Vegetable Industry Carbon Footprint Scoping Study

Discussion Paper 3

What carbon footprinting tools are currently available?

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Purpose of the paper:

The purpose of this paper is to define a "carbon footprint" and provide an insight into the terminologies and approaches included within this concept. A number of key issues are addressed in this discussion.

Firstly, the origins of the "footprinting concept" are addressed to establish the conceptual history (and baggage) associated with this term. Secondly, existing literature is critiqued to scope the various definitions, highlight distinctions and articulate a preferred definition of a carbon footprint. Thirdly, key methodological steps involved in the calculation of a carbon footprint are addressed. Lastly, recommendations of this study are presented, linking the broader debate on "what is a carbon footprint" with implications for the development of a footprinting tool in the Australian Horticultural industry.

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Summary

This paper reviews four calculators/models which have relevance to, or which might be adapted for greenhouse gas accounting within the vegetable industry, namely: the Grains Greenhouse Calculator (DPI Victoria), CarboNZero (New Zealand Crown Research Institute), FullCAM (Australian Department of Environment and Heritage) and APSIM (Agricultural Production Systems Research Unit). The selection of these tools was based on three criteria, namely: 1) the scope and scale of emission accounting; 2) scientific credibility and; 3) suitability for use in Australian agricultural systems. They are also representative of the types of agricultural greenhouse calculators that are available worldwide. The Grains Greenhouse Calculator and CarboNZero employ static, spreadsheet-based approaches, whereas APSIM and FullCAM are dynamic process-based models that capture the flow and stocks of carbon and nitrogen in the atmosphere/plant/soil continuum. Key attributes relating to the design, scope, methodology, operation, availability, and apparent strengths and limitations are described for each tool. Individually, these tools do not appear to be suitable for immediate application in the vegetable industry and investment is required to address apparent scientific, design and operational limitations. However, collectively they capture the key attributes and functions required to develop a vegetable greenhouse accounting calculator.

Introduction

Most of these greenhouse gas calculators available on the web or described in published literature have been designed to enable individuals to calculate their current personal or household carbon footprint and to explore options for amelioration (i.e. behavioural change). These calculators are typically simple to use and work by taking user-defined inputs relating to energy consumption and vehicle use and efficiency, and provide an estimate of the carbon footprint of the user. Many of the calculators go one step further and offer means to mitigate the user’s emissions, typically through buy-in to reforestation projects or renewable energy development. These calculators use a range of methodologies, often involving nationally or internationally recognised algorithms and emission factors. For a review of international web-based individual/household calculators see Padgett *et al* (2008) and Bottrill (2007). Examples from Australia and New Zealand are the Department of Climate Change ‘Greenhouse Gas Emissions Calculator’ (www.environment.gov.au/settlements/gwci/calculator.html), Environmental Protection Authority Victoria’s ‘Australian Greenhouse Calculator’ (www.epa.vic.gov.au/GreenhouseCalculator/) and the New Zealand Crown Research Institute CarboNZero program (www.carbonzero.co.nz).

Estimating greenhouse gas balances for agricultural production systems is more difficult owing to the complexity of these systems, especially in relation to their component carbon and nitrogen cycles. Direct farm scale emissions arise from a mix of sink and source processes in the plant, animal, residue and soil components, all of which are influenced by climate, management and soil characteristics. Emissions also arise from fuel use in farm machinery. Additional complexity arises when there is a range of crop and pasture elements grown in rotation. There are a range of calculators/models which have been developed specifically for greenhouse gas accounting of agricultural production and others that, while developed for other applications, have the potential to be utilised for accounting purposes. These can be broadly divided include static, spreadsheet based tools and dynamic, process-based models that attempt to track the fate of carbon and nitrogen as they move through the agricultural system. Other tools employ a combination of both approaches.

Given the significant number of available calculators and system models relevant for use in agricultural greenhouse gas accounting, an initial screening process was undertaken to select a small number that are potentially relevant for application in the Australian horticultural sector and which are representative of the types of tools available. The selection of these tools was based on three main criteria: scope, scientific credibility and suitability for Australian conditions.

