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

5

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23

24

## 25 **Abstract**

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

43

## 44 **Keywords**

45 Model coupling, Economic modelling, Environmental assessment, Integrated Assessment, Regional  
46 policy, Sustainability

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56 **Abbreviations:** ABM, Agent Based Modelling; CGE, Computable General Equilibrium; EEIM,  
57 Economic-Environment Integrated Model; FP, Footprint; IO, Input Output; LCA, Life Cycle  
58 Assessment; LUC, Land Use Change; MFA, Material Flow Analysis; PE, Partial Equilibrium; SD,  
59 System Dynamics.

60

## 61 **1 Introduction**

62 The transition towards sustainability requires efficient, effective, and feasible policies (European  
63 Economic and Social Committee, 2016; European Parliament, 2014; OECD, 2013, 2011, 2007). These  
64 policies need to be defined at different scales, and a particular emphasis is placed on subnational  
65 policies, *i.e.* at the *meso* scale, which ranges from local communities to subnational regions.  
66 Regulatory obligations regarding environmental assessment prior to public and private projects, plans,  
67 and programmes have been implemented on this scale since the mid-1980s, particularly programmes

68 and projects involving territories and land planning under the responsibility of local authorities (EIA,  
69 European Commission, 2016; SEA, European Parliament, 2001). Local and regional initiatives are  
70 also promoted by International agreements (United Nations Conference on Environment and  
71 Development, 1992) to support transitions towards sustainability, such as local Agenda 21 (Barrutia et  
72 al., 2015), or by European authorities for green and circular economy strategies (European Economic  
73 and Social Committee, 2016; Pitkänen et al., 2016).

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

78 In the economic field, environmental stakes have been integrated through valuation and cost-benefits  
79 analysis methods (Costanza et al., 2014; Farber et al., 2002). Valuating environmental benefits into  
80 monetary units can facilitate communication with a broad audience and raise societal awareness about  
81 environmental issues. However, one major caveat of this method comes precisely from its strength, i.e.  
82 by quantifying all impacts within the same unit, the specificities of the impacts are erased. Moreover,  
83 monetary evaluation may have limits when it comes to assessing critical natural assets (Sunstein,  
84 2005), e.g. the ozone layer or rare biodiversity (Pearce et al., 2006). To address these caveats, methods  
85 coupling environmental tools with economic assessments are being developed, showing an ability to  
86 provide indicators complementary to the monetary units.

87 In this paper, we specifically aim to identify and analyse the existing methods coupling economic  
88 models and environment assessment tools to perform an integrated economic and environmental  
89 assessment at the subnational scale. The paper focuses on tools that provide a quantitative evaluation  
90 of economic effects and biophysical impacts specifically at this scale. On the one hand, different  
91 economic modelling approaches have been identified to carry out studies at regional scales (Irwin et  
92 al., 2010; Lemelin et al., 2008; Loveridge, 2004). Among these, input-output (IO) models are widely  
93 used by regional economists. Regional declinations of models based on equilibrium theory have also  
94 been established for many years (Irwin et al., 2010; Loveridge, 2004; Partridge and Rickman, 2010,  
95 1998). Over the past 20 years, the use of tools developed primarily outside of the economic field, such  
96 as agent-based modelling (ABM) (Chen et al., 2012; Fagiolo et al., 2007; Farmer and Foley, 2009;  
97 Tesfatsion, 2017) or system dynamics (SD) (McCauley and Küffner, 2004; Radzicki, 2009; Sterman,  
98 2005), has gained credibility and importance in modelling economic phenomena. On the other hand,  
99 different environmental assessment tools can be used to quantify the impacts of territorial metabolism,  
100 such as Life Cycle Assessment (LCA) (Loiseau et al., 2012), Material Flow Analysis (MFA)  
101 (Courtonne et al., 2015; Hendriks et al., 2000; Huang et al., 2007; Kennedy et al., 2007), or  
102 environmental Footprints (FP), e.g. Carbon Footprint (CF), Water Footprint (WF), or Ecological  
103 Footprint (EF) (McGregor et al., 2008; K. Turner et al., 2012; Yu et al., 2010).

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

112 This paper is structured as follows. Firstly, we briefly describe the main environmental tools and  
113 economic models to highlight their main features. We then discuss how these models have been  
114 coupled. Secondly, we perform bibliometric analysis to identify what types of coupling of economic  
115 and environmental tools and methods that exist in the scientific literature have been conducted, and in

116 what number. Thirdly, we propose an analysis grid that includes the key criteria for a comprehensive  
117 assessment at a meso scale. Then, we compare the coupled approaches through the proposed analysis  
118 grid. Finally, we draw the main conclusions and perspectives to pave the way for future research on  
119 coupling economic and environmental models at subnational scales.

## 120 **2 Overview of economic modelling approaches and environmental assessment** 121 **methods at the subnational scale**

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

### 125 **2.1 Economic modelling approaches for the subnational scale**

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

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

138 The first group encompasses traditional economic models, which may exist in versions with  
139 analytically solvable or numerically solvable structures. They are consistently used for subnational  
140 applications, and are hence well described. This group includes input output (IO) models and  
141 equilibrium theory models, i.e. Computable General Equilibrium (CGE) and Partial Equilibrium (PE)  
142 models (Irwin et al., 2010; Lemelin et al., 2008; Lovelidge, 2004; Partridge and Rickman, 2010,  
143 1998). The second group encompasses models sometimes referred to as *simulation* models. These  
144 models have been developed in the computer era and have numerically solvable structures only. Their  
145 use in economics applications has largely developed in the last 20 years (Borshchev and Filippov,  
146 2004; Moon, 2017; Scholl, 2001). This second group includes Agent-Based modelling (ABM) (Chen  
147 et al., 2012; Fagiolo et al., 2007; Farmer and Foley, 2009; Tesfatsion, 2017) and System Dynamics  
148 (SD) (McCauley and Küffner, 2004; Radzicki, 2009; Sterman, 2005). Consequently, the review will  
149 focus on five types of economic model, i.e. IO, CGE, PE, ABM, and SD. We provide their main  
150 characteristics in table 1 and more information is given in the Supplementary Information (see SI-1).

<i>Economic models</i>	<i>IO and SAM</i>	<i>Econometric</i>	<i>General equilibrium</i>	<i>Partial Equilibrium</i>	<i>Agent-Based Modelling</i>	<i>System Dynamics</i>
<i>Characteristics</i>						
<i>Formalisation</i>	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
<i>Equations</i>	Linear	Linear and non-linear	Linear and non-linear	Linear and non-linear	Non-linear	Non-linear
<i>Time dynamic</i>	Static	Dynamic	Static and Dynamic	Static and Dynamic	Static and Dynamic	Dynamic
<i>Geographic scale</i>	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
<i>Strengths</i>	Tracks interindustry linkages Easy to implement	Accurate, time-pathed 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
<i>Weaknesses</i>	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 standardisation/tractability, black box effect	Lacks standardisation/tractability, black box effect

152 **2.2 Environmental assessment methods**

153 Several tools can be used to assess the environmental impacts at the subnational scale. Loiseau et al.  
154 (2012) provide a complete description and comparison of the main characteristics of all methods that  
155 have been implemented at the territory scale. Among these, tools based on mono-footprint methods  
156 such as the Ecological Footprint (EF) and tools based on metabolism studies such as Material Flow  
157 Analysis (MFA) are notably widespread among practitioners. This is partly due to the existence of  
158 guidelines and databases that make it possible to apply these tools to cities, subnational regions, and  
159 nations. In addition, some of these methods provide indicators that are easily understandable by the  
160 public. The authors show that Life Cycle assessment (LCA), although less used for territory analysis,  
161 is a promising tool for assessing meso-scale objects. We provide an overview of the main  
162 characteristics of these three types of environmental assessment method in the table below, i.e.  
163 Footprint methods (Ecological, Carbon, and Water Footprint, FP), flow analysis (MFA or Substance  
164 Flow Analysis, SFA), and LCA, and in the Supplementary Information (see SI- 2).  
165

166 **2.3 Towards coupling of economic and environmental assessment tools**

167 Couplings between some of the aforementioned economic and environmental assessment tools have  
168 been performed for 20 years in order to provide more exhaustive information to decision-makers.  
169 Bouman et al. (2000) analysed the case of battery-related pollution using three different methods  
170 simultaneously but separately, i.e. PE models, LCA, and MFA, and called for further integration of  
171 these methods. Earles and Halog (2011), followed by Rajagopal (2017) and Roos and Ahlgren (2018),  
172 reviewed methods using economic models to perform consequential LCA, which refers to an LCA  
173 type where indirect effects induced by a change in the studied system are accounted for by expanding  
174 its boundaries. Halog and Manik (2011) and Moon (2017) reviewed methods that used agent-based  
175 modelling or system dynamics for sustainability assessments and proposed frameworks to compare  
176 them. Integrated Assessment Models (IAMs), hybrid macroeconomic models developed in climate  
177 change research to model industrial and consumption drivers of greenhouse gas (GHG) emissions in  
178 various scenarios, were also coupled with LCA or MFA (Pauliuk et al., 2017; Pehl et al., 2017).  
179 Model coupling ranges from the construction of *ad hoc* indicators (converting an economic output in  
180 an environmental impact with a coefficient) to simultaneous use of different tools for the same case  
181 study to more formalised coupling of models. We propose a simple classification of coupling between  
182 low- and high-level couplings.  
183 Low-level coupling encompasses couplings where economic and environment models are run  
184 separately, using different variables. Output(s) from one model is (are) used as input(s) of the other  
185 model, either at a single period (comparative) or through an iterative process (recursive). Numeric  
186 interfaces can be used to automatize the recursive information transfer. High-level couplings describe  
187 models that are linked and run together, involving variables from the economic and environmental  
188 models in closed loops, e.g. a model where the behaviour of economic agents is environmentally  
189 driven (preferences for environmental considerations in their utility function, production dependent on  
190 environmental assets, etc.).  
191 In both low and high-level couplings, the economic model often drives the entire coupled model. It  
192 defines the level of aggregation of the model, the ability to model the interactions and indirect effects  
193 in the assessed system – the foreground – or in its related systems – the background – and  
194 subsequently, spatial consideration for impact assessment in the foreground. It also sets the time  
195 dynamic. Thus, the economic model defines significantly the modelling abilities of the coupled model.

