Life-cycle assessment of eucalyptus short-rotation coppices for bioenergy production in Southern France

Benoit Gabrielle, Nicolas Nguyen The, Pauline Maupu, Estelle Vial

► To cite this version:

Benoit Gabrielle, Nicolas Nguyen The, Pauline Maupu, Estelle Vial. Life-cycle assessment of eucalyptus short-rotation coppices for bioenergy production in Southern France. 2011. hal-00702356

HAL Id: hal-00702356

<https://hal.science/hal-00702356>

Preprint submitted on 30 May 2012

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Life-cycle assessment of eucalyptus short-rotation coppices for
2 bioenergy production in Southern France

3

4 Running title: Life-cycle assessment of eucalyptus coppices

5

6 Benoît Gabrielle^{1*}, Nicolas Nguyen The², Pauline Maupu^{2,3} Estelle Vial⁴

7

8 *1: AgroParisTech, INRA, UMR 1091 Environnement et Grandes Cultures, 78850 Thiverval-*
9 *Grignon, France*

10 *2: FCBA Station Sud-Est, Domaine universitaire, BP251, 38004 Grenoble cedex 9 France*

11 *nicolas.nguyen-the@fcba.fr*

12 *3: In Vivo, 83-85 avenue de la grande Armée, 75782 Paris cedex 16, France.*

13 *PMAUPU@invivo-group.com*

14 *4 : FCBA Pôle environnement santé, FCBA. 10 av St Mandé 75012 Paris, France*

15 *estelle.vial@fcba.fr*

16

17 * Corresponding author. Tel.: +33 1 30 81 55 51; Fax: +33 1 30 81 55 63

18 E-mail address: Benoit.Gabrielle@agroparistech.fr

19

20

21 **Keywords:** Short Rotation Coppice, Life Cycle Assessment, Carbon storage,
22 Eucalyptus, Biomass, GHG emissions

23 Primary Research Article

ABSTRACT

Numerous international and national policy frameworks were recently put into place to promote renewable energy sources, including biomass. Among the wide range of possible feedstocks, dedicated energy crops such as short rotation coppices (SRCs) are considered prime candidates. They produce good-quality biomass that is easy to harvest, while reducing the competition for forest products between energy and other end-uses when grown on agricultural land. Besides technical, social and economical aspects, environmental issues are important to take into account when developing SRCs. For this purpose, a life cycle assessment (LCA) was implemented to provide an accurate and comprehensive estimate of the environmental impacts of delivering 1 GJ of heat from SRC wood chips. The LCA was applied to various scenarios of eucalyptus SRC in France, based on the established SRC pulp scheme and extended to more theoretical systems of very short rotation coppices (VSRCs) with 3-year rotations.

Compared to equivalent fossil chains, all eucalyptus scenarios achieved savings of fossil energy and greenhouse gas (GHG) emissions in the 80%-90% range. The transportation of wood chips contributed the highest share of fossil primary energy consumption and GHG emissions. The second most important item was fertilization, especially in the case of the VSRC schemes due to the evergreen character of eucalyptus.

The possibility of including ecosystem carbon dynamics was also investigated, by translating the temporary sequestration of atmospheric CO₂ in the above- and below-ground biomass of eucalyptus, relative to a reference land use (in this case a land parcel reverting to wilderness after removal of a vineyard) as CO₂ savings using various published equivalence factors. This offset the life-cycle GHG emissions of heat provision from eucalyptus SRCs by 70 to 400%.

49 **1. Introduction**

50

51 The recent European Directive on renewable energy set ambitious targets for all
52 Member States, in order for the EU to reach a 20% share of energy from renewable sources
53 by 2020 (European Commission, 2009). Amongst renewable energy sources, the biggest
54 contribution (63%) may come from biomass, as suggested by a foresight analysis in Europe
55 (European Commission, 2005). At present, biomass already contributes about 4% of the total
56 EU energy supply, predominantly as heat, and combined heat and power applications to a
57 lesser extent. The production of liquid biofuels for transport from biomass increased several-
58 fold in the last decade, and is currently a major issue.

59 Among various sources of biomass (organic waste, forestry products, cereal straw,
60 etc.), dedicated crops such as short rotation coppices are currently being investigated. These
61 systems involve the cultivation of a fast growing ligneous species with short to very short
62 harvesting cycles. Species with a capacity to sprout after cutting are particularly interesting as
63 they make it possible to harvest the same plantation several times over the lifetime of the
64 trees. Eucalyptus (*Eucalyptus sp.*) is one of the most widely known species used for biomass
65 oriented short rotation coppice, particularly for pulp and paper industries (Iglesias-Trabado
66 and Wisterman, 2008). Poplar (*Populus sp.*) and willow (*Salix sp.*) have been used more
67 recently for energy purpose for example in northern Europe (Lindroth and Bth, 1999,
68 Wilkinson *et al.*, 2007) or in Italy (Manzone *et al.*, 2009).

69 In France, short rotation coppices (SRCs) were developed with poplar and eucalyptus
70 in the mid 1980's on the initiative of pulp companies. Nowadays, some 2000 ha of pulp SRC
71 are still present although only eucalyptus is still being used in the south-western part of
72 France with an average rate of 100-200 ha planted every year (Nguyen The *et al.*, 2004). The

73 typical plantation scheme is based on 10-year rotations with a stand density of 1250 stems ha⁻¹
74 (on a 4 m x 2 m grid). Three harvests in 30 years are expected with an average productivity of
75 10 oven-dry metric tons (ODT) ha⁻¹ yr⁻¹ with the currently-used specie: *E. gundal*, an hybrid
76 between *E. gunnii* and *E. dalrympleana* (Cauvin et al., 1994). The recent drive for renewable
77 energy sources and concerns with the sustainability of biomass production (Robertson et al.,
78 2008; Scharlemann and Laurance, 2008) have sparked interest for SRC given its presumed
79 low environmental impacts since it requires less inputs than agricultural crops (WWI, 2006).

80 The traditional pulp and paper SRC scheme may be directly transposed to biomass
81 production for biofuel, heat or power production purposes. Since SRC is expected to be
82 mainly grown on former cropland, silvicultural schemes with shorter cycles than the
83 traditional 10 year pulp rotation, are being investigated in order to be closer to usual farming
84 systems. Growing cycles may be shortened to 7 years with the same productivity as long as
85 stand density is kept within a 2000-2500 stems ha⁻¹ range, as was already tested with poplar
86 (Berthelot et al., 2004). Similarly, so-called very short rotation coppice (VSRC) are being
87 tested and developed with an objective of 3-year harvesting cycles. This scheme was
88 illustrated with willow (Dimitriou and Aronsson, 2005), and requires far higher stand
89 densities, between 10 000 stems ha⁻¹ and 15 000 stems ha⁻¹. Such systems are currently being
90 trialled in France with eucalyptus and poplar.

91 Independently of economic and technical issues, it is important to consider the
92 environmental performance of these new energy crops. Several issues were raised regarding
93 their actual GHG benefits, impacts on water resources or biodiversity (Robertson et al., 2008;
94 Monti et al., 2009). Here, we chose the LCA methodology to address these issues for
95 eucalyptus SRC, since it is widely-used for bioenergy assessment and is a multi-criteria,
96 holistic method (von Blottnitz and Curran, 2007; Cherubini, 2010). No such assessments have
97 been reported for eucalyptus SRC, to the best of our knowledge, although they exist for

98 traditional eucalyptus forests (Jawjit et al., 2006; Lopes et al., 2003). There is also a growing
99 literature on the LCA of other lignocellulosic feedstocks, whether annual arable crops (Kim
100 and Dale, 2005), perennial grasses such as miscanthus and switchgrass (Monti et al., 2009;
101 Shurpali et al., 2010), or other types of SRC such as willow and poplar (Gasol et al., 2009;
102 Goglio and Owende, 2009), whose performance may be compared with eucalyptus. The
103 objectives of this work were two-fold: i/ to apply LCA to eucalyptus SRCs in southern
104 France, based on the currently existing pulp scheme, and extended to very-short rotation
105 coppices (VSRCs), and ii/ to investigate the possibility of including the temporary storage of
106 atmospheric CO₂ in ecosystem carbon pools in the GHG balance of heat provision from
107 eucalyptus SRC, following the approach suggested by Moura-Costa and Wilson (2000) for
108 forest products. Eucalyptus biomass was used to generate heat, and compared to equivalent
109 fossile energy sources.

