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Streamlining life cycle inventory data generation in agriculture using traceability data and information and communication technologies – Part II: Application to viticulture

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ABSTRACT

Agricultural systems are increasingly subjected to environmental life cycle assessment (LCA) but generating life cycle inventory (LCI) data in agriculture remains a challenge. In Part I, it was suggested that traceability data are a good basis for generating precise LCI with reduced effort, especially when collected by efficient information and communication technologies (ICTs). The aim of this paper is to demonstrate this for wine grape production and generate a list of data to be collected for streamlined LCI generation. The study is carried out in the South of France, on a viticultural farm implementing electronic traceability of each cultivation operation, i.e. tillage, fertilisation, crop protection, weeding, canopy management and harvesting (no irrigation is needed at this vineyard). For each operation, specific emission models which satisfy the trade-off between accuracy and need for data have been identified. Traceability data must be supplemented with data related to the plot, equipment and inputs to feed the models. The sensitivity of the LCA outputs to plot soil type and year of cultivation was studied. Consistent with previous agricultural studies, the results show that operations such as pesticide spraying and fertilising have large environmental impacts in this Mediterranean vineyard. Notable variations occur in life cycle impact assessment indicators, principally due to variations in crop yield; however, the influence of secondary factors such as soil type and agricultural practices is also evident and this contribution allows us to better characterise the variability of grape production and to show that streamlined LCI can be created using traceability data. Ultimately, this paper delivers two results. It provides simple models, and relevant data and methodology to enable viticultural LCAs to be undertaken. Additionally, it demonstrates that accurate LCIs can be built based on data already collected for traceability when supplemented with other easily collectable data (weather and farm structural data). Overall, this work paves the way for streamlined LCI in agriculture.

Keywords: Grape, life cycle inventory, traceability, LCA, agriculture, data

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1. Introduction.

In a first paper (Bellon-Maurel *et al.*, 2014), several approaches were presented for streamlining life cycle inventory (LCI) data generation in agriculture and therein a new approach, called the "traceability" approach was advocated, in which "traceability data" and, where possible, data collected by information and communication technologies (ICTs), are used to generate LCI data. Traceability is defined as "all compulsory or voluntary on-farm records". The aim of this second paper is to demonstrate that traceability data are a good basis for generating LCIs in viticulture, provided that appropriate emission models are used and that certain additional data are available. To achieve this, a life cycle assessment (LCA) is performed on a case study vineyard in southern France using data from cultivation registers. Viticulture was chosen because emissions can be very site-specific and grapevines are grown worldwide in diverse climates using a large range of techniques. Moreover, few LCAs of viticultural systems exist in the literature (Aranda *et al.*, 2005; Pizzigallo *et al.*, 2008; Gazulla *et al.*, 2010; Vázquez-Rowe *et al.*, 2012).

In France, the requirements for traceability in viticulture include 19 documents, with information on the farm (crop rotation, vineyard setting, etc.) and on operations (fertilisation, crop protection, irrigation, harvesting) (Abt *et al.*, 2007). Traceability data can, therefore, cover a broad range of viticultural operations; however, using such data for LCI generation is not straightforward, as it is expressed in units related to the agricultural activities (e.g., fertiliser type and quantity) rather than units of emitted substances. Emissions may be computed by using emission factors attached to activities based on international LCA databases such as Ecoinvent. A more accurate alternative is to use local emission models, but this requires additional data (Poppe and Meeusen, 2000). In agriculture, such data can be classified as:

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- "Structural data" about production methods (e.g., plot size, grape variety, slope, soil type and machinery);
- "Activity data" related to the agricultural operations;
- "Weather data" which are easily obtained from meteorological stations.

The objective of this paper is to demonstrate that the use of traceability data for LCI generation provides accurate results with minimal effort and is a sound approach for streamlining LCA in agriculture. After introducing the case study system, the paper describes the LCI generation phase wherein emission sources in the grape production system are identified and linked to simple emission models, followed by a description of which data must be recorded to compute these emissions. A LCA is then performed with regard to grape production and a sensitivity analysis undertaken to test the robustness of results relative to production year and soil type. The outputs of the paper are: a specification sheet for building a LCA-ready traceability database from data already recorded in viticultural traceability systems; and a full LCA of wine grape production validating the traceability-derived LCI approach.

2. Case study description and modelling approach

2.1 LCA methodology

Established LCA methodology, more thoroughly described in Part I is followed: first, the goal and scope of the study are defined; second, the LCI is constructed; third, the impacts and damages are computed from the inventory via well-known life cycle impact assessment (LCIA) methods; finally, data are interpreted and a sensitivity analysis performed (ISO, 2006). The LCA software SimaPro 7.3.3 (PRé Consultants, NL) was used and the LCIA undertaken using ReCiPe Midpoint (H) 1.07 'hierarchist' consensus model. The H (hierarchical) method is considered the default model and represents a compromise between the 'individualist' approach (which uses

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only proven cause–effect relations in a short-term techno-centric perspective) and the 'egalitarian' method (which is based on the precautionary principle and adopts a longer-term perspective). Ecoinvent v2.2 (Swiss Centre for Life Cycle Inventories at www.ecoinvent.ch) was used to find LCI data for background processes, but for the foreground processes specific to viticulture, emissions/consumptions were computed based on models of each operation.

2.2 Goal and scope

The case study system is one of wine grape production from an experimental 100-plot vineyard owned by INRA in the south of France, where a Mediterranean climate prevails (Pech-Rouge, Gruissan). The cradle-to-farm gate LCA case study describes the production of 1 kg of grapes (functional unit) of one variety (Syrah) in five case study configurations representing variable conditions: three plots (P 22, P 80 and P103) are selected in three different zones to demonstrate the influence of different soil properties. Additionally, one plot (P80) is studied in different years (2004, 2006 and 2008) to examine temporal variability. The geographic boundaries of the study are those of the farm; the transfers from the farm buildings to the plots are not taken into account except for the grape harvesting, as transfers can be numerous. The construction of farm machinery is taken into account, based on the Ecoinvent database. The vineyard plantation and setting phases have not been taken into account, as one of the main objectives of this study is to carry out a sensitivity analysis with regard to the variation of soil and year conditions, for which the plantation phase is of no use. Moreover, the planting / setting phase is only three years out of at least 30 year lifespan for these vineyards (30-60 years) which is a reason why some authors have also excluded it (e.g. Gazulla *et al.*, 2010). Other researchers have shown that for 30-year vines, the planting / setting phases could contribute to 10-15% of the impacts due for fuel, equipment and fertilizers (Pizzigallo *et al.*, 2008).

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The time span of each LCA is one year (starting in September). The viticultural operations can be organised into the following operation classes: tillage (for any soil management operation); operations on the canopy (trimming, pruning, etc.); pesticide spraying; fertilising; and grape harvesting.

2.3 From traceability and additional data to LCI

The INRA viticultural property is equipped with a traceability system named Agreo (Maferme-Neotic, France). Agreo is a computer tool for technical management of agricultural and agro-industrial production which facilitates traceability data capture. This software is presently used on a computer, but it is also available for smartphones. The operator enters data about operations he has carried out on the farm. At the end of the season, Agreo provides tables for each plot with various pieces of information, relative to the date of the operation, the input nature and doses, as well as harvested quantities. As an example, Table 1 shows data for one plot (P80, year 2006) used in this LCA.

Daily weather data (temperature, rainfall, evapotranspiration (ETP) etc.) obtained from INRA weather stations is also available. In addition to these variables, so-called “structural” data relative to the farm are also recorded and used: density of vine stocks on each plot; inter-row distance; soil properties; type of machinery; name of fertilisers and pesticides. Data relative to the plots are described in Table 2 and basic grape growing operational inventory data are summarised in Table 3. Based on data reported in these tables and on appropriate models, LCI is computed.

3. Material and methods: Life cycle inventory

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As stated above, LCI are computed for all background processes (i.e. equipment manufacturing, input production) using Ecoinvent, whereas LCI related to foreground processes (e.g., equipment use, resource inputs) are computed based on emission models. To demonstrate the process, a typical example (i.e. nitrogen emissions) is given below to describe the step-by-step procedure in which traceability and additional data are converted to functional LCI (a more detailed description of this approach is given in the Supplementary data S1).

3.1. Emissions from equipment use

Emissions from equipment use are generated during operations (energy consumption, soil compaction, etc.) or "embodied" in equipment (from manufacturing). As detailed earlier, only emissions from equipment operations are considered in the foreground. There are limited data on energy use in viticultural operations. Fuel consumption depends first on the operation carried out, but is also sensitive to operating conditions (Gaviglio *et al.*, 2009), with vehicle and engine speed having the largest effect. A moderate slope increases tractor fuel consumption by around 10% or more when a tool is attached. Air conditioning increases consumption by 10–15%. Using 4WD has no measurable effect on fuel consumption. For tillage emissions, both the tillage depth and soil moisture content impact fuel consumption rates. Table 4 gives average fuel consumption data for each operation, and its sensitivity to vehicle speed and engine speed (i.e. to setting a lower speed of universal joint shaft).

In addition to emissions related to energy use, emissions may also occur from soil compaction by the machinery. Soil compaction is the process in which a stress applied to a soil causes densification. But this phenomenon appears moderate in viticulture (Van Dijck and Van Asch, 2002; Lagacherie *et al.*, 2006) and is, therefore, excluded here. Accordingly, the most important

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vehicle data to be recorded for LCI are hours of use for each operation and tillage depth. The average vehicle speed and plot conditions (i.e. plot slope, which increases consumption after (Gaviglio *et al.*, 2009)) could be recorded as secondary input variables.

3.2 Tillage and cover crops

Tillage may influence both CO_2 and N_2O emissions, but the phenomena are complex and the literature reflects diverging conclusions. Comparisons of cultivated versus cover-cropped vineyards have shown that the latter generates less N_2O by reducing denitrification (Steenwerth and Belina, 2008; Lee *et al.*, 2009). Steenwerth et al (2010) suggest that soil CO_2 emissions in vineyard are primarily controlled by soil water content in summer and soil temperature in winter, rather than by soil management techniques. Ploughing depth may also induce CO_2 release (Reicosky and Archer, 2007) as well as increasing fuel consumption. Therefore and as outlined above, the type of tillage (i.e. surface or deep) has been recorded.

3.3 Irrigation

Three types of irrigation systems are commonly used in viticulture: surface irrigation; sprinkler; and micro-irrigation (Prichard, 2000). Emissions and resource consumption linked to irrigation are: (i) direct emissions relating to infrastructure, pumping energy consumption (which is linked to the pumped volume, delivery pressure and water table depth) and direct water consumption (Bayart *et al.*, 2010; Nunez *et al.*, 2010; Peters *et al.*, 2010); and (ii) indirect emissions such as leaching (fertilisers, pesticides), salinisation and N_2O emissions from water-saturated areas. Accordingly, data to be recorded are the amount of consumed water, average water depth and type of irrigation system.