196 **3 Material and methods**

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

201 **3.1 Bibliometric analysis**

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

206 We used the Scopus database<sup>1</sup> with a standardized process: in the query, the name - or names - of the  
207 economic model type was crossed with one of the environmental assessment methods in the ‘abstract  
208 – title – keywords’ category. The review was limited to articles published after 1990. This first  
209 research provides insight into the use of EEIMs in the scientific literature. We provide the number of  
210 papers found for each method and a keyword network analysis in the Supplementary Information (see  
211 SI – 3).

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

219 **3.2 An analysis grid to evaluate integrated assessment methods**

220 We developed an analysis grid to carry out a transparent and argumentative comparison of the  
221 EEIMs. We defined criteria that need to be considered when describing and analysing the couplings  
222 following the approach proposed by Finnveden and Moberg (2005), Blanc et al. (2009) and Loiseau et  
223 al. (2012). According to them, we made a distinction between criteria related to the main  
224 characteristics of the EEIMs (i.e. descriptive criteria) and criteria related to the abilities of EEIMs.  
225 These latter are used as qualitative criteria to rate the performances of the different types of couplings  
226 to fit the purpose of performing an assessment of a meso scale entity, taking account of detailed  
227 interdependencies between economic agents, environmental entities, at different spatial scales and  
228 over time. This general approach allows characterising the different couplings and understanding their  
229 appropriateness for different applications.

230 **3.2.1 Descriptive criteria**

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

- 232 (i) The first criterion deals with the objectives addressed by the coupling of models. In other  
233 words, **what are the goals and scope of the study?** This qualitative criterion is proposed  
234 to identify the object of the study, i.e. a complete geographic space such as a nation or a

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<sup>1</sup> *Scopus is currently the best tool available for literature electronic search due to its wider subject and journal range compared to other databases.*



235 subnational region or single sector, and the main purpose of the study, e.g. a diagnosis or  
236 policy eco-design, explorative scenario analysis, etc.

237

238 (ii) The second criterion analyses the intensity of the coupling between the economic and  
239 environmental models, as explained in 2.1.3.

240

### 241 **3.2.2 Qualitative criteria**

242

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

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

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

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

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

257 Further details are provided in the Supplementary Information (See SI-5a).

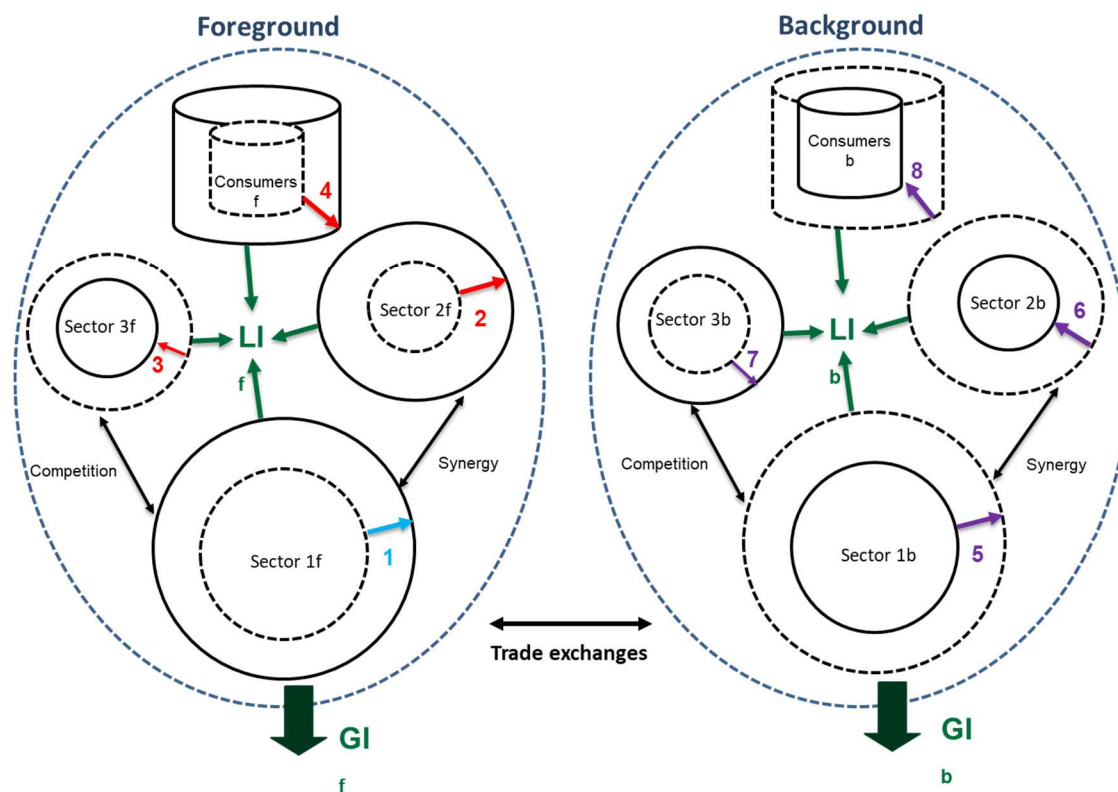
258

259 (iv) The fourth criterion evaluates **the ability of the EEIMs to provide a multicriteria**  
260 **assessment**. This ability is essential to identify the distribution of socioeconomic or  
261 environmental impacts (Finnveden et al., 2009), but also between environmental and  
262 economic impacts. This final point is important to identify the win-win solutions for both  
263 the environment and the economy (Porter and Linde, 1995). Usually, economic models  
264 provide at least output indicators in monetary units (e.g. for a sector or country, such as  
265 Gross Domestic Product) or quantities; other economic indicators may be given, such as  
266 trade surplus, added value, consumer or producer surplus, tax revenue or policy budgetary  
267 costs. At best, socioeconomic indicators such as jobs or wages are provided (Loveridge,  
268 2004; Seung and Waters, 2006). Environmental indicators are related to pressures (i.e.  
269 pollutant emissions or resource use), and certain methods (e.g. LCA) convert these  
270 pressures into impacts on the environment, going further in the DPSIR (Drivers-Pressure-  
271 State-Impact-Response) analytical framework proposed by the European Environment  
272 Agency (EEA Report, Smeets and Weterings, 1999). The same rationale applies to  
273 economic models. The more environmental flows (e.g. fossil and mineral resource use,  
274 water, land use, greenhouse gas, pesticides, or particulates emissions, etc.) and economic  
275 information (quantities, prices, and socioeconomic data) estimated the better.

276

277 (v) **The fifth criterion analyses the ability of the EEIMs to consider indirect effects**. If we  
278 consider that the region or activity under study is the foreground system (see left side of  
279 Figure 1), then, depending on the boundaries of the modelled system, two different types  
280 of indirect effect are considered in relation to the foreground system. First, 'indirect  
281 effects' can refer to the life cycle perspective and the system under study, which has

282 numerous sectoral and geographical linkages with the rest of the world due to increasing  
 283 globalization. All these external linkages comprise the background systems (right side of  
 284 Figure 1). A change in the foreground system can spread over the background system  
 285 through trade exchanges. For instance, building a new biomass power plant in the  
 286 foreground system may import part of its biomass from the background system, thus  
 287 leading to crowding out of part of the biomass used by other industries or consumers in  
 288 the background system. These indirect effects are represented in purple plain arrows on  
 289 Figure 1 and refer to so-called ‘off-site impacts’. Other types of indirect effect are  
 290 investigated in the literature and correspond to arrows 4 and 8 (see SI – 5b for more  
 291 information). Second, indirect effects can also encompass all the modifications of product  
 292 flows due to a change in the economic system after the implementation of a policy or the  
 293 development of an infrastructure. For instance, building a biomass-fed power plant is  
 294 likely to drive changes in (1) the biomass flows not only for the new plant but also for  
 295 other industries (through competition or synergies) and (2) in the flows of final products  
 296 (i.e. power and its substitutes) at the consumer level. These indirect effects at the  
 297 foreground level are represented with red arrows in Figure 2 and refer to the so-called  
 298 ‘consequential effects’.  
 299



300  
 301 **Figure 1- Representation of a set of indirect effects in the foreground and background**  
 302 **systems**

303 In this example, sector *1f* benefits from a direct change, e.g. a policy, which increases its production  
 304 capacity (arrow 1). Sector *2f* indirectly benefits from the policy *via* a synergetic relationship (arrow 2)  
 305 while sector *3f* is badly affected through a competition relationship (arrow 3). Consumers *f* also indirectly  
 306 benefit through price and revenue indirect effects (arrow 4). These three types of indirect effect (2, 3, 4)  
 307 comprise the *consequential effects* of the policy. These changes induce changes in the local environmental  
 308 impacts in the foreground  $LI_f$  and global impacts  $GI_f$ .

