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1 MONITORING AND ENVIRONMENTAL MODELING OF EARTHWORK IMPACTS:
2 A ROAD CONSTRUCTION CASE STUDY
3

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45

46 ABSTRACT

47

48 This study presents the contributions of materials, earth engineering equipment and
49 construction techniques to potential environmental impacts from the main items of
50 typical road earthworks. To achieve this goal, the overall activity at a 1.9-km long
51 French earthworks project site for a heavily trafficked highway was surveyed during
52 its 2007-09 construction period. Using data collected and a numerical model of road
53 life cycle assessment (LCA), i.e. ECORCE, six indicators could be evaluated,
54 namely: energy consumption, global warming, acidification, eutrophication,
55 photochemical ozone creation, and chronic human toxicity. When available, several
56 life cycle inventories were implemented in order to appraise indicator sensitivity with
57 respect to the considered panel of pollutants. Results also allowed estimating from
58 an LCA point of view: i) natural resource conservation of both aggregates and soil,
59 during the application of quicklime treatments; and ii) the duration necessary for
60 projected traffic levels to offset the potential environmental impacts of the earthworks
61 stage.

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63 Keywords: road construction; life cycle assessment; earthwork items; environmental
64 indicators; resource conservation.

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1. INTRODUCTION

1.1 Background

Over the past 15 years, a general consensus has been reached to limit the environmental impacts due to human activity. The United Nations produced a text entitled the "Framework Convention on Climate Change" (or FCCC), which has gathered 192 parties in an effort to stabilize the concentrations of global warming substances in the atmosphere at levels that would prevent dangerous anthropogenic interference with the climate system (UN, 1992). In 1997, the Kyoto Protocol to the FCCC was adopted by 37 countries in order to limit global warming (UN, 1998). Since that time, many agreements have been signed, e.g. a reduction of halogens due to ozone layer depletion (UNEP, 2000), while greater attention has been focused on emitted chemical compounds that increase global acidification, eutrophication and (eco)toxicity. In 2007, the French Grenelle Environment Round Table (<http://www.legrenelle-environnement.fr/-Loi-Grenelle-2-.html>) led to the creation of 257 articles introduced into laws on various topics, including resource conservation. On the basis of these new laws, the private sector undertook full-scale testing and entered into private-public partnerships. The one discussed herein, i.e. the TerDouest research program, has been funded by France's National Research Agency (ANR) and conducted by the French Institute of Science and Technology for Transport, Development and Networks (Ifsttar). Support has been provided by Egis, Lhoist, Cimbeton, Charrier, La Forreziennne / Eiffage groups as well as by the French National Railway Corporation (SNCF) and Interdepartmental Directorates of Roads (DIR - Centre Region) in order to achieve these objectives. In this context, the present study examines earthwork activity for the purpose of appraising work practices through an impact assessment.

91 Due to the complexity of non-road equipment operating conditions, the difficulty of *in*
92 *situ* data collection and the multiplicity of impacts, the risk of environmental
93 degradation creates an unavoidable challenge in the area of earthworks, which affect
94 both the local and global environment by: i) erecting barriers that fragment habitats;
95 ii) modifying the interactions between organisms, e.g. noise generation that may
96 drown out birds' singing during breeding periods or night lighting that modifies den
97 sites and hunting spots for chiroptera; iii) affecting pH and redox conditions of soil,
98 water and air due to treatments with various binders; and iv) producing global
99 warming and/or (eco)toxic compounds due to the fuel burned in machines, with these
100 compounds being transferred into various compartments of the ecosphere. To gauge
101 the impacts of earthworks, a larger dataset is thus required than the datasets derived
102 for aggregate extraction (Jullien *et al.*, 2012) or for asphalt pavement construction
103 assessment (Jullien *et al.*, 2006). Any extensive environmental consideration relative
104 to earthworks is difficult to achieve without introducing life cycle modeling tools. To
105 the best of our knowledge, only a small amount of research has dealt with the entire
106 life cycle of earthwork activity (Xiaodong *et al.*, 2008, 2010) or material use (Mroueh
107 and Wahlström, 2002; Stripple, 2001).

108

109 **1.2 Objectives**

110 In accordance with the French Grenelle Environment Round Table (2007), this study
111 seeks to:

- 112 i) draw environmental conclusions on earthwork practices, to be accomplished
113 by surveying the relative contributions of the various items composing a typical
114 earthworks project (with a distinction made between materials and machinery),
115 regarding energy consumption and potential environmental impacts;

- 116 ii) understand the main parameters governing the potential impacts of local
117 technical choices, e.g. soil treatment using quicklime. This objective implies
118 defining an alternative technical solution for road structures and designs that
119 had not been proposed in the RN7 development plan (for natural aggregates);
- 120 iii) propose solutions for mitigating potential earthworks impacts, to be performed
121 by analyzing results obtained on every single earthwork item and then
122 comparing technical solutions to a reference case: the RN7 projected road
123 traffic.