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3.4 Fertilisation

Viticultural macronutrient demand (N, P, K, Mg, Ca) is lower than that of annual crops (Biala, 2000; Guilbaut, 2006) but still relevant to eutrophication and soil acidification indicators in LCA. The fates of these nutrients depends to a large extent on soil properties, on the natural levels of these nutrients (Mercik *et al.*, 2000) and on conditions of application (Powers, 2007; Langevin *et al.*, 2010; Peters *et al.*, 2011a). As N emissions are very difficult to model, a simple methodology is introduced below that allows viticultural N emissions to be estimated from readily available data.

3.4.1 Nitrogen

Numerous models are available for computing N emissions; Cannavo et al. (2008) reviewed 62 of them and recently an integrated model for computing all N emission was introduced (Parnaudeau *et al.*, 2012). Most models have two drawbacks: first, they generally deal with cereals; second, they require data that are difficult to obtain. In line with previous authors who have developed heuristic approaches for streamlining N emissions computation for LCA (Brentrup *et al.*, 2000), N emissions are estimated here using simple and sometimes empirical models based on a restricted number of parameters. Our approach to N emission computation is based on the following assumptions and parameters:

- NH_3 volatilisation occurs first, i.e. during or just after application (Sommer and Hutchings, 2001);
- N_2O emissions are computed after Brentrup et al (2000) using IPCC emission factors for land-applied N after correction for volatilised NH_3;
- NO_3^- leaching can be computed from the nitrogen budget, after NH_3 and N_2O emissions have been removed (Kücke and Kleeberg, 1997; Brentrup *et al.*, 2000). In our approach,

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and unlike that of Brentup et al (2000) who worked on an annual time basis, this budget is computed on a monthly basis, since rainfall data are daily and plant N uptake is modeled on a monthly basis.

As detailed earlier, volatilisation (NH_3 emission) peaks shortly after application and then quickly declines. Accordingly, our approach assumes that volatilised N derives only from the initial NH_4^+ input following the function:

$$N_{vol} = N_{NH4+} \times Cv$$

where N_{NH4+} is the amount of NH_4^+ in the fertiliser input and Cv is the volatilisation coefficient.

The volatilisation coefficient (Cv) depends on the type of input. It is considered that NH_4^+ follows an exponential decay profile with a half-life of 12 hours. If rain occurs between 0 and 15 days, N volatilisation stops; if not then all originally available NH_4^+ is volatilised. A special case is the foliar fertiliser applied with sprayers, as typically done for pesticide application. No studies report rates of NH_3 volatilisation from foliar urea application to vineyards, only to turf or wheat crops (Freney, 1997). This research indicates very little N loss from volatilisation, hence volatilisation losses from foliar fertilisation in vineyards are considered to be negligible.

Denitrification and N_2O generation are difficult to compute based on mechanistic models, so IPCC guidelines are used for N_2O emissions evaluation here, i.e. 1% of total remaining N (after volatilisation) (IPCC, 2006).

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Leaching of nitrates occurs and the fraction of NO_3^- leached below a depth *h* is calculated by the Burns formula (Burns, 1975):

$$f(t) = \left(\frac{P(t) - ETP(t)}{P(t) - ETP(t) + (V_m / 100)} \right)^h$$

where, for a given period of time *t*, *f(t)* is the fraction of surface-applied nitrate leached below any depth *h* (cm), *P(t)* is the quantity of water brought by rain and irrigation (cm), ETP expresses the quantity of water lost by evapotranspiration (cm) and V_m is the percentage volumetric field capacity.

This formula is applied to the excess N (i.e. N which has been mineralised but which is neither absorbed by plants, nor volatilised, nor denitrified (Kücke and Kleeberg, 1997)) as described by the nitrogen balance, which stipulates that all N exports (i.e. N emissions and plant-absorbed N) counterbalance available nitrogen (N_m) (i.e. nitrates from fertilisers and mineralised from soil and crop residues). In order to be more precise, this N balance is calculated on a sub-yearly timeframe (i.e. monthly) as follows:

$$N_m(soil) + N_m(fertilisers) + N_m(crop\ residues) = N(absorbed\ by\ plants) + N(leaching) + N(volatilisation) + N(denitrification)$$

Nitrogen emission can serve as an example to illustrate our way of translating activity, structural and weather data into emissions. The N balance, the various models described above for volatilization, denitrification and leaching, as well as the bio- or geo- models for computing of various properties of the soil - plant system are used to build a general calculator of the N

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emissions (Figure 1). This conceptual framework is implemented in a spreadsheet (Excel, Microsoft) which provides amounts of N_2O, NH_3 and leached NO_3^-, based on readily available data. The step-by-step procedure is described in Supplementary data S1.

3.4.2 Phosphorus

To compensate for approximately 0.6 kg phosphorus (P) removed per ton of grapes harvested, the grapevine P requirement is around 10–25 kg/ha/yr (CRCV, 2006). Generally, P is non-limiting in vineyards, so P supply is often just basic manure application at planting. Once applied, P can remain in the soil profile for a long time by co-precipitation with Ca^{2+} cations in alkaline soils and Al^{3+} or Zn^{2+} cations in acidic soils. Phosphorus fertilisers are not prone to volatilisation (McConnell *et al.*, 2003) and the most important loss factor is run-off and surface soil erosion (Smith *et al.*, 2001; Peters *et al.*, 2011b). If P is applied in large excess (more than twice the recommended dose), P in agricultural run-off may contribute to eutrophication (Smith *et al.*, 2001). In this study, Nemecek and Kägi's recommendations were followed to compute P emissions (Nemecek and Kägi, 2007). However, other models such as the one proposed by Vadas et al. (2009) may be used, which computes P loss as a function of the amount of applied P (obtained from traceability data), the water-extractable P (which can be included in the database of fertilisers' structure data), and the run-off and the rainfall amount (collected as a weather data). Run-off values may not be readily available and Vadas et al (2009) caution readers that the run-off and erosion estimates are still needed at a level accuracy suitable for their quantification tool.

3.4.3 Potassium

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In the vineyard, potassium (K) fertilisation is generally carried out at planting (basic manure) but regular application may follow. Potassium is present in four cation fractions, three of which are labile. Potassium losses via leaching greatly depend on the cation exchange capacity (CEC) i.e. the K-buffering capacity of soil, which is related to organic matter (OM) content and clay type and content, soil pH, drying/wetting cycles and soil K status. Leaching varies from 0.4–5 kg leached K per 100 mm drainage, according to soil texture and OM content with an average of 1 kg leached K per 100 mm drainage (Askegaard *et al.*, 2004); up to 70% of applied K could remain in heavy soils after the first growing season, whereas in coarse sandy soils a high risk of K leaching occurred at around 20–50 kg K/ha/yr (Askegaard *et al.*, 2004). Catch crops may reduce nutrient leaching (Askegaard and Eriksen, 2008). In summary, K leaching can be modelled similarly to N leaching (i.e. Burns' formula).

3.5 Pesticides

Vineyards are very pesticide-intensive. For example, in France, vineyards represent 4% of the total cropped area but use some 20% of all consumed pesticides (Gil *et al.*, 2007). Pesticide losses can occur either from "point source pollution" (accidental pollution estimated 10% of total losses by experts) and "diffuse pollution" (from normal use). Diffuse pollution is linked to mist and droplet drift during spraying, vapourisation of pesticides during and after spraying, particle-born pesticide run-off, aerial transport and leaching. The inventory challenge resides in the partitioning of pesticides into air, plant and soil compartments (Van Zelm *et al.*). Sinfort *et al.* (2009) studied drift and concluded that: (1) all other conditions being equal, drift loss mainly depends on the type of sprayer used (boom sprayers, air-assisted or pneumatic sprayers, etc.); and (2) partitioning mainly depends on the vegetative stage. Other secondary parameters influencing

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drift are wind speed, droplet size distribution and the wet bulb depression (related to temperature and humidity) (Gil *et al.*, 2007; Gil *et al.*, 2008). Drift mitigation technologies have been shown to change pesticide partitioning (Sinfort *et al.*, 2009); cross-flow spraying significantly reduced losses to air (up to 50%), but yielded inconsistent results for losses to soil, whereas air deflectors did not provide any improvement. Accordingly, the principal factors considered by our approach are: (1) the technology used; and (2) the date of spraying. Based on the data in Sinfort *et al.* (2009) for a pneumatic sprayer, in our study the following air–plant–soil partition is chosen: 0.4:0.2:0.4 and 0.1:0.5:0.4 respectively for "early" (before flowering) and "late" (after flowering) spraying.

Pesticide volatilisation mainly occurs from spray deposits (Van Den Berg *et al.*, 1999). The main factors involved in post-application volatilisation are rainfall, wind speed, temperature, solar radiation, relative humidity, active ingredient and adjuvant physicochemical features such as vapour pressure and K_{ow} (a measure of hydrophobicity) (EPA, 1995; Bedos *et al.*, 2010). Volatilisation from leaves ($Pest_v$) is computed via PestLCI formulas (Birkved and Hauschild, 2006):

$Pest_v = f_{vf} \,.\, Pest_0$ with $f_{vf} = e^{-k_v.t}$ with $k_v = f\,(K'_H)$

Where f_{vf} is the fraction on leaves which volatilises; t is time; k_v is the volatilisation coefficient; K'_H is Henry's constant for volatility.

Pesticide leaching from leaves is estimated by a common rule of thumb. It is commonly considered that if a 20 mm rain event occurs within three days after spraying, 100% of pesticide is leached. Pesticide leaching in soil is modelled as K^+ and NO_3^- leaching following Burns'

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equation. No pesticide run-off or pesticide degradation is taken into account at this stage, as they are considered to be part of the LCIA model (Van Zelm *et al.*, 2014).

4. Results

4.1 LCI and LCIA data

LCI and LCIA data obtained using our approach for the five case studies are described and presented in Supplementary data S2–3 respectively.

4.2 Relevant impact categories in LCA of viticultural operations

In order to determine which of ReCiPe's 18 impact categories are most relevant in this case, the results were normalised against global emissions using the ReCiPe normalisation procedure (http://www.lcia-recipe.net/). Normalised outputs of grape production on P80, years 2004, 2006, 2008 are shown in Figure 2. As frequently encountered in viticulture, the most relevant impact categories are those relating to toxicity, followed by eutrophication, and to a lesser extent, global warming potential and terrestrial acidification. Impacts are primarily linked to pesticide spraying. The following analysis is, therefore, constrained to these most relevant impact categories.

4.3 Contribution analysis of the various operations

As previously mentioned, viticultural operations have been divided into the following operation classes: tillage (for any soil management operation); operation on canopy (trimming, pruning, etc.); pesticide spraying; fertilising; and grape harvesting. As the operations do not vary much from year to year and plot to plot, we have chosen to illustrate the impact contributions for one of

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the five case study configurations only, i.e. P80 2006 which is common to both of the tested variables (i.e. yearly and soil variability). Results are shown in Figure 3.

