LCA Digital Commons Unit Process Data: field crop production

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1. Background

1.1. Project background

Life Cycle Assessment (LCA) is a compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle. Standardized by the International Standards Organization ((International Standards Organization (ISO) 2006a), (International Standards Organization (ISO) 2006b)), LCA describes the life cycle as consecutive and interlinked stages of a product system extending from the acquisition of raw materials (e.g., agriculture, mining, residuals management) through materials processing, technology manufacturing/ construction, technology use/maintenance/upgrade, and the technology retirement. Although most frequently used to quantify environmental impacts such as contributions to climate change and toxic implications for humans or ecosystems, LCA also provides a framework for understanding economic and social impacts (see for example (Fava and Smith 1998) and (United Nations Environment Programme 2009)).

In an LCA, data are collected at the *unit process* level, intended to represent a single industrial activity such as the activities on a farm or in a crude oil refinery. Each single industrial activity (a) produces product (e.g., cotton lint or diesel fuel) and sometimes co-products[1] (e.g., cotton seeds or naphtha); (b) uses resources from the environment (e.g., carbon dioxide (CO_2) from the air, crude oil from the ground); (c) uses resources from other unit processes in the *technosphere* (a.k.a. the industrial sector) (e.g., ammonium nitrate produced at a fertilizer production plant or electricity generated in a power plant); and (d) generates emissions to the environment (e.g., ammonia (NH_3) emissions to air and fuel combustion). In an LCA, the inventory analysis combines unit process data for the life cycle and the impact assessment estimates the impact associated with activities and flows to and from the environment for the inventory.

The field crop unit process data described here have been developed for the *LCA Digital Commons*[2]. The *LCA Digital Commons* is an open access database and toolset being built by the United States Department of Agriculture (USDA) National Agricultural Library in response to a national need for data representing US operations for use in LCAs to support policy assessment, technology implementation decision-making, and publically disclosed comparative product or technology assertions. The *LCA Digital Commons* database will ultimately be seeded with unit process data representing a wide range of industrial production practices, developed by researchers throughout the US at all stages of the life

[1] The product of interest is called the reference product and any additional valuable products are called co-products. It is in the mathematical treatment of co-products in an LCA that manifests *credits* in attributional LCA and many of the indirect market responses studied in consequential LCA.

[2] See http://riley.nal.usda.gov/nal_display/index.php?info_center=8&tax_level=1&tax_subject=757

cycle. The tool set, being developed using the open source OpenLCA code[3], will then allow unit process data to be combined into life cycle inventories and life cycle environmental impacts to be estimated.

The goal of this work is to develop unit process datasets representing US field crop production to serve as initial unit process datasets in the *LCA Digital Commons* database and thus to provide a model for dataset development within the contexts of scope, data format, nomenclature, and the preparation of meta data. The intended audiences are those interested in using data in and developing data for the *LCA Digital Commons* database. Much of this work has benefited from existing LCA database structures and data formats. Notable within this context are the US LCI database (maintained by the US Department of Energy's National Renewable Energy Laboratory), the ecoinvent database/ EcoSpold format, and European Reference Life Cycle Data System (ELCD)/ International Reference Life Cycle Data System (ILCD)[4] format.

1.2. Field crop production data sources and scope

The main data source used for the development of the field crop data described here is the annual USDA Agricultural Resource Management Survey (ARMS[5]). ARMS data are from an annual national survey of field-level farm practices sponsored jointly by USDA Economic Research Service (ERS) and the USDA National Agricultural Statistics Service (NASS). Within ARMS, data representing *Crop Production Practices* provides annual data summaries for field crops at the state level beginning in 1996, with only select crops surveyed each year[6]: corn (1996, 1997, 1998, 1999, 2000, 2001, 2005); cotton (1996, 1997, 1998, 1999, 2000, 2003, 2007); oats (2005); peanuts (1999, 2004); rice (2006); soybeans (1996, 1997, 1998, 1999, 2000, 2002, 2006); and spring, durum, and winter wheat (1996, 1997, 1998, 2000, 2004, 2009). As shown in Table 1, there are 466 crop-state-year combinations (e.g., the production of soybeans in Iowa in 2006) included.

Single year datasets are combined into datasets that represent multiple years of production of a single kg of crop as the weighted production fraction for which single year unit process data have been prepared. Datasets combine 3 or more years of data. There are 70 multi-year datasets listed in Table 2, representing all field crops except oats, peanuts, and rice.