110 **2. Materials and methods**

111 The eucalyptus pulp SRC system was chosen as a basis for the study. This species and its
112 silvicultural scheme have been studied in France for almost 30 years and many technical
113 references already exist (Cauvin and Melun, 1994). This SRC was designed for pulp
114 production but may easily be extended to bioenergy production.

115

116 *2.1. Scope, functional unit and system boundaries for the LCA*

117 The function studied here is heat production from the combustion of SRC wood chips in a
118 boiler. The functional unit selected was therefore 1 GJ of final heat, which means that life-
119 cycle impact indicators were calculated relatively to the production of 1 GJ of heat.

120 The system studied is described on Figure 1, and comprises five main stages:

121 1. The production of cuttings from selected eucalyptus clones, which corresponds to
122 current practices. It includes the production of mother trees in a biotechnology facility and

123 transportation to a nursery. In the inventory, we used data pertaining to a research laboratory,
124 therefore not designed nor optimized an industrial-scale production of cuttings.

125 2. Plantation establishment and removal, including site preparation, fertilization,
126 plantation and weed control during the first 2 years, as well as stump removal at the end of the
127 project.

128 3. Harvest, including felling, forwarding and chipping for SRCs and silage harvester
129 for VSRCs. This stage also includes the transportation of harvesting machines to the tree
130 parcel.

131 4: Transportation of wood chips from the collection site to the boiler. We used a
132 distance of 80 km corresponding to the actual average distance between eucalyptus
133 plantations and the pulp mill of Saint-Gaudens (South-Western France).

134 5: Handling and combustion of wood chips in a boiler.

135

136 2.2. *Management scenarios*

137 The reference scenario was the pulp SRC scheme based on three 10-year harvest cycles (ie a
138 total duration of 30 years), with a stand density of 1250 stems ha⁻¹. From this baseline we
139 designed a scenario dedicated to biomass production for energy by doubling the stem density
140 (2500 stems ha⁻¹) with three harvests every 7 years for a total duration of 21 years. Next, a
141 very short rotation coppice (VSRC) scenario was designed with a density of 5000 stems ha⁻¹,
142 which represents in the present context the maximum possible density considering the costs of
143 eucalyptus cuttings. The scenario plans harvests every 3 years, that is 7 successive harvests
144 over the same 21-year time interval.

145 A set of technological variants technical aspects likely to influence LCA results were
146 considered to enlarge the number of management scenarios:

147 1. Harvest mechanization: approximately 50% of pulp SRCs are currently harvested
148 with felling machines rather than manual felling with chainsaws. Felling machines have a
149 better productivity and make mechanical debarking possible in the field, which results in
150 higher rates of nutrient returns to soils. On the other hand, felling machines consume more
151 fuel and emit more GHGs. VSRCs are usually harvested with adapted agricultural harvesters.

152 2. Productivity: for SRCs, a yield of 10 oven dry metric tons (ODT) ha⁻¹ yr⁻¹
153 considered as a robust average value taking into account the mortality of trees and their partial
154 ground cover. It corresponds to a final cut at a diameter of 7 cm (commercial cut). The full
155 stem harvest leads to an extra 20% of biomass, including leaves (Nguyen The and Deleuze,
156 2004). For the 2nd and 3rd harvest, a 25% gain in biomass production is usually observed due
157 to a faster growth (D. Lambrecq, Fibre excellence, Saint-Gaudens, pers. comm.). For VSRCs,
158 for lack of more accurate references, we assumed the same average figure of 10 ODT ha⁻¹ yr⁻¹

159 3. Fertilizer inputs: Pulp SRCs are currently not fertilized in France because it is not
160 considered as a relevant operation for the sustainability of biomass production. Nevertheless,
161 this is a very critical point, especially for VSRCs whose nutrient exports are expected to be
162 significantly higher than SRCs. Therefore, we assumed in all scenarios fertilizer input rates
163 corresponding to the estimated exports of nutrients at harvest. The differences between
164 scenarios were particularly acute across harvesting techniques, whether including debarking
165 (with the mechanical harvest) or harvesting full stems or logs. Eucalyptus being an evergreen
166 species, harvesting full stems rather than wood logs would lead to far larger nutrient exports
167 because of the high nutrient contents of the leaves. The amount of N, P and K applied were
168 calculated using state-of-the-art knowledge and data on nutrient exports of VSC and VSRC
169 with eucalyptus in France (Nguyen The et al., 2004 and 2010a) and atmospheric deposition
170 rates (Croisé et al., 2002).

171 As a result of the above variants, a total set of 5 scenarios was implemented, whose
172 characteristics are summarized in Table 1.

173

174 2.3. *LCA methodology*

175 The cut-off threshold for neglecting system components was set at $3.6 \cdot 10^{-6}$ %. The production
176 of laboratory equipment was excluded because cuttings production was only a marginal part
177 in the use of this equipment over its total life cycle. The transportation of pesticides and
178 fertilizers (N, P, K and Mg fertilizers in the nursery, herbicides for site preparation and
179 plantation maintenance, field fertilization) were not taken into account due to a lack of
180 accurate information.

181 Chemical inputs in the nursery were exclusively attributed to the production of cuttings,
182 except for fungicides and hormones which were neglected due to the very low dosages used.
183 Nursery propagators were also excluded due to the lack of information on this material (jiffy
184 pellets made from peat). Neither waste nor co-products are produced during the life cycle of
185 SRCs, which alleviated the need for allocations. As usually assumed in the LCA of bioenergy
186 systems, the global warming potential of the CO₂ emitted during the combustion of biomass
187 was considered nil (Cherubini, 2010).

188 LCA calculations were done with the TEAM 4.0 software package (Ecobilan-PWC, Paris)
189 with the EcoInvent 2000 database (V2.01, St-Gallen, Switzerland). Field emissions related to
190 the input of fertiliser N and P were calculated using the methods proposed in the Ecoinvent
191 report (Nemecek et al., 2003). However, the model proposed for nitrate leaching was found
192 unsuitable for eucalyptus, and this flux was thus neglected. The leaching risk was low because
193 fertilizers are usually applied in spring after the winter drainage, and taken up before the onset
194 of drainage in autumn. In addition, nitrate leaching under forests is generally minimal
195 (Galloway et al., 2003). Impacts were characterized with the CML (2001) method, as

196 described in Guinée et al. (2002), and the following categories considered: non-renewable
197 energy consumption, global warming (with a 100-year timeframe), acidification,
198 eutrophication, and photochemical ozone creation potential (POCP).