Tillage often makes a bigger contribution to environmental impacts than harvesting, but the impacts of these two activities tend to vary in proportion compared with the much more variable impact of fertilisation (data not shown). This could be expected, as both tillage and harvesting operations are primarily physical operations involving machinery and diesel. The most heavily impacted category is fossil fuel depletion, due to diesel use. Fertilising mainly impacts climate change (via N_2O emissions) and marine eutrophication (via NO_3^- emissions), whereas pesticide spraying exerts a major influence on toxicity indicators.

4.4. Synthesis: necessary data for LCI compilation.

Based on the farm traceability data—supplemented with weather and structural data—and using the principles and formulas described above, data inventories and impact assessments have been calculated. For illustrative purposes, let us consider the example of emissions due to N fertilisation. The emissions come from three sources: the production of fertilisers; the use of machinery; and the field. For emission due to fertiliser production, traceability data such as fertiliser dose and fertiliser type are requested and Ecoinvent LCI data are used. For emissions due to machinery use, the emission due to machinery manufacture are computed from Ecoinvent database whereas emissions due to machinery work require traceability data such as the duration of operation and if possible the speed. Table 4 can then be used to compute emissions from diesel consumption. Field emissions are by far the most complex and require the following data: traceability data such as fertiliser dose and type and application date; weather information; and structural data such as fertiliser properties and soil properties. The way such data are employed in

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our spreadsheet to compute N emissions has been shown in Supplementary data S1. Due to space constraints, the same demonstration cannot be repeated for all emission types; however, data necessary for carrying out LCI development in viticulture are summarised in Table 6.

Individual pieces of data may be discrete (e.g., time, mass, etc.), binary (Yes/No; Low/High) or descriptive/nominal such as name N_x to be taken from a list x (e.g., operations, equipment, fertiliser and pesticide names). Names in lists are linked to another database containing the specific properties which are required for computing emission factors. For instance, each pesticide name is related to its formulation and the active ingredient, physico-chemical properties (K'_H) which can be found in public databases such as Material Safety Data Sheets displayed in http://e-phy.agriculture.gouv.fr/ and (EPA, 1995). The same process must be carried out for equipment. For each type of machine/infrastructure, data regarding emission/consumption for one hour use are recorded (e.g., embedded emissions, fuel consumption and sensitivity to speed, presence of emission mitigation components such as those for pesticide spraying or fertiliser spreading, and number of rows covered by one vineyard passage). Major pieces of data are listed as “1”, whereas secondary data are listed as “2”. Data are classified according to their origin, i.e. “operational data”, “weather data”, and “plot data”. “Plot data” and “name lists” are structural data.

Data required for these models were shown to be easily available: most are collected from traceability registers and supplemented with additional data. “Operational data” must be recorded for each operation. Out of six pieces of operational data which are of primary importance for emission computation (i.e. noted “1” in Table 5, column 5 to 8), only one (work duration) is not required for traceability. However, it is easily accessible, provided that the operator maintains a log book. Driving data are also likely to be increasingly recorded on an automatic basis in future via

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odometers and on-board computers, or perhaps smart phones. Weather data can be automatically downloaded from local weather stations. "Structural data" relate to data describing the farm infrastructure, including machinery. Such data are generally not requested for traceability. Even if recording them requires additional work with regard to traceability, it is not laborious as they are recorded once only and can then be called upon as required.

5. Discussion

The discussion deals with two points. First, which confidence level can we put into our procedure? To address it, our results have been compared to others found in the literature. Second, which uncertainty level is to be expected? To have a trend, sensitivity analyses have been carried out.

5.1. Comparison with other viticultural LCAs

In order to check the soundness of our approach, some of our results have been compared with relevant literature data. Although publications regarding viticultural LCAs are scarce and generally do not give figures appropriate for robust comparison, one publication (Vázquez-Rowe *et al.*, 2012) was very relevant to our study as it deals with 30 vineyards in Spain, with a climate close to the Mediterranean zone in which our study is based. Values of three midpoint impact categories common to both studies (i.e. global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP)) were compared. As (Vázquez-Rowe *et al.*, 2012) used the CML method, not ReCiPe, computations for the present comparison were redone using this LCIA method.

Table 6 shows a very good level of similarity (generally of the same order of magnitude or better) between the results of our five case studies and those of the 30 case studies introduced by

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(Vázquez-Rowe *et al.*, 2012), which suggests the precision of the proposed approach is satisfactory. Our methodology has the additional advantage of making it possible to study effects of weather or soil, which was not the case of the methodology presented by (Vázquez-Rowe *et al.*, 2012).

5.2. Sensitivity of LCI and LCIA computations to soil conditions

Impacts estimated on plots with similar practices but having three different soils are compared in Figure 4. One plot, P22 2006, has systematically lower impact values than the two others. This is due to the fact that the yield is much higher in this plot (almost the double of the other ones, as shown in Table 3). The only category which displays similar values across all three plots is marine eutrophication, which is due to NO_3^- leaching, suggesting that the mass of nitrate leaching from P22 2006 plot is large. This comes not only from the fact that more fertiliser is applied, but also as a consequence of soil texture: P22 plot is a very sandy soil (see Table 2) which is consistent with a higher rate of leaching. P80 2006 and P103 2006 have similar yields, P80 2006 being slightly higher (5000 versus 4400 kg/ha). This explains why in most cases, P80 2006 impacts are generally smaller or equal to P103 2006 impact values (Figure 4). The sole category for which P80 2006 exceeds P103 2006 is fossil fuel depletion. This is linked to increased consumption of fuel for P80 2006, due to the fact that its soil is difficult to handle and, therefore, machinery fuel consumptions were increased by 30%.

5.2 Sensitivity of LCI and LCIA computations to yearly variations

Figure 5 shows the impacts computed for the same plot (P 80) on three different years (i.e. 2004, 2006 and 2008). The large between-year discrepancy is due to a drop in yield for study year 2008, i.e. yield has declined by 75% (see Table 3). Focusing on 2004 and 2006, it can be noticed

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that 2006 always gives higher impacts than 2004. This is due to the better yield in 2004, whereas agricultural practices are similar (e.g., same amount of fertiliser applied) or improved in 2004. For example, there are seven runs of pesticide spraying in 2006 versus five in 2004, and relatedly, 17 types of pesticides applied in 2006 versus 14 in 2004, presumably due to differences of weather and of phytosanitary pressure from one year to another. This compounding factor is visible when ratios of 2006:2004 impacts are computed; these ratios are larger across all five impact categories related to pesticide inputs (ratios for toxicity, ecotoxicity and freshwater eutrophication range from 1.3–2.6, with an average of 1.7) than for the other categories (i.e. ratios for climate change, fossil depletion and marine eutrophication vary from just 1.16–1.2, with an average of 1.2). As in the preceding case, the main driver for impact changes is the variations in yield.

6. Conclusion

Two principal conclusions are supported by this study. Firstly, precise LCI can be developed using traceability data, a small number of additional data and simple models and heuristics, as shown by the very good correspondence of our results to previously published LCA data related to winegrape production. Secondly, an LCA procedure such as this allows us to analyze sources of variability, such as soils or weather, in LCIA of agricultural productions, here vineyards.

Regarding LCI, it has been demonstrated that extensive data inventories could be obtained with little effort by using simple models and a limited amount of data, most of them being collected for traceability purposes. The analysis of data necessary for LCI, reported in Table 5), showed that only three pieces of data would be required in addition to traceability data recorded in the crop

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book: the work duration, the type of equipment used and the origin of water (if irrigation is used). Work duration could be automatically collected using ISOBUS system (see part I) and the type of equipment is already easily collected in current agricultural equipments by using a flashcode.. This means that only three out of eight pieces of operational data should be collected in addition, whereas soil data would be collected once and for all and weather data could be automatically collected.

When applying this methodology to vineyards, it has been shown that precise inventories could be generated on various real case studies, i.e. grape growing in the south of France. The contribution study contributed to identify pesticide spraying as the most impactful operation on toxicity indicators, while fertilisation influenced GWP and eutrophication potential impact categories, although generally not as greatly as encountered elsewhere in agriculture. The sensitivity analysis showed the overwhelming influence of yield on the final results, which is logical given the use of a fixed product mass as the functional unit. However, when yields are comparable, other secondary factors also influence the results. For instance, in the temporal comparison, the highest use of pesticides was visible (P80 2004 versus P80 2006 comparison), whereas in the soil sensitivity study, the sandy soils gave higher potential marine eutrophication impact.

In conclusion, our goal of generating viable LCI databases for streamlined LCAs in viticulture is within reach. Models presented here will be of value to anybody intending to carry out a LCA on grape or even other fruit production. Most data is available today or should be easily available in the future. Traceability software editors could now modify the traceability database structure according to the recommendations of this study in order to further streamline agricultural LCI data generation.

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Table 1: Example of a traceability log table from the Agreo software (here plot P80, year 2006) (Source: INRA).

Name :	# 80	**Species :**	Vineyard
Zone :	XXX	**Variety :**	Syrah
Area :	0.69 Ha		
Harvest :	2193 kg		

Fertilising	**Commercial name**	**Quantity**	**N**	**P**	**K**
28/09/2006 – Fertilisation	Orga 3 (3-2-3)	907 kg	27	18	27

Harvest	**Input Name**	**Quantity**
30/08/2006 –Harvest		2193 kg

Pesticide spraying	**Commercial name**	**Quantity**	**Target**
11/05/2006 – Miscellaneous	Acarifas	0.5 L/Ha	Clysia
	Sabithane	0.3 L/Ha	Powdery Mildew
	Epylog	3 kg/Ha	Mildew
	Goemar vitiflo E	3 L/Ha	
22/05/2006 – Miscellaneous	vitiflo E	3 /Ha	
	Corail	0.4 L/Ha	
	pantheos (4522C8)	2 kg/Ha	
06/06/2006 – Miscellaneous	Quadris	2 L/Ha	
	Vivifruit	1 L/Ha	

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15/06/2006 – Fungicide	Sulphur (4/336)	30 kg/Ha	
23/06/2006 – Miscellaneous	Cascade	0.4 L/Ha	Clysia
	Karaté K	0.125 L/Ha	Leafhopper
	Microthiol	10 L/Ha	Powdery mild.
08/07/2006 - Fungicide	Vifolcuivre2	3 /Ha	Mildew
	Heliosoufre	7.5 L/Ha	
27/07/2006 – Miscellaneous	Champ Flo	4.3 L/Ha	Mildew
	Steward	0.125 U/Ha	Clysia
Tillage			
03/03/2006 – Harrowing			
24/04/2006 - On-the-row weeding			
16/05/2006 – Harrowing			
17/05/2006 - Interstock tillage			
02/10/2006 – Harrowing			
Canopy management			**Output Quantity**
13/06/2006 – Trimming			
03/08/2006 – Trimming			
01/12/2006 – Pruning			Unknown
05/12/2006 – Pruning residues shredding			

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Table 2: Characteristics of the three grapevine plots under study.

Plots	P 103	P 80	P 22
Soil type	A	B	C
Interrow distance (m)	2.25	2.25	2.5
Ground workability	Easy	Difficult	Easy
Texture	Clayey	Clay and stones	Sandy
Clay (ppt)	500	800	100
Bulk density (kg/m^3)	1200	1100	1700
Organic matter content (%)	2	1	1
Soil depth (h in mm)	500	300	300
$CaCO_3$ (ppt)	100	200	10
% stones	10	50	0

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Table 3: Grape growing operations for the five plots under study. The type of equipment and names of inputs are known for each operation but not reported here.