124 To achieve these objectives, the Life Cycle Assessment (LCA) methodology was
125 applied to elementary earthwork tasks responsible for generating quantifiable
126 environmental impacts. Since databases in the literature provide no detailed
127 inventories for pollutants emitted from earthworks and resource consumption, an
128 extensive data collection effort took place on the study site. These data were then
129 analyzed in order to evaluate the potential environmental impacts of the main phases
130 observed during the earthworks stage of road construction. These phases
131 encompass: i) production and transportation constraints relative to fuel and materials;
132 ii) study area design, which is responsible for determining the project's earthwork
133 volumes; and iii) construction, which includes the work and emissions generated from
134 machinery. This dataset also allowed estimating from an LCA perspective: i) the
135 relative impacts of machines and materials implemented, ii) the conservation of
136 natural aggregate resources when using quicklime treatments as a substitute, and iii)
137 the duration required for road traffic to offset the potential environmental impacts of
138 the earthworks stage.

139

140

2. MATERIALS AND METHODS

141

142 **2.1 The study area**

143 Earthworks on French National Highway 7 (i.e. RN7) constituted the first stage of
144 building an 8.9-km section of highway with two lanes in each direction. The study
145 area was contained within this RN7 development plan, consisting of a 1.9-km long
146 strip designed to relieve urban traffic, as shown at the bottom of Figure 1 (from the
147 0.76 to the 2.66 milepost, i.e. MP). Adjoining the study area, the longitudinal (left-
148 hand side) and transverse (right-hand side) views of the earthworks structure are
149 depicted at the top of Figure 1. Throughout the remainder of this text, we will refer to
150 the main earth categories constitutive of these earthworks as "earthwork items"; they
151 comprised the quicklime-treated fills, treated sub-base layers, enriched soils (i.e. the
152 humic layer of the initial topsoil being stored and then used to re-vegetate the road
153 shoulders and earthen retaining walls prior to completion of the earthworks stage),
154 and the unusable cuts. The aggregate base and base course have not been
155 considered herein. These items are part of the pavement and/or uppermost layers
156 supporting the road and therefore involve different construction techniques and
157 imported materials.

158

159 The RN7 earthworks phase lasted more than 3 years (from end of June 2006 to
160 December 2009). During this period, over one million cubic meters of earth were
161 engineered (i.e. either transported from their original position or locally processed)
162 and 10 pools were excavated to reduce runoff water loading with particles and
163 associated pollutants. RN7 geology is depicted by coarse-grained sandy and clay-silt
164 soils with a clay content locally exceeding 30% and a wide range of gravels. Such
165 soils are very sensitive to water and thus prone to mechanical damage; they are

166 typically found in temperate and subtropical regions (e.g. in the loamy basins of
167 former and current rivers) around the world. As regards the study area, a remarkable
168 characteristic was the magnitude of cuts relative to the fills (see Fig. 1). The cuts
169 were primarily located at 1.00 MP and 1.90 MP, whereas the fills occurred close to
170 2.66 MP, a situation that accounted for increases in both the amounts of unusable
171 cuts and the average distance traveled by the moved earth.

172

173 **2.2 Environmental modeling**

174 2.2.1 Model implementation principles for an earthworks assessment

175 Within the LCA framework, as initiated by the TerDouest research program in 2008,
176 Ifsttar has developed the ECORCE 1.0 application, which was initially dedicated to
177 pavements (Ventura *et al.*, 2009, 2010) in order to evaluate the potential
178 environmental impacts of earthworks. This new tool considers all engineered road
179 layers and includes the initial construction and maintenance stages of pavements.
180 The ECORCE 2.0 application currently allows for a comparison among various road
181 construction techniques and types of materials employed, focusing on: (i) the
182 composition and structure of the road layers under consideration, (ii) machine
183 quantities and tasks, and (iii) the absence / presence of soil treatments. RN7
184 earthwork practices (implementation of several construction techniques depending
185 on local soil characteristics) have enabled researchers to collect a wide array of data
186 along road project lengths ranging from 150 m (Jullien *et al.*, 2006) to 1 km (Stripple,
187 2001) for earthwork items located in the exact same area. This collection method is
188 therefore consistent with the LCA code of practice for comparing technical solutions
189 at the same site; moreover, it complies with the objectives set for both the
190 comparisons of earthwork items and the comparisons of soil treatments and natural

191 aggregate use. Most earthwork case study assessment protocols do not allow for
192 assessing two different technical solutions in the same place using local data
193 collected during the works, as was the case for the RN7 project.

194

195 To correspond with the LCA practice applied to road pavements, a comparison is
196 usually performed among several solutions that offer similar services. In this case,
197 ECORCE has been applied to calculate a set of environmental data regarding the
198 various earthwork items providing complementary services, i.e. treated fills, treated
199 sub-base layers, enriched soils, and unusable cuts. Such items support the RN7
200 project in the form of substrates or abutments (enriched soils and unusable cuts are
201 typically stored as earthen retaining walls adjacent to the road).