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[3] See http://www.openlca.org/index.html

[4] Database websites: US LCI database: http://www.nrel.gov/lci/; ecoinvent: http://www.ecoinvent.ch/; and ILCD: http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm

[5] Data are available at http://www.ers.usda.gov/Data/ARMS/

[6] ARMS data were provided by ERS, as that available through the ARMS website on June 8, 2011. Data for barley and sorghum have not been included here, as they are pending further review by ERS.

Table 1 Number of single year datasets

	Corn grain	Cotton	Durum wheat	Oats	Peanuts	Rice	Soybeans	Spring wheat excluding durum	Winter wheat
Alabama		6			2				
Arizona		6							
Arkansas		7				1	7		1
California		7	1			1			1
Colorado	5							1	6
Delaware									1
Florida					1				
Georgia	2	7			2				1
Idaho								3	6
Illinois	7			1			7		5
Indiana	7						7		
Iowa	7			1			7		
Kansas	6			1			6		6
Kentucky	6						6		1
Louisiana		7				1	7		1
Maryland							1		
Michigan	7			1			6		2
Minnesota	7			1			7	6	2
Mississippi		7				1	7		1
Missouri	7	4				1	7		5
Montana			3					6	6
Nebraska	7			1			7		6
New York	3			1					
North Carolina	6	6			2		6		2
North Dakota	3		6	1			3	6	1
Ohio	7						7		5
Oklahoma									6
Oregon								3	6
Pennsylvania	5			1			2		1
South Carolina	1	3							
South Dakota	7			1			6	5	6
Tennessee		7					7		
Texas	6	7		1	2	1			6
Virginia							2		
Washington								3	6
Wisconsin	7			1			4		

Table 2 Multi-year datasets

	Corn grain	Cotton	Durum wheat	Soybeans	Spring wheat excluding durum	Winter wheat
Alabama		x				
Arizona		x				
Arkansas		x		x		
California		x				
Colorado	x					x
Georgia		x				
Idaho					x	x
Illinois	x			x		x
Indiana	x			x		
Iowa	x			x		
Kansas	x			x		x
Kentucky	x			x		
Louisiana		x		x		
Michigan	x			x		
Minnesota	x			x	x	
Mississippi		x		x		
Missouri	x	x		x		x
Montana			x		x	x
Nebraska	x			x		x
New York	x					
North Carolina	x	x		x		
North Dakota	x		x	x	x	
Ohio	x			x		x
Oklahoma						x
Oregon					x	x
Pennsylvania	x					
South Carolina		x				
South Dakota	x			x	x	x
Tennessee		x		x		
Texas	x	x				x
Washington					x	x
Wisconsin	x			x		

Unit process data representing each ARMS crop-state-year combination covers land occupation and transformation from previous crops, seed use, irrigation, tillage, crop residue management, and the use of nutrients, manure, and pesticides as defined by the ARMS variables[7]. When these data are combined with NASS Quick Stats[8] data representing field crop production for each ARMS crop-state-year combination, the basis for an LCA unit process data flow is created. For example, the data for soybean production in Iowa in 2006 uses the ARMS variables "Average seeding rate" (in pounds per acre) and "Planted acres" are combined with NASS data representing the soybean production in Iowa in 2006 (in lb.) to estimate the seed use ultimately in SI units as kg seed/kg soybeans produced in Iowa in 2006. To complete each field crop dataset, additional information sources (e.g., data and documents from NASS, the US Geological Survey, the US Environmental Protection Agency (EPA), the Intergovernmental Panel on Climate Change (IPCC), and more) are used to estimate a wide variety of field crop production activities and ultimately flows from and to the environment. Given this, all field crop flow data are presented on the basis of the production of a single kilogram wet mass of each field crop, at the time of harvest and at the farm gate.

Each field crop dataset will ultimately be a part of life cycle inventories of final products such as food, biofuels and other bioproducts, as depicted for an LCA of canned creamed corn in Figure 1. As shown, if crop production is considered to be a "tier 1" dataset, creamed corn production would be considered a "tier 0" dataset using corn as a feedstock. Each crop production unit process data similarly uses data in "tier 2" including for example the life cycles of the production of applications such as nitrogen fertilizer. Note that tier 2 data representing farm equipment operation (based in large part of the USEPA NONROAD[9] data), irrigation, and manure production and storage will be available later in 2012.

For the production of 1 kg of each field crop, the unit process scope is defined to include:

- **A reference product,** as 1 kg of each field crop,
- **Co-products,** as corn silage when the reference product is corn grain; as cottonseeds and harvested trash (leaves, burs, sticks, and dirt), etc. when the reference product is cotton lint; and as residue for each field crop.
- **Flows from the environment,** as land occupation and transformation from corn, cotton, fallow, other crops, small grains, and soybeans; the uptake of CO_2 from air and nutrients from air and soil, and the withdrawal of water from ground and surface water sources for irrigation and as used during manure application.

