NATIONAL ENERGY TECHNOLOGY LABORATORY

Documentation for the Calculating Uncertainty in Biomass Emissions Model, Version 2.0 (CUBE 2.0): Contents and Use

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DOCUMENTATION FOR THE CALCULATING UNCERTAINTY IN BIOMASS EMISSIONS MODEL, VERSION 2.0 (CUBE 2.0): CONTENTS AND USE

November 15, 2011

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Preface

About This Document

In an effort to reduce greenhouse gas (GHG) emissions from energy production in the United States, Congress has adopted legislation that requires the use of fuels derived from renewable resources and is considering legislation that would expand renewable requirements to electricity production. Because biomass-based energy is one major category of renewable technology under consideration, estimating the GHG emissions associated with candidate biomass feedstocks is important. Uncertainty in the actual GHG emissions associated with a biomass feedstock could lead to the adoption of policies that impose societal costs while yielding only marginal GHG-emission reductions, if any.

The U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) asked RAND to assess uncertainties in GHG-emission estimates by developing a life cycle assessment (LCA) model of biomass feedstock production that explicitly describes uncertainties in GHG-emission estimates. The Calculating Uncertainty in Biomass Emissions model, version 1.0 (CUBE 1.0) was released in March 2010 and made publicly available through NETL's website, along with the first version of this document. CUBE 2.0 updates the model and includes several additions and corrections to CUBE 1.0.[1] In particular, the functionality and scope have been expanded by adding two additional feedstocks (corn stover and hybrid poplar) and by increasing the potential complexity of processing and transport logistics as well as the number of user choices in these two life cycle stages.

This document is intended to serve as a complement to the extensive documentation contained in the model itself and to provide an overview that accompanies use of the model. This report (1) describes how users can navigate and find information in the model, (2) provides an overview of the structure of the model, and (3) provides a description of the variables and equations contained in the model. Documentation of source literature and default parameter values is provided in the model itself.

The construction of the model and this accompanying documentation were sponsored by the National Energy Technology Laboratory as part of a larger body of ongoing work in the area of assessing biomass resources and energy production potential. This work builds on earlier RAND Corporation efforts sponsored by the National Energy Technology Laboratory in energy technology assessment in general and in the area of biomass energy production in particular. The most relevant past studies are

[11] Both versions of the CUBE model can be obtained from http://www.rand.org/ise/projects/bioemissions.html.

- *Characterization of Biomass Feedstocks*, by David S. Ortiz, Henry H. Willis, Asha Pathak, Preethi Sama, James T. Bartis, RAND DRR-4440-NETL, 2008.

- *Calculating Uncertainty in Biomass Emissions Model, Version 1.0 (CUBE 1.0)*, by Aimee E. Curtright, Henry H. Willis, David R. Johnson, David S. Ortiz, Nicholas Burger, Constantine Samaras, 2010, http://www.rand.org/ise/projects/bioemissions/.

- *Supplying Biomass Energy Resources to Power Plants*, by Tom LaTourrette, David S. Ortiz, Eileen Hlavka, Nicholas Burger, and Gary Ceccine, TR-876-NETL, 2010.

- *Near-term Opportunities for Integrating Biomass into the U.S. Electricity Supply*, by David S. Ortiz, Aimee E. Curtright, Constantine Samaras, Aviva Litovitz, and Nicholas Burger, TR-984-NETL, 2011.

- "Incorporating Uncertainty Analysis into Life Cycle Estimates of Greenhouse Gas Emissions from Biomass Production," by David R. Johnson, Henry H. Willis, Aimee E. Curtright, Constantine Samaras, and Timothy Skone, *Biomass and Bioenergy*.

This research was conducted under the auspices of the Environment, Energy, and Economic Development Program (EEED) within RAND Infrastructure, Safety, and Environment (ISE).

Summary

In an effort to reduce greenhouse gas (GHG) emissions from energy production in the United States, Congress has adopted legislation that requires the use of fuels derived from renewable resources. States and localities have mandated the use of renewable-sourced electricity, and Congress is considering legislation that would expand this to a national requirement. Depending on the specific terms of such policies, incentives may be created that encourage or discourage the use of one renewable technology over another. Regardless of technology pathway, increased government and consumer expenditures relative to fossil-based alternatives could result from renewable mandates (National Research Council, 2009). Ultimately, the success of such policies in reducing GHG emissions will depend on the actual GHG intensity of the renewable technologies that are implemented.

Because biomass-based energy is one major category of renewable technology under consideration, estimating the GHG emissions associated with candidate biomass feedstocks is important. However, the level of GHG-intensity reduction achieved with biomass-based energy relative to fossil-based alternatives is highly dependent on the specifics of how the biomass is produced, transported, processed, and converted into usable fuel or electricity. Failure to account for uncertainty in the actual GHG emissions associated with a biomass feedstock could lead to the adoption of policies that impose societal costs while yielding only marginal GHG-emission reductions, if any. The U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) asked RAND to address this issue by developing a life cycle assessment (LCA) model of biomass feedstock production that explicitly describes uncertainties in GHG-emission estimates.

The Calculating Uncertainty in Biomass Emissions model, version 2.0 (CUBE 2.0) determines the life cycle GHG emissions of biomass feedstocks from planting the biomass to delivery to the bioenergy plant gate ("farm-to-hopper"). Included are emissions associated with feedstock production, transportation, and processing. Emissions associated with production of the fuel from the feedstock and the use of the fuel for transportation, electricity generation, or other purposes are not included within the system boundary. Therefore, this model would need to be used in conjunction with other means of assessing the GHG intensity of biomass conversion and fuel use in order to determine the entire life cycle emissions and associated uncertainties. The feedstocks in CUBE 2.0 include five dedicated energy crops (corn grain, corn stover, switchgrass [SG], mixed prairie biomass [MPB], and hybrid poplar) and two biomass residues (forest residue and mill residue).

The Calculating Uncertainty in Biomass Emissions model, version 1.0 (CUBE 1.0) was released in March 2010 and made publicly available through NETL's website, along with the first version of this document. CUBE 2.0 updates the model and includes several additions and corrections to CUBE 1.0.[2] In particular, the functionality and scope have been expanded by adding two additional feedstocks (corn stover and hybrid poplar) and by increasing the number and complexity of processing and transport choices. Major modifications are summarized in Table S.1.

As a complement to the extensive documentation contained in the CUBE 2.0 model itself, this report provides an overview intended to accompany use of the model. This report: (1) describes how users can navigate and find information in the model, (2) provides an overview of the structure of the model, and (3) provides a description of variables and equations contained in the model. Documentation of source literature and default parameter values are provided in the model itself and will be updated with any subsequently released versions of the model. As such, source literature is *not* referenced in this document.

The report is structured as follows: Section 1 contains introductory material; Section 2 contains a discussion of how uncertainty is represented in the model; Section 3 explains how to use the model; and Section 4 documents the calculations that are performed in the model. Detailed technical appendixes describing general model parameters (Appendix A) and each of the three farm-to-hopper stages—Production, Transportation, and Processing (Appendixes B, C, and D, respectively)—are also included. Model results and implications will be discussed in a forthcoming paper by these same authors and are therefore not presented herein.

[2] The CUBE model can be obtained from www.netl.doe.gov/energy-analyses and www.rand.org/ise/projects/bioemissions.html.

Table S.1. Major Changes in CUBE 2.0

Module (Submodule)	**Changes**	**Notes**
Production (Farming)	Two new feedstocks - Corn Stover - Hybrid Poplar	Corn Stover is correlated with Corn Grain
Production (Carbon Soil and Root Storage Rate)	New structure - Soil and root carbon are now separate rates	All calculations are now performed within CUBE 2.0 using cited, source-literature values[3]
Production (Local and External Sourcing)	New structure - Local and External sourcing regions	CUBE 1.0 included just locally obtained biomass
Transportation (Long-Haul Transport)	New structure and transport options - Trucking (new structure) - Rail or barge (new structure and user options)	Default version ties processed biomass to external biomass
Processing (Processing Method)	New processing methods - Crude torrefied biomass - Torrefied pellets	Default version now assumes pellets and both torrefied products are used for external biomass
Quick Start Guide for New Users	New module	Added a short in-model guide to use
Data Exporter	New module	Added a module to make exporting high-dimensionality analyses easier

[3] Some calculations were originally performed external to the model in CUBE 1.0, resulting in an unnoticed calculation error for the forest baseline ecosystem. The new structure aids transparency and minimizes the opportunity for errors to go unnoticed.

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1.0 INTRODUCTION

In an effort to reduce greenhouse gas (GHG) emissions from energy production in the United States, Congress has adopted legislation that requires the use of fuels derived from renewable resources. States and localities have mandated the use of renewable-sourced electricity, and Congress is considering legislation that would expand this to a national requirement. Depending on the specific terms of such policies, incentives may be created that encourage or discourage the use of one renewable technology over another. Regardless of technology pathway, increased government and consumer expenditures relative to fossil-based alternatives could result from renewable mandates (National Research Council, 2009). Ultimately, the success of such policies in reducing GHG emissions will depend on the actual GHG intensities of the renewable technologies that are implemented.

Because biomass-based energy is one major category of renewable technology under consideration, estimating the GHG emissions associated with candidate biomass feedstocks is important. The use of biomass can potentially lower the net GHG intensity of liquid fuel and electricity supplies by displacing the use of fossil fuels. Because growing biomass captures carbon dioxide (CO_2), the GHG emissions of energy production from biomass inputs can theoretically be negative. When used in conjunction with fossil fuels, biomass feedstocks can greatly reduce or eliminate net emissions, especially if carbon capture, utilization, and sequestration (CCUS) is utilized.

However, the level of GHG-intensity reduction achieved with biomass-based energy relative to fossil-based alternatives is highly dependent on the specifics of how the biomass feedstock is produced, transported, processed, and converted into usable fuel or electricity. Depending on the specific production scenario being considered, projected GHG emissions from the production of biomass will vary substantially. Failure to account for uncertainty in the actual GHG emissions associated with a biomass feedstock could lead to the adoption of policies that impose societal costs while yielding only marginal GHG-emission reductions, if any.

To understand how choices might affect the achievement of climate goals, it is important to assess uncertainties in GHG-emission estimates. This problem has increasingly been highlighted in the literature in recent years (Cherubini et al, 2009; Finnveden et al, 2009; Mullins, 2010; McKone et al, 2011). However, GHG estimates are often still reported as point values for specific scenarios, an approach that limits the ability to appreciate the range of possible outcomes associated with biomass energy mandates. The U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) asked RAND to address this limitation by developing a life cycle assessment (LCA) model of biomass feedstock production that explicitly describes uncertainties in GHG-emission estimates.

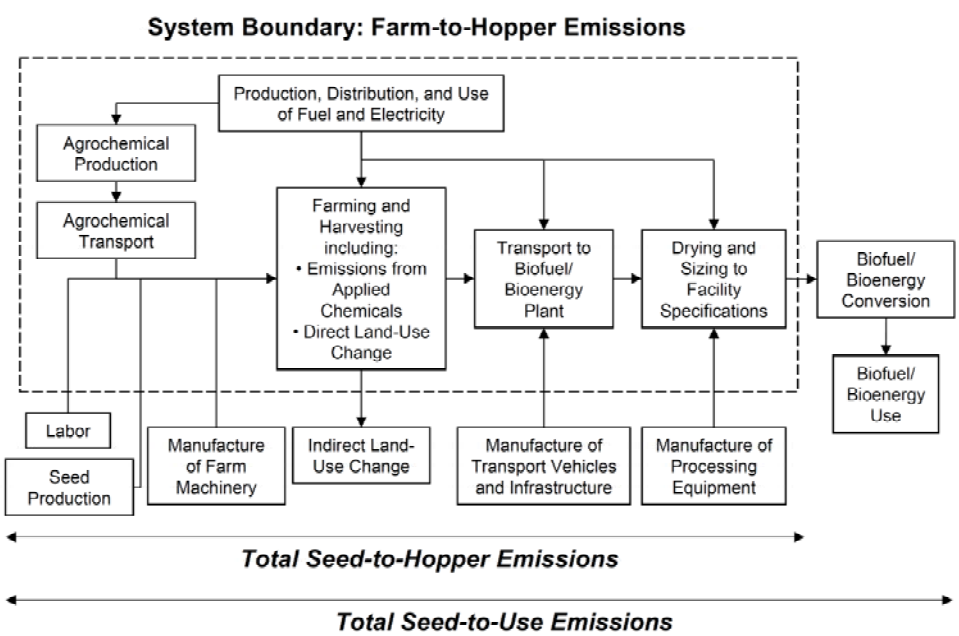
This report provides an overview intended to accompany use of the Calculating Uncertainty in Biomass Emissions model, Version 2.0 (CUBE 2.0). This report (1) describes how users can navigate and find information in the model, (2) provides an

overview of the structure of the model, and (3) provides a description of variables and equations contained in the model. Documentation of source literature and default parameter values is provided in the model itself and, for brevity, has therefore *not* been included in this document.

1.1 Model Overview

CUBE 2.0 was designed to facilitate examination of the sources and magnitude of uncertainties in GHG emissions resulting from cultivation, preparation, and delivery of biomass feedstocks and to allow exploration of the sensitivity of net emissions to these various uncertainties. The model determines the life cycle GHG emissions associated with biomass feedstocks from planting the biomass to delivery of prepared feedstock to the hopper of the energy-conversion facility ("farm-to-hopper"), as illustrated in Figure 1.1. Note that this includes emissions associated with "drying and sizing to facility specifications", including an option in the model to include feedstock grinding, if desired. Included in this characterization are emissions associated with feedstock production, transportation, and processing. Emissions subsequent to the plant gate—namely, those associated with production of the fuel from the feedstock and the use of the fuel for transportation, electricity generation, or other purposes—are not included within the system boundary. Therefore, this model would need to be used in conjunction with other means of assessing the GHG intensity of biomass conversion and fuel use in order to determine the entire life cycle GHG emissions. Key information and model assumptions are summarized in Box 1.1.

Figure 1.1. System Boundary of the Calculating Uncertainty in Biomass Emissions Model, Version 2.0 (CUBE 2.0)



Box 1.1. Model Characteristics

This box highlights important general characteristics for CUBE 2.0.

General Information

- *Scope:* calculates total GHG emissions associated with production of biomass feedstocks, from planting to delivery of conversion-ready biomass to the energy facility ("farm-to-hopper"), as indicated in Figure 1.1
- *Feedstocks:* five dedicated energy crops (corn grain, corn stover, switchgrass [SG], mixed prairie biomass [MPB], and hybrid poplar) and two biomass residues (forest residue and mill residue)
- *Purpose:* to allow direct comparison of how different assumptions about model structure, scenarios, or data affect total farm-to-hopper GHG emissions
- *Application:* comparison of different technology scenarios and policy implications
- *Temporal representation:* results given are annual emissions and generally vary based on the number of years since land conversion that is assumed; the user can also opt to view the sum of emissions over the first 30 years following the land use change.

"Fixed" Model Assumptions

- *Technology:* current "typical" technologies and crop yields are assumed
- *Global warming potential equivalents:* follows Intergovernmental Panel on Climate Change (IPCC)
- *Audience:* assumes that user has a basic knowledge of biomass utilization

Assumptions with Recommended Default Choices Designed for User Modification

- *Scale of operations:* the default consumption is 1 million dry tons/year (~2,700 dry tons/day).
- *Biomass sourcing:* Biomass is assumed to first be harvested in the vicinity of the conversion facility and transported by road vehicles; biomass needs that exceed local availability are sourced externally, pelletized, and transported via rail. All of these assumptions can be changed by the user.
- *Stover utilization:* Stover is assumed to be used as a feedstock in its own right, limited at 25 percent removal, which may affect allocation of GHG emissions to grain, depending on other assumptions; user can select to not assume stover utilization.
- *Co-product allocation:* "Marginal Production Allocation" of GHG emissions between corn grain and stover treats the latter as a pure residue (i.e., grain carries baseline emissions, and stover is penalized for only the additional marginal emissions associated with stover use); user can change settings to "Mass-Based Allocation."
- *Biomass drying:* assumes that waste heat is utilized and therefore assesses no GHG penalty; user can assume that a dedicated heat source is used instead.

The feedstocks in the CUBE 2.0 model are five dedicated energy crops (corn grain, corn stover, switchgrass [SG], mixed prairie biomass [MPB], and hybrid poplar) and two biomass residues (forest residue and mill residue). These feedstocks were selected based on their potential relevance to future energy planning and their representativeness of a broader set of potential energy crops. The model calculates the emissions associated with these seven feedstocks across three stages: production, transportation, and processing. Production emissions include those associated with farming—planting, harvesting, and collecting the biomass—as well as those related to land-use change and agrochemical

inputs.[4] Transportation emissions are those associated with moving the biomass to an energy-conversion facility, and processing emissions are those resulting from sizing and drying to meet specifications required for feedstock use at an energy-conversion facility. If biomass storage is needed prior to use, the model also accounts for storage losses and whether storage occurs before or after transport to the energy facility.[5] Note that model results are given in *annual* emissions that differ depending on how many years the user assumes have passed since land-use conversion; the user can also opt to view the results of a 30-year tally of emissions, none of which have been amortized or discounted and which simply represent the net GHGs for 30 years following land use conversion. The timeframe may be an important distinction because in many scenarios direct land-use change emissions are significant but decline with time after land-use conversion.[6]

The next section of this document contains a discussion of how uncertainty is accounted for and represented in the model (Section 2).[7] The remainder of this document explains how to use the model (Section 3) and what the model calculates (Section 4). Detailed technical appendixes describing general parameters (Appendix A) and each of the three farm-to-hopper stages—production, transportation, and processing (Appendixes B, C, and D, respectively)—are also included.

Note that this document does *not* include a comprehensive list of references to the source literature that informed the model inputs. These sources are referenced in detail in the model itself within each corresponding module, in the same location where numerical values for the various parameters can be found, and any subsequently released versions of the model will therefore contain current source-literature documentation. Note too that this document does *not* present the full range of model results or discuss result implications; one sample workflow with results does appear below in Section 3.3, the "Quick Start Guide for New Users".

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[4] Mill residue is treated as a pure residue, and, accordingly, all of the values in the Production module of this model are 0 for this feedstock. For forest residue, the only nonzero values in the Production module are associated with collection of the residues, which presumably would not occur in the absence of the utilizing the biomass for energy production.

[5] This is important because, depending on where they occur, storage losses can affect the amount of biomass that needs to be transported.

[6] A detailed discussion of the impact of these emissions, and their changes with time, can be found in Curtright *et al.* "Consideration of Direct Land-Use Change Emission Estimates in Biomass-to-Energy Life Cycle Analysis" (in preparation).

[7] A detailed treatment of the issue of uncertainty in LCA can be found in the publication by Johnson *et al.* (2011).

2.0 UNCERTAINTY IN LIFE CYCLE GREENHOUSE GAS EMISSIONS FROM BIOMASS FEEDSTOCKS

2.1 Introduction

Estimates of GHG emissions from biomass feedstocks should inform the policy debate on the use of biomass for energy production. LCA is one way to perform such estimates. However, the level of GHG-intensity reduction achieved with biomass-based energy relative to fossil-based alternatives depends on how the biomass feedstock is produced, transported, processed, and converted into usable fuel or electricity. Fortunately, uncertainty can be assessed and incorporated into LCA models. In all cases, data availability and scientific understanding of life cycle processes should guide the way in which that uncertainty is expressed. CUBE 2.0 was built to examine the sources and magnitude of uncertainty in GHG emissions in biomass feedstocks and to allow exploration of the sensitivity of net emissions to these various uncertainties.

The process of building this model highlighted a number of implications for the treatment of uncertainty in LCA, which we introduce in this section. Others have discussed uncertainty in LCA, increasingly highlighting the importance of this issue in recent years (Ciroth, 2004; Cherubini, 2009; Finnveden, 2009; Hung, 2009; Bojaca, 2010; McKone, 2011). A more detailed treatment of the specific issues we encountered in our work can be found in Johnson *et al.* (2011).

In our work, we discuss three types of uncertainty that are important to LCA: model uncertainty, scenario uncertainty, and data uncertainty. These types of uncertainty, and our approach to modeling them, are described in the next section. Second, there are limits to the precision of the GHG estimates provided by the model resulting from corresponding deficiencies in source data. Third, the absolute variability in the GHG estimates from the model is difficult to determine because of data gaps and incomplete scientific understanding. The limits to precision and to estimating variability are also discussed herein.

2.2 Types of Uncertainty in Life Cycle Assessment

There are three distinct types of uncertainty important to LCA that have been represented in our model. These are model uncertainty, scenario uncertainty, and data uncertainty (Morgan and Henrion, 1990).

2.2.1 Model Uncertainty

Modeling choices constitute the first type of uncertainty in LCA. These include structural decisions about the model system boundaries and scope as well as selection of how emissions are allocated across co-products. All LCAs implicitly address this type of uncertainty in the choices made by the modelers, and, in this way, model uncertainty can introduce biases in the results. Across the biomass LCA literature, studies make different assumptions about model structure. Because these modeling choices strongly affect model results, it is important that they be carefully considered by the modeler and made

completely transparent to the user. It is also useful to be able to assess how results change as assumptions about model structure are changed. Figure 1.1 in Section 1 summarized the modeling choices made in the CUBE 2.0 model with respect to system boundaries.

In this model, users make one important modeling choice by selecting from two approaches to allocate emissions between corn grain and corn stover co-products: (1) marginal production allocation or (2) mass-based allocation.[8] Assuming that stover is used as a biomass feedstock in its own right,[9] the model defaults to assigning only marginal production allocation to the stover—i.e., all of the baseline carbon debts associated with corn production are allocated to the grain, and the stover is penalized only for marginal changes in emissions that result from stover collection.[10] This allocation decision is applied to agrochemical inputs and to soil and root carbon loss in the model. The user can alternatively select to allocate these two sources of emissions between grain and stover based on the relative amounts of biomass harvested ("Mass-Based Allocation").[11]

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[8] Other allocation criteria are also possible, such as energy based and economic-value based allocation. Allocations based on economic value are not included because they rely on other dynamic factors beyond the scope of the model; markets may evolve quickly enough to make our model results obsolete, but results from the modeled allocation methods are more stable and easier to parameterize.

[9] The default model setting assumes stover use. Removal is limited, however, to 25 percent of total stover produced due to consideration for, among other things, minimization of soil carbon losses. (A brief discussion on the debate over the appropriate level of stover removal, and more information on how we arrived at a 25 percent value, can be found in the Proportion of Corn Stover Harvested submodule of the Corn Allocation Factor module.) The user can also choose to assume that stover is not utilized as a feedstock. However, this would have no impact on corn *grain* GHG emission calculations; it is equivalent to the decision to use stover and to select "Marginal Production Allocation," which assigns all carbon debts not associated directly with stover utilization to the grain. (The "Mass-Based Allocation" option is not relevant without stover removal.)

[10] The default setting allocates 100 percent of all non-marginal carbon debts to grain (i.e., the model treats stover as a pure residue and not a crop in its own right). This is consistent with the treatment of mill and forest residue in the model.

[11] It is assumed that corn plants produce grain and stover in a 1:0.89 mass ratio, but, because only 25 percent of stover is assumed to be harvested, the GHG-emission mass-allocation ratio is ~4.5:1 between grain and stover. See Mass Ratio of Corn Stover to Corn Grain and Proportion of Corn Stover Harvested submodules of the Corn Allocations Factors module for further detail and original citations.