202

203 2.2.2 Building flows databases for the ECORCE application

204 The ECORCE application was implemented in order to perform a dual assessment of
205 materials, i.e. those introduced for road infrastructure construction and those
206 produced by earthmoving. This implied combining the available Life Cycle Inventories
207 (LCI) for both the quicklime and natural aggregates put to use (Jullien *et al.*, 2012).
208 Such a combination considers two inputs: i) French site data for materials production,
209 and ii) energy content relative to the appropriate production (i.e. French energy and
210 diesel production from the ELCD database, 2002-2003). As regards quicklime
211 production, several distinct LCIs were independently examined and consulted in
212 order to determine the sensitivity of indicators for the considered panel of pollutants.
213 Two datasets by Stripple (2001) and Ecoinvent (2002) were initially available at the
214 international scale (see Table 1). Since the French manufacturing processes were
215 not available in either of the international datasets, the French Union of Lime

216 Producers performed an LCI suited to quicklime production in France (UPC, 2010);
217 this inventory differed by offering: a broader array of quicklime production plants,
218 technological achievements, and a complete list of flows (Table 1). Despite including
219 fuel and energy production, this new LCI exhibits significantly lower energy
220 consumption and CO₂ emissions than Stripple's. In comparison, Ecoinvent's LCI
221 values more closely resembles those of UPC, which suggests that in order to assess
222 the variability of environmental impacts from quicklime production with LCA, a first
223 step may consist of limiting the scope to the LCIs derived by Stripple and UPC.

224

225 For the 3-year data collection period, the organization of earthworks was scrutinized
226 by separating both the materials and onsite energy consumption. Daily cut and fill
227 volumes were analyzed for every single earthwork item (upper part in Fig. 2), an
228 approach that made it possible to assess: fuel consumption by type of machine, daily
229 work and the corresponding earthwork item (lower part in Fig. 2). This task proved
230 complex since the work completed by all earthmoving equipment cannot be easily
231 isolated at any one time since all materials excavated and compacted are being
232 moved continuously.

233

234 2.2.3 System boundaries and data limitations

235 Since this study focuses on the completed earthwork items and materials employed,
236 the upstream processes (not directly related to the earthwork input / output flows)
237 have not been included in calculations, i.e. of either machine production or the
238 construction of quarry equipment for treating aggregates.

239

240 The LCA for the constructed earthwork items was performed by applying ECORCE
241 with inventories for the various materials employed, machine emissions and
242 production and distribution of consumed energy (grayish zone in Fig. 2). The list of
243 chemical substances available in the ECORCE application has been generated from
244 LCIs dedicated to aggregates (Jullien *et al.*, 2006, 2012), bitumen (Eurobitume,
245 1999), cement (Ecobilan, 2002), quicklime (UPC, 2010) and steel (IISI, 1999).
246 Depending on company practices, these LCA calculations were typically conducted
247 in considering a 1-m³ functional unit of earth.

248

249 The atmospheric emissions of chemical substances from machines were estimated
250 from daily fuel consumption data, along with the emission factors for heavy-duty
251 vehicles (Hugrel and Joumard, 2006). Consequently, these merely consisted of daily
252 average data. However, since uncertainties have not been assigned to data available
253 in the literature, research is currently underway in our laboratory to evaluate
254 variations in the emission factors of earthwork machinery as a function of activity and
255 *in situ* geomorphic / pedological conditions that have not been considered herein.

256

257 2.2.4 Indicators description for earthwork assessment

258 The ECORCE application calculates six environmental indicators (Ventura *et al.*,
259 2009, 2010) (Table 2), namely: energy consumption (EE, in MJ), global warming
260 potential (GWP, in kg eq. CO₂, IPCC, 2001), acidification potential (AP, in kg eq.
261 SO₂, Goedkoop, 2001), the eutrophication index (EI, in kg eq. PO₄, Goedkoop,
262 2001), photochemical ozone creation potential (POCP, in kg eq. C₂H₄, Goedkoop,
263 2001), and chronic human toxicity potential (TP, in kg eq. 1.4 DCB, Huijbregts *et al.*,
264 2000). Throughout this text, we will refer to the selected panel of indicators as I₆.

265 Except for energy, all of the indicators introduced have been formulated in
266 accordance with Bare and Gloria (2008) and Bare (2010) as linear combinations of
267 weighted contributions of emissions:

$$268 \quad I_j = \sum_{i=1}^n \alpha_i^j C_i^j m_i \quad (1)$$

269 where I_j is the indicator relative to potential environmental impact "j" (e.g. GWP), α_i^j
270 the allocation factor of emission "i" to each individual impact category (unitless [0-1],
271 Sayagh *et al.*, 2010), C_i^j the individual contribution coefficient of emission "i" to "j"
272 (indicator units: kg^{-1}), and m_i the mass of "i" released into the environment per m^3 of
273 moved earth or ton of material used (including production, transportation and
274 application). The values of these contribution coefficients are provided in Goedkoop
275 (1996), Huijbregts *et al.* (2000) and IPCC (2007).

276

277

3. RESULTS

278 **3.1 Model inputs: moved/engineered earth volumes and material inflows**

279 A design in accordance with anticipated geotechnical characteristics (CSTCN, 1988)
280 of the various earthwork items was investigated so as to analyze engineered earth
281 volumes and amounts of imported materials introduced. The figures obtained are
282 given in Table 3. The geotechnical characteristics of soils at the study site as well as
283 for all RN7 earthworks were initially found to be insufficient for local reuse without
284 preliminary treatment. The soil moisture content was too high (roughly 8%-10%
285 m/m): the compaction curves developed from standard Proctor compaction tests
286 indicated that the optimal moisture content was between 6% and 8%. The local soils
287 were therefore classified as water sensitive according to the French P11-300
288 standard.