199

200 2.4. Accounting for ecosystem C dynamics and land-use changes

201 In a first variant relative to our baseline LCA calculations, we investigated the possibility of
202 accounting for the temporary storage of atmospheric CO₂ in the biomass of eucalyptus stands.
203 The principle is to derive an equivalence factor with permanently-stored CO₂ based on the
204 cumulative radiative forcing of atmospheric CO₂ over time. Moura-Costa and Wilson (2000)
205 derived such a factor from the number of years over which the reduction in radiative forcing
206 would be identical between the temporary and permanent storages. They estimated the
207 duration for break-even to approximately 55 years, yielding an equivalence factor of 1/55 or
208 0.0182. However, other factors are presently under discussion in relation to carbon trading.
209 Two other factors were thus tested here: a coefficient of 1/26 proposed by the French Ministry
210 for Agriculture (MAP, 2009), corresponding to an economical calculation involving an
211 annual discount rate of 4 %, and the 1/100 factor proposed by PAS (Bsi, 2008) for
212 consistency with the IPCC time horizon in the climate change scenarios (2100). Following the
213 above approach, the temporary effect of C storage may be calculated as :

$$214 \text{ Mitigating effect (in t CO}_2 \text{ eq.)} = Q_c \times T \times EF$$

215 where Q_c is the amount of C stored in tree biomass (t C ha⁻¹), T is the duration of storage
216 (years), and EF the equivalence factor (unitless). The $Q_c \times T$ component of the equation
217 actually corresponds to the cumulative sum of C stored through time, except for the last year
218 when the stand is harvested (Figure 1).

219 The C sequestration of eucalyptus SRC should be compared to a baseline scenario in terms of
220 land-use. Here, we chose abandoned agricultural land (referred to as wildland in the

221 following), which typically occurs after vineyard removal in southern France. Eucalyptus
222 SRCs would therefore be established on former vineyards in our scenario, which excludes
223 indirect land-use change effects. The global C storage was therefore calculated by
224 subtracting the C storage of SRC by C storage of wildland.

225

226 The carbon stored in the above-ground biomass (AGB) of the eucalyptus stands was
227 calculated from the C content of harvested wood, considering that the C content of biomass
228 was 47% (dry weight basis; Paixao et al., 2006 ; Tanabe et al., 2006). Below-ground biomass
229 (BGB) was estimated with an allometric relationship as a fixed proportion of AGB, set to
230 30% (Tanabe et al., 2006).

231 For the wildland, aboveground biomass was considered constant at $0.9 \text{ t C ha}^{-1} \text{ yr}^{-1}$, which is
232 the peak value for grasslands in warm temperate, dry climates given in the IPCC guidelines
233 for GHG inventories (Tanabe et al., 2006). It is in the lower end of the $0.8 - 3.2 \text{ t C ha}^{-1} \text{ yr}^{-1}$
234 range reported in Europe for former arable fields up to 3 years after abandonment (Hedlund et
235 al., 2003), ie in the early years of fallow regeneration. The belowground biomass was set at
236 $2.0 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Tanabe et al., 2006), which is slightly lower than the $2.5 - 3.5 \text{ t C ha}^{-1} \text{ yr}^{-1}$
237 range in annual returns to soils estimated in the classical Rothamsted (UK) long-term
238 wilderness experiments, where arable fields were allowed to undergo natural woodland
239 regeneration in the 1880's (Jenkinson et al., 1992). In the beginning of the transition from
240 arable to wildland, only herbaceous species are involved and their net annual biomass
241 production is entirely returned to soils as litter. Further on during the 30-year life cycle of the
242 eucalyptus plantation, it is likely that some woody species may also appear in the wildland
243 and start accumulating biomass from one year to the next, although the exact dynamics of that
244 transition has not been documented to the best of our knowledge. Over a longer time-frame,
245 observations in the 'Geescroft wilderness' experiment in Rothamsted (UK), an arable field

246 allowed to undergo natural woodland regeneration in 1885, may give us some insight into this
247 process and provide an upper limit for this component. In this plot, the accumulation of AGB
248 was estimated at $0.6 \text{ t C ha}^{-1} \text{ yr}^{-1}$ over the first 100 years of the transition (Grogan and
249 Matthews, 2001), which we considered as the upper limit of what would happen in the first 30
250 years of wildland growth after abandonment (the lower limit being no accumulation at all). A
251 below- to above-ground biomass ratio of 1:3 was assumed for the wildland (Grogan and
252 Matthews, 2001), which is similar to the value used for eucalyptus trees.

253 It is likely that the differences in soil organic carbon (SOC) will appear between the SRC
254 eucalyptus and the baseline land-use over time, due to differences in litter and below-ground
255 inputs (Grogan and Matthews, 2001). However, since eucalyptus SRC systems are relatively
256 recent, there are no long-term experiments documenting the dynamics of SOC after
257 conversion to eucalyptus, let alone comparing them with other land-uses such as arable
258 farming or wildlands. We therefore elected to exclude differences in SOC between eucalyptus
259 SRC and wildland in our analysis. The effect of this hypothesis is addressed in the Discussion
260 section.

261

262

263

264 **3. Results**

265 *3.1. LCA results*

266 Life-cycle consumption of non-renewable energy ranged from 77.0 to 92.7 MJ GJ^{-1}
267 heat output from eucalyptus biomass (Table 2). It was lowest for the S1 scenario with lower
268 stem density and manual harvest, and highest for the very short rotation scenario (S5). In all
269 scenarios, wood chips transport represented the main energy consumption hotspot with a
270 share of 46% to 55 %. Harvesting operations came second with 30 to 36 % of total energy

271 consumption, except for the very short rotation scenario, where their share was only 3.3 %.
272 This is due to the use of an adapted silage harvesting machine instead of heavy, fuel-
273 consuming forestry machines. In the VSRC scenario, the most important steps were
274 fertilization and plant production. Fertilizer inputs were larger than with the SRC schemes
275 because the harvest of whole stems including leaves lead to higher nutrient export rates and
276 enhanced fertilizer requirements. Stem density is also twice higher in the VSRC scenarios
277 compared to the SRC energy scenarios, and this had a significant impact on energy
278 consumption since the production of cuttings takes place in an energy-intensive
279 biotechnology laboratory. The shorter rotations and higher stem densities associated with
280 VSRCs further enhanced this trend, making this scenario the most energy-intensive. Its
281 energy ratio (ratio of heat output to fossil energy inputs) was also the lowest of all scenarios,
282 at 10.8. This ratio increased with decreasing harvesting frequency, leading to the pulp scheme
283 achieving the highest value (13).

284

285 Life-cycle GHG emissions (excluding ecosystem C pools) varied in a narrow range for the
286 four SRC scenarios, from 8.2 (S1) to 8.5 (S4) t CO₂-eq. GJ⁻¹. They were 50% higher for the
287 VSRC scheme (Figure 3), due to its requiring 2 to 3 times more NPK fertilizer inputs than the
288 SRC schemes, altogether with a 20-30% lower productivity (Table 1). The relative
289 importance of the various steps of the life-cycle followed a similar pattern for all scenarios
290 with an important contribution of fertilisation (38 to 44 % of total), transport (32 to 33 %) and
291 harvest (18 to 22 %). The very short rotation scenario (S5) had lower emissions than the short
292 rotation scenarios in the harvest step due to the use of a agricultural harvesters. Its GHG
293 emissions were thus dominated by fertilization, which accounted for 68% of the total
294 emissions.

295

296 Indicators for the eutrophication impact ranged from 48 (S1) to 152 (S5) g PO_4^{2-} eq. GJ^{-1}
297 (Figure 3), and were dominated by the fertilization phase. The losses of P from the plantation
298 by runoff and erosion made up 90% of the impact related to fertilization, while ammonia
299 volatilization contributed the remainder, the impacts of NO emissions from soils being
300 negligible. Because of its larger fertilizer requirements, the very short rotation system had
301 nearly 3-fold higher eutrophication impacts than short rotation ones. Although the latter also
302 received varying rates of fertilizer inputs (Table 1), differences in productivities compensated
303 for these variations and all short rotation schemes had a similar eutrophication impact within a
304 5% relative range. Interestingly, the best scenario was the one with the highest biomass
305 productivity (S4) and not those that with the least fertilizer inputs per ha (S2) which only
306 achieved a mid-range performance.