Another important choice relating to model uncertainty involves which processes are included within the model scope. To address this, the user may also select whether to include a number of other parameters in the total emissions calculated. For example, the user can change the default inclusion of above-ground biomass losses that result from land-use change. This can be viewed as an allocation decision; if the biomass were used as an energy feedstock in its own right, the carbon in the material would be accounted for elsewhere. Similarly, the default settings of the model assume that biomass drying is accomplished using waste heat rather than a dedicated drying heat source. This again is an allocation choice, assigning the carbon debt associated with generating heat to the primary use.[12]

2.2.2 Scenario Uncertainty

The second type of uncertainty in LCA is due to different possible biomass production scenarios. Scenario uncertainty results from both unresolved system choices and unknowable outcomes, including:

- What type of biomass will be utilized?
- Where will the biomass be grown?
- What was the prior use of the land and how long since the use changed?
- Where will biomass be stored and processed?
- In what type of vehicle will the biomass be transported?
- How will GHG-emission policies allocate emissions across co-products and sectors?
- How much will vehicle and dryer efficiencies improve?
- What will the future energy infrastructure look like?

Whether or not a given scenario uncertainty is a yet-to-be made decision or an unknowable outcome depends on the user type and perspective, but in both cases they derive from uncertain future states of the world.

This model enables exploration of the impact of these uncertainties on GHG emissions by allowing the user to select different plausible future scenarios and to change scenario assumptions. This is a unique feature of the CUBE 2.0 model; most LCA addresses scenario uncertainty by incorporating preset modeling choices for many or all parameters in the model, whereas CUBE allows the user to explore different scenario choices and the GHG implications of those choices.

[12] These examples might also be viewed as scenario choices rather than boundary specifications or allocation decisions.

2.2.3 Data Uncertainty

The third source of uncertainty in LCA is associated with the empirical quantities used for variable inputs in the model. There are a number of reasons for this uncertainty, including random error, statistical variation, variability, randomness, and disagreement among experts (Morgan and Henrion, 1990). Input data will have a level of uncertainty that depends on the availability of information and scientific understanding for use in defining the given variable; accordingly, different variables can be expressed in different ways and with different levels of specificity.

This model allows for two approaches to modeling data uncertainty: a "Boundary" Analysis Type and a "Stochastic" Analysis Type.[13] Data with specified uncertainty have been input to the model either as (1) a set of minimum, mean or most likely, and maximum values (min/mean/max or min/most likely/max) or (2) mean values with a corresponding standard deviation or coefficient of variation. Availability of data is assessed qualitatively and used to determine which approach is most appropriate and determines the type of distribution that would most suitably apply to the given variable. When examining results in the "Boundary" analysis mode, sets of min/mean/max or min/most likely/max values are obtained.[14] In the "Stochastic" analysis mode, the data are represented as distributions, as appropriate to the input data, and results reflect statistical simulations drawn from these distributions.

2.3 Limits to Model Precision and Estimates of Variability

The limits to the precision of the GHG estimates provided in LCA result from limitations in the availability of source data. The precision of overall model results are dictated by the precision of the individual data sources that are utilized in the various model calculations. In this model, the inclusion of data with only two significant figures limits the overall precision of the model to 1 percent. In other words, incorporating uncertainty in parameters that would result in less than a 1-percent change in overall GHG emissions is not necessary because the changes in the model outputs that would result are indistinguishable from the precision of the data sources. Model precision could be improved through better data sources, improvements in scientific understanding, or elicitation of expert judgments. Table 2.1 indicates the precision of specific variables in the model and the types of data supporting them.

Variability of the model is determined by two factors: (1) known variance of parameter estimates in the model and (2) data gaps with respect to this variance. Where data allow,

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[13] "Boundary" Analysis Type is the default, and it is recommended that most users run in this default mode.

[14] "Most likely" in "Boundary" mode means that a point estimate is used for a given parameter which is equal to the most likely value of the stochastic distribution estimated.

the model reflects variability from known variance in parameter values. Unfortunately, the full variance of the model GHG estimates cannot be known because the variances of many parameters are not characterized. Table 2.1 summarizes the extent to which the variance of model parameters is assessed in the model.

Table 2.1. Precision and Variability of Selected CUBE 2.0 Model Parameters

Life Cycle Stage	Parameter Title	Data Source: Literature or Expert Judgment	Number of Significant Figures	Approach to Uncertainty
Production	SG Yield Scaling Factor	Both	2	Point estimate
	MPB Yield Scaling Factor	Both	2	Point estimate
	SG Yields	Literature	3	Bounded or stochastic
	MPB Yields	Literature	2	Bounded or stochastic
	Corn Grain Yields	Literature	4	Bounded or stochastic
	Forest Residue Yields	Literature	2	Bounded or stochastic
	Hybrid Poplar Yields	Both	3	Bounded or stochastic
	Carbon Soil and Root Storage Rate	Literature	4	Point estimate
	Stover Removal Carbon Storage Reduction	Literature	4	Point estimate
	Proportion of Corn Stover Harvested	Literature	2	Point estimate
	Mass Ratio of Corn Stover to Grain	Literature	2	Point estimate
	Storage Losses	Literature	2	Bounded
	Above-Ground Biomass Change	Literature	4 (Calculated)	Stochastic
	Benefit of Good Carbon Storage Practices	Both	1	Point estimate
	Energy Use for Farming	Literature	2	Point estimate or stochastic
	Chemical Use in Farming	Literature	3	Point estimate or

Life Cycle Stage	Parameter Title	Data Source: Literature or Expert Judgment	Number of Significant Figures	Approach to Uncertainty
				stochastic
	Energy to Produce Chemicals	Literature	3	Point estimate or stochastic
Production	Corn Grain Energy Use	Literature	3	Point estimate or stochastic
	Energy Use for Chemical Transport per Unit of Chemicals	Literature	3	Point estimate
	N_2O Gas Global Warming Potential	Literature	2–3	Point estimate
	N_2O Release Distribution Parameters	Literature	Calculated	Bounded or stochastic
	Lime ($CaCO_3$) Release Distribution Parameters	Literature	Calculated	Bounded or stochastic
	Supplemental Fertilizer for Stover Removal	Literature	4	Point estimate
	Carbon Density of Fuels	Literature	2	Point estimate
	Energy Density of Fuels	Literature	2	Point estimate
Processing	Energy Demands of Sizing	Literature	2–4	Point estimate
	Moisture Content Parameters	Literature	2	Bounded or stochastic
	Moisture Content Required for Processing Method	Literature	2	Point estimate
	Energy Required for Operating Dryer	Literature	2 (calculated)	Bounded or stochastic
Transportation	Bulk Density by Process	Literature	2–3	Point estimate

Life Cycle Stage	Parameter Title	Data Source: Literature or Expert Judgment	Number of Significant Figures	Approach to Uncertainty
NOTE: N_2O = nitrous oxide.				

3.0 HOW TO USE THE MODEL

3.1 Introduction

The CUBE 2.0 model described herein was developed in Analytica®, an object-oriented modeling environment developed by Lumina Decision Systems.[15] This platform was chosen for its ease of use, intuitive visual influence diagrams that illustrate each process in the life cycle, and flexibility in adding new components. The model was developed for use in analyzing biomass feedstock GHG-emission changes with variation of key input parameters and under alternative scenarios of how to produce, transport, and process biomass crops. A primary objective in construction of the model was to explicitly allow the user to explore the sources and magnitude of uncertainty in GHG emissions for the seven biomass feedstocks included: switchgrass, mixed prairie biomass, corn grain, corn stover, forest residue, mill residue, and hybrid poplar. This section provides a description of the general model structure and the user interfaces.[16]

3.2 Model Structure and General Information

The primary user interface of the model is shown in Figure 3.1. The data and calculations for the three stages that contribute to total farm-to-hopper GHG emissions—production, transportation, and processing—are contained in each of three modules (Production, Transportation, and Processing) that are accessible from this interface. The primary user interface provides access to various sections of the model, as described in Table 3.1.

[15] A free Analytica player for viewing and using this model can be downloaded from Lumina Decision Systems (http://www.lumina.com/support/downloads/).

[16] The CUBE model can be obtained from www.netl.doe.gov/energy-analyses or www.rand.org/ise/projects/bioemissions.html.

Figure 3.1. The Primary User Interface of CUBE 2.0

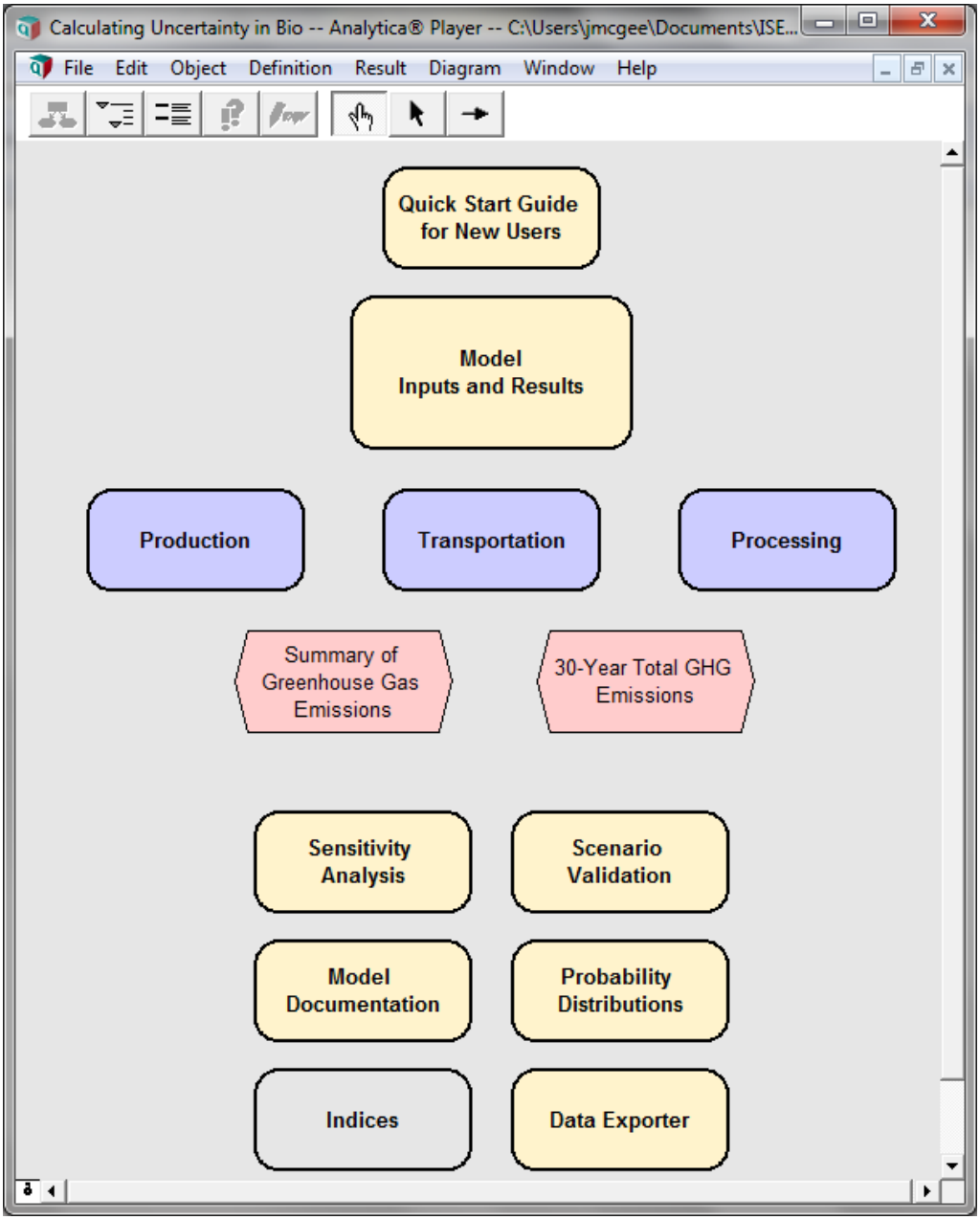


Table 3.1. Main User Interface: Functionality

Module	Action	Notes
Quick Start Guide for New Users	Read basic instructions for using the model, including a multi-step example workflow	This information is duplicated in the "Quick Start Guide for New Users" section below, and includes illustrative screen shots.
Model Inputs and Results	Manipulate model parameters in the data-entry interface; view detailed results	Described in more detail later in this section
Production Transportation Processing	View model structure and calculations	The structure and calculations of the model contained in these modules and the many variables and submodules therein are described in detail in Section 4 and in the appendixes.
Summary of Greenhouse Gas Emissions	View total GHG emissions of each of the farm-to-hopper stages and across the entire model	Farm-to-hopper includes: production, transportation, and processing
30-Year Total GHG Emissions	View total GHGs of each of the farm-to-hopper stages, across the entire model for 30 years following land-use change	Simple sum over 30 years, not amortized or discounted
Sensitivity Analysis	Conduct sensitivity analyses	This module is primarily intended to be a tool used during model development and modification. It allows the determination of a percentage change in a given output based on a specified change in a given input parameter. The modeler can use this module, for example, to determine (1) whether a new variable needs to be included to capture all significant emissions or (2) whether including uncertainty in a given parameter has a significant impact on the model results.[a]
Scenario Validation	View a complete list of invalid scenarios that generate error messages	This module is a central repository of checks for scenario choice combinations that are not logically consistent; these combinations generate and document error messages as an output.
Model Documentation	View model documentation	This module allows the user to (1) access a complete list of sources used to inform the model data inputs and calculations, (2) obtain a chronological listing of significant modifications and structural changes to the model, and (3) generate complete, exportable documentation of variables and modules from a portion of the model

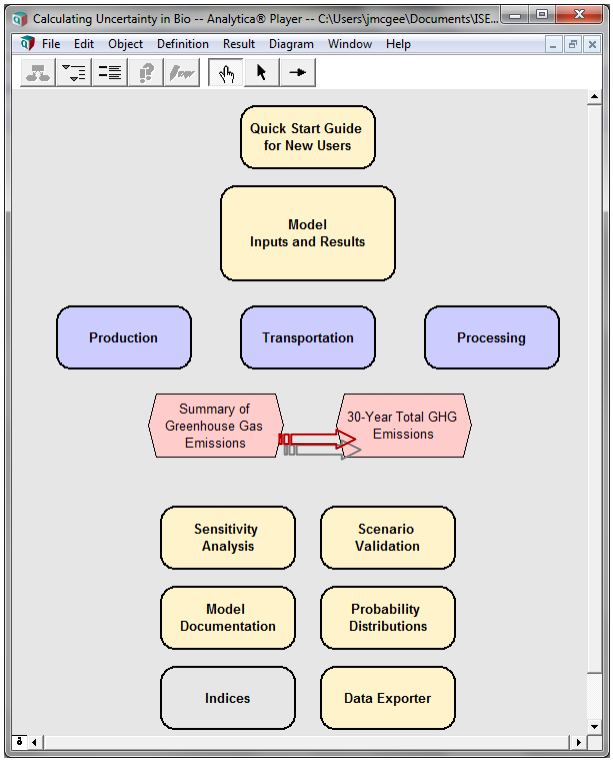
		of interest, including titles, definitions, descriptions, units, and values.
Probability Distributions	Input a user-specified correlation structure that defines the relationships between dependent variables in the model.	If the user specifies, for example, that Analysis Type be "Stochastic," the user also has a choice of whether or not the model treats probabilistic variables as independent. The default setting for Sampling Method in the data-entry interface is set to "Independent." However, if the user sets Sampling Method to "Correlated," the user must also use the Probability Distributions module to input a correlation structure that defines the relationships between dependent variables in the model. Currently, data do not exist to specify this correlation structure, so the default model assumes uncorrelated parameters.
Indices	View a complete listing of all parameters in the model that are indexed, with a brief description of the parameter and the values over which they are indexed	
Data Exporter	For exporting high-dimensionality analyses	For users with a player version of Analytica only, a free trial version of Analytica can be obtained to experiment with this functionality.
[a] *Significant* in this context refers to changes in the total farm-to-hopper emissions by 1 percent or more.		

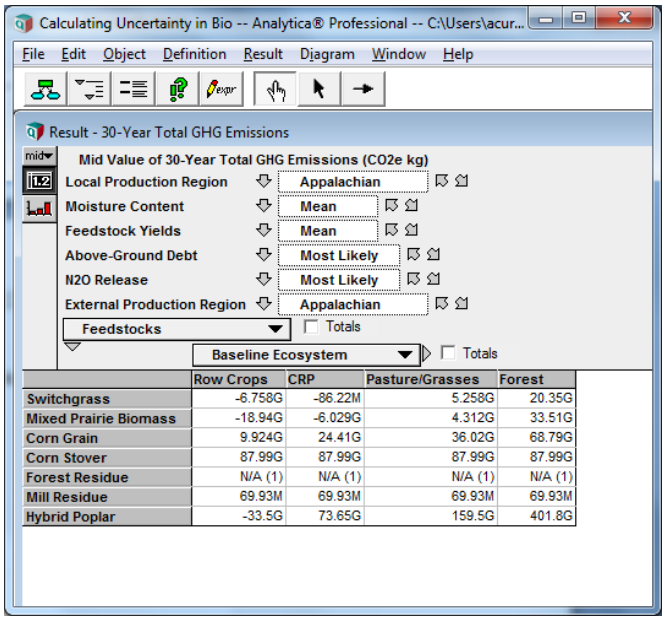
3.3 Quick Start Guide for New Users

CUBE 2.0 is structured as a series of modules encapsulating areas of related functionality, as summarized in Table 3.1 above. Each of these modules contains sub-modules, which in turn may have additional substructure, and so on. A few basic instructions for navigating Analytica are the following:

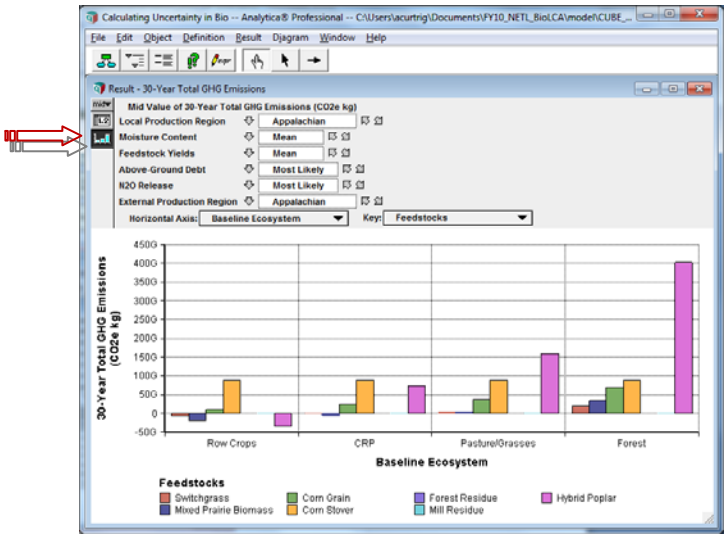
- To open a given module, double-click it.
- To go up one level (that is, to view the module which contains the currently visible sub-module), click the Diagram Window button in the top left of the Analytica window (i.e., the first button at the far left of the toolbar at the top of the window, which shows a green and blue image of an influence diagram and is indicated in Step 4 below) or type the F2 key.
- To evaluate the results of a given module, click the Show Result button (i.e., the fourth button in from the left of the toolbar, with a green image of "!?") or type the F5 key. For example, the two primary model outputs, the Summary of

Greenhouse Gas Emissions and 30-Year Total GHG Emissions, can quickly be obtained by clicking them once (to highlight) and clicking the Show Result button as follows:





	Row Crops	CRP	Pasture/Grasses	Forest
Switchgrass	-6.758G	-86.22M	5.258G	20.35G
Mixed Prairie Biomass	-18.94G	-6.029G	4.312G	33.51G
Corn Grain	9.924G	24.41G	36.02G	68.79G
Corn Stover	87.99G	87.99G	87.99G	87.99G
Forest Residue	N/A (1)	N/A (1)	N/A (1)	N/A (1)
Mill Residue	69.93M	69.93M	69.93M	69.93M
Hybrid Poplar	-33.5G	73.65G	159.5G	401.8G

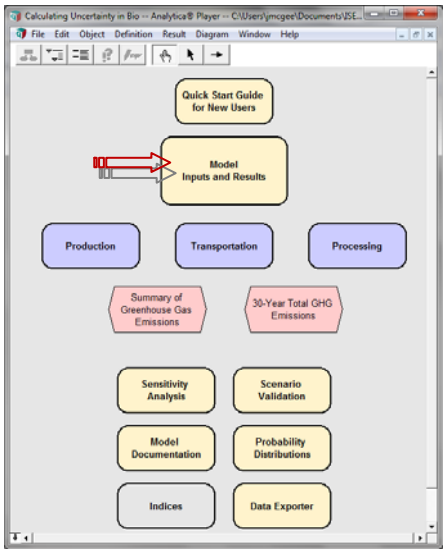


The full Analytica user manual can be accessed from the Help menu in the top ribbon of the model, or by typing the F1 key. An Analytica tutorial is also found under this Help menu.

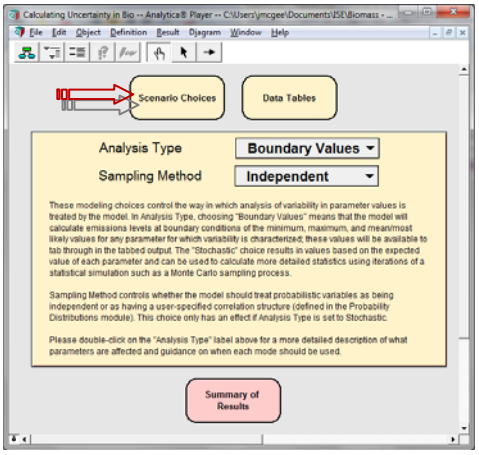
3.3.1 Using the Model

All functionality of CUBE 2.0 can be controlled through the Model Input and Results module. Opening this module and its various sub-modules allows the user to edit scenario choices, change settings, and run analyses. An example workflow follows, where the relevant modules described are indicated by the red arrows:

- Step 1: Double-click the Model Input and Results module to begin using the model:

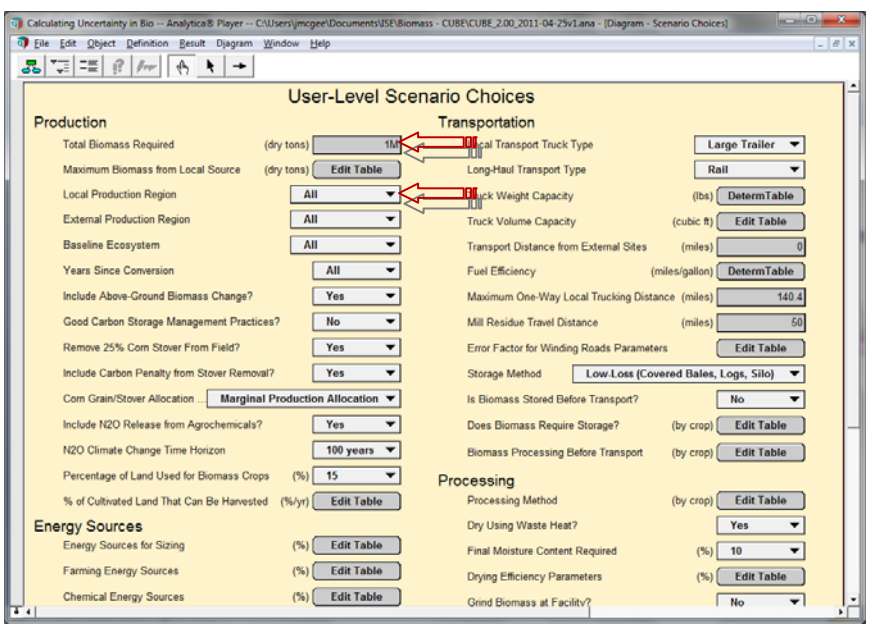


- Step 2: Double-click on the Scenario Choices module to view or adjust model settings related to the current analysis, including making changes to scenario assumptions and modeling choices:



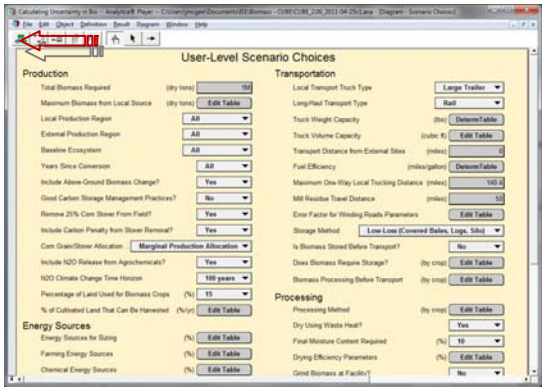
Note that the values in this Scenario Choices module are specifically intended for user modification. On the other hand, the parameters in the Data Tables module are provided primarily for the user's quick reference. It is not recommended that these values be changed without specific new information from the literature or in the case of user expertise on parameter values.

