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1 **A cross-scale impact assessment of European nature protection policies under**
2 **contrasting future socio-economic pathways**

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43 **Abstract**

44 Protection of natural or semi-natural ecosystems is an important part of societal strategies for
45 maintaining biodiversity, ecosystem services and achieving overall sustainable development.
46 The assessment of multiple emerging land use trade-offs is complicated by the fact that land
47 use changes occur and have consequences at local, regional and even global scale. Outcomes
48 also depend on the underlying socio-economic trends. We apply a coupled, multi-scale
49 modelling system to assess an increase in nature protection areas as a key policy option in the
50 European Union (EU). The main goal of the analysis is to understand the interactions between
51 policy-induced land use changes across different scales and sectors under two contrasting
52 future socio-economic pathways. We demonstrate how complementary insights into land
53 system change can be gained by coupling land use models for agriculture, forestry, and urban
54 areas for Europe, in connection with other world regions. The simulated policy case of nature
55 protection shows how the allocation of a certain share of total available land to newly
56 protected areas, with specific management restrictions imposed, may have a range of impacts
57 on different land-based sectors until the year 2040. Agricultural land in Europe is slightly
58 reduced, which is partly compensated for by higher management intensity. As a consequence
59 of higher costs, total calorie supply per capita is reduced within the EU. While wood harvest
60 is projected to decrease, carbon sequestration rates increase in European forests. At the same
61 time, imports of industrial roundwood from other world regions are expected to increase.
62 Some of the aggregate effects of nature protection have very different implications at the local
63 to regional scale in different parts of Europe. Due to nature protection measures, agricultural
64 production is shifted from more productive land in Europe to on average less productive land
65 in other parts of the world. This increases, at the global level, the allocation of land resources
66 for agriculture, leading to a decrease in tropical forest areas, reduced carbon stocks and higher
67 greenhouse gas emissions outside of Europe. The integrated modelling framework provides a
68 method to assess the land use effects of a single policy option while accounting for the trade-
69 offs between locations, and between regional, European and global scales.

70

71 **Keywords:** Land use change, integrated modelling, cross-scale interaction, nature protection,
72 impact assessment

73

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78

79 **1 Introduction**

80 Protection of natural or semi-natural ecosystems is an important part of societal strategies for
81 maintaining biodiversity, ecosystem services and achieving overall sustainable development
82 (Harvey et al. 2010; Stickler et al. 2009; Reid and Miller 1989; Gaston et al. 2008; Radeloff et
83 al. 2013, Jenkins et al. 2009). If societal preferences lead to policy measures that increase the
84 share of land protected for biodiversity and ecosystem services, this limits the possibility for
85 other uses, inherently leading to increased competition with e.g. agriculture, forestry, or urban
86 development (Smith et al. 2010; Verkerk et al. 2014a; Rounsevell et al. 2012). On the other
87 hand, nature protection may lead to improved provisioning of ecosystem services, e.g.
88 improved water quality or carbon storage, which entail important benefits for human well-
89 being (MEA 2005, Chan et al. 2006, Nelson et al. 2009, Naidoo et al. 2008). Multiple
90 emerging trade-offs and synergies between nature protection and other land uses have to be
91 taken into account if nature protection strategies are to be properly assessed.

92 The assessment of multiple land use trade-offs is complicated by the fact that land use
93 changes occur and have consequences at different spatial scales. Specific measures of land
94 use planning primarily have to be implemented and assessed at the local to regional scale, but
95 their effects at the global scale are increasingly recognised due to telecoupling of land change
96 processes (Liu et al., 2013). At the same time, the spatial allocation of protected areas is
97 important (Pouzols et al., 2014). Protecting the same total area of land in different ways, e.g.
98 under different conservation strategies (Brooks et al. 2006), may have very different
99 consequences for landscapes, the level of ecosystem service provision, and other outcomes
100 (Naidoo et al. 2008).

101 However, if protection measures are applied across different regions at the same time, their
102 combined effect may have wider land use change implications at the national and even global
103 scale (e.g. Lambin et al. 2011, Miles et al 2008; Kallio et al. 2006; Mayer et al. 2006).

104 Indirect effects of establishing increased areas of protected land may result from taking a
105 significant share of land out of agricultural or wood production in the EU-27. Such a measure
106 is likely to have consequences for global agricultural and wood markets and thus on land use
107 in other world regions. Feedbacks and rebound effects are important to include in assessments
108 of alternative biodiversity policy and protected area planning (Mayer et al. 2005, Maestre et
109 al. 2012). Single assessment methods are often unable to account for the impact of nature
110 protection policies across different scales (Verburg et al. 2015).

111 In this paper we use a chain of complementary modelling approaches with cross-scale
112 coverage to analyse land-use relevant scenarios. Analyses of global-scale processes (e.g.
113 economic growth and international trade) are linked to EU-wide and national land use
114 dynamics, which are then downscaled to sub-national administrative units as well as
115 geographic grids. With this approach, the relevant land use aspects for different sectors can be

116 assessed with specialised models at the appropriate spatial scale, while the interactions from
117 regional to global scales can be taken into account through information exchange between the
118 loosely coupled models.

119 The objective of this paper is to provide new results on the multi-scale impacts of an increase
120 in nature protection areas as a key policy option in the EU-27, using this innovative modelling
121 chain. This specific policy option is useful to demonstrate how the integration of land use
122 models across different sectors (e.g. agriculture, forestry, cities) and spatial scales (from
123 global to national to local) can provide complementary insights into land system change,
124 which cannot be gained from single-model analyses. The analysis shows the combined
125 impacts of policy parameters such as taxes, land use regulations and international trade
126 policies on land system change and ecosystem service provision. Finally, it helps to
127 understand the interactions between various land-use relevant sectors, and to integrate land
128 management information in spatial land allocation models for Europe.

129 We first describe the coupled modelling chain and the specification of the relevant scenarios
130 in section 2. In section 3 we describe the consequences of a policy scenario aiming at
131 increased nature protection areas in EU-27. Selected model results on European changes in
132 land cover, land management, land patterns, selected ecosystem services, as well as global
133 impacts are described. The modelling results are then discussed, and conclusions for further
134 research and the use of this type of assessments to inform policy decisions are drawn.

135

136 **2 Methods and data**

137 **2.1 Description of the coupled modelling approach**

138 The data flow in the coupled top-down modeling chain is described in Fig. 1. Detailed model
139 descriptions, explanation of acronyms, and scenario-specific settings are available in the
140 Supporting Online Material (SOM). More details on scenario implementation and results from
141 this assessment are provided in Lotze-Campen et al. (2013) and Verburg et al. (2013).

142

143 <<Figure 1>>

144

145 Based on the storylines of two contrasting socio-economic marker scenarios (Nakicenovic et
146 al. 2000; see 2.2), the modeling chain starts with the combined REMIND/MAGPIE models.
147 They use exogenous inputs on expected population growth as well as assumptions on
148 international trade (liberalized vs. regulated), food demand patterns (high vs. low meat
149 consumption), land use regulation (strong vs. weak forest protection in tropical areas), and
150 bioenergy demand (depending on climate mitigation targets). The macro-economic model
151 REMIND (Leimbach et al. 2010) generates growth rates for Gross Domestic Product (GDP)
152 for 10 world regions, while taking feedbacks from the land use model MAGPIE (Lotze-

153 Campen et al. 2008, 2010, Popp et al. 2014) into account. For internal consistency and
154 simplification, it has been tested and assured that the feedback of limited urban land
155 expansion and other land use changes on GDP growth is minor in the REMIND model. The
156 results on population numbers, GDP growth rates, dietary patterns, and required areas for
157 second-generation bioenergy crops are used as exogenous inputs by the MAGNET model
158 (Woltjer et al. 2014) on trade and economic development and the EFI-GTM forest sector
159 model (Moiseyev et al. 2011). Demand for built-up areas in Europe, in terms of land surface
160 needed in the future for urban residential land use, industrial and commercial land uses and
161 transport infrastructure has been computed by the LUISA model (Batista et al., 2014,
162 Baranzelli et al., 2014). Scenarios of urbanization have been defined as a function of
163 projected population growth rates, assuming converging average household sizes among EU
164 regions. Initial input data were collected from the European Statistical Office (population
165 data) and UN databases (national GDP), and projections were taken from the MAGNET
166 model. These changes in urban areas are used as an input by MAGNET, which subsequently
167 calculates changes in worldwide land use, changes in agricultural production and
168 consumption, changes in bilateral trade flows by sub-sector and region, and changes in
169 agricultural prices for key commodities (wheat, coarse grains, rice, oilseeds, sugar, ruminant
170 meat, non-ruminant meat, and dairy products). With regard to changes in agricultural
171 productivity, MAGNET makes assumptions on exogenous yield trends, which are combined
172 with endogenous processes of factor substitution. Based on changes in GDP and population,
173 the EFI-GTM model provides future trends in forest production by sub-sector, forest product
174 trade by sub-sector, and forest product prices.