Case ID	P103-06	P22-06	P80-06	P80-04	P80-08
Soil type	A	C	B	B	B
Year	2006	2006	2006	2004	2008
Yield	4435 kg/ha	8910 kg/ha	5060 kg/ha	5640 kg/ha	1027 kg/ha
Pesticide Spraying[a,b]	7 runs, various dose (15 sprays)	8 runs*, various dose (18 sprays)	7 runs, various dose (17 sprays)	5 runs, various dose (14 sprays)	8 runs*, various dose (14 sprays)
Fertiliser Spreading[a]	700 kg/ha	1000 kg/ha	907 kg/ha	907 kg/ha.	907 kg/ha
Tillage	5 runs	4 runs	4 runs	3 runs	2 runs
Canopy operations	Binding , pruning	Pre-pruning, trellising, trimming pruning	Shoot crushing, pruning	Trellising and pruning	Bud removal trimming, pruning

[a] The name of inputs are known for each operation but not reported here;

[b] one pesticide run can use between 1–4 pesticides, giving the total number of sprayings

* Means “including weeding”

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Table 4: Diesel consumption (L/h) for various viticultural operations, including sensitivity to forward speed and to a lower engine speed

Vehicle tool	Speed (km/h)	Fuel consumption (L/h)	Sensitivity to lower engine speed (economic drive)	Sensitivity to speed (for + 1km/h)	Ref
Disc harrow	5	12.3	−17%	+18%	a
Surface harrow*	5	9.5			a
Inter-vine rotatory	2.5	15	−27%		a
Mowing	5	14	−35%	+4%	a
Shoot shredder	4	8.3	−25%	−12%	a
Sprayer	6	14.4	−30%		a
Grape harvester	3.5	43		+50%	b
Vine topping	6	15.2		+25%	b
Pre-pruning	5	22.7			b
Vine lifting	4	15			b
Farm – plot drive	30	18–27			c

* surface harrowing (for deep harrowing, increase fuel consumption by +50%)

[a] (Gaviglio *et al.*, 2009); [b] IFVV (French institute of wine and vine) and equipment manufacturers; [c] IRSTEA

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Table 5: Data required to compile LCI in viticulture; 3rd column relates to "traced data" (X where data is already traced); 4th column relates to pieces of information that must be linked to each name in the name lists which is; columns 5th to 8th refer to the prominence of this piece of data for computing emissions of this operation (1 = very important, 2 = secondary); all data marked * are structural data.

Key	Primary data	Traceaibility	Linked information	Equipment	Irrigation	Fertilisation	Pesticide
OPERATION DATA							
No	Name of operation*	X	Equipment (Nm) Input (Nf, Np, Ni)	1	1	1	1
Nm	Name of equipment*		Hourly consumption Sensitivity to Sp, Se and Sl Mitigation technologies	1			
T	Work duration			1	1		
Sp	*Speed*			*2*			
Se	*Engine speed (low / high)*			*2*			
Np	Name of pesticide*	X	Active ingredient K'h & Kv				1 1
Nf	Name of fertiliser*	X	N-P-K content % organic N Coefficient of volatilisation Coefficient of mineralisation			1 1 1 1	
Ni	Name of water source		Groundwater or surface water				
Q	Applied quantity	X			1	1	1

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D	Application date	X				1	1
WEATHER DATA							
P	Daily precipitation					1	2
T	Temperature					1	
PLOT DATA							
IR	Interrow distance*			1			
De	Nb of stocks per ha*	X		1			
Sd	Soil data*		Texture Organic matter content CaCO3 content			1 1 1	
Di	Plot-farm distance*			1			
Sl	*Soil hard to handle*: slope, stones… (Yes/No)*			*2*			
Wd	Water Table depth*				1		

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Table 6: Comparison of the values obtained for three midpoint impact categories for our case study (5 samples) and Vázquez-Rowe *et al.* (2012) data (30 samples).

	Acidification Potential (g SO_2 eq)		Global Warming Potential (g CO_2 eq)		Eutrophication Potential (g PO_4^{2-} eq)	
	Vazquez-Rowe *et al*	Our case study	Vazquez-Rowe *et al*	Our case study	Vazquez-Rowe *et al*	Our case study
Mean	4.2	2.4	462	461	1.5	0.9
Lowest	1.2	0.7	160	156	0.3	0.4
Highest	8.6	7.4	910	1392	8.0	2.3

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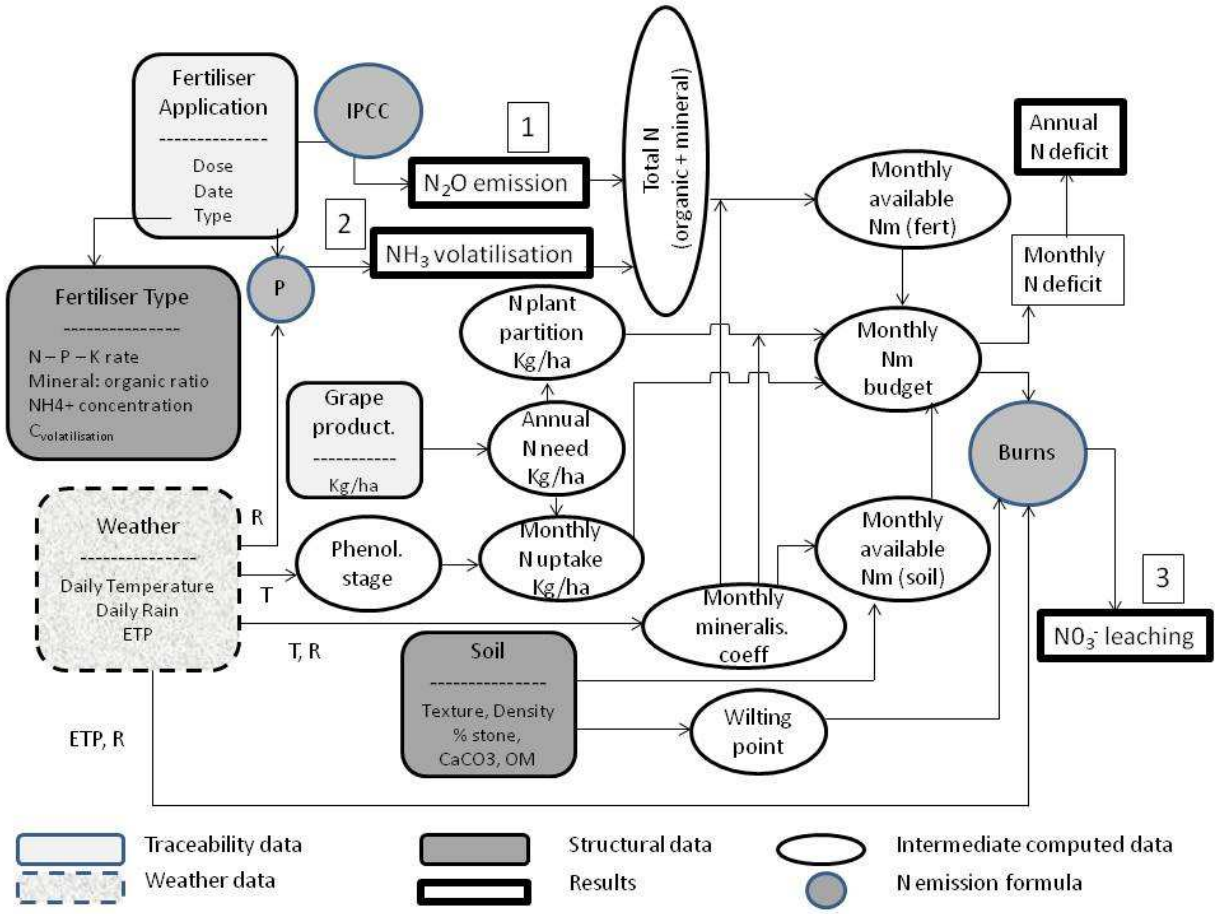

Figure 1: Conceptual framework showing how field N emissions are computed based on traceability, weather and structural data. Figure numbers 1–3 show the order of computation in the algorithm. P stands for PestLCI formula, R for Rainfall, T for temperature, ETP for evapotranspiration, OM for organic matter.

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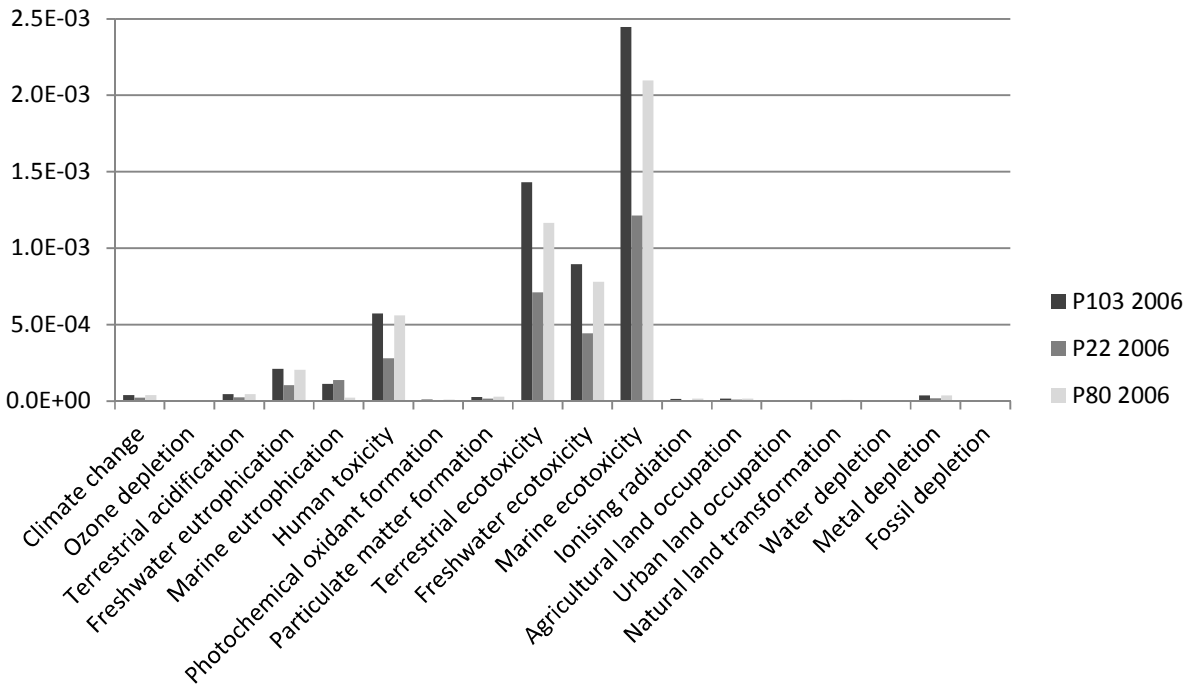