- Step 3: Adjust scenario choices, if desired, by typing in alternate numerical values or clicking on drop down menus and changing default settings:

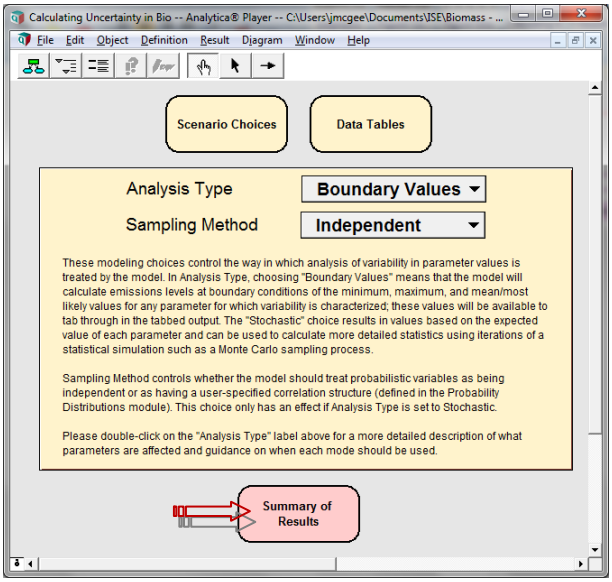


Note that making changes to scenario choices that increases dimensionality substantially, such as selecting “All” for the parameters listed in the Boundary Values Mode Indexes section of the Scenario Choices menu, may cause an Insufficient Memory error during the analysis stage due to memory limitations of the Analytica software. This is most likely to occur in the Boundary Analysis mode. The memory requirements of setting a parameter to “All” is approximately proportional to the number of possible values for that parameter; for example, “Baseline Ecosystem” has four possible values, so setting it to “All” increases the memory used by the model by a factor of four. Default settings have been selected to minimize the likelihood of this problem while still retaining high dimensionality for many of the most significant parameters.

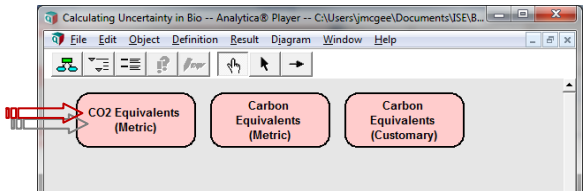
- Step 4: Return to the parent module by clicking on the Diagram Window function button in the top left of the Analytica window, or by using the F2 key:



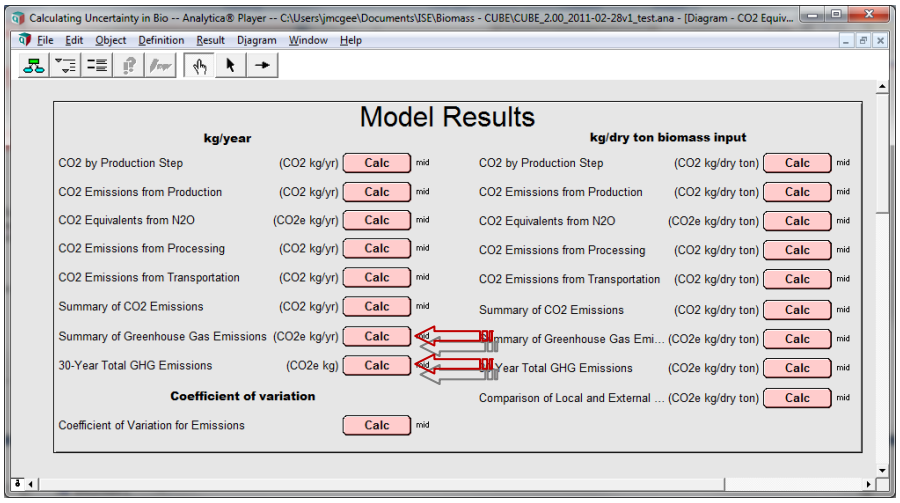
- Step 5: Double-click “Summary of Results” to choose an analysis to run.



- Step 6: Select the desired units for the results of the analyses. For example, double click on CO_2 Equivalents (Metric):



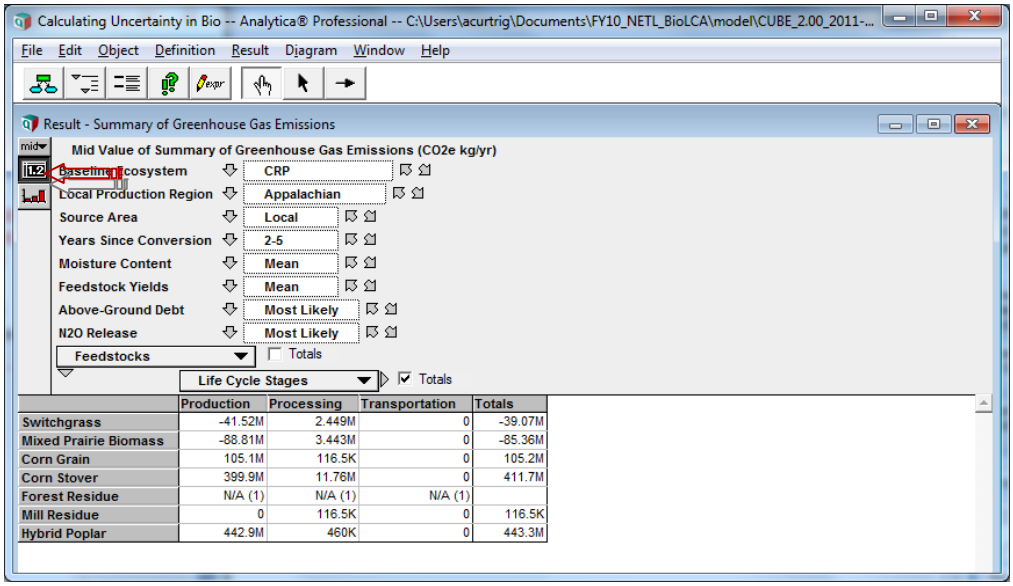
- Step 7: Select the desired analysis to run. For example, double click on the "Calc" button for the Summary of Greenhouse Gas Emissions or the 30-Year Total GHG Emissions:

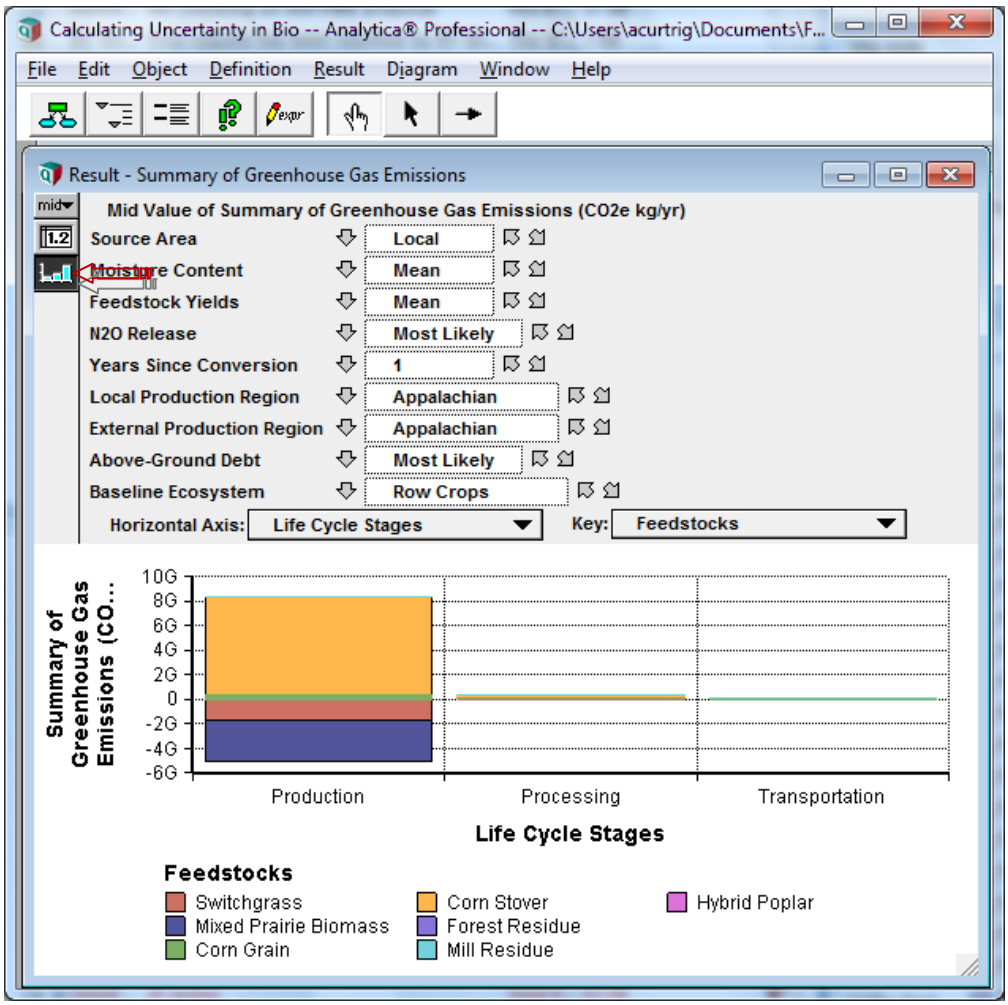


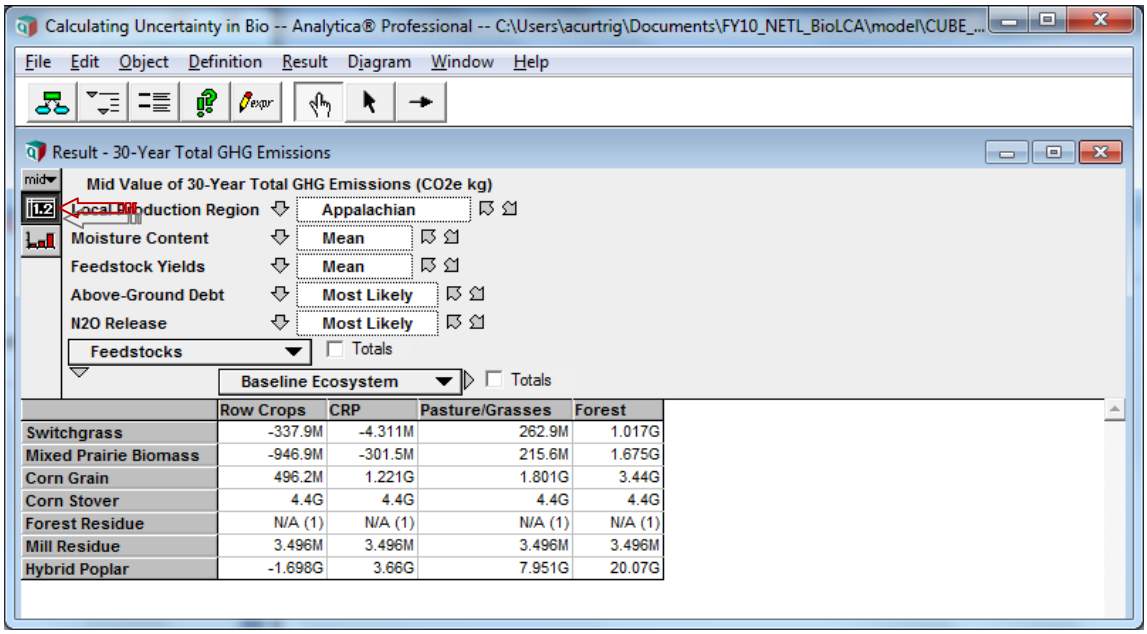
Note that, depending on scenario choices, some analyses with high dimensionality may take a substantial amount of time to run (on the order of one to two minutes) during which Analytica may appear unresponsive.

Note, too, that most calculations in this window are subcalculations of the total farm-to-hopper emissions calculations or are the same calculations expressed differently (i.e., on a per year vs. per ton basis).

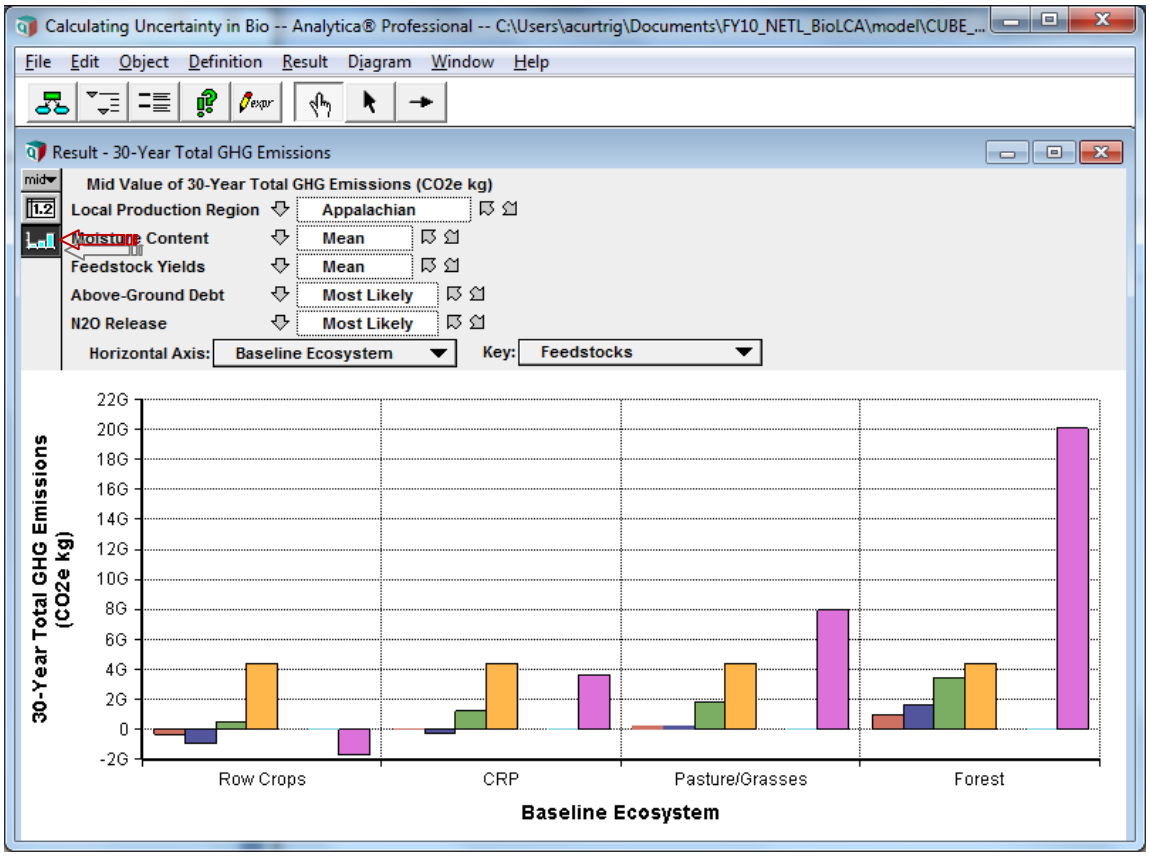
- Step 8: View results and/or export data. Results can be viewed in tabular or graphical form by clicking on the corresponding icons in the upper left corner of the results window. For example, for the Summary of Greenhouse Gas Emissions or the 30-Year Total GHG Emissions, respectively:


Calculating Uncertainty in Bio -- Analytica® Professional -- C:\Users\acurtrig\Documents\FY10_NETL_BioLCA\model\CUBE_2.00_2011-...
File Edit Object Definition Result Diagram Window Help
Result - Summary of Greenhouse Gas Emissions
Mid Value of Summary of Greenhouse Gas Emissions (CO2e kg/yr)
Baseline Ecosystem CRP
Local Production Region Appalachian
Source Area Local
Years Since Conversion 2-5
Moisture Content Mean
Feedstock Yields Mean
Above-Ground Debt Most Likely
N2O Release Most Likely
Feedstocks
Totals
Life Cycle Stages
Totals
Production Processing Transportation Totals
Switchgrass -41.52M 2.449M 0 -39.07M
Mixed Prairie Biomass -88.81M 3.443M 0 -85.36M
Corn Grain 105.1M 116.5K 0 105.2M
Corn Stover 399.9M 11.76M 0 411.7M
Forest Residue N/A (1) N/A (1) N/A (1)
Mill Residue 0 116.5K 0 116.5K
Hybrid Poplar 442.9M 460K 0 443.3M


Calculating Uncertainty in Bio -- Analytica® Professional -- C:\Users\acurtrig\Documents\F...
File Edit Object Definition Result Diagram Window Help
Result - Summary of Greenhouse Gas Emissions
Mid Value of Summary of Greenhouse Gas Emissions (CO2e kg/yr)
Source Area Local
Moisture Content Mean
Feedstock Yields Mean
N2O Release Most Likely
Years Since Conversion 1
Local Production Region Appalachian
External Production Region Appalachian
Above-Ground Debt Most Likely
Baseline Ecosystem Row Crops
Horizontal Axis: Life Cycle Stages
Key: Feedstocks
Summary of Greenhouse Gas Emissions (CO...
10G
8G
6G
4G
2G
0
-2G
-4G
-6G
Production
Processing
Transportation
Life Cycle Stages
Feedstocks
Switchgrass
Mixed Prairie Biomass
Corn Grain
Corn Stover
Forest Residue
Mill Residue
Hybrid Poplar



	Row Crops	CRP	Pasture/Grasses	Forest
Switchgrass	-337.9M	-4.311M	262.9M	1.017G
Mixed Prairie Biomass	-946.9M	-301.5M	215.6M	1.675G
Corn Grain	496.2M	1.221G	1.801G	3.44G
Corn Stover	4.4G	4.4G	4.4G	4.4G
Forest Residue	N/A (1)	N/A (1)	N/A (1)	N/A (1)
Mill Residue	3.496M	3.496M	3.496M	3.496M
Hybrid Poplar	-1.698G	3.66G	7.951G	20.07G



3.3.2 Nodes and Influence Diagrams

Analytica uses influence diagrams to represent information and convey information about the relationships between model inputs, intermediate calculations, and outputs. The

objects in these diagrams are referred to as *nodes*, and the connecting arrows indicate relationships and dependencies between nodes. Nodes are distinguished as variables versus modules by thin and thick outlines, respectively. *Variable nodes* contain a value, a table of values, or an expression. Analytica allows data and uncertainty to be represented as scalars, choices, parameters, or distributions.[17] *Modules* contain another influence diagram with multiple variables and possibly additional submodules; as such, modules incorporate model hierarchy and simplify structure. Nodes labeled in italics contain common input values used across several other parts of the model.

3.3.3 Use of Color and Shapes

Colors and shapes in the model indicate functionality and information type, as summarized in Table 3.2. Colors in CUBE 2.0 distinguish functionality of the given node: Yellow indicates an input, either data or a user choice; blue indicates an interim calculation node; pink is a result node. Node shape distinguishes the type of information and follows Analytica convention—namely, rectangles are decision nodes for input choices (not shown in Figure 3.1); rounded rectangles are variable nodes for either nonchoice data or interim calculations; ovals are chance nodes, which are variables modeled by a probability distribution (not shown); trapezoids are constants (not shown); and hexagons are objective nodes for viewing results.

[17] See the user guide (available at Lumina Decision Systems, undated) for more information on Analytica conventions and use.

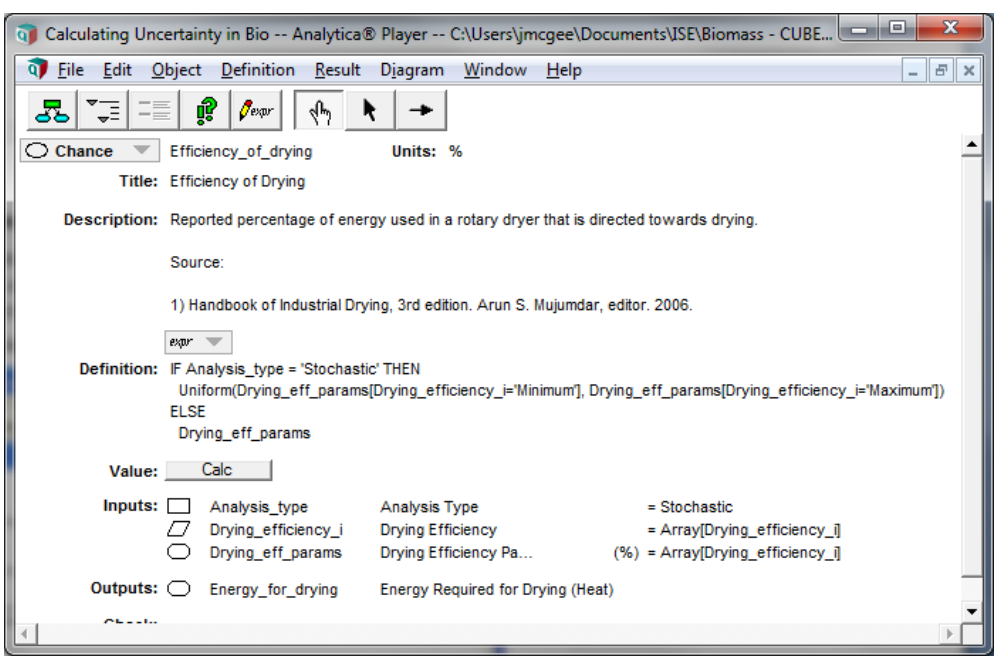
Table 3.2. Functionality and Information Type in CUBE 2.0, as Distinguished by Color and Shape

Appearance in Model	Functionality or Type of Information
Color	
Yellow	Input: data or user choice
Blue	Interim calculation
Pink	Results
Shape	
Rectangle	Decision nodes: input choices
Rounded rectangle	Variable nodes: nonchoice data or interim calculations
Oval	Chance nodes: variables modeled as probability distributions
Trapezoid	Constants
Hexagon	Objective nodes: model results

3.3.4 Documentation in the Model

The documentation of variables is fully contained within each node of the model. Figure 3.2 shows an example of the detailed documentation associated with one variable, the Efficiency of Drying object in the Processing module.

Figure 3.2. The Efficiency of Drying Variable of the Processing Module



In this documentation, the user will find

(1) the shape that indicates the type of information in the node—in this example, an oval "chance" variable

(2) the variable identifier, a short-form name for a node used in internal calculations and formulas that is no more than 25 characters, with words joined by underscores and only the first word capitalized—here, Efficiency_of_drying

(3) the units of the node value (e.g., dry tons/acre)

(4) the node's title or label, in plain English with capitalized words (e.g., Efficiency of Drying). These are also the node titles that appear in the influence diagrams.