309 In the background system, all production sectors and consumers are affected through indirect *off-site*  
310 effects (arrows 5, 6, 7, 8), which are transmitted through trade channels. These changes induce changes in  
311 the local environmental impacts in the background  $Li_b$  and global impacts  $Gi_b$ .  
312

313 (vi) The sixth criterion is based on the **ability of the EEIMs to consider spatial variability**.  
314 The geographical representativeness of the activities or sectors under study increases the  
315 robustness of the study and could be used to quantify regionalized impacts (Potting and  
316 Hauschild, 2006). Explicit spatial modelling of economic activities in both the foreground  
317 and background facilitates the consideration of spatial variability in impact assessment.  
318

319 (vii) The seventh criterion discusses the **ability of the EEIMs to account for the temporal**  
320 evolution of the system in the short, medium, and long term. In economics, short,  
321 medium, and long terms are usually defined according to hypotheses on parameter  
322 variability such as prices, capital formation, or elasticities, as well as technology  
323 maturation or energy efficiency. We distinguish between static, dynamic non-recursive  
324 and dynamic recursive frameworks. Dynamic recursive models allow for simulating of a  
325 development path, while non-recursive models only simulate two time periods: initial and  
326 modified.  
327

328 (viii) The eighth and final criterion assesses the **ability of the EEIMs to be easily usable**. This  
329 rating gathers appreciation of the availability of data as well as the amount of time and  
330 technical knowledge required to run the EEIM and to implement the coupling, the level of  
331 standardisation reached by each model, and/or the tools' abilities to provide results that  
332 are understandable by stakeholders.  
333

334 The EEIMs found in the literature are rated according to criteria (iii) to (viii), comparative to each  
335 other, using a scale ranging from 1 to 4, with 4 being the most satisfying ability and 1 the least  
336 satisfying. The rating system is detailed in Table 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 socioeconomic indicators. Economic indicators are additive.  Environmental indicators: diversity of environmental flows.	1 Information on quantities produced/consumed/transformed
		2 Exhaustive economic information (prices and quantities)
		3 Exhaustive economic information and socioeconomic impacts
		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 consumptions 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 Spatialisation	Case studies scale : Meso (Local/Subnational); Macro (National/International)	1: Rather macro level, global/unspatialised impacts
		2: Rather macro level, mostly global impacts, some foreground spatialisation
	Spatialisation of economic and environmental indicators in the foreground and/or background	3: Rather local/meso level, mostly global impacts, some foreground spatialisation
		4: Rather local/meso level, detailed spatialised foreground, some background spatialisation
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	1: Experimental couplings, specific data collection for the case studies
	Standardisation of models and coupling	2: Technical implementation, more or less data to collect
	Availability and technicality of models and coupling	3: Implementation accessible, consistent databases available
		4: Easy to implement, consistent databases available

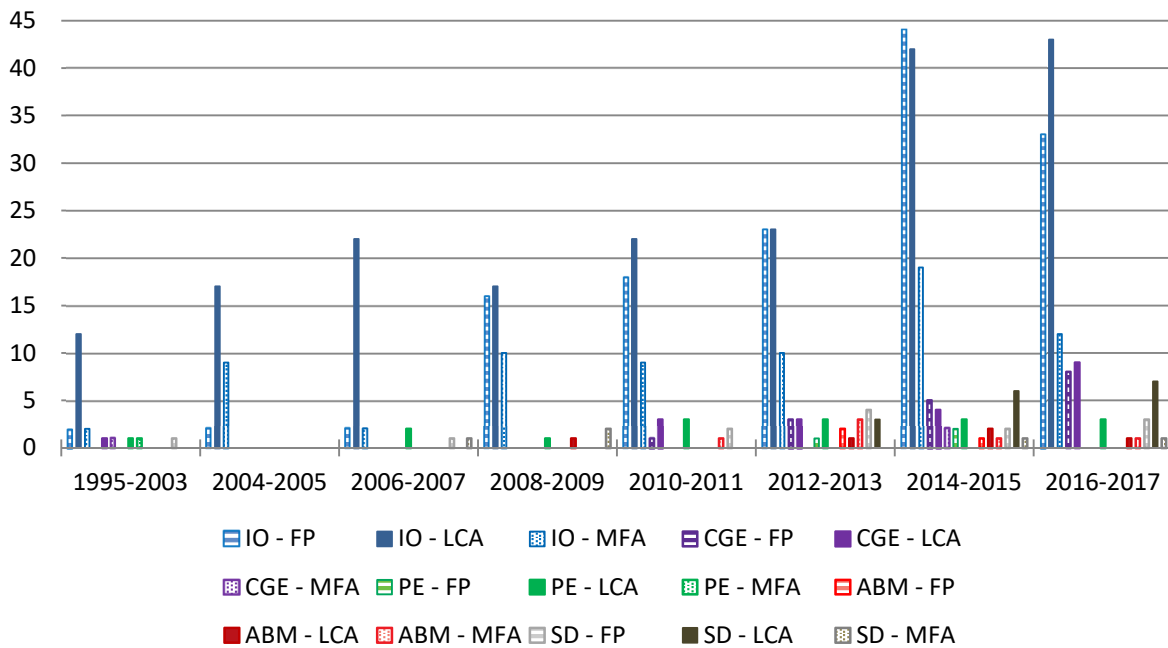
337 **Table 2 - Criteria description and rating system for qualitative comparison of models. IO=Input Output, ABM=agent-**  
 338 **based modelling, SD=System Dynamic, PE=Partial Equilibrium, CGE=Computable General Equilibrium,**  
 339 **FP=Footprint, MFA=Material Flow Analysis, LCA=Life Cycle Assessment**

340 **4 Results and discussion**

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

344 **4.1 Quantitative results of the bibliometric analysis**

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



346

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

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

358 **4.2 Comparison of the couplings through the proposed analysis grid**

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

364

365 **4.2.1 Goal and scope of the study**

366 EEIMs based on IO couplings are best suited for diagnosis of geographic entities as a whole, as they  
 367 generally encompass a large number of sectors at a reasonably disaggregated level (Minx et al., 2009).  
 368 The best example is the coupling of footprints with Multi Regional Input Output (MRIO), i.e. IO  
 369 tables gathering several figures at the regional or country scales, which allow the diagnosis to be  
 370 extended from the foreground to related regions or countries (McGregor et al., 2008; Wiedmann,  
 371 2009). In a complementary way, MFA couplings are most often used to perform a detailed diagnosis  
 372 of a given sector or product family, e.g. metal flows and electronic components at a global or country  
 373 scale (Bollinger et al., 2012; Bonnin et al., 2013; Choi et al., 2016; Dellink and Kandelaars, 2000;  
 374 Elshkaki et al., 2004; Streicher-Porte et al., 2007).

375 EEIMs are also useful for national eco-design policy assessment, mostly with IO-FP (Allan et al.,  
 376 2014; Chen et al., 2017) and CGE-FP, and in some cases IO-LCA and CGE-LCA. MFA couplings  
 377 with ABM or SD are frequently used for recycling/circular economy eco-design. In the same vein,  
 378 there are several examples of SD-based EEIMs addressing infrastructure or large-scale process  
 379 efficiency (Bollinger et al., 2012; Feng et al., 2017; You et al., 2012). Finally, PE/CGE/ABM –  
 380 Footprint/LCA EEIM are shown to be particularly used for scenario analysis related to agriculture,  
 381 biofuels, and land use (Escobar et al., 2017; Marvuglia et al., 2017; Plevin et al., 2015; Rege et al.,  
 382 2016). CGE and FP methods are oriented towards geographic entities rather than specific sectors, the  
 383 opposite of PE and MFA. SD/ABM and LCA are rather process/sectoral oriented but are increasingly  
 384 used at the subnational scale. The main properties and goals of the various EEIMs are given in Table  
 385 3.

386

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

387 **Table 3 – Preferred EEIM method sorted by questions and object of study**

388 *IO-ALL refers to any coupling of IO and an environmental assessment tool, i.e. IO-FP, IO-LCA, and*  
 389 *IO-MFA. Similarly, all-FP refers to any coupling of an economic model and FP, i.e. IO-FP, CGE-FP,*  
 390 *PE-FP, ABM-FP, and SD-FP.*

391 **4.2.2 Intensity of model coupling**

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

399 higher coupling is useless. This remark applies to IO-FP and IO-LCA, depending on the LCI database  
400 structure.