307

308 The acidification indicator ranged from 39 (S1) to 110 (S5) g SO_2 eq. GJ^{-1} , following a pattern
309 similar to eutrophication (Figure 3). The very short rotation scenario had again a 3-fold larger
310 impact than the other scenarios, and for the same reason: its higher fertilizer inputs, which
311 translated in higher field emissions of ammonia and nitric oxide, and indirect emissions due to
312 fertilizers' manufacturing. However, the harvest and transport steps played a more important
313 role than for eutrophication, and the breakdown differed between the scenarios. The share of
314 harvest ranged from 20 to 30% for the SRC, while it was nearly negligible (at 2%) for the
315 VSRC. This stems from the major advantage of the VSRC schemes, namely the use of
316 agricultural machines in lieu of forestry ones which are far more resource-intensive. However
317 the associated savings did not compensate for the large requirements of synthetic fertilizer
318 inputs for the VRSC compared to SRC.

319

320 The photochemical ozone creation potential (POCP) indicator ranged from 2.4 (S5) to 6.8
321 (S1) g C₂H₂ eq. GJ⁻¹, with harvest operations and wood chips transport contributing the most
322 (Figure 3). The much higher emissions of photo-oxidants occurring with the scenario S1 is
323 explained by the chainsaws used for manual felling. The chainsaws used in France are seldom
324 equipped with catalytic exhaust pipes and release volatile organic compounds which have a
325 high potential for ozone formation. These emissions also occur to a lesser extent with the
326 mechanized felling option (in scenarios 2 to 4) because chainsaw operators are necessary for
327 the 2nd and 3rd harvest to thin the coppice before felling machines can be used.

328

329 For all impact indicators, the results were strongly influenced by the distance between the
330 plantation and the boiler, which was set at 80 km in the baseline calculations. Table 3
331 illustrates the influence of various distances on the five LCA impacts for scenario S1. Energy
332 consumption was the most sensitive indicator: it dropped by 28% when halving the transport
333 distance, while GHG emissions and acidification impacts were only reduced by 16%, photo
334 chemical ozone formation by 10 % and eutrophication by 3%. The energy ratio increased
335 from 13.0 to 18.0 when the transportation distance decreased from 80 km to 40 km, and
336 reached 25.2 with a 10 km distance (Figure 4). The other indicators were less sensitive to this
337 parameter,

338

339 A comparison with fossil energy sources was carried out to assess the environmental
340 advantages and drawbacks of using SRC biomass as a substitute to coal, fuel oil and natural
341 gas (Figure 5). In all scenarios, the provision of heat from SRC biomass consumed 90% less
342 fossile energy than when using fossile energy sources. Similarly, GHG emissions were
343 reduced by more than 80 % with the SRC biomass. However, the patterns with the local to
344 regional-range impacts (acidification, eutrophication and photochemical ozone formation)

345 were less clear-cut. Biomass-derived heat had generally much lower acidification and
346 photochemical ozone formation impacts than fossil-based heat except with natural gas,
347 which out-performed the VRSC scenario for eutrophication and scenario SRC S1 (pulp SRC
348 with manual felling) for ozone formation. Natural gas had 2 to 30 times lower impacts than
349 the other fossil sources, especially coal. Conversely, the eutrophication impacts were in the
350 50-135 g PO₄³⁻ eq. GJ⁻¹ range for the eucalyptus scenarios, and in the 5-40 g PO₄³⁻ eq. GJ⁻¹
351 range for the fossils, pointing to a weakness of the biomass-based chain. The two-fold higher
352 eutrophication impacts of the VSRC compared to the other scenarios were clearly due to the
353 larger fertilizer inputs required by the former.

354

355 3.2. Inclusion of ecosystem C dynamics

356

357 Figure 6 depicts the dynamics of aboveground and belowground biomass in the
358 eucalyptus plantation (Scenario 1) and the baseline wildland representing the baseline
359 alternative land-use. Over the 30-year period of the eucalyptus life-cycle, biomass
360 accumulation was several-fold larger in the SRC than in the wildland, even when considering
361 the appearance of ligneous species in the latter. This hypothesis had a significant impact since
362 it leads to a 8-fold higher estimate of total biomass after 30 years compared a wildland solely
363 composed of annual species. The larger biomass accumulation in the eucalyptus SRC was due
364 to a higher net primary production and an important storage in the belowground compartment,
365 which kept increasing though the cuts. When averaged over the 30 years of the SRC rotation,
366 the differences between SRC and wildland range from 16 to 24 t C ha⁻¹ for the aboveground
367 biomass, and from 26 to 37 t C ha⁻¹ for the total biomass (Figure 6). These gaps represent the
368 net ecosystem CO₂ gains incurred when substituting wildland with SRC, for instance after the
369 abandonment of a vineyard. They are related to land-use effects may be included in the life-

370 cycle GHG emissions of eucalyptus biomass production by using equivalence factors to
371 account the temporal value of C sequestration in the biomass. This lead to savings of 0.57 to
372 5.16 t CO₂-eq ha⁻¹ yr⁻¹ (Table 4), depending on the equivalence factors and the carbon pools
373 taken into account. Including these CO₂ savings the LCA of eucalyptus-derived heat offset
374 GHG emissions by 70 to 400 % (Figure 7), and therefore had a large impact on the global
375 warming indicators. With the most favorable equivalence factors (1/26 and 1/55), the C stored
376 in eucalyptus biomass resulted in heat provision being a net GHG sink.

377

378 4. Discussion

379 4.1 Benefits and drawbacks of eucalyptus SRC

380 Substituting fossile sources with biomass from eucalyptus SRC leads to a 80-90% abatement
381 of life-cycle GHG emissions and fossil energy consumption per MJ of heat supply, for all
382 SRC management scenarios. These figures confirm the strong benefits of bioenergy chains
383 and are consistent with other LCAs of heat from biomass. For instance, Reinhardt et al.
384 (2000) reported a 95% abatement in GHG emissions and energy consumption when
385 displacing oil or natural gas with short-rotation willow for district heating in several European
386 countries. In addition, inclusion of the temporary storage of CO₂ in the plant biomass, which
387 was ignored in previous literature, more than doubled the GHG savings compared to fossil
388 sources. The relevance of this hypothesis is discussed in subsection 4.3.

389 Conversely, the benefits of SRCs were far from obvious for the other impact categories,
390 especially when displacing natural gas which had 3 to 4-fold lower impacts per functional unit
391 than the other fossile sources. This trade-off between global impacts (global warming and
392 fossil energy consumption) and local impacts has often been reported for bioenergy chains
393 (Reinhardt, 2000; Gabrielle and Gagnaire, 2008), and is almost inevitable because of the

394 gaseous and leaching losses of nutrient occurring upon the feedstock production phase.
395 Despite the relatively low fertilizer N requirements of eucalyptus stands compared to arable
396 crops, none of the management scenarios achieved lower eutrophication impacts than the
397 fossil-based alternatives. Furthermore, the impact estimates were conservative because some
398 losses of nutrients were neglected, as discussed in subsection 4.2.

399 In terms of management scenarios, the very short rotation scenario (VSRC) was outperformed
400 by the conventional SRC scenarios for all impact categories except ozone formation, by a
401 factor of 50% to 250%. Since the economics of this system are also unfavourable (Nguyen
402 The et al. 2010b), VSRCs do not emerge as a good candidate compared to short rotation
403 scenarios. Thus, the benefits from a quicker biomass growth and simplified harvesting made
404 possible by the 3-year growing cycle of VSRC were outweighed by their larger fertilizer input
405 and stem density requirements. The only advantage of VSRCs over SRCs appeared in the
406 photochemical ozone creation potential (POCP), in which harvesting operations were
407 predominant. However, VSRCs only out-performed SRC systems by a margin of 20%, which
408 is within the uncertainty range of this indicator given the uncertainties on the characterization
409 factors of ozone precursors (Labouze et al., 2004).