(5) the variable description, including any calculations performed outside of the model to obtain the input values and any source literature.

(6) the variable definition, which is either a value or table of values if it is a data node or an expression in Analytica code if the node is an intermediate calculation; the example in Figure 3.2 contains an "IF…THEN" statement because chance nodes must handle uncertainty differently depending on whether the model is run with Analysis Type set to "Boundary" or "Stochastic."

(7) the value button, which allows the user to view the input data value(s) or the intermediate calculation value(s)

(8) a list of inputs and outputs that indicate how the node is connected to other nodes in the model.

In describing the variables and the calculations being performed by the model in the main body of this documentation, we reference the node title; equations and formulas in the appendixes are written in terms of the identifier. Identifiers are generally named as an abbreviated version of the node's title, but this is not always possible due to the length limit. In the appendixes, tables that list and describe the variables link each node's title and identifier.

3.4 Data-Entry Interface: Viewing and Modifying Model Parameters and Viewing Results

The data-entry interface of the model, shown in Figure 3.3, is located in the primary user interface in the Model Inputs and Results module. This data interface is described in Table 3.3.

Figure 3.3. Model Inputs and Results, the Data-Entry Interface of CUBE 2.0

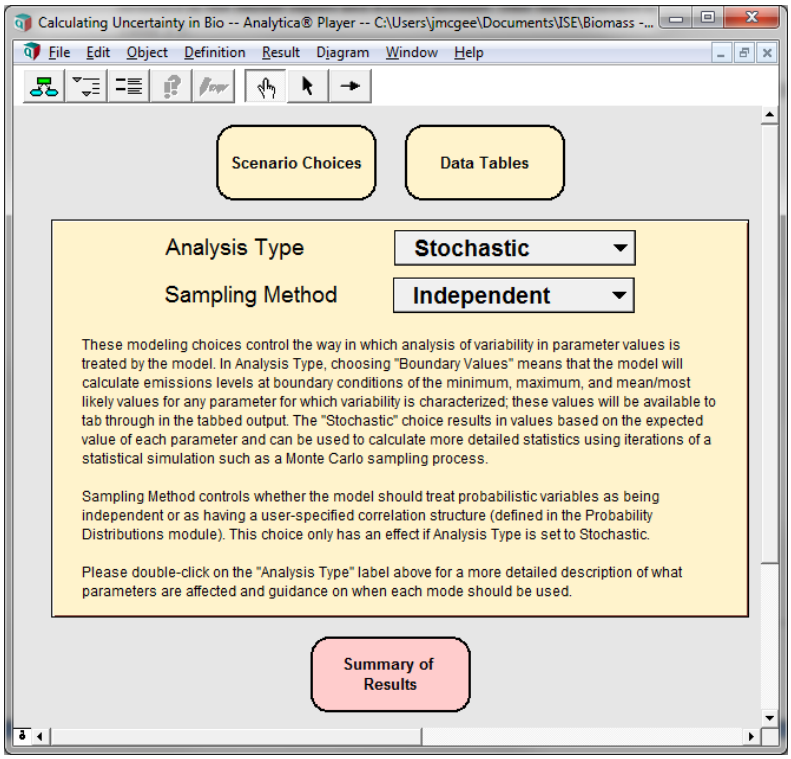


Table 3.3. Data-Entry Interface: Functionality

Module	Action	Notes
Scenario Choices	View all scenario choices that specify the assumptions made in the model and change these default assumptions. For some choices, the user can select a single value or "ALL"; in the later case, a toggle switch appears in the results table for scrolling through this choice.	The values in this module are specifically intended for user modification. However, increasing the dimensionality of parameters beyond what is specified in the default settings may cause Insufficient Memory errors, particularly while running a "Boundary" analysis."N/A" may appear in some cell results, which indicates an error or that the dimensions of that cell have an invalid or implausible combination of values. If the N/A is followed by a numeric value in parentheses, this code can be looked up in the Scenario Validation module for an explanation. "INF" indicates that the model will calculate the maximum theoretical value, subject to constraints built into the model.[18]
Data Tables	View the data tables of set literature values used by the model	The values in this module are provided primarily for the user's quick reference. It is not recommended that these values be changed without specific new information from the literature.
Analysis Type	Specify the analysis type	Users can decide whether to represent variability using "Boundary" or "Stochastic" as described in Section 2.2.3.
Sampling Method	Specify the way correlation among variables is modeled	"Independent" or "Correlated"; available only if Analysis Type = "Stochastic" as described in Table 3.2.
Summary of Results	Obtain the model results based on specifications made in the first	The user can opt to view the model output in different units (e.g., CO_2 versus carbon

[18] In other words, Maximum Biomass from Local Source will be calculated based on the Maximum One-Way Local Trucking Distance, which imposes a limit on how far away from the facility biomass can be sourced regardless of yield-based and land use-based availability. Thus, even if set to INF (infinite availability), some biomass may be sourced from the external region if the productive capacity within the economic radius of the facility is less than the required total tonnage.

	four areas	equivalents; metric versus U.S. customary) and over different portions of the model (e.g., individual steps in production, all steps in processing, overall GHG equivalents from farm to hopper).

3.4.1 Guidance on Exploring Scenario, Modeling, and Data Uncertainty

Users can explore uncertainty by changing default settings in the Data-Entry Interface module of CUBE. Within this module, the Scenario Choices submodule primarily contains a number of scenario uncertainties, but also some modeling choices and in the case of the Boundary Values Mode Indexes a few data uncertainties[19], that the user may wish to modify. The Data Tables submodule has been assembled primarily for the user's reference; these values will not likely be changed by the typical CUBE user. Table 3.4 provides some examples of the types of uncertainty represented by the variables in these two submodules, as well as whether or not the user might expect these variables to be exogenous factors (i.e., parameters which may be beyond their control but which nevertheless influence net GHG emissions), decision-based parameters (e.g., biomass producer choices, scenario choices subject to policy levers), or system parameters (i.e., variables that may not be uncertain but which need to be specified to run an analysis).[20] Note that most variables that are a decision-based parameter for one type of user will necessarily be exogenous to another, and vice versa.

3.4.2 Limitations of the Model

All of the numerical values and structural assumptions that informed the Scenario Choices and Data Tables in CUBE 2.0, as well as the model at large, were based on the modeling team's understanding of the current literature at the time of the model's release. This understanding was augmented by consultation with experts in the field, and the resulting model has been subjected to peer review, so this information is accurate to the best of our knowledge and understanding. Since many default and recommended values (and their associated uncertainties) are based on this current understanding in a fast moving field, many of these numbers may need to be updated in the future. Additional scientific study will undoubtedly impact parameter values and the magnitude of

[19] Several *data* uncertainty parameters have been placed in the Scenario Choices module in order to improve the performance of CUBE. See the Note About Changing Boundary Values Mode Indexes module at the bottom of the Scenario Choices window for more information.

[20] For further discussion of these distinctions and the corresponding framework for uncertainty, see Lempert et al. (2003).

uncertainty around those values in many areas, such as the rate of N_2O volatilization of nitrogen fertilizers.

Additionally, some of these scientific uncertainties are the subject of debate, and some users may wish to explore the implications of assumptions that differ from the ones made herein (e.g., the impact of management practices on soil carbon sequestration). Finally, there are some important factors which may not be included in this analysis at all, although we have strived to include everything that is important to net "farm-to-hopper" feedstock emissions. Notably, indirect land-use change emissions are *not* included in CUBE 2.0 because, while they may be significant in magnitude, it is virtually impossible for us to speculate on the likelihood of them occurring; accordingly, they are considered to be out of scope.

A final note is that CUBE may be underestimating uncertainty in some scenarios since not all parameters in the model have associated ranges or distributions (see Table 2.1). Bounding and stochastic analysis are therefore necessarily only performed with respect to certain parameters. However, in all cases where a parameter does not explicitly include a range, the potential uncertainty was deemed to be insignificant relative to the overall precision of the model, or the uncertainty for the given parameter is expressed as a scenario choice rather than as a range on a single scenario value. In either case, pending future updates to CUBE, the information contained in CUBE 2.0 should be considered a static snapshot in an evolving field.

Table 3.4. Examples of Types of Uncertainty Represented in CUBE

Parameter (Parent Modules)	**Type of Uncertainty: Model, Scenario, Data**	**Exogenous (X), Decision-Based (D), or System Parameters (S)**
Total Biomass Required (Production/Scenario Choices)	Scenario	X or D
Baseline Ecosystem (Production/Scenario Choices)	Scenario	X, D, or S
Years Since Conversion (Production/Scenario Choices)	Model or Scenario	S
Include Above-Ground Biomass Change? (Production/Scenario Choices)	Model or Scenario	X or D
Corn Grain/Stover Allocation (Production/Scenario Choices)	Model	X or D
Farming Energy Sources (Production/Scenario Choices)	Scenario	X, D, or S
Local Transport Truck Type (Transportation/Scenario Choices)	Scenario	X or D
Maximum One-Way Local Trucking Distance (Transportation/Scenario Choices)	Scenario	X or D
Processing Method (Processing/Scenario Choices)	Scenario	X or D
Lime Release Rate[21] (Production/Scenario Choices)	Data	S

[21] Note that this parameter is one of the *data* uncertainties represented in the Scenario Choices module in order to improve the performance of CUBE.

Mass Ratio of Corn Stover to Corn Grain (Production/Data Tables)	Data	S
Energy Demands of Sizing (Processing/Data Tables)	Data	S

4.0 WHAT THE MODEL CALCULATES

4.1 Summary of Greenhouse Gas Emissions Calculations

Variables and calculations in the model fall into the three modules—Production, Transportation, and Processing—corresponding to the three stages of the same names. For a given biomass feedstock under a given set of scenario choices, the total farm-to-hopper emissions are the sum of emissions across these three stages:[22]

Summary of Greenhouse Gas Emissions = Production + Transportation + Processing. (4.1)

Positive values of carbon emissions correspond to net GHG emissions (a carbon debt or penalty), and negative emissions indicate carbon storage (a carbon credit). Model results are given in *annual* emissions that, for non-residue feedstocks, will differ depending on how many years the user assumes have passed since land-use conversion.[23] The model default is to calculate annual emissions in years 2–5 since the land-use change to the current biomass feedstock production. The user can also tabulate the total of (non-discounted) emissions for the first 30 years following land-use conversion.

The following three sections describe the calculations being performed by the model to yield the net GHG emissions from a given life cycle stage. Further detail of the calculations performed can be found in the appendixes, including tables that list and define all variables utilized by the model; variables that affect emissions in more than one stage of the life cycle are included in Table A.1 in Appendix A, and variables specific to each of the three stages can be found in Appendixes B, C, and D for the Production, Transportation, and Processing modules, respectively.

4.2 Production Calculations

Production emissions in CUBE 2.0 include GHG emissions associated with planting, growing, and harvesting the biomass feedstock. These include chemical inputs, such as fertilizers and any soil carbon storage or loss associated with direct land-use changes. The screen shot of the Production module influence diagram is shown in Figure 4.1. This module sums the total emissions from each of the four submodules that contribute to overall production emissions, and outputs total emissions indexed by biomass feedstock and scenario choices (e.g., geographic region, baseline ecosystem), as follows:

---

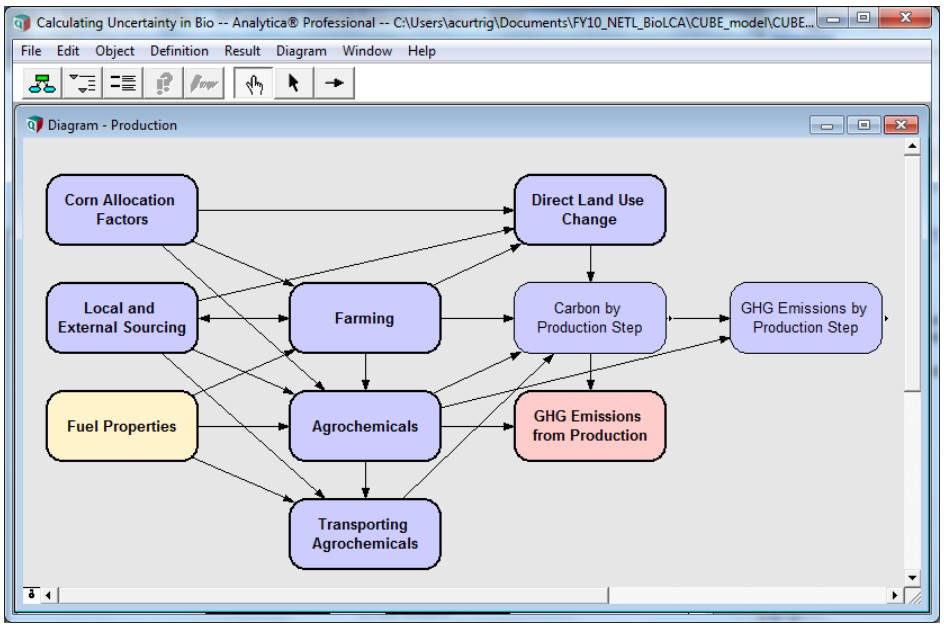
[22] In this equation and throughout the main body of the documentation, the variables and modules are referred to by the actual node title found in the model. In the main text, these names are title-cased, e.g., Title of Node. In the appendixes, variable identifiers are used. The appendixes also contain tables that link node title to node variable identifiers.

[23] This temporal difference does not apply to forest residue or mill residue since they are assumed to induce no land-use changes

Production = Farming + Direct Land Use Change + Agrochemicals + Transporting Agrochemicals. (4.2)

The calculations performed in each of these four submodules are described next.

Figure 4.1. Production Module of CUBE 2.0



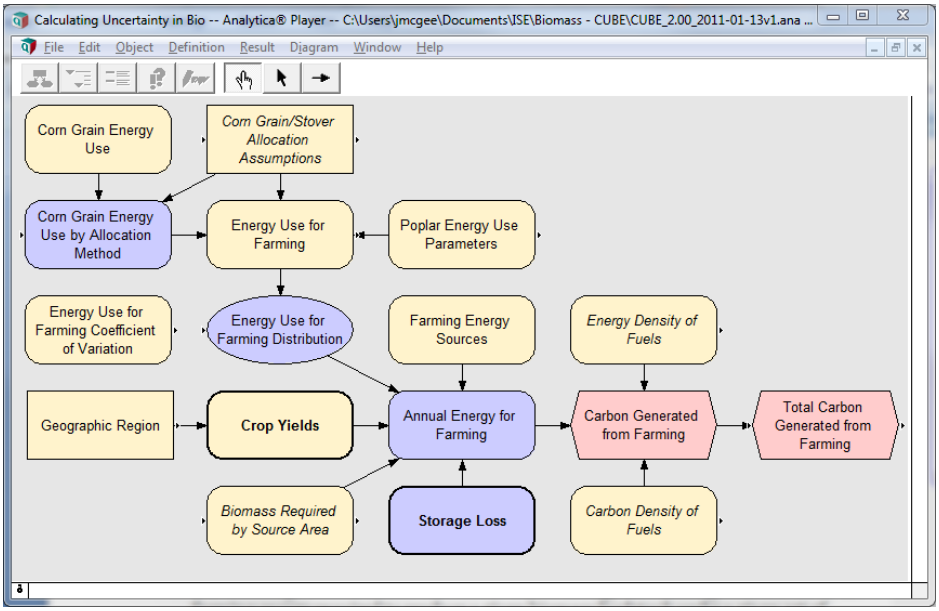
4.2.1 Submodule Calculations of the Production Module

Calculations in the six submodules of the Production module—Farming, Direct Land Use Change, Agrochemicals, Transporting Agrochemicals, Local and External Sourcing, and Corn Allocation Factors—are described in the following six sections. Further detail on all six of these submodules can be found in Appendix B.

The Fuel Properties submodule is located in the Production module and is described in Appendix B, but its submodules are also utilized in the Transportation and Processing modules.

Calculation of Emissions from Farming. Farming emissions include those associated with planting, growing, and harvesting the biomass feedstocks, excluding chemical inputs and the transport of these chemicals to the site of use. The Farming submodule is shown in Figure 4.2.

Figure 4.2. Farming Submodule of the Production Module



The Farming submodule first calculates Annual Energy for Farming, which is the total farming energy required to produce a given biomass feedstock under a given set of scenario choices. Based on Biomass Required, Crop Yields, and the expected biomass Storage Loss, the annual required acreage is determined. These values are then scaled by the per-acre energy intensity of the farming processes (the Energy Use for Farming) and apportioned among various Farming Energy Sources to give the final Annual Energy for Farming value, as follows:

$$\text{Annual Energy for Farming} = (\text{Biomass Required} \div \text{Crop Yields}) \times \text{Storage Loss} \times \text{Energy Use for Farming Distribution} \times \text{Farming Energy Sources}. \quad (4.3)$$

Each of these contributions to Annual Energy for Farming is then converted to a net-GHG emissions value[24] based on Energy Density of Fuels and Carbon Density of Fuels, yielding the Carbon Generated from Farming values across all feedstocks and geographic regions as follows:

[24] The model result at this point is the total emissions from production, separately tallied for the local and external tonnages required to meet the total biomass tonnage and subject to any constraints on local production. These are imposed exogenously by the user or, in the default case, by the size of the economically feasible local collection area.

Carbon Generated from Farming = Annual Energy for Farming × (Energy Density of Fuels ÷ Carbon Density of Fuels). (4.4)

Note that corn grain feedstock is distinguished in the model from other feedstocks because of the potential use of corn stover as a biomass feedstock in its own right. As such, the model explicitly allows the user to vary the allocation of GHG emissions between corn grain and corn stover; this allocation choice affects the Corn Grain Energy Use by Allocation Method variable. Further details of the Farming submodule calculations, and the complete list of variables utilized to determine total emissions in the Farming submodule, can be found in Appendix B.

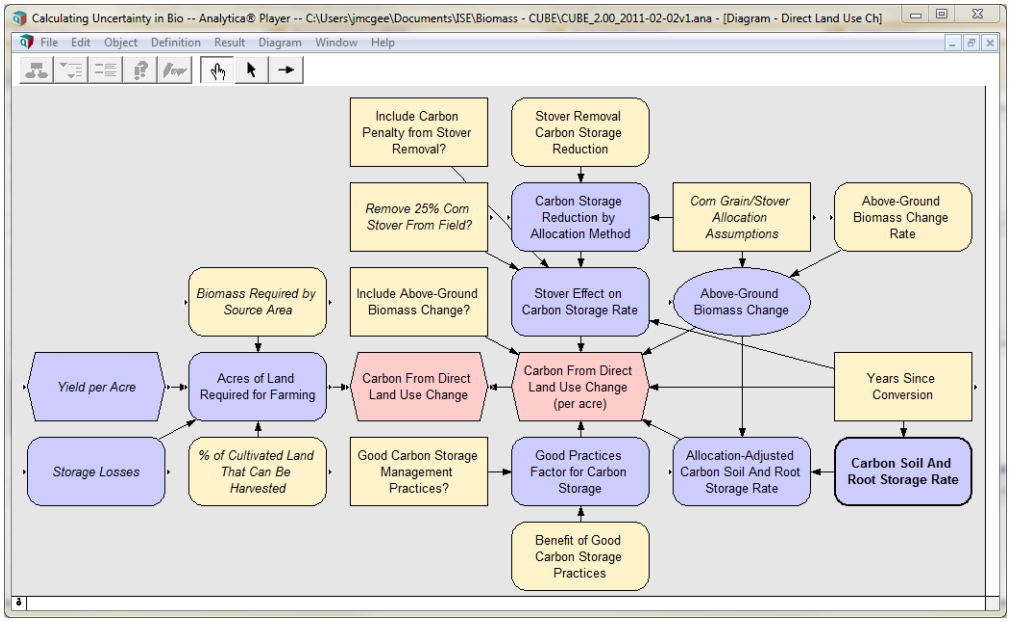
Calculation of Direct Land-Use Change Emissions. The Direct Land Use Change submodule accounts for the GHG penalty or credit associated with any direct land-use change that results when a given biomass feedstock is grown on a specific baseline ecosystem.[25] This GHG penalty or credit is due to (1) relative loss or gain of above-ground biomass and (2) relative loss or gain of below-ground biomass, including both soil and root carbon. In this model, the above-ground biomass loss is assumed to occur in the first year after land-use change and to result in a complete conversion of the biomass to GHG emissions.[26] The full below-ground biomass carbon penalty or credit occurs in this model over a 100-year time span, with rates that decline over the course of that time period as indicated in the literature.[27] The Direct Land Use Change submodule is shown in Figure 4.3.

[25] Indirect land-use changes that result from converting a baseline ecosystem to a new use are *not* within the scope of this model. These emission values are highly uncertain and are potentially large in magnitude (Fargione et al., 2008; Searchinger et al., 2008). The uncertainties in ILUC emissions are, in part, a result of global economic forces which CUBE does not attempt to incorporate and which cannot be accurately predicted.

[26] The user can opt to change this assumption of above-ground biomass conversion to GHG emissions by selecting “no” for the “Include Above-Ground Biomass Change?” scenario choice; this would be appropriate, for example, if the biomass was itself utilized as a fuel feedstock.

[27] A detailed discussion of the impact of these emissions, and their changes with time, can be found in Curtright *et al.* “Consideration of Direct Land-Use Change Emission Estimates in Biomass-to-Energy Life Cycle Analysis” (in preparation).

Figure 4.3. Direct Land Use Change Submodule of the Production Module



The Direct Land Use Change submodule first calculates the Carbon Soil And Root Storage Rate as the sum of the Annual Root Carbon Storage and Annual Soil Carbon Storage. Each of these is calculated similarly:

Annual Root Carbon Storage = (Root Carbon Starting Level – Root Carbon Equilibrium Level) × Root Storage Over Time / Length of Time Block (4.5)

Annual Soil Carbon Storage = (Soil Carbon Starting Level – Soil Carbon Equilibrium Level) × Soil Storage Over Time / Length of Time Block (4.6)

This rate is then added to the Stover Effect on Carbon Storage Rate and scales this value by the Good Practices Factor for Carbon Storage. This value is then added to the Above-Ground Biomass Change value, and the entire term is scaled by the land required to meet the biomass need by multiplying by the Acres of Land Required for Farming, as shown in the following equation:

Direct Land Use Change = [(Carbon Soil And Root Storage Rate + Stover Effect on Carbon Storage Rate) × Good Practices Factor for Carbon Storage + Above-Ground Biomass Change] × Acres of Land Required for Farming. (4.7)

The Stover Effect on Carbon Storage Rate applies a soil and root carbon penalty associated with the removal of stover; however, note that, in this version of the model,

the Stover Effect on Carbon Storage Rate default value is 0 because the Corn Grain/Stover Allocation Assumptions value is set to "Marginal Production Allocation" and, therefore, this marginal debt is applied to corn stover only[28]. Note also that the Good Practices Factor for Carbon Storage, which would theoretically assign a soil and root carbon benefit to "good" agricultural practices, is not included under the default settings of the model.[29] Finally, the Above-Ground Biomass Change is nonzero only in the first year after conversion to the present feedstock crop, while the default model calculations are for years two through five. Therefore, when using the default model assumptions, the calculation simplifies to

$$\text{Direct Land Use Change} = \text{Carbon Soil And Root Storage Rate} \times \text{Acres of Land Required for Farming.} \quad (4.8)$$

Further details of the Direct Land Use Change submodule calculations, and the complete list of variables utilized to determine total emissions in the Direct Land Use Change submodule, can be found in Appendix B.[30]

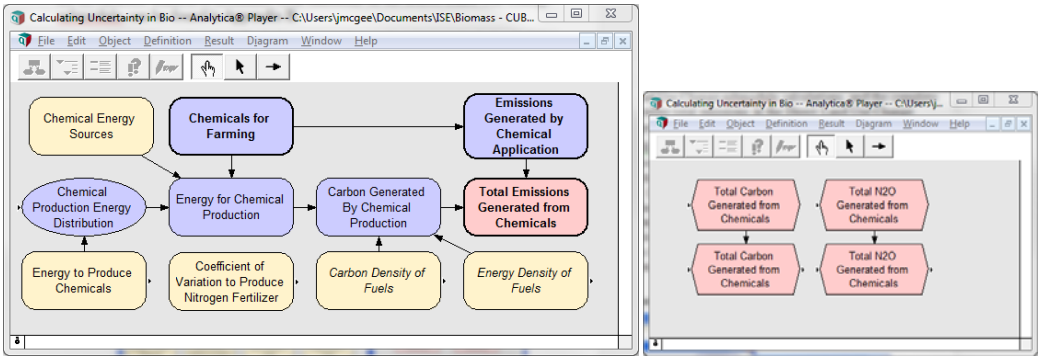
Calculation of Agrochemical Emissions. Agrochemical emissions include all GHG emissions associated with the use of fertilizers and pesticides for the production of biomass feedstocks, excluding their transportation to the use site. This module includes two distinct types of emissions: (1) carbon emissions associated with the energy required for production of agricultural chemicals, and (2) emissions resulting from the volatilization of certain agrochemicals from the field, including both CO_2 emissions associated with $CaCO_3$ application and N_2O emissions associated with direct and indirect volatilization of excess nitrogen fertilizer. The Agrochemicals submodule, and the Total Emissions Generated from Chemicals submodule contained therein, is shown in Figure 4.4.