289

290 Quicklime (CaO) is commonly used to lower the moisture content of engineered
291 earth. Due to the high moisture content of local soils, quicklime was imported and
292 then added to the fills and sub-base layer. In the presence of water, CaO forms
293 slaked lime, i.e. Ca(OH)₂, within a few minutes of an exothermic reaction. The
294 emitted energy (1160 MJ t⁻¹) results in both a significant temperature rise of the
295 treated soils and a higher dry solid content due to subsequent evaporation: the
296 moisture content decrease is assumed to be proportional to the percentage of added
297 quicklime (a 1%-to-1% correspondence). For this reason, the geotechnical
298 characteristics (such as bearing capacity) of treated soils is locally enhanced. The
299 additional amounts of quicklime were determined according to figures in the log kept
300 for managing all daily construction activities, i.e. the quantities and durations of work,
301 type of activities, equipment implemented, and amounts of materials and supplies
302 received. These quicklime amounts equaled 1%-2% (m/m) of the engineered earth.

303

304 Due to quicklime treatments and the ensuing improvement in bearing capacity of
305 treated soils, the aggregates imported from local quarries represented < 10%, i.e.
306 19,200 m³, of the volume of engineered earth (Table 3). This imported amount rose
307 to approx. 30% and 40% when used as lateral reinforcement for the treated sub-base
308 layer and drainage course under the treated fills, respectively (Fig. 1). The remaining
309 volume of aggregates, i.e. estimated at 6,000 m³, was primarily used to construct the
310 basins receiving surface water discharges. In order to reduce uncertainties, the
311 imported aggregates (small amounts used at the RN7 site) were not taken into
312 consideration during the LCA of earthwork items.

313

314

315 **3.2 Model inputs: earth movements and *in situ* fuel consumption**

316 The average distance crossed by moved earth (\bar{L}) was determined for every single
317 earthwork item included in the study area and RN7 earthworks. Based on fuel tank
318 capacity and their refill frequency, the daily fuel consumption could be evaluated for
319 the two main categories of earth engineering equipment, namely earth movers (i.e.
320 dumpers and trucks) and earth processors (bulldozers, excavators, graders and
321 vibratory rollers). Once the daily fuel consumption was known, then the total fuel
322 consumption was calculated per cubic meter of moved / engineered earth as well as
323 per earthwork item (Table 4).

324

325 The value of \bar{L} was determined by using the collected daily data within the time-
326 location plane for *in situ* earthmoving machinery. This value was formulated as
327 follows:

$$328 \quad \bar{L}_{\text{item}} = \frac{\sum_{i=1}^n (L_i m_i)}{\sum_{i=1}^n m_i} \quad (2)$$

329 where " L_i " is the distance (measured at the metric scale, in m) between the origin and
330 destination of the moved earth, and " m_i " the amount (in kg) of transported material.

331 The soil density considered in Eq. 2 is that of compacted earth after being placed in
332 fills (i.e. 2 tons m^{-3}). The density of earth placed in the earth movers was excluded
333 since it may widely vary depending on the geological nature of soils and excavation /
334 extraction methodology implemented (e.g. excavators, loaders, scrapers, bulldozers).

335 The subscript "i" stands for the various earth movements relative to the considered
336 earthwork item.

337

338 The formula for \bar{L} implicitly took into account the typology, quantity and load capacity
339 of earthmoving machinery (mostly dumpers, 8-20 m³ capacity). Regarding all
340 machines taken as a whole, the entire RN7 earthworks project (resp. just the 1.9-km
341 study area section) deployed up to 85 (resp. 48) earth engineering machines
342 including, but not restricted to, bulldozers (with a net engine power of 80-480 kW),
343 dumpers (220-750 kW), excavators (90-420 kW), graders (130-220 kW), scrapers
344 (270-410 kW), vibratory rollers (110-150 kW) and trucks (180-320 kW).

345

346 **3.3 Potential environmental impacts: comparison of earthwork items**

347 Figure 3 shows the contribution of each earthwork item to the potential environmental
348 impacts of the study area. These contributions were calculated using the ECORCE
349 application with Stripple's (top panel) and UPC (bottom panel) quicklime production
350 LCIs and the selected I_6 environmental indicators.

351

352 Among the various earthwork items, the contribution of unusable cuts to the volume
353 of engineered earth and associated fuel consumption was predominant, i.e. 110,000
354 m³ (Table 3) and 90.9 m³ (Table 4), respectively, or the equivalent of ~50% of overall
355 values for the study area. Unlike the treated fills and construction of treated sub-base
356 however, the contribution of unusable cuts to the I_6 environmental indicators
357 amounted to 5%-40% (Stripple LCI) and 4%-34% (UPC LCI), respectively (Fig. 3).
358 This finding confirms that the engineered earth volume and related fuel consumption
359 are not adequate indicators for measuring the potential environmental impacts of the
360 treated items.