410

411 To our knowledge, no LCAs have been carried out so far on eucalyptus SRCs, whether for
412 energy or pulp and paper. Our results may still be compared with those pertaining to
413 traditional eucalyptus plantations published by Jawjit et al (2006) in Thailand. Their study
414 used system boundaries and characterization factors similar to ours, but found much lower
415 impact values in general. Plant-gate life-cycle GHG emissions were estimated at only 3.1 kg
416 CO₂-eq. GJ⁻¹, compared to the 8-12 kg CO₂-eq. GJ⁻¹ range we obtained here. The acidification
417 impact was 22 g SO₂-eq. GJ⁻¹ in the Thailand study compared to our 40-110 g SO₂-eq. GJ⁻¹
418 range, while the photo-chemical ozone formation potential amounted to 1.6 g C₂H₂-eq. GJ⁻¹ in

419 Thailand compared to our 2.5-7.0 g C₂H₂-eq. GJ⁻¹ range. Eutrophication was an exception with
 420 similar impacts between Thailand and France, at 41 g PO₄²⁻-eq. GJ⁻¹ and an average of 50 g
 421 PO₄³⁻-eq. GJ⁻¹ for the SRC systems, respectively.

422 Some of these discrepancies are explained by the higher yields of 17.4 ODT ha⁻¹ yr⁻¹
 423 achieved by eucalyptus under the tropical conditions of Thailand, compared to the 9.5 – 14
 424 ODT ha⁻¹ yr⁻¹ range assumed here. The eutrophication impact was relatively higher because
 425 35% to 20% of the fertiliser N and P applied was supposed to leach to water bodies in this
 426 Thailand study, whereas those losses were neglected here, as they were in other LCAs on
 427 herbaceous and tree species for lack of specific references (Gasol et al., 2009; Monti et al.,
 428 2009).

429 Our results on eucalyptus SRC may be compared more broadly to other lignocellulosic
 430 feedstocks: willow in France (Reinhardt, 2000) and Italy (Goglio and Owende, 2009), poplar
 431 SRC in Italy (Gasol et al., 2009), reed-canary grass in Finland (Shurpali et al 2010), and four
 432 perennial grasses in Italy (Monti et al 2009). All of these studies used similar system
 433 boundaries with the exception of the combustion step, and relied on the same set of
 434 characterization coefficients (from Guinée et al., 2002). Most of them also used the EcoInvent
 435 data base for the life-cycle inventory phase.

436 Compared to the poplar SRC system assessed by Gasol et al. (2009) in Italy, the production
 437 and harvest of eucalyptus biomass consumed 1.8 to 2.5 more primary energy, essentially
 438 because the harvest was 3-fold less energy-intensive per ton of biomass than eucalyptus (for
 439 the SRC system) or because poplars required 4-fold less fertilizers (for the VSRC systems).
 440 Also, the data on fuel consumption by farm machinery were adapted from the EcoInvent
 441 database based on local records but the exact corrections were not given by the authors.
 442 When including the transportation of wood chips, albeit with a shorter distance than our
 443 nominal hypothesis (25 vs. 40 kms), the GHG emissions of poplar totalled 1.93 kg CO₂-eq.

444 GJ^{-1} , $\text{kg CO}_2 \text{GJ}^{-1}$, which is 4 to 6 times less than our 8-12 $\text{kg CO}_2\text{-eq. GJ}^{-1}$ range for
 445 eucalyptus. The gap was even wider for the other impact categories: the eutrophication impact
 446 of poplar was estimated at 3.4 $\text{g PO}_4^{3-}\text{-eq. GJ}^{-1}$ vs. 40-135 $\text{g PO}_4^{3-}\text{-eq. GJ}^{-1}$ for eucalyptus ;
 447 acidification amounted to 15.7 $\text{g SO}_2\text{-eq. GJ}^{-1}$ vs 40-110 $\text{g SO}_2\text{-eq. GJ}^{-1}$ for eucalyptus ; and
 448 POCP totalled 0.3 $\text{g C}_2\text{H}_2\text{-eq. GJ}^{-1}$ for poplar compared to 2.4- 7 $\text{g C}_2\text{H}_2\text{-eq. GJ}^{-1}$ for eucalyptus.
 449 Besides differences in management and inventory data for farm machinery, these large
 450 discrepancies arise because direct field emissions contributed only a minor share of the
 451 impacts in the Gasol et al. study, whereas they predominated in our LCA. There are reasons to
 452 believe some of these emissions were somehow under-estimated: for instance, N_2O emissions
 453 from Gasol et al. were similar to our estimates on a ha basis, whereas NO emissions were 2-
 454 fold lower. This contradicts current literature, which indicates that NO and N_2O emissions fall
 455 within a similar range (Stehfest and Bouwman, 2006). Our estimate of N_2O emissions also
 456 included background emissions (ie non anthropogenic) and the contribution of eucalyptus
 457 residues.

458 Our LCA results for eucalyptus are overall closer to those reported by Reinhardt (2000) and
 459 Goglio and Owende (2010) for short-rotation willow in Germany and Ireland, respectively.
 460 These authors reported energy consumptions of 33 MJ GJ^{-1} heat and 56.4 MJ GJ^{-1} ,
 461 respectively, compared to our 55.6 MJ GJ^{-1} figure for scenario 1 (S1) with a similar
 462 transportation distance (40 kms). The lower figure from Reinhardt (2000) was due to a less
 463 energy-intensive harvest for willow, whereas the Goglio and Owende (2009) study involved a
 464 drying phase prior to combustion. The GHG emissions were very similar, at 7.13 $\text{kg CO}_2\text{-eq. GJ}^{-1}$
 465 for willow in Germany vs 6.80 $\text{kg CO}_2\text{-eq. GJ}^{-1}$ for the S1 eucalyptus system here, while
 466 the eutrophication impact for willow was 94 $\text{g PO}_4^{3-}\text{-eq. GJ}^{-1}$, well within the 40-135 g PO_4^{3-}
 467 -eq. GJ^{-1} range reported here for our systems, although it should be noted that the estimation
 468 of nitrate and phosphate losses was not explicitly described in the willow study. Lastly, the

469 acidification emissions of willow in Germany totalled 174 g SO₂-eq. GJ⁻¹, compared to a 40-
 470 110 g SO₂-eq. GJ⁻¹ range for eucalyptus SRCs. This is probably due to higher combustion
 471 emissions of acidifying compounds in the Reinhardt (2000) study than listed in the EcoInvent
 472 database, which pertains to more recent technologies. For the same reason, POCP impacts
 473 were also larger with willow, at 18 C₂H₂-eq. GJ⁻¹ in comparison to 6.1 C₂H₂-eq. GJ⁻¹ g for the
 474 S1 system. Lastly, eucalyptus SRCs may be compared to the range of perennial grasses
 475 assessed by Monti et al. (2010), involving miscanthus, switchgrass, cynara and giant reed,
 476 with a cradle to farm-gate system boundary. Energy consumption ranges from 33 to 142 MJ
 477 GJ⁻¹ biomass energy content, compared to approximately 35 MJ GJ⁻¹ for eucalyptus SRC
 478 (Table 2), putting the latter on a par with the best performers, giant reed and miscanthus.
 479 However, their GHG emissions were significantly lower, at 1.75 kg CO₂-eq. GJ⁻¹
 480 compared to 5.5 – 9.4 for kg CO₂-eq. GJ⁻¹ eucalyptus. The same applied to eutrophication
 481 impacts, ranging from 4 to 20 g PO₄³⁻-eq. GJ⁻¹ for grasses and from 45 to 132 g PO₄³⁻-eq. GJ⁻¹
 482 for eucalyptus, and also to acidification impacts, which are 2 to 2.5 lower for the grasses than
 483 eucalyptus. As with the Gasol et al. (2009) study, it may be that field emissions were under-
 484 valued, since fertilizer N input rates were rather higher than the eucalyptus SRC systems (at
 485 80 kg N ha⁻¹ yr⁻¹ compared to a 6-40 kg N ha⁻¹ yr⁻¹ range for eucalyptus). The Monti et al.
 486 (2010) paper does not mention direct emissions of nitrate or P in the field.
 487 Because of differences in local contexts, in the sources of life-cycle inventory data and
 488 estimation methods for field emissions, it is not possible to directly compare the eucalyptus
 489 systems tested here with other coppices or herbaceous plants since these differences are likely
 490 to overrule the differences between feedstocks per se. With the exception of the Gasol et al.
 491 (2009) study, the LCA indicators of eucalyptus were within the range of impacts reported for
 492 other lignocellulosic feedstocks, but no robust patterns emerged in terms of ranking with other
 493 species.