175 Outputs from LUISA (on urban land use), MAGNET (agricultural trade and world market
176 price changes) and EFI-GTM (demand and trade for forestry products and changes in forestry
177 areas) are fed into three European-scale models: CAPRI (on national and sub-national
178 agricultural production; Gocht and Britz 2010), EFISCEN (on forest resources; Sallnäs 1990,
179 Schelhaas et al. 2007), and Dyna-CLUE (on spatial land use allocation; Verburg and
180 Overmars 2009). These three models interact with each other and generate a range of land-use
181 relevant results at the sub-national scale for the whole EU-27 (see also Stürck et al., in press).
182 CAPRI provides results on agricultural production and profitability, land requirements, and
183 nutrient balances. Results from the LUISA statistical urban expansion model and CAPRI are
184 used as inputs to Dyna-CLUE to refine land use allocation patterns at a very fine spatial scale
185 (1km²) across the EU. EFISCEN utilizes the resulting changes in forest area, as well as
186 demand for roundwood from EFI-GTM to project forest resource development, wood and
187 biomass production, and management intensity. At this level of detail, all relevant influences
188 from different sectors and scales are brought together for generating a consistent land-use
189 pattern. Selected model results can be used for specific ecosystem service assessments, e.g.

190 EFI-SCEN results for wood supply and carbon sequestration on forest land, and Dyna-CLUE
191 results on landscape diversity (see section 3.4 and Verkerk et al 2014b).
192 It is important to note that we link these models across scales in a very loosely coupled
193 approach. Due to the different model structures, sectoral disaggregations and data sources at
194 different scales, outputs from one model often cannot be used directly by other models.
195 Instead, transferred data have to be interpreted and translated into model-specific settings. In
196 many cases, relative changes in key results, e.g. specific land areas, are transferred along the
197 modelling chain, instead of making absolute numbers consistent, which is not possible. The
198 impacts of these specific model translations can only be explored in a systematic sensitivity
199 analysis, which is possible, but beyond the scope of this exercise. Nevertheless, our coupling
200 approach allows us to make full use of the complementary strengths of the different modelling
201 approaches.

202

203 **2.2 Marker scenario specification as a reference for model implementation and** 204 **policy assessment**

205 We use two marker scenarios as a reference for contrasting future socio-economic
206 developments in different dimensions. They serve as a background for the analysis of a
207 specific European nature protection policy and its land use implications. Impacts of increased
208 nature protection may differ in a scenario with a focus on economic growth and development,
209 compared to a scenario with a trend towards environmental preferences and related
210 restrictions on land use and land use change.

211 The two markers build on the A2 and B2 scenarios as described in the Special Report on
212 Emission Scenarios (SRES; Nakicenovic et al. 2000). They have been specified for the
213 European land-use context by replacing the “economic vs. environmental priority” axis by a
214 “less intervention vs. more intervention” axis (see Paterson et al. 2012).

215 The A2 scenario represents a fragmented world with modest economic growth, high
216 population growth, high growth of food and feed demand, weak regulation on land use change
217 (i.e. weak tropical forest protection), no change in the Common Agricultural Policy (CAP),
218 and phased-out bioenergy mandates. B2 represents a fragmented world with modest economic
219 growth, modest growth of food and feed demand, some regulation on land use change, some
220 protection of tropical forest areas, no change in the CAP, and modest bioenergy demand.

221 Detailed marker scenario descriptions, their model implementation, and specific model results
222 are provided in Lotze-Campen et al. (2013) and Verburg et al. (2013). Summary results from
223 the coupled modelling chain illustrate key characteristics of the two contrasting socio-
224 economic pathways (Tab. 1).

225

226 <<Tab. 1>>

227

228 **2.3 Defining and implementing a policy scenario on nature protection in Europe**

229 Our policy scenario assumes (a) maintaining current levels of protection through the existing
230 NATURA2000 sites, and (b) an expansion of protected areas beyond Natura2000, based on
231 various sources explained below) to create a robust ecological corridor network and
232 strengthen constraints on land cover conversions and land management. Human intervention
233 and land cover change are restricted within an improved network of European protected areas,
234 and incentives are provided to limit fragmentation and increase connectivity according to the
235 Pan-European Ecological Network (PEEN) (Jongman et al. 2011). As a side effect, strong
236 restrictions on land conversion in protected sites may result in more intensive use of
237 unprotected areas as well as less abandonment of agricultural land in other regions. These
238 policies and their consequences have been simulated with the EU-scale models CLUE,
239 CAPRI, and EFISCEN, and the global land use model MAgPIE (see Fig. 1).

240 As a first step in the modelling setup, specific nature areas throughout Europe were identified,
241 which are effectively connected, undisturbed and protected from intensive management,
242 fragmentation and urban sprawl. These areas include the core corridors identified in the PEEN
243 project, a buffer around existing Natura2000 protected areas, and existing areas up to level IV
244 from the World Database on Protected Areas (WDPA; www.protectedplanet.net). Altogether,
245 an increase in protected areas by 26% was designated (an area equivalent to about 6% of
246 usable agricultural area). For the designated areas, constraints on land cover conversions were
247 defined in the Dyna-CLUE land allocation model. This included restrictions on deforestation,
248 built-up area expansion, and conversion of extensive pastures. The establishment of more
249 connectivity in the corridor areas was stimulated by assuming incentives that reduce the
250 competitiveness of agriculture in these areas and favour conversion to natural areas (including
251 forest, natural vegetation, abandoned pasture and arable land). Nature protection measures
252 were assumed to lead to a quicker succession of abandoned farmland into natural land. The
253 agricultural sector model CAPRI uses, for each administrative region at the European NUTS2
254 level, the spatially explicit changes in protected areas from the Dyna-CLUE model. CAPRI
255 then calculates a new land balance (agricultural land availability), which may result in more
256 intensive use of unprotected areas. The global land use model MAgPIE is subsequently used
257 to estimate the effects of this reduced agricultural area in Europe on land use change and
258 related greenhouse gas emissions in other world regions. Furthermore, the extent of protected
259 areas also affects potential wood supply. In the forest resource model EFISCEN, felling
260 restrictions (Verkerk et al. 2014a) were assumed for newly protected forests (i.e. forested
261 Natura2000 sites, which are not classified as a protected area in the reference scenarios). This
262 reduces the supply of wood for material and energy use. The reduced potential is handed over
263 to the forest sector model EFI-GTM, which estimates future demand for wood from domestic

264 harvest. Future wood harvest demand and changes in forest area as estimated by Dyna-CLUE
265 were fed back into EFISCEN.

266

267 **3 Results**

268 In this section we present selected results from the coupled modelling framework to illustrate
269 the benefit from using complementary approaches to assess policy impacts on land use
270 change at different scales. A broader range of more-detailed results from the specific models
271 for all the sub-sections below is available in Lotze-Campen et al. (2013) and Verburg et al.
272 (2013).

273

274 **3.1 Changes in land cover extent**

275 Total usable agricultural area (UAA) in EU-27 is reduced by about 6% in the nature
276 protection policy scenario. This happens in addition to a reduction in agricultural area
277 between 2010 and 2040 in the underlying marker scenarios (Tab. 1). As grassland areas are
278 mostly affected by the nature protection implementation (see 2.3), the relative decrease in
279 grassland area exceeds the decrease in arable crop area. The extra land demand for nature
280 protection leads to more intensive agricultural use in the remaining agricultural land. Reduced
281 feed production on extensive grassland is compensated for by more intensive arable crop
282 production in other regions. Moreover, in CAPRI some low-input marginal grassland is also
283 suitable for cropping and converted to arable land. The spatial distribution of the area change
284 at the regional level (NUTS2) across EU-27 is shown in Fig. 2. Strongest reductions in UAA
285 occur in grassland-dominated areas, e.g. in northern UK and Ireland, Spain, and southeast
286 Europe. Only small reductions occur in cropland-dominated areas, e.g. in southern UK,
287 France, Denmark, and parts of Poland.