401 We identified two types of issue where high-level coupling is relevant. 1) When environmental  
402 impacts have endogenous effects on the stock of capitals and/or the efficiency of the use of the  
403 production factors; examples of high level coupling are SD-EF where the environmental consequences  
404 of strategic decisions within an industry are embedded in the model (Feng et al., 2012; Jin et al.,  
405 2009). 2) When economic agents internalise environmental policies in their decision process. Such a  
406 feature is considered in Knoeri et al. (2013) and tested by Davis et al. (2009). It would allow us to  
407 compare various environmental policy instruments, e.g. regulation, norm, communication, taxes, and  
408 labelling.

409

#### 410 ***4.2.3 Model comprehensiveness and detail***

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

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

428

#### 429 ***4.2.4 Ability to provide a multicriteria assessment***

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

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

445 agricultural sector or quantities for one or a few given sectors (Knoeri et al., 2013; Elshkaki et al.,  
446 2004; Onat et al., 2016; Shrestha et al., 2012).

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

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

455 For all-FP couplings, only one aggregated indicator is provided, ranging from emissions, as carbon  
456 footprint inventories (Druckman and Jackson, 2009; McGregor et al., 2008; Minx et al., 2009), to  
457 sectoral resource consumptions, as water footprint and land based ecological footprints tables (Feng et  
458 al., 2012; Wang et al., 2013; Yu et al., 2010; Zhang and Anadon, 2014). In some cases, several  
459 footprints are considered simultaneously to provide more than one footprint indicator. For instance,  
460 some EF couplings connect the monetary outputs with a diversified set of impact categories on both  
461 CO<sub>2</sub> emissions and resources consumption (Turner et al., 2007; Wiedmann et al., 2007) or carbon and  
462 water footprint in order to diversify impacts measurements (Ewing et al., 2012; Galli et al., 2013;  
463 Steen-Olsen et al., 2012).

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

468

#### 469 ***4.2.5 Ability to consider diverse indirect effects: consequential and off-site effects***

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

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

485 ABM-FP/LCA models are used to test various behaviour effects such as new agricultural practices  
486 adoption (Bakam et al., 2012; Bichraoui et al., 2015; Marvuglia et al., 2017; Morgan and Daigneault,  
487 2015) or consumer behaviour (Bravo et al., 2013). Thus, these models, built on agent behaviour more  
488 sophisticated than profit or utility maximisation as in the equilibrium model, provide consequential  
489 effects that are particularly relevant at a local scale. In return, they usually lack endogenous prices.  
490 This may be compensated for by coupling the ABM-ALL framework with an additional economic  
491 mechanism for price information, such as a PE or CGE model (Morgan and Daigneault, 2015).



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

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

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

506

#### 507 **4.2.6 Spatial resolution**

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

512 Most IO-ALL models have a national level foreground resolution, with national and supranational  
513 background resolution – « Rest of the world » regions in IO tables. IO-FP/LCA models reach meso  
514 level resolution for foreground and background (G. Chen et al., 2017; Cicas et al., 2007; Yi et al.,  
515 2007). At best, some IO-FP models such as Cazcarro et al. (2015) or Cong et al. (2017) couple local  
516 level data with GIS data to build impact maps with a local level resolution for the foreground.

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

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

535

#### 536 *4.2.7 Time dynamic and temporal horizons*

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

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

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

561

#### 562 *4.2.8 Usability*

563 All the EEIMs require significant amounts of data but, for some, the databases are more available or  
564 detailed. Data availability at the regional scale is a constant challenge compared to the national scale.  
565 Developing regional datasets requires specific methods and is time-consuming (Irwin et al., 2010;  
566 Ruault, 2014; Turner et al., 2007). At the national scale, IO-ALL models require less effort on that  
567 specific point while others such as IO tables are widely available (Miller and Blair, 2009; Minx et al.,  
568 2009; Wiedmann, 2009). Moreover, IO-FP/LCA may be synergic as IO tables provide a part of the  
569 inventory. This advantage does not apply to IO-MFA, as connections between IO tables' values and  
570 material flows data are not straightforward, with the exception of resource flows.

571 CGE models require much more time, econometric modelling skills, and important amounts of data,  
572 particularly for regional studies (Allan et al., 2017). PE/CGE-FP/LCA as well as PE/CGE-MFA  
573 couplings require additional efforts to fit the product categories of PE/CGE with FP/LCA inventories,  
574 but linking models is not too difficult. Coupling with LCA is more time consuming when the Process-  
575 LCA approach compared to the Economic Input Output-LCA approach (EIO-LCA)<sup>2</sup>, although there  
576 are available databases such as Ecoinvent (Wernet, G. et al., 2016).

---

<sup>2</sup> Process LCA is the original approach of itemising 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-

577 ABMs require specific data on agent behaviour for consistent programming of the interaction rules  
578 ((Borshchev and Filippov, 2004; Richiardi, 2003; Tesfatsion, 2017). If the ABM model's outputs are  
579 simple – quantities, values –, coupling ABM with FP/LCA is straightforward, as it is in most ABM-  
580 FP/LCA case studies. In Bravo et al. (2013) where consumption patterns are used or in Davis et al.  
581 (2009) where the ABM model's outputs are integrated in the LCA database's technology matrix,  
582 additional adaptations or design efforts are required. ABM usability is degraded in explorative  
583 approaches as the latter consist in performing thousands of simulations when varying all agent  
584 parameters, which may be computationally intensive and time consuming (Bollinger et al., 2012).  
585 ABM-MFA studies are theoretical (Fernandez-Mena et al., 2016; Knoeri et al., 2013), and are thus  
586 rated less usable than ABM-FP/LCA couplings.

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

592 MFA does not benefit as much from existing databases and frameworks and always requires specific  
593 work of data collection, a burden that can vary greatly depending on the scope of the studied system.  
594 To sum up, IO-ALL models are the most accessible, followed by PE-ALL models, because of data  
595 availability and manageable technicality. CGE-ALL, ABM-FP/LCA, and SD-FP are rated with an  
596 average-low usability, due to various balances of important data collection needs on the one hand and  
597 lesser spread and knowledge of the tools on the other hand. ABM-MFA and SD-LCA/MFA are  
598 considered the most experimental couplings.

599

---

LCA relies on monetary inter-industry relationships described in EIO tables to catch indirect inputs and outputs.

600

	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
<b>Disaggregation</b>	4	4	3	3	3	2	3	3	3	1	1	2	2	1	2
<b>Multicriteria analysis</b>	2	2	1	3	4	3	2	3	2	2	3	2	2	3	2
<b>Off-site and consequential effects</b>	2	2	1	3	4	3	2	3	2	2	3	3	2	3	3
<b>Scale and spatialisation</b>	3	2	1	3	2	1	4	3	2	3	2	1	3	1	2
<b>Temporality</b>	1	2	1	3	3	2	3	3	3	3	3	3	3	3	4
<b>Usability</b>	4	4	4	2	2	2	3	3	3	2	2	1	2	1	1

601

602

603

**Table 4 - Tables for 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**

#### 604 4.3 Main findings and perspectives

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

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

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

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

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

643 Among PE/CGE-FP/LCA couplings, the choice between PE and CGE depends on the need for  
644 comprehensive socioeconomic indicators and the scope of the study. CGE-FP/LCA provide a more  
645 exhaustive framework, when PE-FP/LCA are suitable for sector specific issues. PE/CGE-FP appear as  
646 a better option than PE/CGE-LCA, as detailed local level spatial resolutions have been more  
647 consistently implemented using this first type of coupling. Yet, LCA has a twofold advantage, i.e. it  
648 complies with exhaustive environmental issues and it is possible to simplify an LCA into an FP while  
649 the opposite is not possible. Overall, PE/CGE-LCA emerges as the most promising framework to

650 perform multicriteria assessment at the meso scale and we recommend testing associations of this  
651 framework with other tools and models to improve its performance and add modelling abilities.  
652

## 653 5 Conclusion

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

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

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

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

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

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

699 Eventually, our review was focused on models and tools that can be used to quantify impacts on  
700 environmental and economic dimensions. The resulting indicators can be used to go further in the  
701 assessment by using optimisation tools such as Data Envelopment Analysis (DEA) or decision-making  
702 approaches such as Multi Criteria Analysis (MCA). These complementary approaches will strengthen  
703 the benefits of EEIMs in a decision-making context. Ultimately, all these tools and methods add food  
704 for thought to develop the economic and environmental dimensions of the Life Cycle Sustainability  
705 Assessment (LCSA) framework (Guinée and Heijungs, 2011). This paves the way for future research.  
706



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712 **7 References**

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714 Ala-Mantila, S., Heinonen, J., Junnila, S., 2014. Relationship between urbanization, direct and indirect  
715 greenhouse gas emissions, and expenditures: A multivariate analysis. *Ecol. Econ.* 104, 129–139.  
716 <https://doi.org/10.1016/j.ecolecon.2014.04.019>

717 Allan, G., Lecca, P., McGregor, P., Swales, K., 2014. The economic and environmental impact of a  
718 carbon tax for Scotland: A computable general equilibrium analysis. *Ecol. Econ.* 100, 40–50.  
719 <https://doi.org/10.1016/j.ecolecon.2014.01.012>