[28] The model allows the user to change the allocation of this Stover Effect on Carbon Storage Rate to be partially attributed to the corn grain by selecting "Mass-Based Allocation" if desired.

[29] This is due to controversy in the literature. Recent results indicate that positive effects of good management practices on soil carbon, such as no-till farming, may in fact be artifacts of incomplete or inconsistent sampling methods.

[30] As noted, results are tallied separately for locally and externally produced biomass feedstocks.

Figure 4.4 Agrochemicals Submodule of the Production Module



Carbon emissions from energy use are calculated in the Carbon Generated By Chemical Production variable and are tallied in the Total Emissions Generated from Chemicals submodule as the first component of Total Carbon Generated from Chemicals; CO_2 emissions from lime are calculated in one submodule of the Emissions Generated by Chemical Application submodule and are tallied as the second component of Total Carbon Generated from Chemicals. The sum of carbon emissions for the Agrochemicals module is therefore

Total Carbon Generated from Chemicals = Carbon Generated By Chemical Production + Carbon Released From Lime. (4.9)

N_2O emissions from nitrogen fertilizer are also calculated in the Emissions Generated by Chemical Application submodule but are tallied as a separate set of emissions in Total N_2O Generated from Chemicals.

The calculations that lead up to these final tallies are described in the next two subsections, on Total Carbon Generated from Chemicals and Total N_2O Generated from Chemicals.

Total Carbon Generated from Chemicals. As noted, this submodule combines two contributions to determine the Total Carbon Generated from Chemicals:

Total Carbon Generated from Chemicals = Carbon Generated By Chemical Production + Carbon Released From Lime. (4.10)

The Agrochemicals submodule determines the first type of emissions, the Total Carbon Generated from Chemicals, based on the amount of chemicals utilized and the energy used to produce them. The total amount of chemicals used, calculated in the Chemicals for Farming submodule, is based on the chemicals required per ton of biomass produced, the Chemical Use in Farming, and the Biomass Required scaled by Storage Losses, as follows:

Chemicals for Farming = Chemical Use in Farming × Biomass Required ÷ Storage Losses. (4.11)

These chemical amounts are then converted to equivalent amounts of energy required to produce them—Energy for Chemical Production. This calculation utilizes the energy intensities of chemical production, the Chemical Production Energy Distribution values, and different assumed ratios of Chemical Energy Sources for each material:

Energy for Chemical Production = Chemicals for Farming × Chemical Production Energy Distribution × Chemical Energy Sources. (4.12)

Finally, the total energy required is converted to carbon intensity as follows:

Carbon Generated By Chemical Production = Energy for Chemical Production × (Energy Density of Fuels ÷ Carbon Density of Fuels). (4.13)

The second type of emissions, Carbon Released From Lime, is calculated based on the lime component of Chemicals for Farming values and the Lime Release Rate, as follows:

Carbon Released From Lime = Chemicals for Farming [Lime] × Lime Release Rate. (4.14)

Note that this second term is relevant only to corn production, which requires the periodic addition of $CaCO_3$ to counteract acidification of the soil by nitrogen fertilizers.

Total N_2O Generated from Chemicals. The final set of emission values in the Agrochemicals submodule is calculated in the N_2O Release submodule, which determines a percentage of the total applied nitrogen fertilizer, which was determined in Chemicals for Farming, as follows:

Total N_2O Generated from Chemicals = Nitrogen Fertilizer (of Chemicals for Farming) × N_2O Release Rate. (4.15)

This value is also converted to a value for Carbon Equivalents from N_2O for use in the calculation of the Summary of Greenhouse Gas Emissions values. This calculation is based on the N_2O Climate Change Time Horizon and the most recent IPCC values for N_2O Gas Global Warming Potential as follows:

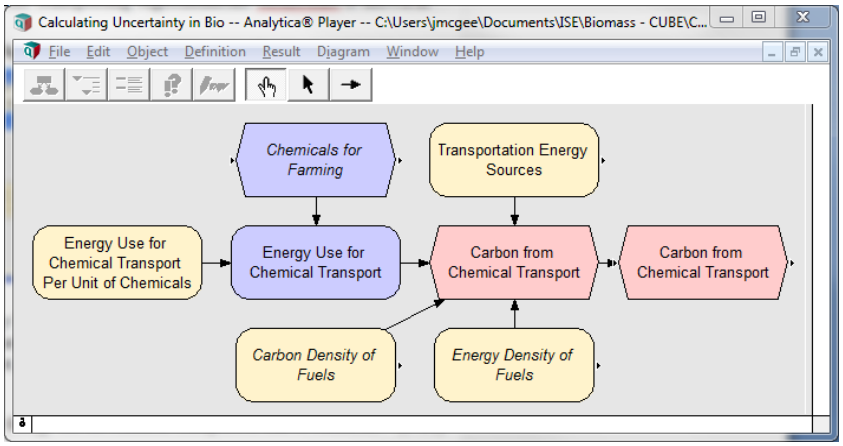
Carbon Equivalents from N_2O = N_2O Gas Global Warming Potential × N_2O Released. (4.16)

Note that the separation of the two Agrochemicals module outputs, Total Carbon Generated from Chemicals and Total N_2O Generated from Chemicals, is retained throughout the model. For example, the model results do not include N_2O in the output values for Carbon by Production Step, Carbon Emissions from Production, and Summary of Carbon Emissions. N_2O emissions are instead separately given by model results for Carbon Equivalents from N_2O and, as noted, are included in the values from the Summary of Greenhouse Gas Emissions.

Further details of the Agrochemicals submodule calculations, and the complete list of variables utilized to determine total emissions in the Agrochemicals submodule, can be found in Appendix B.

Calculation of Transporting Agrochemicals Emissions. The Transporting Agrochemicals submodule calculates the emissions associated with the transportation of chemical inputs from the production facility to the site where they are used as an input for biomass feedstock production. The Transporting Agrochemicals submodule is shown in Figure 4.5.

Figure 4.5. Transporting Agrochemicals Submodule of the Production Module



The model first converts Energy Use for Chemical Transport Per Unit of Chemicals, with units of energy intensity per mass of chemical, into Energy Use for Chemical Transport, an annual energy-intensity value, based on the amount of chemicals used, Chemicals for Farming, as follows:

$$\text{Energy Use for Chemical Transport} = \text{Energy Use for Chemical Transport Per Unit of Chemicals} \times \text{Chemicals for Farming}. \quad (4.17)$$

This energy intensity is then converted to a carbon intensity based on an assumed fuel mix and on the physical properties of the fuel via the following equation:

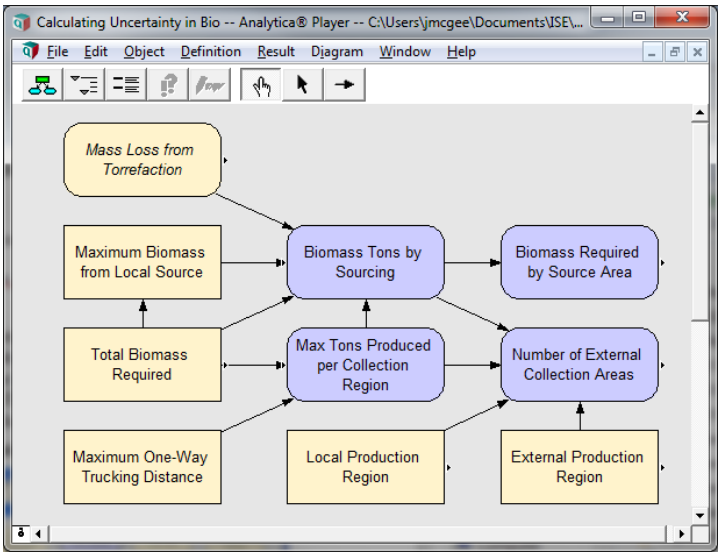
$$\text{Carbon from Chemical Transport} = \text{Energy Use for Chemical Transport} \times \text{Transportation Energy Sources} \times (\text{Energy Density of Fuels} \div \text{Carbon Density of Fuels}). \quad (4.18)$$

Further details of the Transporting Agrochemicals submodule calculations, and the complete list of variables utilized to determine total emissions in the Transporting Agrochemicals submodule, can be found in Appendix B.

Calculation of Local and External Sourcing. The Local and External Sourcing submodule calculates the biomass required by source area, that is, the quantity of biomass required for energy production stratified by location into tonnage produced locally in a collection region centered around the biomass conversion facility and tonnage produced

remotely in another area and transported to the facility by barge or rail. The Local and External Sourcing submodule is shown in Figure 4.6.

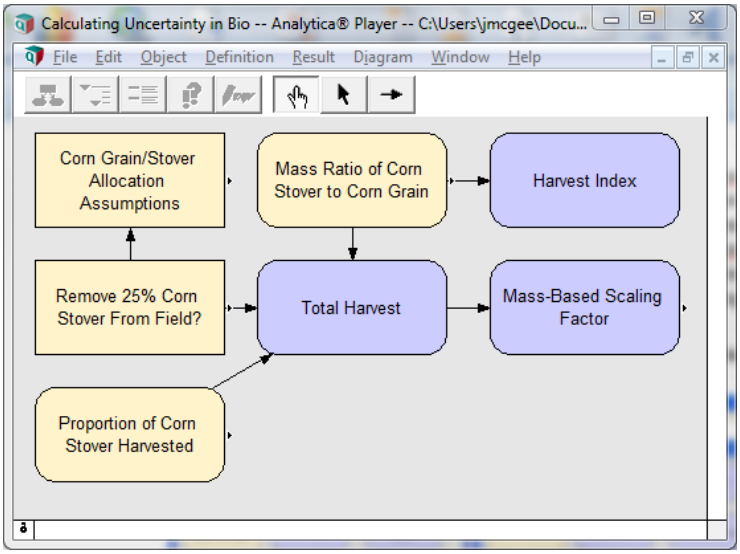
Figure 4.6. Local and External Sourcing Submodule of the Production Module



Calculation of Corn Allocation Factors. The Corn Allocation Factors submodule calculates a mass-based allocation scaling factor, which is applied directly in the Farming, Agrochemicals (within the Chemicals for Farming submodule), and Direct Land Use Change submodules of the Production module. The scaling factor is relevant only to the corn grain feedstock in these modules and is utilized only with the selection of the nondefault setting of "Mass-Based Allocation" for the Corn Grain/Stover Allocation Assumptions.

The Corn Allocation Factors submodule is shown in Figure 4.7.

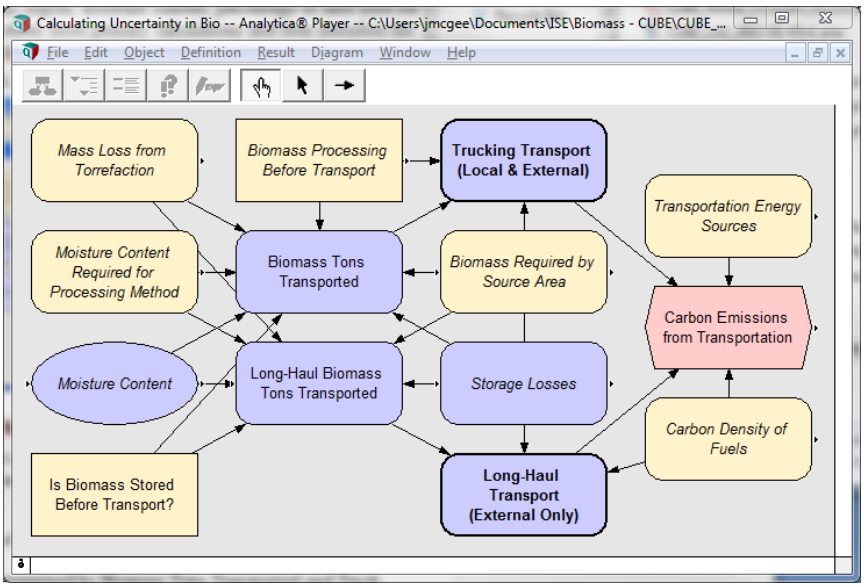
Figure 4.7. Corn Allocation Factors Submodule of the Production Module



4.3 Transportation Calculations

Transportation emissions in the CUBE 2.0 model are the GHG emissions associated with transporting biomass feedstocks from the site of production to the location where processing occurs, either before or after any necessary storage, as specified by the user. The Transportation module is shown in Figure 4.8. The module calculates Transportation Fuel Used for biomass feedstock collection and converts this to GHG intensities, Carbon Emissions from Transportation. These emission values are indexed by feedstock and scenario choices (e.g., geographic region, moisture content, percentage of land used for biomass). This section first describes these primary calculations and then describes the prerequisite intermediate and submodule calculations.

Figure 4.8. Transportation Module of CUBE 2.0



4.3.1 Primary Calculations for Transportation

Transportation is modeled such that local biomass takes priority over external biomass – where the boundary between "local" and "external" is defined in the scenario choice Maximum One-Way Local Trucking Distance. That is, all available local biomass must be used before biomass is gathered externally.[31] Local transport is modeled as truck-only, and external transport can be set to use rail, barge, or truck.

[31] The absence of an external constraint on the collection of all available local biomass is indicated in the model as "INF", i.e., the local biomass constraint is infinite, subject to yield, economic and land availability constraints built into the model.

The module then calculates the value of Carbon Emissions from Transportation as the product of the amount of Transportation Fuel Used, the mix of Transportation Energy Sources, and Carbon Density of Fuels in addition to Emissions from Long-Haul Transport, as follows:

Carbon Emissions from Transportation = Transportation Fuel Used × Transportation Energy Sources × Carbon Density of Fuels + Emissions from Long-Haul Transport.[32] (4.19)

Further details of the Transportation module calculations, and the complete list of variables utilized to determine total emissions in the Transportation module, can be found in Appendix C.

4.3.2 Intermediate and Submodule Calculations for Transportation

For local sourcing, the Trucking Transport (Local & External) submodule first determines the amount of Transportation Fuel Used based on Number of Trucks Needed, Trucking Transport Distance, and Fuel Efficiency for the Local Transport Truck Type in use, as follows:

Transportation Fuel Used = Number of Trucks Needed × Trucking Transport Distance ÷ Fuel Efficiency. (4.17)

Number of Trucks Needed is determined by Biomass Tons Transported and Truck Capacity:

Number of Trucks Needed = Biomass Tons Transported ÷ Truck Capacity. (4.18)

The submodule then calculates the value of Carbon Emissions from Transportation as the product of the amount of Transportation Fuel Used, the mix of Transportation Energy Sources, and Carbon Density of Fuels, as follows:

Carbon Emissions from Transportation = Transportation Fuel Used × Transportation Energy Sources × Carbon Density of Fuels. (4.19)

The intermediate Biomass Tons Transported calculation is based on the (annual) Biomass Required, which is scaled by changes in mass related to Moisture[33] and Storage Losses, as follows:

[32] Note that Emissions from Long-Haul Transport will be zero in some cases, i.e., in scenarios where no long-haul transport is required because all biomass is obtained locally, this will be a zero value.

Biomass Tons Transported = Biomass Required × Moisture × Storage Losses. (4.20)

Note that the Storage Losses factor is included only if the "Yes" value is selected for Is Biomass Stored Before Transport?

The Trucking Transport (Local & External) submodule contains two submodules:

The Trucking Transport Distance submodule determines Average Travel Distance based on Size of Collection Area and several scaling factors. The required Size of Collection Area depends on Biomass Required and Yield per Acre, scaled by Storage Losses and % of Cultivated Land That Can Be Harvested.

The Truck Capacity submodule determines whether the vehicle is weight or volume limited and then assigns the value of the limiting parameter to the output.

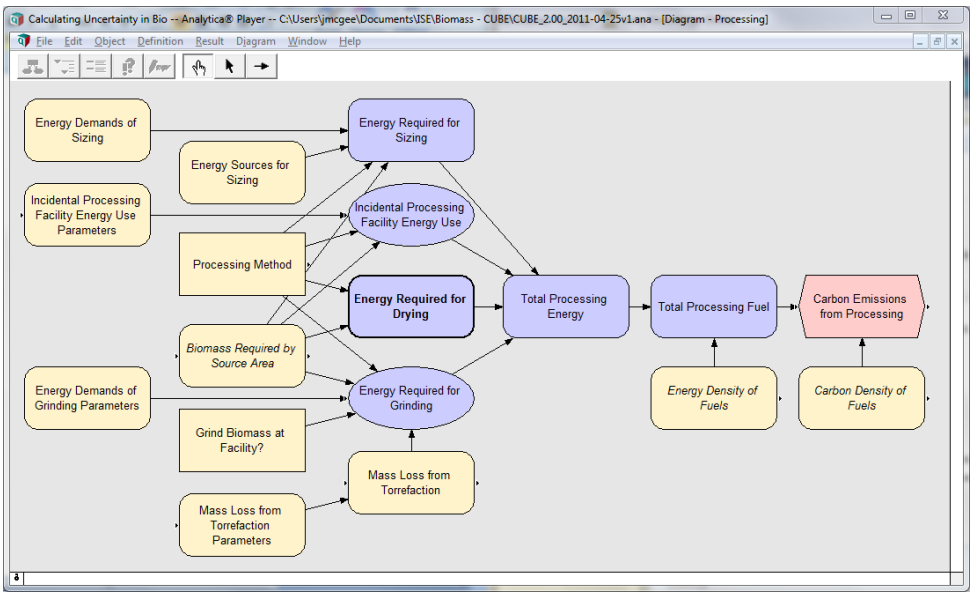
Screen shots and details of the calculations for these two submodules can be found in the "Submodule Calculations in Transportation" section of Appendix C.

4.4 Processing Calculations

Processing emissions in the CUBE 2.0 model include GHG emissions associated with drying and sizing biomass to energy-conversion facility specifications. The Processing module is shown in Figure 4.9. The module calculates the Total Processing Fuel required for drying and sizing and then converts this to GHG intensity, the Carbon Emissions from Processing, indexed by feedstock, source area (e.g., local vs. external), and sometimes also by other parameters (e.g., moisture content). This section first describes these primary calculations and then describes the prerequisite submodule calculations.

[33] Moisture is defined as a variable in the Biomass Tons Transported parameter definition. The value of Moisture is equal to the moisture content of the raw feedstock if it is not processed before transport, or is set to the moisture content resultant from any processing (pelletization, torrrefaction, etc) otherwise.

Figure 4.9. Processing Module of CUBE 2.0



4.4.1 Primary Calculations for Processing

Total Processing Fuel is determined by the fuel mix utilized by the processing equipment (Energy Sources for Processing), the annual energy intensity of the biomass feedstock processing (Total Processing Energy), and Energy Density of Fuels as follows:

Total Processing Fuel = Energy Sources for Processing × Total Processing Energy ÷ Energy Density of Fuels. (4.21)

Total Processing Energy is the sum of the four possible sources of energy use in this module:

Total Processing Energy = Energy Required for Sizing + Energy Required for Drying + Energy Required for Grinding + Processing Facility Energy Use + Incidental Processing Energy Facility Use.[34] (4.22)

The value of each of these energy sources (and whether they contribute at all) are determined by the selected Processing Method, as well as any associated parameters. The Energy Required for Drying submodule is described in more depth later in this section.

The Processing module then calculates Carbon Emissions from Processing from Total Processing Fuel and Carbon Density of Fuels as follows:

[34] The default calculation does not include Energy Required for Grinding.

Carbon Emissions from Processing = Total Processing Fuel × Carbon Density of Fuels. (4.23)

Further details of the Processing module calculations, and the complete list of variables utilized to determine total emissions in this module, can be found in Appendix D.

4.4.2 Submodule Calculations for Processing

The Energy Required for Drying submodule determines the Energy Required for Drying (Heat) value based on the sum of two contributions: (1) the mechanical energy to run the dryer and (2) the energy needed to actually remove the water by heating.

- The mechanical energy is determined by Energy Required for Operating Drying and Biomass Required.[35]
- The value for heat for water removal is set to 0 in the default model settings because waste heat from the gasification process can often be used, incurring no additional GHG penalty (i.e., Dry Using Waste Heat? = "Yes"). If included,
    - Amount of Water Evaporated by Drying is first calculated as the difference between the lower of the two moisture-requirement values (Final Moisture Content Required for Gasification versus Moisture Content Required for Processing Method) and the actual Moisture Content of the biomass feedstock.
    - Amount of Water Evaporated by Drying is then scaled by Efficiency of Drying and other conversion factors.

Screen shots and details of the calculations for this submodule can be found in the "Submodule Calculations in Processing" section of Appendix D.

[35] This is only nonzero assuming that some moisture needs to be removed; if the biomass already meets both processing and gasification moisture requirements, this value is 0.

Appendix A: General Parameters and Definitions

Input parameters that are utilized in more than one of the three farm-to-hopper stages of the model, including user inputs for scenario choices, literature values in the data tables, and intermediate calculated values, are listed in Table A.1.

Table A.1. Parameters Utilized Across Multiple Modules

Variable Identifier	Description and Notes
User inputs	
Biomass_required	- Output of Biomass Required by Source Area decision node (Local and External Sourcing submodule) - Annual biomass required by energy production facility - Dry tons/year; default is 1.3 megatons (Mtons)/year - Found in Tables B.2, B.3, and B.4 in Appendix B; Table C.1 in Appendix C; and Table D.1 in Appendix D
Corn_allocation	- Output of Corn Grain/Stover Allocation Assumptions (Corn Allocation Factors submodule) - Default is "marginal production allocation," which assigns only marginal values associated with harvesting stover to the stover feedstock; corn grain is assigned a value of 0 as default - "Mass-Based Allocation" assigns both baseline inputs and changes, as well as marginal ones, to both grain and stover on a mass basis; note that the grain: stover harvest ratio is ~4.5:1 on a per-acre basis, the implications of which are discussed in the description fields of the relevant modules.[36] - Found in Tables B.2, B.3, B.4, and B.5 in Appendix B
Remove_corn_stover	- Output of Remove 25% Corn Stover From Field? - Found in Tables B.2, B.4, and B.5 in Appendix B
Literature input values	
Energy_density_fuel	- Output of Energy Density of Fuels - Found in Fuel Properties submodule of the Production module and utilized in the Processing module - Units of British thermal units Btu/gallon - Found in Tables B.2, B.5, and B6 in Appendix B and Table D.1 in

[36] The 4.5:1 grain-to-stover *harvest* ratio is derived from the combination of the 1:0.89 grain-to-stover *production* ratio, and the constraint that only 25 percent of stover be removed for harvest (i.e., 1.124/0.25 = 4.494). See Mass Ratio of Corn Stover to Corn Grain and Proportion of Corn Stover Harvested submodules of the Corn Allocations Factors module for further detail and original citations.