288

289 <<Fig2>>

290

291 **3.2 Changes in land management**

292 The land use changes associated with agricultural production depend to a large extent on
293 changes in land management and intensification. In CAPRI, intensification depends on
294 relative prices of primary production factors. In both nature protection scenarios, EU average
295 use of mineral fertiliser increases by 1%, and animal manure per ha of agricultural land
296 increases by 4% (Fig. A3.1, SOM). Average nitrogen application from animal manure per ha
297 of grassland increases by 5% as the decrease in overall grassland area exceeds the decrease in
298 number of animals. However, these changes in both A2 and B2 nature protection scenarios
299 occur in addition to quite different trends in the underlying marker scenarios. The B2 scenario
300 assumes population decrease for Europe. This results in lower demand for agricultural

301 products and, therefore, less intensive production technology and lower fertiliser and animal
302 manure use in B2 (-3%) compared to A2 (+17%) (Tab. 1).
303 Due to felling-restrictions in forested Natura2000 sites, the stemwood harvest potential in the
304 EU is estimated to be substantially lower in the nature protection scenarios as compared to the
305 marker scenarios. Potential wood supply is reduced by 53 million m³ / yr (9% of potentials)
306 in the A2 nature protection scenario and by 78 million m³ / yr (13% of potentials) in the B2
307 nature protection scenario in 2040 (Fig. 3).

308

309 <<Fig3>>

310

311 Due to the reduced production of industrial roundwood in Europe, as estimated by EFI-GTM,
312 stemwood harvest is projected to increase only slightly from 448-452 million m³ / yr in 2010
313 to 455-466 million m³ / yr in 2040. Compared to the marker scenarios in 2040, the stemwood
314 removals in EU are estimated to be reduced by 45 million m³ / yr in the A2 nature protection
315 scenario and by 74 million m³ / yr in the B2 nature protection scenario.

316

317 **3.3 Changes in land use patterns**

318 The implementation of the nature protection scenarios results in the expansion of natural areas
319 (i.e. forest, natural vegetation, abandoned pasture and arable land). The area of natural land
320 cover is approximately 5.5% higher in both nature protection scenarios, relative to the marker
321 scenarios (an increase by 10.5 million ha in A2 nature protection and 10.4 million ha in B2
322 nature protection). Pronounced increases in natural land both nature protection scenarios
323 occur in southern Spain, Eastern Europe, the UK and Ireland. The share of total natural area
324 increases at different locations as result of the targeting in the policy option. In the B2 nature
325 protection scenario grasslands within the extended Natura 2000 network or in the ecological
326 corridors are protected and maintained, whereas in the A2 nature protection scenario they are
327 often abandoned as natural land.

328 The original land cover in 2000 and the expansion of protected areas are shown in Figure 4
329 for a selected region with substantial increases in Natura2000 expansion and additional
330 ecological corridors, covering Romania, eastern Hungary, Slovakia and south-eastern Poland.
331 In some places the protected areas are expanded by a large area but in general the expansion
332 is a more subtle addition to the original areas. These areas are protected by strong restrictions
333 to land use conversion, such as no new built-up area and no new agricultural area being
334 allowed. Incentives to convert farming areas to natural land uses, as implemented in the
335 PEEN areas, encourage the development of ecological corridors (top-right panel of Fig. 4).
336 The effects of the nature protection policy option are visible as an increase in forested and
337 natural areas in the simulated land use by 2040. The increase in natural area in the nature

338 protection scenario tends to take place close to areas that have natural land cover, hence it is
339 not easily visible on the maps. The difference tends to be most obvious between the A2
340 marker and A2 nature protection scenarios. Especially the effect of ecological corridors is
341 easily visible as these were not encouraged in the A2 marker scenario. In both the A2 and B2
342 nature protection scenarios an increased density of forest area and natural areas can be seen,
343 e.g. in the Carpathian mountains. The effect of different priorities in nature management can
344 also be observed. For example in the northern Carpathians, in the B2 nature protection
345 scenario more grassland areas remain in use, because they are protected for ecosystem service
346 provision. This is in contrast to the A2 nature protection scenario where succession tends to
347 take place in these areas and there is an increase in natural vegetation.

348

349 <<Fig4>>

350

351

352 **3.4 Changes in land-based ecosystem services**

353 As total agricultural land area decreases, food provisioning through agricultural production, as
354 reported by the CAPRI model in kcal per capita, is reduced by about 2.5% in the nature
355 protection scenarios in Europe as a whole, compared to the markers. This is partly caused by a
356 loss in comparative advantage in international trade, as imports are increasing. The total
357 amount of deadwood in forests, as a proxy measure for biodiversity conservation services, is
358 projected by EFISCEN to increase by 30-33 Tg dry matter (+2%) in both nature protection
359 scenarios between 2010 and 2040. This increase is smaller than in the marker scenarios,
360 because less harvest is taking place, which reduces the amount of small deadwood fractions
361 from e.g. stem tops. However, the amount of large-diameter standing deadwood is increasing
362 in both nature protection scenarios as compared to the markers. Forests also provide carbon
363 sequestration services in the form of above-ground forest biomass (Figure A3.2, SOM). In the
364 B2 nature protection scenario, the size of the carbon sink is about 100 Tg CO₂ larger than in
365 the B2 marker. In the A2 nature protection scenario, the difference is only about half this size.
366 The sink is nevertheless projected to decline over time.

367

368 **3.5 Global land impacts**

369 The specific effects of a prescribed 6% reduction in total agricultural area in Europe as part of
370 the nature protection scenario have been explored for nine other world regions with the
371 REMIND-MAGPIE models. Since grassland in this specific model version is fixed (due to
372 data limitations in several world regions outside of Europe), we analyse here a proportional
373 change in cropland only. Effectively, due to internal adjustments in agricultural intensity,
374 cropping patterns, and trade, total cropland in Europe (including Turkey in the MAGPIE

375 model) is reduced by almost 8% as compared to the marker scenarios. While cropland is
376 reduced in Europe by 13.8 Mha in the B2 nature protection scenario and 17.7 Mha in the A2
377 nature protection scenario, it is expanded mainly in Sub-Saharan Africa, Latin America, and
378 South Asia. On average, agricultural productivity is higher in Europe than in most other world
379 regions. Since land use is shifted to less productive areas (on average) outside of Europe,
380 cropland area in the rest of the world expands by 27.6 Mha in the B2 nature protection
381 scenario, and by 57.0 Mha in the A2 nature protection scenario (Tab. 2). As a consequence,
382 global cumulative carbon emissions increase by about 10 Gt in A2 nature protection. In this
383 scenario, tropical forests are not protected, and cropland expansion, especially in Sub-Saharan
384 Africa and Latin America, occurs in carbon-rich forest areas. By contrast, in B2 nature
385 protection, tropical forests are increasingly protected over time. Hence, total cropland
386 expansion is about 50% lower than in A2, and global cumulative carbon emissions increase
387 only by about 1.4 Gt, i.e. substantially less than in A2.

388

389 <<Table2>>

390

391 The reduced supply of wood within the EU, as estimated by EFISCEN, was provided to EFI-
392 GTM to constrain the maximum industrial roundwood harvest for each European country.
393 This leads to reduced industrial roundwood removals compared to the marker scenario harvest
394 levels and increased imports of industrial wood into the EU (Figure 5). Increased wood
395 imports only partially compensate for reduced harvests. Forest production in the EU-27 is
396 reduced, with the pulp and wood panels industry mostly affected. The reaction in the B2
397 scenario on forest conservation is somewhat stronger than in A2.

398

399 <<Fig5>>

400

401

402 **4 Discussion**

403 We have analysed the consequences of a nature protection policy in Europe with a new multi-
404 model, multi-sector assessment framework. The ex-ante model-based assessment of potential
405 policy pathways can identify key trade-offs and synergies between different socio-economic
406 sectors and land uses, like agriculture, forestry, urban development, and nature protection.
407 External effects of a European policy choice for regions outside Europe are also covered. Our
408 chain of complementary models generates aggregate macro-outcomes, e.g. on agricultural and
409 forestry product trade, as well as spatially explicit maps showing the regional heterogeneity
410 and distribution of indicators like land use shares, forest productivity, agricultural
411 management intensity, and carbon sequestration. Specifically for a nature protection scenario,

412 our analysis shows how the spatial allocation of a certain share of total available land to
413 newly protected areas has various impacts on different land-based sectors. Agricultural land is
414 slightly reduced, which is partly compensated for by higher management intensity. Due to
415 land constraints and increased production costs, total calorie supply per capita is reduced
416 within the EU-27. While wood harvest is projected to decrease, carbon sequestration rates
417 increase in European forests as compared to the marker scenarios. At the same time, imports
418 of industrial roundwood from other world regions increase.