361

362 In contrast with unusable cuts, the construction of treated fills accounted for 35% (i.e.
363 80,000 m³, Table 3) of the engineered earth volume and 33% (i.e. [59.2] 10³ L, Table
364 4) of total fuel consumption. However, treated fills induced 40%-65% (Stripple LCI)
365 and 42%-64% (UPC LCI) of the potential overall I₆-related environmental impacts
366 (Fig. 3). This discrepancy becomes even more significant when considering the
367 treated sub-base layer, which represents 9% (i.e. 22,000 m³, Table 3) of the
368 engineered earth volume and 11% (i.e. [20.4] 10³ L, Table 4) of total fuel
369 consumption, while inducing 16%-30% (Stripple LCI) and 17%-31% (UPC LCI) of the
370 potential overall I₆-related environmental impacts. More specifically, the treated items
371 primarily contributed to the GWP indicator: I_{GWP} relative to the treated sub-base layer
372 and fills equaled > 90%. In comparison, the generation of enriched soils and
373 unusable cuts only amounted to < 1% and 4%-9% of I_{GWP}, respectively.

374

375 **3.4 Potential environmental impacts: quicklime and machine contributions**

376 An important parameter affecting the I₆ panel of environmental indicators was the
377 presence / absence of quicklime treatment, thus leading us to compare the
378 contributions of both quicklime (in terms of production, transportation and
379 implementation) and the use of earth engineering machinery (Fig. 4).

380

381 Regarding energy consumption and emissions of global warming substances, the
382 quicklime treatments represented 77% (Stripple LCI) and 64% (UPC LCI) of I_{EE}, and
383 91% (Stripple LCI) and 83% (UPC LCI) of I_{GWP}, respectively. Calculations have
384 indicated that except for the POCP and TP indicators, the potential environmental
385 impacts of quicklime treatment have invariably originated from the quicklime
386 production step, i.e. 93%-87% of I_{EE}, 98%-95% of I_{GWP}, 88%-65% of I_{AP} and 83%-

387 56% of I_{EI} , as obtained from the Stripple and UPC LCIs, in this order. For instance,
388 the production step yields carbon dioxide (CO_2 , a low-toxicity substance, i.e. toxic at
389 levels $> 1\%$ in the atmosphere) emissions when limestone is heated. In contrast, the
390 *in situ* implementation (42%-45%) and on-road transportation (14%-15%) steps
391 dominated the I_{POCP} contributions of quicklime treatment. Distance from the lime kiln
392 measured ~ 150 km. This observation also was partially true for I_{TP} . *In situ*
393 implementation and on-road transportation accounted for respectively 62% and 21%
394 of I_{POCP} for quicklime treatment when using the Stripple LCI. Yet, these factors only
395 accounted for $< 1\%$ and 2% when using the UPC LCI.

396

397 The potential environmental impacts from earth engineering equipment
398 systematically exceeded that of quicklime treatment for I_{POCP} , i.e. 72% (Stripple LCI)
399 and 73% (UPC LCI), respectively (Fig. 4). The I_{TP} of machinery only prevailed when
400 using Stripple's quicklime production LCI (79%, top panel in Fig. 4), whereas the
401 corresponding I_{AP} and I_{EI} only dominated when using the UPC quicklime production
402 LCI (61% and 66%, bottom panel in Fig. 4). For these indicators, the associated
403 quicklime treatment contributions of treated fills and the sub-base layer were minimal,
404 i.e. 20%-16% and 46%-40%, respectively (Fig. 3). Accordingly, the POCP indicator
405 and, to a lesser extent, I_{AP} and I_{EI} (due to its LCI sensitivity, the use of I_{TP} remains
406 problematic) were affected by machine-related processes such as the *in situ*
407 movements of excavated earth.

408

409 In the earthworks field, moved earth is transported from the cuts to fills and/or to the
410 earthwork items. To maintain the frequency of earth movements, the quantity of earth
411 movers has increased with \bar{L} (from 2 to > 8 dumpers). Hence, fuel consumption

412 varied markedly among the earthwork items, ranging from $1.4 \cdot 10^3$ L for enriched soils
413 to $42 \cdot 10^3$ L for treated fills (Table 4). Fuel consumption by earth movers contributed
414 to raising the POCP indicator through the emission of photochemical ozone
415 precursors (mainly NO_x and NMOC) into the atmosphere. This was apparent from the
416 strong positive correlations between earthwork item contributions to I_{POCP} (for both
417 the Stripple and UPC LCIs) and the local fuel consumption: $r^2 = 0.95$, $I_{\text{POCP}}(i) = 10$
418 $\text{Fuel}(i) + 80$, where fuel is expressed in 10^3 L and "i" refers to the given earthwork
419 item. As regards I_{AP} , I_{EI} and I_{TP} , the r^2 values were 0.46-0.86, 0.58-0.91 and 0.96-
420 0.23, in this order.