Scope

The calculation of greenhouse gas balances can either be confined to the boundaries of the farm or extended to encompass what happens to inputs and outputs before and after entering or leaving the farm. Dick *et al* (2008) divides farm emissions into three groups: 1) indirect emissions associated with goods and services imported onto the farm (e.g. chemical and fertiliser manufacture, tractor manufacture, seed, the transporting of supplies to the farm, energy consumption); 2) Direct farm emissions (e.g. fuel emissions from tractor and other farm machinery, crop residue decomposition or burning, soil organic matter decomposition, manure storage, livestock emissions, changes in carbon storage in soil and vegetation); and 3) carbon sequestered in products exported from the farm (e.g grain, silage, beef). There is currently no standard international agreed methodology regarding the allocation of emissions between producers, their suppliers and the final consumers of their products. Dick *et al* (2008) argue for a simple approach where the attribution of greenhouse gas emissions is within business boundaries. This ’farm gate’ approach will encourage best practice during each step in the production cycle. Nevertheless, many farm businesses will want to take into account off-farm emissions and indeed may choose to adjust some of their input purchase decisions based on the carbon footprint of the input. For example, farmers may choose to purchase 'green' power instead of thermal power or they may choose to generate energy supplies on farm (e.g. wind, solar, hydro).

There is some uncertainty/ambiguity associated with the inclusion or otherwise of carbon stored in the biomass of annual crops. While the IPCC guidelines recognise carbon sequestration in perennial woody vegetation in orchards, vineyards and agroforestry, carbon sequestered in annual crops is regarded as ephemeral and not credited. Dick *et al* (2008) suggests that this approach does not appear to take into account the export of carbon into soils by plants via the roots and other plant structures remaining post-harvest. Depending on the balance of gains (photosynthate) and losses (decomposition), soil can be a net sink of carbon and soils can accumulate carbon over long periods of time (e.g. peat). Similarly, Australia’s NGGI methodology assumes that the flux of CO_2 from the soil/plant/animal system is neutral.

A key application of any future calculator will be to assess the impact of current and alternative management practices on the greenhouse gas balance. Practices that have an impact on the flow and stocks of carbon and nitrogen in an agricultural system include crop selection and timing, fertiliser and irrigation management, tillage practice and the management of residues and mulches. Furthermore, vegetable crops are often grown in rotation with other cereal, pasture and industrial crops and consequently it is difficult to isolate the emissions of one crop due to the 'carry-over' of soil nutrients and organic matter and surface residues along a rotation.

The preferred scope of any future calculator for the vegetable sector in Australia will be a key subject for discussion at the workshop. For this reason, the tools selected for description below vary in the range of direct and indirect emission processes that are accounted for, and the capacity for dealing with the unique physiology and management practices of different vegetable crops and systems.

Scientific credibility

Given the potential financial and environmental impact of decisions relating to the reduction and mitigation of greenhouse gas emissions on-farm, it is important that selected calculators be based on sound science. Each of the tools described below have been developed by reputable scientific organisations, employ accepted greenhouse accounting methodologies and modelling approaches that have been subjected to independent peer review.

Suitability for Australian conditions

The agricultural systems of Australia have unique attributes in terms of soil, climate, crop and management characteristics. Furthermore, there has been significant Government investment in the development of modelling tools to capture these unique characteristics and also in the development of greenhouse accounting tools. Hence, it is appropriate that preference be given to utilising and, if need be, modifying these ‘local’ tools.

Based on these criteria, this paper reviews four tools which have relevance to the development of, or which might be adapted for use as a greenhouse gas accounting tool for the vegetable industry, namely: the Grains Greenhouse Calculator (DPI Victoria), CarboNZero (New Zealand Crown Research Institute), FullCAM (Australian Department of Environment and Heritage) and Agricultural Production Systems Research Unit (APSIM). The Grains Greenhouse Calculator and CarboNZero employ static, spreadsheet-based approaches, whereas APSIM and FullCAM are dynamic process-based models that capture the flow and stocks of carbon and nitrogen in the atmosphere/plant/soil continuum.

Grains Greenhouse Calculator

This is one of a number of sector-specific, spreadsheet-based calculators developed by DPI Victoria’s Greenhouse in Agriculture (GIA) program (www.greenhouse.unimelb.edu.au). Specifically, this spreadsheet estimates the greenhouse gas emissions from grain-producing systems based on the NGGI methodologies. The calculator allows individual growers to estimate their greenhouse footprint and compare the relative contributions from: 1) fuel consumption in farm machinery; 2) soil processes (nitrogen); 3) residue burning and 4) fertilizer addition. The calculator can be downloaded from the web (or used on-line) and requires a small number of inputs relating to fuel usage (type and annual usage volume), grain production (yield, area sown and harvested, per cent burnt) and fertilizer usage (type and rate). The total whole farm emission is expressed in carbon dioxide (CO_2) equivalents (per annum and per ha).

