomie à une échelle régionale, en considérant les nombreuses interactions entre secteurs économiques et échelles spatiales. Cette méthode est centrée sur l'étude du secteur forestier, utilisé comme preuve de concept afin d'étudier la faisabilité de la démarche et son intérêt en termes d'aide à la décision.

Pour réaliser cet objectif, plusieurs verrous méthodologiques doivent être levés.

La prise en compte des différentes interactions requiert un cadre d'évaluation adapté, susceptible d'intégrer de multiples mécanismes économiques et d'évaluer des impacts biophysiques, en tenant compte des différentes échelles et temporalités.

De plus, ces évaluations doivent pouvoir s'appliquer aussi bien à des stratégies développées dans des logiques descendantes ou « top-down », plutôt institutionnelles, qui déclinent au niveau local des objectifs globaux dans une logique de « downscaling » (Eriksson *et al.*, 2020), qu'à des stratégies locales développées sur un contexte spécifique, dans une approche ascendante ou « bottom-up », mais qui tiendraient compte de répercussions globales.

Enfin une question centrale, dès lors que l'on cherche à accompagner l'aide à la décision est celle des indicateurs. Cette question est d'autant plus prégnante que les approches environnementales produisent des résultats multivariés – typiquement entre 3 et 18 indicateurs selon l'approche choisie.

Cette thèse bi disciplinaire vise à répondre à la problématique générale suivante :

« **Peut-on construire un modèle de simulation basé sur le couplage interdisciplinaire entre modèles économique et environnemental pour évaluer la durabilité (performances économique et environnementale) de stratégies régionales de développement du secteur forestier, en tenant compte des effets multi-échelles et multi-secteurs ?** »

Cet objectif principal se décline en trois objectifs, abordés dans trois articles qui constituent les chapitres I, II et III du manuscrit.

Le premier objectif consiste à identifier et analyser les méthodes existantes proposant un couplage entre un modèle économique et un outil d'évaluation environnementale pour réaliser une évaluation économique et environnementale intégrée à l'échelle régionale, afin d'identifier les forces et faiblesses de chacune.

Le deuxième objectif est l'élaboration d'un cadre méthodologique combinant la modélisation économique et environnementale pour calculer des indicateurs régionaux d'éco-efficience en considérant un ensemble d'interactions multi-échelles et multi-secteurs.

Le troisième objectif est de vérifier la pertinence de ce cadre sur un cas d'étude : la mise en œuvre de stratégies de développement bois énergie de la bioéconomie orientées vers le bois-énergie, à l'échelle nationale et au niveau régional dans le Grand Est. Nous étudierons l'éco-efficience de différents scénarios basés sur des combinaisons de différentes politiques et de contraintes exogènes.

Dans le chapitre I de cette thèse, nous décrivons et nous comparons à l'aide d'une grille de critères les principaux types de couplages utilisés dans la littérature pour réaliser des évaluations économiques et environnementales à l'échelle méso.

Dans le chapitre II, nous présentons un cadre méthodologique basé sur le couplage entre un modèle d'équilibre partiel et une Analyse du Cycle de Vie (ACV) permettant de quantifier des indicateurs d'éco-efficiences. Ces ratios produits par le modèle combinent des indicateurs économiques de surplus et des impacts environnementaux potentiels et évités (intégrant les impacts évités par la non-consommation d'énergie fossile par rapport à un scénario de base). Ce cadre est testé sur un cas d'application simple d'une politique régionale en faveur du bois énergie. Elle montre l'importance du développement d'indicateurs d'éco-efficience prenant en compte les impacts évités.

Le chapitre III met en œuvre plus largement ce cadre, en analysant et en comparant l'éco-efficience de stratégies de bioéconomie dans la filière forêt bois, à l'échelle nationale et au niveau de la région Grand Est.

Enfin, une discussion générale sur les apports et les limites du cadre méthodologique et des résultats du couplage est proposée dans le chapitre 5. Nous traçons également quelques perspectives sur les axes de développement de ce type d'approche.

Chapitre I : Couplages entre modèles économiques et méthodes d'évaluation environnementale pour l'analyse de politiques à l'échelle régionale : une revue critique de la littérature

Dans ce premier chapitre, nous menons une réflexion et une synthèse sur les méthodes existantes pour quantifier la performance économique et environnementale d'un territoire infranational, ou région. Nous procédons à une revue par disciplines, en nous penchant dans un premier temps sur les outils utilisés en économie à l'échelle régionale. Cinq grandes catégories d'approches ont été identifiées, i.e., i) les modèles d'équilibre partiel et ii) d'équilibre général, iii) les modèles input output, iv) la modélisation multi agents, et v) les modèles de dynamique des systèmes. D'autre part, nous nous appuyons sur l'analyse des méthodes d'évaluation environnementale utilisées à l'échelle territoriale proposée par Loiseau *et al.* (2012).

Afin de répondre à la problématique de la thèse, nous nous sommes focalisés sur les couplages bidisciplinaires entre méthodes d'évaluation économique et environnementale identifiées préalablement. Nous avons retenu 15 types de couplages basés sur 5 modèles économiques (IO, équilibre partiel et général, modèle multi agent, Système dynamique), et 3 modèles environnementaux (empreintes, analyse de flux de matière, ACV).

Nous effectuons une analyse bibliométrique pour identifier les types de couplage utilisés dans la littérature scientifique. La comptabilisation des articles faisant appel à ce type de couplage montre la prédominance des couplages entre les modèles IO et les différents types d'outils d'évaluation environnementale, en majorité de type ACV ou empreintes. L'utilisation de modèles d'équilibre général en combinaison avec l'ACV et les empreintes carbone ou eau est croissante.

Dans un deuxième temps, nous proposons une grille d'analyse basée sur 8 critères afin d'évaluer et de comparer les différents types de couplages. Ces critères sont les suivants : 1) le périmètre d'étude et le type de problématique 2) le niveau de couplage 3) la désagrégation sectorielle de l'économie 4) la diversité des indicateurs fournis 5) les effets indirects, conséquentiels et off-site 6) la spatialisation du modèle, 7) la dynamique temporelle et 8) la facilité d'utilisation.

Les résultats montrent que les différents couplages recensés ne sont pas tous performants pour les mêmes critères. Cela traduit une complémentarité entre les approches en fonction des problématiques posées. Sur l'ensemble des critères retenus, les couplages entre modèles d'équilibre (PE ou CGE) et les approches empreintes et ACV répondent le mieux aux besoins définis pour une analyse à l'échelle régionale. Il est apparu que, compte tenu des caractéristiques du secteur forestier, le couplage PE – ACV était prometteur pour étudier des stratégies de bioéconomie au niveau régional.

Chapitre II : Combiner modèle d'équilibre partiel et Analyse du Cycle de Vie pour calculer des indicateurs régionaux d'éco-efficience : méthodologie et application à une mesure de stimulation de la demande de bois énergie dans la région Grand Est

Dans ce deuxième chapitre, nous développons le couplage entre modèle d'équilibre partiel et ACV. En nous appuyant sur les résultats du premier chapitre, nous avons décidé d'utiliser comme base de travail le modèle économique de secteur forestier French Forest Sector Model (FFSM), modèle d'équilibre partiel doté d'une composante relative aux dynamiques de croissance forestière.

Différents verrous ont été identifiés dans la mise en œuvre du couplage. Ils concernent la mise en relation des flux entre modèles économiques et ACV, l'homogénéisation de la représentation des flux de matières, et la mise en place de substitutions entre les produits des secteurs forestiers et d'autres secteurs économiques (p. ex. le secteur énergétique).

FFSM modélise les 22 anciennes régions françaises ou 12 régions IGN correspondant dans la plupart des cas aux nouvelles régions, leur marché et leurs ressources forestières, et permet de calculer des variations de quantités et de prix de produits de la filière forêt bois en réaction à des politiques nationales ou régionales (taxes, prix fixés, subventions…), en interaction avec les marchés mondiaux. Il comprend 3 produits primaires (bois d'œuvre de feuillus, bois d'œuvre de résineux, bois industrie et bois énergie) et 6 produits secondaires (sciages de feuillus, sciages de résineux, placages, panneaux, pâte à papier, bois énergie).

Dans un premier temps, le lien entre les sorties du modèle FFSM et les inventaires du cycle de vie (ICV) a été étudié. Les sorties FFSM sont une liste de quantités et de prix pour différents produits de la filière bois. Ces produits sont sous forme plus ou moins agrégée et plusieurs approches sont possibles pour les connecter à des ICV. Nous utilisons l'ACV process, qui est généralement mobilisée pour modéliser des systèmes à l'échelle « micro ». Les sorties du modèle économique sont désagrégées à l'aide d'une Analyse de Flux de Matière du secteur forestier réalisée par Lenglet et al. (2017). Ensuite, elles sont combinées à des ICV issus de la base de données Ecoinvent. Nous combinons le modèle FFSM avec l'ACV pour calculer l'éco-efficience, un ratio entre indicateurs de services socioéconomiques et indicateurs d'impacts environnementaux, appliqués à différentes politiques sur la filière forêt-bois.

Dans un deuxième temps, nous avons ajouté des effets de substitution entre bois énergie et énergie fossile, et ainsi intégré les effets sur d'autres secteurs de l'économie dans le modèle FFSM. Nous avons testé l'effet de scénarios faisant varier les élasticités de substitution entre le bois énergie et les énergies fossiles, après un travail de revue de littérature sur ces élasticités prix croisés entre produits substituts. Les effets étant peu contrastés, nous avons mis en place des scénarios plus classiques basés sur des subventions à la consommation de bois énergie. Les résultats sont analysés à travers la question des interactions entre échelles géographiques et secteurs économiques. D'une part, nous observons la façon dont les effets d'une politique centrée sur une région – le Grand Est – se diffusent aux autres régions. D'autre part, nous évaluons les impacts environnementaux évités grâce à la substitution d'énergies fossiles par du bois énergie. Nous évaluons globalement les impacts environnementaux des scénarios de subvention et utilisons le surplus économique tiré du FFSM afin de calculer des ratios d'éco-efficience. Dans un premier temps, nous calculons la variation d'éco-efficience par rapport à un scénario de référence à partir du surplus économique et des impacts environnementaux potentiels, sans prendre en compte les impacts évités par substitution. Nous nommons cet indicateur Partial Eco Efficiency (PEE).

Dans un 2e temps, la prise en compte de ces impacts environnementaux évités peut induire des impacts environnementaux nuls ou négatifs pour certaines catégories d'impacts – épuisement des ressources fossiles notamment. Ces impacts étant présents dans le dénominateur des ratios d'éco-efficience standard, nous dérivons un autre indicateur, appelé Full Eco Efficiency (FEE) afin de disposer d'un indicateur pertinent, quelles que soient les valeurs prises par les indicateurs économiques et les indicateurs environnementaux.

Ce cadre est testé sur un cas d'application simple d'une politique régionale de stimulation de la consommation de bois énergie à travers une subvention. La politique est éco-efficiente quel que soit le type d'indicateur, PEE ou FEE, mais nous montrons des différences substantielles selon que les impacts évités sont pris en compte ou non.

Ces éléments constituent différentes contributions en réponse au deuxième objectif formulé pour le chapitre II. Tout d'abord, nous avons proposé des indicateurs d'éco-efficience basés sur un ratio entre surplus économique de la filière forêt bois et impacts environnementaux liés à l'ensemble des produits. Ensuite, nous avons mis en évidence les adaptations à apporter à un modèle d'équilibre partiel et à la méthode ACV afin de disposer d'un couplage cohérent, répondant aux objectifs formulés. Ces modifications portaient notamment sur un bilan équilibré des flux de matières entre modèles. Nous avons également intégré un mécanisme de substitution entre le bois énergie et les énergies fossiles. Cette fonctionnalité nous a permis de développer un indicateur d'éco-efficience, la Full Eco-Efficiency, prenant en compte dans un ratio unique des impacts environnementaux évités par substitution entre le bois énergie et la consommation d'énergies fossiles.

Chapitre III : Évaluer l'éco-efficience de stratégies de développement de la bioéconomie à l'échelle nationale et régionale : le cas de du bois énergie en France et dans le Grand Est

Le troisième sous objectif, traité dans ce chapitre III, a consisté à mettre en œuvre notre démarche pour étudier les impacts économiques et environnementaux de stratégies de développement de la bioéconomie. Ces stratégies sont traduites sous la forme de scénarios qui représentent certaines des tendances actuelles des politiques publiques et des initiatives locales : incitations économiques à la demande de bois de chauffage, promotion de l'offre locale et conservation des forêts. Nous avons également inclus un choc des prix de l'énergie, afin de simuler un facteur externe. Nous avons comparé ces scénarios entre eux à deux échelles, sur la base des indicateurs d'éco-efficience, d'une part, en appliquant ces mesures et ces contraintes à l'échelle nationale, et d'autre part, à l'échelle régionale, appliquée au cas de la région Grand Est. L'analyse est fondée sur la Full Eco Efficiency, définie dans le chapitre précédent.

Nous avons produit diverses combinaisons de ces mesures à l'échelle nationale et régionale et avons calculé les ratios d'éco-efficacité qui en découlent. Les résultats ont montré que les incitations économiques sous la forme d'une subvention pour le bois de chauffage étaient celles qui augmentaient le plus l'éco-efficience par rapport au scénario de référence, au niveau régional et national. Ce résultat repose notamment sur les bénéfices des impacts évités grâce à la substitution du bois de chauffage en remplacement des combustibles fossiles. La combinaison de la mesure de subvention avec des mesures de protection et/ou d'approvisionnement local a eu tendance à augmenter ou à diminuer légèrement son éco-efficience selon l'échelle de mise en œuvre.

Notre cadre a montré que divers facteurs déterminent l'éco-efficacité d'une politique dans une région donnée, notamment les caractéristiques de la ressource forestière, l'importance de la filière bois locale tant du côté de l'offre que de la demande, et les caractéristiques des régions voisines. Les paramètres du modèle tels que les mécanismes commerciaux, les fonctions d'offre et de la demande, la concurrence entre le bois de chauffage et les combustibles fossiles ou l'ACV du mix énergétique sont déterminants dans le résultat final.

Ces applications illustrent l'intérêt de mobiliser des indicateurs de performance économiques et environnementaux multicritères, permettant une comparaison détaillée des différentes stratégies de développement de la bioéconomie évaluées. Nous avons mis en évidence les bénéfices économiques et environnementaux de politiques de soutien à la bioéconomie sur plusieurs critères. Notre approche a permis d'identifier des synergies entre politiques bioéconomiques, mais aussi des arbitrages sur certaines catégories d'impacts qui se manifestent différemment pour des stratégies régionales ou nationales. Plus généralement, notre démarche démontre l'importance de la prise en compte des interactions multi-échelles.

Discussion et conclusion

Notre démarche procède du besoin de construire un outil spécifique pour évaluer la performance économique et environnementale à l'échelle régionale de stratégies de développement de la bioéconomie basées sur l'utilisation de biomasse forestière. Ce besoin émane tant du développement des politiques bioéconomiques au niveau national et européen que de l'émergence d'innovations techniques et organisationnelles dans la filière forêt bois au niveau des territoires. Déclinées à l'échelle régionale, ces stratégies doivent être évaluées en considérant tant les caractéristiques locales, que les effets directs et indirects à des échelles spatiales et temporelles multiples.

Ces enjeux nécessitent un outil d'évaluation multicritère, adaptés à l'échelle méso. Nous avons formulé l'hypothèse de recherche suivante : un couplage interdisciplinaire entre modèle économique et évaluation environnementale permet d'évaluer et comparer la performance économique et environnementale de mesures régionales de développement dans le secteur forestier en prenant en compte leurs effets directs et indirects, à des échelles multiples et imbriquées. Nous avons interrogé et confirmé cette hypothèse dans trois sous objectifs, développés dans les chapitres I à III. Puis, nous avons mis en évidence les forces et les limites de notre approche dans le chapitre 5, ainsi que plusieurs pistes d'approfondissement.

Nous avons ainsi mentionné que certaines données d'inventaires doivent être précisées, notamment sur en ce qui concerne la substitution bois-énergie/énergies fossiles ou la comptabilité dynamique du carbone biogénique. Nous avons souligné également que les interactions multisectorielles sont simplifiées par la structure du modèle. Développer des interactions entre produits bois et secteurs de la construction notamment permettrait d'évaluer des stratégies de développement de la bioéconomie orientées vers les usages matériaux du bois. Dans cette logique d'approfondissement de la modélisation, d'autres éléments pourraient apporter. FFSM tient compte des spécificités régionales de la ressource, mais les marchés des produits bois reposent sur les mêmes fonctions dans chaque région. De même, l'ACV de la filière n'est pas différenciée par région. Une spatialisation plus détaillée permettrait notamment d'étudier d'autres types de scénarios, comme l'implantation de projets de grande envergure.

En ce qui concerne la mise à disposition des résultats, l'opérationnalisation de la démarche est un enjeu important. Notre approche a vocation à poser les bases d'un outil pouvant être mis en œuvre au-delà des milieux de recherche, parcimonieux en temps et en données, et facilement utilisable par les décideurs publics, y compris dans des approches participatives. La mise à disposition et le partage de données peuvent faciliter la reproduction de couplages de ce type. Ce souci de mise à disposition des évaluations de la durabilité de la bioéconomie répond à un besoin d'alimenter des processus démocratiques. L'appropriation par les élus et les citoyens des enjeux relatifs au développement de ces filières est une condition nécessaire de leur développement efficace et durable (McCormick and Kautto, 2013).

La consolidation de l'outil développé, de ses indicateurs et de ses résultats devrait permettre d'étendre ce type d'approche à d'autres problématiques et d'autres secteurs. Parallèlement, la confrontation à des couplages basés sur d'autres outils comme les modèles multi-agents ouvre la voie à un approfondissement de la modélisation de mécanismes socio-économiques déterminants à l'échelle méso.

La confrontation à d'autres outils de simulation ouvre la question du choix des modèles pour évaluer indicateurs de long terme dans le domaine du risque de l'incertain. La prise en compte de phénomènes stochastiques tels que les tempêtes, sécheresses, et feux sont des enjeux majeurs dans le secteur forestier. Les approches déterministes présentent des limites en la matière. Des outils dans le champ du machine learning seraient susceptibles de contribuer à modéliser l'occurrence de ce type de phénomène.

Cette perspective de rapprochement entre la modélisation de phénomènes socio-économiques complexes au niveau local et la prise en compte des risques et incertitudes fortes auxquels les sociétés et les écosystèmes sont exposés ouvre la question de l'évaluation de la résilience des territoires.

Table des Matières

Liste des Figures

Liste des Tables

Introduction générale

1 Évaluer la durabilité de stratégies de développement de la bioéconomie dans le secteur forestier à différentes échelles

1.1 La notion de durabilité au service des processus de transition écologique : quelques éléments de contexte

La conception contemporaine des crises écologiques, perçues comme des phénomènes globaux et imminents représentant des menaces vitales pour l'humanité, prend racine dans le développement des questions environnementales dans les années 1970. L'idée d'une exploitation non durable de l'environnement par la société se cristallise dans les travaux du Club de Rome sur les limites de la croissance et la finitude des ressources non renouvelables (Meadows *et al.*, 1972). Ces préoccupations montantes s'installent dans le jeu politique et institutionnel international dans les années 1980, avec notamment l'émergence de la notion de développement durable, qui doit concilier la prise en compte des besoins présents et futurs de l'humanité dans son ensemble, avec la préservation de son environnement (Bergandi and Blandin, 2012). Le rapport Brundtland le définit comme « un mode de développement qui répond aux besoins du présent sans compromettre la capacité des générations futures de répondre aux leurs et correspond au devoir des générations actuelles de transmettre un monde vivable, viable et reproductible » (Brundtland *et al.*, 1987). Malgré une certaine polysémie et des emplois du concept renvoyant parfois à des rapports à l'environnement et la nature aux antipodes (Vivien, 2003), cette notion demeure fondamentale pour articuler les enjeux de développement économique et social et la pression exercée par les activités humaines sur les différentes composantes de l'environnement. Elle s'est trouvée traduite récemment dans les objectifs de développement durable des Nations Unies (United Nations, 2020), qui portent aussi bien sur des enjeux économiques et sociaux qu'environnementaux, en tenant compte de leurs interdépendances.

Une difficulté centrale de l'élaboration de trajectoires de développement durable tient précisément à la multiplicité et l'interrelation des enjeux socio-économiques et environnementaux qui s'y rattachent. Pour pallier cette difficulté et hiérarchiser les actions à mettre en œuvre, des métriques ont été développées pour évaluer les différents piliers de la durabilité. Sur la dimension environnementale, les limites planétaires (Rockström *et al.*, 2009) proposent un cadre englobant neuf processus naturels impactés par les activités humaines, i.e., changement climatique, intégrité de la biosphère, flux biogéochimiques de phosphore et d'azote, utilisation des terres, consommation d'eau douce, acidification des océans, aérosols atmosphériques, épuisement de l'ozone stratosphérique, entités nouvelles[1]. Un des objectifs centraux de ce cadre est de définir des seuils pour ces différents processus, au-delà desquels le bon fonctionnement des sociétés humaines est mis en péril. Certains de ces enjeux sont bien identifiés, comme le changement climatique, bien que de fortes

[1] D'autres limites socio-économiques et environnementales peuvent être identifiées, comme l'épuisement des ressources énergétiques non renouvelables (Murphy, 2014) ou minérales (Prior *et al.*, 2012).

incertitudes demeurent dans la définition de points de basculements en lien avec la concentration en Gaz à Effet de Serre (GES) dans l'atmosphère (IPCC, 2014). En matière de déclin de la biodiversité, les synthèses scientifiques sont plus récentes (IPBES, 2019) et des difficultés importantes subsistent également pour quantifier ces seuils (Montoya, Donohue and Pimm, 2018b, 2018a). Globalement, si des incertitudes demeurent, des transformations profondes des activités de production et de consommation sont nécessaires pour contrôler l'impact environnemental des sociétés humaines et éviter les risques d'effondrement.

Ces nécessités de transformation économique se concentrent dans la notion de découplage entre la provision de biens et services et les atteintes environnementales, tant sur le plan de l'utilisation des ressources, que des émissions de polluants dont les gaz à effet de serre (Fischer-Kowalski *et al.*, 2011). Des trajectoires de développement permettant un découplage peuvent être établies en théorie (Schandl *et al.*, 2016), mais, jusque-là, leur mise en œuvre effective s'est trouvée limitée dans la pratique (Vadén *et al.*, 2020). Les questions et difficultés relatives à la conception de ces trajectoires de développement et à leur mise en œuvre se concentrent dans la notion de transition, déclinée sous de multiples formes – transition énergétique, transition vers une économie bas carbone, transition écologique (Audet, 2016). Parmi elles, la notion de transition écologique, principe de recherche-action ayant vocation à englober les multiples enjeux socio-économiques et environnementaux (Hopkins, 2008), s'est démarquée. En effet, elle désigne désormais au niveau institutionnel, notamment en France, le processus général de transformation économique vers une meilleure prise en compte de l'environnement (Audet, 2016).

1.2 Développement de la bioéconomie et critères de durabilité

Un pan significatif de la transition écologique repose sur le développement des activités liées à l'utilisation de ressources naturelles renouvelables, dans une perspective de gestion durable, en remplacement des ressources fossiles et minérales. Dans ce cadre, le concept de bioéconomie[2] est mobilisé par diverses institutions supranationales et nationales pour mettre en avant les perspectives de développement de ces activités fondées sur les secteurs agricoles, forestiers, de la pêche et l'aquaculture. L'OCDE propose une définition large du terme bioéconomie comprenant tous les secteurs et activités économiques liés à la production et à la transformation de biens et de services basés sur des ressources biologiques, ainsi qu'à la production de services écosystémiques (OECD, 2009).

Dans le but de développer ces secteurs, des initiatives ont été lancées dans différentes instances, i.e. le programme d'action de l'OCDE (OECD, 2018), la stratégie bioéconomie de la Commission Européenne (European Commission, 2018) ou la National Bioeconomy Blueprint aux États-Unis (The White House, 2012). Neuf pays européens ont formulé des stratégies nationales spécifiques déclinant les modalités de mise en œuvre locales de la bioéconomie (European Commission, 2020).

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[2] Nous utilisons ici le terme « bioéconomie » dans le sens de la « bio-based economy », à distinguer notamment de la bioéconomie de Georgescu-Roegen (1971) ou du concept développé dans le champ de la biologie.

En France, la stratégie nationale pour la bioéconomie est orientée notamment sur la biomasse forestière destinée à des usages énergétiques et matériaux (Ministère de l'Agriculture et de l'Alimentation, 2018). Dès les années 90, les politiques publiques orientées vers le secteur forestier ont mis en avant les perspectives environnementales favorables, soit à travers la séquestration de carbone ou les bénéfices en termes de conservation des habitats, soit, plus récemment, à travers la substitution carbone liée à l'utilisation du bois pour l'énergie ou les matériaux (Lenglet and Caurla, 2020). Depuis les années 2000, les politiques se sont focalisées sur les utilisations énergétiques du bois par le biais de diverses mesures d'incitation à la demande de bois-énergie, complétées par des mesures directes ou indirectes de soutien à l'offre. Dans cette thèse, nous étudions plus particulièrement ces politiques orientées vers les usages énergies du bois, auxquels est destinée plus de la moitié de la biomasse forestière, aussi bien en France que pour l'UE. Du point de vue de la production de bioénergie en général, elle repose à plus de 60% sur la biomasse forestière (Scarlat *et al.*, 2019).

Les orientations des stratégies de développement de la bioéconomie forestière soulèvent toutefois des questions en matière de durabilité : une politique sectorielle, a priori vertueuse, est-elle vraiment durable ? Cette question s'est notamment posée pour les agro-carburants de première génération, promus sans analyse environnementale approfondie, alors que les impacts environnementaux se sont avérés notables (Koh and Ghazoul, 2008). Des critères de durabilité ont été établis au niveau de l'Union européenne (European Union Law, 2018), basés sur le risque d'émissions indirectes liées à des changements d'utilisation des terres, en fonction du type de biomasse utilisée et des catégories d'utilisations des terres susceptibles d'être mobilisées pour la produire. En ce qui concerne la biomasse forestière, des recommandations existent, mais sont inégalement mises en œuvre parmi les États membres (Banja *et al.*, 2019). De manière générale, l'élaboration de ces cadres légaux se heurte aux difficultés de l'évaluation de la performance face à l'hétérogénéité des systèmes techniques, des conditions locales, et du poids du choix des méthodes (Finkbeiner, 2014; Ter-Mikaelian, Colombo and Chen, 2015; Brandão *et al.*, 2019). De plus, le secteur forestier cristallise des enjeux et des attentes parfois contradictoires, souvent évalués séparément, pour lesquels des synergies ou des arbitrages peuvent exister : sur les enjeux économiques – bioénergie, bois d'œuvre, commerce – ou environnementaux – carbone, biodiversité, pollutions. L'existence de ces arbitrages doit être explicitée grâce à des évaluations multicritères sur les différents piliers de la durabilité. Néanmoins, si les outils d'évaluation des critères environnementaux et économiques sont à un stade de maturité avancé, les mesures du critère social sont moins abouties et font encore l'objet de recherches à part entière (Chhipi-Shrestha, Hewage and Sadiq, 2015; Kühnen and Hahn, 2017).

1.3 Enjeux et spécificités de l'échelle régionale

Une caractéristique notable des plans de développement de la bioéconomie réside dans l'importance accordée à ses déclinaisons régionales. L'approche française met l'accent sur le développement des marchés locaux de la biomasse et des chaînes régionales d'approvisionnement en bois énergie, notamment en fixant des objectifs régionaux de production de biomasse (Ministère de la Transition Ecologique et Solidaire, 2020). Par ailleurs, en vis-à-vis des politiques développées par l'angle de la bioéconomie, des innovations sociotechniques dans le secteur forestier émergent également à partir des territoires. Des acteurs locaux développent des innovations techniques et organisationnelles dans une logique intégrant tant le développement économique territorial que la durabilité des pratiques (Lenglet, 2018).

Qu'il s'agisse de politiques institutionnelles ou d'initiatives locales, l'intérêt pour cette échelle provient notamment de la possibilité d'articuler des enjeux spécifiques liés à la gestion durable de la ressource avec des dynamiques économiques régionales. La pertinence de l'échelle locale peut néanmoins être interrogée à l'aune des nombreuses interactions susceptibles de peser sur l'évaluation de la durabilité du système étudié. Citons les effets économiques directs et indirects entre différentes entités géographiques, les impacts environnementaux à différentes échelles, ou des changements globaux de long terme.

1.4 L'évaluation de ces effets comme objectif de la thèse

Notre objectif est de contribuer à développer une méthode scientifiquement robuste pour estimer les impacts économiques et environnementaux de la mise en œuvre d'une stratégie de développement de la bioéconomie à une échelle régionale, en considérant les nombreuses interactions entre secteurs économiques et échelles spatiales. Cette méthode est centrée sur l'étude du secteur forestier, utilisé comme preuve de concept afin d'étudier la faisabilité de la démarche et son intérêt en termes d'aide à la décision.

Pour réaliser cet objectif, plusieurs verrous méthodologiques doivent être levés.

La prise en compte des différentes interactions requiert un cadre d'évaluation adapté, susceptible d'intégrer de multiples mécanismes économiques et d'évaluer des impacts biophysiques, en tenant compte des différentes échelles et temporalités.

De plus, ces évaluations doivent pouvoir s'appliquer aussi bien à des stratégies développées dans des logiques descendantes ou « top-down », plutôt institutionnelles, qui déclinent au niveau local des objectifs globaux dans une logique de « downscaling » (Eriksson *et al.*, 2020), qu'à des stratégies locales développées sur un contexte spécifique, dans une approche ascendante ou « bottom-up », mais qui tiendraient moins nécessairement compte de répercussions globales.

Enfin une question centrale, dès lors que l'on cherche à accompagner l'aide à la décision est celle des indicateurs. Cette question est d'autant plus prégnante que les approches environnementales produisent des résultats multivariés – typiquement entre 3 et 18 indicateurs selon l'approche choisie, dans les méthodes d'Analyse du Cycle de Vie (ACV).

Dans la section suivante, nous décrirons comment ces différentes caractéristiques du système socio-économique du bois-énergie et de l'objectif opérationnel recherché se traduisent en enjeux de recherche.

2 Verrous méthodologiques de l'évaluation des performances économiques et environnementales de la filière bois-énergie

2.1 Des indicateurs pour l'action

Un premier choix porte sur la nature des indicateurs, qu'ils soient quantitatifs et/ou qualitatifs. La formalisation et le partage de données qualitatives sur la durabilité présentent des défis en termes de cohérence des évaluations (Alexander *et al.*, 2020). Les outils d'évaluations économiques et environnementaux étant très largement orientés vers des évaluations quantitatives, nous nous focaliserons sur ce type d'indicateurs. Comme indiqué plus haut, les évaluations quantitatives sur le pilier social de la durabilité étant significativement moins développées que sur les dimensions économiques et environnementales, l'évaluation de la performance sera réalisée sur ces deux derniers volets. L'indicateur de durabilité (limité aux critères économique et environnemental) doit être suffisamment simple pour être facilement manipulé par des profanes, mais avec un niveau de précision suffisant pour permettre de motiver un choix s'appuyant sur un système de valeurs.

Pour répondre à ce cahier des charges, l'économie de l'environnement propose un indicateur unique, sous forme d'indicateur monétaire. En effet, l'évaluation des bénéfices environnementaux en unités monétaires peut faciliter la communication avec un large public et sensibiliser la société aux questions environnementales. Cependant, un défaut de cette méthode vient précisément de sa force : en quantifiant tous les impacts au sein d'une même unité, les spécificités des impacts sont effacées. De plus, les évaluations monétaires présentent des limites quand il s'agit d'évaluer des capitaux naturels critiques (Ray, 1997) comme la couche d'ozone ou la biodiversité remarquable (Pearce, Atkinson and Mourato, 2006).

Cette question rejoint celle de l'opposition entre durabilités forte et faible, dont les lignes de fractures se superposent en partie à des contours disciplinaires, la durabilité faible étant historiquement associée à la théorie de Solow (1956) sur laquelle s'inscrit la majorité des économistes de l'environnement, tandis que la durabilité forte est associée aux modèles issus des sciences de l'environnement (Loiseau *et al.*, 2016).

Ces deux courants, s'ils adoptent le même concept de capital naturel, s'opposent sur la substituabilité entre les différents capitaux. La durabilité faible suppose une substituabilité importante, voire totale, du capital naturel et des capitaux humains – intellectuels ou manufacturés, dans une perspective de maximisation de l'utilité et d'allocation optimale des ressources. L'approche de durabilité forte postule que certains capitaux naturels sont critiques et irremplaçables et doivent être protégés (Neumayer, 2013). Les approches de durabilité forte préconisent généralement des démarches transdisciplinaires, articulant sciences sociales et évaluation biophysiques, pour déterminer les capitaux naturels critiques (Dedeurwaerdere, 2014).

Notre démarche s'inscrit dans ce dernier courant et nous choisissons de conserver conjointement des indicateurs issus d'évaluations monétaires et de modélisation biophysique. Ces choix méthodologiques étant faits, le verrou scientifique consiste maintenant à sélectionner ces indicateurs environnementaux et socioéconomiques et de les associer pour une lecture facilitée et une bonne compréhension par les porteurs d'enjeux.

La production d'indicateurs combinés, comme des indicateurs d'éco-efficience constituent une perspective particulièrement prometteuse. L'éco-efficience, définie initialement par le World Business Council for Sustainable Development (WBCSD), est un ratio d'indicateurs de deux types, i.e. i) une valeur liée à une production de biens ou de services et ii) un indicateur d'impact environnemental (Stigson *et al.*, 2006). Il peut être appliqué au niveau « micro » (c'est-à-dire des entreprises) ou au niveau « macro » (national) (Basset-Mens, Ledgard and Boyes, 2009; Egilmez, Kucukvar and Tatari, 2013) ainsi qu'à l'échelle « méso » intermédiaire, où elle a été utilisée pour évaluer les performances économiques et environnementales de stratégies régionales (Seppälä *et al.*, 2005) ou d'aménagement du territoire (Loiseau *et al.*, 2014). Toutefois, aucune de ces études n'aborde en détail les questions spécifiques soulevées par les effets indirects causés par une décision sur de multiples échelles temporelles et spatiales (Loiseau *et al.*, 2018). Cela constituera également un verrou méthodologique à aborder.

2.2 Des modèles pour calculer les indicateurs

Aux échelles régionales qui nous intéressent, de nombreux outils sont disponibles pour fournir une évaluation quantitative des effets économiques et des impacts biophysiques.

Dans le champ de la modélisation économique appliquée au secteur forestier, les modèles d'équilibre partiels sont les plus utilisés. Souvent bien désagrégés, ils font le lien entre la diversité des produits modélisés et les caractéristiques des ressources nécessaires pour leur production. Ils manquent par définition de capacité à modéliser des effets multisectoriels. En élargissant la question de la modélisation à l'échelle méso-économique à d'autres secteurs, les modèles Input Output (IO) sont particulièrement utilisés en économie régionale (Loveridge, 2004; Irwin *et al.*, 2010). Dans la même optique intersectorielle, des adaptations des modèles d'équilibre général à l'échelle régionale existent depuis les années 1990, mais leur niveau d'agrégation tend à limiter notamment le champ de leurs applications (Partridge and Rickman, 1998, 2010). Cette échelle demeure peu traitée par rapport au niveau microéconomique de la firme et au niveau macroéconomique national et global, pour des raisons notamment de disponibilités des données. Parallèlement, des outils de simulations issus d'autres disciplines se développent depuis 20 ans pour modéliser des phénomènes économiques en interaction avec leur environnement. Dans cette veine, citons les modèles multi-agents (Farmer and Foley, 2009; Tesfatsion, 2017), assez présents dans les approches en matière de bioéconomie (Parker *et al.*, 2003; O'Brien *et al.*, 2017), la possibilité de modéliser des comportements socio-économiques complexes se prêtant à la simulation de choix d'utilisation des terres à une échelle fine.

En matière d'approches systémiques en évaluation environnementale, différents outils peuvent être utilisés (Loiseau *et al.*, 2012). L'empreinte écologique est plutôt mobilisée pour des échelles nationales, mais peut être décomposée au niveau de régions ou de territoires urbains (Wiedmann *et al.*, 2007; Graymore, Sipe and Rickson, 2008; Turner *et al.*, 2012). À l'échelle régionale, les Analyses de Flux de Matières (Material Flow Analysis, MFA) ont été utilisées régulièrement pour cartographier des flux à l'échelle de territoires (Barles, 2009; CGDD, 2014;

Courtonne *et al.*, 2015). Enfin, des adaptations du cadre de l'ACV pour l'échelle méso ont été développées récemment (Loiseau *et al.*, 2013), permettant de fournir une évaluation multicritère, sur l'ensemble du cycle de vie, des activités de production et de consommation d'un territoire dans son ensemble (Loiseau, 2014).

La disponibilité de modèles n'étant pas limitante, un verrou scientifique consiste à choisir les plus pertinents compte tenu du cas d'étude, tout en minimisant les efforts à fournir pour renseigner les modèles, dans une perspective d'opérationnalité. Pour cela, nous proposons de coupler les modèles économiques et environnementaux, afin de produire une évaluation intégrée des performances.

2.3 Le couplage de modèles pour une évaluation intégrée de la performance économique et environnementale de stratégies régionales

La création d'un outil interdisciplinaire, basé sur un couplage, pose un certain nombre de défis méthodologiques.

Pour fournir une évaluation exhaustive des impacts tant environnementaux qu'économiques de stratégies régionales, des outils quantitatifs, adaptés aux spécificités de l'échelle méso, sont nécessaires. De nombreux outils bien identifiés, évoqués dans la section précédente, existent tant en économie que dans le domaine de l'évaluation environnementale. Les modèles économiques et les modèles d'évaluation environnementale peuvent être combinés dans un couplage « soft », ce qui signifie que les résultats des modèles économiques sont utilisés comme entrées pour alimenter un modèle d'évaluation environnementale.

Les sorties d'un modèle économique sont en général des quantités de biens unitaires ou des valeurs agrégées d'un ensemble de biens. Les modèles ACV, lorsqu'ils représentent des systèmes étendus à l'échelle territoriale ou sectorielle, s'appuient quant à eux sur des inventaires de flux environnementaux (consommations de ressources et émissions de substances polluantes) et technologiques (biens et services) exprimés en unités physiques – masse, volume, énergie.

Le couplage soft entre les sorties du modèle économique et les entrées du modèle environnemental pose donc le verrou méthodologique de l'interopérabilité et de l'intégrité des flux. Un travail d'harmonisation des modèles dans le cadre des couplages reste donc à mettre en œuvre.

Enfin, nous avons souligné la nécessité de prendre en compte une large gamme d'interactions à différents niveaux (entre filières, entre échelles spatiales…) pour produire une évaluation exhaustive et robuste.

Un dernier verrou méthodologique consiste donc en l'opposition entre un besoin de sophistication pour intégrer ces effets inter-échelles et une nécessaire simplicité, afin d'éviter une construction trop complexe qui cumulerait les besoins de données et les incertitudes. Il s'agira de construire une architecture cohérente, permettant d'une part de prendre en compte les échelles supra, dès que nécessaire, et d'autre part de conserver une approche claire et parcimonieuse du système.

3 Question de recherche et démarche générale

Nous avons identifié des verrous scientifiques, à partir desquels nous formulons la problématique générale de la thèse de la façon suivante

« **Peut-on construire un modèle de simulation basé sur le couplage interdisciplinaire entre modèle économique et modèle d'évaluation environnementale pour évaluer la durabilité (performances économique et environnementale) de stratégies régionales de développement du secteur forestier, en tenant compte des effets multi-échelles et multi-secteurs ?** »

La réponse à cette problématique se décline en trois objectifs, abordés dans trois articles qui constituent les chapitres I, II et III du manuscrit.

Le premier objectif consiste à identifier et analyser les méthodes existantes proposant un couplage entre un modèle économique et un outil d'évaluation environnementale pour réaliser une évaluation intégrée à l'échelle régionale, afin d'identifier les forces et faiblesses de chacune.

Le deuxième objectif est d'élaborer un cadre méthodologique combinant la modélisation économique et environnementale pour calculer des indicateurs régionaux d'éco-efficience en considérant un ensemble d'interactions multi-échelles et multi-secteurs.

Le troisième objectif est de vérifier la pertinence de ce cadre sur un cas d'étude : la mise en œuvre de stratégies de développement de la bioéconomie orientées vers le bois-énergie, à l'échelle nationale et au niveau régional dans le Grand Est. Nous étudierons l'éco-efficience de différents scénarios basés sur des combinaisons de différentes politiques et de contraintes exogènes.

Plus précisément, dans le chapitre I de cette thèse, nous décrivons et nous comparons à l'aide d'une grille de critères les principaux types de couplages utilisés dans la littérature pour réaliser des évaluations économiques et environnementales à l'échelle méso. Dans cette revue bibliographique, nous avons identifié quinze types de couplages basés sur cinq modèles économiques (IO, équilibre partiel et général, modèle multi agent, système dynamique), et trois modèles environnementaux (empreintes, MFA, ACV). Nous avons établi huit critères d'analyse pertinents pour évaluer la performance économique et environnementale à l'échelle méso. Les résultats montrent que les différents couplages recensés ne sont pas tous performants pour les mêmes critères. Cela traduit une complémentarité entre les approches en fonction des problématiques posées. Sur l'ensemble des critères retenus, les couplages entre modèles d'équilibre (PE ou CGE) et les approches empreintes et ACV présentent le plus d'avantages.

Dans le chapitre II, nous présentons un cadre méthodologique basé sur le couplage entre un modèle d'équilibre partiel et une ACV permettant de quantifier des indicateurs d'éco-efficience. Ces indicateurs prennent la forme de ratios combinant des indicateurs économiques de surplus et des impacts environnementaux. Nous en testons deux types selon que les impacts évités par la substitution de bois énergie à des énergies fossiles par rapport à un scénario de référence sont inclus ou non dans les impacts environnementaux. Ce cadre est testé sur un cas d'application simple d'une politique régionale de stimulation de la consommation de bois énergie à travers une subvention. La politique est éco-efficiente quel que soit le type d'indicateur. Nous montrons des différences substantielles selon que les impacts évités sont pris en compte ou non.

Nous mettons plus largement en œuvre ce cadre dans le chapitre III. Nous analysons et comparons l'éco-efficience de stratégies de développement de la bioéconomie dans la filière forêt bois, à l'échelle nationale et au niveau de la région Grand Est. Ces stratégies sont déclinées en plusieurs scénarios, qui combinent deux mesures de développement la bioéconomie – stimulation de la demande de bois énergie, approvisionnement local en bois – avec des mesures de conservation des forêts et des contraintes extérieures. Cette démarche permet notamment d'étudier les interactions entre politiques, compte tenu du contexte local et du contexte global.

Enfin, une discussion générale sur les apports et les limites du cadre méthodologique et des résultats du couplage est proposée dans le chapitre IV. Nous traçons également quelques perspectives sur les axes de développement de ce type d'approche.

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I

Coupling economic models and environmental assessment methods to support regional policies: a critical review

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Abstract

This review analyses and compares the most promising methods to perform *ex ante* economic and environmental assessment of policies at the *meso* scale, *i.e.* from local communities to subnational regions. These methods called Economic-Environment Integrated Models (EEIM) are based on the coupling of formalized economic modelling tools with environmental assessment methods. The economic modelling tools considered are Input Output (IO) models, Computable General Equilibrium (CGE) and Partial Equilibrium (PE) models, Agent-Based models (ABM), and System Dynamics (SD) models, which we pair with environmental assessment methods such as Footprints (FP), Life Cycle Assessment (LCA), or Material Flow Analysis (MFA). A grid of criteria is developed to perform a qualitative rating of the EEIMs according to existing literature. The grid encompasses the detail level of the economic modelling, the level of coupling between environmental and economic tools, the quality and diversity of indicators, the ability to account for diverse indirect effects, spatial differentiation, time aspects, and the coupled model usability. First, the results show that the couplings do not perform on the same criteria, which shows complementarity to deal with diverse issues. Second, overall, for most criteria, PE/CGE models coupled with FP/LCA ranked highest. Third, a few case studies showed that couplings involving a third tool can be beneficial — for instance AB modelling or MFA with PE/CGE-LCA/FP may allow overcoming some shortcomings such as agent behaviour modelling or data availability for biophysical flows.