421

422

4. DISCUSSION

4.1 Data robustness for treated and untreated soil comparisons

424 To strengthen the applicability of these calculated environmental indicators, several
425 key LCA parameters have been verified and validated. For instance, the relevance of
426 selected pollutants with respect to the earthworks field has been examined in order to
427 evaluate the proportion of impacts attributable to the machinery or energy production.
428 The procedures employed for characterizing emissions were considered adequate to
429 assess the credibility (hence uncertainty) ascribed to the chemical flows. Moreover,
430 the contributions of each chemical substance to the various impact categories have
431 been carefully monitored so as to update the current databases.

432

433 Differences between the considered LCIs consisted of system boundaries, a broader
434 array of quicklime production plants, a more complete flow list and technological
435 accomplishments (see Section 2.2.2 and Table 1). Sensitivity analyses indicated that
436 the principal factors responsible for indicator values discrepancies with Stripple, UPC

437 or Ecoinvent LCIs were: i) technological achievements with respect to lower energy
438 consumption and global warming substance emissions; and ii) more complete flow
439 list (as initiated by ISO 14040-4, 2006 and NF P01-010, 2004 standards), in this
440 order. According to Stripple (2001) and in reading the data shown in Figure 4, a total
441 of 9,240 MJ are consumed and 2,040 kg of CO₂ emitted per ton of quicklime
442 produced. These amounts were about twice the values provided by UPC (2010) or
443 Ecoinvent (2002): 4,500 / 5,800 MJ ton⁻¹ and 1,080 / 960 kg (CO₂) ton⁻¹, respectively.
444 The significantly smaller UPC energy consumption and CO₂ emissions had however
445 limited the impact on quicklime treatment contributions, as expressed in percentages,
446 which only decreased by < 15% (Fig. 4). This observation highlights that due to the
447 intrinsically high energy consumption and CO₂ emissions during the production step,
448 the contribution of quicklime to the I_{EE} and I_{GWP} indicators prevails regardless of the
449 preferred life cycle inventory. This finding has been further substantiated by the
450 quicklime production inventories in the Ecoinvent database (quicklime in loose pieces
451 at the plant / quicklime milled loose at the plant, 2000-2002) (Kellenberger *et al.*,
452 2004).

453

454 Another critical observation is the leap in I_{TP} quicklime treatment contribution upon
455 implementation of the UPC quicklime production LCI (Fig. 4). Such a leap was
456 unexpected since French lime kilns from 2010 would have been expected to offer
457 cleaner production processes than kilns from 2001 (due to the indication of lower
458 energy consumption and CO₂ emissions). 99% of the observed increase actually
459 originated from the PAHs, which were not available in Stripple's LCI (Table 2). PAHs
460 are formed in flames (T > 500°C, Bittner and Howard, 1981; Frenklach *et al.*, 1984;
461 Marinov *et al.*, 1998), presumably during the calcination of limestone whenever fuel

462 hydrocarbons are not completely combusted. This finding was confirmed by the fact
463 that the production step accounted for 98% of I_{TP} (UPC LCI) vs. just 18% of I_{TP}
464 (Stripple's LCI), i.e. $720 \cdot 10^3$ kg eq. 1.4 DCB vs. 3,000 kg eq. 1.4 DCB, respectively.
465 For the sake of comparison, I_{TP} with the Ecoinvent LCIs for quicklime exhibited
466 intermediary values, i.e. $140 \cdot 10^3$ kg eq. 1.4 DCB (38% for the production step). It is
467 worth noting that the lack of consistency between the LCIs implemented and the high
468 sensitivity to a few key substances undermines the pertinence of multi-pollutant
469 indicators such as I_{TP} . Due to the absence of uncertainties attributed to the data in
470 the literature and the LCIs of the materials and construction techniques deployed
471 herein, the results obtained should therefore only be considered as indicative.

472

473 **4.2 Natural resource consumption: soil treatment vs. aggregate use**

474 As previously mentioned, quicklime treatments are initially anticipated so as to
475 optimize the use of local materials (e.g. to limit aggregate input) and minimize the
476 output of unusable earth (and thus fuel consumption and surface occupancy). Hence,
477 natural resource conservation (both aggregates and soil) was evaluated in terms of
478 the mass of materials introduced and their related potential environmental impacts.

479

480 In the absence of quicklime treatment, the volume of imported aggregates used
481 would have been equivalent to that of the treated earth, i.e. $102,000 \text{ m}^3$ (Table 3),
482 which roughly represents 214,200 tons of aggregate (overall average density of the
483 local dry - i.e. < 1% water content - 0-31.5 mm calcareous aggregate: 2.1 tons m^{-3})
484 and necessitates the combustion of 132,300 L of fuel (122,090 L for transportation,
485 based on a 20-km distance between the RN7 worksite and an available quarry, plus
486 10,200 L for *in situ* implementation). Similar calculations have pointed out that if

487 considered as waste, the same volume of treated earth would have necessitated the
488 combustion of 89,050 L of fuel to be exported and used to construct artificial fills (the
489 mean density of earth is 1.8 tons m^{-3} , and the distance to the waste disposal site is
490 assumed to be close to 10 km). The transportation of aggregates and unusable earth
491 also represents 8,930 and 7,650 km of on-road truck hauling, respectively. The per-
492 kilometer fuel consumption for loaded and empty trucks equaled: 0.380 L km^{-1} and
493 0.304 L km^{-1} , respectively. The resulting amounts of materials and their relative
494 contributions to study area natural resource consumption (NRC, in tons) and the I_6
495 panel of environmental indicators are displayed in Figure 5. These calculations were
496 based on the French LCIs for quicklime production and aggregate extraction by UPC
497 and Jullien *et al.* (2012), respectively.