Figure 2: Normalisation of LCA outputs for 1 kg Syrah grape production grown in three different plots on the same year (ReCiPe Midpoint (H) V1.07 / World ReCiPe H)

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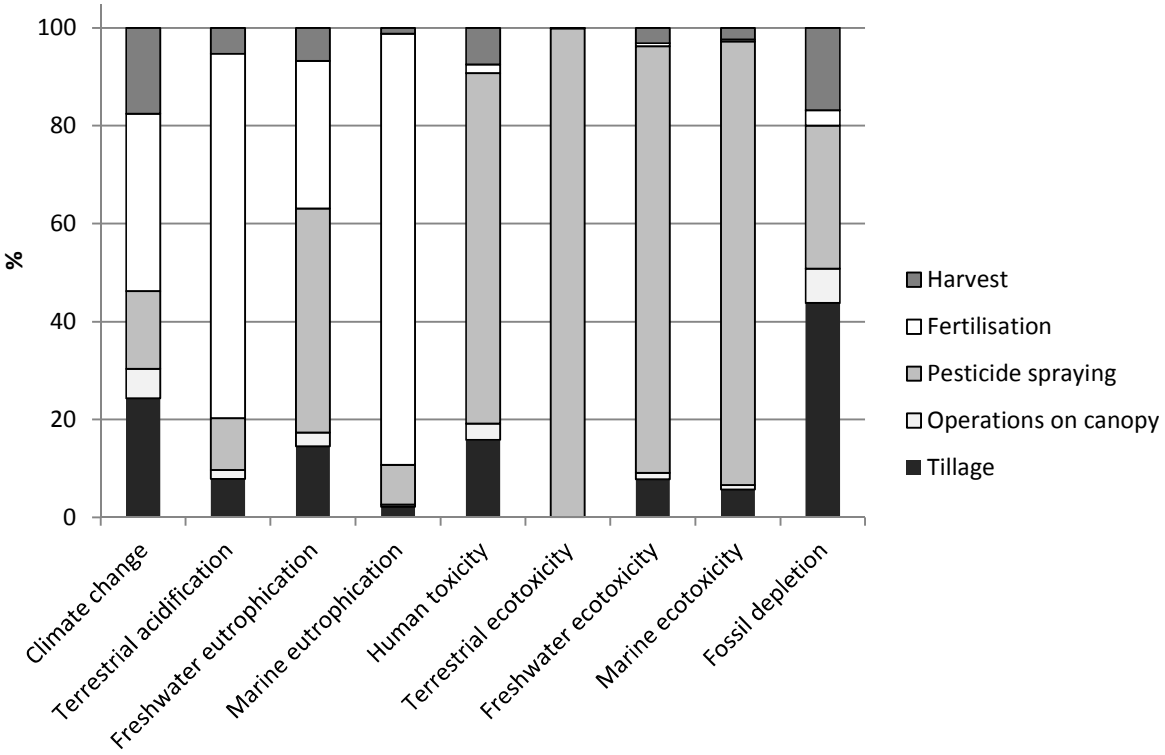

Figure 3: Contributions of the various viticultural operations to LCIA of grape production (Plot P 80 2006; FU = 1 kg grape production; ReCiPe Midpoint (H) V1.07 / World ReCiPe H)

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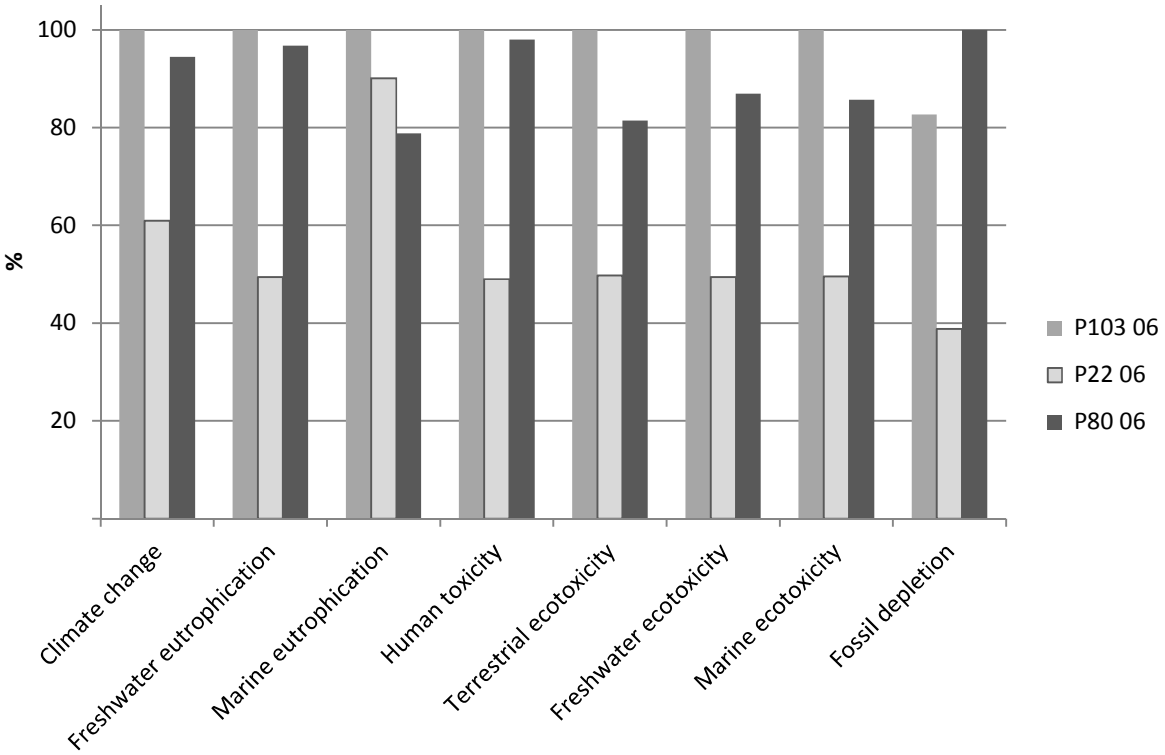

Figure 4: LCIA of the production of 1 kg grape of the same variety (Syrah), on the same year (2006), in three different plots having different soils of the same farm in South of France; P103 2006, P22 2006 and P80 2006 (characterisation by ReCiPe Midpoint (H) V1.07 / World ReCiPe H).

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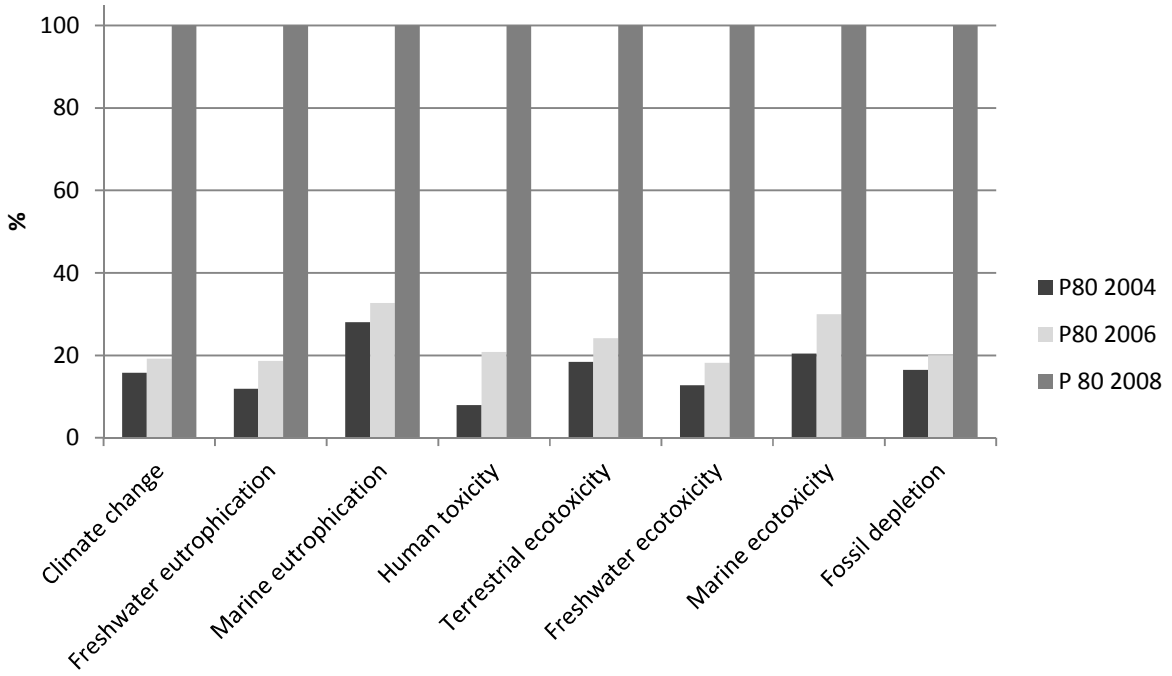

Figure 5: LCIA of the production of 1 kg grape of the same variety (Syrah), on the same plot (P 80) and on three different years (2004, 2006, 2008) in South of France (characterisation by ReCiPe Midpoint (H) V1.07 / World ReCiPe H).

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Supplementary data S1: Step-by-step procedure for computing nitrogen losses

Step 1: Volatilisation

The potential volatilisable N is computed as

$N_{vol} = N_{NH4+} \times Cv$

where N_{NH4+} is the amount of NH_4^+ in the fertiliser input, *Cv* is the volatilisation coefficient.

But if rain falls, it is assumed that NH_4^+ infiltrates and therefore is no longer available for volatilization. Therefore, we consider N_{NH4+} has a half-life of 12 hours, and this process may be stopped by rain. Therefore

$N_{NH4+} = N_{NH4+_tot} \cdot (1- e^{-\lambda.t})$

With λ is the half-life (λ= 0,5 days) and t is the number of days with no rain (> 20 mm) after spreading.

$N_{remain1} = N_{tot} - N_{vol}$

Step 2: Denitrification

The assumptions contained in the IPCC protocol (2006) are used, once volatilized N has been removed:

$N_{denit} = 1\% \cdot N_{remains1}$

$N_{remains2} = N_{remains1} - N_{denit} = 99\% \, N_{remains1}$

Step 3: N leaching

Leaching is treated in two separate ways depending on whether the N sources are organic or mineral. Organic N must first be turned into mineral N. This deals with N from organic fertiliser, from soil and from vegetal organs (for instance leaves or shoots of year n-1).

Sub-step 1: Monthly mineralized nitrogen

We make the assumption that mineralization of organic fertilisers and vegetal organs follow soil mineralization monthly kinetics (but with different levels).

First step is to compute the maximum potential mineralized N for each source of organic N.