	Appendix D
C_density_of_fuels	- Output of Carbon Density of Fuels - Found in Fuel Properties submodule of the Production module and utilized in the Transportation and Processing modules - Units of pounds (lb.) carbon/gallon - Found in Tables B.2, B.5, and B.6 in Appendix B; Table C.1 in Appendix C; and Table D.1 in Appendix D
Harvest_availability	- Output of % of Cultivated Land That Can Be Harvested - Percentage, annualized - Found in Table B.4 in Appendix B and Table C.1 in Appendix C
Transportation_fuels	- Output of Transportation Energy Sources - Percentage; default is “100% Diesel” - Found in Table B.6 in Appendix B and Table C.1 in Appendix C
Moisture_by_process	- Output of Moisture Content Required for Processing Method - Percentage - Found in Table C.1 in Appendix C and Table D.1 in Appendix D
Calculated values	
Yield_per_acre	- Output of Yield per Acre - Minimum, average, maximum values for “Boundary” Analysis Type; distribution for “Stochastic” type - Indexed by feedstock, in dry tons/acre - Found in Tables B.3 and B.4 in Appendix B and Table C.1 in Appendix C
Storage_losses	- Output of Storage Losses module (Storage Loss submodule) - Percentage; varies by feedstock and storage method - Found in Tables B.3, B.4, and B.5 in Appendix B and Table C.1 in Appendix C
Land_required	- Output of Acres of Land Required for Farming - Acres - Found in Table B.4 in Appendix B and Table C.1 in Appendix C
Moisture_content	- Output of Moisture Content - Percentage

	- Found in Table C.1 in Appendix C and Table D.1 in Appendix D
Torrefaction_loss	- Output of Mass Loss from Torrefaction - Percentage

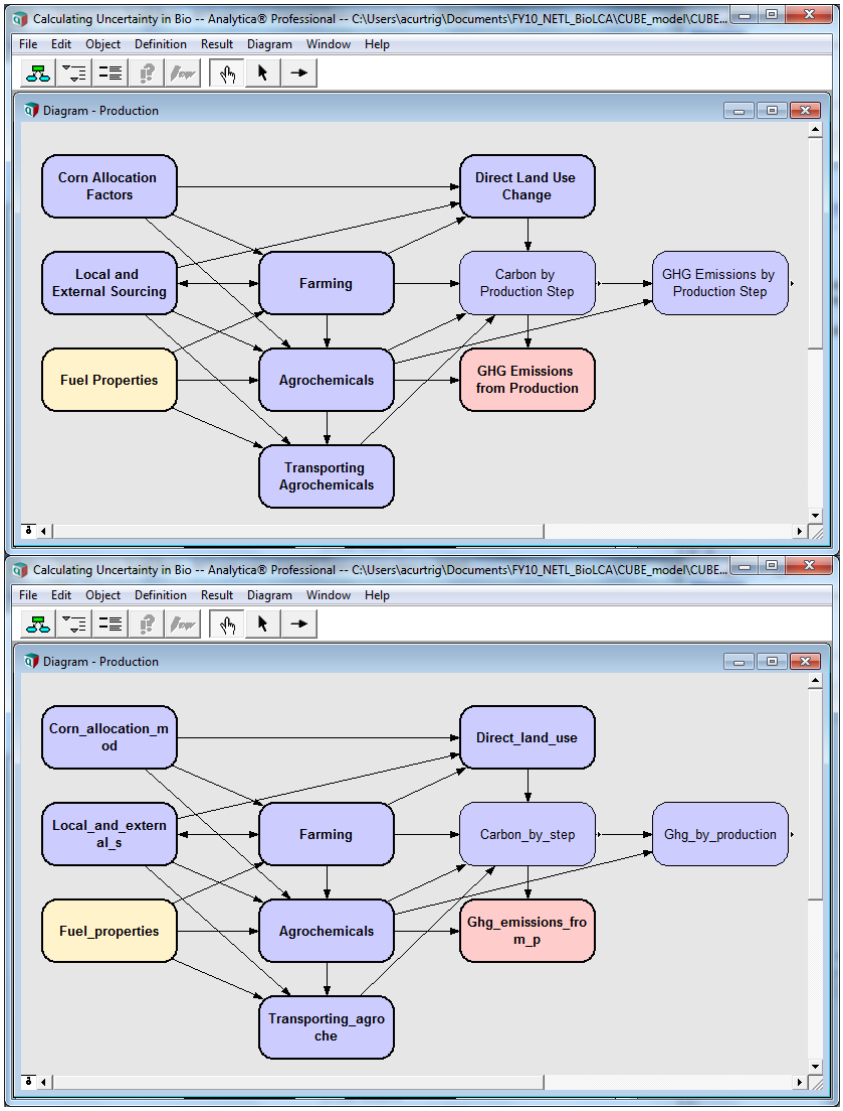
Appendix B: Production Equations and Variables in Detail

The total farm-to-hopper GHG emissions in this model are determined as follows:

Summary_of_ghg_emiss = (Production_carbon + Carbon_from_n2o) + Processing_carbon + Transport_carbon, (B.1)

where Production_carbon and Carbon_from_n2o are both outputs of the Production module. This appendix details the calculations performed within the Production module, including the actual equations used by the model.

Figure B.1. Production Module, by Label and by Variable Identifier



The Production module is shown in Figure 4.1 in Section 4 and is shown again in Figure B.1 as both module label and variable identifier screen shots; submodules are listed in Table B.1. The module computes the following:

Production_carbon = Farming_carbon + Dir_land_use_change + Total_carbon_chem + Carbon_chem_trans. (B.2)

Note that N_2O emissions from the Agrochemicals submodule (Carbon_from_n2o) are not included in Total_carbon_chem; N_2O emissions are tallied separately from CO_2 emissions.

Table B.1. Variables and Submodules in the Production Module

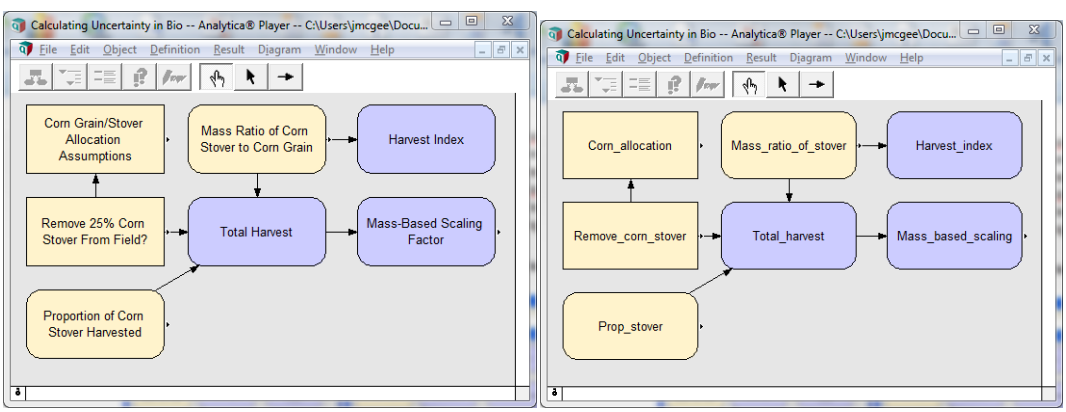
Variable Identifier	Description and Notes
User inputs	
Biomass_required	- See Table A.1 in Appendix A.
Submodules	
Fuel_properties (Energy_density_fuel and C_density_of_fuels)	- Output of Fuel Properties submodule - Contains Energy Density of Fuels and Carbon Density of Fuels submodules - See Table A.1 in Appendix A.
Farming_carbon	- Output of Carbon Generated from Farming (Farming submodule) - lb. carbon (C)/year
Dir_land_use_change1	- Output of Carbon From Direct Land Use Change (Direct Land Use Change submodule) - lb. C/year
Total_carbon_chem	- Output of Total Carbon Generated from Chemicals (Agrochemicals submodule) - lb. C/year
Total_n2o_generated	- Output of Total N_2O Generated from Chemicals (Agrochemicals submodule) - lb. N_2O/year
Carbon_chem_trans	- Output of Carbon from Chemical Transport (Transporting Agrochemicals submodule) lb. C/year
Other calculated values	
Mass_based_scaling	- Output of Mass-Based Scaling Factor (Corn Allocation Factors submodule) - Unitless
Carbon_by_step	- Output of Carbon by Production Step - lb. C/year - Does not include N_2O emissions from Agrochemicals submodule

Ghg_emissions_from_p	- Outputs of GHG Emissions from Production - Contains Carbon Emissions from Production and N_2O Emissions from Production result nodes - lb. C/year and lb. N_2O/year, respectively
Ghg_by_production	- Outputs of GHG Emissions from Production, by Production Step - Contains Carbon Emissions from Production and N_2O Emissions from Production result nodes - lb. C/year and lb. N_2O/year, respectively

Corn Allocation Factors Submodule

The Corn Allocation Factors submodule is shown in Figure B.2. This submodule utilizes variables in both Table A.1 in Appendix A and Table B.2 to calculate a mass-based allocation scaling factor, which is applied directly in the Farming, Agrochemicals (within the Chemicals for Farming submodule), and Direct Land Use Change submodules of the Production module.[37] The scaling factor is relevant only to the corn grain feedstock in these modules and is utilized only with the selection of the nondefault setting of "Mass-Based Allocation" for the Corn Grain/Stover Allocation Assumptions.[38]

Figure B.2. The Corn Allocation Factors Submodule of the Production Module, by Label and by Variable Identifier



[37] The scaling factor also affects the Transporting Agrochemicals submodule indirectly via an output from the Agrochemicals submodule.

[38] It would also be relevant to corn stover were it to be incorporated into a future version of the model.

Table B.2. Variables in the Corn Allocation Factors Submodule of the Production Module

Variable Identifier	Description and Notes
User inputs	
Corn_allocation	- See Table A.1 in Appendix A.
Remove_corn_stover	- See Table A.1 in Appendix A.
Literature input values	
Prop_stover	- Output of Proportion of Corn Stover Harvested module - Fraction
Mass_ratio_of_stover	- Output of the Mass Ratio of Corn Stover to Corn Grain module - Fraction
Calculated values	
Harvest_index	- Output of the Harvest Index module - Fraction
Total_harvest	- Output of the Total Harvest module - Fraction
Mass_based_scaling	- See Table A.1 in Appendix A.

Based on the specified mass ratio of corn to stover,[39] this module first calculates a Total Harvest value as follows: [40]

$$\text{Total_harvest} = 1 + \text{Prop_stover} \times \text{Mass_ratio_of_stover}. \quad \text{(B.3)}$$

Assuming that the model is running with the default selection of removing corn stover for use as a feedstock in its own right (i.e., Remove_corn_stover = “Yes”), this is the value

[39] The model value is a Mass_ratio_of_stover value consistent with modern farming practices and cultivars.

[40] The model contains structure for modification of the Prop_stover value, but this is presently a fixed value due to correlation of this choice with, for example, Stover_carbon_effect, as defined in Table B.4.

utilized for subsequent calculations. If Remove_corn_stover = "No," the value is set to one. The module then defines Mass-Based Scaling Factor as

$$\text{Mass_based_scaling} = 1 \div \text{Total_harvest}. \tag{B.4}$$

This Mass_based_scaling factor is applied in five places in the Production module: (1) the Corn Grain Energy Use by Allocation Method variable (in the Farming submodule); (2) the Corn Grain Chemical Use by Allocation Method variable (in the Agrochemicals submodule, within the Chemicals for Farming submodule); (3) the Supplemental Fertilizer by Allocation Method variable (in the Agrochemicals submodule, within the Chemicals for Farming submodule); (4) the Carbon Storage Reduction by Allocation Method variable (in the Direct Land Use Change submodule); and (5) the Above-Ground Biomass Change variable (in the Direct Land Use Change submodule).

The Corn Grain/Stover Allocation Assumptions value, Corn_allocation, defines the allocation method with a default to "Marginal Production Allocation" for the relevant modules and variables elsewhere in the model. Again, this assumes that the model is running with the default selection of removing corn stover for use as a feedstock in its own right (i.e., Remove_corn_stover = "Yes"). It is only when the nondefault selection of "Mass-Based Allocation" is selected that the model applies the Mass_based_scaling factor to the calculation of total corn grain GHG emissions.

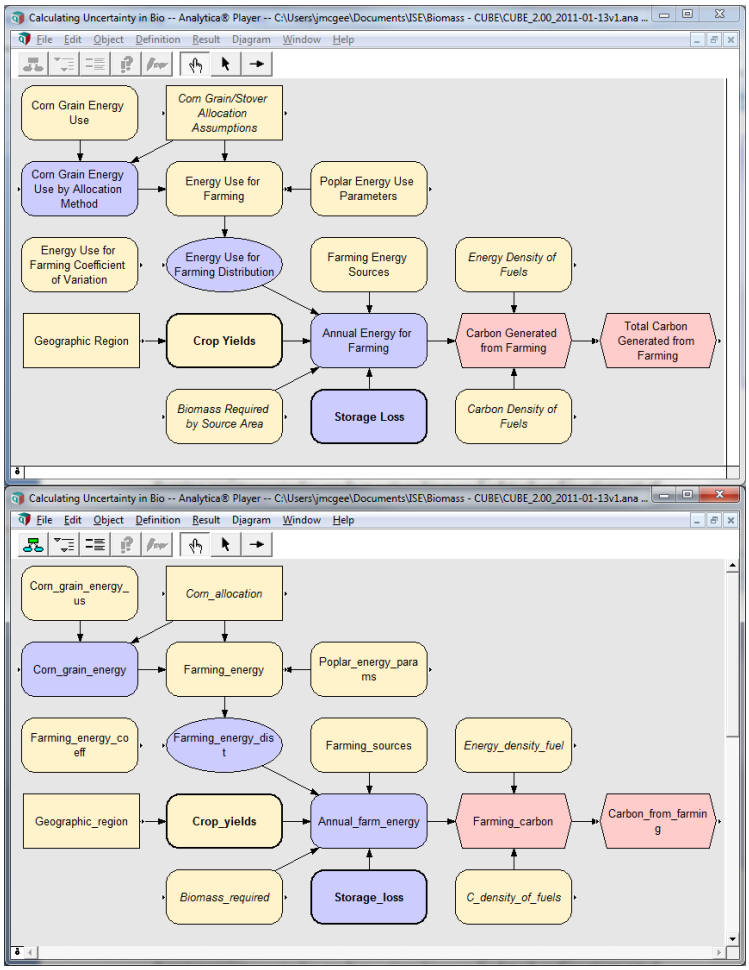
The Harvest Index variable calculates a Harvest_index value, strictly for the user's reference, as

$$\text{Harvest_index} = 1 \div (1 + \text{Mass_ratio_of_stover}). \tag{B.5}$$

Farming Submodule

The Farming submodule is shown in Figure B.3. This submodule utilizes variables in both Table A.1 in Appendix A and Table B.3 to calculate the total farming energy required to produce a given biomass feedstock under a given set of scenario choices and then converts this value to a GHG intensity per unit output.

Figure B.3. Farming Submodule of the Production Module, by Label and by Variable Identifier



First, based on the total Biomass_required, Yield_per_acre of a given feedstock for the user-specified Geographic_region, and the expected biomass Storage_loss, annual required acreages are calculated. These values are then multiplied by Farming_energy_dist, either as a point value or as a distribution, depending on Analysis Type; this energy intensity is apportioned among various Farming_sources (e.g., diesel, electricity) by feedstock. This is summarized by the following equation:

$$\text{Annual_farm_energy} = (\text{Biomass_required}/\text{Yield_per_acre}) \times (100/1 - \text{Storage_losses}) \times (\text{Farming_energy_dist}) \times (\text{Farming_sources}/100). \quad \text{(B.6)}$$

Each of these contributions to Annual_farm_energy is then converted to a GHG intensity based on C_density_of_fuels and Energy_density_fuel, yielding the Farming_carbon values across all feedstocks and Geographic_regions as follows:

Farming_carbon = Annual_farm_energy × C_density_of_fuels ÷ Energy_density_fuel. (B.7)

Table B.3. Variables Used to Calculate Total Emissions from the Farming Submodule of the Production Module

Variable Identifier	Description and Notes
User inputs	
Biomass_required	- See Table A.1 in Appendix A.
Geographic_region	- Output of Geographic Region - Unitless; indexed by feedstock - USDA-defined regions; model default is "Cornbelt"
Storage_needed	- Output of Does Biomass Require Storage? (Storage Loss submodule) - Default is "Yes" for all feedstocks except mill residue, for which input could be collected on demand
Storage_method	- Output of Storage Method (Storage Loss submodule) - Default is low-loss method, which varies by feedstock
Corn_allocation	- Output of Corn Grain/Stover Allocation Assumptions - See Table A.1 in Appendix A.
Literature input values	
Sg_yield_params Mpb_yield_params Appalachian_corn_yie F_res_yield_params (and similar)	- Input parameters of various feedstock submodules of Crop Yields module - Parameters, submodule structure, and calculations vary by feedstock due to differing sources and differing detail in source information.
Storage_losses	- See Table A.1 in Appendix A.
Storage_loss_methods	- Output of Storage Loss by Method (Storage Loss submodule) - Percentage; values vary by feedstock
Farming_energy	- Output of Energy Use for Farming - Btu/dry ton - Energy use to produce biomass crops, indexed by feedstock - For corn, user chooses allocation; default is "Marginal Production

	Allocation," but user can select "Mass-Based Allocation." - Mill residue is 0.
Farming_energy_dist	- Output of Energy Use for Farming Distribution - Btu/dry ton - In the "Stochastic" analysis mode, this variable is the truncated normal distribution based on the values for Farming_energy and Farm_energy_coeff; in the "Boundary" analysis mode, the Farming_energy values are used.
Farming_energy_coeff	- Output of Energy Use for Farming Coefficient of Variation - Unitless - The coefficient of variation across several estimates of farming energy use
Corn_grain_energy_us	- Output of Corn Grain Energy Use - Btu/acre - Relevant only for corn grain feedstock; baseline value for Corn Grain Energy Use by Allocation Method
Farming_sources	- Output of Farming Energy Sources - Percentage
Poplar_energy_params	- Output of Poplar Energy Use Parameters - Btu/acre
Calculated values	
Yield_per_acre	- See Table A.1 in Appendix A (Crop Yields submodule).
Switchgrass_yield Mpb_yield Corn_yield F_res_yield M_res_yield	- Outputs of Switchgrass Yield By Region, Mixed Prairie Biomass Yield by Region, and so on for each type. - Dry tons/acre
Corn_grain_energy	- Output of Corn Grain Energy Use by Allocation Method - Btu/acre

	- Relevant only for corn grain feedstock - Values depend on user selection of "Marginal Production Allocation" (default selection) or "Mass-Based Allocation"; note that grain:stover harvest ratio is ~4.5:1 per acre.[41]
Annual_farm_energy	- Output of Annual Energy for Farming - Btu/year - Interim calculation
Farming_carbon	- Output of Carbon Generated from Farming - lb. CO_2/year
Carbon_from_farming	- Output of Total Carbon Generated from Farming - lb. CO_2/year - Value is added to other submodule values in the Production module to determine the overall emissions, Production_carbon.
NOTE: USDA = U.S. Department of Agriculture.	

Intermediate and Submodule Calculations Within the Farming Submodule

The Farming submodule determines a number of intermediate values prior to the Farming_carbon calculation. These values are determined in the Yield_per_acre and Storage_losses submodules and in calculations of Farming_energy_dist and Farming_sources variables.

- **Yield_per_acre** values are based on selection of Geographic_region, feedstock, and analysis type. The complexity of these conversions depends on the data available for a given feedstock. For example, switchgrass Yield_per_acre values, Switchgrass_yield, are based on regional means and standard deviations of data from the literature, the Sg_yield_params values, which are converted to regional min/mean/max sets (Sg_bounding_values) or lognormal distributions (Sg_distribution) depending on the analysis type and are then scaled by the expected decrease in efficiency when moving from small test plots to large-scale biomass farming practices, the Sg_yield_scaling factor.

[41] As noted above, the 4.5:1 grain-to-stover *harvest* ratio is derived from the combination of the 1:0.89 grain-to-stover *production* ratio, and the constraint that only 25 percent of stover be removed for harvest (i.e., 1.124/0.25 = 4.494). See Mass Ratio of Corn Stover to Corn Grain and Proportion of Corn Stover Harvested submodules of the Corn Allocations Factors module for further detail and original citations.

- **Storage_losses** values are based on the literature and on user-determined need to store the biomass, Storage_needed = "Yes," and Storage_method.
- **Farming_energy_dist** are point values or distributions based on literature values, feedstock, and analysis type.[42]
- **Farming_sources** are point values based on the literature.

Direct Land Use Change Submodule

The Direct Land Use Change submodule is shown in Figure B.4. This submodule utilizes the variables in Table B.4 to calculate the GHG penalty or credit associated with the direct land-use change that results when a specific biomass feedstock is grown on a particular baseline ecosystem. The model performs the following calculation to determine the Direct Land Use Change value:

$$\text{Dir_land_use_change} = [(\text{C_soil_storage_rate} + \text{Stover_carbon_effect}) \times (1 \pm \text{Good_practice_factor}) + \text{Above_ground_change}] \times \text{Land_required}. \quad \text{(B.8)}$$

However, when using the default model assumptions, Direct Land Use Change simplifies to

$$\text{Dir_land_use_change} = \text{C_soil_storage_rate} \times \text{Land_required}. \quad \text{(B.9)}$$

[42] These distributions or point values are based on the values specified in Farming_energy. For corn grain feedstock, Corn_allocation, Corn_grain_energy_us, and Corn_grain_energy values affect the allocation of the farming energy between grain and stover.

