Concept for assessing product-related pesticide footprint

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Abstract Increased environmental awareness has motivated retailers to label products with carbon footprints. This allows consumers to choose products according to their global warming potential. Public concern is also targeting pesticides. Heightened customer sensitivity to residues has already led to a ban on using certain pesticides by European retailers. A tool is needed for assessing the environmental impact of pesticides used for producing a specific product. This paper introduces the concept of the pesticide footprint (PFP), which fills this gap by estimating the total loss of pesticides, and their respective impact on humans and ecosystems, per product unit in a life-cycle framework. The impact assessment considers how these losses affect humans through the consumption of the product containing residues, and ecosystems through the exposure to residues in the environment. The PFP includes the production of the pesticide, its application in the orchard, and the final disposal of waste.

Keywords conceptual framework, life-cycle analysis, life-cycle impact assessment, life-cycle management, pesticide residues, horticultural products.

INTRODUCTION

Climate change, increased environmental awareness and changing consumer attitudes are driving the footprint quantification for products, individuals, activities, businesses, industries and nations. Of all footprints, the carbon footprint is the most widely used and an internationally accepted standard, the British PAS2050 (British Standards Institution 2008) has been established. Carbon footprints are measures of the amount of greenhouse gas produced during the life-cycle of a product: from its production through processing and storage to its use and disposal by the consumer. The labelling of products with carbon footprints allows consumers to choose products according to their global-warming potential. The second important incentive for all carbon footprint quantification and analysis is to identify hot spots and develop mitigation strategies that reduce greenhouse gas emissions. Climate change is not the only environmental problem being addressed. Other footprints are emerging, like the water footprint, to provide tools for developing environmentally-friendly and economically-sensible production strategies.

Public concern is extending to the environmental risks associated with pesticide use. Heightened customer sensitivity to pesticide residues in food and water resources that are potentially linked to cancer and hormone imbalances has already led to bans on several pesticides by some European retailers. Pesticides, however, continue to play a vital role in most modern horticultural production systems for controlling pests, diseases and understorey growth. In New Zealand, 4000 t of active ingredients were applied in 2001 (Manktelow et al. 2005). Often less than 0.1% of the applied mass of these inherent toxic compounds (Pimentel & Levitan 1986) reaches its intended target, so considering and assessing the wider environmental implications arising from the use of pesticides in horticultural systems is important. The New Zealand horticultural industry has a special responsibility due to its large share of total pesticide use, and high application rates, which are unmatched by other production sectors (Manktelow et al. 2005).

A product-related pesticide footprint should integrate amounts of pesticides used, amounts of active ingredient lost to the various compartments of the environment, and their impact on the environment and health. Ideally, this complex information would be merged into a single score, the pesticide footprint of a product, but currently such a tool is not available. The first obstacle is that inventory data on pesticide use are not collected in New Zealand. Two comprehensive reports on pesticide use in New Zealand have been conducted on behalf of MAF and MfE (Holland & Rahman 1999; Manktelow et al. 2005). The central recommendation of both reports was that a databank collating pesticide use data is required. Some New Zealand horticultural sectors, e.g. the apple and kiwifruit industries, are mainly producing for export markets. Their growers are required to maintain extensive spray diaries for all spraying operations to ensure access for their products in export markets. This could be a model for other industries.

What happens to pesticides following application has been intensively investigated since Rachel Carson's publication *Silent Spring* (1962) and has resulted in a large variety of pesticide-fate models with different foci. Most of these models focus on pesticide fate within a single environmental compartment, e.g. ground water resources, and aim to predict environmental concentrations depending on climate, soil and other boundary conditions. Multimedia fate-models as developed by Mackay and co-workers (Mackay & Paterson 1991) target mainly persistent pesticides and their transfer between the different environmental compartments on a global scale, and are not appropriate for quantifying pesticide footprints. Regulatory risk assessment models simulate worst case scenarios and therefore provide conservative estimates of potential pesticide impacts (Jarvis et al. 2007). On the contrary, the aim of the pesticide footprint is to provide a best estimate of pesticide losses and impacts. Birkved & Hauschild (2006) affirmed that no single pesticide risk assessment model provides estimates of emissions to all compartments. They developed PestLCI, a modular model for estimating pesticide emissions from field applications to the different environmental compartments for agricultural life cycle analyses/assessments (LCAs), specific to conditions in Denmark. While PestLCI incorporates undesirable emissions to the most relevant environmental compartments, it deliberately oversimplifies processes to keep the estimation of pesticide losses manageable in an LCA framework. The LCA integrates not only the impacts of pesticides but extends to other impact assessments including, for example, acidification and global warming. As a consequence, PestLCI does not take advantage of the latest advances in pesticide research, nor is it linked to models assessing toxicological impacts of pesticides. In fact, the integration of pesticide fate modelling with ecotoxicological impact assessment is generally poor (Dubus & Surdyk 2006).