For fertilisers, it depends on the fertiliser type and this amount is part “f” the fertiliser database;

For vegetal organs, the potentially mineralized N is the amount of plant material which is not humificated; the humification coefficient k1 depends on the type of organ (k1 varies from 0,1 for mown grass to 0,25 for pruning residues). In order to know the total amount of potential mineralizable N in a year, i.e. the total

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amount of leaves, shoots, the grape production of year (n-1) must be know as well as the way the plot is cultivated (covered crops with mown grass, shoots removed or left on the soil…);

For soil, the maximum mineralized N is provided by the annual mineralization rate K_{2pot}, which is given by the following formula (Machet et al, 1990)

K_{2pot} = 1200 x [(0,2 . T_{moy}) - 1] / [(clay + 200) x (0,3 . CaCO3 + 200)]

Where T_{moy} is the annual mean temperature once the base Temperature (T_{base}) has been subtracted (T_{base} = 10°C for soil microorganisms); clay is the amount of clay in per thousand, $CaCO_3$ is the amount of calcium carbonate in parts per thousand.

Monthly, the mineralization also depends on the soil moisture, f(t,H): experts describe f(t,H) as a bell-type curve with a maximum at moisture just below field capacity. It is zero for moisture below wilting point or beyond field saturation.

Therefore for organic sources of N

$N_{min}(t) = K_{2pot} * N_{remains2(organic)} * f(t,H)$

This rule is used to compute a monthly mineralization rate of soil N.

The same f(t,H) function is applied to fertilisers potential mineralized N and for vegetal organs.

At the end of this step, the monthly available mineralized N is known

<u>Sub-step2: Monthly plant N needs.</u>

The total N need is given by the grape production rate. Needed N is computed from the grape production. For 9-10 T of grapes (/ha), from 45 to 80 kg N are uptaken by the whole plant (Biala, 2000; Guilbaut, 2006).

Monthly uptake is computed based on expert knowledge giving the general profile of uptake by vines during the year (Gary, 2007), according to the phenological stages.

In our calculator, the phonologic stages are computed from the degree days, calculated from weather data.

At the end of this step the monthly N uptakes by the plant are known.

<u>Sub-Step 3: Monthly mineralized nitrogen balance</u>

The monthly balance of mineralized N is computed, by removing N uptake (sub-step 2) from mineral, ie available, N (sub-step 1).

If there is a N excess, it is likely to leached (provided that the conditions are favorable to leaching);

If there is a N deficit, it is accounted for.

<u>Sub-Step 4 : Leaching computation</u>

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Leaching for each day (t) is computed from in excess N, by using the Burns formula (Burns, 1975):

$$f(t) = \left(\frac{P(t) - ETP(t)}{P(t) - ETP(t) + (V_m / 100)} \right)^h$$

where, for a given period of time *t*, *f(t)* is the fraction of surface-applied nitrate leached below any depth *h* (cm), *P(t)* is the quantity of water brought by rain and irrigation (cm), ETP is the amount of water lost by ETP (cm) and V_m is the percentage volumetric field capacity.

V_m is computed from the knowledge of soil texture.

P and ETP are known from weather data

Total leaching is the sum of the amount of N leached each day.

Conclusion

Finally, necessary data for N emission computation are:

= The amount of fertiliser spread;

= The date(s) of spreading;

= The type of fertiliser and associated data (see Figure 1, in the manuscript text);

= Weather data;

= Soil data;

= Grape production (year n and n-1).

This process has been implemented on an EXCEL spreadsheet, which makes it easy to use. A graphical depiction of the input/output spreadsheet is given in Figure S1. For other emissions types, the same type of procedure for making simple but relevant and timely models has been carried out.

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Full Amount of Fertiliser (Ton/ ha)	Month of Appli.	Incorporation in the soil? (first 24h)	N_ORGA (n-1)	N_ORGA (n-2)	Rain during the first 7 days ? Which day?
0,7	September	Non	3,26	2,80	0
Name of the fertilizer	**Type of soil / Limestone**	**O.M. in the Soil (%)**	**$CaCO_3$ (in parts per thousand)**	**Soil Horiz with O.M. (in cm)**	**Average annual temperature (°C)**
Orga 3	No limestone	2%	100	20	15
Mineral Fertiliser with controlled liberation?	**Soil depth (in mm)**	**Soil bulk density (in Kg/m3)**	**Amount of Clay (in parts per thousand)**	**C/N of O.M. in the soil**	**% of stones**
Yes	500	1200	500	10	10
	Type of Soil?	**Soil wilting point**	**Year of Appli.**	**Bud burst date**	**Production (Ton/ha)**
	CLAYEY-SILTY	30	2006	05/03/2006	9

RESULT	VOLATILISED N Kg N-NH3	DENITRIFIED N Kg N-N20	LEACHED N Kg N-NO3-	N ABSORBED BY PLANTS (Kg-N)	N DEFICIT (Kg-N)
	1,71	**1,13**	**14,68**	**49,20**	**1,20**

	Traceability data		Data chosen from a list (database)
	Structural data		Computed data

Figure S.1: Spreadsheet built up for computing N emission from traceability (in light grey), structural (medium grey) and weather data (dark grey). Hashed boxes show data which are chosen in a list (ex: list of soil texture, list of fertilisers), and which are related to a database of the properties. Dotted boxes are obtained from computation. Note that daily weather data used for computation are linked from another file.

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Supplementary data S2: LCI data

P80 2004

Equipment

Soil management

	Fuel consumption L/ha	Hours/ha
In-row superficial tillage	38.00	4.00
Intercep tillage/ mechanical weeding	0	
tillage	0	
stone crushing	0	

Fertilisation

	Fuel consumption L/ha	Hours/ha
fertilisation	3.20	0.36

Pesticide Spraying

	Fuel consumption L/ha	Hours/ha
Pesticide/Foliar fertiliser spraying	32.09	2.22
Chemical weeding	0	

Canopy management

	Fuel consumption L/ha	Hours/ha
pre-pruning	0	
trimming		
vine lifting	35.55	1.78
disbudding/ desuckering	0	
Shoot crushing	0	0

Harvest

	Fuel consumption L/ha	Hours/ha
Harvest	71.11	1.78
Transport	2.03	0.04

Total fuel (L/ha)	181.75

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Phytosanitary products

Insecticides/ Fungicides -		Emissions to AIR	Emissions to WATER
molecules	quantity (g/ha)	quantity (g/ha)	quantity (g/ha)
folpel	3200	1700.03	1499.97
Fosétyl Aluminium	2000	887.38	1112.62
dinocap	97.5	49.50	48.00
myclobutanil	22.5	10.61	11.89
Bifenthrine	20	10.15	9.85
Tébufenpyrad	50	25.38	24.62
azoxystrobine	187	82.97	104.03
Bore (B)	79.8	37.64	42.16
Molybdène(Mo)	0.9	0.42	0.48
Flufénoxuron	40	17.25	22.75
Tebuconazole	100	49.21	50.79
Diméthomorphe	226	111.22	114.78
Lambda cyhalothrine	13	7.42	5.58
sulphur	70000	33834.65	36165.35

Emissions from Herbicides	
quantity (g/ha) in AIR	quantity (g/ha) in SOL
0	0

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Fertilisation

Fertiliser -	kg/ha
Compost (orga 3)	907

P / K emissions to water	
	(Kg/ha)
P2O5	0.2640
K	0

Nitrogenous emissions

N_volat	1.95	Kg N_NH3	AIR
N_Denit	0.32	Kg N_N2O	AIR
N_Leach	1.77	Kg N_NO3-	WATER

Grape production

Yield (Kg/ plot)	2443
Yield (Ton/ ha)	5.64

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P80 2006

Equipment

Soil management

	Fuel consumption L/ha	Hours/ha
In-row superficial tillage	38.00	4.00
Intercep tillage/ mechanical weeding	40.00	2.67
tillage	0.00	0.00
stone crushing	0.00	0.00

Canopy management

	Fuel consumption L/ha	Hours/ha
pre-pruning	0.00	0.00
trimming	24.24	2.13
vine lifting	0.00	0.00
disbudding/ desuckering	0.00	0.00
Shoot crusching	12.44	1.33

Fertilisation

	Fuel consumption L/ha	Hours/ha
fertilisation	3.20	0.36

Harvest

	Fuel consumption L/ha	Hours/ha
Harvest	71.11	1.78
Transport	1.82	0.04

Pesticide Spraying

	Fuel consumption L/ha	Hours/ha
Pesticide/Foliar fertiliser spraying	44.92	3.11
Chemical weeding	0.00	0.00

Total fuel consumption (L/ha)	235.71

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Phytosanitary products

Emissions from Insecticides/ Fungicides

molecules	quantity (g/ha)	Emissions to AIR (g/ha)	Emissions to WATER (g/ha)
Bifenthrine (g/L)	20	10.15	9.85
Tébufenpyrad (g/L)	50	25.38	24.62
dinocap (g/L)	97.5	49.50	48.00
myclobutanil (g/L)	22.5	10.61	11.89
folpel (g/kg)	3250	2292.48	1857.52
Fosétyl Aluminium (g/kg)	1200	532.4	667.57
Bore (B) : 26.6 g/L	159.6	76.91	82.69
Molybdène (Mo) : 0.30 g/L	1.8	0.87	0.93
Tebuconazole (g/L)	100	49.2	50.79
Diméthomorphe (11.3%)	226	111.2	114.78
azoxystrobine (g/L)	187	80.6	106.37
indoxacarbe (30% ou 150g/L)	37.5	18.5	19.05
Lambda cyhalothrine (g/L)	12.5	7.13	5.37
Sulphur	43050	6569.9	6780.1
Copper from copper sulfide (15%)	450	221.4	228.5
Copper from copper hydroxyde (g/L)	1548	761.8	786.2

Emissions from Herbicides

	quantity (g/ha) in AIR	quantity (g/ha) in SOL
glyphozate (g/L)	0	0
sulfate d'ammonium (g/L)	0	0

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Fertilisation

Fertiliser -	kg/ha
Compost (orga 3)	907

P / K emissions to water	
	(Kg/ha)
P2O5	0.26
K	0

Nitrogenous emissions

N_volat	1.95	Kg N_NH3	AIR
N_Denit	0.32	Kg N_N2O	AIR
N_Lessiv	2.07	Kg N_NO3-	WATER

Grape production

Yield (Kg/ plot)	2193
Yield (Ton/ ha)	5.06

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P 80 2008

Equipment

Soil management

	Fuel consumption L/ha	Hours/ha
In-row superficial tillage	25.33	2.67
Intercep tillage/ mechanical weeding	0.00	0.00
tillage	0.00	0.00
stone crushing	0.00	0.00

Canopy management

	Fuel consumption L/ha	Hours/ha
pre-pruning	0.00	0.00
trimming	12.12	1.07
vine lifting	0.00	0.00
disbudding/ desuckering	24.00	2.67
Shoot crusching	0.00	0.00