One of the more significant greenhouse gases in agricultural systems is nitrous oxide resulting from the denitrification of soil nitrate. Many factors influence the extent of N_2O emission but perhaps the most important are fertiliser addition and soil disturbance. N_2O emissions in agricultural systems are typically higher due to the higher rates of mineralisation associated with disturbance combined with higher rates of nitrogen deposition due to nitrogen fixation, stubble incorporation etc. In the Grains Greenhouse Calculator, N_2O emissions are estimated using a soil disturbance emission factor which relates emissions under a disturbed cropping system to those in an undisturbed ecosystem. The soil disturbance emission factor is based on measurements taken from a wheat crop and an adjacent area of undisturbed Mallee woodland in Victoria. N_2O emissions from fertiliser addition are based on a fertiliser emission factor which relates emissions from a fertilised crop to those from an unfertilised crop. Reported N_2O emissions factors vary widely due to differences in climate, fertiliser type, soil texture, crop type and the duration over which measurements are made. The process for selecting a fertiliser emission factor for use in the calculator involved gathering all available estimates and then screening out factors derived from: 1) grain crops; 2) inorganic fertilisers; 3) the absence of nitrification inhibitors and 4) at least 100 days of measurement.

Greenhouse gas emissions from fossil fuel combustion in farm machinery and from the burning of crop residue are estimated directly from NGGI algorithms and related emission factors. Residue biomass is estimated from user inputs of grain yield and production area.

The NGGI methodology assumes that the flux of CO_2 from the soil/plant/animal system is neutral and hence is discounted. The methodology also discounts sequestration of carbon in the soil or vegetation. This greatly simplifies the accounting process and hence the input requirements for the calculator. Consequently, the Grains Greenhouse Calculator is quick and easy to use. The developers acknowledge that there are tradeoffs in terms of accuracy associated with uncertainties in emission factors, the farm activity data, and the fact that emission algorithms do not take into account all processes and environmental influences on greenhouse gas production. The calculator accounts for the on-farm emissions of a single enterprise (i.e. grains). Adaptation to an equivalent enterprise-specific, vegetable application would require re-parameterisation of the fertiliser and soil disturbance emission factors and the crop-specific harvest index.

CarboNZero Program

This program was established in 2001 by Landcare Research, one of New Zealand’s Crown Research Institutes (CRI) (http://www.carbonzero.co.nz). The program involves four steps: 1) the measurement of greenhouse gas emissions; 2) the identification and implementation of management practices to reduce greenhouse emissions; 3) the implementation of mitigation strategies for any remaining emissions and; 4) the marketing of the greenhouse credentials of the client.

The program utilises a number of different calculators for different applications. Simple household and personal calculators are freely available from the web. A more comprehensive, enterprise/business scale emission calculator can be accessed at-cost via the program’s certification scheme. The main calculation tool the program operates is E-Manage, a spreadsheet based emissions calculator claimed to meet and exceed the requirements of relevant international standards: the Greeenhouse Gas Protocol for corporate accounting and reporting and ISO 14064-1 the international standard for quantification and reporting of greenhouse gas emissions and removals. The emissions factors used in these calculators are sourced from the Intergovernmental Panel on Climate Change (IPCC) emission factors database, the New Zealand Ministry of Economic Development annually published energy-related greenhouse gas emissions data, the United Kingdom Department for the Environment, Food and Rural Affairs for some international freight emission factors not otherwise available, the Australian Department for Climate Change emissions factor workbook, and published research.

The CarboNZero calculators enable users and clients to quantify their individual, household or business carbon footprint and to explore the potential impact of various behavioural and management changes. In the case of business clients, the CarboNZero team provides direct assistance in the investigation and documentation of emissions and helps determine the most effective reduction options.

Having identified and implemented greenhouse gas reduction management options, clients are then assisted by CarboNZero to offset the residual carbon footprint via the purchase of carbon credits through verified schemes such as native forest regeneration, renewable energy generation.

Organisations that have measured, managed (reduced) and mitigated (offset) their greenhouse gas emissions can be CarboNZero certified. Prior to certification, an external audit is conducted to ensure that each step of the process has been implemented. Certification is subsequently reviewed every 12 months. The organisation can then use the CarboNZero certification for marketing purposes.

