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A fuel consumption model for off-road use of mobile machinery in agriculture

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ABSTRACT

Until 2009, the annual reporting of emissions by off-road transport in agriculture in Belgium was based on a 1994 calculation model that needed to be updated. An energy consumption model was established for plant production in Belgium as a backbone for a new emission model. The model starts from agricultural activities involving off-road fuel consumption. Effects of soil type, tractor size, field size and machine load are modelled. Twenty-seven FCIs (fuel consumption indicators) were computed for plant production. FCIs are expressed per year and are used for emission estimates on a regional level. FCIs ranged from 37 to 311 L/ha. Sensitivity analysis showed the highest impact of tractor size with a surplus fuel consumption between 10 and 41% depending on the crop type. Fuel consumption (L) can be further processed into greenhouse gas emissions. FCIs can be adopted in LCA (life cycle assessment) studies. With ~310 L/ha, orchards are most fuel intensive, followed by field vegetables and sugar beets (~150 L/ha). The total off-road energy consumption of field vegetables is high because second cropping is a common practice.

1. Introduction

Global warming and climate change in general are gaining increasing public attention. In contrast to 10 years ago, we are more aware of, and more concerned about, the environment and the rapid, intense changes it is undergoing. Burning fossil fuels releases greenhouse gases which cause global warming [15].

Over a decade ago, most countries joined an international environmental treaty – the UNFCCC (United Nations Framework Convention on Climate Change) – with the goal of achieving “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”; ([33], The Convention, article 2, 1994). In 1997, 37 industrialized countries approved an addition to the treaty: the Kyoto Protocol. That protocol, whose aim is to fight global warming, contains more powerful and legally binding measures. As an international political body, the European Commission has engaged itself to achieve the following goals by 2020: reduce GHG (greenhouse gas emissions), reduce energy consumption and increase energy efficiency by 20%, and increase the share of renewable energy to 20%. Each Member State has a separate commitment. As part of this EU Regulation, national governments are required to report their annual greenhouse gas emissions [9]. Along with the reports of emissions to the EU, Belgium also inventories its yearly national energy consumption per industrial sector per region. This data is published as ‘Energy Balance’ reports for Flanders, Wallonia and Brussels, the three Belgian regions, and include the energy consumption for agriculture and horticulture (e.g. Ref. [3]). Furthermore, detailed information about the fuel consumption in agriculture can be used as an important part of LCA (Life Cycle Assessment) and carbon footprint studies that involve animal and plant production and agricultural products.

These regional reports often contain subcategories such as “off-road transport”. This subcategory includes agricultural machinery and other off-road vehicles. The energy consumption and emissions for agriculture in the three Belgian regions for this subcategory were calculated from energy consumption indicators retrieved from literature and compiled by Hens [14]. In 2008, the Flemish government commissioned a study to update the model because agricultural machinery has changed substantially since 1996 in terms of engine and operational efficiency. For example, this

Abbreviations: LCA, life cycle assessment; FCI, fuel consumption indicator; $PFC_{F.O.}$, field operation-specific partial fuel consumption (L/ha); EC model, energy consumption model; FC, fuel consumption; CLC, Corine land cover; $SFC_{F.O.}$, field operation-specific fuel consumption (L/ha).

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increasing efficiency has resulted in fewer field runs. The energy savings and emissions reductions that result from the latest innovations required the 1996 model to be updated. Upon request of the Flemish government, in 2009 an emission model for mobile machinery during off-road use was established, called OFFREM (off-road emissions), that included data for each of the Belgian regions [31].

The 2009 OFFREM model includes exhaust and non-exhaust emissions for each of Belgium's three regions. The exhaust emissions are determined by the fuel type and the engine type, capacity, technology and age. Non-exhaust emissions resulting from the wearing of machine parts or the abrasion of the surface ridden upon are also measured. The core of this emission model is the fuel consumption data for agricultural equipment.

In general, models are not frequently used to assess fuel consumption and off-road emissions for emission inventory purposes. Most countries apply emission factors to the inventoried energy use. Denmark, like Belgium, does apply the Tier 3 methodology of the EMEP/EEA (European Monitoring and Evaluation Programme/ European Environment Agency) guidebook [12], which is equipment-specific and technology-stratified. The emissions for on- and off-road transport in Denmark are based on fuel consumption models [34]. For agriculture, the off-road fuel consumption depends on the vehicle fleet and its characteristics as described by Winther [35]. Per machine type and engine size, the number of engines and their annual working hours, in combination with their specific fuel consumption in g/kWh, the load factor, and the average engine size in kW, all determine the total off-road fuel consumption. Although this approach has been widely used [22,23,29,32], the calculation heavily relies on sales figures, import, export and production statistics of machinery, and available data on load factors and annual operating time. An alternative computation model for emissions inventory is presented by Dyer [11] for Canada.