Keywords

Model coupling, Economic modelling, Environmental assessment, Integrated assessment, Regional policy, Sustainability

1 Introduction

The transition towards sustainability requires efficient, effective, and feasible policies (OECD, 2007, 2011, 2013; EUROPEAN UNION, 2011; European Economic and Social Committee, 2016). These policies need to be defined at different scales, and a particular emphasis is placed on subnational policies, i.e. at the *meso* scale, which ranges from local communities to subnational regions. Regulatory obligations regarding environmental assessment prior to public and private projects, plans, and programmes have been implemented on this scale since the mid-1980s, particularly programmes and projects involving territories and land planning under the responsibility of local authorities (EIA, European Commission, 2016; SEA, European Parliament, 2001). Local and regional initiatives are also promoted by International agreements (Cappelletti *et al.*, 2009) to support transitions towards sustainability, such as local Agenda 21 (Barrutia et al., 2015), or by European authorities for green and circular economy strategies (European Economic and Social Committee, 2016; Pitkänen et al., 2016).

These strategies are based on win-win assumptions, i.e. aiming at both environmental and economic benefits (Loiseau *et al.*, 2016). With respect to these objectives, quantitative tools are required to provide an exhaustive assessment of both the environmental and economic impacts of subnational projects.

In the economic field, environmental stakes have been integrated through valuation and cost-benefit analysis methods (Farber, Costanza and Wilson, 2002; Costanza *et al.*, 2014). Valuating environmental benefits into monetary units can facilitate communication with a broad audience and raise societal awareness about environmental issues. However, one major caveat of this method comes precisely from its strength, i.e. by quantifying all impacts within the same unit, the specificities of the impacts are erased. Moreover, monetary evaluation may have limits when it comes to assessing critical natural assets (Ray, 1997), e.g. the ozone layer or rare biodiversity (Pearce, Atkinson and Mourato, 2006). To address these caveats, methods coupling environmental tools with economic assessments are being developed, showing an ability to provide indicators complementary to the monetary units.

In this paper, we specifically aim to identify and analyse the existing methods coupling economic models and environmental assessment tools to perform an integrated economic and environmental assessment at the subnational scale. The paper focuses on tools that provide a quantitative evaluation of economic effects and biophysical impacts specifically at this scale. On the one hand, different economic modelling approaches have been identified to carry out studies at regional scales (Irwin et al., 2010; Lemelin et al., 2008; Loveridge, 2004). Among these, input-output (IO) models are widely used by regional economists. Regional declinations of models based on equilibrium theory have also been established for many years (Irwin et al., 2010; Loveridge, 2004; Partridge and Rickman, 2010, 1998). Over the past 20 years, the use of tools developed primarily outside of the economic field, such as agent-based modelling (ABM) (Chen et al., 2012; Fagiolo et al., 2007; Farmer and Foley, 2009; Tesfatsion, 2017) or system dynamics (SD) (McCauley and Küffner, 2004; Sterman, 2005; Radzicki, 2009), has gained credibility and importance in modelling economic phenomena. On the other hand, different environmental assessment tools can be used to quantify the impacts of territorial metabolism, such as Life Cycle Assessment (LCA) (Loiseau et al., 2012), Material Flow Analysis (MFA) (Hendriks *et al.*, 2000; Huang *et al.*, 2007; Kennedy, Cuddihy and Engel-Yan, 2007; Courtonne *et al.*, 2015), or environmental Footprints (FP), e.g. Carbon Footprint (CF), Water Footprint (WF), or Ecological Footprint (EF) (McGregor et al., 2008; K. Turner et al., 2012; Yu et al., 2010).

Some environmental-economic couplings have been reviewed for specific topics: climate change mitigation (Pauliuk *et al.*, 2017; Pehl *et al.*, 2017), land use change (LUC), and indirect land use change (ILUC) (Halog and Manik, 2011). However, no exhaustive analysis of all possible couplings between the aforementioned economic and environmental assessment tools has so far been proposed. This paper aims at contributing to filling this gap. More precisely, we have identified all types of coupling of economic modelling and environmental assessment methods that exist in the scientific literature and compared them in terms of their ability to provide exhaustive and quantitative information to decision makers at meso-scale.

This paper is structured as follows. Firstly, we briefly describe the main environmental tools and economic models to highlight their main features. We then discuss how these models have been coupled. Secondly, we perform bibliometric analysis to identify what types of coupling of economic and environmental tools and methods that exist in the scientific literature have been conducted, and in what number. Thirdly, we propose an analysis grid that includes the key criteria for a comprehensive assessment at a meso scale. Then, we compare the coupled approaches through the proposed analysis grid. Finally, we draw the main conclusions and perspectives to pave the way for future research on coupling economic and environmental models at subnational scales.

2 Overview of economic modelling approaches and environmental assessment methods at the subnational scale

This paper focuses on integrated assessments methods that have coupled existing and standardized economic modelling tools with environmental assessment methods. Before identifying these coupled models in the literature, we provide a brief overview of each group of methods separately.

2.1 Economic modelling approaches for the subnational scale

The economic model review is based on the definition of *economics* as 'the science dealing with the allocation of scarce resources to meet unlimited needs' (Samuelson and Nordhaus, 1992). We therefore extend the review to all modelling tools that study human behaviour when it comes to extracting, producing, transforming, exchanging and consuming resources, goods, and services, and optimizing these activities.

We consider five categories, depending on the way economic behaviours are represented (see Figure A.1 in A.1). First, we distinguish empirical models from mixed theoretical-empirical models. Pure empirical models refer to econometric models (EC) built on statistical analysis of economic data, while theoretical-empirical models encompass all modelling tools built on a theoretical structure using key variables calibrated with empirical data and/or statistical methods. We omitted from our analysis purely theoretical models that provide qualitative insights as they only depict stylized behaviours. Within mixed theoretical-empirical models, two consistent groups are considered.

The first group encompasses traditional economic models, which may exist in versions with analytically solvable or numerically solvable structures. They are consistently used for subnational applications, and are hence well described. This group includes input output (IO) models and equilibrium theory models, i.e. Computable General Equilibrium (CGE) and Partial Equilibrium (PE) models (Irwin et al., 2010; Lemelin et al., 2008; Loveridge, 2004; Partridge and Rickman, 2010, 1998). The second group encompasses models sometimes referred to as *simulation* models. These models have been developed in the computer era and have numerically solvable structures only. Their use in economics applications has largely developed in the last 20 years (Scholl, 2001; Borshchev and Filippov, 2004; Moon, 2017). This second group includes Agent-Based modelling (ABM) (Fagiolo, Moneta and Windrum, 2007; Farmer and Foley, 2009; Chen, Chang and Du, 2012; Tesfatsion, 2017) and System Dynamics (SD) (McCauley and Küffner, 2004; Sterman, 2005; Radzicki, 2009). Consequently, the review will focus on five types of economic model, i.e. IO, CGE, PE, ABM, and SD. We provide their main characteristics in Table I.1 and more information is given in the Appendix (see A.1).

2.2 Environmental assessment methods

Several tools can be used to assess the environmental impacts at the subnational scale. Loiseau et al. (2012) provide a complete description and comparison of the main characteristics of all methods that have been implemented at the territory scale. Among these, tools based on mono-footprint methods such as the Ecological Footprint (EF) and tools based on metabolism studies such as Material Flow Analysis (MFA) are notably widespread among practitioners. This is partly due to the existence of guidelines and databases that make it possible to apply these tools to cities, subnational regions, and nations. In addition, some of these methods provide indicators that are easily understandable by the public. The authors show that Life Cycle assessment (LCA), although less used for territory analysis, is a promising tool for assessing meso-scale objects. We provide an overview of the main characteristics of these three types of environmental assessment method in the table below, i.e. Footprint methods (Ecological, Carbon, and Water Footprint, FP), flow analysis (MFA or Substance Flow Analysis, SFA), and LCA, and in the Appendix (see A.2).

Economic models ***Characteristics***	***IO and SAM***	***Econometric***	***General equilibrium***	***Partial Equilibrium***	***Agent-Based Modelling***	***System Dynamics***
Formalization	Linear relationship between economic output data embedded in tables	Relationship between various data from regressions	Supply and demand equilibrium based on econometrically estimated functions	Supply and demand equilibrium based on econometrically estimated functions	Behaviour rules	Stock, flows, and feedback loops
Equations	Linear	Linear and non-linear	Linear and non-linear	Linear and non-linear	Non-linear	Non-linear
Time dynamic	Static	Dynamic	Static and Dynamic	Static and Dynamic	Static and Dynamic	Dynamic
Geographic scale	From Meso to Macro	All scales	Rather macro oriented, meso-scale exists	From Meso to Macro	Very Macro or very micro oriented	Very Macro or very micro oriented
Strengths	Tracks interindustry linkages Easy to implement	Accurate, time dynamic forecasts in the short term	Endogenous prices and substitution effects	Endogenous prices and substitution effects, simpler than general equilibrium	Freedom to model agent behaviour and interactions compared to analytical economic models	Freedom to implement any relevant variable and complex interactions
Weaknesses	Prices are fixed, no substitution effects. Tend to overestimate policy impacts	Predictive power tied to data quality and restricted to short term	Implementation cost, high data requirement, black box effect	Limited to one or a few economic sectors, less detailed socio-economic indicators than general equilibrium	Lacks standardization/tractability, black box effect	Lacks standardization/tractability, black box effect

Table I.1 - Main characteristics of regional economic modelling tools

2.3 Towards coupling of economic and environmental assessment tools

Couplings between some of the aforementioned economic and environmental assessment tools have been performed for 20 years in order to provide more exhaustive information to decision makers. Bouman et al. (2000) analysed the case of battery-related pollution using three different methods simultaneously but separately, i.e. PE models, LCA, and MFA, and called for further integration of these methods. Earles and Halog (2011), followed by Rajagopal (2017) and Roos and Ahlgren (2018), reviewed methods using economic models to perform consequential LCA, which refers to an LCA type where indirect effects induced by a change in the studied system are accounted for by expanding its boundaries. Halog and Manik (2011) and Moon (2017) reviewed methods that used agent-based modelling or system dynamics for sustainability assessments and proposed frameworks to compare them. Integrated Assessment Models (IAMs), hybrid macroeconomic models developed in climate change research to model industrial and consumption drivers of greenhouse gas (GHG) emissions in various scenarios, were also coupled with LCA or MFA (Pauliuk *et al.*, 2017; Pehl *et al.*, 2017).

Model coupling ranges from the construction of *ad hoc* indicators (converting an economic output in an environmental impact with a coefficient) to simultaneous use of different tools for the same case study to more formalized coupling of models. We propose a simple classification of coupling between low- and high-level couplings.

Low-level coupling encompasses couplings where economic and environment models are run separately, using different variables. Output(s) from one model is (are) used as input(s) of the other model, either at a single period (comparative) or through an iterative process (recursive). Numeric interfaces can be used to automatize the recursive information transfer. High-level couplings describe models that are linked and run together, involving variables from the economic and environmental models in closed loops, e.g. a model where the behaviour of economic agents is environmentally driven (preferences for environmental considerations in their utility function, production dependent on environmental assets, etc.).

In both low- and high-level couplings, the economic model often drives the entire coupled model. It defines the level of aggregation of the model, the ability to model the interactions and indirect effects in the assessed system – the foreground – or in its related systems – the background – and subsequently, spatial consideration for impact assessment in the foreground. It also sets the time dynamic. Thus, the economic model defines significantly the modelling abilities of the coupled model.

3 Material and methods

We present here the general approach we followed to select the literature to review and perform the qualitative comparison of the couplings of the economic models and the environmental tools presented in the precedent section. We base this comparison on a specific analysis grid including eight key criteria.

3.1 Bibliometric analysis

The bibliometric analysis was focused on papers using couplings of economic and environmental tools, hereafter called Economic-Environment Integrated Model (EEIM). We omitted approaches using econometric forecast models for such couplings, as there were only two relevant papers. The review eventually considers 15 types of EEIM.

We used the Scopus database[3] with a standardized process: in the query, the name - or names - of the economic model type were crossed with one of the environmental assessment methods in the 'abstract – title – keywords' category. The review was limited to articles published after 1990. This first research provides insight into the use of EEIMs in the scientific literature. We provide the number of papers found for each method and a keyword network analysis in the Appendix (see A.3).

We then selected articles within the results of this first search, based on the abstracts, retaining those that showed a particular focus on the integration of economic modelling and environmental assessment tools to model a region, economic sector(s) from the local to global scale, and sets of economic agents. A few articles that were not obtained with the first search but that were often cited were also added. We did not fully restrict the selection to regional applications at this point in order to diversify the examples of EEIM. In this manner, we built a pool of case studies and articles for each of the 15 EEIMs. We provide the full list in the Appendix (see A.4).

3.2 An analysis grid to evaluate integrated assessment methods

We developed an analysis grid to carry out a transparent and argumentative comparison of the EEIMs. We defined criteria that need to be considered when describing and analysing the couplings following the approach proposed by Finnveden and Moberg (2005), Blanc et al. (2009) and Loiseau et al. (2012). According to them, we made a distinction between criteria related to the main characteristics of the EEIMs (i.e. descriptive criteria) and criteria related to the abilities of EEIMs. These latter are used as qualitative criteria to rate the performances of the different types of couplings to fit the purpose of performing an assessment of a meso scale entity, taking account of detailed interdependencies between economic agents, environmental entities, at

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3 *Scopus is currently the best tool available for literature electronic search due to its wider subject and journal range compared to other databases.*

different spatial scales and over time. This general approach allows characterizing the different couplings and understanding their appropriateness for different applications.

3.2.1 Descriptive criteria

The first group of criteria states the main characteristics of the EEIM:

I. The first criterion deals with the objectives addressed by the coupling of models. In other words, **what are the goals and scope of the study**? This qualitative criterion is proposed to identify the object of the study, i.e. a complete geographic space such as a nation or a subnational region or single sector, and the main purpose of the study, e.g. a diagnosis or policy eco-design, explorative scenario analysis, etc.

II. The second criterion analyses the intensity of the coupling between the economic and environmental models, as explained in 2.1.3.

3.2.2 Qualitative criteria

The second group of criteria qualifies the main features of the EEIMs:

III. The third criterion addresses the **ability to model the studied system in a comprehensive and detailed way**. It is decomposed into two dimensions. 1) The number of economic sectors or products under consideration. The model represents either one or a few related sectors or most to all economic sectors. 2) The level of aggregation or disaggregation of the sectors or products. The type of economic model used mainly determines the level of aggregation (using, for instance, the International Standard of Industrial Classification of All Economic Activities (ISIC, 2007)). We distinguish:

a) Aggregated frameworks when categories correspond mostly to the ISIC top level, usually with 10 to 20 or fewer sectors, each with a representative value.

b) Semi disaggregated frameworks, when it corresponds rather to the ISIC secondary level from approximately 30 to approximately 60 sectors/products.

c) Very disaggregated frameworks, with more than 100 industries or products, more detailed than the ISIC secondary level.

Further details are provided in the Appendix (See A.5a).

IV. The fourth criterion evaluates **the ability of the EEIMs to provide a multicriteria assessment**. This ability is essential to identify the distribution of socio-economic or environmental impacts (Finnveden et al., 2009), but also between environmental and economic impacts. This final point is important to identify the win-win solutions for both the environment and the economy (Porter and Linde, 1995). Usually, economic models provide at least output indicators in monetary units (e.g. for a sector or country, such as Gross Domestic Product) or quantities; other economic indicators may be given, such as trade surplus, added value, consumer or producer surplus, tax revenue or policy budgetary costs. At best, socio-economic indicators such as jobs or wages are provided (Loveridge, 2004; Seung and Waters, 2006). Environmental indicators are related to pressures (i.e. pollutant emissions or resource use), and certain methods (e.g. LCA) convert these pressures into impacts on the environment, going further in the DPSIR (Drivers-Pressure-State-Impact-Response) analytical framework proposed by the European Environment Agency (EEA Report, Smeets and Weterings, 1999). The same rationale applies to economic models. The more environmental flows (e.g. fossil and mineral resource use, water, land use, greenhouse gas, pesticides, or particulate emissions, etc.) and economic information (quantities, prices, and socio-economic data) estimated the better.

V. **The fifth criterion analyses the ability of the EEIMs to consider indirect effects.** If we consider that the region or activity under study is the foreground system (see left side of Figure I.1), then, depending on the boundaries of the modelled system, two different types of indirect effect are considered in relation to the foreground system. First, 'indirect effects' can refer to the life cycle perspective and the system under study, which has numerous sectoral and geographical linkages with the rest of the world due to increasing globalization. All these external linkages comprise the background systems (right side of Figure I.1). A change in the foreground system can spread over the background system through trade exchanges. For instance, building a new biomass power plant in the foreground system may import part of its biomass from the background system, thus leading to crowding out of part of the biomass used by other industries or consumers in the background system. These indirect effects are represented in purple plain arrows on Figure I.1 and refer to so-called 'off-site impacts'. Other types of indirect effect are investigated in the literature and correspond to arrows 4 and 8 (see A5b for more information). Second, indirect effects can also encompass all the modifications of product flows due to a change in the economic system after the implementation of a policy or the development of infrastructure. For instance, building a biomass-fed power plant is likely to drive changes in (1) the biomass flows not only for the new plant but also for other industries (through competition or synergies) and (2) in the flows of final products (i.e. power and its substitutes) at the consumer level. These indirect effects at the foreground level are represented with red arrows in Figure I.1 and refer to the so-called 'consequential effects'.

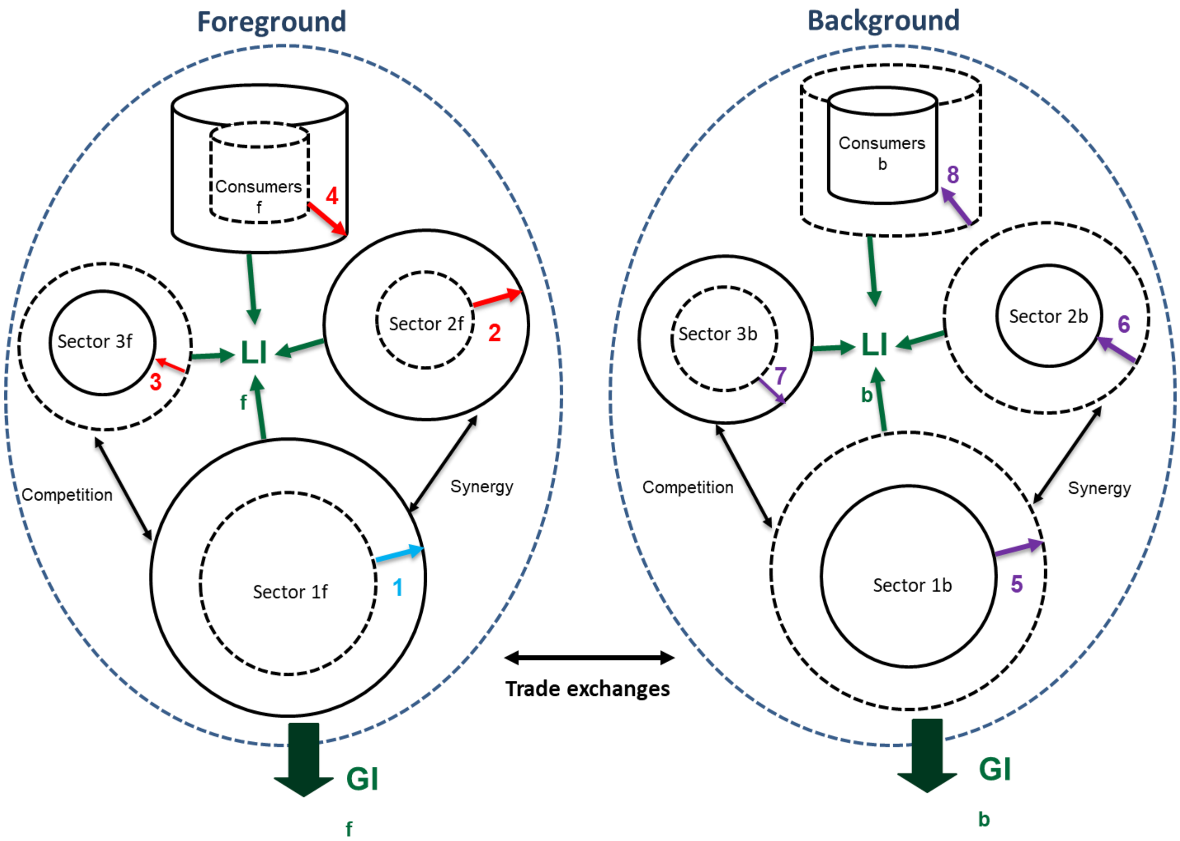

Figure I.1 - Representation of a set of indirect effects in the foreground and background systems

In this example, sector *1f* benefits from a direct change, e.g. a policy, which increases its production capacity (arrow 1). Sector *2f* indirectly benefits from the policy *via* a synergetic relationship (arrow 2) while sector 3f is badly affected through a competition relationship (arrow 3). Consumers *f* also indirectly benefit through price and revenue indirect effects (arrow 4). These three types of indirect effect (2, 3, 4) comprise the *consequential effects* of the policy. These changes induce changes in the local environmental impacts in the foreground Li_f and global impacts Gi_f.
In the background system, all production sectors and consumers are affected through indirect *off-site* effects (arrows 5, 6, 7, 8), which are transmitted through trade channels. These changes induce changes in the local environmental impacts in the background Li_b and global impacts Gi_b.

VI. The sixth criterion is based on the **ability of the EEIMs to consider spatial variability**. The geographical representativeness of the activities or sectors under study increases the robustness of the study and could be used to quantify regionalized impacts (Potting and Hauschild, 2006). Explicit spatial modelling of economic activities in both the foreground and background facilitates the consideration of spatial variability in impact assessment.

VII. The seventh criterion discusses the **ability of the EEIMs to account for the temporal** evolution of the system in the short, medium, and long-term. In economics, short, medium, and long terms are usually defined according to hypotheses on parameter variability such as prices, capital formation, or elasticities, as well as technology maturation or energy efficiency. We distinguish between static, dynamic non-recursive and dynamic recursive frameworks. Dynamic recursive models allow for simulating of a development path, while non-recursive models only simulate two time periods: initial and modified.

VIII. The eighth and final criterion assesses the **ability of the EEIMs to be easily usable**. This rating gathers appreciation of the availability of data as well as the amount of time and technical knowledge required to run the EEIM and to implement the coupling, the level of standardization reached by each model, and/or the tools' abilities to provide results that are understandable by stakeholders.

The EEIMs found in the literature are rated according to criteria (iii) to (viii), in comparison with each other, using a scale ranging from 1 to 4, with 4 being the most satisfying ability and 1 the least satisfying. The rating system is detailed in Table I.2.

Criteria	*Description*	*Rating scale*
Ability to model in a comprehensive and detailed way	Number of economic sectors or products: *One or a few related sectors *Most or all sectors are included. Level of aggregation of the economic sectors or products *Aggregated ('agricultural products') *Semi Aggregated ('cereals') *Disaggregated ('wheat')	**1: one or a few sectors, aggregated products** **2: one or a few sectors, one or a few disaggregated products** **3: either disaggregated products for one or a few sectors or aggregated products for all sectors** **4: disaggregated products for all sectors**
Ability to provide a multicriteria assessment	Each rating comprises a coupling of the economic models and the environmental models' ratings, scaled back from 1 to 4. Economic Indicators: Diversity and/or presence of socio-economic indicators. Economic indicators are additive.	**1 Information on quantities produced/consumed/transformed** **2 Exhaustive economic information (prices and quantities)** **3 Exhaustive economic information and socio-economic impacts**
	Environmental indicators: diversity of environmental flows.	**1 A few environmental flows** **2 Exhaustive environmental flows** **3 Exhaustive environmental impacts**
Ability to model indirect effects: consequential and off-site effects	Consequential effects on the foreground/background *Intersectoral trade and intermediate consumption effects *Market effects and product substitutions, rebound effects *Demand/supply thresholds, learning curves *Social behaviours (adoption…) Off-site effects from economic modelling and environmental tools' background modelling. Environmental background modelling and Economic background modelling	**1: A few consequential effects with limited background interactions** **2: A few consequential effects with some background modelling/Many consequential effects with limited background modelling** **3: Many consequential effects with some background modelling** **4: Many consequential effects, with detailed background interactions**
Ability to model Spatialization	Case studies scale Meso (Local/Subnational); Macro (National/International	**1: Rather macro level, global/unspatialized impacts** **2: Rather macro level, mostly global impacts, some foreground spatialization** **3: Rather local/meso-level, mostly global impacts, some foreground spatialization**
	Spatialization of economic and environmental indicators in the foreground and/or background	**4: Rather local/meso-level, detailed spatialized foreground, some background spatialization**
Ability to account for temporal aspects	Time dynamics	**1 Static** **2: Dynamic non-recursive** **3: Dynamic recursive** **4 : Dynamic recursive with dynamic environmental impacts**
Usability	Data availability Standardization of models and coupling Availability and technicality of models and coupling	**1: Experimental couplings, specific data collection for the case studies** **2: Technical implementation, more or less data to collect** **3: Implementation accessible, consistent databases available** **4: Easy to implement, consistent databases available**

Table I.2 - Criteria description and rating system for qualitative comparison of models.

4 Results and discussion

The results are presented as follows: first, we provide the results of the bibliometric analysis and then analyse the reviewed articles using the criteria grid developed in 3.2. Finally, we draw the main results and findings from the review.

4.1 Quantitative results of the bibliometric analysis

The evolution of the number of articles for each type of EEIM is plotted in Figure I.2

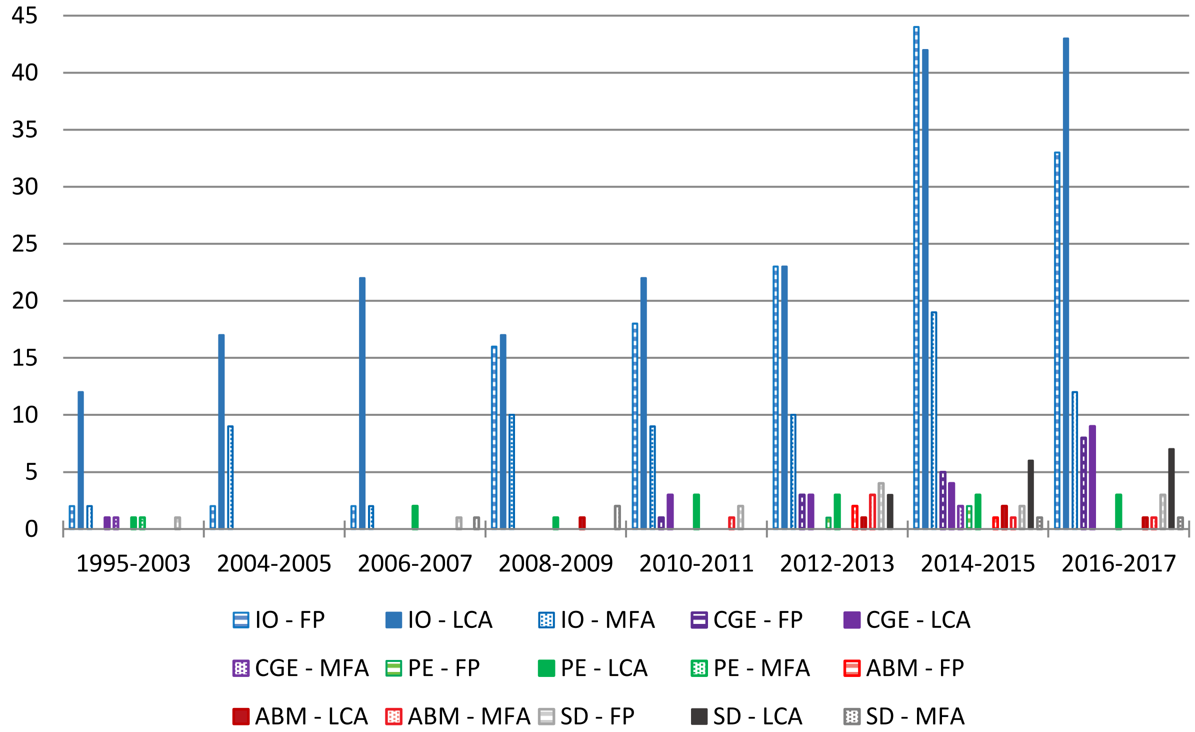

Figure I.2 - Number of articles per EEIM, for the period 1995-2004 and then every 2 years following. IO=Input Output, ABM=Agent-based modelling, SD=System Dynamic, PE=Partial Equilibrium, CGE=Computable General Equilibrium, FP=Footprint, MFA=Material Flow Analysis

Since the 1990s, couplings of economic IO models with various environmental assessment methods have been performed, with the first couplings conducted with LCA. Figure I.2 shows that IO is by far the most used economic modelling type in EEIM. It is also the oldest form of economic and environmental model coupling. The use of CGE models, although limited, is clearly increasing at the end of the period, while the use of PE, ABM, and SD remains stable. This demonstrates a growing interest in more exhaustive approaches. Other types of EEIM are used on a much lower order of magnitude. Besides, EEIMs involving MFA appear to be less frequently used than those using LCA and FP.

4.2 Comparison of the couplings through the proposed analysis grid

We reviewed the pool of selected papers, i.e. 115 out of 536 papers found from the systematic search, using the analysis grid presented in section 2.3 in order to provide comparisons of the different EEIMs. We performed a qualitative scoring of the EEIMs based on the grid. The results are presented and discussed in the eight following sections. The complete ratings are summarized in the following Table I.4 at the end of the section.

4.2.1 Goal and scope of the study

EEIMs based on IO couplings are best suited for diagnosis of geographic entities as a whole, as they generally encompass a large number of sectors at a reasonably disaggregated level (Minx et al., 2009). The best example is the coupling of footprints with Multi Regional Input Output (MRIO), i.e. IO tables gathering several figures at the regional or country scales, which allow the diagnosis to be extended from the foreground to related regions or countries (McGregor et al., 2008; Wiedmann, 2009). In a complementary way, MFA couplings are most often used to perform a detailed diagnosis of a given sector or product family, e.g. metal flows and electronic components at a global or country scale (Dellink and Kandelaars, 2000; Elshkaki *et al.*, 2004; Streicher-Porte *et al.*, 2007; Bollinger *et al.*, 2012; Bonnin *et al.*, 2013; Choi, Cao and Zhao, 2016).

EEIMs are also useful for national eco-design policy assessment, mostly with IO-FP (Allan et al., 2014; Chen et al., 2017) and CGE-FP, and in some cases IO-LCA and CGE-LCA. MFA couplings with ABM or SD are frequently used for recycling/circular economy eco-design. In the same vein, there are several examples of SD-based EEIMs addressing infrastructure or large-scale process efficiency (Bollinger *et al.*, 2012; You *et al.*, 2012; Feng *et al.*, 2017). Finally, PE/CGE/ABM – Footprint/LCA EEIM are shown to be particularly used for scenario analysis related to agriculture, biofuels, and land use (Plevin *et al.*, 2015; Rege *et al.*, 2015; Escobar *et al.*, 2017; Marvuglia *et al.*, 2017). CGE and FP methods are oriented towards geographic entities rather than specific sectors, the opposite of PE and MFA. SD/ABM and LCA are rather process/sectoral oriented but are increasingly used at the subnational scale. The main properties and goals of the various EEIMs are given in Table I.3.

Object of study *Aim*	***Whole geographic entity***	***Product category/Economic sector***
Diagnosis	IO-ALL, CGE-ALL, all-FP	All-MFA, (PE-all, all-LCA)
Policy/Process Eco-design	CGE – FP	SD-all, All-LCA, all-MFA
Scenario analysis	PE-ALL, CGE-ALL, IO-FP, all-LCA	PE/ABM-LCA; IO-MFA, SD-FP

Table I.3 - Preferred EEIM method sorted by questions and object of study

4.2.2 Intensity of model coupling

Most case studies present low-level couplings, i.e. the output of a model is used as inputs or parameters for the other. In most examples of IO/PE/CGE couplings, the economic model provides economic outputs with which an environmental impact assessment is performed. In fewer cases, the environmental modelling framework is used to provide data or parameter constraints for the economic modelling, for instance to model the effects of an environmental policy (Allan et al., 2014; Dellink and Kandelaars, 2000; Lenglet et al., 2017). It is noteworthy that in case studies where the coupling consists of a linear economic model whose output data feed a linear environmental assessment model, higher coupling is useless. This remark applies to IO-FP and IO-LCA, depending on the LCI database structure.

We identified two types of issue where high-level coupling is relevant. 1) When environmental impacts have endogenous effects on the stock of capitals and/or the efficiency of the use of the production factors; examples of high-level coupling are SD-EF where the environmental consequences of strategic decisions within an industry are embedded in the model (Feng et al., 2012; Jin et al., 2009). 2) When economic agents internalize environmental policies in their decision process. Such a feature is considered in Knoeri et al. (2013) and tested by Davis et al. (2009). It would allow us to compare various environmental policy instruments, e.g. regulation, norm, communication, taxes, and labelling.

4.2.3 Model comprehensiveness and detail

Generally, IO models use multiregional tables containing more than 50 industries for all sectors of the economy. CGE models, which are more aggregated, have fewer products, generally between 30 and 50. Most PE applications deal with 5 to 20 products for one or two related sectors such as agriculture (Calzadilla *et al.*, 2013; Vázquez-Rowe *et al.*, 2013; Morgan and Daigneault, 2015), forestry (Eriksson *et al.*, 2012; Earles *et al.*, 2013; Lenglet, Courtonne and Caurla, 2017), or bioenergy (Bernard and Prieur, 2007; Rozakis *et al.*, 2013; Escobar *et al.*, 2017). Although there are theoretically no restrictions on the number of sectors represented, ABM models are found to be used for a single sector, with one or a few products; for instance, switchgrass, dairy products, or wheat (Bichraoui-Draper *et al.*, 2015; Morgan and Daigneault, 2015; Marvuglia *et al.*, 2017). In the same way, SD models are involved in EEIMs applied to a single sector, with agriculture being well represented among SD-FP (El-Gafy, 2014; Inman *et al.*, 2016; Feng *et al.*, 2017) with moderately disaggregated products. SD-LCA and SD-MFA are applied to industrial sectors, and are very detailed in some case studies involving MFA coupling (Elshkaki *et al.*, 2004; Choi, Cao and Zhao, 2016). Indeed, LCA was long restricted to product, process, or at best single economic sectors (You *et al.*, 2012; Pergola *et al.*, 2013; Wood and Hertwich, 2013).

To sum up, IO-ALL models provide the most detailed and comprehensive representations of the economy, followed by CGE-ALL and PE-ALL. ABM-ALL and SD-ALL papers comprise mixes of case studies on specific products or sectors and a few studies of multisectoral systems.

4.2.4 Ability to provide a multicriteria assessment

IO-ALL models provide the output in terms of quantities or value for the economic sector. Yet, economic outputs may be translated into other socio-economic indicators using given exogenous conversion coefficients.

PE and CGE are run with endogenous prices in addition to quantities, which allows us to calculate producer and consumer surpluses. Nevertheless, most PE-ALL models focus on simpler economic indicators, i.e. sector or product outputs in monetary units or quantities (Calzadilla et al., 2013; Escobar et al., 2017; Vázquez-Rowe et al., 2013), with a few providing explicitly more detailed economic assessments (Bernard and Prieur, 2007; Lenglet et al., 2017). Some CGE-ALL models are able to deliver socio-economic indicators as endogenous wages, employment, and tax amounts (Dellink and Kandelaars, 2000; Cong *et al.*, 2017; Cui *et al.*, 2017). SD and ABM models usually process socio-economic variables other than price and quantity (Tesfatsion, 2017) and thus tend to be able to provide more socio-economic indicators derived from these variables. In this vein, Bravo et al. (2013) give another level of information with an ABM model providing the household expenditures associated with given consumption patterns. However, in the reviewed ABM-ALL and SD-ALL case studies, the indicators are basic: cultivated areas in the many ABM-ALL models focus on the agricultural sector or quantities for one or a few given sectors (Knoeri et al., 2013; Elshkaki et al., 2004; Onat et al., 2016; Shrestha et al., 2012).

The possibilities offered by SD are more deeply exploited in some case studies to assess variables such as capital investment and capital vintage (Davidsdottir and Ruth, 2005) or recycling rates (Streicher-Porte et al., 2007).

As far as environmental performance is concerned, LCA was explicitly developed to perform multicriteria environmental impact assessment and usually provides the highest number of impact categories compared to other environmental assessment methods. All-MFA coupling provides one (or more) indicator, mostly quantities for the materials whose flows are tracked, expressed in the same unit (Kytzia et al., 2004; Matsubae-Yokoyama et al., 2009; Risku-Norja and Mäenpää, 2007).

For all-FP couplings, only one aggregated indicator is provided, ranging from emissions, as carbon footprint inventories (Druckman and Jackson, 2009; McGregor et al., 2008; Minx et al., 2009), to sectoral resource consumption, as water footprint and land-based ecological footprint tables (Feng et al., 2012; Wang et al., 2013; Yu et al., 2010; Zhang and Anadon, 2014). In some cases, several footprints are considered simultaneously to provide more than one footprint indicator. For instance, some EF couplings connect the monetary outputs with a diversified set of impact categories on both CO_2 emissions and resource consumption (Turner et al., 2007; Wiedmann et al., 2007) or carbon and water footprint in order to diversify impacts measurements (Ewing et al., 2012; Galli et al., 2013; Steen-Olsen et al., 2012).

To recap, the rating for this criterion being the combination of the economic model's rating and the environmental tool's rating, CGE-LCA ranks best, followed by CGE-FP/MFA and PE/ABM/SD-LCA. IO-FP/LCA and the couplings of PE, ABM, and SD with FP and MFA mix diverse economic indicators with a few environmental flows. IO-MFA examples provide the least indicators.

4.2.5 Ability to consider diverse indirect effects: consequential and off-site effects

We identified two aspects in terms of the ability to model indirect effects: first, the diversity of indirect effects represented and, second, the possibility of assigning these indirect effects between the foreground and the background. IO-ALL models track the linear relationships between the economic sector, in terms of production or consumption. This comprises a simple type of consequential effect, associated with exhaustive background modelling that allows detailed off-site impact calculation. These effects are as detailed as the IO model, ranging from MRIO models that represent the global economy with more or less aggregated sectors and countries, to subnational scale interregional models which provide a decomposed view of a national economy (Cicas *et al.*, 2007; Yi *et al.*, 2007; Cazcarro *et al.*, 2015).

PE/CGE-FP/LCA offer improved ability to deal with consequential effects. Providing endogenous prices with production and consumption functions including price elasticities, equilibrium models adjust more smoothly to changes in supply or demand. In particular, they offer more sophistication in tracing factor market adjustments and resulting price and income induced effects (Turner et al., 2012). PE/CGE-MFA offer similar economic interaction possibilities in the foreground and in the economic background but fewer details on background flows, which limits off-site effect accounting.

ABM-FP/LCA models are used to test various behaviour effects such as new agricultural practices adoption (Bakam, Balana and Matthews, 2012; Bichraoui-Draper *et al.*, 2015; Morgan and Daigneault, 2015; Marvuglia *et al.*, 2017) or consumer behaviour (Bravo *et al.*, 2013). Thus, these models, built on agent behaviour more sophisticated than profit or utility maximization as in the equilibrium model, provide consequential effects that are particularly relevant at a local scale. In return, they usually lack endogenous prices. This may be compensated for by coupling the ABM-ALL framework with an additional economic mechanism for price information, such as a PE or CGE model (Morgan and Daigneault, 2015).

SD-FP/LCA are used to build ad hoc models with detailed interactions chains for a sector or territories at the local or meso-scale (Shrestha *et al.*, 2012; Inman *et al.*, 2016). Compared to PE/CGE, they emphasize material constraints over price and value mechanisms (Onat, Kucukvar and Tatari, 2016) and may lack consequential effects between the foreground and a macro level background, due to the lack of intersectoral details.

In the same way, ABM/SD-MFA makes it possible to model detailed systems with complex consequential effects, with more features for intrasectoral interactions along the value chain, but may lack intersectoral interactions.

To summarize, CGE-LCA provides the best combination of consequential and off-site effects. CGE/FP-MFA, PE-LCA, and ABM/SD-LCA/MFA case studies combine several consequential effects with some background modelling for off-site effects, and are thus rated 3 out of 4. EEIMs rated 2 out of 4 are implemented either with many consequential effects and limited off-site effects – such as PE-FP/MFA or ABM/SD-FP - or limited consequential effects and detailed off-site effects – such as IO-FP/LCA. IO-MFA couplings have few indirect effects on both aspects.

4.2.6 Spatial resolution

We rate spatial resolution according to the resolution of the economic and environmental impacts, in the foreground and background. Most EEIMs are applied at the national/global scale. Studies at the meso/local scale account for approximately one-fifth of the sample set, with a few including detailed spatial mapping or spatial differentiation.

Most IO-ALL models have a national level foreground resolution, with national and supranational background resolution – 'Rest of the world' regions in IO tables. IO-FP/LCA models reach meso level resolution for foreground and background (Cicas *et al.*, 2007; Yi *et al.*, 2007; Chen, Hadjikakou and Wiedmann, 2017). At best, some IO-FP models such as Cazcarro et al. (2015) or Cong et al. (2017) couple local level data with GIS data to build impact maps with a local level resolution for the foreground.

In the same way, many PE/CGE-FP/LCAs are built at a macro scale, and impacts are thus determined for countries or macroregions (Sanchez *et al.*, 2012; Calzadilla *et al.*, 2013). PE/CGE-FP couplings - particularly Water Footprint and Ecological Footprint - offer the most detailed regionalisation and reach local and meso levels in terms of foreground and background resolution (Connor *et al.*, 2015; Cazcarro, Duarte and Sánchez Chóliz, 2016), as well as with SD-FP (Feng *et al.*, 2017; Lu and Chen, 2017). Detailed spatial resolution for background activities is useless when the environmental impacts investigated are global, as is the case for studies that focus on GHG emissions (Earles *et al.*, 2013; Escobar *et al.*, 2017). ABM-FP models are implemented with detailed spatial resolution (Morgan and Daigneault, 2015) as well as basic data, e.g. unspatialised and restricted to a single sector of activity (Bakam, Balana and Matthews, 2012). ABM-LCA and SD-MFA are mostly conducted at a national scale. The least spatially accurate couplings in our sample are CGE-MFA, SD-LCA, and ABM-MFA. Indeed, all-MFAs are often used to assess a specific sector or product supply chain on a global scale, which may remove the need for spatial representativeness.

To recap, the most spatially accurate case studies are conducted in all-FP couplings. PE-FP couplings display the highest proportions of studies with subnational scale resolution of impacts. IO/CGE/ABM-MFA as well as SD-LCA couplings have not been used below the national scale, with low background resolution. Thus, these couplings have the lowest rating. IO/CGE/ABM-LCA and PE/SD-MFA have been used for a few works with meso scale resolution of impacts and are thus rated just above.

4.2.7 Time dynamic and temporal horizons

A feature of IO-ALL models is the use of static accounting methods, e.g. IO-FP couplings (among others (Ala-Mantila, Heinonen and Junnila, 2014; Salvo *et al.*, 2015; Chen *et al.*, 2017). Dynamic non-recursive case studies comprise either IO-ALL models as in Choi et al. (2010) and Risku-Norja and Mäenpää (2007) or equilibrium models, e.g. CGE-MFA (Dellink and Kandelaars, 2000). That said, most of the reviewed case studies comprise dynamic recursive models.

Regarding temporal horizons, technology changes are a key issue for both economic modelling and environmental impact assessment. IO models are considered reliable only on short-term horizons; nevertheless, IO-LCAs have been used to study the long-term effects of technology changes in the energy sector (Finnveden et al., 2009; Gibon et al., 2015; Hertwich et al., 2015). PE and CGE models can be adapted for various time horizons depending on hypotheses of capital formation, technology changes, savings, or investments (Partridge and Rickman, 2010; Marvuglia *et al.*, 2013). In our sample, these range from medium/short term (Cazcarro *et al.*, 2015; Escobar *et al.*, 2017) to medium/long term (Plevin et al., 2015, Eriksson et al., 2012) to very long term modelling (Calzadilla *et al.*, 2013; Earles *et al.*, 2013). ABM-LCA has been used to take into account supply chain evolutions (Davis, Nikolíc and Dijkema, 2009) or emerging technology adoptions and impacts (Miller *et al.*, 2013). SD models may directly address the issue of parameter temporality, by implementing time dependant variables in the model, allowing more reliable projections to be built. This is particularly performed in SD-MFA coupling (Bollinger et al. (2012) Davidsdottir and Ruth (2005)) to include capital vintage and investment in a system dynamics model of the wood industry.

To summarize, IO-FP/MFA couplings have the lowest abilities for time consistent modelling. IO-LCA case studies comprise a mix of static and dynamic non-recursive. SD-MFA case studies have the best features with which to deal with long-term effects in addition to having a recursive dynamic. All other EEIMs are rated 3 out of 4, being used for various temporal horizons with a mostly dynamic recursive time dynamic.