Toxicological assessments use either hazard ranking or environmental indicators data. Hazard ranking takes into account the potential of compounds to cause harm based solely on physicochemical properties but does not consider exposure modelling. Hazard ranking is therefore of limited application when determining pesticide footprints. The potential for pesticides to elicit environmental damage is extremely site-specific and is not solely dependent on the environmental toxicity of the pesticide. Environmental indicators investigate the use of pesticides within a crop protection context at the farm level (Reus et al. 2002). Exposure to pesticides is usually estimated from pesticide properties. For example, the GUS index (Gustafson 1989) is used in many environmental indicators to estimate pesticide leaching and only requires sorption and degradation properties of the pesticide. The main disadvantage of the low data requirement of environmental indicators is their use of generic parameters and lack of scientific validation. Environmental indicators could be improved by supporting exposure estimations in environmental media through determining environmental pesticide concentrations with deterministic fate models. The Environmental Yardstick for Pesticides, for example, uses the PESTLA model to estimate pesticide concentration in ground water (Reus et al. 2002). Another advanced example of an environmental indicator using deterministic models is p-EMA (Brown et al. 2003), which uses the MACRO model to predict pesticide losses to surface and ground water. MACRO is implemented in p-EMA as a meta-model, meaning all the simulations are pre-run with the MACRO model and linked to p-EMA as a look-up database. FOOT-FS is the successor; a farm-scale tool developed by FOOTPRINT project and is anticipated to be released in 2010 (FOOTPRINT 2010).

According to ISO 14042 (2000), life-cycle inventory (LCI) results (here, the estimated undesired losses of pesticides to the environment) are classified into impact categories with category indicators. The category indicator can be located at any point between the LCI results and the damage category (where the actual environmental effect occurs) in the cause-effect chain. Classical life-cycle impact assessment methods restrict quantitative modelling to the early stages in the cause-effect chain to limit uncertainties and classify and characterise life-cycle inventory results in midpoint categories. Hauschild & Wenzel (1998) developed the EDIP (Environmental Design of Industrial Products) with nine midpoint categories ranging from global warming to resource consumption and human toxicity. In contrast, Eco-indicator 99 (Goedkoop & Spriensma 2002) models the cause-effect chain up to point of actual damage. This, however, is inflicted with high uncertainties and requires normalisation and weighing steps. Newer approaches, such as IMPACT 2002+ (Jolliet et al. 2003) work with midpoint and damage categories. Established life-cycle assessment criteria of food commodities include 'pesticide use' alongside global-warming potential, primary energy use, land requirement, and others (DEFRA 2008). However, the concept for including pesticides into commodity LCAs is not yet well advanced. Often, the amounts of active ingredient of all applied pesticides are combined in a single figure and considered as a total, regardless of the specific environmental fate and ecotoxicological profile of active ingredients (DEFRA 2008).

The concept presented here addresses this gap. The specific goals for the pesticide footprint concept were (1) to develop a method for assessing the actual environmental impact of the pesticides used for producing a specific product and (2) to assess human toxicity and the ecotoxicological impacts of the individual pesticides used for producing a specific good.

DEVELOPMENT OF THE FRAMEWORK

A conceptual framework of a pesticide footprint embedded in a Life Cycle Assessment (LCA) framework was developed. A LCA is the quantification and evaluation of the environmental impacts associated with a product, process or activity and usually consists of four phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation of the results (ISO 14040 2006). A pesticide footprint was defined as the sum of the total loss of pesticides, and its respective impact on humans and ecosystems, associated with using pesticides for producing a unit of a horticultural product, in a life-cycle framework. The three core objectives and associated aims of the pesticide footprint are listed below.

1. To provide a Decision Support Tool (DST) for growers and the industry using the following steps:
   - establish a baseline in the form of a LCA of pesticide usage and emissions for horticultural products;
   - develop life-cycle management strategies to minimise the pesticide footprint of a specific horticultural product;
   - evaluate alternative management practices that reduce a product's pesticide footprint while maintaining and enhancing financial performance; and
   - eco-verify claims for environmentally sustainable products.

2. To provide a DST for Regional Councils and Regulatory Authorities that identifies:
   - production systems with the lowest pesticide footprint within geographical regions and under specific growing conditions (climate, soils), especially if pesticides threaten aquatic resources; and
   - risks associated with given pesticides.