494 4.2 *Uncertainties in the life-cycle inventories*

495 Field emissions are particularly difficult to correctly address in the LCA of agricultural or
496 forestry systems as they depend to a large extent on local conditions (soil properties, climate)
497 and on their interactions with management practices, which govern the fate of chemical or
498 organic inputs. Since very little data on field emissions has been published for eucalyptus
499 SRC in temperate zones, we used estimation methods developed for other species, or assumed
500 some emissions were negligible. Such was the case for nitrate leaching and P losses, which
501 may have lead to an under-estimation of eutrophication impacts. Lopes et al. (2003) found
502 these emissions negligible in their LCA of eucalyptus-derived paper, and so did Jawjit et al.
503 (2006) although their estimates of nitrate and phosphate emissions from eucalyptus
504 plantations were rather large: they assumed that 35% and 20% of fertilizer N and P inputs
505 were leached to water bodies, respectively, according to the 1997 IPCC guidelines for GHG
506 inventories. The 35% emission factor for nitrate (which was revised to 30% in the 2006 IPCC
507 guidelines – Tanabe et al., 2006) should in principle apply to managed forests, but no
508 reference specific to forest or energy plantation is given in the literature base that served to
509 determine this value. Further research is therefore warranted to provide a more accurate
510 estimate of nitrate leaching for eucalyptus SRC. The same applies to P losses, and also to
511 gaseous emissions of N_2O , NH_3 and NO . The latter were calculated according to the IPCC
512 (2006) guidelines for managed ecosystems, using default emission factors which are
513 characterized by a large uncertainty range (Stehfest and Bouwman, 2006). Unfortunately, no
514 literature data were found for eucalyptus SRC or forests in Europe to refine those estimates.

515 4.3 *Relevance of including ecosystem C dynamics*

516 Accounting for variations in ecosystem C stocks, compared to the alternative land-use
517 (wildland in our case) had a drastic effect on the GHG balance of eucalyptus-derived heat,

518 whose magnitude depended on the factor chosen for the equivalence between C stored in
519 ecosystem pools and atmospheric CO₂. Even when using the most conservative value of 1:100
520 (ie that least favorable to eucalyptus), ecosystem C pools offset GHG emissions by 50 to
521 70%, depending on the inclusion of below-ground biomass. This made net eucalyptus a nearly
522 carbon-neutral source of heat, and stresses the influence of ecosystem C dynamics in relation
523 to land-use changes (LUC) in LCAs, already noted by Ndong et al. (2009) for biodiesel from
524 jatropha in West Africa, and Shurpali et al. (2010) for reed-canary grass in Finland. Note that
525 the latter authors effectively used an equivalence factor of 1:1, since they used measurements
526 of net ecosystem exchanges of CO₂ over reed-canary grass, as cumulated over one year, as a
527 measure of the C sink strength of the field where this crop was grown. Such hypothesis was
528 also implicit in the GHG budgets of farmland and woodland management computed by Palm
529 et al. (2010) in 2 villages in Africa, or by Ceschia et al. (2010) for cropping systems across
530 Europe. In both references, ecosystem C fixation was put on a par with CO₂ emissions from
531 fossil sources or N₂O emissions from soils. This may be justified on a short-term basis, but is
532 misleading in the long-run since most of the C taken up by ecosystems on a given year will be
533 released back to the atmosphere after a few years since it enters fresh organic matter pools
534 with rapid turnover (Jenkinson, 1990). From a life-cycle perspective, whereby one attempts at
535 estimating the cumulated past and future effects of substituting one product by another, using
536 such an hypothesis would have over-emphasized the sink capacity of SRC stands compared to
537 wildland, and given wrong results on the actual GHG benefits of eucalyptus biomass. The use
538 of equivalence factors, which are up to 2 orders of magnitude lower, is thus fully justified.

539 Of course the magnitude and direction of this effect strongly depends on the LUC hypotheses
540 made in the LCA. Adverse effects were conversely noted for biofuels when including indirect
541 land-use change effects whereby the displacement of food crops for biofuels in the US
542 entailed the conversion of natural ecosystems to arable farming in other parts of the world

543 (Fargione et al., 2008). Our scenarios for eucalyptus growth did not involve such effects since
544 they considered the farming of eucalyptus SRC as an opportunity to value former arable land
545 or vineyards that had been abandoned because of a drop in the market prices of wine.

546 Soil organic matter (SOM) pools were not included in the ecosystem pools for lack of robust
547 estimates of SOM variations under both eucalyptus SRC and wildland. This pool was actually
548 responsible for most of the land-use offset of GHG emissions in the LCA of Jatropha by
549 Ndong et al. (2009). Similarly, given the differences in net primary production between the
550 SRC stands and the wildland, it is likely that the former have a higher SOM content than the
551 latter, and therefore further accrue their GHG benefits. Grogan and Matthews (2001) thus
552 argued from a very preliminary modelling study that 'short-rotation coppice systems have the
553 capacity to sequester substantial amounts of carbon, comparable to, or even greater than, an
554 undisturbed naturally regenerating woodland'. This results from C inputs from SRCs being
555 higher than from the regenerated woodland, which is comparable to our wildland system here.

556 Field samplings were carried out in our study area to estimate SOM contents under vineyards,
557 eucalyptus SRC of various ages, wildlands and arable land. Although the comparison was
558 confounded by soil clay content, SOM was clearly lowest under the vineyards and
559 comparable between wildlands and SRCs. Conversion shortly after vineyard abandonment
560 would therefore maximize the benefits of eucalyptus SRCs in terms of SOM gains from land-
561 use change. Further work (in particular SOM modelling) is nevertheless required to provide
562 more robust estimates of the magnitude of these potential gains.

563

564 *Acknowledgements*

565 These results were obtained in the framework of the CULIEXA project funded by the
566 ENERBIO fund of the TUCK foundation (Rueil-Malmaison, France).

567 *References*

- 568 Berthelot A, Bouvet A, Sutter B (1994) Taillis à courtes rotations de peuplier -
569 Influence de la densité sur la biomasse récoltable d'une première rotation. *Annales des*
570 *recherches sylvicoles AFOCEL*, # **1994**, 189-210.
- 571 Bsi (2008) PAS 2050:2008 - Specification for the assessment of the life cycle
572 greenhouse gas emissions of goods and services. British Standards Institution, London.
- 573 Cauvin B, Melun F (1994) Guide de culture du TCR Eucalyptus. AFOCEL, Fiche
574 Informations-Forêt no 486, Paris.
- 575 Ceschia E, Béziat P, Dejoux J-F et al. (2010) Management effects on net ecosystem
576 carbon and GHG budgets at European crop sites. *Agriculture, Ecosystems & Environment*,
577 **139**, 363 – 383.
- 578 Cherubini F (2010) GHG balances of bioenergy systems - Overview of key steps in
579 the production chain and methodological concerns. *Renewable Energy*, **35**, 1565 – 1573.
- 580 Croisé L, Ulrich E, Duplat P, Jaquet O (2002) RENECOFOR – Deux approches
581 indépendantes pour l'estimation et la cartographie des dépôts atmosphériques totaux hors
582 couvert forestier sur le territoire français. Office National des Forêts, Paris. ISBN 2-84207-
583 258-8.
- 584 Dimitriou I, Aronsson P (2005) Des saules pour l'énergie et la phytoremédiation en
585 Suède. *Unasylva*, **221**, 47-50.
- 586 European Commission (2005) Biomass, green energy for Europe. Eur21350A, Office
587 for Official Publications of the European Communities, Luxembourg.
- 588 European Commission (2009) Directive 2009/28/EC of the European parliament and
589 of the council of 23 April 2009 on the promotion of the use of energy from renewable
590 sources. Official Journal of the European Union, June 5th, 2009.