419 While the aggregate results at the European level for some of the sectors are relatively
420 modest, the spatial details at the local administrative level or on a geographic grid may differ
421 substantially. We here show selected spatially explicit results for specific changes in
422 agricultural land use, allocation of protected areas, and resulting land-use patterns (3.1, 3.3).
423 In a related paper, it has been shown that very different outcomes, sometimes even opposite
424 land use change trajectories, can be expected across Europe, due to the large diversity in local
425 environmental and socio-economic conditions (Stürck et al., in press).

426 The spatial land use patterns in the Dyna-CLUE model are to a large extent determined by the
427 land use demand taken from CAPRI and LUISA simulations, but also influenced by the
428 spatial restrictions and incentives from the specific Dyna-CLUE settings. These factors are
429 both integral parts of the policy options and cannot be easily separated. The model outputs
430 from CAPRI, Dyna-CLUE and EFISCEN have also been used for further ecosystem service
431 assessments with complementary methods (Mouchet et al. 2014).

432 While the area of natural land cover in Europe is approximately 5.5% higher in both nature
433 protection scenarios, the analysis would be incomplete without considering effects outside of
434 Europe. Through our coupling approach we use consistent scenario input data along the top-
435 down modelling chain, which covers multiple land use sectors. Moreover, feedbacks from
436 regional scenario implementations, like a European nature protection strategy, to global land
437 use change have been analysed. This is a major innovation, compared to previous European-
438 wide modelling efforts with less comprehensive approaches (e.g. Helming et al. 2008,
439 2011a,b; Jansson et al. 2008, Verburg et al. 2008). Due to nature protection in Europe,
440 agricultural production is partly shifted to other parts of the world. The net increase in global
441 agricultural area reduces tropical forest areas and related carbon stocks, and increases GHG
442 emissions.

443 The results of this multi-model assessment have to be discussed in light of the recent literature
444 on the effects of nature protection policies in EU-27 at different scales. Our nature protection
445 scenario largely follows the logic of the land sparing approach (Green et al. 2005; Boncina
446 2011), i.e. it takes specific areas out of use, especially in its implementation in the A2 nature
447 protection scenario. But for Europe and many other parts of the world, this land-sparing focus
448 of a nature protection and biodiversity conservation strategy is not the only option, and

449 continued extensive use of land or even further extensification may be an appropriate
450 alternative (referred to as land sharing, e.g. Green et al. 2005). This has only been tested to a
451 limited extent by the different implementations of nature protection in the A2 and B2
452 scenarios. Further integration of a land sharing approach with a focus on maintaining
453 ecosystem services in larger agricultural areas could also be assessed with the modelling
454 chain to allow for a simplified assessment of the two strategies. The fact that at this stage no
455 model is included that would be able to assess impacts on specific habitats and biodiversity is
456 a major impediment for a more specific assessment. However, the coupled modelling chain is
457 set up in a flexible way and allows for adding models required for specific research and
458 assessment questions.

459 One clear benefit of the coupled multi-model approach applied here is the use of consistent
460 input data and scenario assumptions across models from different sectors. The specific
461 implementations of different aspects of the scenario storylines need to leave some degrees of
462 freedom to the various modelling groups involved, due to structural differences in sector-
463 specific models. However, an intensive information exchange and repeated iterations among
464 the involved modellers to reconcile the different definitions and disciplinary epistemologies
465 has assured consistency of the scenario implementation to the maximum extent possible
466 (Verburg et al., 2015). We see huge benefits in this loosely coupled modelling approach,
467 where each model can make use of well-researched inputs provided by other models, which
468 would not be accessible in a typical study based on any single model. A further important
469 added value of the described approach across scales is that different dimensions (land cover,
470 land management, land patterns, global land impacts) can be covered consistently with
471 specialized complementary models for different land use sectors (agriculture, forestry, urban
472 land use), rather than a single model covering the same land use sectors with less detail.

473 Our approach adds quality, credibility, and complementary information to sector-specific
474 results, which is an important asset especially when dealing with well-informed stakeholders
475 across different land use sectors. At the same time, by coupling the different models, a larger
476 number of interactions and feedbacks can be explicitly taken into account. If, for example,
477 specific European models on agriculture or forestry can make use of explicit model results
478 from linked global models, they do not have to rely on their own assumptions about future
479 developments in other world regions or in other sectors (e.g. on energy demand and prices).

480 For internal quality assurance, the coupled approach heavily relies on extensive validation and
481 sensitivity analysis of the single models in previous work (see SOM for specific examples for
482 all the models involved). Where validation is limited due to a lack of observational data, the
483 robustness of model results has also been checked in extensive model comparison exercises
484 (e.g. MAGNET and MAgPIE are part of the Agricultural Model Intercomparison and
485 Improvement Project, www.agmip.org).

486 While the data exchange and consistency between different models can be sufficiently
487 managed through repeated iterations and translation between the modelling groups,
488 challenges remain with regard to error propagation and uncertainty along the whole modelling
489 chain. In this study we did not intend to provide a comprehensive and well-structured
490 sensitivity analysis for the whole modelling framework, because this task was too complex
491 and we have to leave it to future research work. However, we did take some parts of the
492 underlying uncertainty explicitly into account, by using two contrasting marker scenarios as a
493 reference for our specific nature protection policy assessment. Through our coupled approach
494 and the continuous information exchange between the modellers we tried to make sure as
495 much as possible that the scenario storylines were implemented in a consistent way at
496 different scales in the different sectors involved.

497

498 **5 Conclusions**

499 We have completed a multi-scale, multi-sector land use scenario assessment for a European
500 nature protection policy, based on a novel modelling approach. The policy scenario is
501 combined with two contrasting socio-economic pathways, to explore the robustness of
502 achieving sustainable land use in Europe. Our coupled modelling approach is capable of
503 assessing major trade-offs related to land use outcomes in a consistent way across different
504 spatial scales, from local to global. Socio-economic outcomes, e.g. on agricultural and
505 forestry production and trade, have been explicitly linked with environmental indicators and
506 non-market ecosystem services. A number of challenges remain, especially regarding
507 uncertainty propagation and consistency of specific results across different models and scales.
508 In addition, coverage of policy options and their implementation at different scales remains
509 rather simplistic. Furthermore, the list of relevant land use indicators, e.g. the quality of
510 specific habitats, needs to be improved. Specifying additional policy options and running
511 them with the complete modelling chain is resource demanding and limits the flexibility of
512 such a highly integrated land use assessment approach.

513

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517

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Tables

Table 1: Summary outputs per model for marker scenarios in 2040 (percentage changes compared to 2010) (Source: own calculations)

Model	Indicator	A2	B2
REMIND/MagPIE	Global GDP per capita	9.4 kUS\$	13.7 kUS\$
	GDP per capita in EUR, incl. Turkey	38.8 kUS\$	42.2 kUS\$
	Global cropland area	1930 Mha	1761 Mha
MAGNET	Change in agricultural area in Europe, cf. 2010	-3%	-5%
	Change in agricultural sector productivity, cf. 2010	+18%	+8%
	Change in nominal agricultural prices, cf. 2010	+80%	+75%
LUISA	Total demand for built-up areas in EU-27	26.8 Mha	25.1 Mha
EFI-GTM	EU industrial roundwood harvest	405 Mm ³	437 M m ³
	EU pulpwood prices	55 US\$/m ³	69 US\$/m ³
	EU industrial wood imports	45 Mm ³	26 Mm ³

Table 1 (continued): Summary outputs per model for marker scenarios in 2040 (percentage changes compared to 2010) (Source: own calculations)

Model	Indicator	A2	B2
CAPRI	Change in EU-27 cropland, cf. 2010	+1%	+1%
	Change in EU-27 grassland, cf. 2010	-6%	-6%
	Changes in nominal cereal prices, cf. 2010	+68%	+46%
	Changes in nominal meat prices, cf. 2010	+62%	+42%
	Change in EU-27 mineral fertilizer use on cropland, cf. 2010	+17%	-3%
EFISCEN	Stemwood harvest potentials from forest in Europe	--	591 Mm ³ /year
	Carbon sequestration in Europe	-190 TgCO ₂	-160 TgCO ₂
Dyna-CLUE	Net change in EU-27 built-up area, cf. 2010	+15%	+7%
	Net change in EU-27 arable land, cf. 2010	0%	-1%
	Net change in EU-27 pasture land, cf. 2010	-4%	-4%
	Net change in EU-27 natural vegetation, cf. 2010	-40%	-45%
	Net change in EU-27 forest area, cf. 2010	+18%	+20%