An example application is the certification of the New Zealand Wine Company (Gilkison 2008). Its emissions were identified according to scopes: Scope 1 - direct emissions from sources that are owned or controlled by the company, such as fuel used by its plant, equipment and vehicles; Scope 2 - emissions from the off-site generation of electricity or other energy which is purchased and used by the company; Scope 3 - emissions that occur as a consequence of the companies activities, but from sources that it does not own or control. These include employee air travel, road and rail freight and international shipping of wine. Scopes 2 and 3 were essential for certification. After managing as much as they could, the company purchased carbon credits and used them for regeneration of native forests. Gilkison (2008) reports that certification had many economic benefits for the company including energy cost savings, increased sales, cost-effective promotion etc.

To date, participants in the CarboNZero program have primarily been non-agricultural businesses and hence specific agricultural system functionality within the E-Manage calculator is restricted. According to Scott Fraser from CarboNZero (pers comm., September 2008), E-Manage does not capture carbon and nitrogen flows and stores but does capture nitrous oxide emissions associated with fertiliser additions. In response to growing interest in the use of the program in the horticultural/agricultural sectors, the operators of CarboNZero are beginning to develop the required capability via collaboration with industry and researchers within the CRI.

The apparent strength of the CarboNZero program is that it offers a complete service from measurement through to certification. This makes the task much easier for companies, improves the accuracy of the analysis, and ensures that management and mitigation practices are implemented to effect. The New Zealand Wine company example indicates that the cost of such a service is readily recouped through subsequent economic benefits. The other potential advantage of the CarboNZero program is that it is geared up to consider emissions beyond the farm gate (Scopes 2 and 3 above).

National Carbon Accounting Toolbox (NCAT) / Full Carbon Accounting Model (FullCAM)

NCAT is a derivative of the National Carbon Accounting System (NCAS) which was established in 1998 to provide a complete accounting and forecasting system for human-induced sources and sinks of greenhouse gas emissions from Australian land based activities. NCAT provides tools for tracking greenhouse gas emissions and carbon stock changes from land use and management. The key component of NCAT is the Full Carbon Accounting Model (FullCAM) which calculates the stocks and flows of carbon and nitrogen for land subject to different land use and management activities. (Richards and Evans 2000). It assists land managers to monitor emissions effectively and to identify more sustainable land management practices. NCAT (including FullCAM is available on CD free of charge from the Department of Climate Change (www.climatechange.gov.au/ncas/ncat/).

FullCAM draws together a suite of verifiable component models: CAMFor (forest systems, Richards and Evans 2000), CAMAg (cropping and grazing systems, Richards and Evans 2000), 3PG (forest growth, Landsberg and Waring 1997), GENDEC (microbial decomposition, Moorehead *et al* 1990), RothC (agricultural soil carbon, Coleman *et al* 1990). These models can be run either separately or in an integrated format. Agricultural versions of RothC and GENDEC are incorporated within CAMAg which provides the broader systems framework.

FullCAM models all carbon and nitrogen pools, plus interchanges and fluxes within the plants, debris, mulch, soil minerals and atmosphere. It tracks the movement of carbon and nitrogen from their removal from the atmosphere, through the growth of the plant, to their return to the atmosphere or leaching from soils after passing through plants, debris, mulch, soil, grazing animals, wood or agricultural products. FullCAM can also account for carbon and nitrogen changes due to a variety of management practices. Note that the current version of FullCAM in NCAT accounts for carbon stock changes only. Capacity to account for nitrogen cycling exists in the ‘research’ edition of FullCAM and is to be incorporated into future versions of the toolbox.

The model simulates carbon and nitrogen fate in homogeneous *plots* (paddocks) of a set (i.e. output expressed as t/ha) or user-specified area (i.e. output expressed as t). There is also an *estate* (i.e. farm) simulation which can track changes within an arbitrary collection of plots each of a specified area (ie a diverse area of agricultural land with different crops, pastures and management systems). Simulating estates consists of many plot simulations with output aggregated across the plots. Each plot can either have a forest or agricultural *system* or a mix of the two. Each of these systems is partitioned into *layers*, namely plant, debris, soil, mineral and product.