4.2.8 Usability

All the EEIMs require significant amounts of data but, for some, the databases are more available or detailed. Data availability at the regional scale is a constant challenge compared to the national scale. Developing regional datasets requires specific methods and is time-consuming (Irwin et al., 2010; Ruault, 2014; Turner et al., 2007). At the national scale, IO-ALL models require less effort on that specific point while others such as IO tables are widely available (Miller and Blair, 2009; Minx et al., 2009; Wiedmann, 2009). Moreover, IO-FP/LCA may be synergic as IO tables provide a part of the inventory. This advantage does not apply to IO-MFA, as connections between IO tables' values and material flows data are not straightforward, with the exception of resource flows.

CGE models require much more time, econometric modelling skills, and important amounts of data, particularly for regional studies (Allan et al., 2017). PE/CGE – FP/LCA as well as PE/CGE-MFA couplings require additional efforts to fit the product categories of PE/CGE with FP/LCA inventories, but linking models is not too difficult. Coupling with LCA is more time consuming with the Process-LCA approach compared to the Economic Input Output-LCA approach (EIO-LCA)[4], although there are available databases such as Ecoinvent (Wernet, G. *et al.*, 2016).

ABMs require specific data on agent behaviour for consistent programming of the interaction rules ((Richiardi, 2003; Borshchev and Filippov, 2004; Tesfatsion, 2017). If the ABM model's outputs are simple – quantities, values – , coupling ABM with FP/LCA is straightforward,

[4] Process LCA is the original approach of itemizing exhaustively inputs and outputs in a production process, with the limit of having to define the limits of the system's boundaries at some point. EIO-LCA relies on monetary inter-industry relationships described in EIO tables to catch indirect inputs and outputs.

as it is in most ABM-FP/LCA case studies. In Bravo et al. (2013) where consumption patterns are used or in Davis et al. (2009) where the ABM model's outputs are integrated in the LCA database's technology matrix, additional adaptations or design efforts are required. ABM usability is degraded in explorative approaches as the latter consist in performing thousands of simulations when varying all agent parameters, which may be computationally intensive and time consuming (Bollinger et al., 2012). ABM-MFA studies are theoretical (Fernandez-Mena et al., 2016; Knoeri et al., 2013), and are thus rated less usable than ABM-FP/LCA couplings.

SD economic models are far less widespread than other models among economists and are thus less accessible (Radzicki, 2009). Specific design is required in all cases and the data requirements depend on the project size. SD-FP and SD-MFA EEIMs are often built ad hoc for a given micro system (Inman et al. (2016) or El-Gafy (2014) for SD-FP or Choi et al. (2016) and Elshkaki et al. (2004) for SD-MFA), or based on existing economic formalizations (Wei, Zeng and Wu, 2013; Feng *et al.*, 2017).

MFA does not benefit as much from existing databases and frameworks and always requires specific work of data collection, a burden that can vary greatly depending on the scope of the studied system.

To sum up, IO-ALL models are the most accessible, followed by PE-ALL models, because of data availability and manageable technicality. CGE-ALL, ABM-FP/LCA, and SD-FP are rated with an average-low usability, due to various balances of important data collection needs on the one hand and lesser spread and knowledge of the tools on the other hand. ABM-MFA and SD-LCA/MFA are considered the most experimental couplings.

4.3 Main findings and perspectives

The results of the analysis of the EEIMs with regard to the six criteria are summarized in Table I.4. It should be noted that the couplings developed in the literature reviewed do not always fully represent all the possibilities theoretically offered. For instance, most CGE-all models do not use all the socio-economic indicators that this type of economic model is able to generate. Table I.4 shows that some couplings score better than others. For instance, CGE-LCA has better overall scores than ABM-FP. Nevertheless, the differences are not huge and adding together these qualitative grades to calculate an overall grade and thus to rank each coupling would not be relevant. That said, some criteria such as usability or disaggregation are more discriminant than others. Thus, a modeller with specific focus on given criteria can choose a coupling more clearly over others. For instance, if usability is not considered as an issue, CGE-FP/LCA appears as the most promising coupling.

	IO			CGE			PE			ABM			SD		
	IO - FP	IO - LCA	IO - MFA	CGE - FP	CGE - LCA	CGE – MFA	PE - FP	PE - LCA	PE - MFA	ABM - FP	ABM - LCA	ABM - MFA	SD - FP	SD - LCA	SD - MFA
Disaggregation	4	4	3	3	3	2	3	3	3	1	1	2	2	1	2
Multicriteria analysis	2	2	1	3	4	3	2	3	2	2	3	2	2	3	2
Off-site and consequential effects	2	2	1	3	4	3	2	3	2	2	3	3	2	3	3
Scale and spatialisation	3	2	1	3	2	1	4	3	2	3	2	1	3	1	2
Temporality	1	2	1	3	3	2	3	3	3	3	3	3	3	3	4
Usability	4	4	4	2	2	2	3	3	3	2	2	1	2	1	1

Table I.4 - Qualitative comparisons of EEIM based on selected criteria and qualitative rating. 1 (light grey) denotes the lowest ability to satisfy the criteria, 4 (dark grey) the highest

All in all, PE/CGE-FP/LCA emerge as the most promising couplings according to their ratings. The first difference between these couplings is the scale criterion for PE/CGE-LCA, for which there are fewer examples of meso-scale studies with detailed resolution than for PE/CGE-FP. CGE-FP/LCA models provide more indicators than PE-FP/LCA. The higher level of disaggregation of PE-FP/LCA models balances CGE-FP/LCA's comprehensive representation of economic sectors. Regarding other couplings, IO-FP/LCA rank better in disaggregation and usability, and some SD-MFA couplings deal better with temporality. ABM-ALL models allow us to integrate different indirect effects.

Some couplings show complementary features. In this vein, Morgan and Daigneault (2015) propose an ABM-PE-FP model where the PE model provides endogenous prices and ABM farmer behaviour, dealing with multiple consequential effects with a high spatial resolution. Hawkins et al. (2007) merge IO, LCA, and MFA in order to obtain more detailed and diverse indicators. Bollinger et al. (2012) propose coupling SD and ABM within an MFA, the first to model systemic macro effects and the second to model economic agents' decisions. Coupling some of the methods, such as ABM and PE/CGE – FP/LCA, appears as an interesting modelling perspective: such multiple couplings may accrue advantages from several types of model and compensate some shortcomings. Other attempts to couple several methods (multiple couplings) may be beneficial. SD-MFA methods that introduce non-marginal, threshold, or long-term effects (Bollinger et al., 2012; Davidsdottir and Ruth, 2005) show potential complementarity with PE/CGE models as they generate consequential effects that are usually not dealt with by the equilibrium models. Other effects, which can be particularly relevant at the meso scale, are heterogeneous social behaviours implemented with ABM (Bravo *et al.*, 2013; Bichraoui-Draper *et al.*, 2015). Coupling any model with ABM may also help to address shortcomings on subnational scale data availability, as in Bollinger et al. (2012) or Marvuglia et al. (2017), where randomized behaviour parameters are used.

Building high couplings including feedback loops allowed us to include additional indirect long-term effects, i.e. effects of environmental quality on economic productivity or internalization of environmental policies by economic agents – although this adds an additional layer of complexity.

The shortcoming to these multiple couplings and high-level coupling possibilities is that they induce a risk of building heavy, ad hoc, undecipherable models.

Among PE/CGE-FP/LCA couplings, the choice between PE and CGE depends on the need for comprehensive socio-economic indicators and the scope of the study. CGE-FP/LCA provide a more exhaustive framework when PE-FP/LCA are suitable for sector-specific issues. PE/CGE-FP appear as a better option than PE/CGE-LCA, as detailed local level spatial resolutions have been more consistently implemented using this first type of coupling. Yet, LCA has a twofold advantage, i.e. it complies with exhaustive environmental issues and it is possible to simplify an LCA into an FP while the opposite is not possible. Overall, PE/CGE-LCA emerges as the most promising framework to perform multicriteria assessment at the meso scale and we recommend testing associations of this framework with other tools and models to improve its performance and add modelling abilities.

5 Conclusion

This paper aimed at clarifying the options for modelling and quantifying the environmental and economic impacts of projects and development scenarios at the meso-scale, in order to support public and private stakeholders' decision-making. We analysed through a systematic review the 15 possible couplings out of 5 types of economic modelling method and 3 environmental assessment tools, i.e. IO, PE, CGE, ABM, and SD models and FP, LCA, and MFA. For this purpose, we proposed a list of eight criteria reflecting the ability of these couplings to meet these modelling objectives. The criteria describe the ability to provide multi-criterion assessment of a multisector socio-economic system, in interaction with other socio-economic systems and the environment in its background, compliant with life-cycle thinking, and including spatial variability and a time dynamic. For most of the 15 EEIMs types, at least one or a few meso scale case studies existed. IO-FP/LCA/MFA couplings are the most used and PE/CGE-FP/LCA couplings are also quite frequent while PE/CGE-MFA, SD-ALL, and ABM-ALL are less represented. Data availability appears to be the major obstacle to developing frameworks at subnational scales. More generally, EEIMs at all scales require multidisciplinary work and technical skills to build model interfaces and one inherent risk of model coupling is to increase complexity, leading to a black box effect and a loss of replicability.

Our findings are threefold. First, the proposed methodology showed that the EEIMs do not get the same scores on the same criteria. They have different strengths and weaknesses, and may be best suited to dealing with different policy questions. Considering the intensity of coupling criteria, almost all paper reviewed used low-level coupling, indicating that it was sufficient for most studies. That said, high-level couplings are needed: to explore the long-term development path, where feedback loops between the environment and the economic system can have significant effect. It is especially true for models consistent with strong sustainability objectives, for which hard constraints on environmental states are more likely to induce major retroactions on the repartition of economic activities than substitutions defined in a weak sustainability framework by environment value and efficiency of production factors. Second, we identified that PE/CGE models coupled with FP/LCA ranked best considering most criteria. These findings urge to develop further regionalized versions of PE/CGE models and an LCA database, paying particular attention to the validation of these macro-oriented methods when transposed at the *meso* scale.

Nevertheless, none of the couplings fully answered all the aforementioned expectations for an exhaustive meso-scale assessment model. Other couplings have strengths such as innovative ways to deal with complex non-marginal changes and indirect effects, such as ABM-LCA/MFA or SD-MFA.

Third, a few case studies showed that couplings involving a third tool can be beneficial — for instance AB modelling or MFA with PE/CGE-LCA/FP allows overcoming some shortcomings – respectively regarding agent behaviour modelling or data availability on biophysical flows. This finding suggests testing the associations of PE/CGE-LCA/FP couplings with other tools and models to improve its performance and add modelling abilities, and eventually, developing a regional EEIM able to address all criteria with the best rating.

Our methodology shows some limits. First, the set of criteria analysed is limited and we restricted our analysis to those that we considered as important regarding the design of meso scales policies. Second, the rating is based on the existing literature, which is recent, and do not always reflect the full abilities of the couplings used. Some couplings could improve in the future, making the ratings and the mutual rankings dynamic.

Third, the case studies reviewed do not always apply to the same questions, limiting the comparison of their results. One way to overcome this issue would be to use the different methods to answer a same question, as done in Bouman et al. (2000).

Eventually, our review was focused on models and tools that can be used to quantify impacts on environmental and economic dimensions. The resulting indicators can be used to go further in the assessment by using optimisation tools such as Data Envelopment Analysis (DEA) or decision-making approaches such as Multi Criteria Analysis (MCA). These complementary approaches will strengthen the benefits of EEIMs in a decision-making context. Ultimately, all these tools and methods add food for thought to develop the economic and environmental dimensions of the Life Cycle Sustainability Assessment (LCSA) framework (Guinée and Heijungs, 2011). This paves the way for future research.

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II

Combining partial equilibrium modelling and Life Cycle Assessment to compute regional eco-efficiency metrics: application to a wood energy incentive in a French region

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Abstract

We present a modelling framework to compute eco-efficiency indicators at meso-scale with an application to the wood energy sector. In this perspective, we couple a bioeconomic model of the forest sector with Life Cycle Assessment (LCA) and account for spatial and economic interactions with other sectors, such as competition between wood energy and non-wood energy substitutes. Several adaptations were required to ensure consistency between the original economic model and LCA, in terms of material balance, yields or allocations. We applied the framework to a case study of the fuelwood sector in the French Grand Est region, and compared the eco-efficiency of this sector when a subsidy is implemented to that of a business-as-usual baseline scenario. We defined two eco-efficiency indicators: Partial Eco-Efficiency (PEE) which does not include avoided impacts from energy substitution, and Full Eco-Efficiency (FEE), which includes them. We show that the subsidy provides clear benefits and increases both PEE and FEE. However, most benefits come from the avoided impacts, with FEE far exceeding PEE. Using FEE despite an increased consumption of wood products, the scenario with the subsidy is 10% to 50% more eco-efficient than the baseline, due to economic gains and avoided impacts.

Keywords

Model coupling, Multi-sector interactions, Multi-scale assessment, Environmental impacts, Socio-economic services, Temporal dynamics

1 Introduction

Diverse strategies and initiatives support the transition towards sustainability through meso-scale policies - from local communities to subnational regions. In European countries, local and regional initiatives are promoted by international agreements such as the local Agenda 21 (Barrutia *et al.*, 2015), or by European authorities for green and circular economy strategies (Pitkänen *et al.*, 2016; European Commission, 2018). These local development strategies are based on win-win assumptions, i.e. aiming at both environmental and economic benefits (Loiseau *et al.*, 2016). In terms of policy analysis, this underlines the need for assessment at an intermediate meso scale, in between micro and macro analysis.

To provide an exhaustive assessment of both the environmental and economic impacts of programmes and policies, quantitative tools, adapted for the specificities of the meso-scale, are required. Economic modelling tools are used regularly for subnational applications and are well described (Partridge and Rickman, 1998, 2010; Loveridge, 2004; Lemelin, 2008; Irwin *et al.*, 2010; Ruault, 2014). Additionally, several tools can be used to assess the environmental impacts of programmes at the subnational scale (Loiseau *et al.*, 2012). In particular, adaptations of the Life Cycle Assessment (LCA) framework make it possible to assess the environmental performances of a territory as a whole including all types of human activities (Loiseau *et al.*, 2013). Coupling economic models and environmental assessment models may combine the best of both fields (Beaussier *et al.*, 2019) through *soft* coupling, meaning that economic model outputs are used as inputs to feed an environmental assessment model in a consequential perspective (Igos *et al.*, 2015). In various sectors such as agriculture, forestry, or bioenergy (Earles *et al.*, 2013; Igos *et al.*, 2014; Albers *et al.*, 2019), a significant part of these coupled models only provides separate economic and environmental indicators, although indicators combining both, such as eco-efficiency indicators, are more informative. Eco-efficiency, as defined by the World Business Council for Sustainable Development (WBCSD), is a ratio of two types of indicators, i.e. i) a value related to the production of goods or services and ii) an indicator of environmental impacts (Stigson *et al.*, 2006). It may be applied at the micro (i.e. companies) or the macro level (national) (Basset-Mens, Ledgard and Boyes, 2009; Egilmez, Kucukvar and Tatari, 2013) as well as at the intermediate meso scale, where it has been used as a tool for supporting regional policy (Seppälä *et al.*, 2005) and land planning (Loiseau *et al.*, 2014). However, none of these studies addresses in detail the specific issues raised by multiple temporal and spatial scales and by sectoral interactions (Loiseau *et al.*, 2018).

Our aim here is to develop a consistent methodological framework combining economic modelling and LCA to compute regional eco-efficiency metrics. This framework will account for economic interactions between regions and sectors in order to consider a wide range of indirect effects (Beaussier *et al.*, 2019). We chose to explore the wood energy sector precisely because it interacts with many other sectors (other energies, other wood products, e.g. paper industry, but also forest ecosystem services such as recreation, etc.). These interactions take the form of trade in wood products from one region to another as well as economic interactions with other sectors, such as competition between wood energy and non-wood energy substitutes. We build our framework from a partial equilibrium bioeconomic model of the forest sector, the French Forest Sector Model (FFSM) (Lecocq *et al.*, 2011; Lobianco, Delacote, *et al.*, 2016), and we combine it with LCA with a specific focus on the wood energy subsector. We place particular emphasis on modelling consistency between the two approaches and make proposals to ensure mass balance. The methodology in its entirety is described in section 2, as along with the case study used as a proof of concept. Section 3 then provides the results of the study on the assessment of the environmental and economic performances of a wood energy incentive in the French Grand Est region using eco-efficiency ratios. Section 4 provides a detailed discussion of the issues involved in such approaches, in terms of both the implications for decision support and consistent modelling. Finally, section 5 draws conclusions and brings perspectives for future research.

2 Material and Methods

The overall approach is based on the combination of an economic model, i.e. FFSM, and LCA via a soft coupling. This modelling framework provides economic indicators and environmental indicators as shown in Figure II.1. These two types of indicators are then used to compute eco-efficiency ratios as defined in territorial LCA approaches (Loiseau *et al.*, 2018) to compare the performances of different planning options at a regional level.

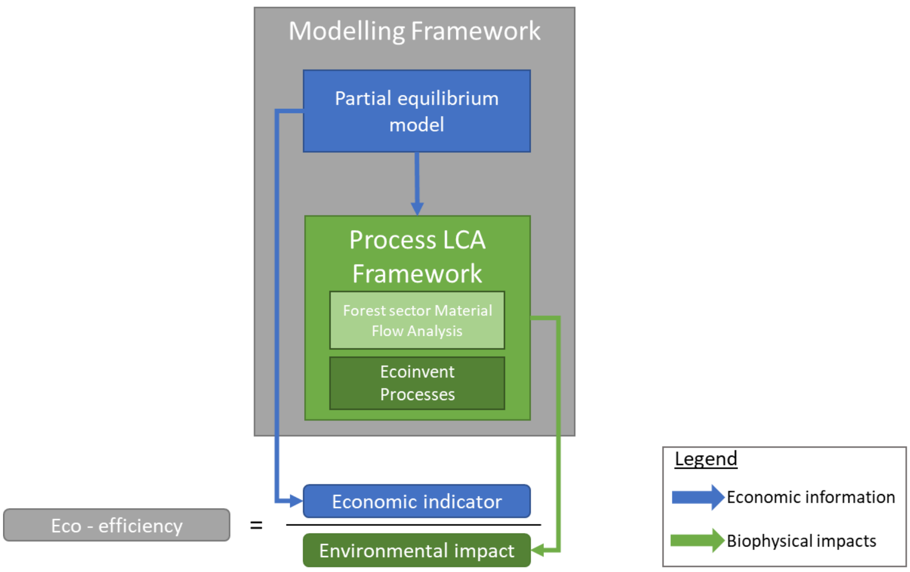

Figure II.1- An overview of the soft-coupling procedure performed to produce eco-efficiency ratios.

In the rest of this section, we describe the different stages of the framework adapting the standard LCA steps, i.e. i) goal and scope, ii) scenario modelling, iii) data inventory and iv) indicators computed.

2.1. Goal and scope

2.1.1 The forest sector in eastern France

Forests and woodland in France have strong potential for the development of bioeconomy strategies as a lever both to transition towards a decarbonized economy and to develop economic activities in rural areas. The forest sector in our case study region, the Grand Est, is both a significant part of the French forest sector and a meaningful activity in the region's economy (Figure II.2). It represents 12% of French forest sector jobs and 18% of revenues, as well as 12% of the French forest area (Ministère de l'Agriculture et de l'Alimentation, 2016; Institut National de la Statistique et des Etudes Economiques, 2019).

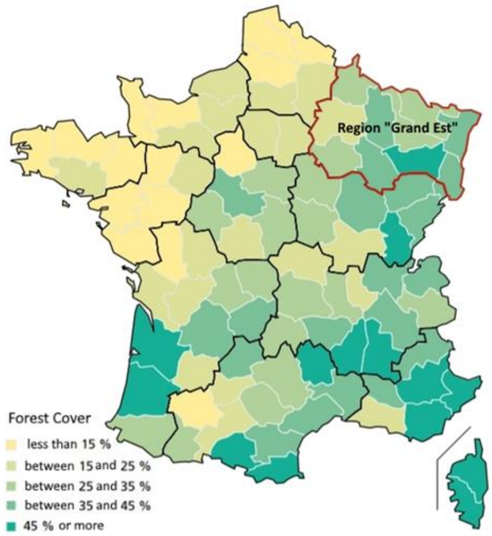

Figure II.2- Regions and forest cover by Department in France (French National Institute of Geographic and Forest Information (IGN))

The forest-based sector covers a wide range of activities, from forest management and harvesting, to various processing industries such as sawing, paper production, construction materials or furniture production downstream (

Figure II.3).

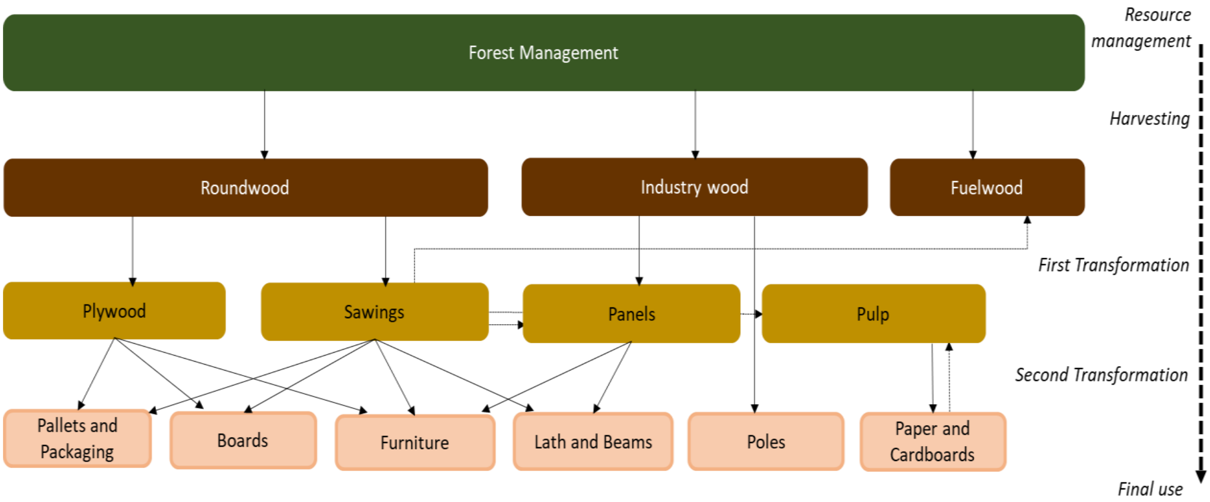

Figure II.3- Structure of the forest and wood industries sector

As a proof of concept, we will illustrate the framework developed by assessing eco-efficiency when a subsidy is implemented to increase final demand for fuelwood among domestic households, local authorities or industrial facilities. We chose this type of demand side incentive as it is the main driver used by policies promoting wood biomass use in France. National guidelines place particular emphasis on the development of local biomass markets and regional energy wood supply chains, setting regional biomass production targets (Ministère de la Transition Ecologique et Solidaire, 2020). Economic incentives for wood energy demand mostly consist in tax expenditures towards individual households equipment (fuelwood tax expenditures have stood at €130 M per year since 2006) and in subsidies from the government budget towards heating networks for communities and industries (€6 M per year towards wood biomass units since 2006). Two scenarios will be compared: i) a baseline scenario where no policy incentive is implemented and ii) a scenario where a subsidy accounting for 50% of the fuelwood price is applied to increase fuelwood consumption, starting in 2020 and ending in 2050.

2.1.2 System boundaries

System boundaries are set from cradle to gate, i.e. all upstream processes (energy supply, machine tools, chemical production, etc.) related to the forest-based sector, and its main outputs are considered, i.e. forest management, harvesting, and the first transformation. The downstream supply chain (second transformation) is not included so as to maintain consistency between economic and environmental modelling.

In terms of environmental accounting, as soon as a wood product is exported from the region to the rest-of-the-world, the associated downstream processes (e.g. wood sawn abroad) are not considered, according to the principle of territorial responsibility (Eder and Narodoslawsky, 1999). The only exceptions are downstream processes that are located in other French regions. In such cases, the impacts of these processes are allocated to the region which is the most downstream in the supply chain, to avoid double counting at the aggregated scale (Lenzen, 2008).

To perform an exhaustive assessment, both consequential and off-site effects must be considered (Beaussier *et al.*, 2019). Consequently, the system boundaries should also include different types of interactions between economic sectors at different geographic and temporal scales (see Figure II.4).

First, the whole forest-wood sector in the case-study region is considered. Intra-sectoral interactions, i.e. flow exchanges between wood products due to competition or synergy effects, are also taken into account in the approach and are represented by the circular arrows noted 1 in Figure II.4.

Second, flow exchanges with wood sectors of other French regions are included in the study, e.g. a decision taken in a given region can affect the supply and demand for wood products in other regions. These are inter-regional interactions and are represented by the curved arrows noted 2 in Figure II.4.

Third, flow exchanges between a given regional forest-wood sector and the worldwide energy sector are taken into account, as the studied economic measure concerns subsidies for fuelwood. These flows represented by arrows noted 3 stand for both the effects of competition induced by the worldwide energy sector on the regional forest-wood sector and the energy flows imported by the regional forest-wood sector for its operations. As energy is a global market, fuelwood prices and quantities exchanged in French regions are partly driven by international energy prices. To be comprehensive, the model should account for avoided impacts induced by the increase in fuelwood consumption compared with the baseline scenario, assuming that additional fuelwood consumption replaces fossil fuel consumption.

Other exchanges between the studied regions and the rest-of-the-world economy are represented by the arrows noted 4 (wood products and all other types of material inputs) and stand for the life cycle perspective.

Finally, all these interactions must be studied dynamically, and an annual time step has been chosen to take into account this temporal dynamic. The time horizon was set at 2050, as this period is long enough to observe the consequences of dynamic interactions between sectors related to forest products.

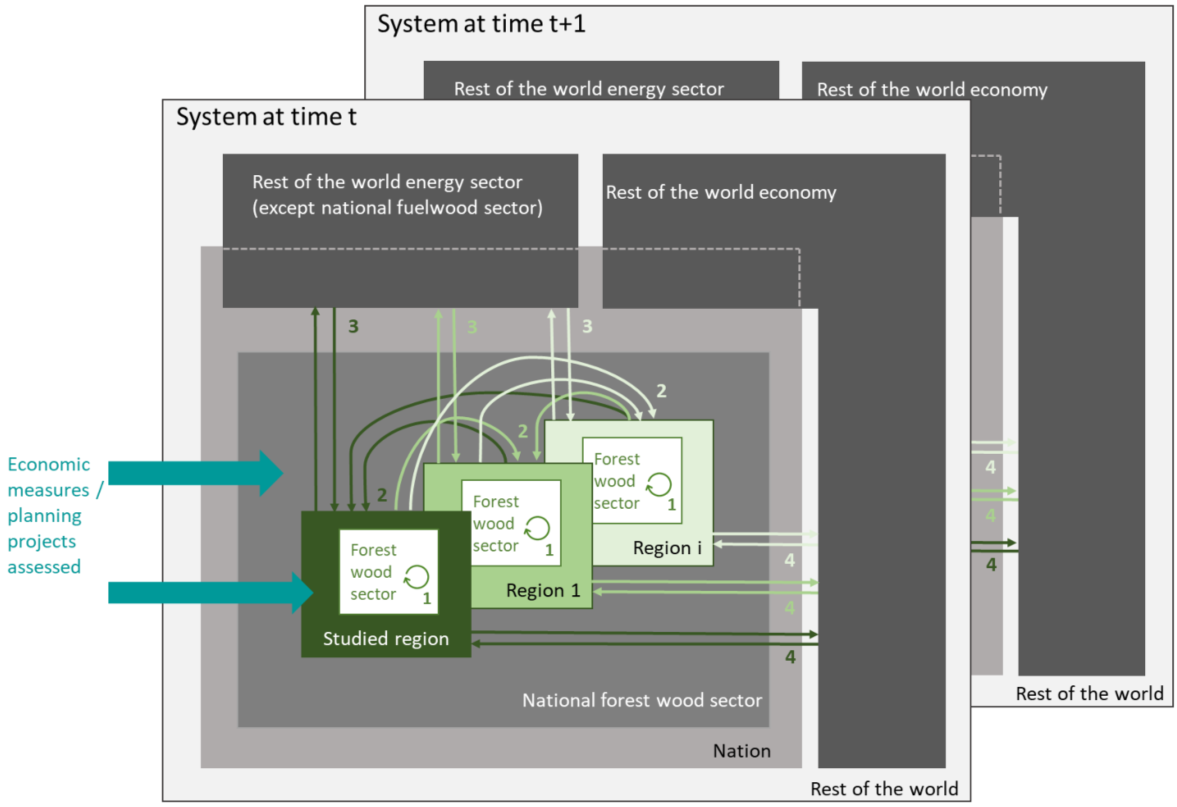

Figure II.4 - System boundaries, flows, interactions, and temporal dynamic in the coupled modelling framework.
Arrows indicate flows between regions and are marked in the colour of the region where the impacts are accounted for.

2.2 Scenario modelling based on the French Forest Sector Model (FFSM)

FFSM is the only model representing the French forest sector in both its biophysical resource and its economic dimensions. The economic module is built on a partial equilibrium model and recursively projects economic variables on a yearly basis. The partial equilibrium model carries out analyses at a disaggregated level but implies that indicators are calculated without interactions and feedback with other sectors of the economy. We dealt with this issue by extending the capacities of FFSM, as explained in Section 2.2.2 below. Another shortcoming with partial equilibrium models compared to a general equilibrium framework is the absence of constraints related to the factors of production and their movement across sectors (labour, capital, land). This hypothesis is acceptable in the forest sector for a time horizon of 30 years, as capital movement is slow and land use change is strictly controlled.

2.2.1 FFSM principles

FFSM (Lecocq *et al.*, 2011) endogenously computes, on a yearly basis, and for each of the 22 French regions, the quantities produced, consumed and exchanged as well as the prices of 9 groups of wood products (see B.1 in the Appendix): softwood and hardwood roundwood, raw industry wood, softwood and hardwood sawings, plywood, fuelwood, panels, paper pulp. Three types of relationships make these products dependent on each other. First, some products are derived from each other through a transformation process that is represented by a Leontief production function: e.g., sawings are derived from roundwood. Second, some processed products compete for the same raw materials: e.g., pulp, panels and energy wood all compete for industrial raw wood. Third, some products are jointly produced: e.g. sawing production comes with a production of sawmill residues that can be used as industrial wood. All products are exchanged from one region to another following Samuelson's spatial price theory (Paul A. Samuelson, 1952). In addition, exports of raw products and imports of transformed products are represented through the Armington theory of imperfect substitutability, representing trade with the rest of the world, all foreign countries aggregated (Armington, 1969). As a bio-economic model, it integrates information on the dynamics and management of forest resources. In particular, the calculation of the optimal supply of timber in the partial equilibrium takes the level of available forest resources into account and cannot exceed it.

Full details, figures and equations describing the model principles and modules are provided in the Appendix and online.[5]

2.2.2 Introducing product substitution into FFSM

Starting from the original version of FFSM, we introduce the competition between fuelwood and a fossil fuel substitute to compensate for the lack of representations of intersectoral relationships in a partial equilibrium model.

[5] More details on the FFSM are given on https://ffsm-project.org/

Following Caurla *et al.* (2013), we model this competition via a price competition approach, by modifying the initial demand function for fuelwood (Eq. (2) in B.1) via the introduction of a demand cross elasticity. This competition module alters fuelwood demand according to the variation in the ratio between fuelwood and fossil fuel prices.

$$D_{fw,i,t} = D_{fw,i,t-1}\left(\frac{P_{fw,i,t}(1-Sub_t)}{P_{fw,i,t-1}(1-Sub_{t-1})}\right)^{\sigma_p}\left(\frac{\left(\frac{P_{fw,i,t}}{P_{ff,i,t}}\right)}{\left(\frac{P_{fw,i,t-1}}{P_{ff,i,t-1}}\right)}\right)^{-\varepsilon_{fw,ff}} \quad (1)$$

Where:

$D_{fw,i,t}$ is the regional demand for fuelwood in region i at year t

$P_{fw,i,t}$ and $P_{ff,i,t}$ are the prices in region i at year t of fuelwood and fossil fuel substitute respectively

Sub_t is the level of the price subsidy at year t

$\sigma_p$is the price elasticity of demand for fuelwood.

$\varepsilon_{fw,ff}$is the cross elasticity of demand between fuelwood and fossil fuels

The price of the energy substitute $P_{ff,i,t}$ is exogenous and is calibrated using historical data on Brent crude oil prices, then assumed to increase steadily at a yearly 2% rate over the whole simulation period (Macrotrends, 2018). We use a value of 0.3 for the cross elasticity of demand $\varepsilon_{fw,ff}$. In the literature, cross price elasticities between fuelwood and other fuels vary between 0.1 and 0.4, depending on a wide range of socio-economic characteristics such as residential or industrial heat, use of wood as a primary or secondary heat source, or household revenue (Couture, Garcia and Reynaud, 2012; Zhang, Gilless and Stewart, 2014).

2.2.3 Model outputs and economic indicators

For each wood product in each region, a partial equilibrium is computed each year and gives an endogenous price index of wood products as well as the quantity produced or consumed. Wood prices for the rest of the world are calibrated exogenously (Buongiorno *et al.*, 2012). These pieces of information allow us to calculate various economic welfare indicators: consumer surplus and producer surplus, budgetary cost of subsidies (computed as the amount of the subsidy, times the quantity produced or consumed), total surplus (computed as the sum of producer and consumer surplus and budgetary cost). Consumer surplus can be seen as a proxy of consumer welfare (Willig, Willig and D, 1976) while producer surplus is equal to producer profit, and social welfare is the sum of both. Thus, a change in consumer (producer) surplus is used to measure the gain or the loss in consumer welfare (private profits). In welfare analysis, economic surpluses are generally considered as reliable and relevant indicators compared to national (or regional) incomes (Harberger, 1971).

2.3 Data inventory: connecting economic modelling outputs with Life Cycle Inventories (LCI)

Building the inventory of consumed resources and emitted pollution is a key point in LCA studies. In order to build an exhaustive inventory of the environmental flows associated with a given scenario, we have to associate LCI data to each quantity of wood products produced and consumed as computed in FFSM. These FFSM outputs are provided at an intermediary scale, which means that they are too aggregated to be directly connected in processing LCA databases, while too disaggregated with regard to products found in Environmental Extended Input Output databases such as Exiobiase (Merciai and Schmidt, 2018). This issue arises when dealing with meso-scale objects, and hybrid approaches can be adopted to compute data (Peters, 2010). As our study deals with few products, we developed a processed-based bottom-up approach to connect FFSM outputs with LCI, in order to ensure that the process modelling remained fine.

2.4.1 A general procedure to provide consistent flow accounting

The general procedure is to disaggregate FFSM products into products that match LCI process databases such as Ecoinvent (Wernet, G. *et al.*, 2016) for the forest management and wood industries. We use data from various sources, as presented in Table II.1. It is mainly based on the detailed results of a MFA applied to the French forest sector (Lenglet, Courtonne and Caurla, 2017; Courtonne and Wawrzyniak, 2019). In addition, we use existing LCI processes to disaggregate products such as sawings, using yield values.

FFSM product	***LCI process***	***Proportion***	***Data sources***
Roundwood - softwood (SW) and hardwood (HW)	Raw Sawlog	See Figure II.5	Ecoinvent, MFA
	Debarked Sawlog		
Industry wood (pulpwood and fuelwood)	Pulpwood	See Figure II.5	Ecoinvent, MFA
	Cleft timber		
	Harvest residues		
	Bark Chips		
	Sawmill residues		
Sawnwood - softwood (SW) and hardwood (HW)	Beam	40%	Ecoinvent
	Lath	45%	
	Board	15%	
Plywood	Plywood	100%	MFA
Fuelwood	Domestic heating	20%	MFA
	District/industrial heating	80%	
Panel	Particle board, indoor	50%	Ecoinvent, FCBA
	Particle board, outdoor	50%	
Pulp	Paper pulp, Sulphate ECF	100%	Ecoinvent, MFA

Table II.1 - Product disaggregation from FFSM to LCI

Finally, all LCI processes used were adapted to the French Grand Est region context (e.g. scarce use of mechanical forest harvesters and tree seedlings, French electricity mix for industrial processes, adapted transportation distance for product imports and exports). Complete details, data and sources are provided in B.2 – tables A.6 to A.14, and modifications are specified in the comments.

Still, some discrepancies remain between economic outputs and LCI needs. In particular, economic models focus on product quantity and price relationships, whereas LCIs focus on elementary flows and matter conservation. Due to these differences, consistency issues arise regarding several features i.e. input/output coefficients in the Leontief function of FFSM and yields, coproducts, allocations, system limits, end uses and time dynamics. We detail below how we dealt with these issues.

2.4.2.1 Yield and matter conservation

The first issue is the need to match yields at each transformation process. By default, FFSM and LCI processes use different yields in terms of input and output quantities at each step of the supply chain. In FFSM, a Leontief function represents the transformation of raw products into processed products (see Table A.5 in B.1), connecting a given quantity of raw products with a quantity of processed products, both expressed in Mm^3. Input-output coefficients used in the Leontief function are calibrated for each group of products using MFA results built using data reconciliation methods (Lenglet, Courtonne and Caurla, 2017). The quantity of raw products used is consistent with actual technical coefficients. This corresponds to the left-to-right black arrows in Figure II.5.

However, FFSM does not fully track matter conservation, as co-products are not economically represented in an independent fashion. Sawmills and harvest residues are partially accounted for as by-products of sawing, i.e. a mass ratio of the quantity of softwood and hardwood sawings is allocated as an additional quantity to the industry raw wood. Thus, flows between sawmills, panel and pulp industries, and fuelwood, are not accounted for separately but as a whole.

The second issue is the aggregation discrepancy between FFSM and LCI processes. Despite harvest and sawmill residue quantities not being explicitly computed, the inventory of products processed from industry raw wood, i.e. fuelwood, panels, and pulp, is disaggregated using MFA data. This enables us to take into account the quantities and proportions of the various types of pulpwood and residues used in secondary products, as shown in Figure II.5. The main shortcoming is that the proportions are fixed. This method does not allow varying proportions of sub-products – sawmill residues, cleft timber - within the industry wood category.

Processes from LCI databases come with given yields for each transformation step. Yields are harmonized by modifying those in LCI processes using the same MFA results used for FFSM. However, for some downstream steps, such as the ones after splitting sawings between beams, laths and boards, LCI databases provide more disaggregated products than MFA and are thus used.

We summarize this procedure in Figure II.5, which shows the main processes used and how they are combined with economic outputs. More details on the LCI process used, data and sources are provided in B.2.

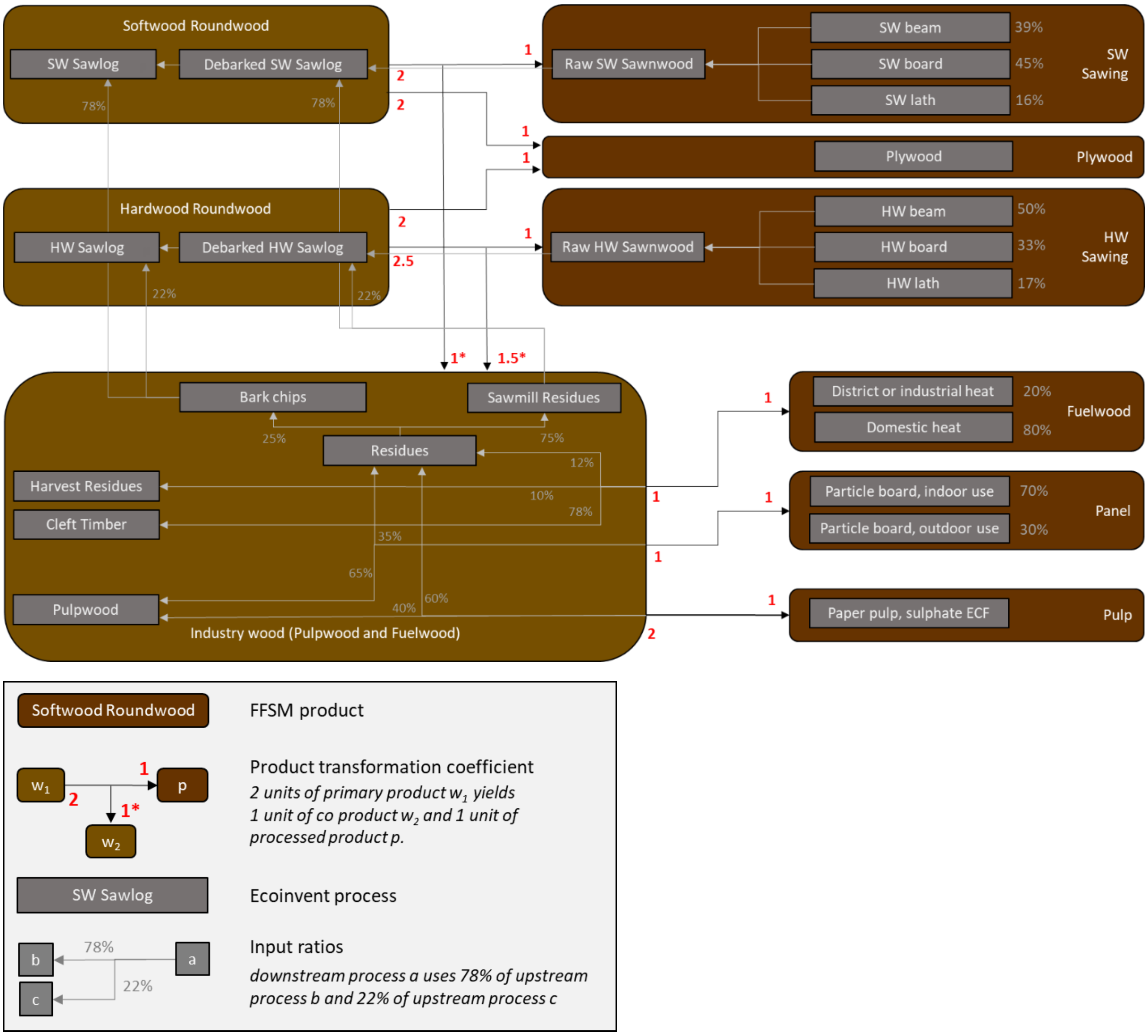

Figure II.5 - Yields, LCI disaggregation ratios, and consistency between the FFSM economic model and the LCA framework.

2.4.2.2 Allocations

The proportion of each raw forest product – roundwoods, industry wood and fuelwood – in the total quantity of wood harvested is used to perform mass allocation for forest harvest processes and to carry out a carbon balance on all products in the forest-based sector. The data used in LCI databases are consistent with the MFA data at national scale. More details are shown in B.2, tables A.15 to A.16 In addition, Ecoinvent processes are based on monetary values to perform an economic allocation in all the downstream steps of the forest supply chains. This will concern the allocation of impacts between sawing co-products: debarked logs and bark, sawings and sawmill residues. In the study, the allocation values are not changed and do not take into account the possible price fluctuations calculated by FFSM.

2.4.3 Multisector interactions: Assessment of avoided impacts for energy consumption

In addition to the LCI for forest and wood products, we include the impacts avoided due to the substitution of fossil fuel energy by fuelwood products for heating purposes. We estimate quantities substituted by assuming that the additional consumption of fuelwood induced by the studied subsidy replaces an energy-equivalent quantity of a mix of fossil fuels.

$Q_{substituted} = Q_{subsidy} - Q_{baseline}$, expressed in Mm^3

Where $Q_{substituted}$ is the quantity of fuelwood substituted for the mix of fossil fuels, $Q_{subsidy}$ is the quantity of fuelwood consumed in the subsidy scenario and $Q_{baseline}$ is the quantity of fuelwood consumed in the baseline scenario.

The quantity of heating energy substituted $Energy_{substituted}$ in MJ is calculated as follows:

$$\begin{aligned} Energy_{substituted} &= Q_{substituted} \times -(Calorific\ Power_{Fuelwood} \times mix_{fossil\ fuels}) \\ &= Q_{substituted} \times -(Calorific\ Power_{Fuelwood} \times (share_{oil} + share_{gas})) \end{aligned}$$

Starting out from LCI data, we use an average calorific power of fuelwood of 4500 MJ/m3 (Wernet, G. *et al.*, 2016). Based on residential heating mix data for the Grand Est region (Ministère de la Transition Ecologique et Solidaire, 2019), we assume a substituted mix composed of a 0.6 share of gas and a 0.4 share of oil. Coal use is negligible for heating purpose and we consider electricity heating as fixed. These assumptions on the simple substitution mechanism and energy shares are deemed valid, as electricity production in France is managed at national level, and fossil energy is provided by large operators historically established nationwide which source from international markets when it comes to gas and oil distribution.