Table 2: Change in cropland areas, due to nature protection and reduced cropland use in Europe (Mha by 2040, compared to marker scenario) (Source: REMIND-MAgPIE model)

	A2	B2
Sub-Saharan Africa	28.5	11.2
Centrally-planned Asia (incl. China)	0.1	0.0
Europe (incl. Turkey)	-17.7	-13.8
Former Soviet Union	0.0	0.0
Latin America	22.1	0.4
Middle East/North Africa	0.0	1.5
North America	0.0	5.0
Pacific OECD (Japan, Australia, New Zealand)	-0.4	0.0
Pacific Asia	-8.7	0.0
South Asia (incl. India)	15.3	9.5
Global	39.2	13.8
Rest of the World (excluding Europe)	57.0	27.6

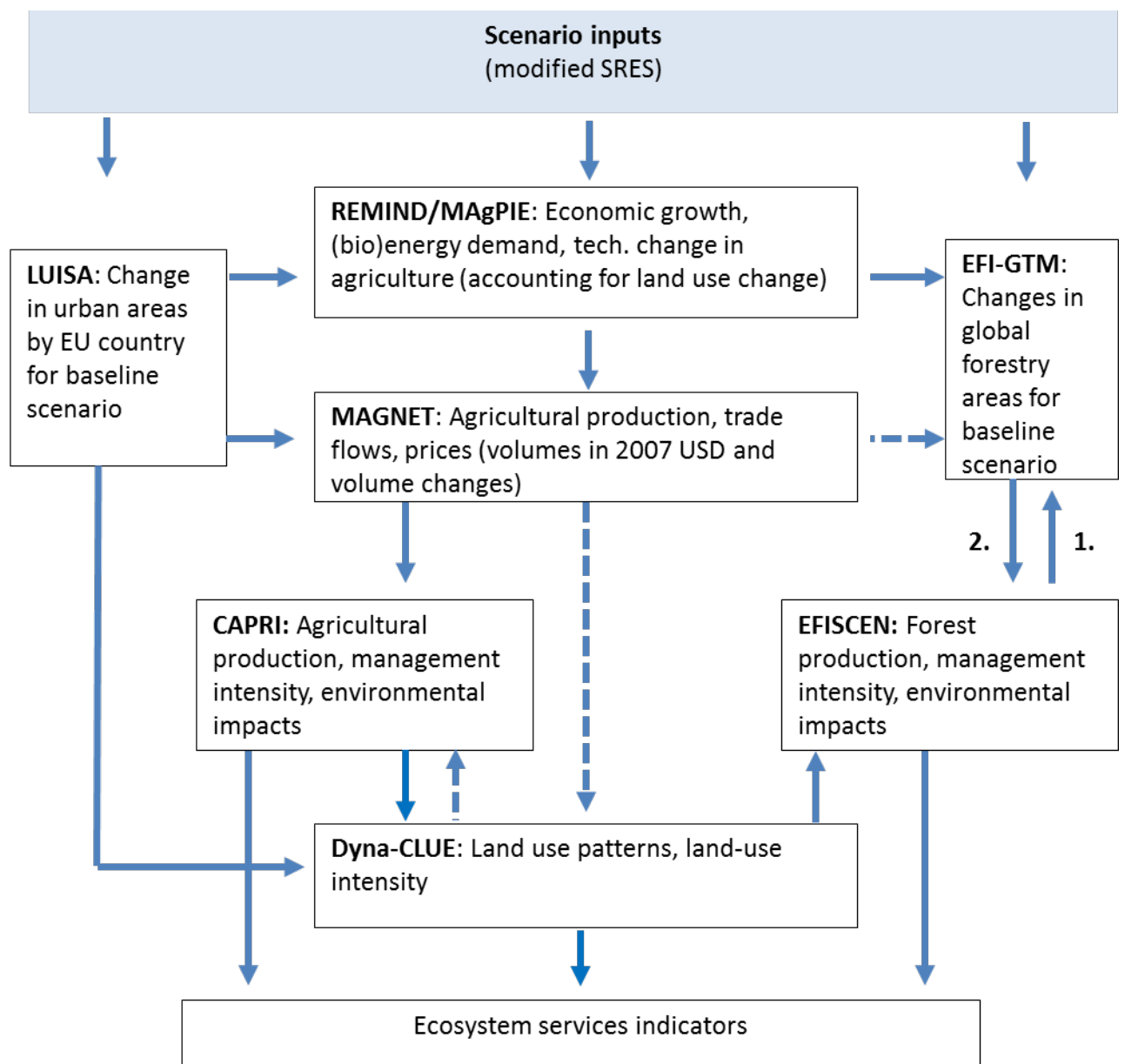


Figure 1: Data flow within the modeling chain (see Lotze-Campen (2013) and SOM for model descriptions)

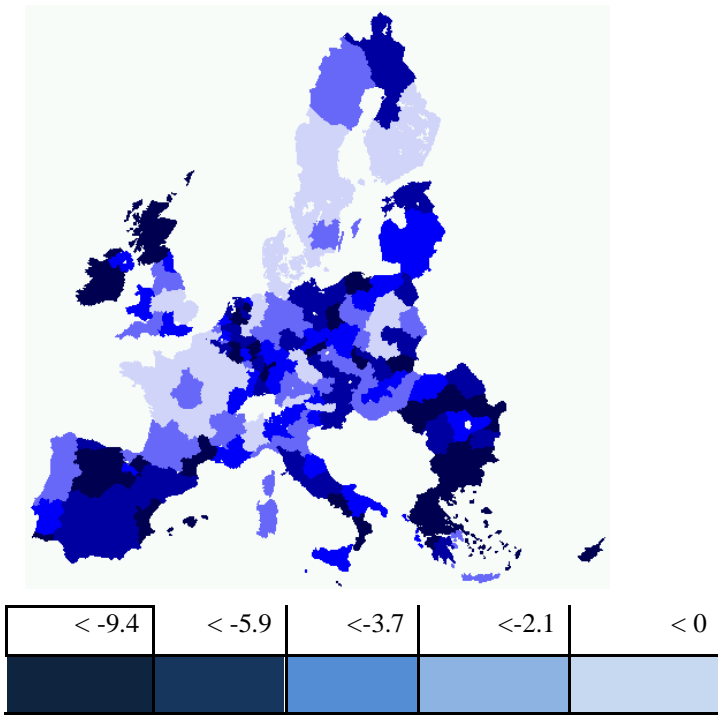


Figure 2: Map of average changes in usable agricultural area (UAA) (%) in 2040 under policy scenario “nature protection” as compared to the A2 marker scenario per NUTS2 region in the EU27 (Source: CAPRI model, based on Dyna-CLUE inputs)

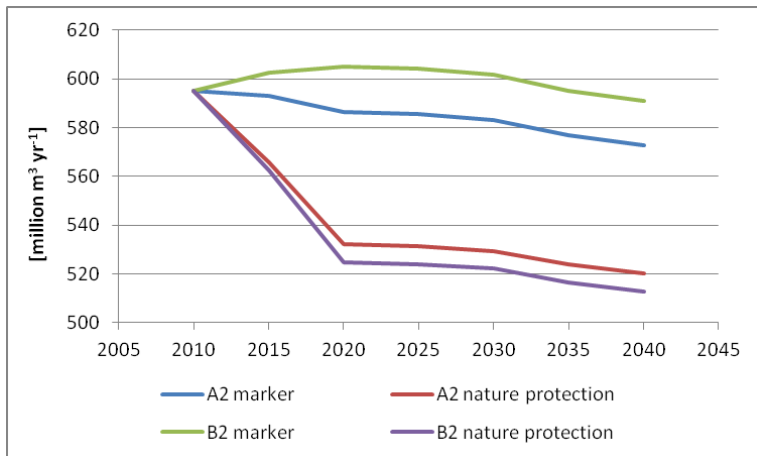


Figure 3: Development of realizable stemwood harvest potentials from forests in the European Union. The development of the potentials is presented in total volumes for the EU (Source: EFISCEN model)