Plant growth is simulated via net primary production (NPP), which is the net increase in plant mass taking into account both photosynthesis and respiration; and yield which is NPP less turnover (i.e. senescence). NPP, yield and biomass partitioning is set by plant allocation and increment tables which set how much biomass is allocated to each plant part in each time interval of the simulation. Plant material moves to the debris layer via turnover or plant death, harvesting or fire; to the products layer by harvesting; and crop material moves by grazing to the atmosphere, the products and the soil layers. Turnover percentages are included in the model database for each species and each component of the species. The model also simulates stem and plant mortality by allowing the user to specify the rate and time of death. If there is insufficient nitrogen in the mineral pool for all the processes to consume the amount they wish, nitrogen rationing occurs which means that less of the processes occur (e.g plant growth slows). The user specifies a crop species or sequence of crops (i.e rotation) to grow in the agricultural system. Each plant part of each species is allocated a carbon percentage and carbon to nitrogen ratio (maximum and minimum values which limit the movement of material into a specific pool). The model database includes carbon percentage and carbon to nitrogen ratio values for a wide range of pasture, crop and tree species. There is limited specificity for horticultural and vegetable crops.

The *debris* layer is comprised of plant material that is dead but which has not reached the soil or mulch. Breakdown processes move material from the debris pool to the mulch or active soil layers. Within the debris there are resistant and decomposable pools. The user specifies decomposition resistant percentages that determine the mass of plant material that goes into the decomposable and resistant pools of debri and soil. The user specifies the decomposition rate for the debris pool which determines how long it takes material to pass through the debris pool in one year (i.e how much is broken down to atmospheric breakdown products which move to the atmosphere; and solid breakdown products which move to the soil). The fraction going to atmosphere and solid breakdown products is also user defined.

The *soil* layer is partitioned into ‘active’ material that can be moved elsewhere in the model via microbial decomposition processes (i.e. to atmosphere, ‘bio’ and ‘humus’ pools in the active soil); and an ‘inert’ material produced via encapsulation from the humus pool that does not move anywhere else in the model. There is temperature, carbon to nitrogen ratio and water sensitivity functionality for decomposition (which modifies the potential rate) of both the debris and soil materials.

The *mineral* layer is a store for nitrogen which is assumed to be in contact with all the other pools. Nitrogen flows are the same as the carbon flows and in addition, various processes consume or generate nitrogen. If there is insufficient N, the usual processes of production and decomposition moving material around may be limited.

The *products* layer refers to plant material taken offsite such as wood or agricultural products. Material may move to the atmosphere by decomposition at a rate that is specified by the user.

Each layer (except atmosphere and minerals) is further partitioned into several *pools* which is a collection of homogeneous material with roughly similar characteristics (e.g crop layer is comprised of stem, leaf, root pools).

FullCAM captures a number of agricultural management options including planting, harvesting, fire, ploughing, herbicide application, grazing change and fertilisation (inorganic and organic) and the resultant effects on the carbon and nitrogen balances and greenhouse emission. The model does not take into account irrigation management, nor the effect of water stress on plant growth.

The FullCAM model is complex and requires a large input dataset. To aid the user and to reduce the need to collect a large number of input variables, the model comes with a database of default settings relating to land use activities, species information, and soil properties to be used for establishing ‘benchmarks’ for specific system design / landuse. Alternatively, the user can change the settings to suit their own requirements. The interface is comprised of tab linked configuration pages. Input variables are grouped into bundles of like variables that can be entered through a single input page. Diagrams are provided to illustrate the stocks and flows between the various pools of carbon and nitrogen. The interface also provides links to supporting documentation and electronic help information.

FullCAM currently accounts for direct, on-farm CO_2 emissions only. The accounting of other on-farm greenhouse gases such as methane and nitrous oxide is currently under development.

Agricultural Production systems Simulator (APSIM)

The farming systems model, APSIM (Agricultural Production Systems simulator; Keating *et al*., 2003) was developed to simulate biophysical processes in agricultural production systems. The APSIM framework is comprised of four main components:
1) A set of biophysical modules that simulate the key biological and physical processes in agricultural systems. These include a soil water module SOILWAT2 (Probert *et al.* 1997), a soil nitrogen and carbon module SOILN2 (Probert *et al.* 1997) a residue module RESIDUE2 (Probert *et al.* 1997) and a library of species-specific plant modules covering a wide range of crop, pasture and forest types;
2) A set of management modules that allow the user to specify a wide range of on-farm management activities;
3) Modules to facilitate data input and output to and from the model;
4) A simulation engine that drives the simulation and facilitates communication between the independent modules.