2.4 Indicators of eco-efficiency

Eco-efficiency indicators are computed based on the economic and environmental indicators provided by the modelling framework. The total economic surplus defined in 2.2.3 is used as an economic indicator. The environmental indicators are the Life Cycle Impact Assessment (LCIA) outputs obtained with the impact assessment method ReCiPe (v1.13, Hierarchist). LCIA methods provide midpoint and endpoint impacts. Endpoint impacts quantify potential impacts at the end of the cause-effect leading to an environmental impact – for example, damage to ecosystems or human health. Midpoint impacts quantify a potential impact earlier in this cause-effect chain: for example, Global Warming Potential expressing additional radiative forcing to assess climate change. We chose the levels of the three endpoint categories as potential environmental impacts to compute eco-efficiency indicators.

To emphasize the role of accounting for avoided impacts through energy substitution in the eco-efficiency, we define two types of eco-efficiency ratios. First, we compute the Partial Eco-Efficiency ratio (PEE), without including avoided impacts:

$$PEE = \frac{Socioeconomic\ indicators}{Potential\ environmental\ impacts}$$

Second, we define the Full Eco-Efficiency ratio (FEE), with avoided impacts. The introduction of 'avoided impacts' potentially raises a mathematical issue, as 'total impacts' is the sum of 'potential environmental impacts' and 'avoided environmental impacts': this sum may converge towards zero and could even take negative values as the share of consumed fuelwood increases. When the total impacts take negative values, the meaning of the FEE is nonsensical. To overcome this limitation, we propose to create an Impact Avoidance Ratio (IAR), as:

$$IAR = \frac{Potential\ Environmental\ Impacts - Substitution\ Environmental\ Impacts}{Potential\ Environmental\ Impacts}$$

Then we define the Full Eco-Efficiency as:

$$FEE = PEE \times IAR$$

'Substitution Environmental Impacts' only deal with substitution related to energy. They are negative if substitution leads to impacts being avoided (if fuelwood consumption increases), meaning that IAR>1, and is positive if there are more impacts due to substitution (i.e. if fuelwood consumption decreases), meaning that IAR <1.

3 Case study results

First, we describe the effects of the subsidy on wood product quantities produced and consumed and on prices; then we present the environmental impacts of the two scenarios, and finally, the eco-efficiency indicators as combinations of the first two.

3.1 Market impacts

We present the results of the simulation for the horizon 2012–2050 on market impacts, e.g. price variations, quantities of fuelwood consumed and, finally, welfare. The focus is on two regions: the region where the 50% subsidy is implemented, i.e. Grand Est (GE), and a region nearby, with no subsidy, namely the Bourgogne-Franche-Comté (BFC) region (Table II.2).

<table>
<tr><th></th><th colspan="6">Subsidy scenario compared to baseline, year 2050</th></tr>
<tr><th></th><th colspan="3">Grand Est
Main effect</th><th colspan="3">Bourgogne Franche-Comté
Crowing-out effect</th></tr>
<tr><th>Fuelwood price and quantities</th><th>Initial value</th><th>variation</th><th>% variation</th><th>Initial value</th><th>variation</th><th>% variation</th></tr>
<tr><td>Fuelwood consumption (Mm³)</td><td>8,98</td><td>2,85</td><td>32%</td><td>4,80</td><td>-0,20</td><td>-4,1%</td></tr>
<tr><td>Fuelwood perceived price (€/m³)</td><td rowspan="2">34</td><td>-14</td><td>-42%</td><td rowspan="2">35</td><td rowspan="2">1,7</td><td rowspan="2">4,7%</td></tr>
<tr><td>Fuelwood nominal price (€/m³)</td><td>+5</td><td>+15%</td></tr>
<tr><td>Welfare indicators</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Subsidy cost (M€)</td><td>-</td><td>232</td><td>-</td><td>-</td><td>0</td><td>-</td></tr>
<tr><td>Consumer surplus (M€)</td><td>1412</td><td>494</td><td>35%</td><td>703</td><td>-16</td><td>-2,2%</td></tr>
<tr><td>Producer surplus (M€)</td><td>444</td><td>16</td><td>3,6%</td><td>227</td><td>3,5</td><td>1,6%</td></tr>
<tr><td>Total surplus (M€)</td><td>1856</td><td>279</td><td>15%</td><td>930</td><td>-12</td><td>-1,3%</td></tr>
</table>

Table II.2 - Economic outputs in 2050, in the subsidy scenario compared to the baseline, in the region Grand Est (GraEst) where the subsidy policy is applied and the nearby region Bourgogne-Franche-Comté (BouFra).

3.1.1 Prices and quantities

In order to compare price changes for fuelwood between regions, we display here the nominal market price and the *perceived price* for the consumer, i.e. the market price minus the subsidy for Grand Est. Following the implementation of the consumer subsidy, the perceived price of fuelwood decreases by 42% in Grand Est in 2050 compared to the baseline. In absolute terms, this corresponds respectively to a €14/m³ reduction. Conversely, prices increase by up to 4.7% in Bourgogne-Franche-Comté in 2050 (i.e. by €1.7/m³ in absolute terms). This outcome reflects a spatial crowding-out effect caused by the scarcity effect brought by the subsidy in Grand Est.

Inversely proportional to prices, quantities of fuelwood consumed increase in Grand Est by up to 32% compared to the baseline. Fuelwood's share in the total volume of all transformed wood products increases from 54% to 61%, as shown in Table II.3.

		Fuelwood	**Softwood sawings**	**Pulp**	**Panels**	**Hardwood sawings**	**plywood**
Subsidy	Share of total volume	61%	14%	13%	8%	3%	1%
	Volume in Mm3	11,83	2,67	2,58	1,54	0,51	0,12
Baseline	Share of total volume	54%	16%	16%	9%	3%	1%
	Volume in Mm3	8,98	2,69	2,67	1,55	0,51	0,12

Table II.3 - Volume in Mm3 and share of total volume of all wood products for each wood product in the Grand Est region

Concurrently, fuelwood production decreases in Bourgogne-France-Comté by up to 4%, as shown in Figure II.6. This higher consumption of fuelwood also affects the production of pulp and panels, which are in competition with fuelwood for raw industry wood. Indeed, the increase in raw industrial wood production is not sufficient to supply the additional demand for fuelwood. Due to this shortage, panel production is entirely replaced by fuelwood production in Grand Est and demand is met with a trade of 0.95Mm³ panels and 0.12Mm³ fuelwood from Bourgogne-Franche-Comté to Grand Est. Paper pulp is slightly affected, with a 0.33Mm³ decrease, which is partially offset in turn by production increases in more distant regions such as Aquitaine-Poitou (AQ), Rhône-Alpes (RA), or Auvergne-Limousin (AL). Other products – roundwoods, sawings and plywood – are not significantly affected.

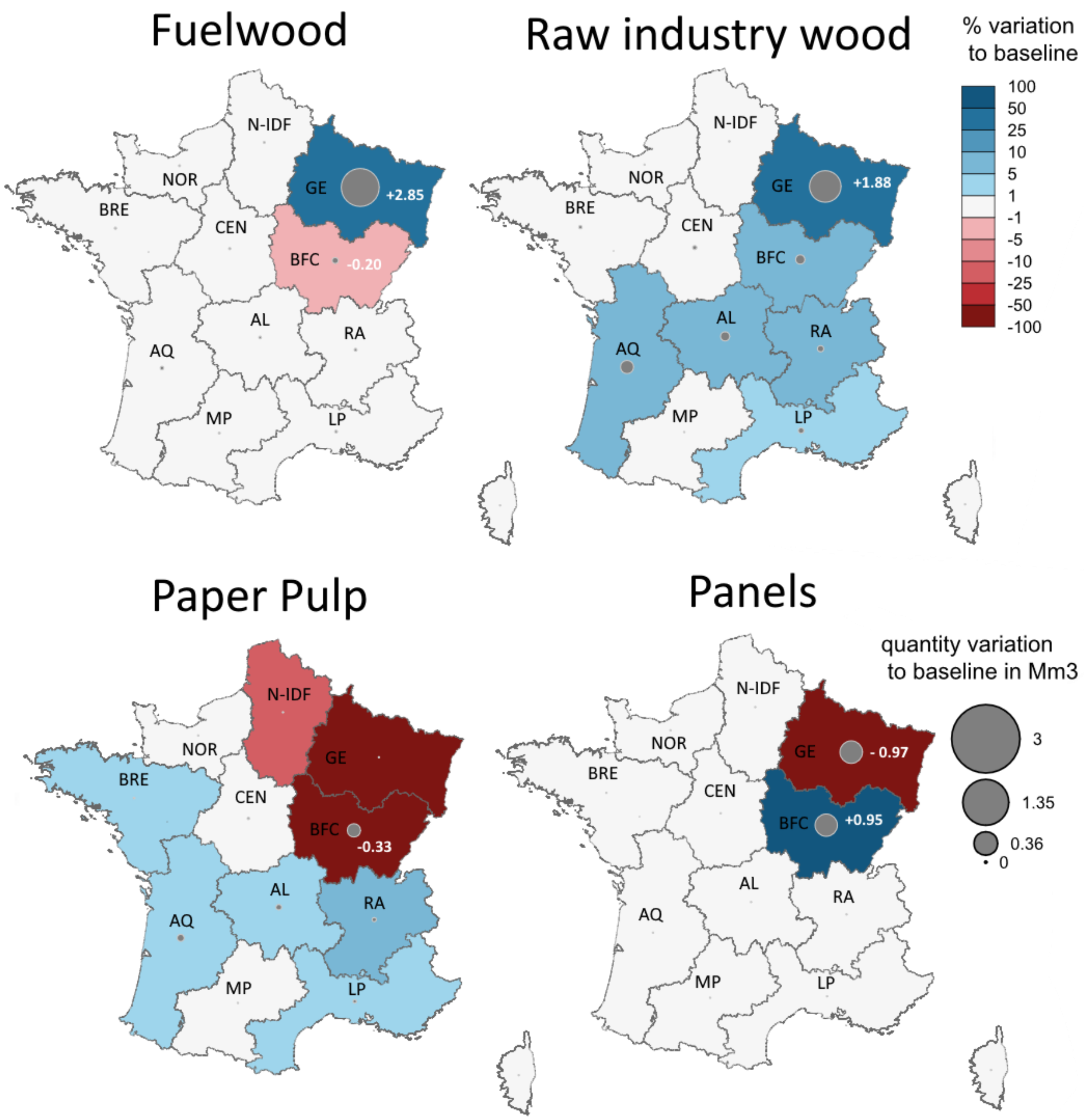

Figure II.6 – Variations in quantities consumed when a subsidy is implemented compared to a business-as-usual baseline in each region - year 2050.
Region names : AQ = Aquitaine + Poitou, AL = Auvergne + Limousin, BFC = Bourgogne + Franche-Comté, BRE = Bretagne + Pays de la Loire, CEN = Centre, GE = Grand Est, LP = Languedoc-Roussillon + Provence-Alpes-Côte d'Azur, MP = Midi Pyrénées, N-IDF = Nord + Picardie + Île-de-France, NOR = Normandie, RA = Rhône-Alpes

This trade spreads competition for raw industry wood and increases its price in several regions, as shown in Figure II.7.

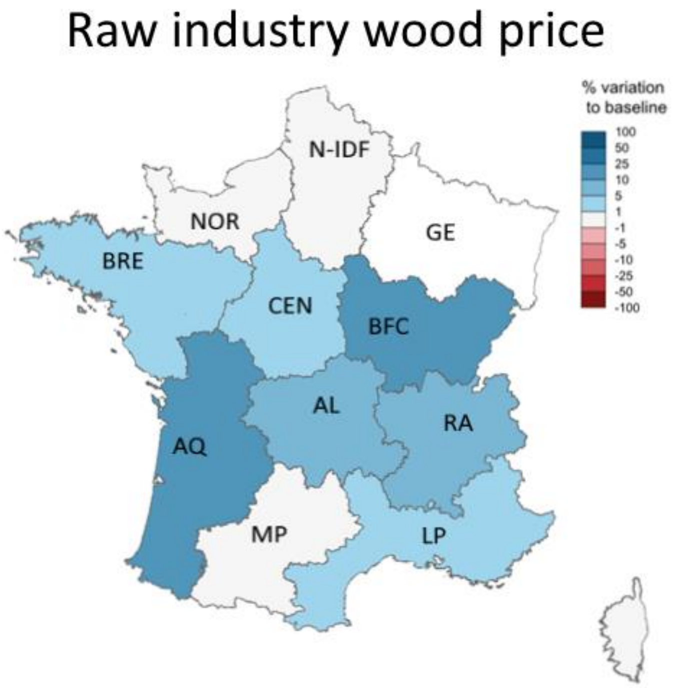

Figure II.7- Raw industrial wood prices when a subsidy is implemented compared to a business-as-usual baseline as a percentage, year 2050

However, the effects of this competition are moderate on the price and quantities consumed of transformed products. This is because the available forest resource is sufficient to feed the increased demand, in line with Caurla et al. (2013) who showed that, for France, competition between transformed products only appears at national scale when resource availability is restricted.

3.1.2 Welfare impacts

These market impacts affect the welfare of economic agents in the wood sector, be they wood producers or consumers. Given that the simulated economic incentive consists in subsidizing fuelwood consumption in the Grand Est region, the welfare of Grand Est fuelwood consumers is significantly enhanced. In 2050, consumer surplus is 35% higher in the scenario with a subsidy compared to the baseline. In addition, the effects of the subsidy irrigate the upstream part of the sector: producer surplus increases by 3.6% compared to the baseline under the combined effect of higher raw industry wood prices and larger production to feed the additional consumption.

Finally, a consumer subsidy is costly for the public authority as it usually leads to a significant windfall effect: consumers that would have purchased fuelwood anyway (i.e. under the baseline scenario) also benefit from the subsidy. To improve the cost effectiveness of a fuelwood subsidy, existing solutions encompass targeting the additional consumption only or subsidizing investment in new boilers (such as tax exemptions).

3.2 Environmental impacts: potential and avoided impacts

In this section, we describe the environmental impacts of the wood sector to the horizon 2050. Figure II.8 shows the impacts quantified at the midpoint level, including the avoided impacts (named 'substitution', in brown, negative figures), for the scenario with the 50% subsidy in the Grand Est region. Considering all impact categories, fuelwood and pulp have the most impacts due, respectively, to the absolute quantities produced (see volume percentages in Table II.3) and their high impact per unit compared to other products. Panels, then softwood sawings, whose most notable impacts are a 10 to 20% share in impact categories related to land use, follow them. Indeed, a more significant proportion of forestry's high impact on land use is allocated to sawings due to the higher share of roundwoods in total volume compared to industry wood – see Table II.4 in 4.2. However, this allocation does not take into account the higher density in terms of volume of wood per hectare in forest stands more specialized towards the production of roundwoods. Transportation impacts related to quantities traded between regions and with the rest of the world are low compared to other contributors. Avoided impacts are most important in climate change, fossil depletion, and ozone depletion as alternative fuels are a mix of fossil fuels.

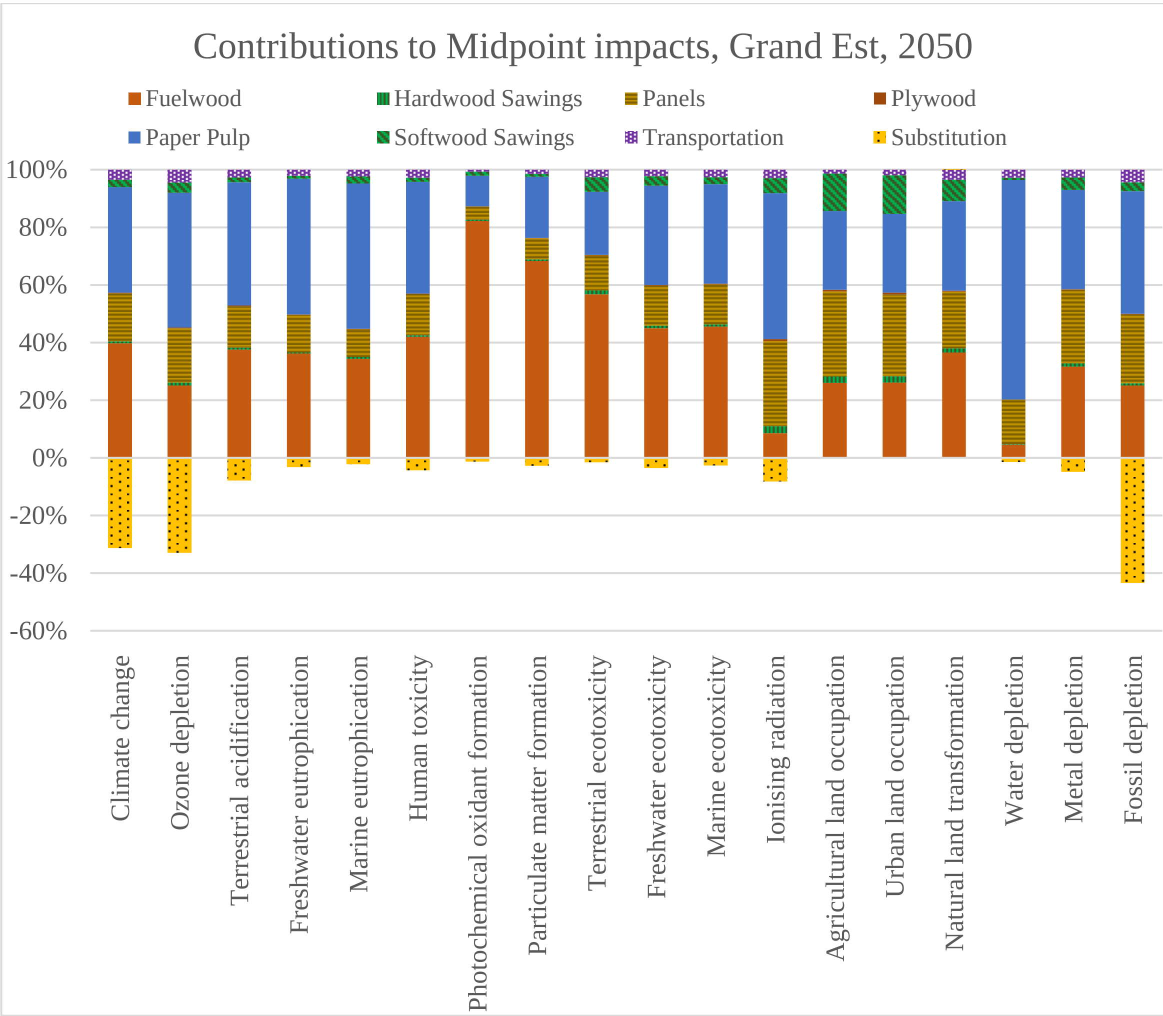

Figure II.8 - Midpoint impact: contributions of the products and processes for the subsidy scenario in 2050 in the Grand Est region modelled with the ReCiPe 1.13 method.

Figure II.9 compares the environmental impacts for the two scenarios at the endpoint level. Due to higher production of fuelwood, the scenario with a subsidy has higher impacts on all categories compared to the baseline, as the higher production of fuelwood is not offset by comparable decreases in other products – see Table II.3. However, despite the increase in fuelwood quantities (+32%), differences are not significant in terms of environmental impacts except for human health when avoided impacts are not accounted for. One explanation is that fuelwood releases high quantities of particulate matters that contribute to damage to human health. For other damages, other wood products such as pulp and panels are still important contributors, due partly to high energy consumption and land occupation.

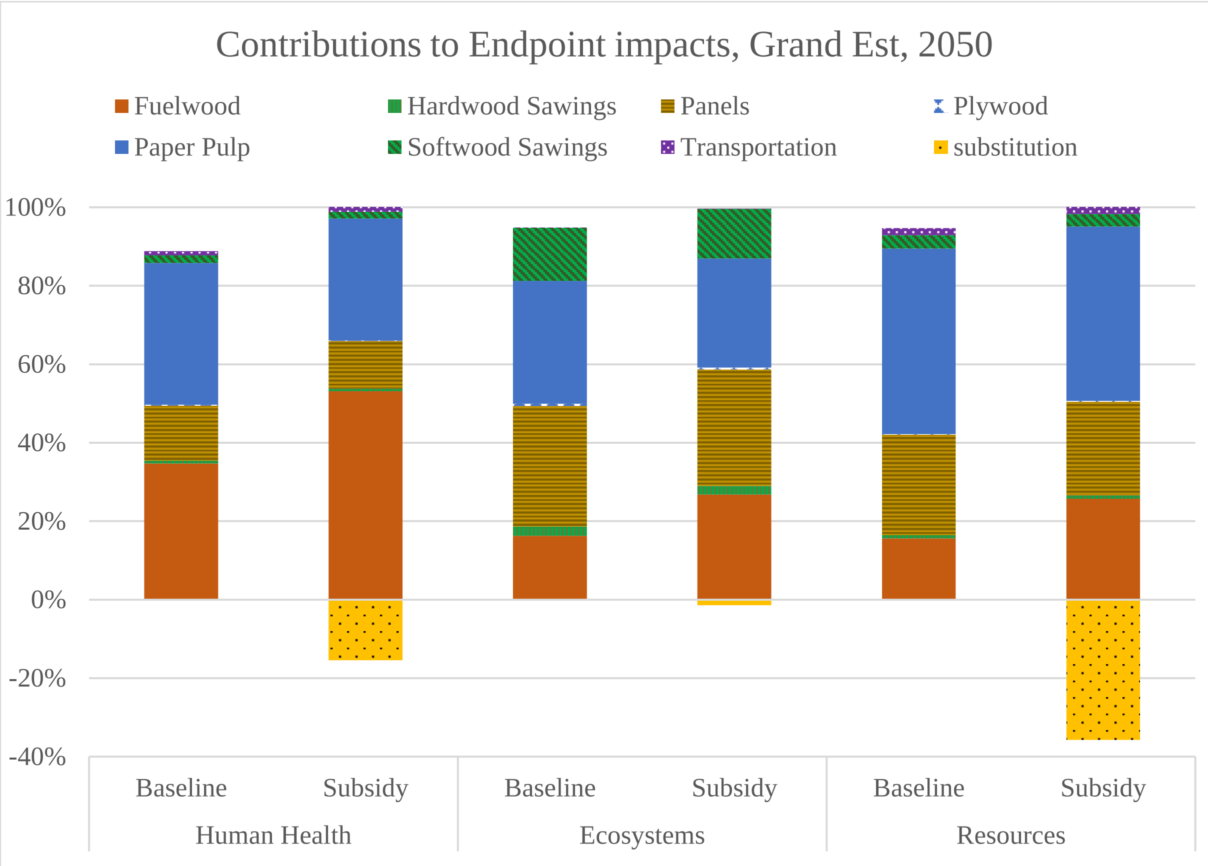

Figure II.9- Comparison between the impacts in the Grand Est region on the endpoint damage indicators between the baseline and the subsidy scenario for the year 2050, modelled with the ReCiPe 1.13 method

The bigger avoided impacts due to fossil fuel substitution are related to the resource impact category, then human health, where it greatly offsets the impact increase. These results underline that considering avoiding impacts is decisive.

3.3 Eco-efficiency (EE)

We compute FEE and PEE ratios using the three endpoint impact categories for the baseline and subsidy scenarios. For better clarity, we computed the ratio of figures obtained in both scenarios, i.e. the EE for the subsidy scenario was divided by the EE for the baseline. These ratios are shown in Figure II.10 for FEE and PEE.

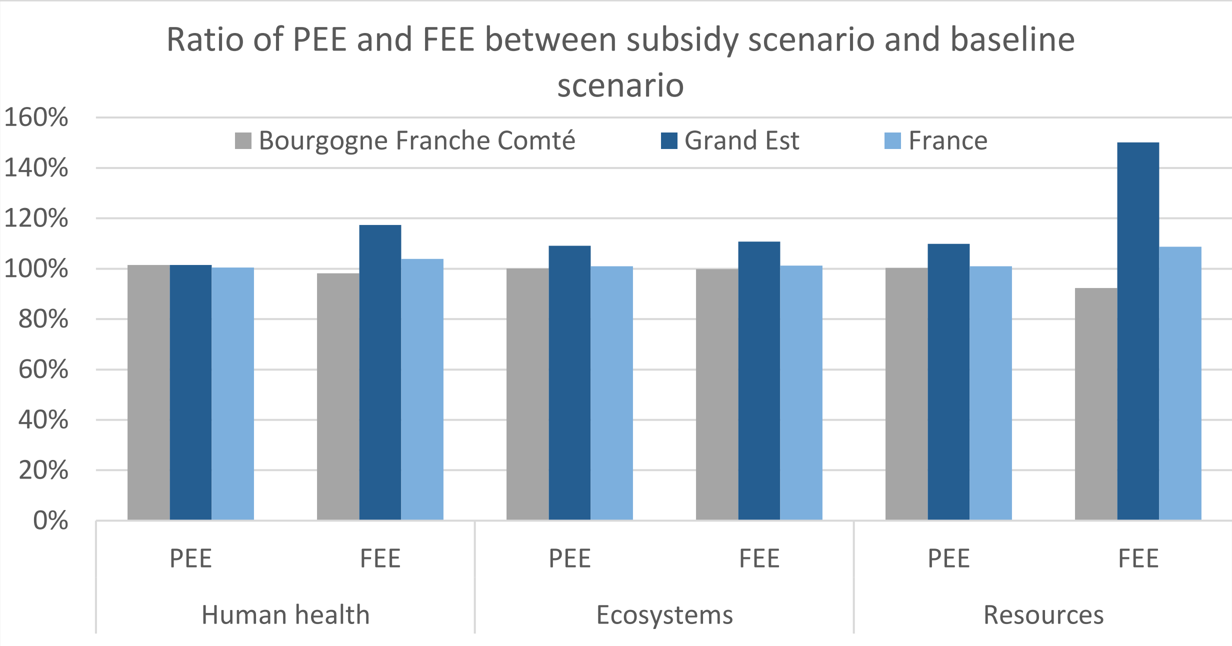

Figure II.10 - Comparison of PEE and FEE for two regions and for France, for year 2050. Ratio of the PEE and FEE of the subsidy scenario divided by the PEE and FEE of the baseline scenario

In 2050, in the Grand Est region, the PEE of forest and wood products is 2 to 10% higher than the baseline one. The subsidy increases the quantities of fuelwood consumed, inducing both a higher economic surplus and higher environmental impacts - not taking into account substitution effects. The subsidy has a positive effect on surpluses, on both the consumer and the producer side, which is higher than the economic cost of the subsidy. Moreover, this total surplus gain exceeds the environmental impact increase. The effect of the subsidy on the producers' surplus in the other regions identified in section 3.1 is not significant.

In the Grand Est region, the FEE ratio for the 'Resources' category reaches 150%, showing that the subsidy scenario outperforms the baseline by up to 50%. It also better performs in the 'human health' category, by up to 17%. Notably, in this case, moving from PEE to FEE induces a shift from a non-significant effect to a much higher eco-efficiency compared to the baseline. Conversely, for the 'Ecosystems' category, FEE is almost the same as PEE, in line with the small avoided impacts for this area of protection. All in all, it appears that, in this case study, the subsidy provides clear benefits. Most benefits come from the avoided impacts: with FEE, clear positive eco-efficiency effects can be shown whereas they do not appear when substitution is not accounted for. Overall, crowding-out effects in other regions are small and offset by benefits in the region where the subsidy is implemented.

4 Discussion

4.1 Indicators and policy implications

Eco-efficiency increases with the subsidy, due to the increase in the economic surplus and the decrease in environmental impacts. Yet these variations are interrelated: economic surplus positively depends on wood product quantities just like environmental impacts. However, a significant difference occurs here between FEE and PEE. Using wood instead of renewable energy has positive substitution effects that should be taken into account, as we do in FEE.

As for price variations, their impacts on the total economic surplus and, therefore, on eco-efficiency, is not straightforward. Indeed, a price increase would result in a gain in producers' surpluses and a loss in consumers' surpluses, making the effect on total economic surplus unclear and highly dependent on price elasticities. As quantities have a positive linear relation with environmental impacts, on the one hand, and a positive non-linear impact on surplus on the other, prices, which only affect economic indicators, are the main source of non-linearity when calculating eco-efficiency.

In this case study, the subsidy for energy wood consumption induces a decrease in the perceived price by consumers and an increase in market price for producers in the Grand Est region. Therefore, in this region, the subsidy clearly increases the economic component of the eco-efficiency ratio. However, a crowding-out effect increases the prices of energy wood and other wood products in neighbouring regions, which (1) reduces the quantities of fuelwood consumed in these neighbouring regions and (2) drastically reduces the FEE gains at national scale. One policy implication of this indirect effect is that eco-efficiency highly depends on the geographic scale. Thus, regional policies should be coordinated in order to prevent any leakage effects. Another policy implication is that if the objective is to reach an energy wood consumption target at the country level, the measure has to be set up at a national level to prevent any crowding-out effects.

Other metrics could add valuable insights into the socio-economic effects of measures, such as wages/household income and employment, but a general equilibrium framework is required to compute such indicators endogenously. Proxies such as employment multipliers could be used to estimate employment variations from output and price variations (Fuentes-Saguar, Mainar-Causapé and Ferrari, 2017), but quantitative estimations are to be used with care: when evaluating an investment or project from a simulation model, variations are more relevant than absolute levels. Moreover, such estimations would be strictly proportional to the surplus/revenue estimations, giving no additional information when calculating terms of eco-efficiency.

As for the environmental impact, the individual contributions show that pulp and panels have the highest environmental impact with fuelwood. We have shown that the main driver of environmental impact variation was substitution. The fossil fuel mix has a significantly higher impact per MJ than fuelwood for several impact categories. However, this result depends on the nature of the energy mix used (Wolf *et al.*, 2016). The impact of an increase in fuelwood use in the energy mix can be investigated in more detail by combining FFSM outputs with other energy models, accounting for the hierarchy of usage for energy sources in France (Caurla *et al.*, 2018; Albers *et al.*, 2019).

4.2 Model Robustness and dynamics

In this second part, we examine the various choices and hypotheses underlying the coupling method we have developed and the possibilities of enhancing the consistency of the modelling framework.

4.2.1 Coupling economic outputs and LCI

In the study, economic outputs are combined with LCI process data, when alternatives such as IO-LCA or a hybrid approach would have been possible. As discussed by Peters (2010), modelling meso-scale systems for LCA (e.g. cities, regions or economic sectors) often relies on hybrid approaches combining bottom-up methods such as LCA process, and top-down methods such as IO-LCA. On the one hand, economic outputs are more aggregated than most data available in the LCI databases such as Ecoinvent. On the other hand, they are more disaggregated than products found in EEIO databases such as Exiobiase (Merciai and Schmidt, 2018). These two main LCA approaches can be used to connect FFSM economic outputs with LCIs. In this paper, detailed data on wood flows were made available by carrying out a MFA of the French forest sector, which enabled us to disaggregate economic model outputs properly in a bottom-up approach. An advantage of IO-LCA approaches is that it better accounts for upstream impacts, especially for complex, globalized supply chains (Majeau-Bettez, Strømman and Hertwich, 2011). To assess the effect of LCI modelling types of results, a comparison with IO-LCA approaches could be carried out.

4.2.2 Dynamic modelling

The LCA framework is based on static inventories, while the FFSM model is temporally dynamic. Several steps could be planned to make the framework completely dynamic.

1) Dynamic Inventory

Shortcomings in the inventory are (i) the fixed ratios used to disaggregate economic outputs to match LCA process data; ii) fixed economic allocations.

Disaggregation ratios are based on the material flows for the initial year. However, these ratios change over time according to forest and economic dynamics. Ideally, FFSM products should be more disaggregated, especially for products related to raw industry wood: cleft timber, pulpwood, residues. Doing so would require data that are lacking for some products, especially residues or cleft timber. Indeed, these products are often directly consumed by producers on site or exchanged through informal markets, causing a lack of consistent data on prices. Some minor alterations could be implemented, e.g. estimating residues dynamically according to sawing products. A fully disaggregated description of residues would make it possible to take into account recycling loops and thus add up, in the environmental assessment, non-linear relationships that are difficult to assess outside such a framework.

Allocations are another cause of consistency issues. A mass allocation is performed for the impacts of products from harvest – roundwoods, industry wood. However, the proportions of products will not necessarily be the same between the LCI database and FFSM beyond the initial years, as shown in Table II.4: the output from harvest may vary according to resource availability and market price dynamics.

	Ecoinvent (based on German data)	***FFSM initial year 2011***	***FFSM final year 2050***
Roundwood	55% (HW 12%, SW 88%)	55% (HW 26%, SW 29%)	49% (HW 26%, SW 23%)
Pulpwood and Fuelwood	45%	45%	51%

Table II.4 - Proportions of roundwoods and Industry Wood + energy wood from harvest. HW stands for Hardwood and SW for Softwood

More generally, the allocation made for primary products from harvest does not take into account the higher density in terms of volume of wood per hectare in forest stands that are more specialized towards the production of roundwoods. FFSM calculates detailed information on the types of forest stands – high forests, coppices, intermediate stands - and the diameter classes of trees at the scale of 8x8km pixels. This information could be used to determine a typology of intensive/extensive forest operations, thus allocating the impacts of forest operations according to yield.

Except for these products from harvest for which a mass allocation is performed, economic allocations are used for LCA coproducts, i.e. sawing products and residues. Prices used for the allocation performed in the Ecoinvent database are different from those used as initial conditions of the model. We kept Ecoinvent prices for simplicity reasons in the allocation process, as allocation prices are embedded in Ecoinvent data and recalculating allocation based on different prices would have required significant work. Prices are displayed in Table II.5.

This table shows that for sawing products, FFSM prices and Ecoinvent prices are in the same range. Moreover, these allocations direct most of the impact toward products with a low share of the total potential impacts in the Grand Est Forest sector (up to 2% for Hardwood Sawings and up to 14% for Softwood Sawings). However, the variation within FFSM in the long run may be high (+75% for softwood roundwoods between 2011 and 2050). Using these higher 2050 prices would marginally increase the impact of sawings and decrease the impact of fuelwood, panels, and paper pulp.

Process	Co products	Ecoinvent (EUR2005)	FFSM initial year 2011 Grand Est (EUR2011)	FFSM final year 2050 Grand Est (EUR2011)	Comment
Debarking	Debarked log	80€/m³	99€/m³ HW 62€/m³ SW	112€/m³ HW 109€/m³ SW	Hardwood (HW)/ Softwood (SW)
	Bark chips	12€/m³ (0,034 €/kg)	NA	NA	Converted in €/m³ using a volumic mass of 350kg/m³ GuidEnR BOIS-ENERGIE > Les caractéristiques du combustible pour le bois-énergie - Masse volumique
Sawing	Sawing	265 €/m³	516€/m³ HW 172€/m³ SW	478€/m³ HW 159€/m³ SW	Hardwood (HW)/ Softwood (SW)
	Sawdust	12€/m³ (0,034 €/kg)	NA	NA	Converted in €/m³ using a volumic mass of 350kg/m³ [6]
	slab and sidings	49€/m³ HW 34€/m³ SW (0,077€/kg)	NA	NA	Converted in €/m³ using a volumic mass of 640 kg/m³ HW /440kg/m³ SWWernet, G. et al., 2016

Table II.5 - Ecoinvent prices used for allocations and FFSM prices in the initial year

Implementing dynamic price allocations, i.e. prices calculated by the model for each year, could be relevant to explore the effects on residue valuations in scenarios favouring cascading uses of wood. However, such variability in the price-based allocation raises issues regarding the robustness of the indicators and the validity of proceeding with economic allocations (Ardente and Cellura, 2012). Thus, dynamic allocations should not be implemented and used systemically. Performing sensitivity studies to parameters such as initial product prices would allow this variability to be isolated. In a long-term research perspective, using a stochastic economic model instead of a deterministic one should lead to more stable calculated prices.

2) Dynamic modelling of environmental impacts

FFSM provides outputs that may help enhance the life cycle inventory or provide a dynamic assessment of environmental impacts.

First, it provides information on forest stands: while the total forest area remains constant, the type of forest stands – species, diameter class, management - can change yearly according to economic and environmental pressures (Lobianco *et al.*, 2015). It would be excessively detailed to feed LCA with impact categories such as natural land occupation, as LCIA methods do not distinguish species in forest stands, but it may be extrapolated into biodiversity indicators or other metrics for ecosystem services. In particular, broad-leaved forests and/or high forests are usually associated with higher performance on biodiversity indicators than coniferous forests or coppices (Gao *et al.*, 2014; Storch, Dormann and Bauhus, 2018).

In the framework used in this paper, carbon accounting is not detailed. We used the assumption of carbon neutrality for biogenic carbon, though this has its shortcomings (Wiloso *et al.*, 2016). Thus, global warming impacts are based on emissions related to process data on forest operations, transport and industry operations (inventories from Ecoinvent), as well as emissions related to fossil fuel production and use in the event of substitution. A simple accounting of biogenic carbon using FFSM capabilities is possible (Lobianco, Caurla, *et al.*, 2016), but precise estimations of the carbon footprint would require significantly deeper work, including detailed modelling of further transformation industries. This matters most for material substitution and wood product end-of-life, as shown by recent works pointing out the specifications for a complete biogenic carbon framework to assess the impacts of biomass use for energy policies (Albers *et al.*, 2019).

5 Conclusion

Our goal was to compute eco-efficiency metrics while taking account of interactions at multiple scales - with economic sectors and other regions. To do so, we coupled a national multi-regional partial equilibrium economic model with a LCA model so we could easily compute economic and environmental indicators with a time dynamic frame. By calculating the ratio of both, we obtained eco-efficiency indicators of the regional economic measure.

We tested this framework with a case study based on a subsidy for energy fuelwood consumption implemented in a single French region, Grand Est. Focusing on fuelwood and on the related wood industries allowed us to explore interactions at multiple scales. Indeed, the wood sector is tightly interconnected with other economic sectors (energy, construction, packing, etc.), with significant stakes both at the local level – forest management and land use – and at the global level in relation to the high potential of forests for climate change mitigation.

Substitution impacts had to be taken into account in order to fully integrate the impact of switching from a fossil fuel to wood as a heating energy source. To account for substitution effects, we extended the modelling capacities of the FFSM economic model to include interactions with the energy sector. We completed the framework to account for elementary flows with the environment by coupling economic outputs of the model (essentially quantities of wood products) with a LCA framework.

A first challenge was to ensure consistency between the system modelling of the two approaches. We propose an approach to consistently link the outputs of the economic model and the process LCA data based on material balance. The need for further developments has been identified, such as dynamic yields or more disaggregated economic outputs for wood residues. This will pave the way for a stronger coupling between the two approaches.

Two eco-efficiency indicators were built. The first, PEE, was without avoided impacts, and the second, FEE, included impacts avoided due to energy substitution. Theoretically, only PEE would need to be applied. However, it was possible to include substitution and to compute FEE for the energy sector as it is organized in easy-to-model national and global markets. The implementation of product substitution for other markets, such as the construction sector, where wood substitutes for other energy-intensive products, is restricted by several limitations. In this case, substituting wood for concrete, for instance, would induce direct competition with local activities such as concrete production, construction material retail, and tradespeople. Thus, our assessment of the economic impacts of an economic measure targeting these markets would necessarily miss consequential crowding-out effects on the local construction sector. In these cases, PEE may arguably be more helpful.

We strongly believe that this new methodology could be used to test the eco-efficiency of policies designed to enhance the use of wood products, in particular in a context of the promotion of wood product consumption (Lenoir *et al.*, 2007; European Parliament and Council of the European Union and EUR-lex, 2009; *Innovating for sustainable growth: A bioeconomy for Europe*, 2012). The coupled models could be tested with more advanced prospective scenarios on fossil energy prices in the long run to further explore the sensitivity of the model to exogenous energy prices.

In the context of bioeconomic policies placing a strong emphasis on the development of regional biomass markets and energy wood supply chains, indicators such as FEE can provide crucial insights for policy design, thanks to its ability to integrate diverse indicators and to encompass a wide perimeter including multiple scales and sectors.

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III

Assessing the eco-efficiency of bioeconomy strategies at both regional and national scale: application to the French energy wood sector

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Abstract

We investigate the economic and environmental performance of national and regional bioeconomy strategies oriented towards energy wood development in the French forest sector. Eco-efficiency indicators are calculated for scenarios built on different combinations of national and regional policies, including fuelwood demand incentives, local wood supply, and forest conservation. We compute eco-efficiency using a simulation model based on a coupling between a partial equilibrium model of the French forest sector and a Life Cycle Analysis (LCA) framework. This approach allows taking account of indirect effects at multiple scales, i.e. local forest resources, wood flows through interregional trade or substitution between fuelwood and fossil fuels on global markets. We show that the scenario based on a combination of fuelwood demand incentives and local supply constraints is the most eco-efficient one both at national and regional scale. It increases the eco-efficiency compared to the baseline for all environmental impact categories: 16% and 18% on ecosystems, 21 and 25% on human health, 42 and 59% on resources, respectively for an implementation at national level and an implementation in the region Grand Est.

Keywords
Decision support, Bioeconomy, Wood bioenergy, Economic performances, Environmental impacts, Multi-scale assessment

1 Introduction

A wide definition of the bioeconomy comprises all economic sectors and activities related to the production and processing of goods and services based on biological resources, as well as the production of ecosystem services (OECD, 2009). Its development is an essential compound of the transition from a fossil-based economy into a bio-based sustainable economy. To implement it, initiatives have been launched worldwide including the OECD's Policy Challenges for a Sustainable Bioeconomy (OECD, 2018), the European Commission's Sustainable Bioeconomy for Europe strategy (European Commission, 2018) or the National Bioeconomy Blueprint in the USA (The White House, 2012). Among them, the European bioeconomy strategy has recently taken a step forward by presenting a bioeconomy action line that aims at strengthening and scaling up the bio-based sectors, unlocking investment and markets as well as fostering local bioeconomy agendas. As a result, nine European countries have formulated dedicated national strategies (European Commission, 2020).

Forest and wood biomass account for more than 60% of the EU's total biomass supply (Banja *et al.*, 2019; Scarlat *et al.*, 2019). In France, the national bioeconomy strategy deliberately focuses on wood biomass for energy and material use (Ministère de l'Agriculture et de l'Alimentation, 2018), and policies are being designed to promote energetic uses of wood through various incentives to wood energy demand, completed by direct or indirect measures of supply support. In practice, Economic incentives to wood energy demand mostly consist in tax expenditures towards households (fuelwood tax expenditures reach 130 M€ per year since 2006) and in subsidies from the government budget towards heating networks for communities and industries (6 M€ per year towards wood biomass units since 2006). On the supply side, economic incentives consist in tax expenditures and subsidies to private forest owners to improve forest management.

More recently, a particular emphasis has been put on the development of local biomass markets and regional energy wood supply chains, notably through the implementation of regional biomass production targets (Ministère de la Transition Ecologique et Solidaire, 2020). In parallel, as the consumer demand for local consumption grows, non-monetary incentives such as labels and buyer cooperatives emerge and foster the relocation of wood products economy (Lenglet and Caurla, 2020). However, these dynamics may confront local and global stakes. While wood resources are abundant at national scale, the relative availability of resources regarding forest area, forest stands types, and natural area protection varies at local scales. In particular, energy oriented incentives are likely to conflict locally with regulations oriented towards biodiversity and landscapes conservation (Bonin and Kleinschmidt, 2019). Forest conservation measures are increasing and may reduce access to forest resources. Meanwhile, this happens in a context of uncertainty over fossil energy prices. Future price instability could affect the demand for wood energy.

All these incentives are expected to support the transition towards a sustainable economy in some way, but may have competing effects. Forests and wood industries are to play a significant role to improve the environmental performances of human activities on diverse issues such as climate change, resource consumption, or biodiversity loss. In a socio-economic perspective, the forest wood sector can be a driving force for boosting the economy especially in rural territories (Hyttinen, Niskanen and Ottitsch, 2000; Hoogstra, Schanz and Wiersum, 2004). Yet, the development of fuelwood use may also have adverse environmental and economic effects: local pollution, forest harvesting intensification, or competition with other forest products. The effects of these diverse socio-economic and environmental stakes need to be assessed in a multi-criteria approach when implementing bioeconomy strategies, in order to ensure that sustainable goals are effectively pursued over time. The EU pursues this objective (Robert et al., 2020).

We stressed the importance of both local and global contexts in which these strategies are implemented. Global changes may affect their performance on a short term as well as long-term time horizons. We question as well whether a regional strategy could be more efficient compared to a national strategy. Besides, the environmental and economic performances of a regional bioeconomy strategy and can differ depending on the local contexts. Indeed, some French regions have a well-developed forestry economy with the presence of large forest areas and strong companies. In other regions, the forest economy is less structured. Therefore, national strategies may favour the whole forestry sector or only well-developed forestry areas, potentially leading to a growing competition between regions. In that respect, the potential competition or synergy between French regions is explored.