Figure B.4. Direct Land Use Change Submodule of the Production Module, by Label and by Variable Identifier

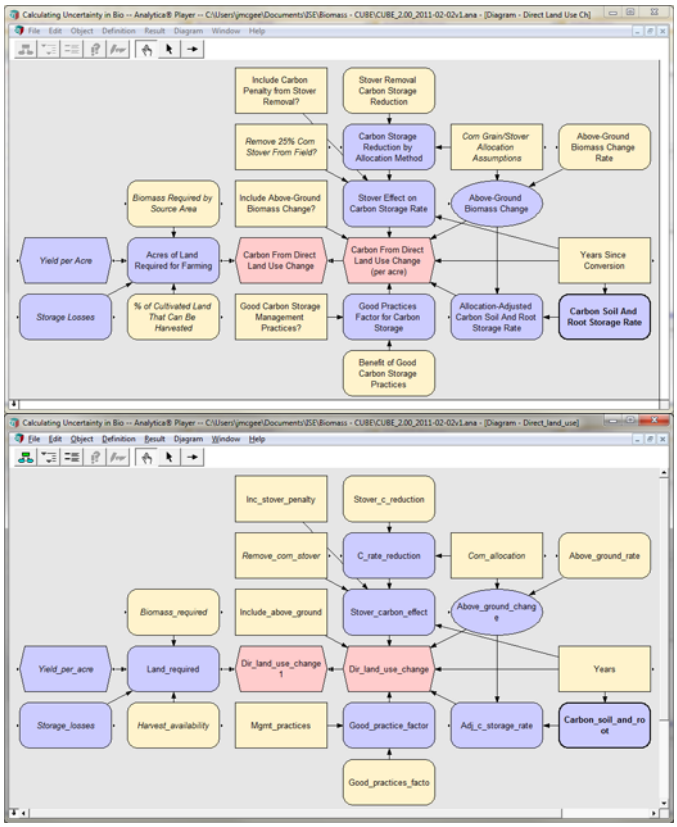


Table B.4. Variables Used to Calculate Total Emissions from the Direct Land Use Change Submodule of the Production Module

Variable Identifier	Description and Notes
User inputs	
Biomass_required	- See Table A.1 in Appendix A.
Years	- Output of Years Since Conversion - Default is 2–10 years
Remove_corn_stover	- See Table A.1 in Appendix A. - Default is "Yes," which increases the soil carbon loss relative to practices that leave all stover behind. - Relevant only in years 1–10 after ecosystem conversion; in the default version of the model, all debt is allocated to corn stover, so there is no impact on corn grain GHG emissions.
Corn_allocation	- Output of Corn Grain/Stover Allocation Assumptions - See Table A.1 in Appendix A.
Mgmt_practices	- Output of Good Carbon Storage Management Practices? - Default is "No."[a]
Include_above_ground	- Output of Include Above-Ground Biomass Change? decision node - Default is "Yes," but user would specify "No" if above-ground biomass was to be put to productive use; choice affects only first year after ecosystem conversion.
Length_of_time_block	- Output of Length of Time Blocks (Carbon Soil and Root Storage Rate submodule)
Inc_stover_penalty	- Output of Include Carbon Penalty from Stover Removal? - Default is "Yes"
Literature input values	
Yield_per_acre	- See Table A.1 in Appendix A.
Storage_losses	- See Table A.1 in Appendix A.
Harvest_availability	- See Table A.1 in Appendix A.
Stover_c_reduction	- Output of Stover Removal Carbon Storage Reduction

	- lb./acre-year - Relevant only for corn grain feedstock; baseline value for Carbon Storage Reduction by Allocation Method
Good_practices_facto	- Output of Benefit of Good Carbon Storage Practices - Fraction; default value is 0 because the default value for Mgmt_practices is "No"
Above_ground_change	- Output of Above-Ground Biomass Change - lb./acre - Geographically distinct values
Annual_root_carbon_s	- Output of Annual Root Carbon Storage (Carbon Soil and Root Storage Rate submodule)
Annual_soil_carbon_s	- (Carbon Soil and Root Storage Rate submodule)
Root_carbon_starting	- Output of Root Carbon Starting Point (Carbon Soil and Root Storage Rate submodule) - lbs/acre
Soil_carbon_starting	- Output of Soil Carbon Starting Point (Carbon Soil and Root Storage Rate submodule)
Root_carbon_eqbm_lvl	- Output of Soil Carbon Eqbm Level (Carbon Soil and Root Storage Rate submodule)
Soil_carbon_eqbm_lvl	- Output of Soil Carbon Eqbm Level (Carbon Soil and Root Storage Rate submodule)
Root_c_over_time	- Output of Root Storage Over Time (Carbon Soil and Root Storage Rate submodule)
Soil_c_over_time	- Output of Soil Storage Over Time (Carbon Soil and Root Storage Rate submodule)
Calculated values	
C_rate_reduction	- Output of Carbon Storage Reduction by Allocation Method - lb./acre-year - Because the default allocation setting is "Marginal Production Allocation" and because corn stover is not a feedstock in the

	present version of the model, this parameter does not affect any GHG-intensity values; under "Mass-Based Allocation," corn carries 80% of the carbon debt (due to ~4.5:1 harvest ratio by mass on a per-acre basis).[43]
Stover_carbon_effect	- Output of Stover Effect on Carbon Storage Rate - lb./acre-year - See note on allocation for C_rate_reduction description above.
Good_practice_factor	- Output of Good Practices Factor for Carbon Storage - Fraction; default value is 0 because default value of Mgmt_practices is "No."
Above_ground_change	- Output of Above-Ground Biomass Change - lb./acre
Land_required	- See Table A.1 in Appendix A.
Annual_root_carbon_s	- Output of Annual Root Carbon Storage (Carbon Soil and Root Storage Rate submodule)
Annual_soil_carbon_s	- Output of Annual Soil Carbon Storage (Carbon Soil and Root Storage Rate submodule)
C_soil_and_roo1	- Output of Carbon Soil And Root Storage Rate (Carbon Soil and Root Storage Rate submodule) - C/acre-year
Dir_land_use_change	- Output of Direct Land Use Change - lb. C/year - Value is added to other submodule values in the Production module to determine the overall emissions, Production_carbon.
[a] Although the default setting specifies that this scaling factor not be used, the value presently in the model is set at 5 percent. Recent literature has called into question the carbon benefits of "good management practices," such as no-till farming.	

[43] As noted, the 4.5:1 grain-to-stover *harvest* ratio is derived from the combination of the 1:0.89 grain-to-stover *production* ratio, and the constraint that only 25 percent of stover be removed for harvest (i.e., 1.124/0.25 = 4.494). See Mass Ratio of Corn Stover to Corn Grain and Proportion of Corn Stover Harvested submodules of the Corn Allocations Factors module for further detail and original citations.

Intermediate and Submodule Calculations of Direct Land Use Change Submodule

The Carbon Soil And Root Storage Rate submodule outputs values for C_soil_storage_rate, which depend on scenario choices for feedstock, geographic region, baseline ecosystem, and Years Since Conversion (Figure B.5). The C_soil_storage_rate values provide a positive or negative value (for soil and root carbon loss and storage, respectively) for each feedstock-baseline ecosystem combination for the specified USDA-defined geographic region and over the specified time period of interest. Note that the value is 0 for both residue feedstocks. The model performs the following calculation to determine the Carbon Soil And Root Storage Rate value:

Carbon_soil_and_roo1 = Annual_root_carbon_s + Annual_soil_carbon_s (B.10)

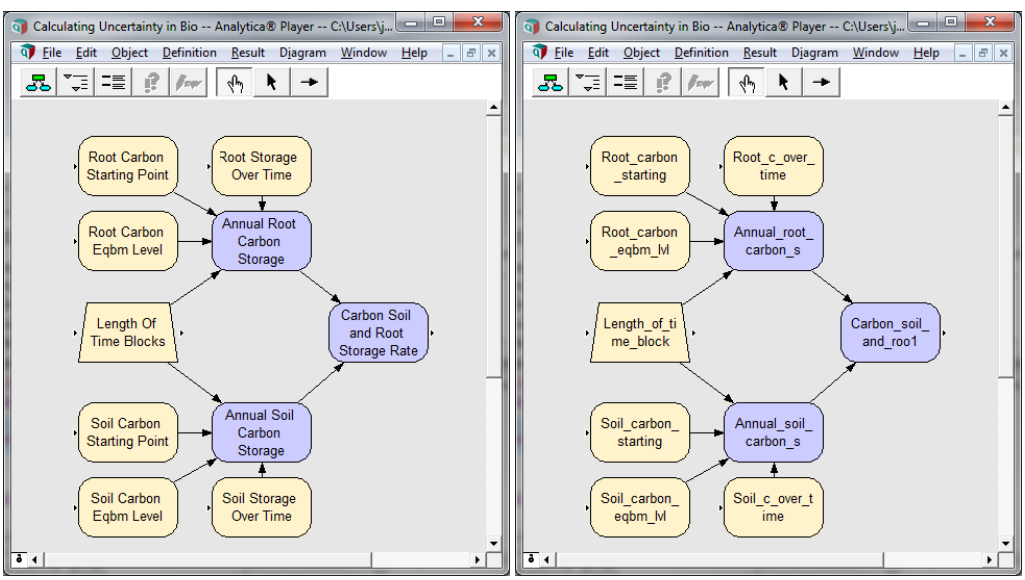
Annual_root_carbon_s and Annual_soil_carbon_s are calculated similarly:

Annual_root_carbon_s = Root_carbon_starting - Root_carbon_eqbm_lvl)*Root_c_over_time/Length_of_time_block (B.11)

Annual_soil_carbon_s = Soil_carbon_starting - Soil_carbon_eqbm_lvl) * Soil_c_over_time / Length_of_time_block (B.12)

unless the feedstock is Mill Residue, then both are zero.

Figure B.5. Carbon Soil and Root Storage Rate Submodule of the Direct Land Use Change Subodule



In this version of the model, the Stover Effect value is 0 because (1) the Corn Grain/Stover Allocation Assumptions value is set to “Marginal Production Allocation” and, therefore, this marginal debt is applied to corn stover only, and (2) corn stover is not an included feedstock. The model allows the user to change the allocation of this Stover

Effect on Carbon Storage Rate to be partially attributed to the corn grain by selecting "Mass-Based Allocation" if desired. Therefore, this choice has no impact on any of the feedstock GHG intensities. However, the calculation is included, should the user decide to partially apply this penalty to corn grain, by selecting "Mass-Based Allocation," or should the model be extended to include the additional stover feedstock. In this hypothetical version of the model, Stover_carbon_effect would be nonzero for stover even in the default setting. The value for Stover_carbon_effect is based on literature and is applied only to the relevant feedstock and only to each of the first ten years after change from the baseline ecosystem; this value is defined by the C_rate_reduction[44] variable and is switched off and on by the Remove_corn_stover value being "No" and "Yes," respectively.[45]

The Good Practices Factor for Carbon Storage is not included in the default version of the model and is nonzero only if selected by the user (i.e., default value is 0); the value is positive if the net soil carbon rate (i.e., C_soil_storage_rate + Stover_carbon_effect) is negative and vice versa. The value for Good_practice_factor in CUBE 2.0 is set to 5 percent; the value is defined by the Good_practice_factor variable and is switched off and on by the Mgmt_practices value being "No" and "Yes," respectively.

Above-Ground Biomass Change is nonzero only in the first year after conversion to the present feedstock crop; note that the default model calculations are for years 2–10. The value of Above_ground_change is determined by the Above_ground_forest values for conversion from a forest baseline ecosystem and by Above_ground_non_for for all other baseline ecosystems; these are separated in the model due to the important regional differences in the magnitude of this value for the forest baseline ecosystem, which is not necessary for other baselines. The parameter can be switched off and on by toggling between "No" and "Yes" for the value of Include_above_ground; turning this parameter off presumably would indicate that some non–CO_2-generating use had been made of the above-ground biomass.

Land_required is the area of cropland required to produce the specific tonnage of biomass specified by the user and is dependent on the Yield_per_acre and Harvest_availability of a given biomass feedstock. It is calculated in the following way:

[44] C_rate_reduction is determined by Stover_c_reduction and Corn_allocation values.

[45] Note that this Stover_carbon_effect is one of two differences between net production emissions in years 6-10 and years 11-20; the other is Annual_root_carbon_s. For some baseline-feedstock combinations, the emissions in these two time bins will be the same.

Land_required = Biomass_required ÷ [Yield_per_acre × (1 – (Storage_losses/100)) × (Harvest_availability ÷ 100)]. (B.10)

Agrochemicals Submodule

The Agrochemicals submodule is shown in Figure B.5. This submodule utilizes the variables in Table B.5 to determine the total GHG emissions generated from the Agrochemicals portion of the Production process. The submodule output values are defined, with non-N_2O and N_2O emissions tallied separately, as follows:

Total_carbon_chem = Chemical_production + Carbon_from_lime, (B.11)

where Chemical_production is summed over all chemicals and fuel types, and

Total_n2o_generated = N2o_released. (B.12)

Total_carbon_chem is indexed by feedstocks, and Total_n2o_generated is indexed by feedstock and baseline ecosystem, although all values in the present version of the model are the same for a given feedstock across baselines. Note that units for the former are in units of C lb./year, while units for the latter are in N_2O lb./year.

Figure B.5. Agrochemicals Submodule of the Production Module, by Label and by Variable Identifier

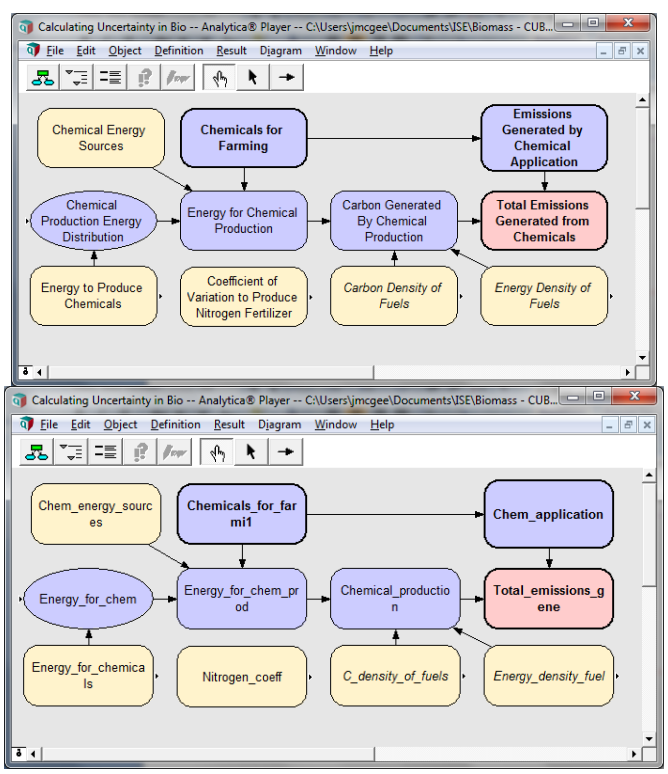


Table B.5. Variables Used to Calculate Total Emissions from the Agrochemicals Submodule of the Production Module

Variable Identifier	Description and Notes
User inputs	
Remove_corn_stover	- See Table A.1 in Appendix A. - Default is "Yes"; removal of stover requires increased chemical inputs to grow corn. - In the default version of the model, all marginal chemical inputs are allocated to corn stover, so there is no impact on corn grain GHG emissions.
Corn_allocation	- Output of Corn Grain/Stover Allocation Assumptions (Chemicals for Farming submodule) - See Table A.1 in Appendix A.
Include_n2o_release	- Output of Include N_2O Release from Agrochemicals? (N_2O Release submodule) - Default is "Yes."
N2o_time_horizon	- Output of N_2O Climate Change Time Horizon (N_2O Release submodule) - 20- or 100-year time horizon; 100-year is default.
Literature input values	
Energy_density_fuel C_density_of_fuels	- See Table A.1 in Appendix A.
Energy_for_chem_prod	- Output of Energy to Produce Chemicals - Btu/g
Nitrogen_coeff	- Output of Coefficient of Variation to Produce Nitrogen Fertilizer - Unitless - In the "Stochastic" analysis mode, this coefficient of variation is used to produce a normal distribution based on the values for Energy_for_chemicals (for nitrogen fertilizer only).
Chem_energy_sources	- Output of Chemical Energy Sources - Percentage
Supp_fertilizer	- Output of Supplemental Fertilizer for Stover Removal (Chemicals

	for Farming submodule) - g/dry ton - Baseline for Supplemental Fertilizer for Allocation Method
Corn_grain_chemical	- Output of Corn Grain Chemical Use (Chemicals for Farming submodule) - g/dry ton - Baseline for Corn Grain Chemical Use by Allocation Method
Chemical_use	- Output of Chemical Use in Farming (Chemicals for Farming submodule) - g/dry ton
Chemical_use_coeff	- Output of Chemical Use Coefficients of Variation (Chemicals for Farming submodule) - Unitless - In the "Stochastic" analysis mode, these coefficients of variation are used to produce normal distributions based on the values for Energy_for_chemicals.
Poplar_chemical_use	- Output of Poplar Chemical Use (Chemicals for Farming submodule) - g/dry ton
Lime_release_params	- Output of Lime ($CaCO_3$) Release Distribution Parameters (Lime [$CaCO_3$] Release submodule of Emissions Generated by Chemical Application) - Fraction
Lime_release_rate	- Output of Lime Release Rate (Lime [$CaCO_3$] Release submodule of Emissions Generated by Chemical Application) - Fraction
N2o_release_params	- Output of N_2O Release Distribution Parameters (N_2O Release submodule) - Fraction, with min, max, and most-likely values
N2o_gas_global	- Output of N_2O Gas Global Warming Potential (N_2O Release submodule) - CO_2 equivalent (CO_2e)
Calculated values	
Energy_for_chem	- Output of Chemical Production Energy Distribution

	- Btu/g
Energy_for_chem_prod	- Output of Energy for Chemical Production - Btu/year
Chemical_production	- Output of Carbon Generated By Chemical Production - Lbs/year
Chemicals_farming	- Output of Chemicals for Farming (Agrochemicals and N_2O Release submodules) - g/year
Addl_fertilizer	- Output of Supplemental Fertilizer for Allocation Method (Chemicals for Farming submodule) - g/dry ton
Corn_grain_chemical	- Output of Corn Grain Chemical Use by Allocation Method (Chemicals for Farming submodule) - g/dry ton
Corn_chemicals	- Output of Total Corn Grain Chemical Use (Chemicals for Farming submodule) - g/dry ton
Chemical_use_distrib	- Output of Chemical Use In Farming Distribution (Chemicals for Farming submodule) - g/dry ton - In the “Stochastic” analysis mode, this variable is the (truncated) normal distribution based on the values for Chemical_use and Chemical_use_coeff. - In the “Boundary” analysis mode, the average values from Chemical_use are used.
Storage_losses	- See Table A.1 in Appendix A (Chemicals for Farming submodule).
Carbon_from_lime	- Output of Carbon Released From Lime (Lime [$CaCO_3$] Release submodule of Emissions Generated by Chemical Application) - lb./year
Total_carbon_chem	- Output of Total Carbon Generated from Chemicals (Total Emissions Generated from Chemicals submodule) - lb./year - Includes energy-related emission from agrochemical production and CO_2 emissions from applied lime

	- Does not include N_2O, which is tallied separately - Value is added to other submodule values in the Production module to determine the overall emissions, Production_carbon.
N2o_release_rate	- Output of N_2O Release Rate (N_2O Release submodule of Emissions Generated by Chemical Application) - Fraction
N2o_released	- Output of N_2O Released (N_2O Release submodule of Emissions Generated by Chemical Application) - N_2O lb./year
Carbon_from_n2o	- Output of Carbon Equivalents from N_2O (N_2O Release submodule) - lb./year - This value is used for calculation of, e.g., *Summary_of_ghg_emis1* and *Carbon_equivlanet_kg*.
Total_n2o_generated	- Output of Total N_2O Generated from Chemicals (Total Emissions Generated from Chemicals submodule) - N_2O lb./year; defined as N2o_released value

Total Carbon Generated from Chemicals

The Agrochemical submodule calculates the Chemical_production value of the Carbon Generated by Chemical Production submodule for a given feedstock as follows:

$$\text{Chemical_production} = \text{Energy_for_chem_prod} \times \text{C_density_of_fuels}/\text{Energy_density_fuel}. \quad \text{(B.13)}$$

The intermediate calculations for the Chemical_production value for a given feedstock are

Energy_for_chem_prod = Chemicals_farming × Energy_for_chem × (Chem_energy_sources ÷ 100). (B.14)

Chemicals_farming = Biomass_required × Chemical_use_distrib ÷ (1 – (Storage_losses ÷ 100)),

where Chemical_use_distribution is either a table of values generated from literature values (if Analysis Type = "Boundary") or a truncated normal distribution based on the same values and their coefficient of variation (if Analysis Type = "Stochastic").[46]

Energy_for chem = Energy_for_chem_prod,

where Energy_for_chem_prod is either a table of values (if Analysis Type = "Boundary") or, in the case of nitrogen fertilizers, a distribution ("Stochastic").

Chem_energy_sources is a table of values.

The Agrochemicals submodule then calculates the Carbon_from_lime value as follows:

Carbon_from_lime = Chemicals_farming × Lime_release_rate × (2.2 ÷ 1,000), (B.15)

where Chemicals_farming is restricted to just the lime values, and 2.2 ÷ 1,000 converts from grams to pounds. The Lime_release_rate is a set of min/mean/max values in the "Boundary" mode and a triangular distribution in the "Stochastic" mode, both defined by Lime_release_params values.

Finally, the energy-related and lime-related terms are summed to give the Total Carbon Generated from Chemicals, as follows:

Total_carbon_chem = Chemical_production + Carbon_from_lime. (B.16)

Total N_2O Generated from Chemicals

The Agrochemicals submodule also calculates the N2o_released value (not shown in Figure B.4, but within the N_2O Release submodule of the Emissions Generated by Chemical Application submodule) as follows:

[46] Other submodules of Chemicals_farming used in the calculation are Supp_fertilizer, Addl_fertilizer, Corn_chemicals, Corn_grain_chemical, Corn_grain_chemical, Corn_allocation, Chemical_use, and Chemical_use_coeff.

$$N2o_released = Chemicals_farming\ (over\ nitrogen\ fertilizer\ only) \times N2o_release_rate \times (2.2 \div 1{,}000), \quad (B.17)$$

where N2o_release_rate is either the min, most-likely, and max values from N2o_release_params ("Boundary" mode) or a distribution based on these values. This value is calculated only when Include_n2o_release = "Yes"; 2.2 ÷ 1,000 converts from units of g/year to lb./year.

Carbon_from_n2o is calculated for inclusion in the total GHG emissions of the production stage, assuming that Include_n2o_release = "Yes," as follows:

$$Carbon_from_n2o = N2o_gas_global \times N2o_released \times (12 \div 44), \quad (B.18)$$

where the value of N2o_gas_global is defined by the value set in N_2O_time_horizon.

Transporting Agrochemicals Submodule

The Transporting Agrochemicals submodule is shown in Figure B.6. This submodule utilizes the variables in Table B.6 to calculate a value for Carbon from Chemical Transport as follows:

Carbon_chem_trans = Energy_use_for_chemi × (Transportation_fuels ÷ 100) × C_density_of_fuels/Energy_density_fuel. (B.19)

Figure B.6. Transporting Agrochemicals Submodule of the Production Module, by Label and by Variable Identifier

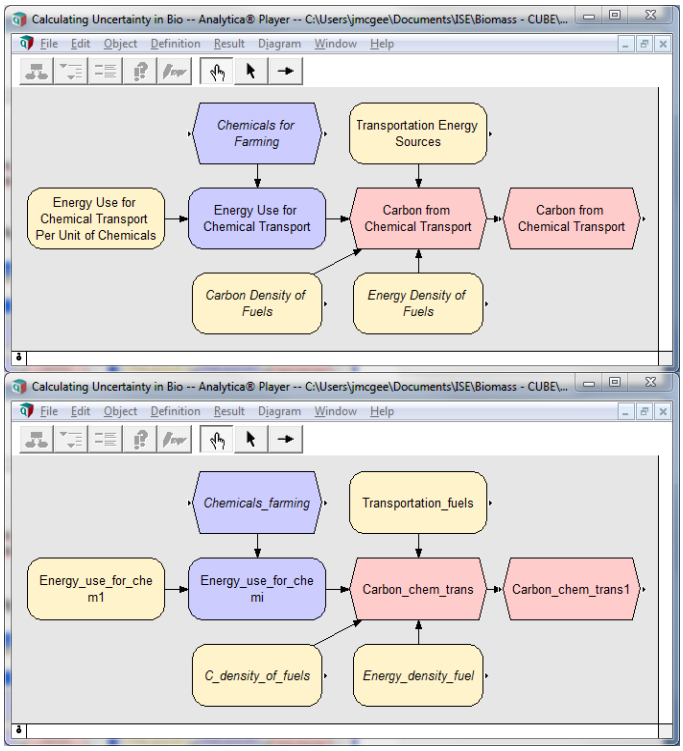


Table B.6. Variables Used to Calculate Total Emissions from the Transporting Agrochemicals Submodule of the Production Module

Variable Identifier	Description and Notes
User inputs	
Transportation_fuels	- See Table A.1 in Appendix A.
Literature input values	
Energy_density_fuel C_density_of_fuels	- See Table A.1 in Appendix A.
Energy_use_for_chem1	- Output of Energy Use for Chemical Transport Per Unit of Chemicals - Btu/g; default value is set in Data Tables rather than Scenario Choices
Calculated values	
Energy_use_for_chemi	- Output of Energy Use for Chemical Transport - Btu/year
Carbon_chem_trans	- Output of Carbon from Chemical Transport - lb./year - Value is added to other submodule values in the Production module to determine the overall emissions, Production_carbon.