Fertilisation

	Fuel consumption L/ha	Hours/ha
fertilisation	0.00	0.00

Harvest

	Fuel consumption L/ha	Hours/ha
Harvest	71.11	1.78
Transport	0.37	0.04

Pesticide Spraying

	Fuel consumption L/ha	Hours/ha
Pesticide/Foliar fertiliser spraying	44.92	3.11
Chemical weeding	6.00	0.67

total fuel consumption (L/ha)	185.29

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Phytosanitary products

Insecticides/fungicides

molecules	quantity (g/ha)	quantity (g/ha) in AIR	quantity (g/ha) in SOL
Tebuconazole (g/L)	200	94.33	105.67
fosétyl aluminium (g/kg)	1884	835.91	1048.09
métirame zinc (g/kg)	1320	670.10	649.90
Folpel (60%)	2200	1116.83	1083.17
Diméthomorphe (11.3%)	226	106.59	119.41
ferchélate (13%)	91	42.92	48.08
Bifenthrine (g/L)	20	10.15	9.85
Tébufenpyrad (g/L)	50	25.38	24.62
azoxystrobine (g/L)	187	82.97	104.03
sulphur (g/L)	45150	22219.7	22930.31
Copper from copper hydroxyde (g/L)	1548	761.82	786.18
indoxacarbe (30% ou 150g/L)	37.5	18.45	19.05

Herbicides

	quantity (g/ha) in SOIL	quantity (g/ha) in AIR
glyphozate (g/L)	2000	0
sulfate d'ammonium (g/L)	2300	0

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Fertilisation

Fertiliser -	kg/ha
Compost (orga 3)	907

P / K emissions to water	
	(Kg/ha)
P2O5	0.26
K	0

Nitrogenous emissions

N_volat	1.95	Kg N_NH3	AIR
N_Denit	0.32	Kg N_N2O	AIR
N_Lessiv	0.26	Kg N_NO3-	WATER

Grape production

Yield (Kg/ plot)	445
Yield (Ton/ ha)	1.027

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P 22 2006

Equipment

Soil management

	Fuel consumption L/ha	Hours/ha
In-row superficial tillage	15.20	1.60
Intercep tillage/ mechanical weeding	0.00	0.00
Tillage	13.98	0.96
stone crushing	0.00	0.00

Canopy management

	Fuel consumption L/ha	Hours/ha
pre-pruning	21.82	0.96
trimming	26.18	1.37
vine lifting	10.47	0.96
disbudding/ desuckering	0.00	0.00
Shoot crusching	0.00	0.00

Fertilisation

	Fuel consumption L/ha	Hours/ha
fertilisation	2.40	0.27

Harvest

	Fuel consumption L/ha	Hours/ha
Harvest	38.40	0.96
Transport	*1.34*	0.02

Pesticide Spraying

	Fuel consumption L/ha	Hours/ha
Pesticide/Foliar fertiliser spraying	26.95	1.87
Chemical weeding	4.32	0.48

total fuel consumption (L /ha)	160.47

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Phytosanitary products

Insecticides/ fungicides

molecules	quantity (g/ha)	quantity (g/ha) in AIR	quantity (g/ha) in SOIL
Bifenthrine (g/L)	20	10.15	9.85
Tébufenpyrad (g/L)	50	25.38	24.62
dinocap (g/L)	97.5	49.50	48.00
myclobutanil (g/L)	22.5	10.61	11.89
folpel (g/kg)	4150	2153.97	1996.03
Fosétyl Aluminium (g/kg)	1200	532.43	667.57
Crème d'algues GA 14	0	0.00	0.00
Bore (B) : 26.6 g/L	79.8	37.64	42.16
Molybdène (Mo) : 0.30 g/L	0.9	0.42	0.48
Tebuconazole (g/L)	100	47.16	52.84
Diméthomorphe (11.3%)	226	106.59	119.41
azoxystrobine (g/L)	187	82.97	104.03
sulphur	43350	20719.37	22630.63
Flufénoxuron (g/L)	40	17.25	22.75
Lambda cyhalothrine (g/L)	12.5	7.13	5.37
Copper from copper sulphate (15%)	450	221.46	228.54
Copper from copper hydroxyde (g/L)	1548	761.82	786.18
indoxacarbe (30% ou 150g/L)	37.5	18.45	19.05

Herbicides

molecules	quantity (g/ha) in SOIL	quantity (g/ha) in AIR
flumioxazine (50%)	200	0
glyphosate (g/L)	1796.625	0

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Fertilisation

Fertiliser -	kg/ha
Compost (orga 3)	1000

P / K emissions to water	
	(Kg/ha)
P2O5	0.266
K	0

Nitrogenous emissions

N_volat	2.05	Kg N_NH3	AIR
N_Denit	0.35	Kg N_N2O	AIR
N_Lessiv	37.3	Kg N_NO3-	WATER

Grape production

Yield (Kg/ plot)	11635
Yield (Ton/ ha)	8.91

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P103 2006

Equipment

Soil management

	Fuel consumption L/ha	Hours/ha
In-row superficial tillage	16.89	1.78
Intercep tillage/ mechanical weeding	40.00	2.67
tillage	15.53	1.07
stone crushing	0.00	0.00

Canopy management

	Fuel consumption L/ha	Hours/ha
pre-pruning	0.00	0.00
trimming	0.00	0.00
vine lifting	11.64	1.07
disbudding/ desuckering	0.00	0.00
Shoot crusching	0.00	0.00

Fertilisation

	Fuel consumption L/ha	Hours/ha
Fertilisation	2.67	0.30

Harvest

	Fuel consumption L/ha	Hours/ha
Harvest	42.67	1.07
transport	4.32	0.108

Pesticide Spraying

	Fuel consumption L/ha	Hours/ha
Pesticide/Foliar fertiliser spraying	29.95	2.07
Chemical weeding	0.00	0.00

Total fuel consumption (L/ha)	164.21

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Phytosanitary products

Insecticides / fungicides

molecules	quantity (g/ha)	quantity (g/ha) in AIR	quantity (g/ha) in SOiL
Bifenthrine (g/L)	20	10.15	9.8
Tébufenpyrad (g/L)	50	25.38	24.6
dinocap (g/L)	97.5	49.50	48
myclobutanil (g/L)	22.5	10.61	11.89
folpel (g/kg)	4150	2153.97	590.8
Fosétyl Aluminium (g/kg)	1200	532.4 3	667.6
Crème d'algues GA 14	0	0.00	0
Bore (B) : 26.6 g/L	79.8	37.64	42.16
Molybdène (Mo) : 0.30 g/L	0.9	0.42	0.47
Tebuconazole (g/L)	100	47.16	52.83
Diméthomorphe (11.3%)	226	106.59	119.41
azoxystrobine (g/L)	187	82.97	104.03
sulphur	43350	21333.8	22016.14
Flufénoxuron (g/L)	40	17.25	22.75
Lambda cyhalothrine (g/L)	12.5	7.13	5.36
Copper from copper sulphate (15%)	450	221.46	228.54
Copper from copper hydroxyde (g/L)	1548	761.82	786.18
indoxacarbe (30% ou 150g/L)	37.5	18.45	19.04

Herbicides

	quantity (g/ha) in AIR	quantity (g/ha) in SOIL
glyphozate (g/L)	0	0
sulfate d'ammonium (g/L)	0	0

Fertilisation

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Fertiliser -	
700	kg/ha
700	kg/ha

P / K Emissions to water	
	(Kg/ha)
P2O5	0.25
K	0

Nitrogenous emissions

N_volat	1.71	Kg N_NH3	AIR
N_Denit	0.26	Kg N_N2O	AIR
N_Lessiv	14.68	Kg N_NO3-	WATER

Grape production

Yield (Kg/ plot)	890.5
Yield (Ton/ ha)	4.435

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Supplementary data S3: LCIA by work type for the 5 plots under study

SimaPro 7.3	Impact assessment
Calculation:	Analyse
Results:	Impact assessment
Product:	1 kg grape
Method:	Recipe Midpoint (H) V1.07 / World ReCiPe H
Indicator:	Characterisation
Unit:	%
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

P80 2004

Yield (Kg/ha) = 5640

Impact category	Unit	Total	Soil Management	Canopy management	Phytosanitary treatments	Fertlization	Harvest
Climate change	kg CO2 eq	0.224070888	0.028369835	0.021469066	0.034202789	0.097022311	0.043006887
Ozone depletion	kg CFC-11 eq	1.9051E-08	3.23865E-09	2.65995E-09	6.92825E-09	9.447E-10	5.27946E-09
Terrestrial acidification	kg SO2 eq	0.001627796	6.41357E-05	4.29058E-05	0.000145187	0.001291173	8.43952E-05
Freshwater eutrophication	kg P eq	3.79788E-05	4.94444E-06	2.10695E-06	1.0855E-05	1.64689E-05	3.60357E-06
Marine eutrophication	kg N eq	0.000143752	1.91358E-06	9.59012E-07	1.41978E-05	0.000124863	1.81814E-06
Human toxicity	kg 1,4-DB eq	0.025190793	0.00574444	0.002805553	0.01095308	0.001258358	0.004429363
Photochemical oxidant formation	kg NMVOC	0.000396297	6.17824E-05	3.29292E-05	0.000125642	0.000115849	6.00943E-05
Particulate matter formation	kg PM10 eq	0.000355768	3.93752E-05	2.28253E-05	6.27384E-05	0.000185728	4.51018E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	0.005763303	2.57761E-06	1.99543E-06	0.005754029	7.38054E-07	3.96328E-06
Freshwater ecotoxicity	kg 1,4-DB eq	0.002370839	0.00016192	5.46911E-05	0.00203672	2.36721E-05	9.38366E-05
Marine ecotoxicity	kg 1,4-DB eq	0.003442656	0.000174301	6.19956E-05	0.003074578	2.48978E-05	0.000106883
Ionising radiation	kg U235 eq	0.016303126	0.003962422	0.001568389	0.005982633	0.002054328	0.002735354
Agricultural land occupation	m2a	0.115611006	0.000186315	7.52604E-05	0.114145821	0.001081985	0.000121625
Urban land occupation	m2a	0.002347859	9.16275E-05	4.81757E-05	0.002019063	9.59948E-05	9.29982E-05
Natural land transformation	m2	6.91843E-05	1.18194E-05	1.01296E-05	2.48775E-05	1.99015E-06	2.03677E-05
Water depletion	m3	0.000931439	8.93688E-05	4.26448E-05	0.000652735	6.77593E-05	7.89314E-05
Metal depletion	kg Fe eq	0.005060247	0.002400844	0.000632292	0.000995097	0.000187449	0.000844564
Fossil depletion	kg oil eq	6.01384E-05	2.07508E-05	5.9366E-06	1.98945E-05	2.49415E-06	1.10623E-05