The SOILN2 module describes the dynamics of both carbon and nitrogen in soil. The approach is similar to that adopted in FullCAM with four main pools of carbon and nitrogen simulated: fresh organic matter (FOM, root or recently incorporated surface residues); soil organic matter which is divided into a more labile ‘biom’ pool representing the soil microbial biomass and microbial products and ‘hum’ which comprises the rest of the soil organic matter; and mineral nitrogen. The flows between the different pools are calculated in terms of carbon, the corresponding nitrogen flows depending on the carbon to nitrogen ratio of the receiving pool. The rate of decomposition of FOM, biom and hum pools are determined by fixed rate constants modified by factors involving soil temperature, moisture and (in the case of FOM) carbon to nitrogen ratio. To simulate the reduction in susceptibility to decomposition with increasing soil depth, the user can specify the fraction of biom that is subject to decomposition in each layer. Mineralisation or immobilisation of mineral-N is determined as the balance between the release of nitrogen during decomposition and immobilisation during microbial synthesis and humification. An inadequate supply of mineral-nitrogen to satisfy the immobilisation demand results in a slowing of the decomposition. Both ammonium- and nitrate-nitrogen are available for immobilisation, though ammonium-nitrogen is used preferentially. Decomposition of any organic matter pool results in evolution of CO_2 to the atmosphere and transfers of carbon to the biom and hum pools.

The rate of nitrification (ammonium to nitrate conversion) is set by a fixed rate, modified by temperature, water and pH factors. Similarly, the rate of denitrification is a fixed rate modified by temperature and water factors and the concentration of carbon in the FOM and biom pools. The loss of nitrate via leaching beyond the root zone is simulated by the SOILWAT2 module in conjunction with saturated and unsaturated water flow. Nitrate uptake by the crop is captured within the plant modules.

The RESIDUE2 module describes the fate of surface residues. Residue can be either burnt, removed without burning, incorporated into the soil via tillage operations, or decomposed. The fraction of residue burnt, removed or incorporated can be set by the operator, as can the depth of incorporation. All above ground residues are considered as a single pool which is defined in terms of mass, carbon to nitrogen ratio, and specific area. Tillage results in a transfer of some surface residue into the soil FOM pool. The rate of decomposition is set by a fixed rate, modified by temperature, carbon to nitrogen ratio, water and contact factors. Decomposition results in loss of some carbon as CO_2 and transfer of carbon and nitrogen to the biom and hum soil pools. Decomposition of residues with a high carbon to nitrogen ratio creates an immobilisation demand, which is satisfied from mineral-nitrogen in the uppermost soil layers; in extreme situations, inadequate mineral-nitrogen in soil restricts decomposition of residues. The specific area of residue is used to calculate cover due to residue and is used by water balance modules to modify runoff and evaporation.

The SOILWAT2 module simulates the key component processes of the soil water balance; surface runoff and evaporation, saturated and unsaturated flow between layers based on soil-specific water holding characteristics and deep drainage. Crop water uptake is simulated by the plant modules.

Within APSIM there is a library of plant modules covering a wide range of broadacre crop, pasture, vegetable and forest species. The approaches for simulating growth vary to some extent but broadly involve the interception of radiation by the canopy and the conversion of that radiation into biomass via species specific radiation use efficiency (RUE). Canopy growth is driven by thermal time and takes into account plant architecture and component processes of leaf appearance, expansion and senescence. Biomass is partitioned into the component root, leaf, stem, floral and grain structures. Crop development is driven by thermal time and photoperiod. Growth is sensitive to water, nitrogen and temperature stress with growth potentially affected via reductions in leaf expansion, rate of development and RUE. The plant modules are closely integrated with the residue (i.e. detachment of senesced biomass and harvesting), soil water and nutrient (i.e. crop uptake) modules.

APSIM has extensive management functionality that covers fertiliser management (product, composition, rate, time of application and depth of incorporation), irrigation management (time of application, rate and efficiency), tillage (timing, depth, fraction of surface residues incorporated), sowing (timing and depth), crop (rotation, cultivar) and harvest (timing). All of these activities are linked to, and impact on the carbon and nitrogen cycles.