720 Allan, G.J., Lecca, P., McGregor, P.G., McIntyre, S.G., Kim Swales, J., 2017. Computable General  
721 Equilibrium Modelling in Regional Science, in: *Advances in Spatial Science*. Springer, Cham,  
722 pp. 59–78. [https://doi.org/10.1007/978-3-319-50590-9\\_4](https://doi.org/10.1007/978-3-319-50590-9_4)

723 Bakam, I., Balana, B.B., Matthews, R., 2012. Cost-effectiveness analysis of policy instruments for  
724 greenhouse gas emission mitigation in the agricultural sector. *J. Environ. Manage.* 112, 33–44.  
725 <https://doi.org/10.1016/j.jenvman.2012.07.001>

726 Barrutia, J.M., Echebarria, C., Paredes, M.R., Hartmann, P., Apaolaza, V., 2015. From Rio to Rio+20:  
727 Twenty years of participatory, long term oriented and monitored local planning? *J. Clean. Prod.*,  
728 Bridges for a more sustainable future: Joining Environmental Management for Sustainable  
729 Universities (EMSU) and the European Roundtable for Sustainable Consumption and Production  
730 (ERSCP) conferences 106, 594–607. <https://doi.org/10.1016/j.jclepro.2014.12.085>

731 Bernard, F., Prieur, A., 2007. Biofuel market and carbon modeling to analyse French biofuel policy.  
732 *Energy Policy* 35, 5991–6002. <https://doi.org/10.1016/j.enpol.2007.08.005>

733 Bichraoui, N., Guillaume, B., Halog, A., Bichraoui-Draper, N., Xu, M., Miller, S.A., Guillaume, B.,  
734 2015. Agent-based life cycle assessment for switchgrass-based bioenergy systems. *Resour.*  
735 *Conserv. Recycl.*, The 3rd International Conference on Sustainable Future for Human Security,  
736 SUSTAIN 2012, 3-5 November 2012, Clock Tower Centennial Hall, Kyoto University, JAPAN  
737 103, 171–178. <https://doi.org/10.1016/j.resconrec.2015.08.003>

738 Bollinger, L.A., Davis, C., Nikolić, I., Dijkema, G.P.J., 2012. Modeling Metal Flow Systems: Agents  
739 vs. Equations. *J. Ind. Ecol.* 16, 176–190. <https://doi.org/10.1111/j.1530-9290.2011.00413.x>

740 Bonnin, M., Azzaro-Pantel, C., Pibouleau, L., Domenech, S., Villeneuve, J., 2013. Development and  
741 validation of a dynamic material flow analysis model for French copper cycle. *Chem. Eng. Res.*  
742 *Des.* 91, 1390–1402. <https://doi.org/10.1016/j.cherd.2013.03.016>

743 Borshchev, A., Filippov, A., 2004. From System Dynamics and Discrete Event to Practical Agent  
744 Based Modeling: Reasons, Techniques, Tools, in: *Proceedings of the 22nd International*  
745 *Conference of the System Dynamics Society*, 25-29 July, Oxford.

746 Bouman, M., Heijungs, R., Van Der Voet, E., Van Den Bergh, J.C.J.M., Huppes, G., 2000. Material  
747 flows and economic models: An analytical comparison of SFA, LCA and partial equilibrium  
748 models. *Ecol. Econ.* 32, 195–216. [https://doi.org/10.1016/S0921-8009\(99\)00091-9](https://doi.org/10.1016/S0921-8009(99)00091-9)

749 Bravo, G., Vallino, E., Cerutti, A.K., Pairotti, M.B., 2013. Alternative scenarios of green consumption  
750 in Italy: An empirically grounded model. *Environ. Model. Softw.* 47, 225–234.  
751 <https://doi.org/10.1016/j.envsoft.2013.05.015>

752 Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R.S.J., Ringler, C., 2013. Economywide impacts of climate  
753 change on agriculture in Sub-Saharan Africa. *Ecol. Econ.* 93, 150–165.  
754 <https://doi.org/10.1016/j.ecolecon.2013.05.006>

- 755 Cazcarro, I., Duarte, R., Sánchez-Chóliz, J., Sarasa, C., Serrano, A., 2015. Environmental Footprints  
756 and Scenario Analysis for Assessing the Impacts of the Agri-Food Industry on a Regional  
757 Economy: A Case Study in Spain. *J. Ind. Ecol.* 19, 618–627. <https://doi.org/10.1111/jiec.12209>
- 758 Cazcarro, I., Duarte, R., Sánchez Chóliz, J., 2016. Tracking Water Footprints at the Micro and Meso  
759 Scale: An Application to Spanish Tourism by Regions and Municipalities. *J. Ind. Ecol.* 20, 446–  
760 461. <https://doi.org/10.1111/jiec.12414>
- 761 Chen, G., Hadjikakou, M., Wiedmann, T., 2017. Urban carbon transformations: unravelling spatial  
762 and inter-sectoral linkages for key city industries based on multi-region input–output analysis. *J.*  
763 *Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2016.04.046>
- 764 Chen, S.H., Chang, C.L., Du, Y.R., 2012. Agent-based economic models and econometrics. *Knowl.*  
765 *Eng. Rev.* 27, 187–219. <https://doi.org/10.1017/S0269888912000136>
- 766 Chen, W., Wu, S., Lei, Y., Li, S., 2017. China’s water footprint by province, and inter-provincial  
767 transfer of virtual water. *Ecol. Indic.* 74, 321–333. <https://doi.org/10.1016/j.ecolind.2016.11.037>
- 768 Choi, C.H., Cao, J., Zhao, F., 2016. System Dynamics Modeling of Indium Material Flows under  
769 Wide Deployment of Clean Energy Technologies. *Resour. Conserv. Recycl.* 114, 59–71.  
770 <https://doi.org/10.1016/j.resconrec.2016.04.012>
- 771 Choi, J.K., Bakshi, B.R., Haab, T., 2010. Effects of a carbon price in the U.S. on economic sectors,  
772 resource use, and emissions: An input-output approach. *Energy Policy, Large-scale wind power*  
773 *in electricity markets with Regular Papers* 38, 3527–3536.  
774 <https://doi.org/10.1016/j.enpol.2010.02.029>
- 775 Cicas, G., Hendrickson, C.T., Horvath, A., Matthews, H.S., 2007. A regional version of a US  
776 economic input-output life-cycle assessment model. *Int. J. Life Cycle Assess.* 12, 365–372.  
777 <https://doi.org/10.1065/lca2007.04.318>
- 778 Cong, R.G., Stefaniak, I., Madsen, B., Dalgaard, T., Jensen, J.D., Nainggolan, D., Termansen, M.,  
779 2017. Where to implement local biotech innovations? A framework for multi-scale socio-  
780 economic and environmental impact assessment of Green Bio-Refineries. *Land use policy* 68,  
781 141–151. <https://doi.org/10.1016/j.landusepol.2017.07.036>
- 782 Connor, J.D., Bryan, B.A., Nolan, M., Stock, F., Gao, L., Dunstall, S., Graham, P., Ernst, A., Newth,  
783 D., Grundy, M., Hatfield-Dodds, S., 2015. Modelling Australian land use competition and  
784 ecosystem services with food price feedbacks at high spatial resolution. *Environ. Model. Softw.*  
785 69, 141–154. <https://doi.org/10.1016/j.envsoft.2015.03.015>
- 786 Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S.,  
787 Turner, R.K., 2014. Changes in the global value of ecosystem services. *Glob. Environ. Chang.*  
788 26, 152–158. <https://doi.org/10.1016/j.gloenvcha.2014.04.002>
- 789 Courtonne, J.Y., Alapetite, J., Longaretti, P.Y., Dupré, D., Prados, E., 2015. Downscaling material  
790 flow analysis: The case of the cereal supply chain in France. *Ecol. Econ.* 118, 67–80.  
791 <https://doi.org/10.1016/j.ecolecon.2015.07.007>
- 792 Cui, C.X.C.X., Hanley, N., McGregor, P., Swales, K., Turner, K., Yin, Y.P.Y.P., 2017. Impacts of  
793 regional productivity growth, decoupling and pollution leakage. *Reg. Stud.* 51, 1324–1335.  
794 <https://doi.org/10.1080/00343404.2016.1167865>
- 795 Davidsdottir, B., Ruth, M., 2005. Pulp nonfiction: Regionalized dynamic model of the U.S. pulp and  
796 paper industry. *J. Ind. Ecol.* 9, 191–211. <https://doi.org/10.1162/1088198054821618>
- 797 Davis, C., Nikolíc, I., Dijkema, G.P.J.J., Nikolíc, I., Dijkema, G.P.J.J., 2009. Integration of life cycle  
798 assessment into agent-based modeling toward informed decisions on evolving infrastructure