The aim of this paper is to investigate the economic and environmental performance of bioeconomy strategies oriented towards wood energy production and consumption, both at the national and the regional scales. Our approach integrates interactions (resource, markets) at multiple geographic and time scales in an effort to capture indirect effects of the strategies.

In order to achieve this goal, we develop an integrated modelling approach combining an economic forest sector model with a LCA model to compute eco-efficiency ratios at regional and national scales (Beaussier *et al.*, 2020). Eco-efficiency combines economic and environmental indicators into a single ratio, defined as the ratio of an economic performance indicator divided by environmental impacts (Seppälä *et al.*, 2005).

First, we propose to study different bioeconomy strategies, defined as combinations of policies (or measures) and constraints set by regulations and exogenous risks. Then we briefly describe the main principles of the modelling framework to compute eco-efficiency ratios. Afterwards, we present results on the one hand for national level and, on the other hand, for a French region, i.e. the Grand Est region, in order to assess the performances of the different bioeconomy strategies in a context of global changes. Finally, we analyse the effects of the scenarios to explore how the different policies interact.

2 Material & Methods

2.1 Goal and scope

2.1.1 Case Study: the French forest sector

Our case study focuses on the French forest sector and wood industries. The case of France captures several issues at play in the forest sector of temperate developed countries because of its important forest resource, its diversity, and territorial development stakes. We encompass the forest sector as the whole set of activities from forest management and harvesting to first processing industries downstream, in interaction with the rest of the world. The time horizon spans from 2020 to 2050 on a year-to-year basis.

The main objective is to assess the eco-efficiency of bioeconomy strategies for two contrasted implementation scales, i.e. (i) the national scale (all French regions) and (ii) the regional scale (a single region, namely Grand Est region). The national scale allows us to assess the performances of a centralized strategy, while the regional scale allows us to investigate the eco-efficiency of a decentralized strategy. The forest sector in Grand Est is both a significant part of the French forest sector and a meaningful economic activity in the region's economy. It represents 12% of French forest sector jobs and 18% of revenues, for 12% of the French forest area (Ministère de l'Agriculture et de l'Alimentation, 2016; Institut National de la Statistique et des Etudes Economiques, 2019). In both cases, a particular emphasis is placed on assessing multiscale interactions between regions and economic sectors induced by bioeconomy strategies implementation.

2.1.2 Bioeconomy strategies

Different options can be implemented to foster bioeconomy at national and regional scale. Among them, we will focus on two main economic policies intended to stimulate the demand for local wood energy products: economic incentives and local supply constraints. First, demand side economic incentives aimed at stimulating wood biomass consumption. This type of measures have been the core of biomass-oriented policies since their inception in the mid-2000s (Banja *et al.*, 2019). They are expected to provide beneficial effects on local economic activity (Caurla, Delacote, Lecocq and Barkaoui, 2013) while reducing environmental impacts through substitution mechanisms with fossil fuels (Gustavsson *et al.*, 2007). Second, a local supply constraint for raw wood products. Local supply chains are praised for lower environmental impacts thanks to reduced transportation distances, better producer revenue and lower costs for consumers through the reduction of intermediaries (Kneafsey *et al.*, 2013; Lenglet and Caurla, 2020). This trend is apparent both at the institutional level and in the development of grassroots initiatives fostering local consumption such as labels and charters. Nevertheless, local characteristics in terms of forest resource availability, production costs and consumer demand, imports and exports, are determinants to the eco-efficiency of such local markets.

In addition to economic policies, our analysis also considers the changing context in which bioeconomy strategies will be implemented. Societal demand or socio-economic issues may drive these changes. For example, society is increasingly concerned about biodiversity protection. For forests, it results in increasing forest conservation as a general trend in Europe (Forest Europe, 2015, European Commission, 2020). We thus integrate constraints on forest resources availability due to the introduction of conservation measures. In any given region, the availability of wood for commercial uses depends on the forest area protected by regulations related to biodiversity and landscape conservation and the level of protection defined by these regulations (Alberdi *et al.*, 2020), with potential local availability thresholds (Ferranti, 2014). Regulations may vary according to local administration governance or stakeholders' preferences, e.g. revenues from wood harvesting versus social demand for nature conservation, whether or not they are in line with guidance from the national level. French forests are also characterized by a large amount of small land owners with a low level of active forest management, who do not respond much to economic incentives (Deuffic *et al.*, 2015; Petucco, Abildtrup and Stenger, 2015). The level of biomass availability can also be considered an indicator of this situation.

Finally, the wood energy sector is connected directly and indirectly to other economic sectors. In particular, we chose to investigate the interaction of energy prices with fuelwood demand. We implement an exogenous shock consisting in sharp energy prices increase in order to test how it affects the performances of the bioeconomy strategies, including the sensitivity of different regions, with or without relocation and resource availability constraint.

In sum, two economic policies and two types of changing context due to societal or socio-economic issues will be analysed. The combination of these four types of measures and constraints will lead to the construction of several scenarios detailed in section 2.3.

2.2 Modelling Framework and implementation of economic measures and constraints

The main principle of the modelling framework is the soft coupling of a partial equilibrium model and LCA, i.e. the outputs of the economic model feed the LCA framework without feedback. The scope and main characteristics of this coupled framework and its subparts – the partial equilibrium model and process LCA framework - are detailed in Beaussier et al. (Beaussier *et al.*, 2020). This modelling framework provides two types of indicators as shown in Figure III.1, i.e. economic indicators and environmental indicators.

Both will be used to compute eco-efficiency ratios as defined in territorial LCA approaches (Loiseau *et al.*, 2018) to compare the performances of bioeconomy strategies at regional and national levels.

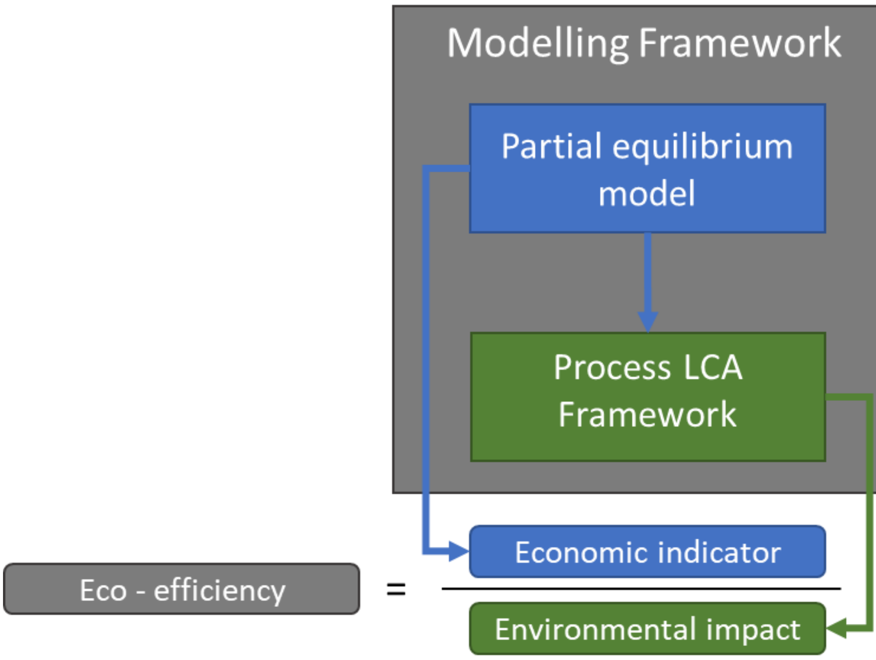

Figure III.1- An overview of the soft-coupling procedure performed to compute eco-efficiency ratios at national and regional scale.

In the following, we describe the main features of both economic and environmental model. We precise in what manner the measures and constraint are implemented in the economic model, and how constraints are considered in the scenarios.

2.2.1 Scenario modelling based on a Partial Equilibrium Model of the French Forest Sector Model (FFSM)

The partial equilibrium model used in our modelling approach is the French Forest Sector Model (FFSM). More details on the FFSM model are available in previous works (Lecocq *et al.*, 2011; Caurla, Delacote, Lecocq, Barthès, *et al.*, 2013; Lobianco *et al.*, 2015).

FFSM is a bioeconomic model simulating the French forest sector with a yearly time step, considering interactions between forest biological dynamics, forest management and markets. It is composed of three main modules, i.e. i) a forest resource dynamic module, ii) a market module, and iii) a forest management module.

The market module is a recursive partial equilibrium with a one-year time step which computes for each French region quantities produced, consumed and exchanged, as well as prices, for 9 groups of wood products - softwood and hardwood roundwood, raw industry wood, softwood and hardwood sawings, plywood, fuelwood, panels, paper pulp. Supply of raw wood products depends on resource availability as determined by the forest resource module. All products can be exchanged from one region to another following Samuelson spatial price theory (Paul A. Samuelson, 1952), making each regional equilibrium different due to transport costs and resource availability. In addition, exports of raw products and imports of transformed products are represented through the Armington theory of imperfect substitutability (Armington, 1969).

The market module provides back the volume of wood harvested to the forest resource module, which computes the volume of resources in forest through a Markov-like model. Besides, using expectations on price, growth and mortality, a forest management module determines the forest type to regenerate on the harvested areas for the forest resource module.

Full details, figures and equations describing the model principles and modules are provided in the Appendix and online[6].

2.2.2 Implementation of the measures and constraints in FFSM

2.2.2.1 Economic incentive

The various forms of economic incentives to fuelwood consumption – tax expenditures and subsidies for privately owned boilers or larger scale plants – result generally in a reduced perceived price of fuelwood for the final consumers, either domestic households , local authorities or power generator owners (Caurla *et al.*, 2018). In this study, we implement a subsidy to encapsulate in a single measure the various elements of this policy mix. It is modelled by modifying the price variables in the demand functions of the market module. Equations are specified in Appendix and previous works (Caurla, Delacote, Lecocq and Barkaoui, 2013).

This subsidy is expected to increase the quantities of fuelwood produced and consumed. We compare two levels: 40% and 60% of the fuelwood price. The 40% level corresponds to the amount needed to trigger an increase in consumption in line with national targets defined in the National Strategy for the Mobilization of Biomass (Ministère de la Transition Ecologique et Solidaire, 2018). This level is determined through a backward process, by trial and error. Adding VAT exemptions, tax cuts for households and equipment subsidies, current incentives are equivalent to a 20% to 30% subsidy level. The subsidy is implemented either in only one region or equally in all regions allowing assessing the eco-efficiency of a centralized versus decentralized strategy.

2.2.2.2 Local supply preference

In FFSM, products are exchanged between regions according to an adaptation of Samuelson's spatial equilibrium. Traded quantities $e_{w,i,j}$ for product w from any region i to any region j are determined according to relative primary products prices $P_{w,j}$ and $P_{w,i}$ and transport costs $C_{w,i,j}$.

The following equation of maximization of trade agent surplus is incorporated in the maximization program of all economic agents along with consumer and producer surplus.

$$\sum_{p,i,j\neq i}(P_{w,j} - P_{w,i} - C_{w,i,j})e_{w,i,j} \qquad (1)$$

More details are provided in previous works (Lecocq *et al.*, 2011; Caurla, Delacote, Lecocq and Barkaoui, 2013) and online.

[6] More details on the FFSM are given on https://ffsm-project.org/

Our aim here is not to have a fine description of local supply preferences, but to have some contrasted results about the importance of local versus non-local consumption. Thus, we materialize relocation incentives in FFSM - such as labels, charters, or public contracts - by blocking trade of raw wood products between any given two regions. To do so, we artificially increased transport costs between regions for these products to the point that exchange becomes too costly, and no more products are exchanged. For this purpose, we set arbitrarily transport costs at a 100-times higher value than initial costs.

2.2.2.3 Resource availability and protected areas

The structure of FFSM allows us to implement constraints on resource availability in the resource module that affects wood supply in the market module.

The forest resource module is a spatially explicit biological model where French regions are divided in an 8*8km pixel grid, as in Figure III.2.

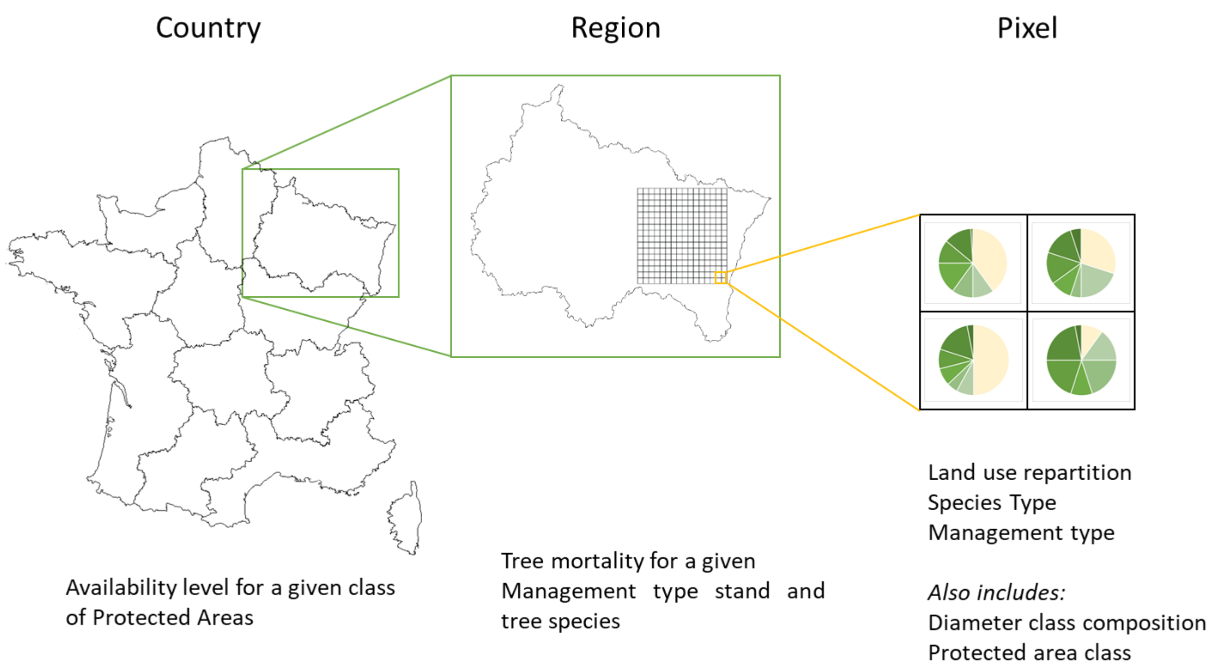

Figure III.2- Spatial scales in FFSM
Colours at pixel level indicate the land use repartition between the fixed non-forest area and the types of forest areas (among 6 existing combinations of species type (coniferous, broad-leaved, mixed) and management type (High Forest, intermediate, coppice))

Each type of information on the forest area and stand composition – land use repartition, management types (high forest, coppices, intermediate), tree species, diameter class, protected area level – is based on inventory data from the French National Forest Inventory (Colin and Chevalier, 2009).

This information is used to calculate $F_{w,i,t}$ The volume of wood in standing forests that can be harvested for product w, which is provided to the market module for any region i and year t.

The volume $F_{w,i,t}$ is incorporated in the supply function in the following way:

$$S_{w,i,t} = S_{w,i,t-1}\left(\frac{P_{w,i,t}}{P_{w,i,t-1}}\right)^{\epsilon_w}\left(\frac{F_{w,i,t}}{F_{w,i,t-1}}\right)^{\beta w} \quad (2)$$

Where :

$S_{w,i,t}$ is the regional supply of product w in region i at year t

$P_{w,i,t}$ is the price of product w in region i at year t

ϵ_w is the price elasticity of supply (positive) for product w

β_w is the stock elasticity of supply (positive) for product w

The volume of wood available $F_{w,i,t}$ is determined for any given year by an equation that includes notably the volume available in the previous year, mortality, and the volume harvested for the year. It is detailed in B.1 and previous works (Lobianco *et al.*, 2015). We can increase or reduce this volume through an 'availability coefficient' that depicts the level of resources that may be used in the forest sector.

We modify the availability coefficient defining the availability level for each category of protected area either at country level or for the single region Grand Est, using the values provided in Table III.1. Default values are divided by 2 in the increased natural area protection scenario.

IUCN Protected Areas Categories System:	***Availability percentage***	
	Increased protection	Default
Ia Strict Nature Reserve	0 %	0 %
Ib Wilderness Area	5 %	10 %
II National Park	40 %	80 %
III Natural Monument or Feature	5 %	10 %
IV Habitat/Species Management Area	5 %	10 %
V Protected Landscape/ Seascape	45 %	90 %
VI Protected area with sustainable use of natural resources	50 %	95 %

Table III.1 - Availability coefficient of various levels of area protection. Default values correspond to the default calibration based on data from the French National Institute of Geographic and Forest Information (IGN).
Details and equations are provided in previous works and SI (Lobianco et al.*, 2015).*

2.2.2.4 Exogenous shocks - Changing energy prices

We introduce an exogenous shock on international fossil energy prices through the fuelwood demand function assuming that fossil energy price interacts with fuelwood demand.

Competition is represented through a price competition approach. Basically, competition between fuelwood and fossil fuel substitutes is represented through a cross elasticity of demand (eq (3)). This competition module alters the fuelwood demand according to the variation of the ratio between fuelwood and fossil fuel prices. $(1 - Sub_t)$ corresponds to the subsidy described in 2.2.1.

$$D_{fw,i,t} = D_{fw,i,t-1}\left(\frac{P_{fw,i,t}(1-Sub_t)}{P_{fw,i,t-1}(1-Sub_{t-1})}\right)^{\sigma_p}\left(\frac{\left(\frac{P_{fw,i,t}}{P_{ff,i,t}}\right)}{\left(\frac{P_{fw,i,t-1}}{P_{ff,i,t-1}}\right)}\right)^{-\varepsilon_{fw,ff}} \quad (3)$$

Where:

$D_{fw,i,t}$ is the regional demand of fuelwood *fw* in region i at year t

$P_{fw,i,t}$ and $P_{ff,i,t}$ are the price in region i at year t of fuelwood and fossil fuel *ff* substitute respectively

Sub_t is the level of the price subsidy at year t

$\sigma_p$is the price elasticity of demand for fuelwood.

$\varepsilon_{fw,ff}$is the cross elasticity of demand between fuelwood and fossil fuels

A fossil fuel price vector is defined exogenously using crude oil prices historic data then assumed to increase steadily at a yearly 2% rate over the whole period of the simulation, which is the range of projections of international organizations (International Energy Agency, 2012; BEIS, Department for Business and BEIS, 2017; U.S. Energy Information Administration, 2019). A price shock vector is also defined, based on price increase rates similar to the 70s/80s and 2000s energy crises as shown in Appendix C.1 (Macrotrends, 2018). When this price increases, fuelwood demand increases in proportions related to the substitution coefficient, and vice versa. Current projections regarding energy prices are mixed. Sustained low prices can be expected due to increased competition among oil producers when peak oil demand will be reached (Department of Business, 2018). However, long periods of price volatility are to be expected, notably due to political unrest, and will sustain themselves by causing divestment and bankruptcy (Pickl, 2019). The perspective of a decline in the production of Europe's major fossil energy suppliers supports in particular the case of future instability for the European Union (Auzanneau, 2020).

2.2.3 Life cycle inventories (LCI) and impact assessment (LCIA): connecting economic modelling outputs with LCA

A LCA framework is coupled to FFSM which provides quantities of wood products as inputs to compute their environmental impacts. From cradle to gate, all upstream processes (energy supply, machine tools, chemical production) used in the forest-based sector and wood industries are accounted for in the Life Cycle Inventory (LCI). This includes forest management operations and products from the first and the second transformation. We also include transports according to the quantities of products traded between regions, imports and exports as described in 2.2.2. Building up the LCI being the most time-consuming approach in LCA; our proposal is to couple FFSM and LCA, i.e. to feed LCI with FFSM outputs, through a bottom-up approach. The procedure is based on the detailed results of a Material Flow Analysis (MFA) (Lenglet, Courtonne and Caurla, 2017; Courtonne and Wawrzyniak, 2019) carried out on the French forest sector; this allows us to disaggregate FFSM outputs into specific products that match processes found in the Ecoinvent database (Wernet, G. *et al.*, 2016) for forest management and wood industries. In addition, the Ecoinvent database is also used to disaggregate some FFSM products using process yield values. Extended information on the coupling procedure as well as on the different data used is provided in a previous work (Beaussier *et al.*, 2020).

Potential environmental impacts are computed based on Life Cycle Impact Assessment (LCIA), using the impact assessment method ReCiPe (v1.13, Hierarchist), which provides impacts both at the midpoint and the endpoint levels. Midpoint impacts rely on fewer assumptions and are thus are more reliable, when endpoint impacts provide a more easily understandable information to non-specialists (Van Hoof *et al.*, 2013).

2.2.4 Computing eco-efficiency indicators

Eco-efficiency indicators are computed as the ratio of an economic versus an environmental indicator provided by the modelling framework. The total economic surplus is computed as the sum of producer surplus, the consumer surplus and the budgetary cost (negative); it is used as the economic indicator (numerator). As denominator, we chose the value of one of the three endpoint categories (potential environmental damages), i.e. human health, ecosystems and resources. In addition, we take into account avoided impacts due to substitution of fossil fuel energy by fuelwood products for heating purposes. We estimate quantities substituted by assuming that the additional consumption of fuelwood induced by the studied subsidy replaces an energy-equivalent quantity of a mix of fossil fuels.

2.2.5 Link between Modules

We summarize the links between the different modules and components of the FFSM-LCA coupling in Table III.2.

Module	***Level***	***Input from other modules***	***Output to other modules***
Market	Country, region	Availability	Volume harvested, prices, quantities, surplus
Forest Dynamic	Country, region, pixel	Regeneration areas, Volume harvested	Harvested areas, availability
Forest Management	Country, region, pixel	Prices, Harvested areas	Regeneration areas
LCA framework	Country, region	Quantities	Environmental impacts
Eco-Efficiency	Country, region	Surplus, Environmental impacts	-

Table III.2 - Spatial levels and interactions of FFSM modules.

In this paper, the market module operates at the regional level, whereas forest dynamic and area allocation at pixel level. The LCA framework operates on products whose quantities produced and consumed are defined at national and regional level, using inventory data for the national level.

2.3 Summary of the scenarios tested

In this section, we describe the combination of measures, constraints and shocks which have been carried out to design the scenarios that are tested in the model. We divide the scenarios studied in three blocks.

The first block consists in scenarios based on independent measures, i.e. measures taken one at the time: subsidy, local supply, and forest conservation are set either at national scale or for the region Grand Est only. These scenarios are shown in Figure III.3.

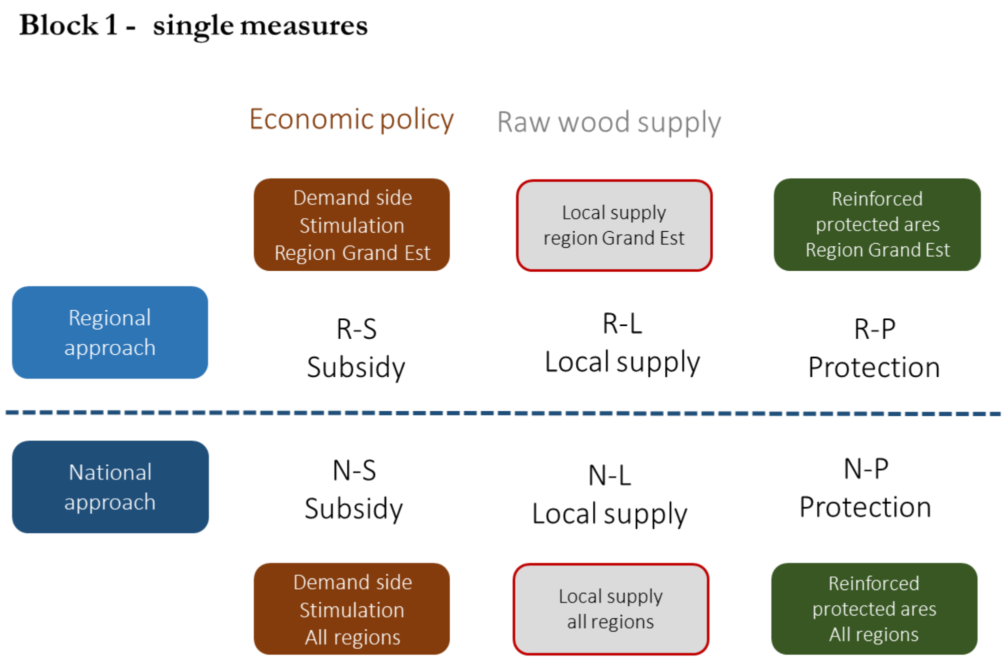

Figure III.3 - Scenarios tested in the simulation first block – single measure scenarios

In the second block of scenarios, we further explore interaction between measures and the effects of a changing context by combining measures and constraints, e.g. subsidy, local wood supply constraint and resource availability constraints. Each combination is tested either at regional or national scale. These scenarios are shown in Figure III.4.

The last block of scenarios confronts the previous scenarios, in either regional or national setup, with an exogenous shock on energy prices.

For each scenario, the model runs up to 2050, and the results are compared to a business-as-usual situation. The baseline corresponds to the situation where no measure is implemented.

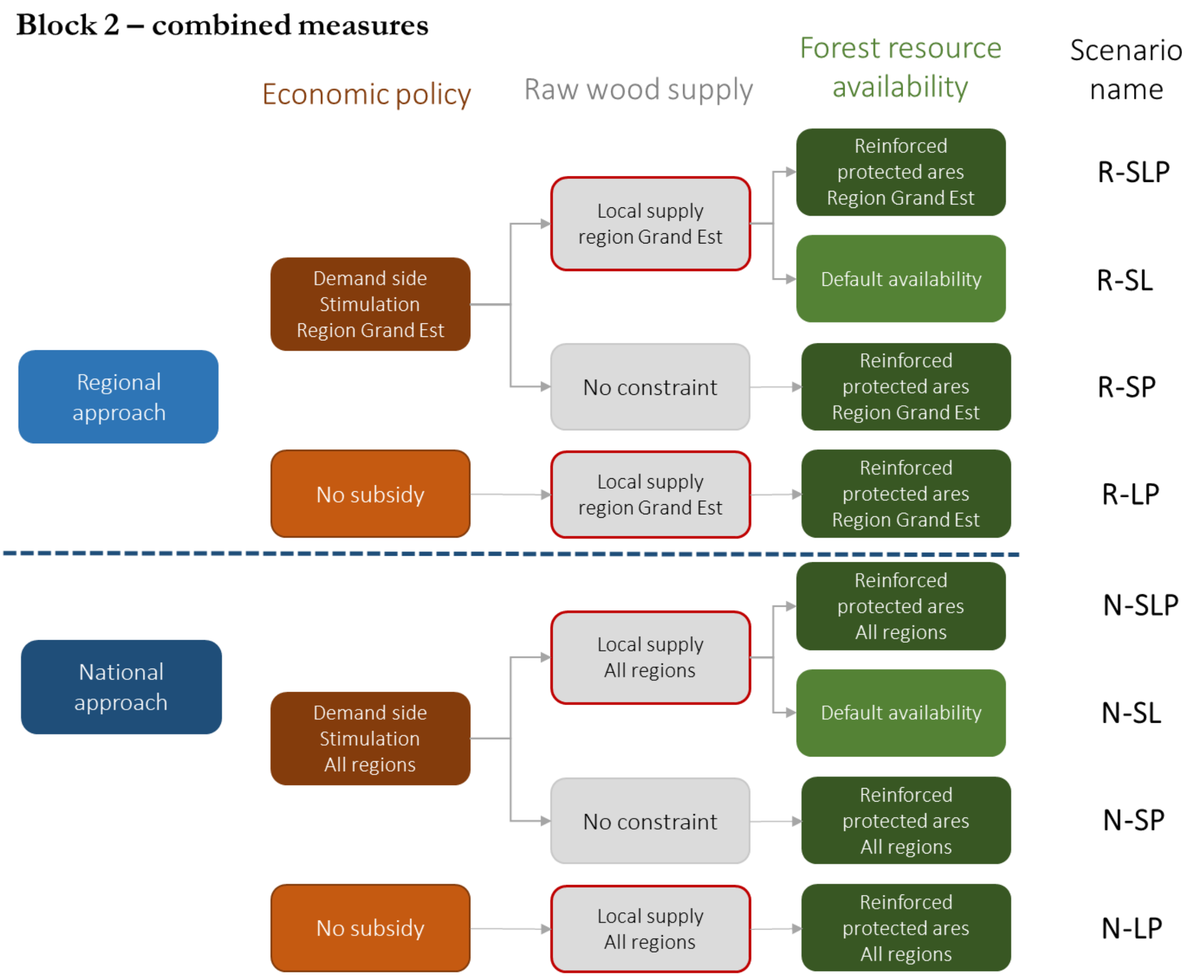

Figure III.4 – Scenarios tested in the second block - combined measures scenarios

3 Results

In this section, we describe the results of the different scenarios presented in section 2.3. First, we present the effect of each measure separately – subsidy, local supply, and reinforced natural area protection - at both national and regional scale (block 1 scenarios). Then, we show results when several measures are implemented at the same time and how their effects interact (block 2 scenarios). Finally, we analyse the effects of exogenous perturbations with a focus on an energy price shock (block 3). Results are presented as a variation percentage of the eco-efficiency of the scenario compared to the eco-efficiency of the baseline where no measure is applied.

3.1 Effect of each measure

We describe the effects of each measure at the national level, and then their effect when implemented at the Grand Est region level only. Next, we compare the performances of regional and national strategies.

3.1.1 National Scale measures

The eco-efficiency variation relative to the 3 endpoint categories in each French region is displayed for each national measure on Table III.3 and Figure III.5 below. The economic indicator is the total surplus (Producer surplus + consumer surplus - Policy cost). At this scale, the most eco-efficient measure is the subsidy, with eco-efficiency increases from 5 to 45% in most regions.

Scenario	*Environmental indicator*	*Variation % in*
		France
National 40% subsidy	Ecosystems	11%
	Human health	16%
	Resources	42%
Local supply in all regions (N-L)	Ecosystems	7%
	Human health	6%
	Resources	-6%
Reinforced natural area protection in all regions (N-P)	Ecosystems	2%
	Human health	-2%
	Resources	-14%

Table III.3 - Single measure scenarios at national scale: assessment based on Eco-efficiency variation in % compared to the baseline
Time horizon 2050.
Units: total surplus divided by endpoint impacts with surplus in M€, ecosystems impact in species.yr, human health in DALY, Resources in $.

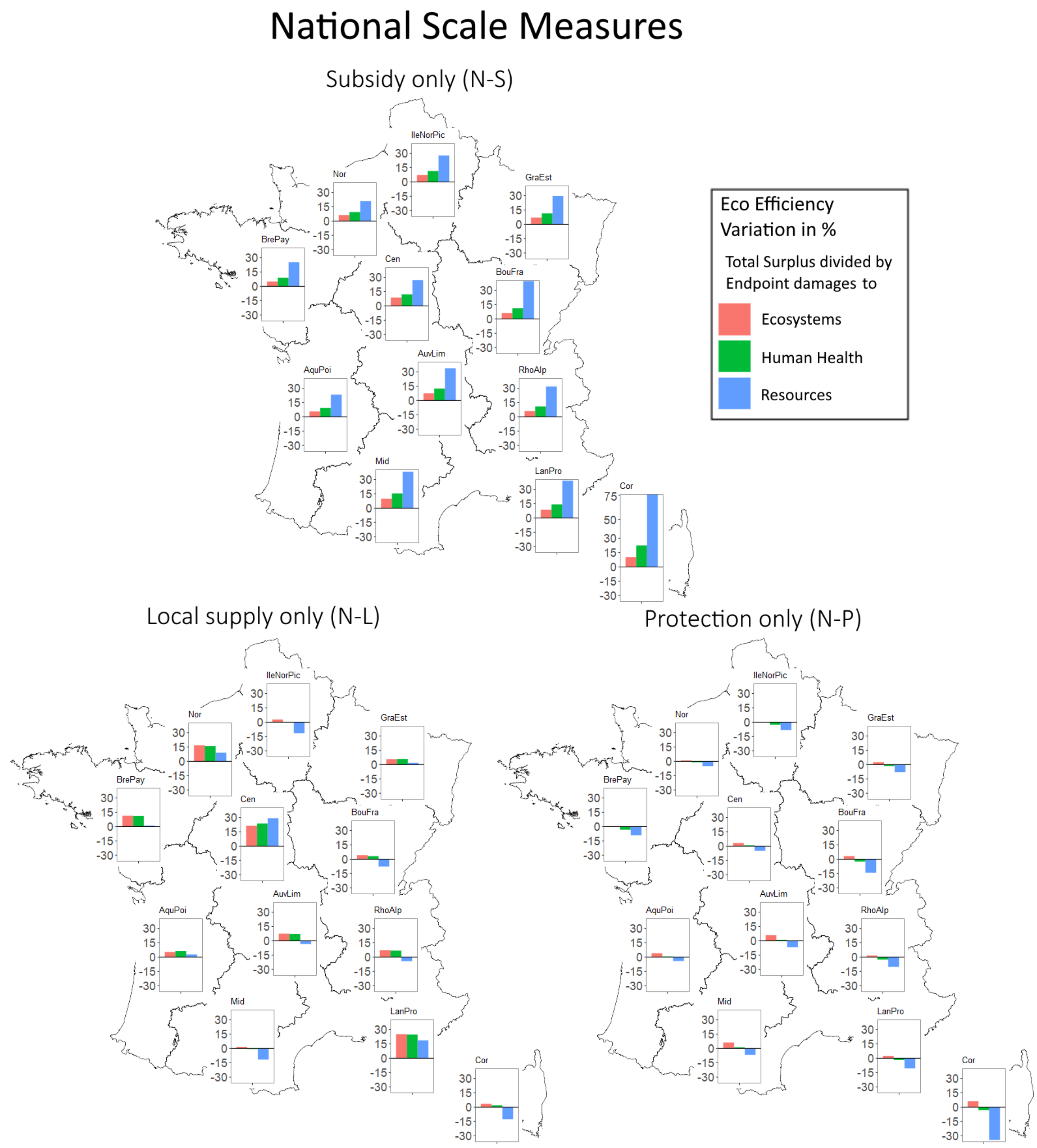

Figure III.5 - Eco-efficiency variation (in %) compared to the baseline for the three measures implemented at the national scale. Time horizon is 2050.

3.1.1.1 Subsidy

First, in terms of material flows, in all regions, wood energy consumption increases by 20% compared to the baseline scenario. This corresponds to an average increase of 0.8Mm3 in the quantities consumed, up to 1.9Mm3 for the Grand Est region. In total, the national demand for wood energy increases by 9.4Mm3. This increase in fuelwood consumption leads to a slight crowding out effect affecting paper pulp production: consumption levels for this product decrease by 5% in most regions.

Higher quantities of fuelwood produced and consumed, associated with a lower perceived price for the consumer, lead to higher producer and consumer surpluses. Even when the cost of the subsidy is included, the total net surplus increases compared to the baseline.

The subsidy measure for wood energy consumption implemented at national level systematically increases eco-efficiency in all regions for all three categories of endpoint impacts. The ecosystem category is the least favoured compared to the baseline, while the resources category is the most favoured. This is due to the positive effect of the fuelwood subsidy on the economic surplus and the impacts avoided by substitution of other energy sources. Avoided impacts have a stronger incidence on the resources category than on other impact categories. At the midpoint level, higher fuelwood consumption strongly increases eco-efficiency relative to climate change, while having little effect on land occupation, and a small negative impact on eco-efficiency compared to particulate matter formation and photochemical oxidant formation.

The subsidy benefits most regions where the wood sector is smaller and where fuelwood represents a higher share of its demand compared to other wood products, such as the region Corsica where fuelwood represents 90% of the regions' wood products demand, expressed in Mm3. The eco-efficiency increase is lower in Aquitaine-Poitou region (AquPoi) where fuelwood represents only 48% of total wood product demand.

We also investigated the effect of a higher subsidy, contributing to 60% of the market price rather than 40%. Higher wood consumption induces higher environmental impacts, but also induces higher consumer and producer surpluses. Overall, the effect on eco-efficiency increases more than proportionally with the 60% subsidy. It is mostly due to a proportionally higher economic effect due to non-linear consumers and producers' responses to subsidy.

3.1.1.2 Local supply

The implementation of the local supply measure produces contrasted variations of eco-efficiency from a region to another. We observe significant increases in 4 regions where the eco-efficiency is 10% higher compared to the baseline for the three endpoint impact categories. In 3 regions, we observe a 12% decrease in eco-efficiency relative to resources, with a trade-off with eco-efficiency relative to ecosystem preservation.

These effects stem in the way the local supply measure favours or disfavours each wood product in any given region. At national level, this measure reduces the consumption of fuelwood by 9% (-4.9Mm^3), while increasing softwood roundwood production and softwood consumption by 13% and 10% respectively (3.7 and 1.6Mm^3 respectively). Roundwoods and sawings have a higher eco-efficiency on all impact categories, due to higher value and lower environmental impacts per Mm3. Then, reduced fuelwood consumption increases environmental impacts by substitution with fossil-based heating. This explains a lower eco-efficiency compared to the baseline especially in the resources endpoint category, as the latter is most affected by the substitution effect of fuelwood.

Looking at the specific effects in each region, regions with eco-efficiency increases are the ones where fuelwood production increases. The subsequent surplus variations are more sensible in regions with i) imbalances between production and consumption, notably for fuelwood and ii) a smaller wood sector.

3.1.1.3 Reinforced natural area protection

In comparison to the baseline, a measure reinforcing natural area protection increases eco-efficiency relative to ecosystems endpoint impact and decreases the one regarding resources. Its effects on the human health category are either slightly negative or positive. This trade-off is based on a simple cause. Due to the lower availability of wood in forests, production and consumption decrease for all wood products. It results in lower producer and consumer surpluses compared to the baseline, with no policy cost. Although total surplus decreases, potential environmental impacts on the ecosystem category are also reduced, mainly due to a lower harvest. Soft roundwood (-14%), hard roundwood (-12%), and fuelwood (-10%) production levels are most affected, evenly among regions. The decrease in fuelwood consumption causes an increase in substitution impacts, which reverberates more specifically on the resource impact category.

3.1.2 Regional Scale measures

The eco-efficiency variation relative to the 3 endpoint categories in each French region is displayed for each regional measure on Figure III.6 below. Values in Grand Est and at national level are compared for each measure in Table III.4. At this scale, the most eco-efficient for Grand Est is the subsidy. Reinforced natural area protection in Grand Est increases the most eco-efficiency for all regions.

Scenario	***Environmental indicator***	***Variation in %***	
		Grand Est	**France**
Regional 40% subsidy in Grand Est (R-S)	Ecosystems	10%	1%
	Human health	17%	1%
	Resources	47%	0%
Local supply in Grand Est (R-L)	Ecosystems	8%	3%
	Human health	9%	3%
	Resources	12%	1%
Reinforced natural area protection in Grand Est (R-P)	Ecosystems	-9%	8%
	Human health	-14%	8%
	Resources	-13%	14%

Table III.4 - Single measures scenarios at regional scale: assessment based on Eco-efficiency variation in % compared to the baseline
Time horizon 2050.
Units: total surplus divided by endpoint impacts with surplus in M€, ecosystems impact in species.yr, human health in DALY, Resources in $.

3.1.2.1 Subsidy

When implemented in the Grand Est region only, the subsidy measure for wood energy consumption increases the eco-efficiency of its regional forest sector, by up to 47% for the resource endpoint category. This effect is based on a 32% increase (+3.2Mm³) of consumed fuelwood, that provides additional economic surplus while allowing avoided impacts by substitution with fossil-based heating. In parallel, we observe a crowding out effect which decreases fuelwood consumption in other regions. However, it does not offset the increase in Grand Est region, as the total fuelwood consumption for France increases by 2.1Mm³. The eco-efficiency loss in regions without subsidy is limited and varies from a 1% to 10%.

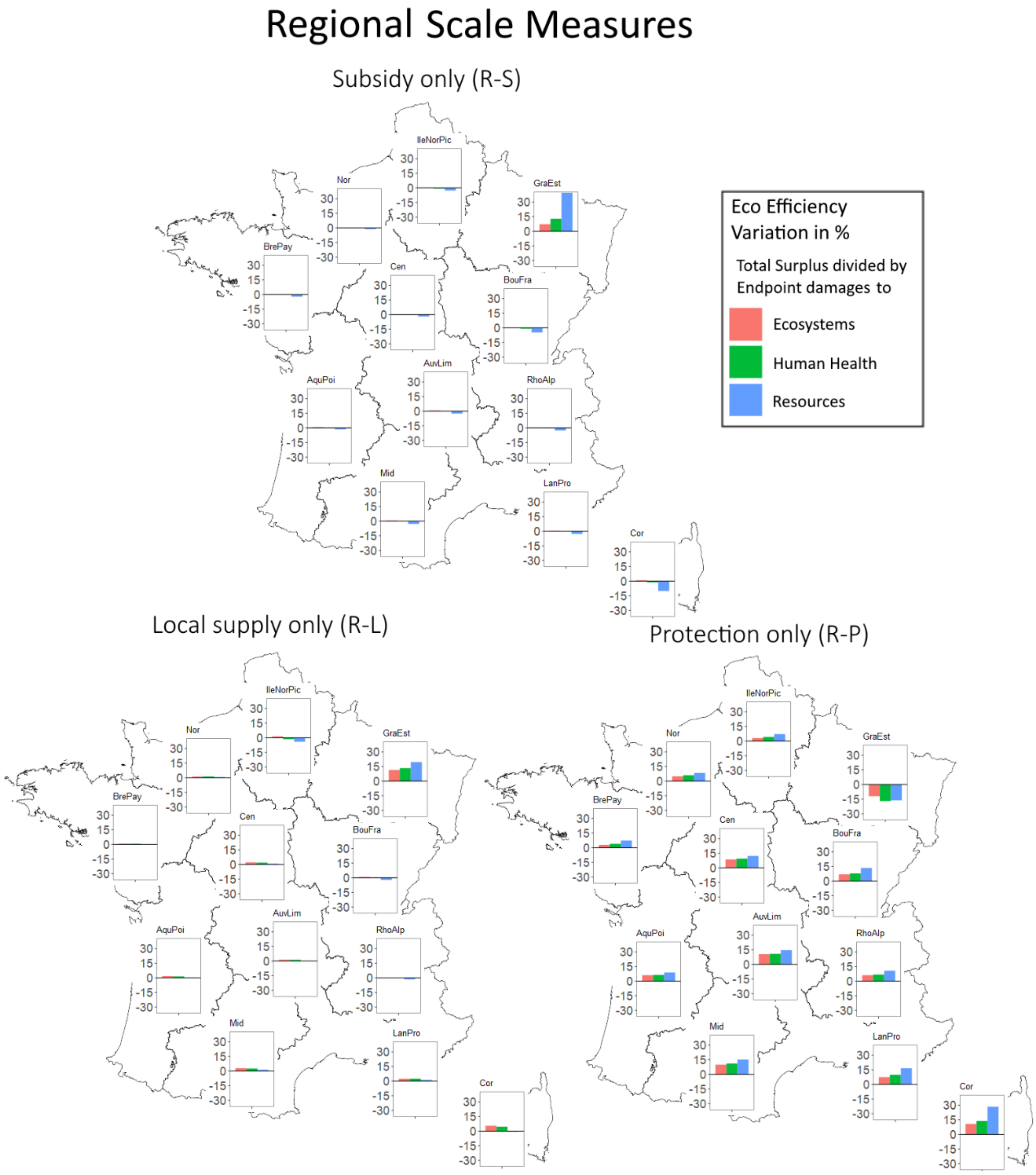

Figure III.6 - Eco-efficiency variation compared to the baseline for the three measures implemented in the region Grand Est only, time horizon 2050.

3.1.2.2 Local supply measure

The implementation of the local supply measure in Grand Est region increases its eco-efficiency compared to the baseline for all endpoint impact categories, in a range of 10-15%. Simultaneously, marginal effects spread on other regions, with slight eco-efficiency increases or decreases.

The measure stimulates roundwood production in Grand Est (+24% for softwood and +47% for hardwood) as well as fuelwood consumption (+4%). This additional production increases producer surplus in Grand Est and creates a 5-to-10% crowding effect decreasing roundwood production in other regions. This decrease is due to increasing sawings exports from Grand Est and a domino-effect-like reconfiguration of fuelwood exchanges that involved Grand Est directly and indirectly.