3. To provide a marketing tool and labelling protocol for retailers that:
   - develops a product label to inform environmentally aware customers; and
   - enables product transparency.

CALCULATION OF A PESTICIDE FOOTPRINT

A pesticide footprint is an indicator of the total impacts of pesticides related to the production of a unit of a horticultural product. The entire life-cycle of pesticides is considered for the calculation of a product-related pesticide footprint. This distinguishes between and integrates the impacts occurring during the production of the pesticide, the impacts related to its application in the orchard and those associated with the final disposal of pesticide containers. This is a cradle-to-grave approach. The spatial dimension of the pesticide footprint is reflected by the three vertical pillars in Figure 1, representing the three life-stages of pesticides – production, use and disposal.

Determination of the pesticide footprint comprises three main steps (Figure 1), as follows.

1. Estimation of the fraction of pesticides used for producing a unit of a specific horticultural product that is lost to the environment in a Life Cycle Analysis (LCA) framework.
2. Assessment of the toxicological impact of the total amount of pesticides lost to the environment in a Life Cycle Impact Assessment (LCIA) framework.
3. Development of mitigation strategies to minimise the pesticide footprint in a Life Cycle Management (LCM) framework.

Within each of the three stages, three environmental compartments are considered – soil, water and air.

1. Life Cycle Analysis framework

The aim of this stage of the product-related pesticide footprint is the estimation of the total amount of active ingredient lost to the environment. It is conducted as an inventory in a LCA framework considering all the pesticides applied for the production of a unit of a specified horticultural product. The inventory starts in the orchard by collecting information on all pesticides applied: product, date and amount of active ingredient. The losses of active ingredient to soil, water and air compartments are determined for the lifetime of the pesticides, including their production, application and waste disposal. During, and after the pesticide application in the orchard, active ingredient is lost to the air, soil and water. The processes and resulting emissions can be modelled with pesticide fate models. The complexity of the models needs to be carefully chosen according to data availability. The model PestLCI (Birkved & Hauschild 2006), for example, provides estimates of pesticide masses emitted to soil, water and air as fractions of the pesticide amounts applied. It provides moderate capability

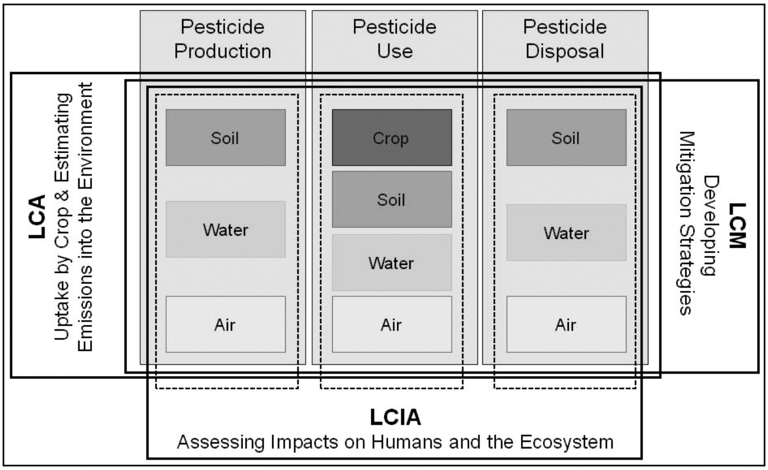

Figure 1 Conceptual scheme of a product-related pesticide footprint.

for including effects of the natural capital of soil, water and climate, plus the human dimension of the impact of management decisions on the emissions. The resulting emission fractions represent best estimates for an average pesticide application (Figure 2). The model could be improved to yield better estimates of losses for a particular application scenario with well-defined spatial and temporal dimensions.

2. Life Cycle Impact Assessment framework

The unintended emissions to the different environmental compartments of soil, water and air are the basis for the second stage of the pesticide footprint. This impact assessment considers how the pesticide losses affect humans through the consumption of produce containing residues, and ecosystems via the exposure to residues transferred to and retained within the

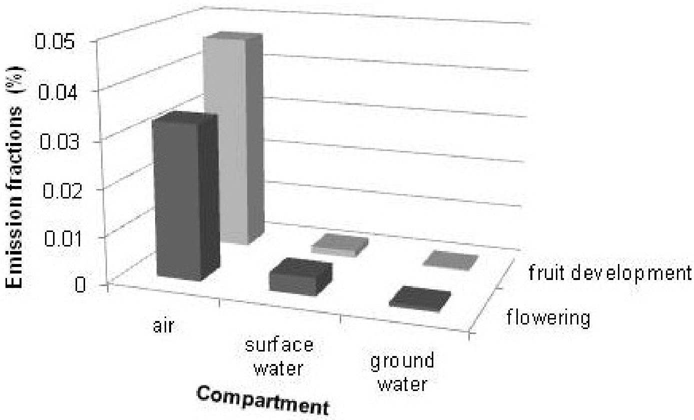

Figure 2 Modelled bentazone emission fractions to surface water, ground water and air after its application to maize at (a) flowering in June and (b) fruit development in August. Data from Birkved & Hauschild (2006).