- 799 systems. *J. Ind. Ecol.* 13, 306–325. <https://doi.org/10.1111/j.1530-9290.2009.00122.x>
- 800 Dellink, R.B., Kandelaars, P.P.A.A.H., 2000. An empirical analysis of dematerialisation: Application  
801 to metal policies in The Netherlands. *Ecol. Econ.* 33, 205–218. [https://doi.org/10.1016/S0921-](https://doi.org/10.1016/S0921-8009(99)00138-X)  
802 [8009\(99\)00138-X](https://doi.org/10.1016/S0921-8009(99)00138-X)
- 803 Druckman, A., Jackson, T., 2009. The carbon footprint of UK households 1990-2004: A socio-  
804 economically disaggregated, quasi-multi-regional input-output model. *Ecol. Econ.* 68, 2066–  
805 2077. <https://doi.org/10.1016/j.ecolecon.2009.01.013>
- 806 Earles, J.M., Halog, A., 2011. Consequential life cycle assessment: A review. *Int. J. Life Cycle*  
807 *Assess.* 16, 445–453. <https://doi.org/10.1007/s11367-011-0275-9>
- 808 Earles, J.M., Halog, A., Ince, P., Skog, K., 2013. Integrated Economic Equilibrium and Life Cycle  
809 Assessment Modeling for Policy-based Consequential LCA. *J. Ind. Ecol.* 17, 375–384.  
810 <https://doi.org/10.1111/j.1530-9290.2012.00540.x>
- 811 El-Gafy, I.K., 2014. System Dynamic Model for Crop Production, Water Footprint, and Virtual Water  
812 Nexus. *Water Resour. Manag.* 28, 4467–4490. <https://doi.org/10.1007/s11269-014-0667-2>
- 813 Elshkaki, A., Van Der Voet, E., Van Holderbeke, M., Timmermans, V., 2004. The environmental and  
814 economic consequences of the developments of lead stocks in the Dutch economic system.  
815 *Resour. Conserv. Recycl.* 42, 133–154. <https://doi.org/10.1016/j.resconrec.2004.02.008>
- 816 Eriksson, L.O., Gustavsson, L., Hänninen, R., Kallio, M., Lyhykäinen, H., Pingoud, K., Pohjola, J.,  
817 Sathre, R., Solberg, B., Svanaes, J., Valsta, L., 2012. Climate change mitigation through  
818 increased wood use in the European construction sector-towards an integrated modelling  
819 framework. *Eur. J. For. Res.* 131, 131–144. <https://doi.org/10.1007/s10342-010-0463-3>
- 820 Escobar, N., Manrique-de-Lara-Peñate, C., Sanjuán, N., Clemente, G., Rozakis, S., 2017. An agro-  
821 industrial model for the optimization of biodiesel production in Spain to meet the European GHG  
822 reduction targets. *Energy* 120, 619–631. <https://doi.org/10.1016/j.energy.2016.11.111>
- 823 European Commission, 2016. Strategic Environmental Assessment - SEA - Environment - European  
824 Commission [WWW Document]. URL <http://ec.europa.eu/environment/eia/sea-legalcontext.htm>  
825 (accessed 11.2.17).
- 826 European Economic and Social Committee, 2016. The Circular Economy: Beneficial for All.
- 827 European Parliament, 2014. Directive 2014/52/EU of the European Parliament and of the Council of  
828 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public  
829 and private projects on the environment Text with EEA relevance.
- 830 European Parliament, 2001. Directive 2001/42/EC of the European Parliament and of the Council of  
831 27 June 2001, on the assessment of the effects of certain plans and programmes on the  
832 environment, Official Journal of the European Communities.
- 833 Ewing, B.R., Hawkins, T.R., Wiedmann, T.O., Galli, A., Ertug Ercin, A., Weinzettel, J., Steen-Olsen,  
834 K., 2012. Integrating ecological and water footprint accounting in a multi-regional input-output  
835 framework. *Ecol. Indic.* 23, 1–8. <https://doi.org/10.1016/j.ecolind.2012.02.025>
- 836 Fagiolo, G., Moneta, A., Windrum, P., 2007. A critical guide to empirical validation of agent-based  
837 models in economics: Methodologies, procedures, and open problems. *Comput. Econ.* 30, 195–  
838 226. <https://doi.org/10.1007/s10614-007-9104-4>
- 839 Farber, S.C., Costanza, R., Wilson, M.A., 2002. Economic and ecological concepts for valuing  
840 ecosystem services. *Ecol. Econ.* 41, 375–392. [https://doi.org/10.1016/S0921-8009\(02\)00088-5](https://doi.org/10.1016/S0921-8009(02)00088-5)

- 841 Farmer, J.D., Foley, D., 2009. The economy needs agent-based modelling. *Nature* 460, 685–686.  
842 <https://doi.org/10.1038/460685a>
- 843 Feng, K., Siu, Y.L.Y.L., Guan, D., Hubacek, K., 2012. Assessing regional virtual water flows and  
844 water footprints in the Yellow River Basin, China: A consumption based approach. *Appl. Geogr.*  
845 32, 691–701. <https://doi.org/10.1016/j.apgeog.2011.08.004>
- 846 Feng, L., Chen, B., Hayat, T., Alsaedi, A., Ahmad, B., 2017. Dynamic forecasting of agricultural  
847 water footprint based on Markov Chain-a case study of the Heihe River Basin. *Ecol. Modell.*,  
848 Special Issue of China-Korea Joint Seminars on multi-disciplinary and multi-method approaches  
849 toward sustainable human and nature interactions 353, 150–157.  
850 <https://doi.org/10.1016/j.ecolmodel.2016.11.002>
- 851 Fernandez-Mena, H., Nesme, T., Pellerin, S., 2016. Towards an Agro-Industrial Ecology: A review of  
852 nutrient flow modelling and assessment tools in agro-food systems at the local scale. *Sci. Total*  
853 *Environ.* 543, 467–479. <https://doi.org/10.1016/j.scitotenv.2015.11.032>
- 854 Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A.,  
855 Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. *J. Environ.*  
856 *Manage.* 91, 1–21. <https://doi.org/10.1016/j.jenvman.2009.06.018>
- 857 Galli, A., Weinzettel, J., Cranston, G., Ercin, E., 2013. A Footprint Family extended MRIO model to  
858 support Europe's transition to a One Planet Economy. *Sci. Total Environ.* 461–462, 813–818.  
859 <https://doi.org/10.1016/j.scitotenv.2012.11.071>
- 860 Gibon, T., Wood, R., Arvesen, A., Bergesen, J.D., Suh, S., Hertwich, E.G., 2015. A Methodology for  
861 Integrated, Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological  
862 Change. *Environ. Sci. Technol.* 49, 11218–11226. <https://doi.org/10.1021/acs.est.5b01558>
- 863 Guinée, J.B., Heijungs, R., 2011. Life cycle sustainability analysis: Framing questions for approaches.  
864 *J. Ind. Ecol.* 15, 656–658. <https://doi.org/10.1111/j.1530-9290.2011.00398.x>
- 865 Halog, A., Manik, Y., 2011. Advancing integrated systems modelling framework for life cycle  
866 sustainability assessment. *Sustainability* 3, 469–499. <https://doi.org/10.3390/su3020469>
- 867 Hawkins, T., Hendrickson, C., Higgins, C., Matthews, H.S., Suh, S., 2007. A mixed-unit input-output  
868 model for environmental life-cycle assessment and material flow analysis. *Environ. Sci. Technol.*  
869 41, 1024–1031. <https://doi.org/10.1021/es060871u>
- 870 Hendriks, C., Obernosterer, R., Muller, D., Kytzia, S., Baccini, P., Brunner, P.H., 2000. Material flow  
871 analysis: A tool to support environmental policy decision making. Case-studies on the city of  
872 Vienna and the Swiss lowlands. *Local Environ.* 5, 311–328.  
873 <https://doi.org/10.1080/13549830050134257>
- 874 Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez,  
875 A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios  
876 confirms global environmental benefit of low-carbon technologies. *Proc. Natl. Acad. Sci.* 112,  
877 6277–6282. <https://doi.org/10.1073/pnas.1312753111>
- 878 Huang, H., Bi, J., Zhang, B., Li, X., Yang, J., Shi, L., 2007. A critical review of material flow  
879 analysis (MFA). *Shengtai Xuebao/ Acta Ecol. Sin.* 27, 368–379.
- 880 Inman, D., Warner, E., Stright, D., Macknick, J., Peck, C., 2016. Estimating biofuel feedstock water  
881 footprints using system dynamics. *J. Soil Water Conserv.* 71, 343–355.  
882 <https://doi.org/10.2489/jswc.71.4.343>
- 883 Irwin, E.G., Isserman, A.M., Kilkenny, M., Partridge, M.D., 2010. A century Of research on rural  
884 development and regional issues. *Am. J. Agric. Econ.* 92, 522–553.