3.1.2.3 Reinforced natural area protection

In comparison to the baseline, reinforced natural area protection implemented in Grand Est only decreases eco-efficiency locally by 9 to 14%, while increasing it on all endpoint categories in every other region. In this scenario, the asymmetry in wood availability has led to a 70% drop in timber harvests in Grand Est, which reverberates on producer surplus. The resulting 13% decrease in total surplus directly impacts eco-efficiency: the consumption of final products, which determines environmental impacts for a given region in our framework, remains steady. Other regions benefit from the additional production that fills the Grand Est harvest gap. Fuelwood consumption increases by 2.0 Mm^3 as a whole.

3.1.3 National vs Regional measure

The comparison of the national and the regional measures shows different outcomes for each of the three measures. First, for the subsidy, the effect on eco-efficiency is similar for either a regional or a national implementation and the variation is in the same range, as shown in Table III.5.

Scenario	***Environmental indicator***	***Variation in %***				
		AquPoi	BouFra	**GraEst**	RhoAlp	**France**
National subsidy, 40% of price (N-S)	Ecosystems	7%	10%	11%	10%	**11%**
	Human health	11%	15%	15%	15%	**16%**
	Resources	27%	46%	35%	38%	**42%**
Regional subsidy, 40% of price (N-S)	Ecosystems	1%	0%	10%	0%	**-**
	Human health	0%	-1%	17%	-1%	**-**
	Resources	-2%	-5%	47%	-3%	**-**

Table III.5 - National versus regional subsidy scenarios: assessment based on Eco-efficiency variation in % compared to the baseline.
Regions: Grand Est (GraEst), all of France, and three major wood-producing regions: Aquitaine-Poitou (AquPoi), Bourgogne–Franche-Comté (BouFra), Rhône-Alpes (RhoAlp).
Units: total surplus divided by endpoint impacts with surplus in M€, ecosystems impact in species.yr, human health in DALY, Resources in $.

This similarity can be explained by the structure of the model: all regions have the same supply and demand functions. Variability is based solely on the availability of wood in the forest, and the Grand Est region has an abundant resource.

Second, we have seen that the reinforced natural area protection measure has different effects according to its implementation scale. This is displayed in Table III.6. At the national level, reinforced natural area protection (N-P) has a similar effect in all regions and causes a general decrease in production. It has a mixed effect on eco-efficiency. Implemented regionally (R-P), it clearly benefits all regions but the one where it is set. Notably, this conclusion may vary in a region with a small forest sector. If we compare the national economic effects of both measures, total surplus for the whole French Forest sector decreases by 2% with the national measure (N-P) when it increases by 3% with the regional one (R-P) – taking account of the 13% total surplus decrease for the concerned region. A national forest protection measure costs more than a local one in terms of eco-efficiency at a national level.

Scenario	***Environmental indicator***	***Variation in %***				
		AquPoi	BouFra	**GraEst**	RhoAlp	**France**
National reinforced natural area protection (N-P)	Ecosystems	4%	3%	**2%**	1%	**2%**
	Human health	1%	-3%	**-3%**	-4%	**-2%**
	Resources	-5%	-16%	**-10%**	-13%	**-14%**
Region Grand Est reinforced natural area protection (R-P)	Ecosystems	5%	7%	**-9%**	8%	**8%**
	Human health	5%	8%	**-14%**	9%	**8%**
	Resources	8%	14%	**-13%**	14%	**14%**

Table III.6 - National versus regional protection scenarios: assessment based on Eco-efficiency variation in % compared to the baseline.
Regions: Grand Est (GraEst), all of France, and three major wood-producing regions: Aquitaine-Poitou (AquPoi), Bourgogne–Franche-Comté (BouFra), Rhône-Alpes (RhoAlp).
Units: total surplus divided by endpoint impacts with surplus in M€, ecosystems impact in species.yr, human health in DALY, Resources in $.

Third and last, the local supply in Grand Est (R-L) shows similar patterns in Grand Est that to those observed at national scale (N-L), but the measure spread effects are too small to be significant.

3.2 Combined effects

3.2.1 National Scale

Values at national level are compared for each scenario in Table III.7. Maps are displayed on Figure III.7 below.

Scenario	***Environmental indicator***	***Variation in %***				
		AquPoi	BouFra	**GraEst**	RhoAlp	**France**
Subsidy + Local supply (N-SL)	Ecosystems	9%	7%	**9%**	14%	**16%**
	Human health	15%	10%	**13%**	20%	**21%**
	Resources	30%	20%	**21%**	36%	**40%**
Subsidy + Protection (N-SP)	Ecosystems	7%	10%	**11%**	10%	**11%**
	Human health	11%	15%	**15%**	15%	**16%**
	Resources	27%	46%	**35%**	38%	**42%**
Local supply + Protection (N – LP)	Ecosystems	10%	7%	**4%**	6%	**8%**
	Human health	4%	-10%	**-8%**	-5%	**-3%**
	Resources	-8%	-48%	**-32%**	-30%	**-37%**
Subsidy + Local supply + protection (N-SLP)	Ecosystems	9%	6%	**9%**	14%	**16%**
	Human health	15%	10%	**13%**	21%	**21%**
	Resources	29%	19%	**21%**	37%	**40%**

Table III.7 - Combined measures scenarios at national scale: assessment based on Eco-efficiency variation in % compared to the baseline.
Regions: Grand Est (GraEst), all of France, and three major wood-producing regions: Aquitaine-Poitou (AquPoi), Bourgogne–Franche-Comté (BouFra), Rhône-Alpes (RhoAlp).
Units: total surplus divided by endpoint impacts with surplus in M€, ecosystems impact in species.yr, human health in DALY, Resources in $.

At this scale, the most eco-efficient scenario is the combination of the subsidy with local supply (N-SL), on equal terms with the scenario combining subsidy, local supply, and protection altogether (N-SLP). The combination of subsidy and protection (N-SP) provides slightly lower eco-efficiency increases. The scenario combining local supply and protection (N-LP) is the least beneficial, with negative effects, limited on human health but high on resources. It leads to an unbalanced trade-off between eco-efficiency relative to the ecosystem indicator (+8% for France) and eco-efficiency relative to the resource indicator (-37% for France). All wood productions are lower in this scenario, due to protection, with fuelwood consumption variation reaching -30% (-11.3Mm^3) nationwide.

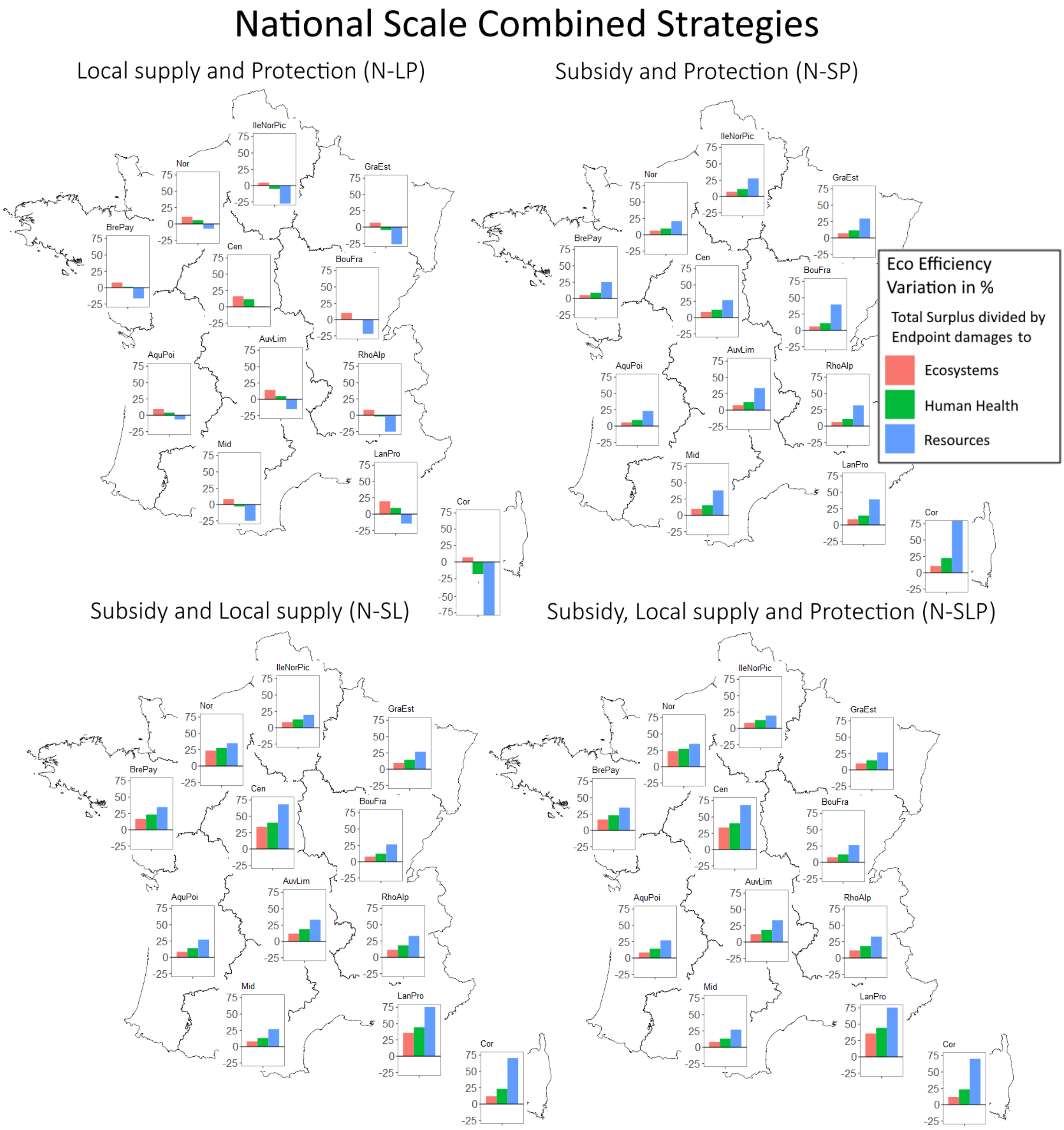

Figure III.7 - Eco-efficiency variation compared to the baseline for the four combined measures implemented at the national scale. Time horizon 2050.

Measures interact in diverse ways when combined in scenarios. The scenario combining subsidy and local supply (N-SL) shows a situation where both measures applied simultaneously create a synergy, making it one of the most favourable situations in terms of eco-efficiency. Eco-efficiency for France reaches +16% relatively to ecosystems, +21% for human health, and +40% for resources, compared to +11%, +16% and +42% respectively for the sole subsidy scenario (N-S). The local supply policy favours roundwoods while the subsidy allows one to maintain fuelwood demand, meaning that the eco-efficiency effects of the subsidy compensate the negative effects that the local supply measure alone has on the resource impact category in certain regions.

In the combination of local supply and protection (N-LP), we observe clear amplifications, as in region Grand Est, Corsica (Cor) or Centre (Cen), rather than a simple addition of the separate effects of the two measures. Otherwise, the additional effect of reinforced protection is null if this measure is combined with the fuelwood consumption incentive (N-SP). Subsidy and protection together produce effects almost completely similar to the scenario with the national subsidy alone (Table III.5). Similarly, the combination of the three measures (N-SLP) gives the same result as the combination of the subsidy and the local supply (N-SL). An explanation to this observation is that the protection measure alone provokes a lower wood availability which disincentivizes production, but the wood resource is sufficient in French forests to meet a higher subsidized demand, even if a significant portion is retrieved from the available stock. However, we must note that compared to the scenarios without protection, a similar eco-efficiency is reached with fewer areas harvested.

3.2.2 Regional Scale

Scenarios based on combined regional level measures are shown in Table III.8. The most eco-efficient regional scenario is the combination of the subsidy with local supply (R-SL).

Scenario	***Environmental indicator***	***Variation in %***				
		AquPoi	BouFra	**GraEst**	RhoAlp	**France**
Subsidy + Local supply Grand Est (R-SL)	Ecosystems	2%	1%	**18%**	0%	**4%**
	Human health	2%	-1%	**25%**	0%	**3%**
	Resources	0%	-6%	**59%**	-3%	**2%**
Subsidy + Protection Grand Est (R-SP)	Ecosystems	2%	2%	**8%**	3%	**4%**
	Human health	1%	1%	**11%**	2%	**3%**
	Resources	0%	-2%	**40%**	1%	**3%**
Local supply + Protection Grand Est (R-LP)	Ecosystems	4%	5%	**3%**	5%	**7%**
	Human health	3%	-1%	**1%**	5%	**6%**
	Resources	4%	-6%	**6%**	7%	**7%**
Subsidy + Local supply + Protection Grand Est (R-SLP)	Ecosystems	4%	5%	**13%**	6%	**8%**
	Human health	3%	-3%	**17%**	5%	**7%**
	Resources	3%	-12%	**50%**	4%	**8%**

Table III.8 - Combined measures scenarios at regional scale: assessment based on Eco-efficiency variation in % compared to the baseline.
Regions: Grand Est (GraEst), all of France, and three major wood-producing regions: Aquitaine-Poitou (AquPoi), Bourgogne–Franche-Comté (BouFra), Rhône-Alpes (RhoAlp).
Units: total surplus divided by endpoint impacts with surplus in M€, ecosystems impact in species.yr, human health in DALY, Resources in $.

The effects of the two measures add up straightforwardly. It is the most eco-efficient scenario relatively to the Grand Est region, but it has negative eco-efficiency effects on other regions, as shown in Table III.8. Adding protection in Grand Est region (R-SLP) slightly lowers the Grand Est region eco-efficiency compared to the R-SL scenario. However, if we consider the impact on other regions, the R-SLP scenario increases eco-efficiency as well as production and value in most of them. Moreover, the protection measures implies that an eco-efficiency level similar to the R-SL scenario is reached while using less forest areas.

The subsidy and protection measures combined (R-SP) also alleviate each other's effects. The loss of eco-efficiency due to the reinforced natural area protection in the Grand Est remains less than the gains related to the subsidy. At the same time, as for the R-SLP scenario, protection in the Grand Est measure benefits other regions. More specifically, compared to the scenario with protection in Grand Est only (R-P, Table III.6), the targeted region loses less roundwood production and significantly increases its fuelwood consumption thanks to the subsidy.

At this scale, the assessment of the LP scenario is twofold. At the regional level, the eco-efficiency gains for the Grand Est region due to the local supply measure make up the shortfall of the eco-efficiency loss related to the protection measure. Its effect is almost neutral. If we consider the effect at the national level, this combination provides an increased eco-efficiency in most other regions. Adding regional variations to calculate nationwide benefits, it ends up appearing as one of the most eco-efficient measures at this scale with a 5% to 8% increase compared to the baseline in each endpoint impact category, although regional measures are not meant to develop other areas.

3.3 Shock due to high energy prices

We tested the effect of a shock, consisting of sharp increase in energy prices, in addition to all previous scenarios. In our framework, higher energy prices stimulate fuelwood demand. Due to the substitution process, the shock on energy prices systematically increases the surplus of the wood sector at no cost, as well as the avoided impacts, thus increasing its eco-efficiency concomitantly. We display below on Figure III.8 the results for a given scenario, e.g. local supply at national scale (N-L), when it is affected by the energy shock.

Without shock, this measure showed a trade-off in eco-efficiency between Ecosystems and Resources (Table III.3). In this case, the benefits of higher fuelwood demand due to high-energy prices overlap the negative effects of local supply. The increase in total eco-efficiency ranges from 10% for ecosystems to 60% for the resource impact category.

These results may be generalized for all scenarios: benefits of the substitution effect add up to the ones of the public policies.

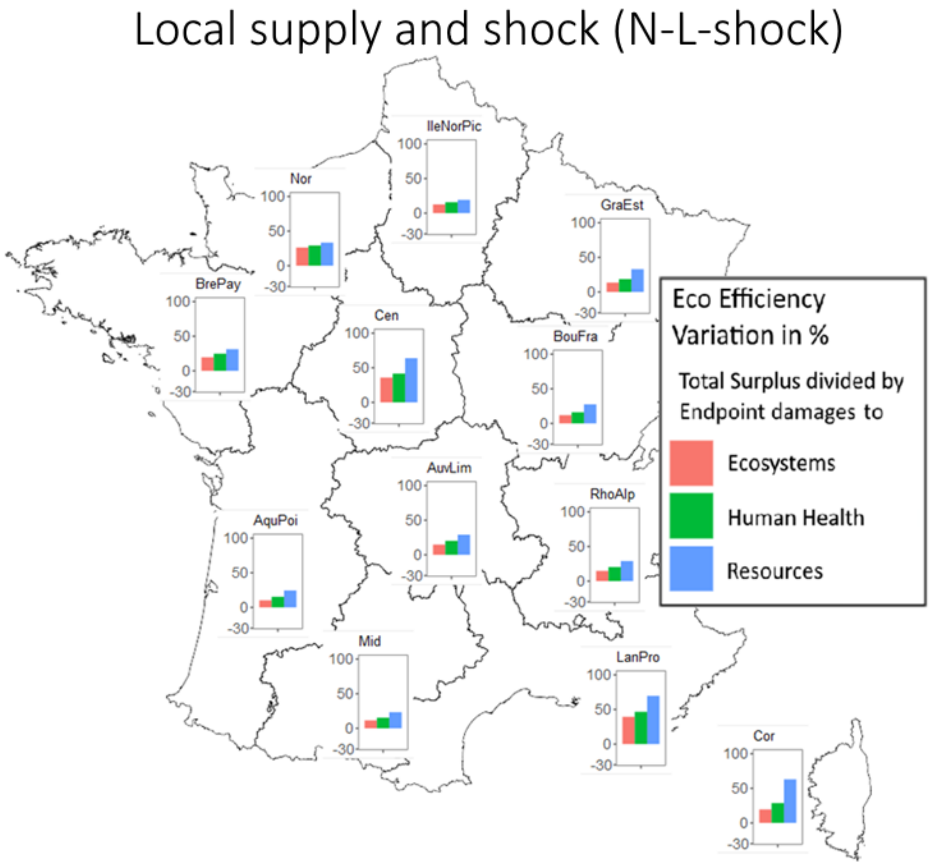

Figure III.8 - Eco-efficiency variation compared to the baseline for the local supply measure at national scale combined with a shock on energy prices. Time horizon 2050.

4 Discussion

First, we explore the implications of our results for decision-making when designing bioeconomy development strategies. Second, we will discuss the limits inherent to our modelling framework and its underlying hypothesis. Last, we review opportunities to further explore the sustainability of bioeconomy strategies.

4.1 Supporting decision-making

Bioeconomy strategies based on wood energy have a strong potential to support sustainable transition at both national and regional scale. Our results showed that most of the scenarios studied allowed increasing eco-efficiency, generally in all endpoint categories. Some policies appeared to be more eco-efficient than others were. Comparing eco-efficiency allowed us to rank the strategies according to their performances at a given scale.

Among single measures, the subsidy provides the highest eco-efficiency increases, at both scales. However, it should be noted that this result serves as a basis for the analysis of combined measurement scenarios, rather than a comparison of policies with different objectives and implementation costs. When it comes to combined measures, results differ between the national and the regional scale. The combination of subsidy and local supply at national level (N-SL) is the most eco-efficient, on par with the combination of subsidy, local supply, and natural area protection (N-SLP). At regional scale, local supply and subsidy (R-SL) increase more eco-efficiency in Grand Est than in the case where natural area protection is added to the regional policy mix (R-SPL), as the protection measure favours other regions. Last, the energy price shock systemically increases eco-efficiency for all measures, by driving further up fuelwood demand and thus benefits from the substitution effect.

Underlying these diverse outcomes, we can extract two observations: i) the scale of implementation can affect the performance of a measure; ii) at both scales, the effects of the measures tend to add up – and more, to create synergies- or compensate each other.

i) The scale of implementation can affect the performance of a measure. Indeed, while the subsidy has the same effect, in the same order of magnitude at both scales, local supply and reinforced natural areas protection have different effects between national and regional scale. This is due to the level of regionalisation of the parameters on which each of these measures is based. First, the subsidy is a measure based on the demand function of the market module, which is the same for every region. Meanwhile, local supply plays on transport costs that differs for every region, according to distance, and disrupts trade equilibria that are specific to each region. Last, reinforced natural area protection acts directly on the forest resource module that integrates strong regional differences, but conveys a moderate effect on the supply function.

These results comfort the hypothesis that when implementing regional policies for the achievement of national objectives, regional institutions should carefully consider their local characteristics. More specifically, policies applying on variables with high degrees of interregional homogeneity (e.g. consumption patterns) can be implemented uniformly region wise, while policies applying on variables with stronger levels of heterogeneity (e.g. forest resources) should be treated taking into account local specificities.

At both scales, the effects of the measures tend to add up or compensate each other, with a few exceptions where non-linear effect appear, such as the LP scenarios combining local supply and reinforced natural areas protection. This exception may find ground in relation to the characteristics of the measures taken independently. Local supply and reinforced natural areas protection both act most on roundwood and fuelwood supply, each measure disrupting the other's effect, with an action on products which have opposed profiles in terms of economic and environmental performance.

We infer from these results the following policy recommendation: when implementing policies, local and national institutions should include in their decision process the potential adverse effects they may have on other sectoral policies, in order to facilitate synergies and avoid trade-offs.

4.2 Indicators and Model limits

Our approach is constrained by the capabilities of our model and its limitations. The simulation of each measure relies on specific mechanisms, whose ability to represent reality is based on more or less strong assumptions.

First, we can add some perspective to these results by decomposing the 3 indicators used to compute eco-efficiency. Indeed, the indicator encompasses a wide range of interactions, at multiple scales to allow us to condensate these effects into a single indicator for comparisons. Its shortcoming is that it may hide pieces of information that are relevant to policy making. For instance, being a comparative ratio, eco-efficiency ratios do not necessarily provide clear information on the absolute quantities produced. Yet absolute values may be a key element of appreciation of the policies. Absolute indicators for economic value are easy to measure but are difficult to forecast realistically in the long run. Indeed, prices calculated in a simulation model as FFSM and economic surplus in general are useful in a comparative approach but have a limited signification in absolute terms. On the environmental side, challenges lies in estimating both potential impacts and planetary boundaries (Bjørn *et al.*, 2016; Chandrakumar and McLaren, 2018; Bjørn, Richardson and Hauschild, 2019).

Results showed that the substitution effect inherent to increased or decreased fuelwood use was a major determinant to eco-efficiency. This requires future improvements in the modelling of fuelwood-fossil fuel competition, in three areas. First, the economic mechanism that we use to implement competition with the energy sector is based on cross price elasticities and relative variation of prices from one year to another between the two products. A framework explicitly modelling the energy sector would be more accurate. Such approaches have been carried out in previous works (Caurla *et al.*, 2018; Albers *et al.*, 2019). Second, our assumptions on the energy mix, with fuelwood necessarily substituting fossil fuels for heating purposes, put the avoided impacts in the upper range of substitution benefits. In fact, electric heating is present in 30% of French households, with a steady share, while electricity consumption has a low carbon impact

profile in France due to the share of nuclear power in the electricity mix. Third, the energy mix we chose is static, while we work on a time horizon of 30 years. In this period, the share of renewables, gas power or biomass itself is likely to increase, and such scenarios on the evolution of the French electricity mix would modify significantly the assessment. Thus, a dynamic LCA based on evolutive emission factors would be worth considering.
Further in this perspective of long-term changes, the physical impact of climate change on forests has to be taken into account. Increases of tree mortality in French regions were introduced in preliminary scenarios but showed no significant effect on wood supply. Previous works on French forests indicate that changes in the composition of forest stands can be expected on a longer time horizon, beyond 2080 (Lobianco *et al.*, 2015; Lobianco, Caurla, *et al.*, 2016).

Another limitation to our model is the mechanism used to represent wood product transportation. Samuelson's spatial equilibrium is a theoretical approach to study trade between regions. Calculated flows may differ from observed flows for various reasons (historical value chains, regional infrastructures such as harbours, presence of borders with a foreign country…). However, it is to note that i) actual flows are difficult to estimate due to data collection issues ii) quantities of primary products traded in the simulation correspond the order scales of actual flows (Courtonne and Wawrzyniak, 2019) iii) our analysis showed that wood product trade in this order of magnitude had a limited significance on environmental impacts – up to 3% of the total contribution to environmental impacts of all wood products.

Other potential improvements to our modelling framework include enhanced spatializations and the implementation of feedback loops regarding ciruclarity. Downstream in the forest sector, a key aspect of policies directed towards the increasing use of biomass is to encourage cascading use of wood, by prioritizing material use and directing harvest and sawmill residues to energy production purposes. Modelling more explicitly the different categories of wood residues in FFSM would allow one to more precisely take into account these stakes. Spatializing production units such as sawmills would permit localizing residue production potential.

Coupling economic and environmental models is particularly relevant when feedback loops are implemented between the two components. A mechanism connecting harvested volumes with forest management inventories should be explored to investigate intensification/extensification strategies.

4.3 Bioeconomy strategies design

The main benefit of our approach using eco-efficiency is to put diverse effects on a common ground, allowing us to sort out which ones are predominant in a complex system of interactions. Moreover, it ought to be an iterative approach: comparing scenarios leads to identifying which model mechanism and which measures weight most in the eco-efficiency. The comparison process puts forward which interaction effects have to be targeted to, in order to enhance hypothesis and subsequently, modelling accuracy. Working simultaneously on economic and environmental performance avoids putting efforts on processes with significant environmental impacts but negligible economic value, and inversely.

Several choices in the design process of bioeconomy strategies show room for alternatives and improvements.

A first path would be to test the effect of regional strategies in a region with a less developed wood sector than the Grand Est region. Taking account of the characteristics of each region, several possibilities exist to enrich the implementation of the subsidy measure. In a perspective of ex-ante policy assessment, the subsidy could be adjusted for each region according to natural biomass growth. Another way to orient subsidy calibration would be to determine levels that optimize surplus for each region, according to resource availability.

More generally, an improved spatialization of the model would pave the way for a deeper analysis of regional strategies. On the economic side, defining regional supply function or spatializing production units and wood flows would allow one to investigate on the effects of the local implementation of large-scale production units. These improvements would be accompanied by an enhanced environmental modelling of forest management practices, and notably, the intensity of management regarding yield.

Other bioeconomy strategies could be considered. A possibility would be to test supply side economic incentives. However, these types of incentives are difficult to implement in reality in France, due to the fragmented structure of forest ownership. 75% of French forests are privately owned, among which two thirds are properties of an area inferior to one hectare. As a result, supply-side public policies are significantly less developed than demand side ones. Moreover, we integrated noneconomic supply side incentives in the form of the local supply measure.

Increasing resource availability as a supply side measure to increase wood production is an option that has been explored. However, it had no significant effect on surplus compared to scenarios with baseline availability. The availability of forest resources in France and in Grand Est region is already very high even in the baseline scenario. Recent work on the effect of increased conservation at global scale show moderate economic effect, due to this high availability in most European countries (Kallio, Moiseyev and Solberg, 2006). However, these characteristics could be affected by future climate change in ways that are difficult to predict. Forest growth available for harvest is expected to decrease (Lobianco, Caurla, *et al.*, 2016).

Measures targeting non-energy wood products could also be explored as another range of bioeconomy strategies to increase eco-efficient economic development. Increased use of wood products for material use presents a high potential of reducing the environmental impacts of diverse construction and manufacturing activities while creating added value locally. Moreover, combining wood uses as fuel and material uses in a perspective of cascading use of wood is advocated for in bioeconomy strategy recommendations. However, such policies do not reach yet the quantities of wood mobilized by energy-oriented measures. Moreover, testing such scenarios in our framework presents a methodological challenge. Including substitution effects for the construction sector would require to model this economic sector at the regional level as it has strong local specificities, contrary to the energy sector.

5 Conclusion

The goal of our study was to investigate jointly the economic and environmental performance of strategies oriented towards energy wood development in the French forest sector, implemented both at national and regional levels. Notably, this approach aims to provide usable assessment for regional governments and stakeholders. In this perspective, we developed and used an integrated indicator, eco-efficiency, built upon a framework coupling economic and environmental models. This indicator offers interesting perspectives, both for the comparison of scenarios and for the communicability of results. This eco-efficiency metric is defined as the ratio of an economic performance indicator divided by environmental impacts indicators. To do so, we developed and used an integrated modelling approach combining an economic forest sector model with LCA assessment to compute eco-efficiency ratios at regional and national scales. Using such a simulation model allows one to take account multiple interactions (markets, scales, time dynamics), effects of which may be difficult to isolate and sort out ex-ante. This aspect is particularly at stake at the regional scale.

We translated several types of measures into scenarios that represent some of the current trends in public policy and local initiatives: economic incentives to fuelwood demand, local supply promotion, and forest conservation. We also included an energy price shock, to simulate an external factor.

We produced various combinations of these measures at both national and regional scale and computed subsequent eco-efficiency ratios. Results showed that economic incentives in the form of a fuelwood subsidy increased eco-efficiency most compared to the baseline, at regional and national level. This result lies notably on the benefits of avoided impacts from substitution fossil fuels by fuelwood. Combining this measure with protection and/or local supply measures tended to increase or decrease slightly its eco-efficiency depending on the scale of implementation.

Our framework showed that various factors determine the eco-efficiency of a policy in any given region, especially, the characteristics of the forest resource, the importance of the local wood sector on the supply as well as the demand side, and the characteristics of its neighbouring regions. Model parameters such as trade mechanisms, supply and demand functions, competition between fuelwood and fossil fuels, or Life Cycle Impact Assessment for the energy mix are critical to the relevancy of the results. Refining model hypothesis will be a way to enhance accuracy. Long-term changes in the structure of global markets, energy supply, or even climate conditions, are also significant factors to the sensitivity of the impact assessment.

Further exploration of the economic and environmental performance of bioeconomy strategies would require new developments to our framework. Disaggregating industry wood, fuelwood and residues would enable us to investigate the effects of policies integrating cascading use of wood products. A deeper spatialization of the model, notably of production units, would provide a better mapping of wood flows and tensions on the resource at a local scale. This paves the way for future research.

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IV

Discussion générale

Les trois articles présentés en chapitres 1, 2 et 3 ont permis de proposer une méthode pour évaluer l'éco-efficience de stratégies de développement de la bioéconomie menées à des échelles régionales et nationales en développant une approche couplant modélisation économique et environnementale. Les métriques issues de ce travail permettent d'apporter des éléments quantitatifs aux décideurs pour accompagner la transition écologique sur leur territoire. Nous proposons à présent de discuter ces apports, en identifiant les principales limites et les perspectives de recherche à venir.

1 Apports

Notre approche se caractérise par une évaluation de la performance économique et environnementale d'une filière, le secteur forestier, dans un territoire, basée sur des indicateurs intégrés produits par un modèle de simulation. Les apports de ce travail sont de plusieurs ordres, à la fois méthodologiques, décisionnels et disciplinaires.

1.1 Apports méthodologiques

Les apports méthodologiques de notre approche portent sur trois principaux points : i) le couplage de modèles économiques et environnementaux, ii) la production d'indicateurs intégrés, et iii) l'intégration d'interactions multi-échelles.

1.1.1 Couplage entre modélisation économique et environnementale et équilibre des flux

Un couplage de type « soft-coupling » a été développé entre le modèle économique de secteur forestier FFSM et une ACV des produits bois issus du secteur forestier français. Les quantités de produits bois calculées par FFSM sont reliées à des inventaires de cycle de vie (ICVs) par produit pour établir l'ensemble des flux élémentaires (consommations de ressources et émissions de substances polluantes) liés aux activités de la filière forêt bois. Le modèle FFSM a fourni par ailleurs des indicateurs économiques en fonction des prix et des quantités qui, combinés aux indicateurs d'impacts environnementaux quantifiés à partir de l'inventaire de cycle de vie, permettent de produire des ratios d'éco-efficience.

Un des apports méthodologiques importants dans ce couplage a été de mettre en place une démarche permettant de respecter au mieux le bilan matière entre les trajectoires du secteur forestier et les inventaires du cycle de vie. La construction de modèles intégrant une modélisation cohérente des processus de fabrication sur l'ensemble du cycle de vie constitue un défi technique important. Cette difficulté résulte de choix d'agrégation et de la quantité de données à récolter pour modéliser des chaînes de valeur mondialisées (Pauliuk *et al.*, 2017). La démarche proposée consiste à équilibrer les flux de matières entre le modèle économique FFSM et la modélisation ACV. Les paramètres influençant ces flux sont les valeurs des rendements des processus de transformation des produits bois ou les proportions des co-produits issus des processus de transformation à sorties multiples. Ils ont été homogénéisés grâce à deux sources de données : d'une part, une analyse de flux de matières de la filière forêt bois française qui contient des données désagrégées et régionalisées sur les flux de produits de la récolte forestière aux industries de première et deuxième transformation (Lenglet, Courtonne and Caurla, 2017; Courtonne and Wawrzyniak, 2019) ; et d'autre part, la modélisation des processus « bois » dans la base de données Ecoinvent, basée sur des données moyennes représentatives des pratiques de la filière bois en Suisse et en Allemagne, et adaptées au contexte français. Les données d'analyse de flux matière sont privilégiées, excepté dans les cas où les données de Ecoinvent offrent un niveau de désagrégation plus fin. Elles sont appliquées dans FFSM aux coefficients de la fonction de production de Leontief utilisée pour la transformation intermédiaire, et pour l'ACV, aux coefficients de rendements entre processus Ecoinvent. Cela permet de mettre en place des règles de conservation de la matière cohérentes entre deux modèles qui représentent chacun en parallèle les mêmes flux physiques. Cette approche innovante est mise en œuvre pour la première fois pour le secteur forestier pour un couplage entre ACV et un modèle d'équilibre. Elle a été explorée pour un couplage ACV – équilibre partiel appliqué au secteur de l'élevage laitier par Salou (2017). Les premiers travaux de couplage entre modèles économiques et ACV utilisent directement des sorties économiques sans vérifier la cohérence des flux de matières (Earles and Halog, 2011; Buyle, Pizzol and Audenaert, 2018). Cela peut conduire à des estimations des impacts d'environnementaux qui ne correspondent pas aux quantités physiques de flux de produits bois calculées par le modèle économique. Ainsi, dans notre cas d'étude, l'utilisation les données de rendements directement issues d'Ecoinvent aurait conduit à sous-estimer les impacts environnementaux attribuables au bois rond destiné aux sciages, par rapport aux quantités et à la valeur économique liées à leur exploitation, donc à surestimer leur éco-efficience par rapport aux produits dérivés du bois d'industrie.

1.1.2 Le développement d'indicateurs d'éco-efficience sectoriels et multisectoriels

Les indicateurs d'éco-efficience produits par notre modèle de simulation sont calculés comme le ratio d'un indicateur économique, le surplus économique total, et d'indicateurs environnementaux, les impacts potentiels au niveau midpoint ou endpoint. Ils présentent plusieurs avantages par rapport à ceux déjà produits dans la littérature. Premièrement, l'indicateur économique utilisé, à savoir le surplus économique total, fournit une évaluation plus sophistiquée de la création et de la répartition de la valeur économique dans la filière forêt bois qu'une simple mesure des quantités et des prix. En effet, le surplus économique total est une mesure du bien-être économique de l'ensemble du secteur forêt-bois. Il tient compte des relations non linéaires entre, d'une part, les quantités produites, les coûts de production et la disponibilité de la ressource au niveau des producteurs et, d'autre part, le prix des produits et les quantités consommées chez les consommateurs. Cet indicateur de surplus agrège ainsi plusieurs niveaux de connaissances sur le comportement des agents économiques. Il résulte d'une part du choix des formes fonctionnelles de la demande et de l'offre de produits bois et, d'autre part, de la calibration de ces fonctions, en particulier des élasticités-prix (Caurla, 2012). Contrairement à des estimations des prix ou des quantités déconnectées du reste de l'économie du secteur, l'utilisation d'un cadre de modélisation en équilibre partiel pour le calcul de ce surplus permet de rendre compte des interconnexions entre les activités d'offre et de demande. De ce point de vue, l'indicateur « Partial Eco-Efficiency » défini dans le chapitre 2, basé sur le ratio du surplus de la filière rapporté aux impacts environnementaux potentiels, étend le champ des effets économiques pris en considération par rapport aux indicateurs d'éco-efficience calculés dans des approches comparables, sectorielles et régionalisées. Cela constitue une approche originale par rapport à des travaux proposant des indicateurs d'éco-efficience calculés sur des quantités de produits uniquement (Basset-Mens, Ledgard and Boyes, 2009), mais aussi par rapport à des ratios développés sur des indicateurs de valeur ou de valeur ajoutée tirés de modèles purement linéaires comme des tables Input Output (Egilmez, Kucukvar and Tatari, 2013).

Deuxièmement, notre approche intègre une large gamme d'indicateurs environnementaux, conformément à l'approche multicritère caractéristique de l'ACV. L'intérêt de l'évaluation d'indicateurs environnementaux multiples réside notamment dans la possibilité d'identifier d'éventuels transferts de pollution entre catégories d'impacts environnementaux. Parmi les catégories d'impacts midpoint, les enjeux pour la filière forêt bois résident notamment sur les catégories du changement climatique, de l'utilisation des terres, des émissions de particules de fines liées à la consommation de bois-énergie, et de la consommation de ressources non renouvelables. Ainsi, à surplus économique équivalent, favoriser l'utilisation de bois-énergie pourra occasionner un transfert d'impact des catégories « écotoxicité » ou « utilisation des terres » vers « formation de particules fines », selon qu'elle se substituera à une production de pâte à papier ou de panneaux.

Troisièmement, l'indicateur « Full Eco-Efficiency » présente l'avantage d'étendre le champ des effets indirects capturés dans la métrique, en prenant en compte des interactions multi-secteurs et multi-échelles. Dans notre application, nous intégrons les impacts environnementaux évités par effet de substitution entre le bois-énergie et des énergies fossiles pour la production de chaleur par rapport à un scénario de référence où aucune mesure ou contrainte ne s'applique. Nous calculons un ratio des impacts évités par rapport aux impacts potentiels (Impact Avoidance Ratio). Nous obtenons la « Full Eco-efficiency, FEE » en pondérant l'indicateur « Partial Eco-Efficiency, PEE » par ce ratio. Les deux approches, PEE et FEE, mènent à des conclusions différentes. Comme nous l'avons vu dans le 2e chapitre, Partial Eco-efficiency ne permettrait pas de conclure à des gains d'éco-efficience significatifs suite à la mise en place d'un scénario de subvention de la demande de bois-énergie, alors que Full Eco-efficiency montre une augmentation claire sur l'éco-efficience relative à la santé humaine et à la consommation de ressources non renouvelables. Cette comparaison illustre l'intérêt de considérer les impacts évités, quand bien même cela rajoute un paramètre et donc des risques d'incertitude (par exemple, le niveau de substitution par le bois-énergie, ce qui est l'hypothèse forte).

1.2.3 La prise en compte d'interactions multi-échelles, compte tenu des spécificités de l'échelle méso et du secteur forestier

Les impacts évités mentionnés dans le paragraphe précédent relèvent d'interactions multi-échelles dont nous avons montré dans les chapitres 2 et 3 qu'elles étaient susceptibles d'être déterminantes dans l'évaluation de la performance économique et environnementale. Ces interactions sont multiples et diversifiées. Elles comprennent les interactions économiques directes et indirectes – compétition, synergie – à différentes échelles, mais pas uniquement. Nous incluons dans cette catégorie les échanges entre régions ou pays. Ces interactions incluent aussi dans notre cas d'étude la dépendance des marchés de produits bois à la ressource forestière, à différents échelons géographiques.

La prise en compte des interactions repose d'une part sur les caractéristiques des outils de modélisation choisis pour le couplage et, d'autre part, sur l'incorporation de fonctionnalités supplémentaires. Sur le choix des outils de modélisation, le type de modèle économique utilisé dans le couplage conditionne fortement la façon dont les interactions multi-échelles sont traitées. En effet, un pan conséquent de ces interactions relève d'effets indirects entre différents secteurs économiques, à différentes échelles géographiques. Or, nous avons vu dans le premier chapitre que des arbitrages devaient être faits entre la complexité des effets indirects représentés (modèles d'équilibre), le niveau de détail et la diversité des secteurs économiques modélisés (modèles Input Output), ou la désagrégation desdits secteurs en catégories de produits plus détaillées (équilibre partiel plutôt qu'équilibre général). En complément de ces interactions intersectorielles, les liens entre activité économique et ressources doivent être particulièrement pris en compte pour les thématiques relevant de la bioéconomie. Si la biomasse forestière est souvent vue comme une manne providentielle et une ressource largement disponible, son utilisation pour les nouvelles filières de la bioéconomie ou de l'écoconstruction pose néanmoins la question de son exploitation raisonnée et durable. Les caractéristiques de la ressource forestière à une échelle spatiale fine et sa dynamique temporelle sont d'autant plus susceptibles de peser sur la performance de mesures mises en œuvre à des échelles territoriales.

Confrontés à ces arbitrages, nous avons privilégié un modèle d'équilibre partiel régionalisé du secteur forêt-bois, le modèle FFSM. Si des modèles d'équilibre général ont été mobilisés pour produire des indicateurs d'éco-efficience à des échelles nationales (Kuosmanen, Bijsterbosch and Dellink, 2009; Sun and Pratt, 2014), l'utilisation d'un modèle d'équilibre partiel pour calculer des indicateurs d'éco-efficience est inédite. FFSM est capable de répondre à plusieurs des enjeux énumérés. Il permet de modéliser des échanges entre régions selon la théorie du prix d'équilibre spatial de Samuelson (Paul A. Samuelson, 1952), ainsi que la dynamique de la ressource à un niveau local. À travers une modification, à la marge, des fonctions de demande de produits bois, nous pouvons représenter les interactions multi-sectorielles relatives à la substitution entre le bois-énergie et les énergies fossiles. Pour cela, nous avons supposé que l'effet économique de la hausse de consommation du bois-énergie au détriment des énergies fossiles était négligeable pour le secteur énergétique vu sa dimension bien supérieure et l'échelle mondialisée de ses chaînes de valeurs, largement extérieures à la région d'étude.

Les résultats obtenus dans le chapitre 3 montrent l'importance des différentes interactions considérées dans l'évaluation de l'éco-efficience. L'effet de substitution entre sources énergétiques pèse généralement le plus, qu'il s'agisse d'une conséquence de mesures de subvention ou du choc énergétique. L'effet économique de la limitation des échanges de produits bois primaires entre régions est globalement plus modéré. Toutefois, il peut s'avérer conséquent dans les régions où le secteur forestier est peu développé. Les effets d'éviction entre produits bois sont nettement moins significatifs, tant pour la compétition relative à l'accès à la ressource pour les produits primaires, que la compétition pour le bois d'industrie pour certains produits transformés. L'abondance de la ressource au niveau national explique fortement cette faible compétition (Caurla, Delacote, Lecocq and Barkaoui, 2013). En effet, le prélèvement annuel est estimé à 46 Mm^3 (IGN, 2018) pour une production biologique annuelle estimée à 85 Mm^3. Il est à noter que des disparités régionales importantes existent en matière de bois commercialement disponibles. Des inventaires récents tenant mieux compte des contraintes technico-économiques permettront de mieux modéliser cette contrainte (Colin *et al.*, 2019). Par ailleurs, les possibilités de reconfiguration de la production via le commerce expliquent également ce faible impact de la compétition entre produits bois. Lorsque la tension sur le bois d'industrie s'accroît dans une région, du fait de la hausse de la demande en bois-énergie par exemple, FFSM simule un déplacement de la production de pâte à papier ou de panneaux dans une région proche où la contrainte est moindre.

Ces différents éléments appellent à l'approfondissement de la prise en compte des interactions multisectorielles et interrégionales, compte tenu de leur influence sur l'éco-efficience.

1.2 Apports pour l'aide à la décision

1.2.1 Principaux résultats au regard des enjeux des politiques forestières

Les forêts et filières bois sont des objets complexes qui mettent en jeu de multiples catégories d'impacts environnementaux. Or les politiques portent souvent sur des objectifs uniques (développement économique, climat, biodiversité) et prennent peu en compte les effets indirects. De ce fait, l'analyse multicritère répond à un besoin d'identification des synergies et arbitrages entre ces objectifs et d'éventuels impacts indirects. Les résultats d'éco-efficience pour une simulation donnée permettent d'identifier les principaux « points chauds » et leviers d'action. Les produits les plus impactant sont identifiés. Le bois-énergie et la pâte à papier, et dans une moindre mesure, les panneaux, sont les produits contribuant de manière significative aux impacts. Pour le bois-énergie, cela tient de manière générale aux importants volumes consommés. Ses impacts les plus importants sont dans la catégorie « formation de particules fines » où ils atteignent 70% des impacts de la filière. Les impacts importants de la pâte à papier résultent de la forte consommation d'énergie, d'eau, et de produits chimiques en comparaison aux autres activités de la filière. À ce titre, l'exemple des dommages sur la santé humaine permet d'illustrer l'intérêt de mener l'analyse des contributions jusqu'au niveau endpoint. Bien que pesant sur des catégories d'impact midpoint différentes, le bois-énergie et pâte à papier ont une contribution équivalente sur la santé humaine (35% et 36% des impacts de la filière respectivement).