498

499 Figure 5 shows that the contribution of quicklime exceeds that of aggregates only for
500 I_{GWP} (x 2.3) and I_{TP} (x 5.6). This important finding demonstrates that quicklime
501 treatment prevents the consumption of a large amount of materials from quarries
502 (4,140 tons of limestone, with 1.77 tons of limestone being calcined per ton of
503 quicklime produced, vs. 214,200 tons of aggregates and 183,600 tons of unusable
504 earth removed from the RN7 site). It also highlights that depending on the indicator,
505 quicklime treatment may cause less loading than the technical aggregate solution on
506 the overall environment (57%, 20%, 18% and 15% of the aggregate contribution to
507 I_{EE} , I_{AP} , I_{EI} and I_{POCP} , respectively). Comparatively speaking, when using the
508 ECORCE application with Stripple's quicklime production LCI, the I_{EE} for quicklime
509 treatment exceeded that of the aggregates by ~9% ($2.3 \cdot 10^7 \text{ MJ}$ vs. $2.1 \cdot 10^7 \text{ MJ}$),
510 which signifies that due to technological achievements in terms of energy
511 conservation and cleaner production, LCI data must be continuously adapted. A

512 critical examination of the sensitivity of selected indicators must be undertaken in
513 order to correctly evaluate the potential environmental impacts of the materials and
514 earth construction techniques introduced.

515

516 Overall, the high I_{GWP} and I_{TP} values inherent in the quicklime production step (i.e.
517 limestone calcination-induced CO_2 and PAH emissions) raise doubts over the use of
518 quicklime in the field of earthworks. Yet on the other hand, quicklime treatments have
519 dramatically lowered: aggregate consumption, the number of passes for rollers, the
520 volume of unusable earth removed from the RN7 earthworks, the quantity of on/off-
521 road heavy vehicles, and the generation of both noise and chemical compounds,
522 which are responsible for a negative influence on global acidification, eutrophication,
523 photochemical ozone creation and chronic human toxicity indicators.

524

525 **4.3 Comparison with the projected RN7 road traffic**

526 Lastly, the NRC and I_6 environmental indicators were calculated for the full set of
527 RN7 earthworks (Table 5). The spatial development of RN7 earthworks was not
528 linear; instead, it consisted of smaller earthwork areas, whose locations depended on
529 the natural and technical obstacles that hinder progress of earth engineering
530 equipment, as well as on the geomorphological and mechanical characteristics of
531 local soils. All these areas were eventually merged in order to complete the entire
532 8.9-km long RN7 earthworks project. Accordingly, the calculations were based on
533 data in the log used to manage daily work for the entire site; these data included: i)
534 type, quantity, task and fuel consumption (1,587,564 L) of the earth engineering
535 machinery; and ii) the volumes of engineered earth and amounts of imported
536 materials for each individual earthwork item (Table 3). The consistency of the I_6

537 environmental indicator values was ultimately verified, a step that consisted of
538 comparing the relative contributions of earthwork items when using the ECORCE
539 application separately with data for both the entire RN7 earthworks (8.9 km long) and
540 the smaller (1.9 km long) study area. The contributions of earthwork items to the I₆
541 panel of environmental indicators exhibited consistent trends: 0.9 < item contribution
542 to I₆ (entire RN7 m⁻³) / item contribution to I₆ (study area m⁻³) < 1.4. This
543 determination corroborates that the newly calculated values of I₆ environmental
544 indicators and those for the study area were relatively consistent and presumably
545 representative of the whole RN7 scope of earthworks (Table 3).

546

547 The full RN7 earthworks accounted for 3.5 10⁷ kg eq. CO₂ (Stripple's LCI), 2.0 10⁷ kg
548 eq. CO₂ (UPC LCI) or 1.9 10⁷ kg eq. CO₂ (Ecoinvent LCI). If an aggregate sub-base
549 and aggregate fills had been employed instead of quicklime treatments, then these
550 results would have amounted to: 1.2 10⁷ kg eq. CO₂ (Table 5). The obtained values
551 were compared to the projected emissions of global warming substances induced by
552 vehicles in covering the 8.9-km long RN7 road. Assuming the RN7 traffic is
553 equivalent to that of the main adjacent road (i.e. ~9,000 vehicles d⁻¹ at 0.13 L km⁻¹ of
554 average diesel fuel consumption), then the total emissions of global warming
555 substances (> 97% as CO₂) would reach 1.2 10⁷ kg eq. CO₂ y⁻¹. Despite the
556 uncertainties surrounding the data, this result clearly shows that RN7 road traffic
557 offsets in less than a few years the GWP impact of the entire earthworks project
558 (either for quicklime treatment or aggregate construction technique). Smaller values,
559 i.e. around 2 years or less, were found for the other environmental indicators.