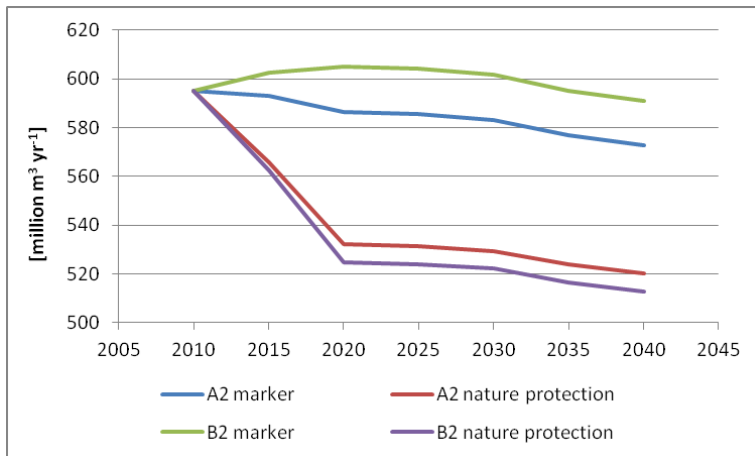


Figure 4: Development of realizable stemwood harvest potentials from forests in the European Union. The development of the potentials is presented in total volumes for the EU (Source: EFISCEN model)

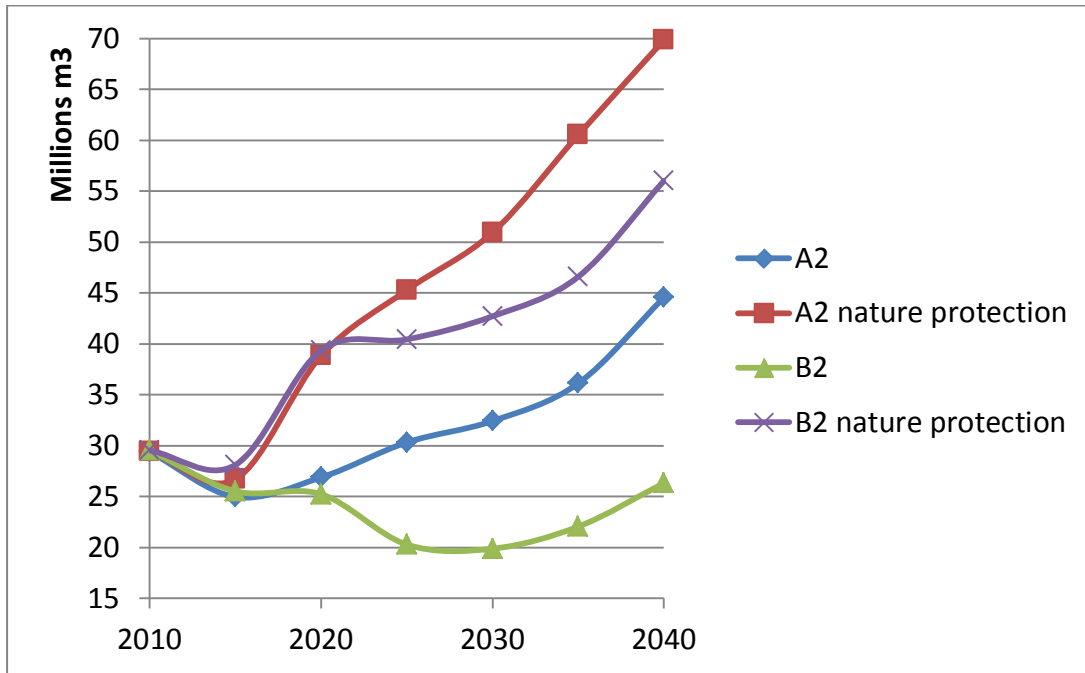


Figure 5. Development of industrial roundwood imports in the EU in marker scenarios A2 and B2 and in associated nature protection scenarios. (Source: EFI-GTM model)

SUPPLEMENTARY MATERIAL

A cross-scale impact assessment of European nature protection policies

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Additional model results

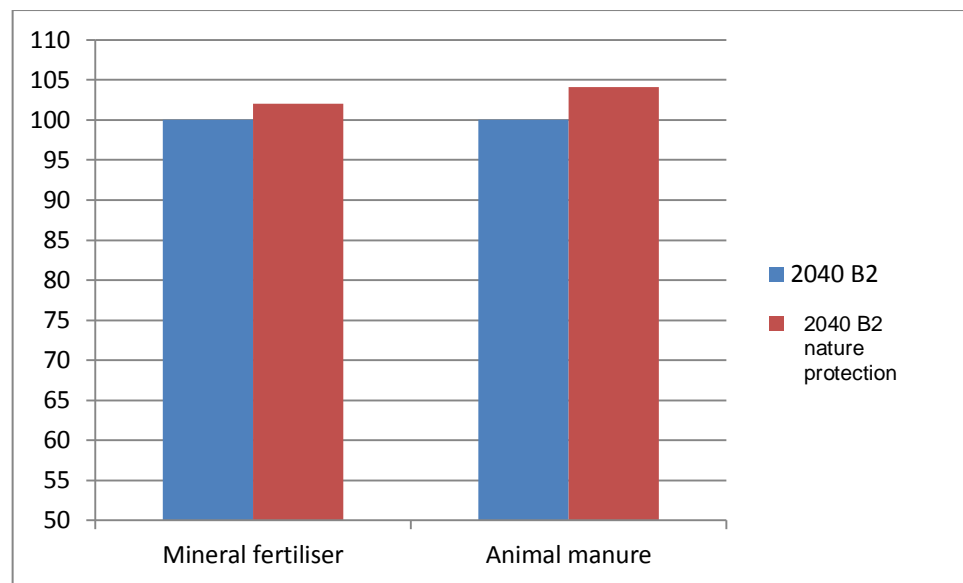


Figure A3.1: Changes in average amount of mineral fertilizer and animal manure per ha arable land in the EU-27 in 2040 under the nature protection policy scenario (Index: B2 in 2040 = 100) (Source: CAPRI model)

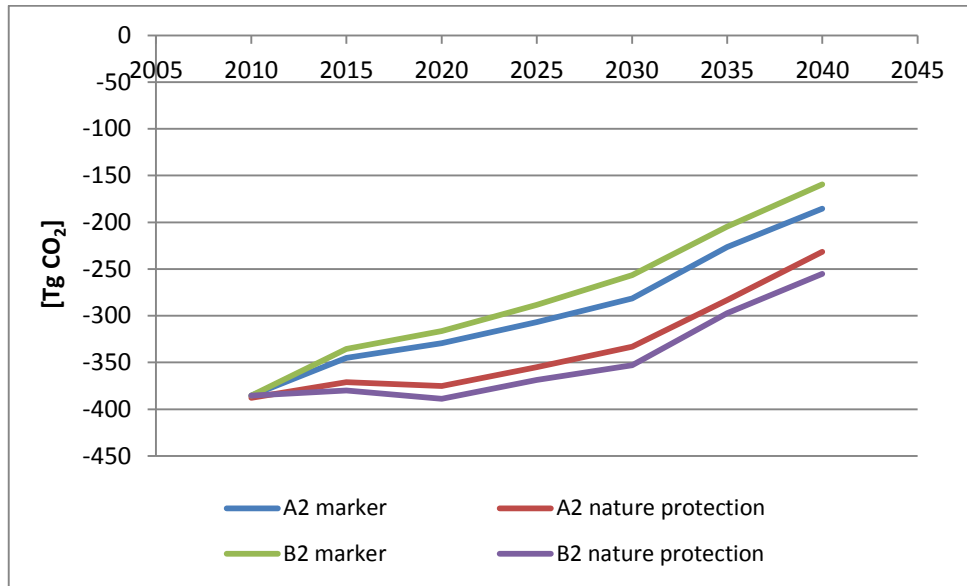


Figure A3.2: Development of carbon sequestration in forest biomass in the EU27. The development of the potentials is presented in total amounts for the EU27 (positive values indicate emissions of CO₂ to the atmosphere and negative values indicate removals of CO₂ from the atmosphere) (Source: EFISCEN model)