L'éco-efficience permet d'approfondir l'approche d'analyse des contributions en rapportant des impacts à une création de valeur. Par exemple, la comparaison de la pâte à papier et du bois-énergie est d'autant plus favorable à ce dernier que son éco-efficience est 30% supérieur à celle de la pâte à papier. Analyser les contributions en termes d'éco-efficience permet donc de communiquer plus directement sur les avantages respectifs des différents produits bois.

Les stratégies de développement de la bioéconomie déclinées dans les scénarios s'inscrivent dans des questionnements toujours ouverts en matière de mesures de développement de la filière forêt bois. Les mesures visant le développement de la biomasse ont été organisées autour de la stimulation de la demande de bois-énergie, qui s'articule de plus en plus avec une logique de territorialisation des politiques. Cette logique se manifeste par exemple par le développement de projets locaux comme les chaufferies bois. Toutefois, des projets de ce type soulèvent des questions multiples pour les acteurs de territoires : quelles retombées économiques peuvent être espérées ? La ressource forestière locale est-elle suffisante, compte tenu des conditions de son exploitation ? Quels sont les impacts environnementaux locaux ? Existe-t-il des transferts de pollution ? Comment concilier protection des forêts et approvisionnement local ? À l'échelle des grandes régions, dont les compétences sont renforcées sur tous les champs de la durabilité, des modèles de simulation peuvent fournir des réponses intégrant ces différents problèmes. Nous évaluons des mesures relevant de ces enjeux multiples – bioéconomie, protection des espaces naturels – en confrontant l'échelle nationale et régionale. La plupart des mesures évaluées augmentent l'éco-efficience de la filière par rapport au scénario de référence, mais des mesures de préservation des forêts peuvent la diminuer. On peut aussi observer des scénarios pour lesquels les indicateurs d'éco-efficience relatifs aux écosystèmes et aux ressources non renouvelables sont opposés. Dans ce cas-là, un arbitrage est à réaliser au niveau de la décision publique entre deux catégories d'impacts environnementaux. L'indicateur d'éco-efficience relatif à la troisième catégorie endpoint, la santé humaine, est rarement discriminant.

Les stratégies intégrant une mesure économique de stimulation de la demande sont celles qui améliorent le plus l'éco-efficience, à un niveau régional comme au niveau national. Ces résultats sont fondés en grande partie sur 1) des variations de la performance économique due aux mesures prises, supérieure aux impacts environnementaux et 2) les impacts évités. De ce fait, la substitution est un levier majeur de la performance économique et environnementale finale. Le poids de ces éléments crée un cadre assurant l'éco-efficience des mesures envisagées, quelle que soit leur échelle. Des arbitrages peuvent néanmoins exister, localement, sur certaines catégories d'impact, et donner lieu à des choix opposés.

1.2.2 Analyse des synergies et compétitions entre mesures dans des stratégies de développement de la bioéconomie

L'un des apports spécifiques de notre approche est d'avoir développé des scénarios combinant plusieurs mesures de natures différentes (stimulation de la demande de produits bois, régulation des flux interrégionaux, mesures de conservation) afin de tester leurs effets conjoints. En effet, ces différentes mesures et contraintes sont susceptibles d'être appliquées de façon concomitante. Notre approche de simulation est capable d'intégrer des interactions multiples, ici stimulées par l'exposition du système à des mesures contrastées. Or, peu d'approches explorent les effets différenciés ou combinés des mesures orientées biomasse ou conservation, a priori contradictoires (Böttcher et al., 2012). La plupart des scénarios montrent que les effets des différentes mesures prises individuellement s'additionnent quand les mesures sont combinées. Ce résultat illustre la nécessité de décloisonner et coordonner les mesures, des politiques économiques nationales aux mesures de conservation locales, afin d'éviter l'accumulation d'effets opposés.

Dans certains cas, des effets non linéaires ont pu apparaître, sous la forme de résultats combinés ne correspondant pas simplement à la somme des effets individuels de chaque mesure. Dans ce cas, la modélisation permet d'évaluer l'effet total de mesures antagonistes dont la résultante ne peut être déterminée ex ante, ou de faire apparaître des synergies.

1.3 Apports pluridisciplinaires

Le couplage a nécessité une démarche pluridisciplinaire, qui s'est appuyée sur des outils préalablement structurés dans leur champ scientifique, aux forces et faiblesses et perspectives d'amélioration souvent bien identifiées au sein des communautés de recherche. Une dimension centrale de l'exercice a consisté à faire transiter concepts et vocabulaires d'une communauté à l'autre.

Avec comme point de départ l'économie de l'environnement, notre proposition était d'utiliser les sciences de l'environnement pour intégrer des impacts biophysiques dans les outils issus de la modélisation économique. Cela s'inscrit dans un mouvement général d'incorporation d'indicateurs biophysiques multicritères intégrant la pensée cycle de vie, à rattacher aux améliorations des « Integrated Assessment Models » (IAM) (Kling *et al.*, 2017; Pauliuk *et al.*, 2017), initialement orientés vers des problématiques relatives au changement climatique. Les difficultés auxquelles ces approches sont confrontées relèvent de l'interopérabilité de bases de données répertoriant des flux qui se superposent partiellement, avec d'une part des flux basés sur la valeur économique, à un niveau agrégé, et d'autre part, des flux physiques désagrégés, décrits dans une logique de bouclage des entrées et des sorties.

En ce qui concerne l'évaluation environnementale, qui approche la question de la durabilité par la modélisation de systèmes combinant un système de production (technosphère) et des processus biophysiques (écosphère), l'enjeu est aujourd'hui d'intégrer des mécanismes économiques. En effet, les systèmes modélisés dans ces disciplines sont souvent statiques, basés sur des scénarios normatifs, ou orientés vers l'optimisation. Ils intègrent rarement des variables socio-économiques permettant de simuler l'évolution de systèmes en tenant compte d'interactions fondées sur des comportements économiques. Or, ces mécanismes peuvent s'avérer essentiels pour bien prendre en compte les effets indirects de choix techniques, ou plus généralement, pour répondre à des objectifs de prospective. Le couplage de modèles économiques non linéaires avec des outils d'évaluation environnementale s'est notamment développé dans le champ des ACVs conséquentielles. Ces approches, encore en développement, ne sont pas standardisées (Font Vivanco and van der Voet, 2014) et d'autres outils que les modèles économiques sont utilisés pour simuler une variation des flux physique au sein du système étudié. À notre connaissance, aucune des ACVs conséquentielles basées sur des modèles d'équilibre ne réalise d'homogénéisation des paramètres entre modèle économique et environnemental (Marvuglia *et al.*, 2013; Roos and Ahlgren, 2018), démarche que nous avons réalisée et décrite dans le chapitre II. Homogénéiser de cette manière les périmètres des branches économiques et environnementales du système doit permettre d'améliorer la précision de l'évaluation. Toutefois, la limite des modèles économiques en tant qu'outil d'appui aux ACVs conséquentielles est qu'ils ne permettent de quantifier que des changements marginaux au sein du système étudié. En effet, de nature plus théorique qu'empirique ces modèles représentent un système économique dans une trajectoire « business as usual », et ne peuvent simuler de façon endogène des phénomènes économiques fondamentaux comme les crises ou les ruptures technologiques.

Considérant ces deux points de départ, nous schématisons donc deux pôles. D'une part, des modèles économiques augmentés d'indicateurs biophysiques dérivés de leurs variables économiques. D'autre part, des modèles d'évaluation environnementale intégrant des variables endogènes de nature économique. Le premier chapitre nous a permis d'identifier un continuum de couplages interdisciplinaires plus ou moins élaborés entre ces deux formes simples. Nous avons produit une synthèse inédite sur l'étude des systèmes à des échelles « méso » en passant en revue une gamme d'outils étendus. Il s'agit majoritairement de « soft coupling », répondant à des questions spécifiques.

La spécificité de notre approche est d'appliquer cette démarche de couplage au secteur « forêt bois » et en faisant le choix de l'échelle méso, avec la création d'un outil dédié. Plus précisément, l'intégration d'indicateurs biophysiques issus de l'ACV est un approfondissement par rapport à la modélisation en économie forestière, dont les indicateurs d'impacts environnementaux portent principalement sur le carbone et dans une moindre mesure sur la biodiversité (Riviere, Caurla and Delacote, 2020).

2 Limites

Le développement du couplage et son application à un ensemble de scénarios représentatifs de mesures de développement territorial présente néanmoins un certain nombre de limites. Nous distinguons les limites de la démarche elle-même et les limites de ses applications.

2.1 Limites de la démarche de couplage

Dans un premier temps, nous abordons des limites relatives aux données utilisées, puis à la structure du modèle.

L'analyse de contributions des différentes trajectoires a permis d'identifier les principaux « hotspots » de l'ACV. C'est sur ces points qu'il est nécessaire d'affiner les données d'ICV. Le premier concerne le mix énergétique pour la substitution bois-énergie à l'énergie fossile. L'hypothèse est celle d'un mix de production de chaleur restreint au gaz et au fioul ; elle pourrait être affinée en tenant compte de l'évolution de la part du chauffage électrique, important en France. Son intégration dans le mix de chaleur réduirait le gain environnemental dû à la substitution, car l'impact environnemental de l'électricité est faible du fait de la part importante du nucléaire. Par ailleurs, l'inventaire de cycle de vie de ce mix et des processus énergétiques en général dans le modèle sont statiques, alors que des approches existent pour tenir compte de changements technologiques ou de mix énergétique à long terme (Gibon *et al.*, 2015).

Un autre point d'amélioration concerne la modélisation des impacts du changement climatique. Nous nous appuyons sur l'hypothèse de neutralité carbone en ce qui concerne le contenu des produits bois. Or cette approche présente des limites, en particulier pour les usages bioénergétiques, compte tenu des temporalités d'émission et de séquestration. Différentes méthodes de comptabilité existent, dont les évaluations sont cohérentes entre elles pour la production d'énergie issue de biomasse forestière hors courtes rotations (Brandão *et al.*, 2019; Liu *et al.*, 2019; Fan, Klemeš and Ko, 2020). Le modèle FFSM fournit un certain nombre de variables relatives au stock de carbone forestier susceptibles d'améliorer cet inventaire. Cela étant, la question du carbone biogénique et des effets de substitution demeure un pan de recherche à approfondir en ACV (Levasseur *et al.*, 2013; Albers *et al.*, 2019).

Le deuxième volet de limites identifiées relève de la structure du modèle, et notamment de la représentation de la compétition entre secteurs économiques.

Dans notre approche, la substitution entre bois-énergie et énergies fossiles a un fort impact sur l'estimation de l'éco-efficience (Full Eco-Efficiency). La modélisation des effets de compétition entre le bois-énergie et les autres énergies fossiles repose sur un mécanisme simplifié sur la fonction de demande, incorporant une élasticité de substitution. Les données relatives au comportement de consommation de bois-énergie (Couture, Garcia and Reynaud, 2012) sur lesquelles nous nous appuyons sont anciennes, et ne tiennent pas compte du développement du chauffage individuel au bois dans la dernière décennie. Plus généralement, la validité de cette approche suppose l'incorporation implicite des effets de substitution au niveau des indicateurs économiques. L'effet sur le secteur énergétique est déduit de façon simplifiée, considérant que toute consommation de bois-énergie supplémentaire se fait au détriment des énergies fossiles comprises dans le mix. D'autres types de modèles permettent de modéliser des interactions sectorielles de façon explicite. Des modèles d'équilibre général permettent de modéliser l'interaction multi-secteur à un niveau plus ou moins agrégé, en incorporant un secteur énergétique détaillé en complément d'un secteur forestier (Plevin, 2017; Welfle, Thornley and Röder, 2020; Winchester and Reilly, 2020). Il est à noter que ces approches plus sophistiquées sont aussi confrontées à des questions de sensibilité aux élasticités de substitution (Antimiani, Costantini and Paglialunga, 2015). Un modèle multisectoriel comme GLOBIOM (Havlík *et al.*, 2018) disposant d'un secteur forestier détaillé, mais aussi d'un secteur agricole et un secteur bioénergie offrirait le type d'interactions sectorielles recherchées. Toutefois, cet outil est construit avant tout pour étudier les problématiques d'utilisation des terres. Plus largement, il ne permet pas d'étudier la mise en compétition des usages énergétiques de la biomasse avec des usages matériaux, notamment dans la construction.

2.2 Limites des indicateurs

Nous relevons également des limites concernant les indicateurs utilisés, ce à plusieurs niveaux.

Tout d'abord, sur le plan économique, l'indicateur de surplus est une mesure utile pour comparer des scénarios, mais sa signification en tant que mesure absolue d'une performance économique doit être contextualisée. En effet, le calcul du surplus repose sur des constructions théoriques. Si les courbes d'offres peuvent être fondées sur des mesures concrètes de coûts de production, la courbe de demande est fondée sur le concept plus théorique de consentement à payer pour un bien. À ce titre, des quantités ou des valeurs ajoutées sont nécessaires pour mesurer une performance économique dans l'absolu. De la même façon, les indicateurs d'impacts potentiels obtenus dans le cadre des ACVs fonctionnent dans une démarche comparative. Dans notre cas d'étude, nous établissons des comparaisons avec un scénario de référence pour lequel aucune mesure ou contrainte n'est appliquée. Toutefois, ce scénario n'est pas totalement neutre. Il suppose un fonctionnement « business as usual » dont la vraisemblance est limitée à moyen-long terme, sur lequel sont greffées des hypothèses : prix exogènes des produits bois internationaux, des produits énergétiques.

Ce scénario de référence pèse également dans la détermination des impacts évités. La différence des quantités de bois-énergie consommées entre un scénario donné et le scénario de référence est attribuée à la substitution. Les impacts évités qui en découlent conditionnent significativement l'éco-efficience (Full Eco Efficiency) du fait des impacts potentiels associés. Ainsi, plus le bois-énergie pèse dans le secteur forestier d'une région, plus l'éco-efficience de la région varie de façon importante à la hausse ou à la baisse. C'est le cas par exemple de la région Corse dans les scénarios du chapitre III.

Des limites existent également quant à l'adéquation de certaines catégories d'impacts ACV pour modéliser les enjeux relatifs à la biodiversité et à la qualité des écosystèmes. En effet, dans la filière forêt bois, les indicateurs ACV sont principalement utilisés pour évaluer les impacts d'utilisations industrielles, ici d'utilisation de la biomasse forestière comme matériau – bioplastiques, matériaux composites – ou source d'énergie –biocarburants, bois-énergie – (D'Amato, Gaio and Semenzin, 2020). Les catégories d'impacts relatives à la pollution dans les écosystèmes continentaux – Écotoxicité, eutrophisation, acidification – sont peu représentées dans l'étude des impacts des produits bois de première transformation agrégés des modèles secteur forestier – sciages, panneaux, pâte à papier. Les variables de modèles comme FFSM sur les peuplements forestiers – essences, structure du peuplement, classes de diamètres, altitude, classe d'aire protégée – à l'échelle du pixel de 8x8km peuvent être utilisées pour modéliser des indicateurs de biodiversité simples sous la forme d'indice de qualité des habitats (Kallio *et al.*, 2008; Basilico *et al.*, 2014; Zilliox and Gosselin, 2014). Toutefois, la modélisation de ces indicateurs dans des modèles de secteur forestier requerrait une meilleure intégration de données locales ou des couplages avec des modèles écologiques (Riviere, Caurla and Delacote, 2020). De plus, cette approche est réalisable à un niveau local et national à partir des indicateurs de FFSM, mais pose des défis supplémentaires pour être généralisée à un niveau global. En toute cohérence, les impacts de l'exploitation forestière dans d'autres pays comme l'Allemagne ou le Canada par exemple devraient être modélisés et pouvoir être comparés sur des bases communes. En conclusion, des convergences sont à réaliser entre les indicateurs écologiques construits spécifiquement pour les écosystèmes forestiers, utilisés pour l'amont du secteur, et les indicateurs ACV relatifs aux dommages sur les écosystèmes, dont la pertinence est plus grande pour quantifier les impacts potentiels des processus industriels en aval de la filière.

3 Perspectives

Sur les bases des limites identifiées dans la section précédente, nous envisageons plusieurs axes d'approfondissements de notre démarche, tant sur le plan du couplage de modèles que sur le choix et la construction des scénarios de développement analysés.

3.1 Développement des interactions multisectorielles

Une première perspective d'application de notre démarche repose sur l'élargissement à d'autres secteurs des effets de substitution pris en compte. L'intégration des impacts évités dans la Full Eco-Efficiency repose sur une modélisation de la compétition entre bois-énergie et énergies fossiles pour la production de chaleur. Ce mécanisme permet de prendre en compte dans notre indicateur final une estimation de l'effet de la substitution énergie. Il serait intéressant de réaliser un travail du même ordre pour l'effet de substitution « matériaux », qui représente un potentiel important d'atténuation du changement climatique (Breton *et al.*, 2018; Hart and Pomponi, 2020), même si l'effet est très variable selon les types de matériaux et les conditions locales (Oliver *et al.*, 2014; Suter, Steubing and Hellweg, 2017). L'un des principaux secteurs pour lequel cet effet entrerait en jeu est celui de la construction. La modélisation au niveau régional des effets économiques et environnementaux de la substitution entre des produits bois et des matériaux de construction comme le béton ou l'acier requerrait une modélisation explicite de ces secteurs, l'économie de la construction étant implantée localement. Pour cela, une première étape consiste en une approche où les secteurs de la construction et de l'énergie sont désagrégés dans un modèle d'équilibre général (Winchester and Reilly, 2020). Toutefois, le secteur forestier y est modélisé sommairement par un produit générique correspondant au bois d'œuvre. Développer la modélisation du secteur forestier dans cette approche d'équilibre général et régionaliser un modèle de ce type permettrait d'étudier la performance économique et environnementale de politiques de soutien à la bioéconomie orientées vers la construction avec des indicateurs cohérents.

3.2 Spatialisation renforcée

Nous envisageons ici une amélioration de la spatialisation de notre modèle. La question de la variabilité spatiale se pose de façon différente pour FFSM d'une part et l'ACV d'autre part. En ce qui concerne FFSM, les enjeux portent sur une spatialisation plus fine du module marché. Dans la forme actuelle, les fonctions d'offre et de demande sont déterminées à l'échelle de la région. Toutefois, leurs caractéristiques sont les mêmes dans toutes les régions, à l'exception du volume de bois disponible, intégré dans la fonction d'offre. Une première possibilité d'affinement consisterait à différencier les fonctions d'offre et de demande au niveau régional, pour mieux différencier les caractéristiques de leurs filières bois respectives.

Pour aller plus loin, il serait intéressant de localiser les capacités de production à l'échelon spatial inférieur, celui du pixel de 8x8km utilisé dans le module ressource. Des propositions de « *downscaling* » ont été appliquées récemment à partir de GLOBIOM et du modèle de secteur forestier suédois (Eriksson *et al.*, 2020). Ce type d'approche permettrait d'explorer des questions de développement local de la bioéconomie tenant compte de façon plus fine de la variabilité spatiale. Cela s'appliquerait notamment à des politiques locales centralisées telles que des projets territoriaux – chaufferie biomasse, complexe immobilier en construction bois, par opposition à des politiques décentralisées telles que les incitations économiques que nous avons étudiées. La structure régionalisée de notre modèle était cohérente avec ce type de politiques décentralisées, dans la mesure où la demande était a priori répartie. Mais cd'autres questions pourraient être explorées. Notre cas d'étude a montré que l'abondance actuelle de la ressource était telle que cette variable n'était que rarement une contrainte pour l'approvisionnement, y compris pour des hausses importantes de la production dans les scénarios de subvention. Une spatialisation accrue de la branche économique du modèle permettrait d'analyser les impacts de stratégies locales ou régionales pour une demande centralisée. Il est envisageable que dans ce type de configuration, des contraintes sur la ressource se manifestent, du fait de variations plus locales de sa disponibilité, notamment d'un point de vue technico-économique. Il serait intéressant d'étudier l'éco-efficience d'un projet de centrale biomasse de grande envergure, en tenant compte aussi bien des interactions multi-échelles que d'une représentation fine du potentiel de la ressource locale.

Par ailleurs, cette démarche de spatialisation pourrait être couplée à une meilleure prise en compte des échanges interrégionaux. En effet, dans FFSM, la modélisation des flux de produits bois entre régions basée sur l'équilibre spatial de Samuelson correspond mal aux estimations réelles. La contribution du transport aux impacts environnementaux de la filière étant de l'ordre de 1%, cette limite est peu contraignante sur cette dimension. Toutefois, la distribution des flux de produits a des effets économiques sur la répartition de la création de valeur ajoutée entre régions. La modélisation du transport peut être améliorée à une échelle fine à l'aide de modèles logistiques (Trømborg *et al.*, 2009) ou avec la même architecture théorique, affinée avec des techniques de calibration dédiées (Havlík *et al.*, 2018; Johansen, Egging and Ivanova, 2018).

En ce qui concerne l'ACV, les possibilités de spatialisation avancée portent sur deux niveaux. Premièrement, l'ACV des produits de la filière forêt bois a été réalisée à partir de données sur les flux de produits bois au niveau national. Les inventaires de cycle de vie tenant compte des caractéristiques nationales ont été utilisés indifféremment pour chaque région. Des analyses de flux de matière régionales existent (Lenglet, Courtonne and Caurla, 2017; Courtonne and Wawrzyniak, 2019), et pourraient être mobilisées pour régionaliser les ICV de la filière forêt bois, en adaptant les rendements, surfaces exploitées, industries représentées. Toutefois, la méthode de réconciliation de données utilisées pour construire ces analyses de flux de matière produit des incertitudes plus fortes au niveau régional que national.

Un deuxième niveau de spatialisation potentielle repose sur l'utilisation de facteurs de caractérisation régionalisés (« site-specific » ou « site-dependent » (Potting and Hauschild, 1997)). Or les facteurs de caractérisations mobilisés dans ces travaux sont globaux (« site-generic »). Affiner ces facteurs de caractérisation s'avérerait tout particulièrement pertinent pour des catégories en jeu dans notre cas d'étude, comme les particules fines issues de la combustion du bois-énergie (Fantke *et al.*, 2015) ou les impacts sur la biodiversité dus à l'occupation et à la transformation des terres (Chaudhary *et al.*, 2015; Larrey-Lassalle *et al.*, 2018).

Plus généralement, la spatialisation ouvre la voie à la mise en œuvre de scénarios de changement globaux autres que le choc énergétique étudié. Il peut s'agir de scénarios découlant des effets du changement climatique, comme des hausses de mortalité, ou des changements d'essence dans les forêts.

3.3 Développement de scénarios et approches de simulation

En matière de modélisation, on peut distinguer 3 grandes catégories d'approches : exploratoires (ou prospective), normatives, et prédictives (Börjeson *et al.*, 2006).

Nous avons procédé à une démarche exploratoire, à l'aide de scénarios développés en tenant compte de différentes tendances en matière de stratégies de développement dans la filière forêt bois. D'autres approches de modélisation pourraient être adoptées avec ce type de simulation. Notamment, des scénarios normatifs intégrant des objectifs de production (Hugues, 2015), par exemple sous la forme d'une contrainte exogène de demande d'énergie issue de la biomasse (Valade *et al.*, 2018). Les approches prédictives sont à exclure avec des outils de simulation comme FFSM.

Plus généralement, les limites de notre approche sont celles des modèles de simulation. Par rapport à des modèles analytiques simples ou des approches statistiques, cette catégorie de modèles présente des inconvénients qui sont le corollaire de ses avantages. Les critiques pointent en général des problèmes d'interprétabilité des résultats, du fait de l'intégration de multiples effets dont les mécanismes sont peu lisibles. Différentes méthodes existent pour analyser la sensibilité des modèles de simulation. Elles varient selon qu'on utilise des modèles stochastiques ou déterministes. Pour des modèles déterministes, comme FFSM, des approches dites « local sensitivity » sont préconisées. On parle d'approche « global sensitivity » pour évaluer des modèles comportant une distribution aléatoire pour certains paramètres en entrée (Borgonovo and Plischke, 2016). Des techniques spécifiques relevant de cette catégorie ont été développées pour les IAM, basées sur la décomposition de la variance (Butler *et al.*, 2014). Les méthodes utilisées pour les modèles stochastiques comme le multi-agents reposent sur des analyses en composante principale assorties de clustering (Fachada *et al.*, 2017; Williams, 2018). L'application de la méthode dite *output space analysis* spécifiquement au secteur agricole offre des pistes en matière de décomposition des interactions entre agents économiques et milieu (Brändle *et al.*, 2015).

3.4 Couplage fort

En termes de typologie de couplage, notre modèle relève d'une forme élaborée de « soft coupling » qui fait le lien entre les variables économiques et les données d'inventaires ACV tout en assurant une cohérence forte entre les périmètres des deux modèles. Cette cohérence pourrait être consolidée en calculant les indicateurs socio-économiques sur l'ensemble du cycle de vie. Ce niveau de couplage constitue une étape préalable à la réalisation d'un couplage fort mettant en jeu une rétroaction entre ACV et modèle économique. Un couplage de ce type permet de mettre en place une large gamme de rétroactions de l'environnement sur l'économie (Hardt and O'Neill, 2017), mais aussi d'intégrer de façon endogène au modèle la prise en compte d'objectifs environnementaux par un décideur public pilotant une politique. Par exemple, un niveau plafond d'impacts peut être défini pour une catégorie, comme les particules fines, et rétroagir sur le niveau de subvention. Un couplage de ce type permet d'étudier une trajectoire temporelle d'évolution de l'éco-efficience. Elle peut être plus particulièrement intéressante en y intégrant aussi des scénarios d'évolution des technologies de production.

3.5 Opérationnalisation de la démarche

Le développement de l'outil de modélisation s'est avéré assez exigeant en termes de temps de développement, sur le plan de la réalisation des ICV, de l'ajustement des modèles pour la réalisation du couplage, du développement des scénarios, des outils de traitement des sorties, et le traitement en général des résultats. Ces exigences sont inhérentes aux démarches de couplages, dans la mesure où elles mettent en jeu des modèles de simulation complexes.

Le modèle couplé est constitué d'une architecture numérique centrée autour de la structure de base de FFSM, à laquelle s'adjoignent un module ACV et un module couplage. Le premier module est une ACV des produits de la filière forêt bois française construite à partir d'exportations de résultats d'ACV calculés sur le logiciel SimaPro et de données MFA. Le second est un module mettant en relation les sorties de FFSM et les impacts environnementaux du module ACV.

L'étendue des bases de données Ecoinvent et la qualité de la mise à disposition des données MFA de la filière forêt bois (Courtonne and Wawrzyniak, 2019) permettent d'avoir accès facilement à des données détaillées. Le développement d'un modèle économique spécifiquement adapté au niveau local, avec un niveau de désagrégation des produits bois plus fin que FFSM permettrait de réaliser un outil similaire en gagnant du temps sur le processus d'interprétation des périmètres respectifs de chaque modèle.

L'opérationnalisation de cette démarche appelle également la formalisation d'une démarche générale de développement du modèle couplé qui soit dérivée de la démarche d'ACV : 1. Définition des frontières du système 2. Inventaire des flux économiques et environnementaux. 3. Évaluation des impacts ; ces trois étapes s'intégrant dans une démarche d'interprétation et d'ajustement itérative. Cette approche serait particulièrement profitable pour l'identification des interactions pesant le plus sur l'éco-efficience du système, afin de cibler plus en amont les « points chauds » dont la modélisation doit être améliorée. Les interactions potentiellement significatives étant d'autant plus nombreuses à l'échelle méso, leur identification, intégration et évaluation constituent un élément central du problème de l'évaluation quantitative et exhaustive à cette échelle.

3.6 Intégration d'outils quantitatifs dans des démarches de recherche participatives

Les évaluations des impacts économiques et environnementaux de mesures de développement régional ont vocation à pouvoir être mobilisées par les parties prenantes des territoires concernés. Ces approches peuvent notamment s'intégrer dans des démarches d'aide à la décision intégrant des processus de concertation entre acteurs locaux – élus, experts, gestionnaires, associations. Ce type de processus d'appropriation des expertises par les élus est une condition nécessaire du développement efficace et durable de la bioéconomie (McCormick and Kautto, 2013).

En termes de communication de résultats, l'éco-efficience permet de présenter un indicateur synthétique pour transmettre un résultat auprès d'un public de décisionnaires.

Toutefois, le choix de rapporter des indicateurs ACV entre impacts midpoints sélectionnés et impacts endpoint (Van Hoof *et al.*, 2013) demeure. De plus, au niveau midpoint comme endpoint, le problème de la coexistence de plusieurs indicateurs pouvant difficilement être agrégés de façon consensuelle en un indicateur unique se pose toujours. Ce type de démarche peut permettre de développer une procédure d'accompagnement de la prise de décision, permettant de contextualiser les enjeux de la prise en considération d'indicateurs multiples (Glucker *et al.*, 2013).

Les échanges entre acteurs de recherche et du territoire peuvent avoir lieu à plusieurs étapes du processus de concertation. Tout d'abord, préalablement aux travaux, des scénarios alternatifs peuvent être développés ou des variables d'intérêt à modéliser peuvent être ciblées afin d'étudier les effets de mesures que les acteurs locaux jugent adaptées ou probables sur la base de leur connaissance des caractéristiques du territoire. Au cours, et à l'issue des travaux de recherche, des efforts de communication sont bénéfiques pour la mise à disposition des résultats de la recherche, et peuvent notamment prendre la forme de la mise en ligne d'un outil de modélisation simplifié utilisable par un public de non-chercheurs (Lurette, Aubron and Moulin, 2013).

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Conclusion générale

Notre démarche procède du besoin de construire un outil spécifique pour évaluer la performance économique et environnementale à l'échelle régionale de stratégies de développement de la bioéconomie basées sur l'utilisation de biomasse forestière. Ce besoin émane tant du développement des politiques bioéconomiques au niveau national et européen que de l'émergence d'innovations techniques et organisationnelles dans la filière forêt bois au niveau des territoires. Déclinées à l'échelle régionale, ces stratégies doivent être évaluées en considérant tant les caractéristiques locales, que les effets directs et indirects à des échelles spatiales et temporelles multiples.

Ces enjeux nécessitent un outil d'évaluation multicritère, adapté à l'échelle méso. Nous avons formulé l'hypothèse de recherche suivante : un couplage interdisciplinaire entre modèle économique et évaluation environnementale permet d'évaluer et comparer la performance économique et environnementale de mesures régionales de développement dans le secteur forestier en prenant en compte leurs effets directs et indirects, à des échelles multiples et imbriquées. Nous avons interrogé et confirmé cette hypothèse dans trois sous objectifs, développés dans les chapitres I à III.

Le premier sous objectif, développé dans le chapitre I, nous a permis de montrer que parmi les différents types de couplages modèle économique – modèle environnemental utilisés dans la littérature, les couplages entre modèles d'équilibre (PE ou CGE) et les approches empreintes et ACV répondaient le mieux aux besoins définis pour une analyse à l'échelle régionale. Il est apparu que, compte tenu des caractéristiques du secteur forestier, le couplage PE – ACV, était prometteur pour étudier des stratégies de bioéconomie au niveau régional.

Nous avons répondu au deuxième sous objectif dans le chapitre II via différentes contributions. Tout d'abord, nous avons proposé des indicateurs d'éco-efficience basés sur un ratio entre surplus économique de la filière forêt bois et impacts environnementaux liés à l'ensemble des produits. Ensuite, nous avons mis en évidence les adaptations à apporter à un modèle d'équilibre partiel et à la méthode ACV afin de disposer d'un couplage cohérent, répondant aux objectifs formulés. Ces modifications portaient notamment sur un bilan équilibré des flux de matières entre modèles. Nous avons également intégré un mécanisme de substitution entre le bois énergie et les énergies fossiles. Cette fonctionnalité nous a permis de développer un indicateur d'éco-efficience, la Full Eco-Efficiency, prenant en compte dans un ratio unique des impacts environnementaux évités par substitution entre le bois énergie et la consommation d'énergies fossiles.

Le troisième sous objectif, traité dans le chapitre III, a consisté à mettre en œuvre notre démarche pour étudier les impacts économiques et environnementaux de stratégies de développement de la bioéconomie, combinant mesures de stimulation de la demande de bois énergie, approvisionnement local et mesures de conservation, en prenant également en compte des chocs de demande d'énergie. Nous avons comparé ces scénarios entre eux à deux échelles, sur la base des indicateurs d'éco-efficience, d'une part, en appliquant ces mesures et ces contraintes à l'échelle nationale, et d'autre part, à l'échelle régionale, au cas de la région Grand Est. Ces applications ont montré l'intérêt de mobiliser des indicateurs de performance économiques et environnementaux multicritères, permettant une comparaison détaillée des différentes stratégies de développement de la bioéconomie évaluées. Nous avons mis en évidence les bénéfices économiques et environnementaux de politiques de soutien à la bioéconomie sur plusieurs critères. Notre approche a permis d'identifier des synergies entre politiques bioéconomiques, mais aussi des arbitrages sur certaines catégories d'impacts qui se manifestent différemment pour des stratégies régionales ou nationales. Plus généralement, notre démarche illustre l'importance de la prise en compte des interactions multi-échelles.

Enfin, nous avons mis en évidence les forces et les limites de notre approche dans le chapitre IV, ainsi que plusieurs pistes d'approfondissement.

Nous avons ainsi mentionné que certaines données d'inventaires doivent être précisées, notamment en ce qui concerne la substitution bois-énergie/énergies fossiles ou la comptabilité dynamique du carbone biogénique. Nous avons également souligné que les interactions multisectorielles sont simplifiées par la structure du modèle. Développer des interactions entre produits bois et secteurs de la construction notamment permettrait d'évaluer des stratégies de développement de la bioéconomie orientées vers les usages matériaux du bois. Dans cette logique d'approfondissement de la modélisation, d'autres éléments pourraient être apportés. FFSM tient compte des spécificités régionales de la ressource, mais les marchés des produits bois reposent sur les mêmes fonctions d'offre et de demande dans chaque région. De même, l'ACV de la filière n'est pas différenciée par région. Une spatialisation plus détaillée permettrait notamment d'étudier d'autres types de scénarios, comme l'implantation de projets de grande envergure.

En ce qui concerne la mise à disposition des résultats, l'opérationnalisation de la démarche est un enjeu important. Notre approche a vocation à poser les bases d'un outil pouvant être mis en œuvre au-delà des milieux de recherche, parcimonieux en temps et en données, et facilement utilisable par les décideurs publics, y compris dans des approches participatives. La mise à disposition et le partage de données peuvent faciliter la reproduction de couplages de ce type. Ce souci de mise à disposition des évaluations de la durabilité de la bioéconomie répond à un besoin d'alimenter des processus démocratiques. L'appropriation par les élus et les citoyens des enjeux relatifs au développement de ces filières est une condition nécessaire de leur développement efficace et durable.

La consolidation de l'outil développé, de ses indicateurs et de ses résultats devrait permettre d'étendre ce type d'approche à d'autres problématiques et d'autres secteurs. Parallèlement, la confrontation à des couplages basés sur d'autres outils comme les modèles multi-agents ouvre la voie à un approfondissement de la modélisation de mécanismes socio-économiques déterminants à l'échelle méso.

La confrontation à d'autres outils de simulation ouvre la question du choix des modèles pour évaluer indicateurs de long terme dans le domaine du risque de l'incertain. La prise en compte de phénomènes stochastiques tels que les tempêtes, sécheresses, et feux sont des enjeux majeurs dans le secteur forestier. Les approches déterministes présentent des limites en la matière. Des outils dans le champ du machine-learning seraient susceptibles de contribuer à modéliser l'occurrence de ce type de phénomène.

Cette perspective de rapprochement entre la modélisation de phénomènes socio-économiques complexes au niveau local et la prise en compte des risques et incertitudes fortes auxquels les sociétés et les écosystèmes sont exposés ouvre la question de l'évaluation de la résilience des territoires.

Annexes

A. Annexe au premier chapitre

A.1: Economic modelling

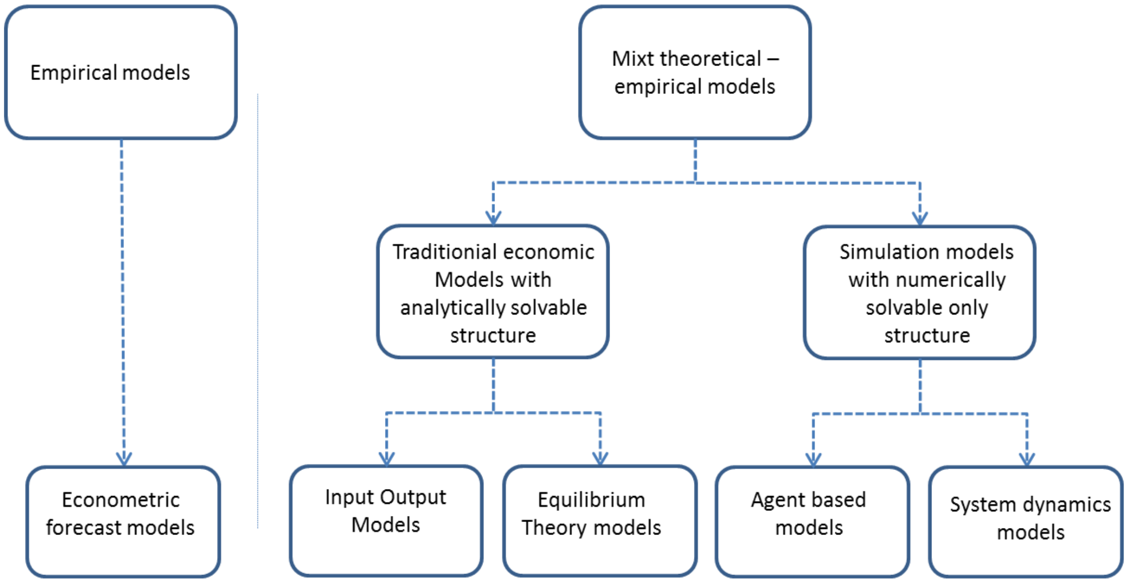

Figure A.1 – Classification of economic models.

Econometric forecast models

Econometric forecast models have been developed to provide accurate forecasts on the short term, for instance to predict growth for next quarters. They may include as diverse socio-economic variables as available past data. They are reliable for time horizons (0-2 years) (Klein and Glickman, 1977; Pindyck and Rubinfeld, 1981; Shourie, 1970). At subnational scale, they are fed using local data that may be difficult to obtain/collect. Also, they usually miss detailed sectoral disaggregation (Loveridge, 2004).

Input Output economic modelling and Social Accounting Matrixes

IO Analysis was developed by Leontief (1936)for national accountability and intersectoral relationship analysis. It assumes exogenous and fixed prices and a perfect elasticity of input supplies of resources, e.g. labour or capital, provided extensively without reducing economic activity anywhere else (Miller and Blair, 2009). These two characteristics may reasonably be considered as acceptable assumptions at regional scale (Dwyer et al., 2006). However, it does not allow taking into account substitution effects between products. No behavioural effect of agents is represented, which can lead to overestimating positive economic impacts (Partridge and Rickman, 2010). Models called Social Accounting Matrixes (SAM) can be considered as input output models with an extended representation with value added, households, institutions and exogenous sectors (Lemelin et al., 2008).

Equilibrium theory models: Computable general equilibrium (CGE) and Partial equilibrium (PE) models

Equilibrium models are based on the equilibrium theory, which assumes that, under conditions of pure and perfect competition, markets reach an equilibrium state where supply equals demand, providing an endogenous market price (Arrow and Debreu, 1954). Supply and demand are typically modelled through functions calibrated with econometric methods. Such functions allow calculating detailed economic indicators of welfare such as consumer and producer surpluses.

PE models include one or a few connected sectors. Prices for all substitute and complement commodities from other markets are fixed as well as consumer income. CGE models include all economic sectors, allowing substitutions effects between sectors, and a representation of the flows between private and public sector, which makes it possible to assess fiscal impacts of policies (McGregor et al., 2010).

Regional applications have been developed over time, as shown by Partridge and Rickman (2010, 1998). For regional approaches, econometric parameters such as elasticities are often derived from national estimations.

Agent Based (AB) modelling

AB modelling is a type of simulation where the system's evolution emerges from the interactions between agents, which are defined by behaviour rules. Its use has expanded in the 1990s in various disciplines such as biology, sociology or geography, and economics in the 2000s (Tesfatsion, 2002) to simulate system trajectory and identify emergent properties of systems.

ABM offers the modeller great freedom about the interaction structure and the economic behaviour, notably compared to analytical models such as IO or equilibrium models (Farmer and Foley, 2009; Richiardi, 2003). Its drawback is that there are numerous *ad hoc* ABM, based on simple local rules, built with various heuristics, making peer quality control sometimes difficult when defining agents' behaviours (Conte and Paolucci, 2014; Epstein, 2006, Farmer and Foley, 2009).

System dynamics (SD)

System Dynamics is a type of simulation used to model and study complex, dynamic, non-linear systems. It was developed by Forrester in the 1950s to model industrial processes, and later used in the WORLD II model developed for the Club of Rome's report *Limits to Growth* (Forrester, 1971). It allows translating the modelled system into any set of stock and flow variables and interactions, in a top-down approach. It makes it possible to identify the causal effects and map their impact on the system stocks and flows through time, but it does not represent economic agent behaviour (McCauley and Küffner, 2004; Sterman, 2000).

Note on Time Dynamics

A static model provides relationships between variables without accounting for time variations. In a dynamic non-recursive model, an initial equilibrium is modified subsequently to a change of given parameters such as demand for a product or an input's cost, and a new equilibrium is calculated. A dynamic recursive model is a succession of such time periods where periods are linked with each other by endogenous and exogenous updating of some variables such as capital stock, population, or even technology change for the most sophisticated models. A last type of model, not considered in our review as non-significantly used, is perfectly dynamic model, also called intertemporal models. Economic agents are assumed to have perfect expectations about future economic conditions and their current economic behaviour takes it into account with a given discount rate, over a given amount of time periods. The modeller can calibrate the economy to follow a steady-growth path or an off-steady-state evolution, using in this case benchmark data and assumptions on the evolution of the economy's main rates (growth rates, rental rate, etc.) (Devarajan and Go, 1998).

A.2: Environmental assessment tools

Material Flow Analysis (MFA)

The key principles of the MFA have been defined at the Wuppertal Institute in the 90s. MFA allows a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner and Rechberger, 2016) to establish its material balance. Recent developments in the industrial ecology (IE) research field emphasize the relevance of MFA methods to obtain a precise understanding of systems and subsystems functioning. It is mostly applied on a national scale due to the easy accessibility to relevant data and the existence of a methodological framework developed by Eurostat (2001). However, there are an increasing number of MFA studies at the regional scales (Courtonne et al., 2015) etc. Substance Flow Analysis, with a focus on a given substance (e.g. copper or nitrogen), could also be conducted at regional scales (Klinglmair et al., 2015).

MFA is now recognized as a scientific support tool for decision makers, notably in the field of environmental policy (Bringezu and Moriguche, 2002 ; Ehrenfeld, 2004). In addition, MFA can also contribute to economic and societal development by shifting from a linear to a circular approach, leading to an overall 'win-win' outcome (Gibbs et al., 2005).

Ecological Footprint (EF) and other footprint methods

The ecological footprint concept was developed by Wackernagel and Rees in the 1990s (Ayres and Ayres, 2002) in response to discussions on the notion of 'carrying capacity'. The carrying capacity is defined as 'the population of a given species that can be supported indefinitely in a given habitat without permanently damaging the ecosystem upon which it depends' (Rees, 1992). Thus, the EF expresses the theoretical area (given by a single indicator i.e. 'global hectare') used by man to produce all the bioresources that he consumes and to assimilate the waste that he generates (including the CO2 resulting from his energy consumption) (Wackernagel et al., 1999). It is widely used at the level of nations or cities ('Global Footprint

Network,' 2011). Yet, there are also case studies at regional level (Bagliani et al., 2008; Graymore et al., 2008). Other footprints can also be computed at the regional scales such as carbon footprint (Roibás et al., 2017) or water footprint (W. Chen et al., 2017; González Perea et al., 2016; Manzardo et al., 2016). Footprint methods account for direct and indirect studied flows related to the system.

Life Cycle Assessment (LCA)

LCA is an internationally standardized and globally applied decision-support tool designed to assess the potential environmental impacts throughout a product or service life cycle from cradle to grave, i.e. from raw material extraction, through materials processing, production, distribution and use stages, to waste management, e.g. disposal or recycling. LCA is a multicriteria approach covering a large range of environmental issues (e.g. climate change, eutrophication, or toxicity), and the impacts are calculated for a functional unit which reflects the function(s) or service(s) provided by the studied system. Although LCA is product-oriented, recent proposals have been made to broaden its object of analysis by studying meso-level systems (Beloin-Saint-Pierre et al., 2016; Loiseau et al., 2013; Nitschelm et al., 2015).