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562

5. CONCLUSION

563 In assessing the potential environmental impacts of typical road earthworks, the
564 contribution of treated earthwork items has typically dominated the I_6 panel of
565 indicators. The discrepancy between the contribution of quicklime treatment and that
566 of the equipment implemented *in situ* rendered the engineered earth volume,
567 machine activity and/or their daily fuel consumption inadequate as an accurate gauge
568 of the potential environmental impacts of the earthwork study area. This is likely to be
569 a general feature of all treated earthworks, including road and railway construction.

570

571 The main findings of the present study have yielded general trends rather than highly
572 accurate indicator values. For instance, quicklime treatment primarily affected the
573 energy consumption and global warming potential indicators. Depending on the
574 selected LCI, these may also drastically increase the chronic human toxicity potential
575 through PAH emissions during the limestone calcination step. In contrast, machine-
576 induced emissions extensively drove the photochemical ozone creation potential and,
577 to a lesser extent, the eutrophication index and acidification potential.

578

579 Understanding the main results on this local case relative to the technical choices of
580 soil treatment with quicklime or natural aggregates leads us to draw several
581 conclusions. The treatments served to conserve natural resources (both aggregates
582 and soil) and, as a result, reduced both the emissions of chemical substances and
583 environmental impacts inherent in the aggregate extraction and transportation steps.
584 Further research is needed however to assess the net benefits of quicklime treatment
585 over traditional techniques (like aggregates) in terms of bearing capacity, compaction
586 time and related changes in the thickness of earthwork items.

587

588 From an overall standpoint, the calculated potential environmental impacts of the
589 RN7 earthworks stage were roughly equivalent to a few months / years of projected
590 road traffic. This was significantly greater than the impacts of pavement construction
591 and/or maintenance (i.e. a few days of road traffic, data not shown). On the other
592 hand, earthwork items require no maintenance and their service life is expected to be
593 considerably longer, i.e. > 100 years. It is also believed that significant impact
594 mitigation can be achieved by using more recent machinery (e.g. mounted with diesel
595 particulate filters) and improving operating conditions so as to decrease peak
596 consumption and emissions. When viewed in this light therefore, earthworks are a
597 "sustainable" investment.

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TABLE CAPTIONS

Table 1: System boundaries and assumptions adopted for quicklime production LCIs available in three literature datasets. The number of outflows and functional units are also displayed.

Table 2: List of chemical substances and physicochemical parameters input into the ECORCE application calculations in order to assess the potential environmental impacts of earthwork activity. The compounds underscored and in bold letters were reported in the quicklime production inventories by Stripple and UPC, respectively.

Table 3: Summary of data on engineered earth volumes and main material inflows used in the environmental calculations for the 1.9-km long study area. The values in parentheses represent the entire (8.9 km long) RN7 earthworks project.

Table 4: Summary of data on *in situ* earth movements and related fuel consumption introduced into the environmental calculations for the 1.9-km long study area. The values in square brackets pertain to the engineered [moved + locally processed] earth.

Table 5: Environmental indicators calculated for the entire (8.9 km long) RN7 earthworks. The values in parentheses represent the smaller (1.9 km long) study area. A distinction is drawn between the impacts for quicklime treatment (with either Stripple's or UPC LCI data) and for aggregate construction techniques. The bottom row indicates the projected annual RN7 road traffic.

FIGURE CAPTIONS

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Figure 1: Schematic views of the RN7 earthworks site and the smaller study area. The surface of the open (resp. filled) squares in the lateral view were set proportional to the volume of moved earth (resp. quicklime applied). The arrow lengths were set proportional to the average distance traversed by moved earth.

Figure 2: Data aggregation chart used to calculate the potential environmental impacts of the various items composing the study earthworks site. A distinction is drawn between the materials used and earth engineering equipment deployed (i.e. either earth movers or earth processors) relative to emissions.

Figure 3: Relative contributions of earthwork items to the I_6 indicators for the study area (1.9 km long). A distinction was drawn between the values obtained using Stripple's (top panel) and the UPC (bottom panel) quicklime production inventories. Definition of acronyms used for indicators: EE: consumed energy; GWP: global warming potential; AP acidification potential; EI: eutrophication index; POCP: photochemical ozone creation potential; and TP: chronic human toxicity potential.

645 Figure 4: Relative contributions of soil quicklime treatment and earth engineering
646 machinery, in terms of emissions, to the I₆ indicators for the study area (1.9 km long).
647 A distinction was drawn between the values obtained using Stripple's (top panel) and
648 the UPC (bottom panel) quicklime production inventories. Definition of acronyms
649 used for indicators: EE: consumed energy; GWP: global warming potential; AP:
650 acidification potential; EI: eutrophication index; POCP: photochemical ozone creation
651 potential; and TP: chronic human toxicity potential.

652

653 Figure 5: NRC and I₆ indicator values of quicklime treatments and aggregate
654 (including unusable earth exportation) construction techniques for the study area (1.9
655 km long). The greatest contribution is set equal to 100%. Definition of acronyms used
656 for indicators: EE: consumed energy; GWP: global warming potential; AP:
657 acidification potential; EI: eutrophication index; POCP: photochemical ozone creation
658 potential; and TP: chronic human toxicity potential.