591 Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land Clearing and the
 592 Biofuel Carbon Debt. *Science* **319**, 1235-1237.

593 Gabrielle B, Gagnaire N (2008) Life-cycle assessment of straw use in bio-ethanol
 594 production: a case-study based on deterministic modelling. *Biomass and Bioenergy* **32**, 431-
 595 441.,

596 Galloway JN, Aber JD, Erisman JW, Seitzinger SP, Howarth RW, Cowling EB,
 597 Cosby BJ (2003) The Nitrogen Cascade, *BioScience* **53**, 341-356.

598 Gasol CM, Gabarrell X, Anton A, Rigola M, Carrasco J, Ciria P, Rieradevall J (2009)
 599 LCA of poplar bioenergy system compared with Brassica carinata energy crop and natural gas
 600 in regional scenario. *Biomass and Bioenergy* **33**, 119 – 129.

601 Goglio P, Owende PMO (2009) A screening LCA of short rotation coppice willow
 602 (*Salix* sp.) feedstock production system for small-scale electricity generation. *Biosystems*
 603 *Engineering*, **103**, 389–94.

604 Grogan P, Matthews, R (2001) Review of the potential for soil carbon sequestration
 605 under bioenergy crops in the U.K. Scientific Report, MAFF report on contract NF0418,
 606 Institute of Water and Environment, Cranfield University, Silsoe.

607 Guinée JB, Gorée M, Heijungs R et al. (2002) Handbook on life cycle assessment.
 608 Operational Guide to the ISO standards. Centre of environmental Science, Leiden University,
 609 Leiden, The Netherlands.

610 Hedlund K, Regina IS, der Putten WHV et al. (2003). Plant species diversity, plant
 611 biomass and responses of the soil community on abandoned land across Europe: idiosyncrasy
 612 or above-belowground time lags. *Oikos*, **103**, 45-58.

613 Iglesias-Trabado G, Wilstermann D (2008) *Eucalyptus universalis*. Global cultivated
 614 eucalypt forests, 2008 map. Version 1.0.1. In: *GIT Forestry Consulting's*
 615 *EUCALYPTOLOGICS*.

616 Retrieved from http://git-forestry.com/download_git_eucalyptus_map.htm (21 December
617 2011)

618 Jawjit W, Kroeze C, Soontaranun W, Hordijk L (2006) An analysis of the
619 environmental pressure exerted by the eucalyptus-based kraft pulp industry in Thailand.
620 *Environment, Development and Sustainability*, **8**, 289-311.

621 Jenkinson D (1990) The turnover of organic carbon and nitrogen in soil. *Philosophical
622 Transactions of the Royal Society of London - Series B: Biological Sciences*, **329**, 361-368.

623 Jenkinson D, Harkness D, Vance E, Adams D, Harrison A (1992) Calculating net
624 primary production and annual input of organic matter to soil from the amount and
625 radiocarbon content of soil organic matter. *Soil Biology and Biochemistry*, **24**, 295-308.

626 Kim S, Dale BE (2005) Life cycle assessment of various cropping systems utilized for
627 producing biofuels: Bioethanol and biodiesel. *Biomass and Bioenergy*, **29**, 426 – 439.

628 Labouze E, Honoré C, Moulay L, Couffignal B, Beekmann M (2004) Photochemical
629 ozone creation potentials *The International Journal of Life Cycle Assessment*, **9**, 187-195.

630 Lindroth A, Båth A (1999) Assessment of regional willow coppice yield in Sweden on
631 basis of water availability. *Forest Ecology and Management*, **121**, 57-65.

632 Lopes E, Dias A, Arroja L, Capela I, Pereira F (2003) Application of life cycle
633 assessment to the Portuguese pulp and paper industry. *Journal of Cleaner Production*, **11**, 51-
634 59.

635 Manzone M, Airolidi G, Balsari P (2009) Energetic and economic evaluation of a
636 poplar cultivation for the biomass production in Italy. *Biomass and Bioenergy*, **33**, 1258-1264.

637 MAP (2009) Memorandum on the methodology to account for the sequestration of
638 carbon in wood stands. Ministry of Agriculture and Fisheries, Paris, France (in French).

639 Monti A, Fazio S, Venturi G (2009) Cradle-to-farm gate life cycle assessment in
640 perennial energy crops. *European Journal of Agronomy*, **31**, 77 – 84.

641 Moura-Costa P, Wilson C (2000) An equivalence factor between CO₂ avoided
642 emissions and sequestration – description and applications in forestry. *Mitigation and*
643 *Adaptation Strategies for Global Change*, **5**, 51-60.

644 Nemecek T, Heil A, Huguenin O, et al. (2003) Life cycle inventories of agricultural
645 production systems. Final report Ecoinvent 2000 No. 15, FAL Reckenholz, FAT Tänikon,
646 Swiss center for life cycle inventories, Dübendorf, CH.

647 Ndong R, Montrejaud-Vignoles M, Saint-Girons O, Gabrielle B, Pirot R, Domergue
648 M, Sablayrolles C (2009) Life cycle assessment of biofuels from *Jatropha curcas* in West
649 Africa: a field study. *Global Change Biology Bioenergy*, **1**, 197-210.

650 Nguyen The N, Lambrecq D, Sionneau J (2004) Eucalyptus establishment in France:
651 20 years of collaboration between research and industry. In: *Proceedings of the IUFRO*
652 *conference “Eucalyptus in a changing world”. Aveiro, Portugal, 11-15 October 2004 (ed*
653 *Borralho N)*, p. 484, RAIZ, Eixo.

654 Nguyen The N, Deleuze C (2004) Biomass and nutrient accumulation for three short
655 rotation coppices of *E. gundal* in southern France. In: *Proceedings of the IUFRO conference*
656 *“Eucalyptus in a changing world”. Aveiro, Portugal, 11-15 October 2004 (ed Borralho N)*,
657 pp. 324-325, RAIZ, Eixo.

658 Nguyen The N, da Silva Perez D, Melun F, Bouvet A (2010) Evaluating the potential
659 of biomass production, nutrient export and woodchips quality by eucalyptus in a perspective
660 of culture in VSRC. In: *Proceedings of the 18th European biomass conference. Lyon 5-9 May*
661 *2010*.

662 Nguyen The N, Gaspard M, Ménard P, Kephaliacos K, Ridier-Martos A, Gabrielle B
663 (2010) The Culiexa project: analysis of technical and socio-economic drivers for the
664 development of woody biomass crops in agricultural farms. Final project report, FCBA, Paris
665 *(in French)*.

666 Paixão FA, Boechat Soares CP, Gonçalves Jacovine LA, Lopes da Silva M, Leite H
667 G, Fernandes da Silva, G (2006) Quantificação do estoques de carbono e avaliação economica
668 de diferentes alternativas de manejo em um plantio de eucalipto. *Revista Árvore*, **30**, 411-
669 420.

670 Palm CA, Smukler SM, Sullivan CC, Mutuo PK, Nyadzi GI, Walsh MG (2010)
671 Identifying potential synergies and trade-offs for meeting food security and climate change
672 objectives in sub-Saharan Africa. *Proceedings National Academy of Sciences*, **46**, 19661-
673 19666.