Environmental assessment methods		**Footprint**	**LCA**	**Material flow analysis**
System Modelling: consideration of the Life Cycle		Good	Excellent	Good
Inventoried Flows	Non-renewable resources	No	Yes	Yes
	Renewable resources	Yes	Yes	Depends
	Water resources	In Water Footprint	Yes	Depends
	Land Use	In Ecological Footprint	Yes	No
	Greenhouse gas emissions	In Carbon and Ecological Footprint	Yes	Yes
	Pollutant emissions	No	Yes	Yes
Indicators provided		Pressure/Impacts	Impacts	Pressure
Usability		Very Accessible	Accessible, costly to perform	Accessible

Table A.1 - Qualitative comparison of methods used for environmental assessment of territories, based on Loiseau & al (2012)

A.3: Bibliometry

Economic modelling methods	**Environmental assessment methods**		
Economic modelling Methods	Carbon/Water/**Ecological Footprint (FP)**	**Life Cycle Assessment(LCA)**	**Material Flow Analysis (MFA)**
Input output Model (IO)	148	201	73
Computable General Equilibrium Model (CGE)	18	20	4
Partial Equilibrium Model (PE)	3	16	1
Agent Based model (AB)	3	5	6
System Dynamics model (SD)	15	16	6

Table A.2- Number of each type of EEIM found by systematic search

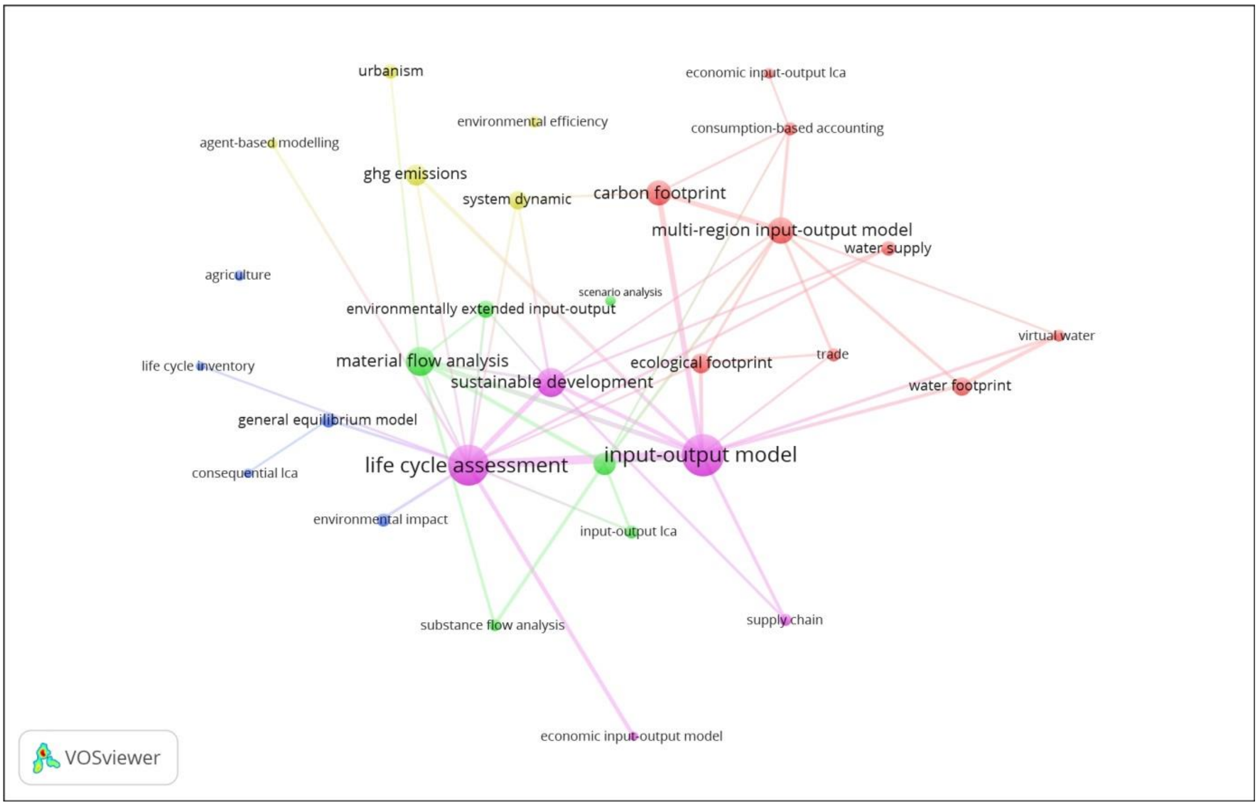

Figure A.2 - Network analysis of the keywords contained in the pool of peer-reviewed articles resulting from the systematic search.

We performed a network analysis using VOSviewer (Leiden University, 2015), mapping relationships between article keywords, based on co-occurrence, i.e. presence in a same paper. VOSviewer offers two options: author keywords or index keywords. We used the author keywords, which are more specific than index keywords, sometimes automatically generated by Scopus. We mapped the 30 most occurring keywords, as a trade-off between comprehensiveness and clarity of the diagram. The resulting map is figure 2.

These keywords are a mix of the methods investigated and the thematic of research that are related. The mapping emphasizes two aspects. First, the strength of the links between methods reflects the results found in table 2: the more there are couplings found for a pair of method, the stronger the link on our map. Second, the links between a given method or coupling and one or several thematic.

We observe a first core group (purple) which gathers the two most important methods, IO and LCA, with the main generic concern, sustainable development. Orbiting close, the MFA family associated with industrial ecology and SFA, which comes close with Environmentally Extended-Input Output (EE-IO). A third group in red is built around multi-regional IO models which are linked with footprint methods in relation to trade issues and virtual water trading. It forms a consistent part of the IO-FP literature. We identify a small group in blue of methods orbiting around LCA, involving CGE models and consequential LCA[7]. At last, a fifth group (yellow) of methods appears further, gathering AB and SD models, which are combined in some works. SD appears close to GHG emissions and carbon footprint, as well as urbanism, a topic for which SD-FP are indeed conducted.

[7] Consequential LCA is a system modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change *as a consequence of a change in demand* for the functional unit (UNEP, 2011)

A.4: List of Reviewed articles

	Footprints Methods			Life Cycle Assessment	Material Flow Analysis
	Carbon print	**Water print**	**Ecological Footprint**		
Input output model (IO)	Ala-Mantila et al., 2014	Cazcarro et al., 2016	Salvo et al., 2015	Cicas et al., 2007	Sinclair et al., 2005
	Chen et al., 2015	Feng et al., 2012	Galli et al., 2013	Bjorn et al., 2005	Bailey et al., 2004
	Choi et al., 2010	Rudenko et al., 2013	Rugani et al., 2014	Caro et al., 2015	Hawkins et al., 2007
	Daly et al., 2015	Wang et al., 2013	Turner et al., 2007	Cellura et al., 2013	Kytzia and Nathani, 2004
	Druckman and Jackson, 2009	Yu et al., 2010	Wiedmann et al., 2007	Choi et al., 2014	Kytzia et al., 2004
	Gilmartin et al., 2008	Zhang et al., 2011		Cortés-Borda et al., 2015	Matsubae-Yokoyama et al., 2009
	McGregor et al., 2008			de Carvalho et al., 2016	Risku-Norja and Mäenpää, 2007
	Minx et al., 2009			Gibon et al., 2015	Chen et al., 2014
	Nansai et al., 2009			Hertwich et al., 2015	Li et al., 2013
	Su and Ang, 2014			Lee et al., 2011	
	Wang and Li, 2012			Malik et al., 2015	

	Wiedmann, 2009			Tukker et al., 2009	
	Zhang et al., 2014			Ukidwe and Bakshi, 2008	
				Yi et al., 2007	
	Galli et al., 2013				
	Ewing et al., 2012				
	Steen-Olsen et al., 2012				
General Equilibrium model (CGE)	Cui et al., 2017	Calzadilla et al., 2013	Cazcarro et al., 2015	Earles and Halog, 2011	Dellink and Kandelaars, 2000
	K. Turner et al., 2012		Banerjee et al., 2016	Marvuglia et al., 2013	Pauliuk et al., 2015
	Karen Turner et al., 2012			Dandres et al., 2011	Wang et al., 2017
	Cai et al., 2015			Dunn et al., 2013,	
	Chen et al., 2013			Oladosu, 2012	
	Plevin et al., 2015			Sanchez et al., 2012	
	Allan et al., 2014				
Partial Equilibrium model (PE)	Morgan and Daigneault, 2015	Calzadilla et al., 2013		Rege et al., 2015	Bouman et al., 2000
	Ariva et al., 2015			Bernard and Prieur, 2007	Lenglet et al., 2017
	Connor et al., 2015			Brown et al., 2013	Binder, 2007

	Rozakis et al., 2013			Earles et al., 2013	
	Eriksson et al., 2012			Escobar et al., 2017	
				Igos et al., 2015	
				Marvuglia et al., 2013	
				Rozakis et al., 2013	
				Vázquez-Rowe et al., 2013	
				Vázquez-Rowe et al., 2014	
Agent Based models (ABM)	Morgan and Daigneault, 2015			Miller et al., 2013	Knoeri et al., 2013
	Bravo et al., 2013			Davis et al., 2009	Bollinger et al., 2012
	Bakam et al., 2012			Florent and Enrico, 2015	Fernandez-Mena et al., 2016
	Bichraoui-Draper et al., 2015			Marvuglia et al., 2017	
System Dynamics models (SD)	Choong and McKay, 2014	Inman et al., 2016	Wei et al., 2013	Xu 2017,	Streicher-Porte et al., 2007
	Shrestha et al., 2012	Feng et al., 2017	Jin et al., 2009	Onat et al., 2016	Davidsdottir and Ruth, 2005
	Ansari and Seifi, 2013	El-Gafy, 2014	Lu and Chen, 2014	Onat et al., 2017	Choi et al., 2016
					Dace et al., 2014
					Müller et al., 2014

					Bollinger et al., 2012
					Sinha et al., 2016
					Elshkaki and Graedel, 2013
					Elshkaki et al., 2004

Table A.3a - List of Reviewed articles

	Footprints Methods			Life Cycle Assessment	Material Flow Analysis methods	
	Carbon print	**Water print**	**Ecological Footprint**		**Material Flow Analysis**	**Substance Flow Analysis**
Input output Model (IO)	(Minx et al., 2009) ; (Chen et al., 2015), (Daly et al., 2015), (Zhang et al., 2014)(Gilmartin et al., 2008), (Ala-Mantila et al., 2014), (McGregor et al., 2008), (Nansai et al., 2009),(Wiedmann, 2009) ; (Druckman and Jackson, 2009); , (Choi et al., 2010), (Wang and Li, 2012), (Su and Ang, 2014)	(Cazcarro et al., 2016) ; (Yu et al., 2010), (Feng et al., 2012), (Wang et al., 2013), (Zhang et al., 2011), (Rudenko et al., 2013)	(Salvo et al., 2015) ; (Galli et al., 2013) ; (Rugani et al., 2014) (Turner et al., 2007); (Wiedmann et al., 2007)	(Cicas et al., 2007) ; (Yi et al., 2007), ;(Gibon et al., 2015) (Choi et al., 2014), (Caro et al., 2015) (Malik et al., 2015), (Bjorn et al., 2005), (Cellura et al., 2013), (Hertwich et al., 2015),(Cortés-Borda et al., 2015) (de Carvalho et al., 2016) (Lee et al., 2011), (Tukker et al., 2009), (Ukidwe and Bakshi, 2008)	(Sinclair et al., 2005), (Risku-Norja and Mäenpää, 2007), (Matsubae-Yokoyama et al., 2009) (Hawkins et al., 2007) ; (Kytzia and Nathani, 2004) (Bailey et al., 2004) (Kytzia et al., 2004)	(Li et al., 2013), (Matsubae-Yokoyama et al., 2009), (Chen et al., 2014) (Bailey et al., 2004)
	(Galli et al., 2013) ; (Ewing et al., 2012); (Steen-Olsen et al., 2012)					
General Equilibrium Model (CGE)	(Cui et al., 2017), (K. Turner et al., 2012), (Karen Turner et al., 2012) (Cai et al., 2015), (Chen et al., 2013) (Plevin et al., 2015) (Allan et al., 2014)	(Calzadilla et al., 2013)	(Cazcarro et al., 2015), (Banerjee et al., 2016),	(Earles and Halog, 2011), (Marvuglia et al., 2013), (Dandres et al., 2011), (Dunn et al., 2013) , (Oladosu, 2012), (Sanchez et al., 2012)	(Dellink and Kandelaars, 2000), (Pauliuk et al., 2015) (Wang et al., 2017)	
Partial Equilibrium Model (PE)	(Morgan and Daigneault, 2015) ; (Ariva et al., 2015) ; (Connor et al., 2015), (Rozakis et al., 2013), (Eriksson et al., 2012)	(Calzadilla et al., 2013)		(Rege et al., 2015); (Igos et al., 2015), (Vázquez-Rowe et al., 2013) (Vázquez-Rowe et al., 2014), ; (Earles et al., 2013); (Escobar et al., 2017) ; (Brown et al., 2013); (Bernard and Prieur, 2007); (Rozakis et al., 2013), (Marvuglia et al., 2013)	(Bouman et al., 2000), (Lenglet et al., 2017) (Binder, 2007)	(Bouman et al., 2000)
Agent Based model (AB)	(Morgan and Daigneault, 2015), (Bravo et al., 2013), (Bakam et al., 2012) (Bichraoui-Draper et al., 2015),			(Miller et al., 2013), (Florent and Enrico, 2015), (Marvuglia et al., 2017), (Davis et al., 2009)	(Knoeri et al., 2013)	(Bollinger et al., 2012), (Fernandez-Mena et al., 2016),
System Dynamics model (SD)	(Choong and McKay, 2014), (Shrestha et al., 2012), (Ansari and Seifi, 2013)	(Inman et al., 2016), (Feng et al., 2017), (El-Gafy, 2014)	(Wei et al., 2013), (Jin et al., 2009), (Lu and Chen, 2014)	Xu 2017, (Onat et al., 2016) ; (Onat et al., 2017)	(Streicher-Porte et al., 2007), (Davidsdottir and Ruth, 2005), (Choi et al., 2016), (Dace et al., 2014), (Müller et al., 2014)	(Bollinger et al., 2012), (Sinha et al., 2016), (Elshkaki and Graedel, 2013) (Elshkaki et al., 2004),

Table A.4 - List of reviewed articles – other layout

A.5: Details on criteria analysis

Detail and comprehensiveness

We provide here a few examples of product categories that corresponds to the aggregation levels considered. For instance, aggregated items are such as ‘agricultural products’ or ‘fossil fuels’, disaggregated items are decomposed into ‘wheat’, ‘maize’, rice’, or can be even more detailed. A semi aggregated intermediate can be ‘cereals’ or ‘dairy products’. Usually, the more products a model contains, the more it is disaggregated. The distinction lies in that some models use a few disaggregated products. The International Standard of Industrial Classification of All Economic Activities (ISIC) established by the United Nations is a convenient standard to define the different level of disaggregation. The top level has 21 categories; the secondary level is subdivided in 99 entries.

Indirect Effects

Here are some other examples of socio-economic indirect effects: 1) Experience curves. Over time, costs in a new technological sector decrease, allowing its market share to increase. It is usually a long-term effect related to the policy support, direct effect 1 for sector *1f* in Figure 2. 2) Economies of scales. Growth of a sector as in arrow 1 may lead to reduced production costs and increase consumer buying power as in arrow 4. 3) Threshold effects. Growth of any arrow is non-proportional to the original direct change. Such effects can be related to production capacity issues, as when an increase in demand requires building new plants. 4) Income-related indirect effects (or induced effects in the IO literature). Income effects may be as detailed as the data and modelling accuracy on the socio-economic profile of consumers. These changes in the production flows directly modelled in the foreground and the background may induce changes of the environmental flows, and allow calculating environmental impacts locally in the foreground and background, and globally.

B. Annexe au deuxième chapitre

B.1 – More details on the French Forest Sector Model (FFSM)

This section comprises specifications on the FFSM model structure. More information is available in the referenced papers and online at https://ffsm-project.org/wiki/en/home.

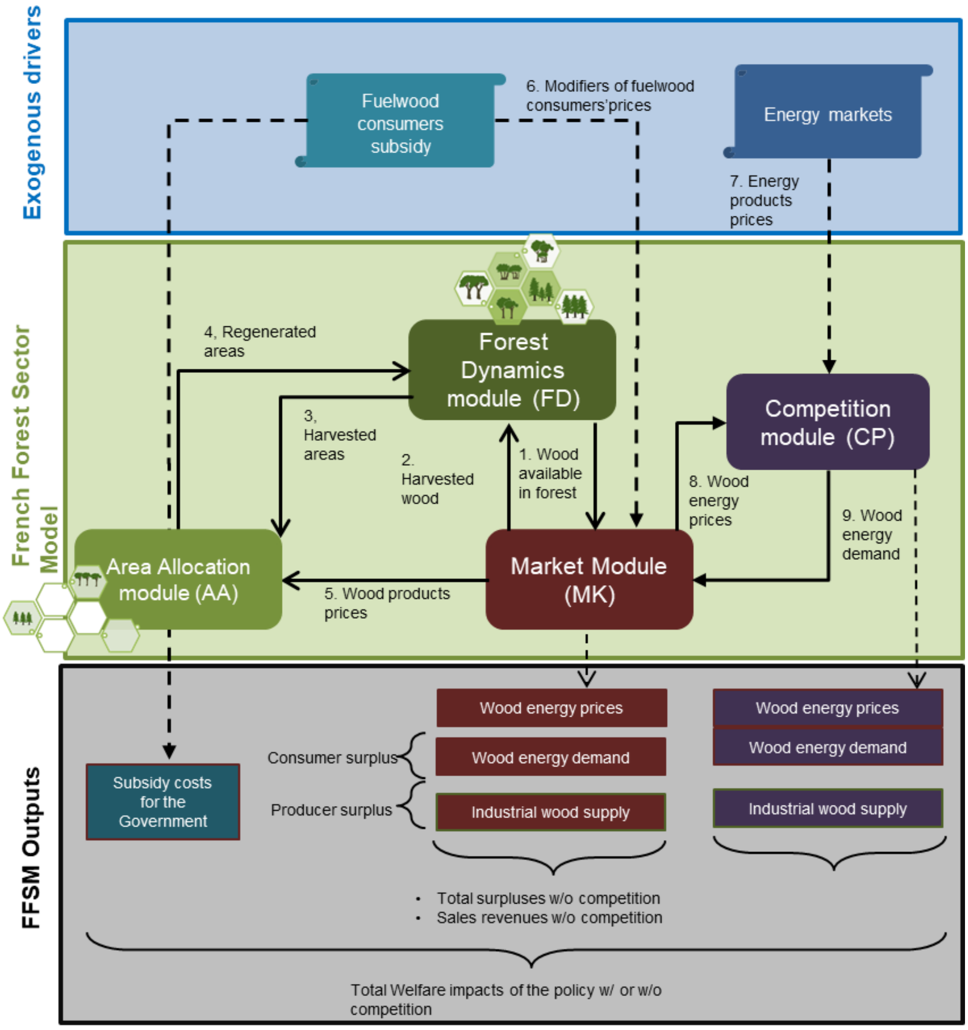

Figure B.1 - Overall structure of FFSM as used in this study

The MK module is a partial equilibrium model of the French forest sector, representing the forest management and wood industries from timber production to the consumption of first transformation wood products. It calculates the optimal harvest level for each year and region, starting from 2011 data. Each year, the forest resource availability computed in the FD modules is used in the form of a supply elasticity that shapes the supply curve. Demand curves are determined from historic data. The module solves a partial equilibrium problem accounting for transportation costs between a set of regions according to Samuelson's spatial price equilibrium framework.

It maximizes at each step an objective function that is the sum of the consumers, producers, processing industries and trade agents' surpluses. Doing so, the MK module computes 1) the optimal demand for processed products p, 2) the optimal supply of primary products w 3) the prices for these quantities, 4) the amount of wood products traded between French regions and with the rest of the world according to an Armington framework assuming that domestic and foreign products are not fully substitutable. The international trade is modelled using exogenous international prices derived from the FAO and elasticities of substitution between local and international products specifically estimated for FFSM in Sauquet et al. (2011).

The regional supply S of primary forest products w in region i takes the form of Eq. (2), where ε_w is the elasticity of supply to price $P_{w,i,t}$ and β_w is the elasticity of supply to available resources in forest. Both elasticities are derived from Buongiorno et al. (2003) and are exogenous in the context of this study.

$$S_{w,i,t} = S_{w,i,t-1}\left(\frac{P_{w,i,t}}{P_{w,i,t-1}}\right)^{\varepsilon_w}\left(\frac{F_{w,i,t}}{F_{w,i,t-1}}\right)^{\beta_w} \qquad (1)$$

Likewise, in each region i, the demand curves D of processed products p use exogenous elasticities of demand to price σ_p, specifically estimated for FFSM in Sauquet et al. (2011).

$$D_{p,i,t} = D_{p,i,t-1}\left(\frac{P_{p,i,t}}{P_{p,i,t-1}}\right)^{\sigma_p} \qquad (2)$$

Once the optimal wood supply level has been computed, it is transferred to the FD module to be subtracted from the current standing wood volume. In addition, equilibrium prices are transferred to the AA module in order to model forest managers' replanting decisions.

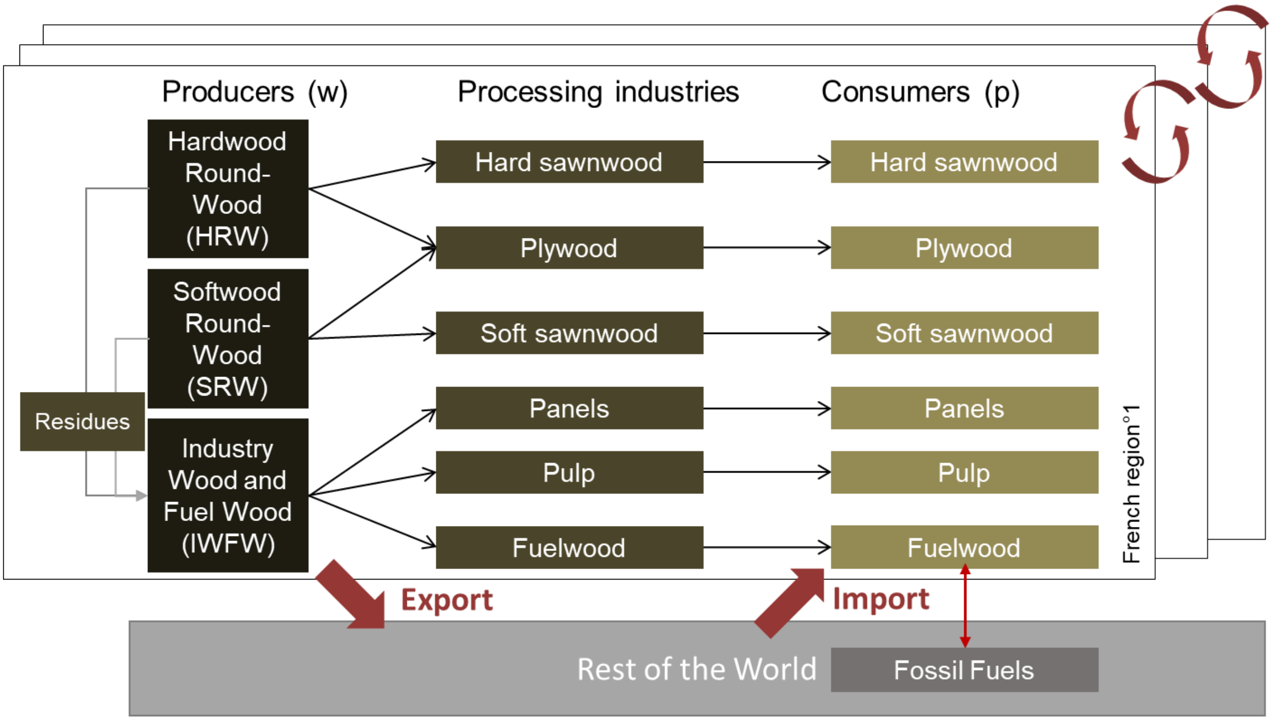

Figure A.3 - FFSM market module

The AA module is responsible for reallocating the harvested forest area to a specific forest type. Differently from the harvesting decision, which is regulated by the MK module partially as a function of timber prices, we model this choice as a long-term investment decision in which the expected profits from the available investment options (i.e. the forest types) are compared. The AA module is hence an agent-based model where individual forest managers are modelled as profit-maximizing economic agents that are heterogeneous in terms of the degree of risk aversion (the level of expected profit that they are willing to trade in exchange for a lower uncertainty over future forest profitability) and level of expectations (ranging from myopic behaviour that considers only observed information to perfect foresight behaviour that accounts for future changes). In other terms, each individual forest manager m is characterized by a risk aversion coefficient αm and expectation level βm that are randomly sampled from scenario-specific distributions. We refer to Lobianco et al., [1] for the description of the functional forms used for the expected profits.

FFSM LEONTIEF FUNCTION

The transformation coefficients are given in table B.1. The unit is m^3 roundwood equivalent per m^3 of processed products.

	Raw industry wood	Hardwood sawings	Softwood sawings	Veneers	Fuelwood	Panels	Pulp
Softwood roundwood	1*		2*	2			
Hardwood roundwood	1.5*	2.5*		2			
Raw industry wood					1	1	2.15

*Table A.5- Transformation coefficients used in the FFSM Leontief function. Stars * indicate coefficients that were modified for the study based on new MFA data*

B.2 – Ecoinvent process and data used to disaggregate FFSM products in the LCI

FFSM Product	Sub products	Ratio	Process 1	Process 2	Process 3	Process 4	Input	Ratio	Comments & modifications
Softwood sawing	Beam	39%	Debarking (Sawlog and veneer logs, softwood, debarked, measured as solid wood {CH}| debarking, softwood | Alloc Rec, U)	Sawing (Sawnwood, softwood, raw, debarked {CH}| sawing, softwood | Alloc Rec, U)	Drying (Sawnwood, softwood, raw, air dried {CH}| softwood, raw, air drying | Alloc Rec, U)	Wood preservation treatment (Wood preservation, softwood, dipping/immersion method, water-based, outdoor use, no ground contact {RER}| | Alloc Rec, U)	Pine roundwood	50%	French electricity mix
	Board	45%					Spruce roundwood	50%	
	Lath	16%							

Table A.6- Disaggregation and LCI of softwood sawings

FFSM Product	Sub products	Ratio	Process 1	Process 2	Process 3	Process 4	Input	Ratio	Comments & modifications
Hardwood Sawing	Beam	50%	Debarking (Sawlog and veneer log, hardwood, debarked, measured as solid wood {CH}| debarking, hardwood | Alloc Rec, U)	Sawing (Sawnwood, hardwood, raw, debarked {CH}| sawing, hardwood | Alloc Rec, U)	Drying (Sawnwood, hardwood, raw, air dried {CH}| hardwood, raw, air drying | Alloc Rec, U)	Wood preservation treatment (Wood preservation, softwood, dipping/immersion method, water-based, outdoor use, no ground contact {RER}| | Alloc Rec, U)	Beech roundwood	75%	French electricity mix
	Board	33%					Oak roundwood	25%	
	Lath	17%							

Table A.7- Disaggregation of hardwood sawings

FFSM Product	Sub products	Ratio 1	Wood Type	Ratio 2	Species	Ratio 3	Process	Inputs	Comments & modifications
Raw industry wood	Pulpwood	56%	Softwood	78%	Pine pulpwood	50%	Pulpwood, softwood forestry, pine | Alloc Rec, U		Natural regeneration, unmecanised exploitation
					Spruce Pulpwood	50%	Pulpwood, softwood forestry, spruce | Alloc Rec, U		
			Hardwood	22%	Beech Pulpwood	75%	Pulpwood, hardwood forestry, beech | Alloc Rec, U		
					Oak pulpwood	25%	Pulpwood, hardwood forestry, oak | Alloc Rec, U		
	Cleft timber	22%	Softwood	78%	Pine pulpwood	50%	Cleft timber, softwood forestry, pine | Alloc Rec, U		
					Spruce Pulpwood	50%	Cleft timber, softwood forestry, spruce | Alloc Rec, U		
			Hardwood	22%	Beech Pulpwood	75%	Cleft timber, hardwood forestry, beech | Alloc Rec, U		
					Oak pulpwood	25%	Cleft timber, hardwood forestry, oak | Alloc Rec, U		
	Wood Chips	22%	Softwood	78%	Pine pulpwood	50%	Wood chips, wet, measured as dry mass {CH}| wood chips production, softwood, at sawmill | Alloc Rec, U		
					Spruce Pulpwood	50%	Wood chips, wet, measured as dry mass {CH}| wood chips production, softwood, at sawmill | Alloc Rec, U		
			Hardwood	22%	Beech Pulpwood	75%	Wood chips, wet, measured as dry mass {CH}| wood chips production, hardwood, at sawmill | Alloc Rec, U		
					Oak pulpwood	25%	Wood chips, wet, measured as dry mass {CH}| wood chips production, hardwood, at sawmill | Alloc Rec, U		

Table A.8- Disaggregation and LCI of raw industry wood

FFSM Product	Sub products	Ratio	Process 1	Process 2	Process 3	Process 4	Inputs	Ratio	Comments
Softwood Sawnwood	Beam	39%	Debarking (Sawlog and veneer log, softwood, debarked, measured as solid wood {CH}| debarking, softwood | Alloc Rec, U)	Sawing (Sawnwood, softwood, raw, debarked {CH}| sawing, softwood | Alloc Rec, U)	Drying (Sawnwood, softwood, raw, air dried {CH}| softwood, raw, air drying | Alloc Rec, U)	Wood preservation treatment (Wood preservation, softwood, dipping/immersion method, water-based, outdoor use, no ground contact {RER}| wood preservation, dipping/immersion, water-based preservative, outdoor use, no ground contact | Alloc Rec, U)	Pine Sawlog, adapted	50%	French electricity mix
	Board	45%					Spruce Sawlogs, adapted	50%	
	Lath	16%							

Table A.9 - Disaggregation and LCI of Softwood Sawings

FFSM Product	Sub products	Ratio	Process 1	Process 2	Process 3	Process 4	Input	Ratio	Comments
Hardwood Sawnwood	Beam	50%	Debarking (Sawlog and veneer log, hardwood, debarked, measured as solid wood {CH}| debarking, hardwood | Alloc Rec, U)	Sawing (Sawnwood, hardwood, raw, debarked {CH}| sawing, hardwood | Alloc Rec, U)	Drying (Sawnwood, hardwood, raw, air dried {CH}| hardwood, raw, air drying | Alloc Rec, U)	Wood preservation treatment (Wood preservation, softwood, dipping/immersion method, water-based, outdoor use, no ground contact {RER}| wood preservation, dipping/immersion, water-based preservative, outdoor use, no ground contact | Alloc Rec, U)	Beech sawnwood	75%	French electricity mix
	Board	33%					Oak Sawnwood	25%	
	Lath	17%							

Table A.10 - Disaggregation and LCI of Hardwood Sawings

FFSM Product	Sub products 1: type of use	Ratio 1	Sub products 2: power	Ratio 2	Sub products 3: type of fuelwood	Ratio 3	Process	Com.
Fuelwood	Domestic use	80%	Furnace 6 kW	95%	Cleft Timber	100%	Heat, central or small-scale, other than natural gas {CH}| heat production, mixed logs, at wood heater 6 kW | Alloc Rec, U	
			Furnace 50 kW	5%	Chips from forest	100%	Heat, central or small-scale, other than natural gas {CH}| heat production, softwood chips from forest, at furnace 50 kW | Alloc Rec, U	
	District or industrial use	20%	Furnace 300 kW	67%	Chips from forest	55%	Heat, district or industrial, other than natural gas {CH}| heat production, softwood chips from forest, at furnace 300 kW | Alloc Rec, U	
					Wood chips at sawmill	45%	Heat, district or industrial, other than natural gas {CH}| heat production, wood chips from industry, at furnace 300 kW | Alloc Rec, U	
			Furnace 1000 kW	25%	Chips from forest	55%	Heat, district or industrial, other than natural gas {CH}| heat production, softwood chips from forest, at furnace 1000 kW | Alloc Rec, U	
					Wood chips at sawmill	45%	Heat, district or industrial, other than natural gas {CH}| heat production, wood chips from industry, at furnace 1000 kW | Alloc Rec, U	
			Furnace 5000 kW	8%	Chips from forest	55%	Heat, district or industrial, other than natural gas {CH}| heat production, softwood chips from forest, at furnace 5000 kW | Alloc Rec, U	
					Wood chips at sawmill	45%	Heat, district or industrial, other than natural gas {CH}| heat production, wood chips from industry, at furnace 5000 kW | Alloc Rec, U	

Table A.11 - Disaggregation and LCI of Fuelwood use

Sub products 1 : type of use	ratio 1	Sub products 2 : power	Ratio 2	Sub products 3 : type of fuelwood	Ratio 3	Process
Domestic use	60%	Furnace 6 kW	95%	Light Fuel oil	35%	heat production, light fuel oil, at boiler 10 kW, non-modulating
		Furnace 50 kW	5%	Natural gas	65%	heat production, natural gas, at boiler atmospheric non-modulating <100 kW
District or industrial use	40%	furnace 1000 kW	50%	Gas	70%	Heat, district or industrial, natural gas {CH}| natural gas, at furnace 1000 kW | Alloc Rec, U
				Oil	30%	Heat, district or industrial, other than natural gas {CH}| heat production, light fuel oil, at furnace 1000 kW | Alloc Rec, U
		furnace 5000 kW	50%	Gas	70%	Heat, district or industrial, natural gas {CH}| natural gas, at furnace 5000 kW | Alloc Rec, U
				Oil	30%	Heat, district or industrial, other than natural gas {CH}| heat production, light fuel oil, at furnace 5000 kW | Alloc Rec, U

Table A.12 - Disaggregation and LCI of Fossil fuel substitutes

FFSM Product	Sub products	Ratio	Process	Inputs	Ratio	Comments
Panels	Particle board, indoor use	70%	Particle board, for indoor use {RER}| production | Alloc Rec, U	Pulpwood	65%	French electricity mix
				Residues	35%	
	Particle board, outdoor use	30%	Particle board, for outdoor use {RER}| production | Alloc Rec, U	Pulpwood	65%	
				Residues	35%	

Table A.13 - Disaggregation and LCI of Panels

FFSM Product	Sub products	Ratio	Process	Inputs	Ratio	Comments
Pulp	Sulphate, ECF	100%	Sulphate pulp {RER}| production, elementary chlorine free bleached | Alloc Rec, U	Pulpwood	40%	French electricity mix. Co-production of 1,15 units of pulp residue for every unit of pulp used for heat production at plant level.
				Residue	60%	

Table A.14 - Disaggregation and LCI of Pulp

Mass allocation MFA		
	Volume (Mm3 eq fibre)	ratio
Hard roundwood	5	8%
Soft roundwood	15	23%
Industry wood	11	17%
Fuelwood	33	52%
Total volume	64	100%

Table A.15- Proportions of wood products from harvesting according to forest sector MFA data

Estimate of the harvestings for the year 2012 as main assortments, for each tree species, solid under bark (sub) (based on Anonymous 2012, Anonymous 2010 and information of the LWF Bavaria)

		Oak	Beech	Pine	Spruce
sawlogs	1000 m³ sub.	673	2'847	6'512	18'985
		34%	26%	50%	71%
industrial wood/energy wood	*1000 m³ sub.*	*1'515*	*9'397*	*7099*	*9'114*
of which extracted	*1000 m³ sub.*	*215*	*1'267*	*485*	*1'190*
industrial wood/energy wood, used	*1000 m³ sub.*	*1'300*	*8'130*	*6'614*	*7'924*
industrial wood	1000 m³ sub.	381	3'262	4'791	4'571
		19%	30%	36%	17%
energy wood	1000 m³ sub.	918	4'869	1'823	3'353
		47%	44%	14%	12%
of which wood chips	*1000 m³ sub.*	*211*	*1'117*	*418*	*770*
		23%	*23%*	*23%*	*23%*
of which cleft timber	*1000 m³ sub.*	*708*	*3'751*	*1'405*	*2'584*
		77%	*77%*	*77%*	*77%*
TOTAL used	*1000 m³ sub.*	1'973	10'977	13'126	26'909

Table A.16 - Proportions of wood products from harvesting according to Ecoinvent (Dataset Information (LCIA), hardwood forestry, beech, sustainable forest management, DE, (Author: Frank Werner)

C. Annexe au troisième chapitre

C.1 Energy shock specifications

A price shock vector is defined based on recent price data, adding price increase rates similar to the 70s/80s and 2000s energy crises. The difference between base scenario and shock is shown in Figure A.4 and values are displayed in Table A.17.

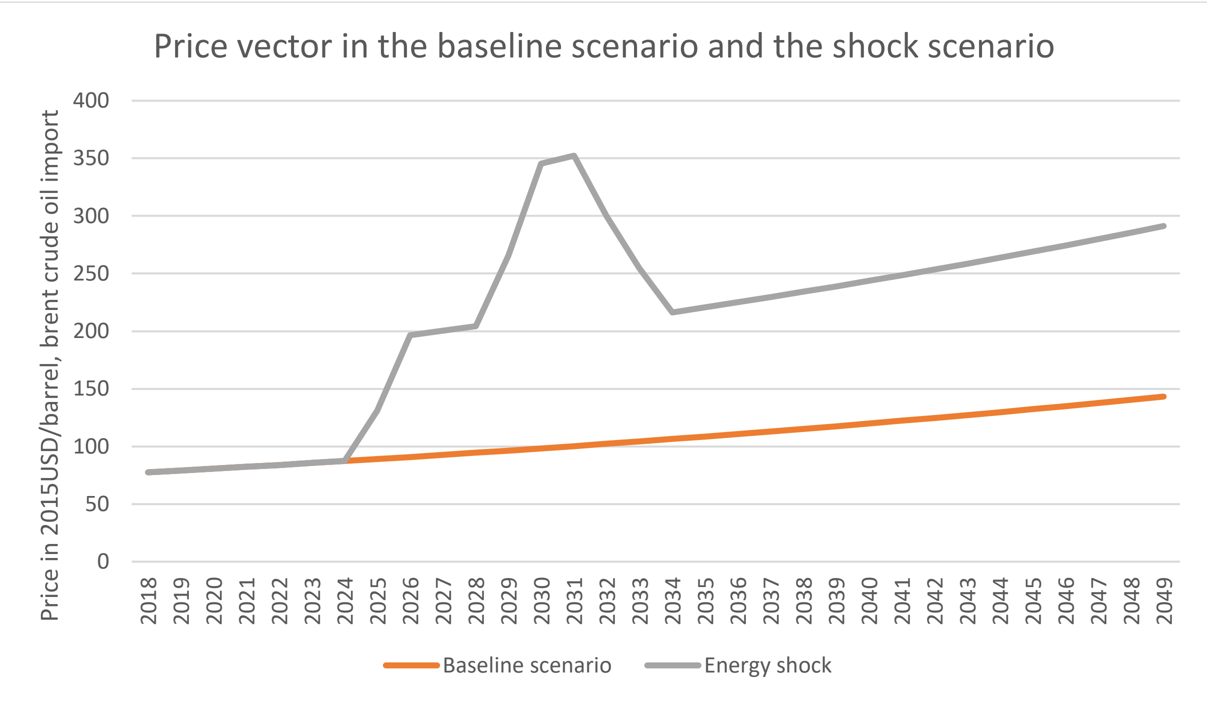

Figure A.4 - Yearly prices of fossil fuels in the baseline scenario and the energy shock scenario

year	**2020**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
USD/bbl	79,1	87,3	131,0	196,4	200,4	204,4	265,7
variation	-	10 %	50 %	50 %	2 %	2 %	30 %
year	**2031**	**2032**	**2033**	**2034**	**2035**	**2040**	**2050**
USD/bbl	345,4	352,3	299,4	254,5	216,4	238,9	291,2
variation	30 %	2 %	-15 %	-15 %	-15 %	10 %	22 %

Table A.17 – Prices and variation rates of fossil fuels used in the shock scenario

D. Bibliographie

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Résumé

L'objectif de cette thèse est d'élaborer une méthode d'évaluation quantitative de la performance économique et environnementale de stratégies de développement régional, appliquée au secteur forestier dans le Grand Est. La démarche s'appuie sur le couplage d'outils de modélisation provenant des sciences économiques et des sciences de l'environnement. Dans le chapitre 1, nous analysons les couplages existants entre 5 modèle économique et 3 outils d'évaluation environnementale. Une grille de critère dédiée permet de comparer leur pertinence pour fournir des évaluations intégratives à l'échelle méso. Les couplages entre modèles d'équilibre d'une part, et Analyse du Cycle de Vie (ACV) d'autre part, répondent le mieux aux objectifs définis. Le chapitre 2 détaille le cadre méthodologique du couplage entre un modèle d'équilibre partiel du secteur forestier français et l'ACV. L'homogénéisation des flux de matières entre les deux modèles permet de produire des indicateurs économiques et environnementaux au périmètre cohérent, dont le ratio fournit deux indicateurs d'éco-efficience. Le premier combine le surplus économique de la filière forêt bois avec ses impacts environnementaux potentiels (Partial Eco-Efficiency, PEE), le second y ajoute les impacts environnementaux évités par la substitution entre le bois-énergie et des énergies fossiles, par rapport à un scénario de référence (Full Eco-Efficiency, FEE). Dans le chapitre 3, nous utilisons ce cadre pour analyser différentes stratégies de développement de la bioéconomie orientées vers le bois-énergie, à l'échelle nationale et au niveau régional dans le Grand Est. Nous comparons la FEE de scénarios construits par combinaisons de différentes politiques : subvention de la demande de bois-énergie, approvisionnement local, protection des forêts, crise énergétique. Les stratégies intégrant une stimulation de la demande de bois-énergie sont les plus éco-efficientes, au niveau régional et national. Cela repose notamment sur les impacts évités via la substitution du bois-énergie aux combustibles fossiles. La combinaison de la subvention avec des mesures de protection et/ou d'approvisionnement local augmente ou diminue légèrement son éco-efficience selon l'échelle de mise en œuvre. D'autres facteurs déterminant de l'éco-efficience d'une politique sont identifiés, comme les caractéristiques de la ressource forestière, l'importance de la filière bois locale, et les caractéristiques des régions voisines.

Mots clefs : Couplage, Bioéconomie, Bois-énergie, Modélisation économique, Analyse du Cycle de Vie, Evaluation multi-échelle.

Abstract

The objective of this thesis is to develop a method for quantitative assessments of the economic and environmental performance of regional development strategies, applied to the forestry sector in the region Grand Est. To this end, we adopt an approach based on the coupling of modelling tools from economics and environmental sciences. In chapter 1, we analyse couplings between 5 economic models and 3 environmental assessment tools from the existing literature. A dedicated criteria grid allows to compare their relevance to provide integrative assessments at the meso scale. Couplings between equilibrium models on the one hand, and Life Cycle Assessment (LCA) on the other hand, best meet the defined objectives. Chapter 2 details the methodological framework of the coupling between a partial equilibrium model of the French forest sector and LCA. The homogenisation of material flows between the two models makes it possible to produce economic and environmental indicators with a coherent perimeter, the ratio of which provides two eco-efficiency indicators. The first combines the economic surplus of the forest-based sector with its potential environmental impacts (Partial Eco-Efficiency, PEE); the second adds the environmental impacts avoided by substitution between wood-energy and fossil fuels, compared to a reference scenario (Full Eco-Efficiency, FEE). In Chapter 3, we use this framework to analyse different wood energy oriented bio-economy development strategies at the national level and at the regional level in the region Grand Est. For this purpose, we compare the FEE of scenarios constructed by combinations of different policies: subsidising wood energy demand, local supply, forest protection, energy crisis. Strategies integrating a stimulation of wood energy demand are the most eco-efficient, at regional and national level. This is based in particular on the benefits of avoided impacts through the substitution of wood energy for fossil fuels. The combination of the subsidy with protection measures and/or local procurement slightly increases or decreases its eco-efficiency depending on the scale of implementation. In addition, we have identified other factors determining most the eco-efficiency of a policy, such as the characteristics of the forest resource, the importance of the local wood sector, and the characteristics of neighbouring regions.

Keywords: Model coupling, Bioeconomy, Wood bioenergy, Economic modelling, Life Cycle Assessment, Multi-Scale analyse.