While APSIM incorporates a comprehensive carbon and nitrogen balance model it does not account for on-farm emissions from fuel combustion in machinery and residue combustion. This was readily overcome in a study of greenhouse gas emissions for the sugar industry by combining output from APSIM model runs with NGGI algorithms and various other established relationships, into a single spreadsheet calculator called GreenCalc (Lisson *et al* 2001).

APSIM was originally developed for use within broadacre dryland cropping systems. However, in recent times there has been growing interest in the use of APSIM in vegetable production systems. This has led to the development of a limited range of new crop models for potato, broccoli, sweet corn and fresh peas.

Like FullCAM, APSIM is more difficult to configure than the simple spreadsheet based models and requires a much larger input dataset. To help with this, APSRU provide regular training sessions for new users and are continually refining the interface to make it easier to operate. One way around the complexities of operating the model is to conduct a large number of targeted model runs and then put the output into a large database from which it can be more readily handled. A variety of APSIM-derived decision support tools are based on this approach.

Discussion / Conclusion

This paper has reviewed four calculators/models which have been developed in Australia and New Zealand based on nationally and internationally recognised accounting methodologies and peer reviewed, verifiable science. The Grains Greenhouse Calculator, FullCAM and CarboNZero have been specifically designed for greenhouse gas accounting. APSIM, while originally designed for broader analysis of agricultural systems, captures many of the relevant greenhouse gas processes and has been used in several accounting studies. Individually, these tools do not appear to be suitable for immediate application in the vegetable industry and investment is required to address apparent scientific, design and operational limitations. However, collectively they capture the key attributes and functions required to develop a vegetable greenhouse accounting calculator.

In terms of methodology and scope, CarboNZero and the Grains Greenhouse Calculator are static, spreadsheet based designs that utilise recognised accounting algorithms, activity and emission factors. The Grains Greenhouse Calculator accounts for direct, on-farm emissions only, whereas CarboNZero also accounts for off-farm and indirect emissions. Both assume that the flux of CO_2 from the soil/plant/animal system is neutral and discount sequestration of carbon in the soil and vegetation. This greatly simplifies the accounting process and reduces the input data, operation time and skill required to drive these models and generate output. Several authors have reported that these assumptions of neutrality and discounting of stored carbon in agricultural systems are not always appropriate and that as we move toward the establishment of carbon markets, we need more sophisticated tools for tracking the flow and stocks of carbon and nitrogen elements.

FullCAM and APSIM attempt to capture these key system processes and associated interactions. Both models are modular in design and integrate pre-existing models with new models for specific components of the agricultural system. Both are process-based, dynamic models that enable the user to explore the fate of nitrogen and carbon over time. Each model has substantial management functionality which enable consideration of the impact of both current and alternative practice on greenhouse emissions and the identification of ‘best-bet’ practice. One key difference between these two models is the way in which plant growth is simulated. FullCAM employs an approach based on net primary production while APSIM uses a radiation use efficiency based approach. Species-specific parameterisation for the wide range of vegetable crops grown in Australia is limited in both models and clearly needs to be addressed if these models are to be adapted to application in the vegetable sector.

In contrast to the spreadsheet-based calculators, APSIM and FullCAM have more substantial input data requirements, take longer to run and generate output, and require more skill to operate effectively. This is likely to be a significant barrier to their widespread use by farm business owners and indeed the experience with APSIM has been that you need an experienced technician (e.g. consultant) to parameterise, operate and interpret model results (alongside the farmer). The incorporation of these tools in a broader integrated program such as CarboNZero which offers a full service to businesses from measurement of footprint through to accreditation would appear to have merit.

Neither APSIM nor FullCAM account for all direct on-farm emissions in a single (or partitioned) CO_2 equivalent term. FullCAM simulates CO_2 emissions but does not currently account for nitrous oxide and methane (under development). Similarly, APSIM does not account for fuel related emissions from farm machinery and from the burning of crop residues and related activities although this could be readily incorporated through the integration of recognised NGGI algorithms.

With the exception of the CarboNZero, the tools that have been described in this paper account for direct farm emissions and have not been set up for full (or partial) life cycle accounting (i.e. including emissions from indirect upstream and downstream processes). The CarboNZero program is routinely used to consider some indirect business-related emissions from (for example) off-site generation of electricity, or emissions that occur as a consequence of business activities but from sources that it does not own or control. As for the fuel and residue burning related emissions mentioned in the previous paragraph, the algorithms and emission factors for these indirect sources are available and could be readily integrated into the other modelling frameworks.

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