P80 2006

Yield (Kg/ha) = 5060

Impact category	Unit	Total	Soil Management P80 2006	Canopy management P80 2006	Phytosanitary treatments P80 2006	Fertlization P80 2006	Harvest P80 2006
Climate change	kg CO2 eq	0.272254075	0.066250761	0.016466574	0.04315397	0.098580498	0.047802272
Ozone depletion	kg CFC-11 eq	2.51591E-08	7.89978E-09	2.02709E-09	8.48854E-09	8.75546E-10	5.8681E-09
Terrestrial acidification	kg SO2 eq	0.001781448	0.000139574	3.30666E-05	0.000187745	0.001327253	9.38083E-05
Freshwater eutrophication	kg P eq	5.92685E-05	8.60016E-06	1.67252E-06	2.71146E-05	1.78751E-05	4.00613E-06
Marine eutrophication	kg N eq	0.000167514	3.61086E-06	7.56963E-07	1.35975E-05	0.000147527	2.02107E-06
Human toxicity	kg 1,4-DB eq	0.065929383	0.010455565	0.002170144	0.047219515	0.00115998	0.004924178
Photochemical oxidant formation	kg NMVOC	0.000442786	0.000119715	2.57677E-05	0.000129993	0.00010051	6.68003E-05
Particulate matter formation	kg PM10 eq	0.000416802	8.02406E-05	1.78503E-05	8.00955E-05	0.000188483	5.01326E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	0.00756982	6.08165E-06	1.5249E-06	0.007557126	6.82443E-07	4.4052E-06
Freshwater ecotoxicity	kg 1,4-DB eq	0.003372037	0.000262073	4.41022E-05	0.002939653	2.18921E-05	0.000104317
Marine ecotoxicity	kg 1,4-DB eq	0.005068615	0.000287153	4.97006E-05	0.004589812	2.31309E-05	0.000118819
Ionising radiation	kg U235 eq	0.019025368	0.006726903	0.001261637	0.006184347	0.001811539	0.003040941
Agricultural land occupation	m2a	0.079823235	0.000316696	6.02488E-05	0.078378154	0.00093292	0.000135216
Urban land occupation	m2a	0.001887446	0.000177963	3.78798E-05	0.001484427	8.38031E-05	0.000103374
Natural land transformation	m2	8.76117E-05	2.96302E-05	7.71261E-06	2.56818E-05	1.94868E-06	2.26383E-05
Water depletion	m3	0.000861356	0.000165459	3.38909E-05	0.000514851	5.94144E-05	8.77409E-05
Metal depletion	kg Fe eq	0.01682017	0.003579957	0.000516575	0.01160464	0.000180014	0.000938984
Fossil depletion	kg oil eq	7.31617E-05	3.20604E-05	5.09592E-06	2.13847E-05	2.32228E-06	1.22984E-05
Urban land occupation	m2a	0.000997084	3.59499E-05	4.92839E-05	0.000832998	4.68301E-05	3.20216E-05
Natural land transformation	m2	3.53861E-05	5.50884E-06	1.04878E-05	1.14239E-05	9.59426E-07	7.00609E-06
Water depletion	m3	0.000417969	3.41027E-05	4.32818E-05	0.000280352	3.30415E-05	2.71918E-05
Metal depletion	kg Fe eq	0.008189322	0.000783506	0.000621571	0.00640209	9.0558E-05	0.000291596
Fossil depletion	kg oil eq	2.83892E-05	7.14313E-06	5.99729E-06	1.02229E-05	1.20889E-06	3.81698E-06

P 80 2008

Yield (Kg/ha) = 1027

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Impact category	Unit	Total	Soil Management P80 2008	Canopy management P80 2008	Phytosanitary treatments P 80 2008	Fertlization P 80 2008	Harvest P 80 2008
Climate change	kg CO2 eq	0.888759397	0.103895972	0.169013888	0.286280578	0.098678992	0.230889967
Ozone depletion	kg CFC-11 eq	2.094E-07	1.18594E-08	2.09232E-08	1.43087E-07	5.18803E-09	2.8342E-08
Terrestrial acidification	kg SO2 eq	0.009448158	0.000234929	0.000331259	0.001338003	0.007090764	0.000453202
Freshwater eutrophication	kg P eq	0.000318459	1.81223E-05	1.47985E-05	0.000175719	9.04425E-05	1.93762E-05
Marine eutrophication	kg N eq	0.000512603	7.01193E-06	7.16097E-06	0.000141116	0.000347545	9.76886E-06
Human toxicity	kg 1,4-DB eq	0.316484692	0.02105429	0.019282664	0.24542075	0.006910554	0.023816434
Photochemical oxidant formation	kg NMVOC	0.002290212	0.000226378	0.00024626	0.000858528	0.000636209	0.000322837
Particulate matter formation	kg PM10 eq	0.002102892	0.000144247	0.000177284	0.000519186	0.001019966	0.000242208
Terrestrial ecotoxicity	kg 1,4-DB eq	0.031373324	9.43961E-06	1.56432E-05	0.031322911	4.05319E-06	2.12777E-05
Freshwater ecotoxicity	kg 1,4-DB eq	0.018599436	0.000593468	0.000393301	0.016978196	0.000130001	0.000504469
Marine ecotoxicity	kg 1,4-DB eq	0.016878966	0.000638832	0.000447795	0.015081064	0.000136732	0.000574543
Ionising radiation	kg U235 eq	0.104306669	0.014523252	0.011098782	0.052694431	0.011281804	0.0147084
Agricultural land occupation	m2a	0.413890215	0.00068292	0.000521302	0.406089903	0.005941961	0.00065413
Urban land occupation	m2a	0.009796567	0.00033571	0.000369062	0.008065105	0.000527177	0.000499512
Natural land transformation	m2	0.000392186	4.3276E-05	8.03845E-05	0.000148265	1.09294E-05	0.000109331
Water depletion	m3	0.004562148	0.000327482	0.000319432	0.003119029	0.000372115	0.000424089
Metal depletion	kg Fe eq	0.067431312	0.008800757	0.00431886	0.048738291	0.001029418	0.004543985
Fossil depletion	kg oil eq	0.000365045	7.60613E-05	4.34665E-05	0.000172326	1.36972E-05	5.94948E-05

P22 2006

Yield (Kg/ha) = 8910

Impact category	Unit	Total	Soil Management P22 2006	Canopy management P22 2006	Phytosanitary treatments P22 2006	Fertlization P22 2006	Harvest P22 2006
Climate change	kg CO2 eq	0.158786683	0.012594202	0.022167067	0.01777586	0.09145246	0.014797094
Ozone depletion	kg CFC-11 eq	1.05744E-08	1.47961E-09	2.74479E-09	4.07562E-09	4.58108E-10	1.8163E-09
Terrestrial acidification	kg SO2 eq	0.000974336	2.70888E-05	4.39823E-05	9.36243E-05	0.000780591	2.90489E-05
Freshwater eutrophication	kg P eq	3.02907E-05	1.80337E-06	2.08881E-06	1.48077E-05	1.0348E-05	1.24294E-06
Marine eutrophication	kg N eq	0.001004592	7.38044E-07	9.71896E-07	7.52487E-06	0.00099473	6.26367E-07
Human toxicity	kg 1,4-DB eq	0.032972157	0.002136712	0.002756755	0.025940373	0.000610548	0.001527769
Photochemical oxidant formation	kg NMVOC	0.000198774	2.41727E-05	3.33772E-05	6.39761E-05	5.65495E-05	2.0698E-05
Particulate matter formation	kg PM10 eq	0.000203568	1.59665E-05	2.34666E-05	3.83312E-05	0.000110278	1.55252E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	0.004626985	1.15012E-06	2.05667E-06	0.004622056	3.57986E-07	1.36363E-06
Freshwater ecotoxicity	kg 1,4-DB eq	0.001917931	5.59982E-05	5.47225E-05	0.001763371	1.14818E-05	3.23572E-05
Marine ecotoxicity	kg 1,4-DB eq	0.002928825	6.09284E-05	6.21127E-05	0.002756864	1.20706E-05	3.68493E-05
Ionising radiation	kg U235 eq	0.007988459	0.0014284	0.001560046	0.00305528	0.001001202	0.000943531
Agricultural land occupation	m2a	0.04551039	6.71785E-05	7.4275E-05	0.044798503	0.000528466	4.1967E-05
Urban land occupation	m2a	0.000997084	3.59499E-05	4.92839E-05	0.000832998	4.68301E-05	3.20216E-05
Natural land transformation	m2	3.53861E-05	5.50884E-06	1.04878E-05	1.14239E-05	9.59426E-07	7.00609E-06
Water depletion	m3	0.000417969	3.41027E-05	4.32818E-05	0.000280352	3.30415E-05	2.71918E-05
Metal depletion	kg Fe eq	0.008189322	0.000783506	0.000621571	0.00640209	9.0558E-05	0.000291596
Fossil depletion	kg oil eq	2.83892E-05	7.14313E-06	5.99729E-06	1.02229E-05	1.20889E-06	3.81698E-06

P 103 2006

Yield (Kg/ha) = 4435

Impact category	Unit	Total	Soil Management P103 2006	Canopy management P103 2006	Phytosanitary treatments P103 2006	Fertlization P 103 2006	Harvest P 103 2006
Climate change	kg CO2 eq	0.271972292	0.058038241	0.009971054	0.037981789	0.130862797	0.03511841
Ozone depletion	kg CFC-11 eq	2.19526E-08	7.00476E-09	1.22186E-09	8.46749E-09	9.46821E-10	4.31165E-09
Terrestrial acidification	kg SO2 eq	0.001782742	0.000118914	2.15495E-05	0.00019256	0.001380841	6.88773E-05
Freshwater eutrophication	kg P eq	6.12641E-05	6.59111E-06	1.44118E-06	2.99542E-05	2.03451E-05	2.9325E-06
Marine eutrophication	kg N eq	0.000837436	2.90493E-06	5.58021E-07	1.52162E-05	0.000817275	1.482E-06
Human toxicity	kg 1,4-DB eq	0.067259769	0.008087215	0.00193563	0.052373431	0.001258957	0.003604536
Photochemical oxidant formation	kg NMVOC	0.000410827	9.71811E-05	1.87835E-05	0.000131896	0.000113966	4.90005E-05
Particulate matter formation	kg PM10 eq	0.000392066	6.69992E-05	1.15764E-05	7.94285E-05	0.000197257	3.6805E-05
Terrestrial ecotoxicity	kg 1,4-DB eq	0.009296108	5.33389E-06	9.33646E-07	0.009285865	7.39209E-07	3.23627E-06
Freshwater ecotoxicity	kg 1,4-DB eq	0.003878225	0.00019367	3.63272E-05	0.003548131	2.37057E-05	7.63912E-05
Marine ecotoxicity	kg 1,4-DB eq	0.005911366	0.000214218	4.03677E-05	0.005544781	2.49659E-05	8.70333E-05
Ionising radiation	kg U235 eq	0.016744959	0.005118517	0.001076748	0.00629396	0.00202994	0.002225794
Agricultural land occupation	m2a	0.091463722	0.000240124	5.37318E-05	0.090008345	0.001062598	9.89238E-05
Urban land occupation	m2a	0.002020223	0.000145379	2.58141E-05	0.001678573	9.45965E-05	7.58607E-05
Natural land transformation	m2	7.37227E-05	2.65434E-05	4.49096E-06	2.40238E-05	2.02722E-06	1.66373E-05
Water depletion	m3	0.000856042	0.00013229	2.49007E-05	0.000567658	6.68525E-05	6.43412E-05
Metal depletion	kg Fe eq	0.016773623	0.00249561	0.000478339	0.012923581	0.000189751	0.000686342
Fossil depletion	kg oil eq	6.04769E-05	2.361E-05	4.1825E-06	2.11843E-05	2.50243E-06	8.99777E-06