- 885 <https://doi.org/10.1093/ajae/aaq008>
- 886 Jin, W., Xu, L., Yang, Z., 2009. Modeling a policy making framework for urban sustainability:  
887 Incorporating system dynamics into the Ecological Footprint. *Ecol. Econ.* 68, 2938–2949.  
888 <https://doi.org/10.1016/j.ecolecon.2009.06.010>
- 889 Kennedy, C., Cuddihy, J., Engel-Yan, J., 2007. The changing metabolism of cities. *J. Ind. Ecol.* 11,  
890 43–59. <https://doi.org/10.1162/jie.2007.1107>
- 891 Knoeri, C., Wäger, P.A., Stamp, A., Althaus, H.J., Weil, M., 2013. Towards a dynamic assessment of  
892 raw materials criticality: Linking agent-based demand - With material flow supply modelling  
893 approaches. *Sci. Total Environ.* 461–462, 808–812.  
894 <https://doi.org/10.1016/j.scitotenv.2013.02.001>
- 895 Kytzia, S., Faist, M., Baccini, P., 2004. Economically extended - MFA: A material flow approach for a  
896 better understanding of food production chain. *J. Clean. Prod., Applications of Industrial  
897 Ecology* 12, 877–889. <https://doi.org/10.1016/j.jclepro.2004.02.004>
- 898 Lemelin, A., 2008. Modèles économiques régionaux : un survol de la littérature, *Économie. Institut de  
899 la statistique du Québec, Québec.*
- 900 Lenglet, J., Courtonne, J.Y., Caurla, S., 2017. Material flow analysis of the forest-wood supply chain:  
901 A consequential approach for log export policies in France. *J. Clean. Prod.* 165, 1296–1305.  
902 <https://doi.org/10.1016/j.jclepro.2017.07.177>
- 903 Loiseau, E., Junqua, G., Roux, P., Bellon-Maurel, V., 2012. Environmental assessment of a territory:  
904 An overview of existing tools and methods. *J. Environ. Manage.* 112, 213–225.  
905 <https://doi.org/10.1016/j.jenvman.2012.07.024>
- 906 Loiseau, E., Saikku, L., Antikainen, R., Droste, N., Hansjürgens, B., Pitkänen, K., Leskinen, P.,  
907 Kuikman, P., Thomsen, M., 2016. Green economy and related concepts: An overview. *J. Clean.  
908 Prod.* 139, 361–371. <https://doi.org/10.1016/j.jclepro.2016.08.024>
- 909 Loveridge, S., 2004. A typology and assessment of multi-sector regional economic impact models.  
910 *Reg. Stud.* 38, 305–317. <https://doi.org/10.1080/003434042000211051>
- 911 Lu, Y.Y., Chen, B., 2017. Urban ecological footprint prediction based on the Markov chain. *J. Clean.  
912 Prod., Achieving Low/no Fossil-carbon Economies based upon the Essential Transformations to  
913 Support them* 163, 146–153. <https://doi.org/10.1016/j.jclepro.2016.03.034>
- 914 Marvuglia, A., Benetto, E., Rege, S., Jury, C., 2013. Modelling approaches for consequential life-cycle  
915 assessment (C-LCA) of bioenergy: Critical review and proposed framework for biogas  
916 production. *Renew. Sustain. Energy Rev.* 25, 768–781. <https://doi.org/10.1016/j.rser.2013.04.031>
- 917 Marvuglia, A., Rege, S., Navarrete Gutiérrez, T., Vanni, L., Stilmant, D., Benetto, E., 2017. A return  
918 on experience from the application of agent-based simulations coupled with life cycle assessment  
919 to model agricultural processes. *J. Clean. Prod.* 142, 1539–1551.  
920 <https://doi.org/10.1016/j.jclepro.2016.11.150>
- 921 Matsubae-Yokoyama, K., Kubo, H., Nakajima, K., Nagasaka, T., 2009. A material flow analysis of  
922 phosphorus in Japan: The iron and steel industry as a major phosphorus source. *J. Ind. Ecol.* 13,  
923 687–705. <https://doi.org/10.1111/j.1530-9290.2009.00162.x>
- 924 McCauley, J.L., Küffner, C.M., 2004. Economic system dynamics. *Discret. Dyn. Nat. Soc.*  
925 <https://doi.org/10.1155/S102602260431201X>
- 926 McGregor, P.G., Swales, J.K., Turner, K., 2008. The CO2 'trade balance' between Scotland and the  
927 rest of the UK: Performing a multi-region environmental input-output analysis with limited data.

- 928 Ecol. Econ. 66, 662–673. <https://doi.org/10.1016/j.ecolecon.2007.11.001>
- 929 Miller, R.E., Blair, P.D., 2011. *Input-Output Analysis : Foundations and Extensions Input-Output*  
930 *Analysis : Foundations and Extensions*. Cambridge University Press.
- 931 Miller, S.A., Moysey, S., Sharp, B., Alfaro, J., 2013. A Stochastic Approach to Model Dynamic  
932 Systems in Life Cycle Assessment. *J. Ind. Ecol.* 17, 352–362. [https://doi.org/10.1111/j.1530-](https://doi.org/10.1111/j.1530-9290.2012.00531.x)  
933 [9290.2012.00531.x](https://doi.org/10.1111/j.1530-9290.2012.00531.x)
- 934 Minx, J.C., Wiedmann, T., Wood, R., Peters, G.P., Lenzen, M., Owen, A., Scott, K., Barrett, J.,  
935 Hubacek, K., Baiocchi, G., Paul, A., Dawkins, E., Briggs, J., Guan, D., Suh, S., Ackerman, F.,  
936 2009. Input-output analysis and carbon footprinting: An overview of applications. *Econ. Syst.*  
937 *Res.* 21, 187–216. <https://doi.org/10.1080/09535310903541298>
- 938 Moon, Y.B., 2017. Simulation modelling for sustainability: a review of the literature. *Int. J. Sustain.*  
939 *Eng.* 10, 2–19. <https://doi.org/10.1080/19397038.2016.1220990>
- 940 Morgan, F.J., Daigneault, A.J., 2015. Estimating impacts of climate change policy on land use: An  
941 agent-based modelling approach. *PLoS One* 10, e0127317.  
942 <https://doi.org/10.1371/journal.pone.0127317>
- 943 OECD, 2013. *Climate and Carbon* 1–57. <https://doi.org/http://dx.doi.org/10.1787/5k3z11hjpg6r7-en>
- 944 OECD, 2011. *Greening Household Behaviour, OECD Studies on Environmental Policy and*  
945 *Household Behaviour - Greening Household Behaviour*.  
946 <https://doi.org/10.1787/9789264096875-en>
- 947 OECD, 2007. *Instrument mixes for environmental policy, Instrument Mixes for Environmental Policy*.  
948 <https://doi.org/10.1787/9789264018419-en>
- 949 Onat, N.C., Kucukvar, M., Tatari, O., 2016. Uncertainty-embedded dynamic life cycle sustainability  
950 assessment framework: An ex-ante perspective on the impacts of alternative vehicle options.  
951 *Energy* 112, 715–728. <https://doi.org/10.1016/j.energy.2016.06.129>
- 952 Partridge, M.D., Rickman, D.S., 2010. Computable general equilibrium (CGE) modelling for regional  
953 economic development analysis. *Reg. Stud.* 44, 1311–1328.  
954 <https://doi.org/10.1080/00343400701654236>
- 955 Partridge, M.D., Rickman, D.S., 1998. Regional computable general equilibrium modeling: A survey  
956 and critical appraisal. *Int. Reg. Sci. Rev.* 21, 205–248.  
957 <https://doi.org/10.1177/016001769802100301>
- 958 Pauliuk, S., Arvesen, A., Stadler, K., Hertwich, E.G., 2017. Industrial ecology in integrated  
959 assessment models. *Nat. Clim. Chang.* 7, 13–20. <https://doi.org/10.1038/nclimate3148>
- 960 Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E.G., Luderer, G., 2017. Understanding  
961 future emissions from low-carbon power systems by integration of life-cycle assessment and  
962 integrated energy modelling. *Nat. Energy* 2, 939–945. [https://doi.org/10.1038/s41560-017-0032-](https://doi.org/10.1038/s41560-017-0032-9)  
963 [9](https://doi.org/10.1038/s41560-017-0032-9)
- 964 Pergola, M., D’Amico, M., Celano, G., Palese, A.M., Scuderi, A., Di Vita, G., Pappalardo, G., Inglese,  
965 P., 2013. Sustainability evaluation of Sicily’s lemon and orange production: An energy, economic  
966 and environmental analysis. *J. Environ. Manage.* 128, 674–682.  
967 <https://doi.org/10.1016/j.jenvman.2013.06.007>
- 968 Pitkänen, K., Antikainen, R., Droste, N., Loiseau, E., Saikku, L., Aissani, L., Hansjürgens, B.,  
969 Kuikman, P.J., Leskinen, P., Thomsen, M., 2016. What can be learned from practical cases of  
970 green economy? –studies from five European countries. *J. Clean. Prod.* 139, 666–676.