Model descriptions

REMIND-MAgPIE

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a mathematical programming model covering the most important agricultural crop and livestock production types in 10 economic regions worldwide (AFR = Sub-Saharan Africa, CPA = Centrally Planned Asia including China, EUR = Europe including Turkey, FSU = the Newly Independent States of the Former Soviet Union, LAM = Latin America, MEA = Middle East/North Africa, NAM = North America, PAO = Pacific OECD including Japan, Australia, New Zealand, PAS = Pacific (or Southeast) Asia, SAS = South Asia including India). It takes regional economic conditions as well as spatially explicit data on potential crop yields, land and water constraints from LPJmL (Lund-Potsdam-Jena dynamic global vegetation model with managed Lands) into account and derives specific land-use patterns for each grid cell. Moreover, the model can endogenously decide to acquire yield-increasing technological change at additional costs. The objective function of the land-use model is to minimize total cost of production for a given amount of agricultural demand. Regional food energy demand is defined for an exogenously given population and income growth in ten food energy categories (cereals, rice, vegetable oils, pulses, roots and tubers, sugar, ruminant meat, non-ruminant meat, and milk), based on regional diets. **REMIND** is an integrated modeling framework that embeds a detailed energy system model within a macro-economic intertemporal growth model and a climate system model that computes the effect of GHG emissions on global mean temperature. REMIND is completely hard-linked and solves the three integrated models simultaneously considering all interactions with perfect foresight. The energy sector comprises a large number of energy conversion technologies that convert primary energy carriers into final energy carriers that are supplied to the macro-economical framework. Given various economic, technological and natural constraints the optimal solution implies an efficient allocation of investments into energy conversion technologies and macro-economic capital accumulation. In the case of exogenous constraints on future climate change, GHG emissions are chosen to minimize the mitigation costs. Since joint optimization of complex models is limited in terms of computational efficiency and solvability, we apply a soft-link approach where the MAgPIE and the REMIND models are solved in isolation and information flows between them are brought into agreement in an iterative process (meta-optimization). The chain starts with REMIND calculating a global bioenergy demand scenario for the energy system up to the year 2100 based on initial biomass cost curves. These data are delivered to MAgPIE that computes new cost curves for biomass for the global bioenergy scenario obtained from REMIND. Due to the global bioenergy demand from REMIND, MAgPIE assumes global availability of cellulosic biomass without any trade restrictions. As an economic optimization model, MAgPIE delivers spatially-explicit land use patterns and converts explicit restrictions on land and water availability into implicit costs of bioenergy production to be used in the energy system model. This iterative process will be repeated until equilibrium is established, i.e. no more change in bioenergy demand (derived by REMIND) and costs (derived by MAgPIE) occurs.

The REMIND-MAgPIE modelling system has regularly been validated against empirical observations. Examples of such validation exercises are shown in Lotze-Campen et al. (2008), Schmitz et al. (2012), Bonsch et al. (2014), and Dietrich et al. (2014). In these publications it has been shown that the land use model MAgPIE captures past trends in agricultural land use and also productivity changes in agriculture well for major world regions. In addition, it has been shown with extensive sensitivity analyses, how the model results are affected by changes in parameters which are particularly uncertain. In the global land use model, the focus of the sensitivity analyses was on specific cost parameters, for example costs for productivity increase and costs for land conversion from non-agricultural land into arable land.

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MAGNET

The MAGNET model which is a multi-regional, multi-sectoral, static, applied general equilibrium model based on neo-classical microeconomic theory (Nowicki et al. (2006) and van Meijl et al. (2006)). The MAGNET model describes the whole world economy, including developments of land use, on a regional scale. It includes details on 10 land-using (agricultural) sectors (7 crop and 3 animal sectors), a number of sectors using agricultural commodities (5 food processing sectors, ethanol, biodiesel, DDGS, biodiesel byproducts) and covers the whole economy (28 sectors in total). The regional aggregation includes all EU-15 countries (with Belgium and Luxembourg as one region) and all EU-12 countries individually, except for three regional aggregates: the Baltic countries which aggregated to a single region, with Malta/Cyprus and Bulgaria/Romania aggregated to a single region. Outside the EU, the analysis covers all important countries and regions from an agricultural production and demand point of view.

MAGNET models land use changes and land transitions in several ways. Land is assumed to be heterogeneous, hence differs in space with respect to environmental and economic conditions. This heterogeneity is implemented by introducing the sectoral heterogeneity of land leading to different substitutability of land used by different sectors. The total land supply is modelled by land supply curves, which specify the relationship between land supply and a land price and assumes that the most productive land will be used first for agricultural production to meet a certain agricultural demand. The higher the demand the more land will be used for production which leads to land scarcity and therefore increased land prices.

Initially, MAGNET uses version 6 of the GTAP data (Dimaranan (2006)) with 2001 as the base year. These data are updated to 2010 situation by taking into account macro-economic developments and policy changes in 2001 – 2010. The GTAP modelling system, from which the MAGNET model is derived, has been validated in various publications in the past, such as Breckman et al. (2011) and Liu et al. (2004).

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CAPRI

The CAPRI model is an EU27 partial equilibrium model for the agricultural sector at NUTS2 level (aggregated regional farm approach). The model consists of a supply module and a global market model. The CAPRI supply module comprises 276 regional farm models: one farm model for each NUTS2 region in the EU27, Norway, Western Balkans and Turkey. The model covers 51 agricultural commodities in the market model. These are produced by about 50 crop and animal activities in each of the regions, using 9 general inputs, 3 crop-specific inputs, 6 intermediate crop outputs, 12 intermediate animal outputs, 3 types of mineral fertiliser and 10 tradable and non-tradable feed inputs. Each regional farm model optimises regional agricultural income at given prices and subsidies and is constrained by land availability, policy variables and feed and plant nutrient requirements in each region. Elasticities to calculate the parameters of the cost function per crop activity per region are derived from econometric estimates using the CAPRI database and model structure (Jansson and Heckeley, 2011). Additional empirical evidence on marginal costs related to milk production has been provided by Kempen et al. (2011).

The CAPRI global market model is a comparative static multi-commodity model, which covers 47 primary and secondary agricultural products (Britz and Witzke, 2012). The CAPRI supply module and global market model are iteratively linked. Equilibrium ensures cleared markets for products and young animals, and matches feed production with feed requirements of total animal stock at the national scale (www.capri-model.org).

Allocation of land to the various activities per region is steered by profit maximising behaviour of the regional farmer, in the supply part of the CAPRI model. If, compared to a calibrated baseline position, a land-based activity becomes more profitable through a policy intervention or some other shock, the land allocated to this activity will increase, as will the marginal production costs (the costs of producing one unit of output extra). Within agricultural activities, there is a division into an extensive (low input, low yield) and an intensive variant (high input, high yield), albeit in a stylised way. In the case of low intensity, it is assumed that yield per hectare of a specific crop is 20% below the average yield per hectare and the variable input use is 25% below the average. In the case of high intensity the reverse is assumed. This applies for all inputs, except for plant protection per hectare, which is 40% below or above the average.

To understand the impact of the different scenarios on land use, it is important to know that CAPRI features an upward sloping land supply curve, meaning that taking more land into production will take place at a price that is higher than current prices. This allows for land leaving and entering the agricultural sector and transformation between arable and grassland in response to relative price changes (Renwick, et al., 2013).

CAPRI features a rather well developed biofuels module (Blanco, et al., 2013). CAPRI models supply and demand of bio-ethanol and biodiesel. Biofuels can be supplied by imports or own production of first generation, second generation or biofuels from non-agricultural sources. First generation bio-ethanol may be produced from cereals, wine and sugar beets. First generation bio-diesel is produced from rape oil, sunflower oil, soya oil and palm oil. Supply and demand of second generation biofuels is exogenous. Second generation biofuels can be produced from new energy crops, implemented as one separate activity in the supply part of CAPRI. Through the land market it competes with other activities. Second generation biofuels can also be produced from crop residues.

For the supply and market module of CAPRI different databases are available. Time series of the most important variables are available at member state level and/or regional level. A full description of the CAPRI database can be found in Britz and Witzke (2012).

The CAPRI model has been validated with respect to official EU data in various publications, e.g. Helming et al. (2008, 2010) and Renwick et al. (2013).

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EFI-GTM

The European Forest Institute Global Trade Model (EFI-GTM) is a regionalized partial equilibrium model of the global forest sector with a special emphasis on Europe. The full mathematical structure of the model is given in Kallio et al. (2004) and Moiseyev et al. (2011), and has previously been applied in various types of studies like Solberg et. al. (2003, 2010), Kallio et al (2006), Lindner et al. (2006), Moiseyev et al., 2010).