Appendix C: Transportation Equations and Variables in Detail

The total farm-to-hopper GHG emissions in this model are determined as follows:

Summary_of_ghg_emiss = (Production_carbon + Carbon_from_n2o) + Processing_carbon + Transport_carbon, (C.1)

where Transport_carbon is the output of the Transportation module. This appendix details the calculations performed within the Transportation module, including the actual equations used by the model. The Transportation module is shown in Figure 4.2 in Section 4 and is shown again in Figure C.1 as both module label and variable identifier screen shots; variables used by the model are listed in Table C.1.

Figure C.1. Transportation Module, by Label and by Variable Identifier

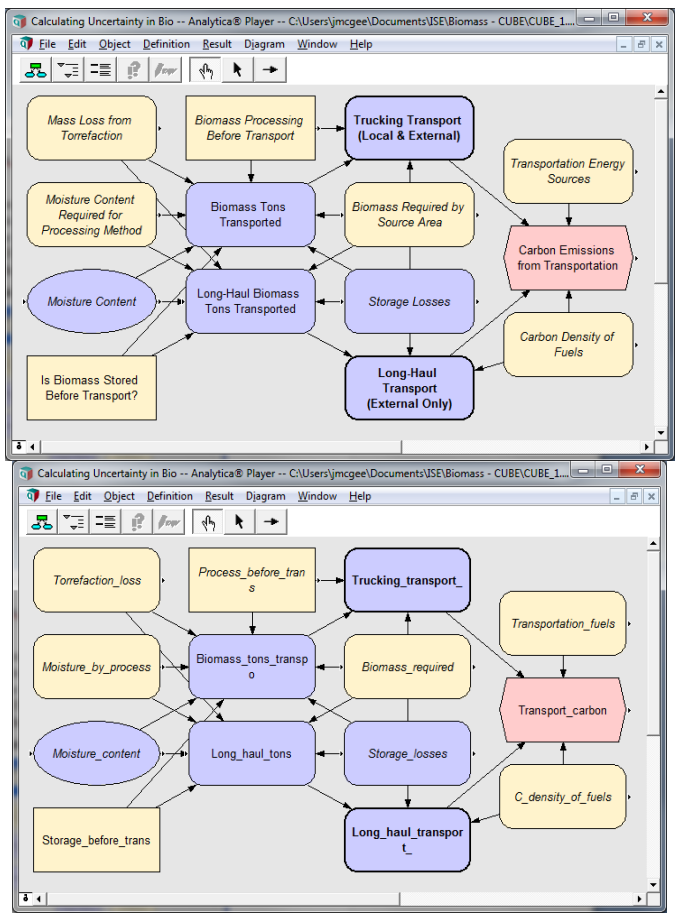


Table C.1. Variables Used to Calculate Total Emissions from the Transportation Module

Variable Identifier	Description and Notes
User inputs	
Biomass_required	- See Table A.1 in Appendix A.
Storage_before_trans	- Output of Is Biomass Stored Before Transport? - Default = "No," indicating that biomass is stored at the processing site rather than the production site
Truck_type	- Output of Local Transport Truck Type (Trucking Transport (Local & External) submodule) - Choices: "Small Trailer"; "Large Trailer" (default); "Chip Van"
Process_before_trans	- Output of Biomass Processing Before Transport? (Truck Capacity submodule) - Indexed by biomass feedstock; default values ("No processing" and "Cut or chipped") vary by crop (nondefault alternatives are "Ground" or "Pelletized")
Land_availability	- Output of Percentage of Land Used for Biomass Crops (Transport Distance submodule) - Percentage
Literature input values	
Transportation_fuels	- See Table A.1 in Appendix A.
Fuel_efficiency	- Output of Fuel Efficiency - Miles/gallon
C_density_of_fuels	- See Table A.1 in Appendix A.
Truck_capacity	- Output of Truck Weight Capacity (Truck Capacity submodule) - lb.
Truck_vol_capacity	- Output of Truck Volume Capacity (Truck Capacity submodule) - Cubic feet
Bulk_density_by_proc	- Output of *Bulk Density By Process* (*Truck Capacity* submodule) - lb./cubic ft
Crude_torr_density	- Output of Bulk Density of Crude Torrefied Biomass (Truck

	Capacity submodule) - lb./cubic ft
Pellet_torr_density	- Output of Bulk Density of Torrefied Pellets (Truck Capacity submodule) - lb./cubic ft
Number_of_trucks	- Output of Number of Trucks Needed - Trucks/year
Transportation_fuel	- Output of Transportation Fuel Used - Gallons/year
Harvest_availability	- See Table A.1 in Appendix A.
Distance_multiplier	- Output of Error Factor for Winding Roads (Trucking Transport Distance submodule) - Unitless
Mill_residue_travel	- Output of Mill Residue Travel Distance (Trucking Transport Distance submodule) - Miles
Moisture_by_process	- See Table A.1 in Appendix A.
Long_haul_transport	- Output of Long-Haul Transport Type (Long-Haul Transport (External Only) submodule)
Fuel_efficiency_of_l	- Output of Fuel Efficiency of Long-Haul Transport (Long-Haul Transport (External Only) submodule) - Ton-miles/gallon
Ext_transport_dist	- Output of Transport Distance from External Sites (Long-Haul Transport (External Only) submodule) - miles
Regional_distances	- Output of Default Region-to-Region Distances (Long-Haul Transport (External Only) submodule) - miles
Calculated values	
Biomass_tons_transpo	- Output of Biomass Tons Transported - Tons/year

Long_haul_tons	- Output of Long-Haul Biomass Tons Transported - Tons
Carbon_per_ton_mile	- Output of Carbon Equivalent Emissions per Ton-Mile (Long-Haul Transport (External Only) submodule) - C eqv. lbs./ton-mile
Ext_distance	- Output of Effective External Transport Distance (Long-Haul Transport (External Only) submodule) - miles
Moisture_content	- See Table A.1 in Appendix A.
Which_capacity_limit	- Output of Is Truck Volume Or Weight Limited? (Truck Capacity submodule) - "Volume limited" or "Mass limited"; default result varies by feedstock and is constant across truck types.
Bulk_density_by_crop	- Output of Bulk Density By Crop (Truck Capacity submodule) - lb./cubic ft
Capacity_by_crop	- Output of Capacity By Crop (Truck Capacity submodule) - lb.
Yield_per_acre Storage_losses Land_required	- See Table A.1 in Appendix A (*Trucking Transport Distance submodule*).
Collection_area	- Output of Size of Collection Area (Trucking Transport Distance submodule) - Acres
Travel_distance	- Output of Average Travel Distance (Trucking Transport Distance submodule) - Miles
Transport_carbon	- Output of Carbon Emissions from Transportation - lb./year

Primary Transportation Calculations

The Transportation module computes the total GHG emissions from transporting biomass feedstocks from production to processing sites as follows:

$$\text{Transport_carbon} = \text{Transportation_fuel} \times (\text{Transportation_fuels}/100) \times \text{C_density_of_fuels} + \text{Long_haul_emissions} \quad \text{(C.2)}$$

over all fuel types utilized and for the specified truck type. Transportation_fuels percentage values are determined by the user-specified fleet fuel mix. The amount of Transportation Fuel Used is calculated as follows:

$$\text{Transportation_fuel} = \text{Number_of_trucks} \times \text{Travel_distance} \div \text{Fuel_efficiency}, \quad \text{(C.3)}$$

where Fuel_efficiency is a user-specified number for each truck type, set to the same value for all three types in the model default. The Travel_distance calculations are performed in the Trucking Transport Distance submodule and are described in the next section, "Submodule Calculations in Transportation."

The intermediate calculations to determine Number of Trucks Needed are the following:[47]

$$\text{Number_of_trucks} = \text{Biomass_tons_transpo} \div (\text{Capacity_by_crop}/2{,}000), \quad \text{(C.4)}$$

where the Truck Capacity submodule calculation that determines the Capacity_by_crop value (described in the next section, "Submodule Calculations in Transportation") and the value of 2,000 converts pounds to tons, and

$$\text{Biomass_tons_transpo} = \text{Biomass_required} \div (1 - \text{Moisture} \div 100) \div (1 - \text{Storage_losses} \div 100), \quad \text{(C.5)}$$

where the final term is included only if Storage_before_trans = "Yes" and where Storage_losses is set as described in the "Farming Submodule" section of Appendix A. Moisture is a variable defined in the Biomass Tons Transported variable definition; it is the minimum of the values for Moisture_content and Moisture_by_process, assuming that the user elects to process the biomass before transporting (i.e., Process_before_trans = "Yes").

Submodule Calculations in Transportation

The Trucking Transport (Local & External) submodule has two submodules, Trucking Transport Distance and Truck Capacity, which are described in detail here.

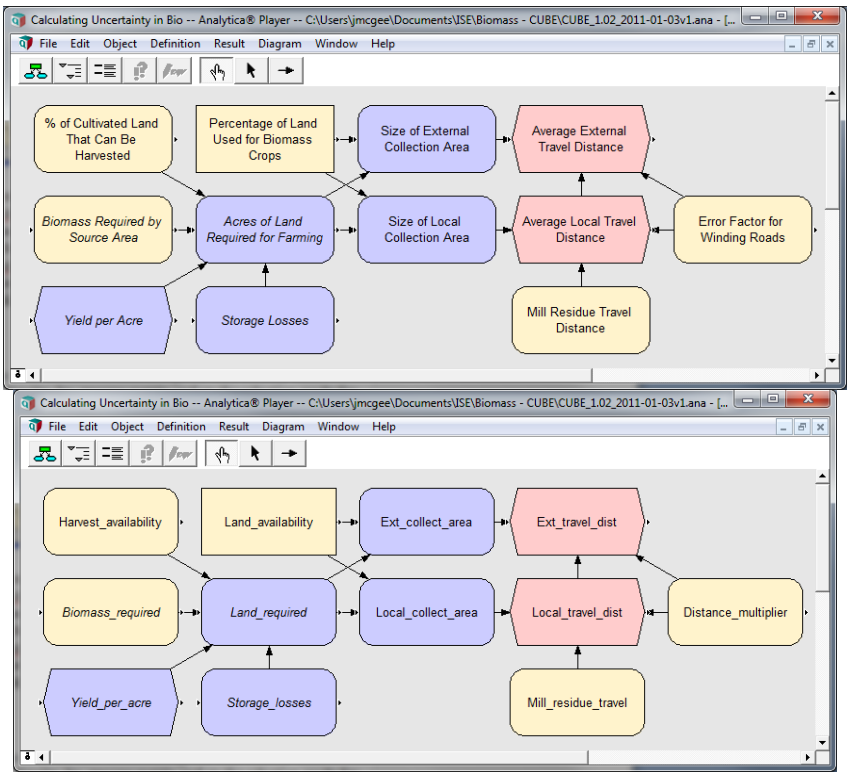
The Trucking Transport Distance submodule of the Trucking Transport (Local & External) submodule is shown in Figure C.2. This submodule utilizes variables in Table C.1 to calculate a value for Average Travel Distance as follows:

[47] The model determines the smallest integer value that is greater than or equal to this calculated value and returns this as the value for Number_of_trucks.

$$\text{Travel_distance} = 2 \times \text{Distance_multiplier} \times (\text{Collection_area} \times 0.001563 \div \pi)^{0.5} \times (2 \div 3), \quad \text{(C.6)}$$

where the factor of two accounts for round-trip travel (i.e., empty trucks traveling to the collection site), 0.001563 converts acres to square miles, and the factor of 2 ÷ 3 accounts for the average distance a given truck will travel because most trucks need not traverse the entire area; the collection area is assumed to approximate a circular region around the processing-plant site. The Distance_multiplier is a number value that accounts for the tortuosity of winding roads. This equation applies to all feedstocks other than mill residue, where Travel_distance = Mill_residue_travel.

Figure C.2. Trucking Transport Distance Submodule of the Trucking Transport (Local & External) Submodule, by Label and by Variable Identifier



Size of Collection Area is determined as follows:

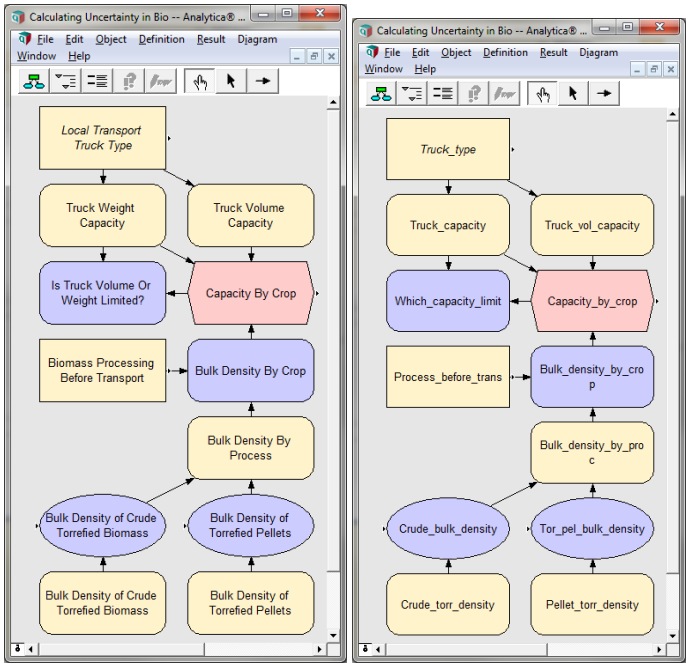
$$\text{Collection_area} = \text{Land_required} \div (\text{Land_availability} \div 100), \quad \text{(C.7)}$$

where

Land_required = Biomass_required ÷ (Yield_per_acre × (1 – (Storage_losses ÷ 100)) × (Harvest_availability ÷ 100)). (C.8)

The Truck Capacity submodule of the Transportation module is shown in Figure C.3. This submodule utilizes the variables in Table C.1 to calculate a value for Truck Capacity indexes by biomass feedstock, Capacity_by_crop.

Figure C.3. Truck Capacity Submodule of the Trucking Transport (Local & External) Submodule, by Label and by Variable Identifier



The module first determines the minimum of two values, Truck_capacity (i.e., the maximum weight) versus Bulk_density_by_crop × Truck_vol_capacity (i.e., the maximum weight based on volume), and assigns this weight value to Capacity_by_crop.[48] To clarify the limiting factor, the Is Truck Volume or Weight Limited? module uses this Capacity_by_crop value to explicitly indicate whether each feedstock/Truck_type combination is volume or weight limited. If Capacity_by_crop is equal to Truck_capacity, then “Mass limited” is indicated; otherwise, “Volume limited” is indicated.

[48] Bulk_density_by_crop assigns each biomass feedstock a given bulk density value based on the values in the Bulk_density_by_process matrix and on the selection made for Process_before_trans for the given feedstock.

Appendix D: Processing Equations and Variables in Detail

The total farm-to-hopper GHG emissions in this model are determined as follows:

Summary_of_ghg_emiss = (Production_carbon + Carbon_from_n2o) + Processing_carbon + Transport_carbon, (D.1)

where Processing_carbon is the output of the Processing module. This appendix details the calculations performed within the Processing module, including the actual equations used by the model. The Processing module is shown in Figure 4.3 in Section 4 and is shown again in Figure D.1 as both module label and variable identifier screen shots; variables used by the model are listed in Table D.1.

Figure D.1. Processing Module, by Label and by Variable Identifier

Table D.1. Variables Used to Calculate Total Emissions from the Processing Module

Variable Identifier	Description and Notes
User inputs	
Biomass_required	- See Table A.1 in Appendix A.
Processing_method	- Output of Processing Method - Indexed by crop
Dry_using_waste_heat	- Output of Dry Using Waste Heat? (Energy Required for Drying submodule) - Default is "Yes," to indicate that low-grade waste heat from gasification process will be used to dry biomass rather than a separate, dedicated energy source.
Literature input values	
Energy_density_fuel C_density_of_fuels	- See Table A.1 in Appendix A.
Energy_sources_proc	- Output of Energy Sources for Processing - Percentage
Energy_req_sizing	- Output of Energy Demands of Sizing - Btu/dry ton
Energy_sources_size	- Output of Energy Sources for Sizing - Percentage
Other_energy_params	- Output of Incidental Processing Facility Energy Use Parameters - Btu/dry ton
Grinding_params	- Output of Energy Demands of Grinding Parameters - Btu/dry ton
Torref_loss_params	- Output of Mass Loss from Torrefaction Parameters - Percentage
Energy_for_dryer	- Output of Energy Required for Operating Dryer (Energy Required for Drying submodule) - Btu/dry ton

Moisture_params	- Output of Moisture Content Parameters (Energy Required for Drying submodule) - Percentage
Moisture_content_req	- Output of Final Moisture Content Required for Gasification (Energy Required for Drying submodule) - Percentage
Moisture_by_process	- Output of Moisture Content Required for Processing Method (Energy Required for Drying submodule) - See Table A.1 in Appendix A.
Drying_eff_params	- Output of Drying Efficiency Parameters (Energy Required for Drying submodule) - Percentage
Calculated values	
Processing_fuel	- Output of Total Processing Fuel - Gallons/year
Processing_energy	- Output of Total Processing Energy - Btu/year
Energy_for_cutting	- Output of Energy Required for Sizing - Btu/year
Energy_for_drying	- Output of Energy Required for Drying (Heat) - Btu/year
Amount_evaporated	- Output of Amount of Water Evaporated by Drying (Energy Required for Drying submodule) - Tons/year
Moisture_content	- Output of Moisture Content (Energy Required for Drying submodule) - See Table A.1 in Appendix A.
Req_water_removal	- Output of Water Removal Required (Energy Required for Drying submodule) - Percentage
Efficiency_of_drying	- Output of Efficiency of Drying (Energy Required for Drying submodule)

	- Percentage
Processing_carbon	- Output of Carbon Emissions from Processing - Total GHG emissions from the module, in lb. of C/year

Primary Processing Calculations

The Processing module computes the total GHG emissions associated with drying and sizing biomass to the appropriate specifications for use as a feedstock at an energy plant. Carbon Emissions from Processing values are calculated as follows:

$$\text{Processing_carbon} = \text{C_density_of_fuels} \times \text{Processing_fuel} \quad \text{(D.2)}$$

over all fuel types used in the fleet mix and where Total Processing Fuel is calculated as follows:

$$\text{Processing_fuel} = (\text{Energy_sources_proc} \div 100) \times \text{Processing_energy} \div \text{Energy_density_fuel}, \quad \text{(D.3)}$$

where Energy_sources_proc is the specified fuel mix for energy processing equipment.

Total Processing Energy is comprised of two components, Energy Required for Sizing and Energy Required for Drying, as follows:

$$\text{Processing_energy} = \text{Energy_for_cutting} + \text{Energy_for_drying}, \quad \text{(D.4)}$$

where Energy_for_cutting = Biomass_required × Energy_req_cutting, and Energy_req_cutting values depend on the selection made for Processing_method. Energy_for_drying is similarly dependent on the Processing_method choice and is described in the next section.

Submodule Calculations in Processing

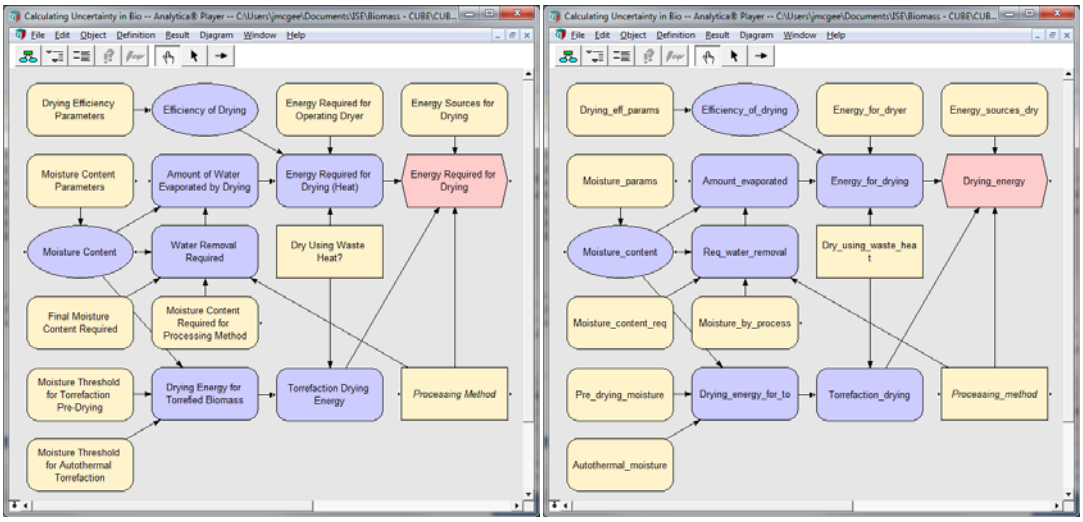
The Processing module has one submodule, Energy Required for Drying, shown in Figure D.2. This submodule calculates Energy_for_drying based on the biomass starting Moisture_content, the moisture content required for processing (Moisture_by_process) and gasification (Moisture_content_req), and the physical specifications of a dryer (Energy_for_dryer, Efficiency_of_drying). The calculation performed is the following:

$$\text{Energy_for_drying} = (\text{Energy_for_dryer} \times \text{Biomass_required}) + (\text{Amount_evaporated} \times 2{,}000 \times 970 \div (\text{Efficiency_of_drying} \div 100)), \quad \text{(D.5)}$$

where the first term, Energy_for_dryer × Biomass_required, is nonzero only if Amount_evaporated > 0 and where any nonzero value of the second term is included only

when waste heat is not available for the process (Dry_using_waste_heat = "No").[49] The first term, the mechanical energy required to operate the dryer, is based on a literature value for Energy_for_dryer; the second term is the energy required to evaporate excess moisture, based on the amount of moisture that needs to be removed, Amount_evaporated, and a range of dryer efficiencies (a min and max value for Energy_for_dryer).

Figure D.2. Energy Required for Drying Submodule of the Processing Module, by Label and by Variable Identifier



Prior to performing this calculation, the model first determines how much moisture needs to be removed, the value for Amount_evaporated. Depending on the selected Processing_method, Req_water_removal is calculated as the maximum of Moisture_content – Moisture_content_req versus Moisture_content – Moisture_by_process.[50] Amount_evaporated is then equal to

$$(\text{Biomass_required} \div (1 - \text{Moisture_content} \div 100)) \times (\text{Req_water_removal} \div 100). \quad \text{(D.6)}$$

[49] The value of 2,000 converts tons to pounds, and 970 Btu/lb. is the standard heat of vaporization for water.

[50] Moisture_content is either a distribution (in stochastic analysis mode) or a set of min, mean, and max values (boundary analysis mode), as defined by the values in Moisture_params.

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