674 Reinhardt G (2000) Bio-energy for Europe. Which ones fit best? Final report EC
675 contract CT98-3832, IFEU, Heidelberg.

676 Robertson GP, Dale VH, Doering OC, et al. (2008) Sustainable Biofuels Redux.
677 *Science*, **322**, 49-50

678 Scharlemann JPW, Laurance WF (2008) How Green Are Biofuels? *Science*, **319**, 43-
679 44.

680 Shurpali NJ, Strandman H, Kilpeläinen A, Huttunen J, Hyvönen N, Biasi C,
681 Kellomäki, S, Martikainen PJ (2010) Atmospheric impact of bioenergy based on perennial
682 crop (reed canary grass, *Phalaris arundinaceae*, L.) cultivation on a drained boreal organic
683 soil. *Global Change Biology Bioenergy*, **2**, 130-138.

684 Stehfest E, Bouwman L (2006) N₂O and NO emissions from agricultural vegetation:
685 summarizing available of global annual emissions. *Nutrient Cycling in Agroecosystems*, **74**,
686 207-228.

687 Tanabe K, Ngara T, Miwa K, et al. (2006) 2006 IPCC Guidelines for National
688 Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories
689 Programme, IGES, Hayama, Kanagawa.

690 von Blottnitz H, Curran MA (2007) A review of assessments conducted on bio-
691 ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life
692 cycle perspective. *Journal of Cleaner Production*, **15**, 607-619.

693 Wilkinson JM, Evans EJ, Bilsborrow PE, Wright C, Hewison WO, Pilbeam DJ (2007)
694 Yield of willow cultivars at different planting densities in a commercial short rotation coppice
695 in the north of England. *Biomass and Bioenergy*, **31**, 469-474.

696 WWI (2006) Biofuels for transportation – Global potential and implications for
697 sustainable agriculture and energy in the 21st century. Worldwatch Institute, Washington
698 D.C.

699

700

701

702

703

704

705 Figure captions

706 Figure 1: Calculation of the cumulative amounts of carbon stored in eucalyptus biomass over
707 time in the 10-year interval between two cuts.

708 Figure 2. System boundaries and steps of the life-cycle.

709 Figure 3. LCA results for global warming, eutrophication acidification, photo-chemical
710 ozone creation potential, per GJ of heat delivered.

711 Figure 4. Energy ratio as a function of the transportation distance from the eucalyptus
712 plantation to the boiler for scenario S1.

713 Figure 5. LCA indicators weighed by the average impact of an European inhabitant and
714 compared to fossil energy sources.

715 Figure 6. Dynamics of above-ground (top) and above- and below-ground (bottom) C storage
716 by pulp eucalyptus SRC (solid line) and wild land with (dotted line) or without (dashed line)
717 consideration of C accumulation in woody species, in the years following conversion to SRC.

718 Figure 7. Greenhouse gas emissions ($\text{g CO}_2 \text{ eq. GJ}^{-1} \text{ heat}$) due to sowing and harvesting
719 operations, fertilization and transport of chips, and CO_2 savings from CO_2 sequestration in
720 ecosystem biomass using various equivalence factors and the lower and upper estimates.

721 Figure 1: Calculation of the cumulative amount of carbon stored in eucalyptus biomass over
722 time in the 10-year interval between two cuts.

723

Figure 2. System boundaries and steps of the life-cycle.

742 Figure 3. LCA results for global warming, eutrophication acidification, photo-chemical ozone
 743 creation potential (POCP), per GJ of heat delivered.

744

745

746

747

748

749

750 Figure 4: Energy ratio as a function of transportation distance from field to boiler for scenario
751 S1.

752

753

754

755

756 Figure 5. LCA impacts per GJ of heat compared to various fossil energy sources.

757

758

760

761

762

763

764

765

766

767

768

769

771 Fig. 6. Dynamics of above-ground (top) and above- and below-ground (bottom) C storage by
 772 pulp eucalyptus SRC (solid line) and wild land with (dotted line) or without (dashed line)
 773 consideration of C accumulation in woody species, in the years following conversion to SRC.

774

775 Figure 7. Greenhouse gas emissions (g CO₂ eq. GJ⁻¹ heat) due to sowing and harvesting
 776 operations, fertilization and transport of chips, and CO₂ savings from CO₂ sequestration in
 777 ecosystem biomass using various equivalence factors and the lower and upper estimates.

778

779

780

781

782

783

784

785 Table 1. Selected characteristics of the eucalyptus management scenarios for the short rotation
786 (SRC) and very short rotation (VSRC).

	Scenario name	Characteristics	Productivity (ODT ¹ ha ⁻¹ yr ⁻¹)	Fertilizer inputs (kg ha ⁻¹ yr ⁻¹)	Duration
Pulp SRC	S1	Chainsaw	11.7	N: 10	3 x 10 years
1250 stems ha ⁻¹		operator - Log harvest		P ₂ O ₅ : 8.7 K ₂ O: 14.8	
	S2	Felling machine - Log harvest	11.7	N: 6.4 P ₂ O ₅ : 7.8 K ₂ O: 10.1	3 x 10 years.
Energy SRC	S3	Felling machine -	11.7	N: 6.4	3 x 7 years
2500 stems ha ⁻¹		Log harvest		P ₂ O ₅ : 8.3 K ₂ O: 10.1	
	S4	Felling machine - Full stem harvest	14.0	N: 23.4 P ₂ O ₅ : 11.2 K ₂ O: 25.2	3 x 7 years
Energy VSRC	S5	Harvester - Full	10	N: 40.0	7 x 3 years
5000 stems ha ⁻¹		stem harvest		P ₂ O ₅ : 18.8 K ₂ O: 49.8	

787 1: ODT: oven-dry metric ton

788 Table 2. Non-renewable energy consumption per life cycle stage of the various SRC systems
 789 (MJ GJ⁻¹), and ratio of energy delivered to primary energy consumption.

Sce- nario	Cuttings production	Site prep.	Fertilisation	Harvest	Transport	Boiler	Total	Energy ratio
S1	1.84	2.96	5.69	23.52	42.67	0.29	77.0	13.0
S3	1.84	2.96	3.99	27.30	42.67	0.29	79.0	12.7
S7	5.24	4.23	4.00	27.30	42.67	0.29	83.7	11.9
S8	4.34	3.51	9.47	27.28	42.67	0.29	87.6	11.4
S9	12.85	5.18	28.63	3.08	42.67	0.29	92.7	10.8

790

791 Table 3. Influence of woodchips transportation distance from plantation to boilers on LCA
 792 indicators for scenario S1, per GJ of heat.

	Transportation distance (km)			
	80	40	20	10
Non-renewable energy consumption (MJ)	77.0	55.6	45.0	39.6
Acidification (g SO ₂ -eq.)	41.7	35.0	31.7	30.0
Eutrophication (g PO ₄ -eq.)	52.0	50.5	49.8	49,4
Photochemical ozone formation (g C ₂ H ₂ -eq.)	6.8	6.1	5.7	5.5
Global warming (kg CO ₂ -eq.)	8.16	6.80	6.11	5.77

793

794

795 Table 4. Carbon storage in the eucalyptus SRC stands (management scenario 1), relative to
 796 the baseline wildland, as averaged over the 30-year duration of the project, in the above-
 797 ground and above- and below-ground biomass pools ($\text{t CO}_2 \text{ ha}^{-1}$). The lower-end of the range
 798 corresponds to the emergence of woody species in the wildlands, which is ignored for the
 799 upper-end value. C stored in biomass pools are transformed into CO_2 sequestration rates using
 800 the 3 possible equivalence factors detailed in the text.

Ecosystem pools	Equivalence factors		
	1/26	1/55	1/100
Above-ground biomass	2.21 – 3.43	1.05 – 1.62	0.57 – 0.89
Above-ground and below-ground biomass	3.67 – 5.16	1.73 – 2.44	0.95 – 1.34

801

802