EFI-GTM covers 6 wood assortments, 7 solid wood product categories, 4 chemical pulp and 4 recovered paper types, 12 paper grades. Production data for base year are from FAOSTAT database (FAO, 2013). Production statistics is required in order to calculate apparent

consumption for the final products (7 solid wood and 11 paper product categories). Bilateral net trade volumes for all EFI-GTM products and regions are derived from EFI Forest Products Trade Flow database (EFI,2010). Demand for the base year's period is defined as production plus net import. In addition bilateral trade flows are entered into the EFI-GTM as starting values for base year. Consequently, the demand equations (demand curves) for 2005 are positioned by base year consumption, price and price elasticity. In order to update demand for the following periods, demand curves are shifted to reflect the exogenous assumptions for GDP annual growth and accounting for the econometrically estimated regional and product specific GDP elasticity (based on FAO's Global Outlook: Jonsson and Whiteman, 2008). The wood supply in each region is characterized by equations that specify quantities of different wood categories as a function of real prices. The supply functions are shifted inter-periodically, reflecting the changes in potential wood harvest. The EFISCEN model is providing European countries' information on the potential sustainable harvest level, which is used to limit the maximum harvest levels.

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EFISCEN

The European Forest Information Scenario Model (EFISCEN) is a large-scale model that assesses the supply of wood and biomass from forests and projects forest resource development on regional to European scale.

In the model the state of the forest is described as an area distribution over age and volume classes in matrices, based on data on area, growing stock and increment by age class and forest type collected from national forest inventories. During simulations, forest area moves between matrix cells, describing different natural processes (e.g. growth and mortality) and human actions (e.g. forest management). Management scenarios are specified at two levels in the model. First, a basic management regime defines the period during which thinnings can take place and a minimum age for final fellings. These regimes can be regarded as constraints on the total harvest level. Second, the demand for wood is specified and EFISCEN may fall

the demanded wood volume if available. Wood demand is the main determinant of forest resource use.

EFISCEN provides data on basic forest inventory data (stemwood volume, increment, age-structure), but relevant to VOLANTE are forest wood/biomass harvest potentials, wood removals, carbon in biomass and soil, deadwood (indicator for biodiversity), recreation preferences, etc for 5-year time steps.

Link to manual:

<http://www2.alterra.wur.nl/Webdocs/PDFFiles/Alterrapporten/AlterraRapport1559.pdf>

The EFISCEN model and its projections have been evaluated and validated by (i) comparing its projections with results obtained from other methods (Groen et al. 2013), (ii) comparing its projections against projections by other models (e.g. Böttcher et al. 2012; Tupek et al. 2010), and (iii) running the model on historic data and comparing the output to present-day forest state for Finland (Nabuurs et al. 2000) and Switzerland (Thürig and Schelhaas 2006). These validation studies showed that the model is able to capture observed forest resource development for 50-60 years for even-aged forests at national level. At sub-national level, there were deviations between reported and projected forest structure, which could be explained (at least partially) by differences in management intensity between regions and between tree species. This issue was addressed in the current study by explicitly considering regional differences in harvesting intensity (Levers et al. 2014; Verkerk et al. 2015).

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LUISA

Built-up area is defined as the sum of all types of artificial surfaces. In practice, it is spatially delineated by all the land use/land cover classes under category 1XX of CORINE Land Cover (CLC), thus including the elements specified in table 4.6.1. For the purpose of this work, the artificial classes of CLC were aggregated in three main 'components', as the table 4.6.1 illustrates: (1) Urban, (2) industrial/commercial, (3) infra-structure.

Built-up area demand refers to the built-up surface area presumably required by society to support future economic development. Demand values were computed in hectares.

Projections of built-up area demand were estimated for a time-span of 40 years (between 2010 and 2040), in time steps of 10 years, for each individual European country.

Urban component

The Urban component corresponds to the portion of built-up that comprises residences, small leisure and cultural facilities and small businesses (e.g. retail, services), also known as urban fabric. It is assumed that the urban component is mainly driven by the size of the population (P) and the total number of households (THH). The THH is, in turn, influenced by the average household size (AHH), which has been consistently decreasing in Europe, along with the tendency of reduction of fertility and family size.

Industrial/commercial component

The estimation of future demand for industrial and commercial areas poses a number of challenging issues. The expansion/contraction of industrial and commercial areas is the result of economic drivers, and is influenced by policy, technology, productivity and regional and sector specificities. In this analysis, the growth of Gross Domestic Product (GDP), as given by the LEITAP model, was taken as a proxy for all the mentioned dynamics.

Infrastructure component

The infrastructure component comprises transport facilities (airports, ports, rail and road networks) as well as mineral extraction sites, waste treatment/disposal facilities and construction sites. The estimation of future area for any of these sub-categories is not a feasible task due to the complexity and diversity of the issues involved. Moreover, unlike most of the urban growth, transport and waste treatment facilities are strictly subject to local, regional and national policy strategies/decisions hardly replicable by any quantitative model at the European scale of analysis. The development of mineral extraction sites is governed by specific market and physical conditions that are not feasible to model in the context of the present project. Finally, to our present knowledge, no holistic land use model has yet the capacity to predict the future location of such land uses.

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Dyna-CLUE

The Dyna-CLUE model which is a recent version of the CLUE model (Verburg *et al.* 1999; Verburg *et al.* 2002). CLUE is one of the most used land allocation models globally and is highly applicable for scenario analysis. The use of the model in many case studies at local and

continental scale by different institutions worldwide (e.g., (Wassenaar *et al.* 2007; Castella *et al.* 2007) has proven its capacity to model a wide range of scenarios. The figure below shows the land use change allocation procedure. There are ‘four boxes’ that provide the information to run the model:

- Spatial policies and restrictions (e.g. nature reserves);
- Land use demand (i.e. agriculture, urban and forest);
- Location characteristics, maps that define the suitable location for each land use type based on empirical analysis; for example, the European soil map is translated into functional properties such as soil fertility, water retention capacity. In addition to the soil map there is a set of 100 factors that range from accessibility to bio-physical properties; the factors can be dynamic in time. A full list of factors considered can be found in Verburg *et al.*, 2006;
- Set of rules for possible conversions (conversion elasticity, land use transition sequences).

A detailed description of the functioning of the Dyna-CLUE land allocation procedure is provided by Verburg and Overmars (2009).

Dyna-CLUE is a spatial land allocation model that downscales demands from sectoral land use models to high-resolution patterns of land cover change. The model allocates land cover types of which the dynamics are the result of changes in several sectors, incl.: agriculture, forestry, urban/industrial, nature conservation. For the European application typically a spatial resolution of 1 km² is chosen and a temporal resolution of 1 year. The CLUE model has been validated in several publications, e.g. Pontius *et al.* 2008 and Verburg *et al.* (2013).

As for any model that is used for future simulations of complex human-environmental systems, Dyna-CLUE simulations have a considerable level of uncertainty, originating from different components of the modelling process. Uncertainties are a result of our incomplete knowledge of the functioning of socio-ecological systems, lack of data and data quality issues, the simplifications necessary in representing reality in the model, and the inherent uncertainty of future socio-economic and political developments. Each type of uncertainty is captured at a different stage of the land use change modelling process. A description of the different uncertainties and a sensitivity analysis for the model used is presented in Verburg *et al.* (2013). Uncertainty in future socio-economic and political developments is commonly captured by simulating a set of scenarios that describe a wide range of likely future developments, as done in this study. The elaboration of scenarios is, however, subject to personal judgements and assumptions, which can give rise to additional uncertainties. Next, uncertainty in input data plays a role. A Dyna-CLUE land use simulation typically uses a large amount of different input data concerning land use, socio-economic conditions and biophysical conditions. The uncertainties of the individual input data are described in the documentation of the different data used in the model. The parameterization and model structure can subsequently cause further error inflation.

Verburg *et al.* (2013) performed a sensitivity analysis on the Dyna-CLUE model to quantify how uncertainties in important driving factors of demand for agricultural land affect the spatial patterns of simulated land change. Land use change simulations were done based on agricultural area demands generated with a range of GDP and population change values in a macro-economic model, which were spatially allocated with the model. The sensitivity analysis demonstrates that uncertainty in GDP estimates propagates into uncertainty in land use change projections. This uncertainty emerges in spatially divergent ways, depending on the country context but also strongly on location conditions. The overall spatial allocation patterns of land use across Europe were, however, relatively insensitive to the uncertainties introduced. Scenario results were rather robust in this respect and the propagation of uncertainties into spatial patterns of land change is unlikely to lead to strongly diverging conclusions on the analysis made in this paper.

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