- 971 <https://doi.org/10.1016/j.jclepro.2016.08.071>
- 972 Plevin, R.J., Beckman, J., Golub, A.A., Witcover, J., O'Hare, M., 2015. Carbon Accounting and  
973 Economic Model Uncertainty of Emissions from Biofuels-Induced Land Use Change. *Environ.*  
974 *Sci. Technol.* 49, 2656–2664. <https://doi.org/10.1021/es505481d>
- 975 Porter, M.E., Linde, C. van der, 1995. Green and Competitive: Ending the Stalemate [WWW  
976 Document].
- 977 Potting, J., Hauschild, M.Z., 2006. Spatial differentiation in life cycle impact assessment: A decade of  
978 method development to increase the environmental realism of LCIA. *Int. J. Life Cycle Assess.*  
979 11, 11–13. <https://doi.org/10.1065/lca2006.04.005>
- 980 Radzicki, M.J., 2009. System Dynamics and Its Contribution to Economics and Economic Modeling,  
981 in: *Complex Systems in Finance and Econometrics*. Springer New York, New York, NY, pp.  
982 8990–9000. [https://doi.org/10.1007/978-0-387-30440-3\\_539](https://doi.org/10.1007/978-0-387-30440-3_539)
- 983 Rajagopal, D., 2017. A Step Towards a General Framework for Consequential Life Cycle Assessment.  
984 *J. Ind. Ecol.* 21, 261–271. <https://doi.org/10.1111/jiec.12433>
- 985 Rege, S., Arenz, M., Marvuglia, A., Vazquez-Rowe, I., Benetto, E., Igos, E., Koster, D., Vázquez-  
986 Rowe, I., Benetto, E., Igos, E., Koster, D., 2016. Quantification of Agricultural Land Use  
987 Changes in Consequential Life Cycle Assessment Using Mathematical Programming Models  
988 Following a Partial Equilibrium Approach. *J. Environ. Informatics* 26, 121–139.  
989 <https://doi.org/10.3808/jei.201500304>
- 990 Richiardi, M., 2003. The Promises and Perils of Agent-Based Computational Economics,  
991 *Computational Economics*.
- 992 Risku-Norja, H., Mäenpää, I., 2007. MFA model to assess economic and environmental consequences  
993 of food production and consumption. *Ecol. Econ.* 60, 700–711.  
994 <https://doi.org/10.1016/j.ecolecon.2006.05.001>
- 995 Roos, A., Ahlgren, S., 2018. Consequential life cycle assessment of bioenergy systems – A literature  
996 review. *J. Clean. Prod.* <https://doi.org/10.1016/j.jclepro.2018.03.233>
- 997 Rozakis, S., Haque, M.I., Natsis, A., Borzecka-Walker, M., Mizak, K., 2013. Cost-effectiveness of  
998 bioethanol policies to reduce carbon dioxide emissions in Greece. *Int. J. Life Cycle Assess.* 18,  
999 306–318. <https://doi.org/10.1007/s11367-012-0471-2>
- 1000 Ruault, J.-F., 2014. L'effet de la consommation de passage sur le développement et l'intégration  
1001 métropolitaine des territoires en Ile-de-France.
- 1002 Salvo, G., Simas, M.S., Pacca, S.A., Guilhoto, J.J.M., Tomas, A.R.G., Abramovay, R., 2015.  
1003 Estimating the human appropriation of land in Brazil by means of an Input-Output Economic  
1004 Model and Ecological Footprint analysis. *Ecol. Indic.* 53, 78–94.  
1005 <https://doi.org/10.1016/j.ecolind.2015.01.027>
- 1006 Samuelson, P., Nordhaus, W., 1992. *Economics* New York. McGraw-Hill.
- 1007 Sanchez, S.T., Woods, J., Akhurst, M., Brander, M., O'Hare, M., Dawson, T.P., Edwards, R., Liska,  
1008 A.J., Malpas, R., 2012. Accounting for indirect land-use change in the life cycle assessment of  
1009 biofuel supply chains. *J. R. Soc. Interface* 9, 1105–1119. <https://doi.org/10.1098/rsif.2011.0769>
- 1010 Scholl, H.J., 2001. Agent-based and system dynamics modeling: A call for cross study and joint  
1011 research, in: *Proceedings of the Hawaii International Conference on System Sciences*. IEEE, p.  
1012 62. <https://doi.org/10.1109/HICSS.2001.926296>



- 1013 Seung, C.K., Waters, E.C., Marine, N., Service, F., Waters, E.C., 2006. A Review of Regional  
1014 Economic Models for Fisheries Management in the U . S . Mar. Resour. Econ. 21, 101–124.
- 1015 Shrestha, E., Ahmad, S., Johnson, W., Batista, J.R., 2012. The carbon footprint of water management  
1016 policy options. Energy Policy 42, 201–212. <https://doi.org/10.1016/j.enpol.2011.11.074>
- 1017 Smeets, E., Weterings, R., 1999. Environmental indicators: Typology and overview [WWW  
1018 Document]. URL <http://www.eea.europa.eu/publications/TEC25> (accessed 7.30.18).
- 1019 Steen-Olsen, K., Weinzettel, J., Cranston, G., Ercin, A.E., Hertwich, E.G., 2012. Carbon, land, and  
1020 water footprint accounts for the european union: Consumption, production, and displacements  
1021 through international trade. Environ. Sci. Technol. 46, 10883–10891.  
1022 <https://doi.org/10.1021/es301949t>
- 1023 Sterman, J., 2005. Business Dynamics, System Thinking and Modeling for a Complex World.  
1024 McGraw-Hill, Inc.
- 1025 Streicher-Porte, M., Bader, H.P., Scheidegger, R., Kytzia, S., 2007. Material flow and economic  
1026 analysis as a suitable tool for system analysis under the constraints of poor data availability and  
1027 quality in emerging economies. Clean Technol. Environ. Policy 9, 325–345.  
1028 <https://doi.org/10.1007/s10098-007-0114-7>
- 1029 Sunstein, C.R., 2005. Cost-Benefit Analysis and the Environment, Ethics. Organisation for Economic  
1030 Co-operation and Development, Paris. <https://doi.org/10.1086/426308>
- 1031 Tesfatsion, L., 2017. Elements of dynamic economic modeling: Presentation and analysis. East. Econ.  
1032 J. 43, 192–216. <https://doi.org/10.1057/ej.2016.2>
- 1033 Turner, K., Lenzen, M., Wiedmann, T., Barrett, J., 2007. Examining the global environmental impact  
1034 of regional consumption activities - Part 1: A technical note on combining input-output and  
1035 ecological footprint analysis. Ecol. Econ. 62, 37–44.  
1036 <https://doi.org/10.1016/j.ecolecon.2006.12.002>
- 1037 Turner, K., Munday, M., McGregor, P., Swales, K., 2012. How responsible is a region for its carbon  
1038 emissions? An empirical general equilibrium analysis. Ecol. Econ. 76, 70–78.  
1039 <https://doi.org/10.1016/j.ecolecon.2012.02.001>
- 1040 Vázquez-Rowe, I., Rege, S., Marvuglia, A., Thénie, J., Haurie, A., Benetto, E., 2013. Application of  
1041 three independent consequential LCA approaches to the agricultural sector in Luxembourg. Int.  
1042 J. Life Cycle Assess. 18, 1593–1604. <https://doi.org/10.1007/s11367-013-0604-2>
- 1043 Wang, Z., Huang, K., Yang, S., Yu, Y., 2013. An input-output approach to evaluate the water footprint  
1044 and virtual water trade of Beijing, China. J. Clean. Prod. 42, 172–179.  
1045 <https://doi.org/10.1016/j.jclepro.2012.11.007>
- 1046 Wei, J., Zeng, W., Wu, B., 2013. Dynamic analysis of the virtual ecological footprint for sustainable  
1047 development of the Boao special planning area. Sustain. Sci. 8, 595–605.  
1048 <https://doi.org/10.1007/s11625-012-0189-x>
- 1049 Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent  
1050 database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.
- 1051 Wiedmann, T., 2009. A review of recent multi-region input-output models used for consumption-  
1052 based emission and resource accounting. Ecol. Econ., Special Section: Analyzing the global  
1053 human appropriation of net primary production - processes, trajectories, implications 69, 211–  
1054 222. <https://doi.org/10.1016/j.ecolecon.2009.08.026>
- 1055 Wiedmann, T., Lenzen, M., Turner, K., Barrett, J., 2007. Examining the global environmental impact

- 1056 of regional consumption activities - Part 2: Review of input-output models for the assessment of  
1057 environmental impacts embodied in trade. *Ecol. Econ.* 61, 15–26.  
1058 <https://doi.org/10.1016/j.ecolecon.2006.12.003>
- 1059 Wood, R., Hertwich, E.G., 2013. Economic modelling and indicators in life cycle sustainability  
1060 assessment. *Int. J. Life Cycle Assess.* 18, 1710–1721. <https://doi.org/10.1007/s11367-012-0463-2>
- 1061 Yi, I., Itsubo, N., Inaba, A., Matsumoto, K., 2007. Development of the interregional I/O based LCA  
1062 method considering region-specifics of indirect effects in regional evaluation. *Int. J. Life Cycle*  
1063 *Assess.* 12, 353–364. <https://doi.org/10.1065/lca2007.06.339>
- 1064 You, F., Tao, L., Graziano, D.J., Snyder, S.W., 2012. Optimal design of sustainable cellulosic biofuel  
1065 supply chains: Multiobjective optimization coupled with life cycle assessment and input-output  
1066 analysis. *AIChE J.* 58, 1157–1180. <https://doi.org/10.1002/aic.12637>
- 1067 Yu, Y., Hubacek, K., Feng, K., Guan, D., 2010. Assessing regional and global water footprints for the  
1068 UK. *Ecol. Econ.* 69, 1140–1147. <https://doi.org/10.1016/j.ecolecon.2009.12.008>
- 1069 Zhang, C., Anadon, L.D., 2014. A multi-regional input-output analysis of domestic virtual water trade  
1070 and provincial water footprint in China. *Ecol. Econ.* 100, 159–172.  
1071 <https://doi.org/10.1016/j.ecolecon.2014.02.006>
- 1072