Next to the above mentioned models for energy or emissions inventory purposes, different fuel consumption models have been reported in literature as part of environmental assessment tools [7,13,18] or as part of case studies on energy consumption or energy efficiency in agricultural production [4,5,10,19,23–26,28]. Different methodologies are applied in these models, as alternative to the Tier 3 methodology of the Ref. [12]. One approach is the use of registered fuel consumption data [19,24]. Another and very common approach is to start from the inventoried field operations and to assign fuel consumption data, retrieved from literature, to each operation. Correction factors are sometimes applied in that process to conform the literature data to the case-specific situation. Examples are energy studies by Refs. [4,5,10,26,28]; with correction for soil type by Refs. [7,8]; with correction for yield, manure type and quantity, and field distance by Ref. [24]; and with correction for relief, stoniness, obstacles on the field, and length of the section by Ref. [30]. A disadvantage of this approach is that the employed FC (fuel consumption) data often disregard the relationship between fuel consumption and e.g. motor capacity, soil conditions, and field size. Sometimes, assumptions are made in order to cope with the lack of more detailed information, e.g. a questionable linear relationship between fuel consumption and field size [8]. A third approach is similar to the previous one, but operation-specific fuel consumption is measured instead of retrieved from literature [16,25].

With the emerging information and communication technologies in agriculture comes a new opportunity to actually record and register instead of measure or compute operational fuel consumption [6], which would greatly facilitate the collection of data to be used in environment assessment tools.

Finally, fuel consumption can also be predicted by models, aiming to reduce energy use for fieldwork, based on technical and/ or social factors. Ref. [27] used artificial neural networks and *inter alia* survey data from 40 farmers to predict fuel consumption in wheat production. The same authors previously predicted direct and indirect energy consumption in wheat production via artificial neural networks and multiple linear regression [26]. Especially farm management appeared to be a key factor in becoming more energy efficient. Ref. [11] established the F4E2 model, validated by survey data, that can assist farmers to make fuel-efficient machinery selections.

Unfortunately, the methodologies that are used in the above models are not appropriate for national inventory purposes in Belgium. The reason is that the emission model should be country-specific and easily updateable. The required input data on the agricultural vehicle fleet (number, nominal power, and age) are not readily available and involve quite some assumptions [29]. Fuel records in accountancies are aggregated and monetary data do not include fuel used by contract workers. The annual national statistics report on the cultivated area per crop type and the number of livestock farms per animal type. The model should take into account these available input data.

1.1. Objectives

This paper presents the calculation model for off-road fuel consumption (FC) during agricultural production in Belgium as embedded in the 2009 emission model. The model is called **the energy consumption model** and is hereafter referred to as the **EC model**. FCIs (Fuel consumption indicators) for most cultures are calculated on a regional scale. The functional unit is L/ha, in compliance with the goal and the necessary and available input data. The final goal of the model is to establish average fuel consumption data for agricultural production in Belgium, which can easily be updated every year. The model for animal production is not discussed here because the functional unit of the FCIs (L/farm) makes the indicators less meaningful to other countries and less applicable in other studies.

2. Material and methods

In 2010, Belgium had a total of 1,358,019 ha of arable land [1]. More than half is located in Wallonia (740,885 ha; nearly 54% of the total arable area). Agricultural production in Flanders covered 616,866 ha or 45% of the arable land in 2010. Brussels, with only 268 ha, represents 2%. Soil types and field sizes differ greatly among the three Belgian regions. Because fuel consumption depends largely on these factors, the model considers the three Belgian regions (Flanders, Wallonia and Brussels) as separate case studies. Remark that off-road fuel consumption does not include power consumption in any subsector.

2.1. Model structure and assumptions

2.1.1. The model is generic

The final goal of the model is to establish average fuel consumption data for crop cultures in Belgium. This model differs fundamentally from accounting or sales figures based models because it is generic. Although the model and this study focus on Belgium, this fuel consumption model (and therefore the OFFREM emission model) is adaptable to any comparable situation. The model starts from the off-road farming activities and their associated fuel consumption. These farming activities are the basis for the calculations and are listed in technical sheets on cultivation practice. The model outputs are **fuel consumption indicators** (FCIs) for plant production. There are obvious advantages to this generic approach. For example, the model does not distinguish whether the