environmental compartments of soil, water and air. These three environmental compartments will be assessed separately. Furthermore, the impact of the residues will be assessed independently within the three life stages of the pesticides – production, application and disposal (Figure 1). Every active ingredient will be analysed individually. The impact on humans is directly associated with the product while impacts on soil, water and air are related to the total amount of active ingredient applied per hectare.

One framework that could be used to estimate the impact of pesticides on human health and ecosystems is the 'critical surface time' approach (Margni et al. 2002). In this framework, the emissions to each compartment are transferred to humans and the ecosystem through an intake factor that takes into account a dilution volume, and a residence time in the specific compartment. No effect concentrations for ecotoxicity (NOEC) and human reference doses for human toxicity are applied as the toxicity measures. Normalisation to a reference substance allows the comparison of the potential impact of different pesticides, and the calculation of a total final impact score per environmental compartment related to a unit of the horticultural product.

3. Life Cycle Management framework

The aim of the third stage of a pesticide footprint is to minimise the pesticide footprint of a specific horticultural product. Alternative management practices will be assessed that reduce a product's pesticide footprint, while maintaining or increasing the yield and quality of the product.

The Integrated Fruit Production Programme (Batchelor et al. 1997) is designed to reduce pesticide use by replacing calendar-based spraying by monitoring and threshold-based treatments. This has led, for example, to a drastic reduction in total insecticide use for New Zealand apple production accompanied by choosing alternative compounds with different properties and ecotoxicological profiles (Figures 3a & 3b). However, it remains to be determined whether or not these beneficial improvements result in a reduction of the pesticide footprint. Currently, there is no tool to assess the total impact of such management changes. The pesticide footprint framework that is proposed here will provide an important tool to demonstrate the wider impact and environmental benefits of different horticultural management practices to growers, industry stakeholders, regulators and the consumer.

OUTLOOK

A method has been developed for assessing the product-related overall effects of pesticides by using embedded LCA, LCM and LCIA frameworks. These will allow the comparison of pesticides that can be used alternatively for the same purpose in a production system, and will enable reporting of improvements in the reduction of the size of the pesticide footprint.

The pesticide footprint could also be extended to enable calculation of the eco-efficiency (EF) of the pesticides applied during the production of a unit of a horticultural product. This metric could be the ratio: EF = product value ($/t product) divided by the impact of pesticides on the environment (total impact score/ t product).

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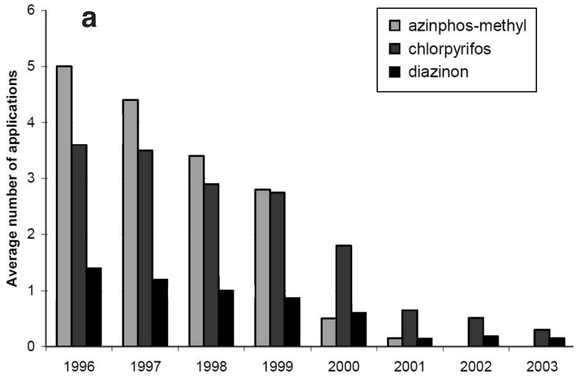

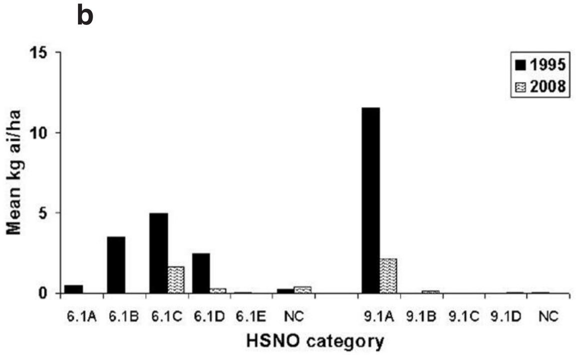

Figure 3 (a) Organophosphate insecticide use on apples over time (Manktelow et al. 2005). (b) A comparison of the mean active ingredient use of HSNO classified 6.1 (human toxicity) and 9.1 (eco-toxic) insecticides applied to apples in 1995 and 2008 (Walker et al. 2009).

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