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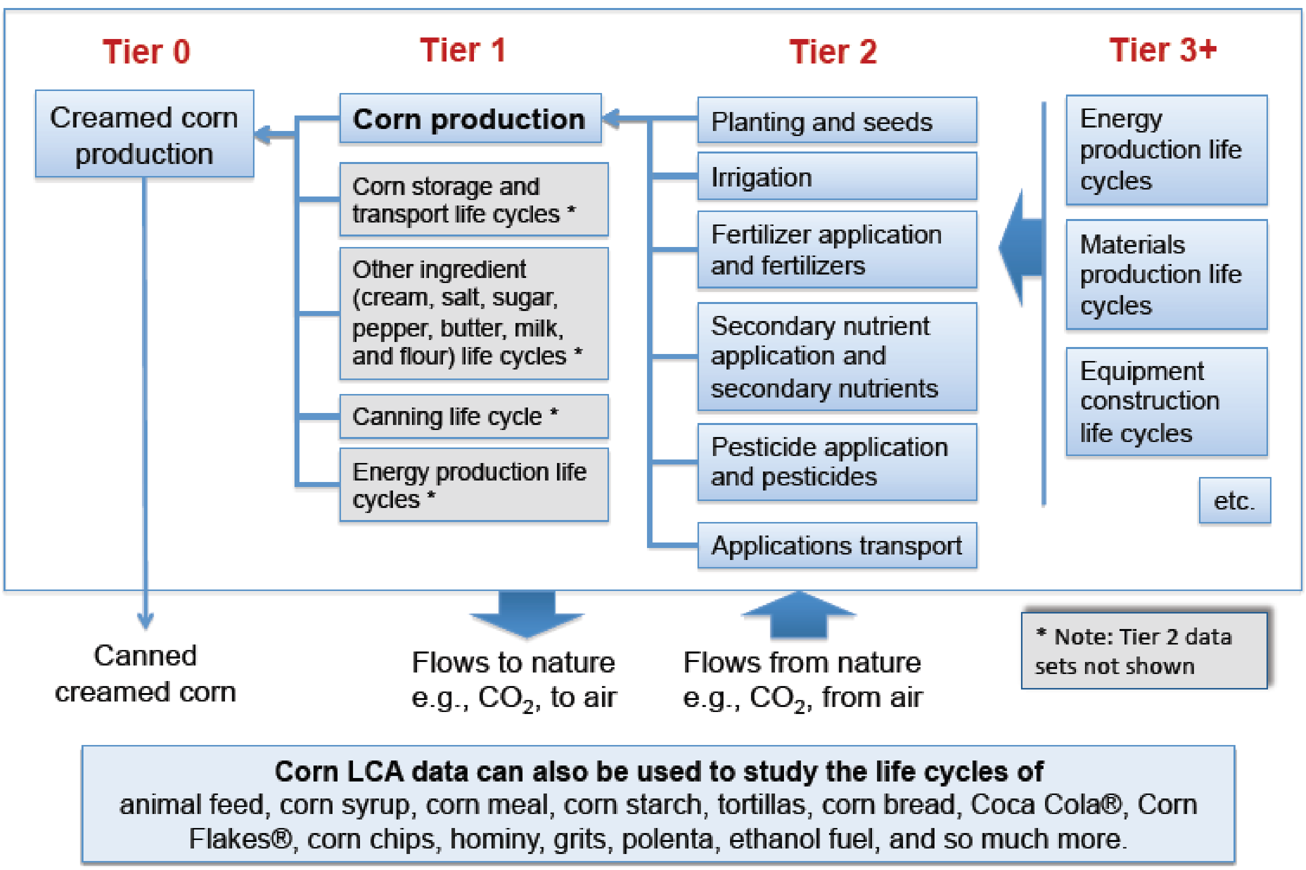
[7] See http://www.ers.usda.gov/Data/ARMS/Variables.htm for a list of ARMS variables.

[8] See http://QuickStats.nass.usda.gov/

[9] See http://www.epa.gov/otaq/nonrdmdl.htm

- **Flows from the technosphere (a.k.a. intermediate flows),** including the amounts of any applications (as seeds, fertilizers, secondary applications (e.g., limestone, dolomite, and zinc compounds), and pesticides), work processes/ equipment use (e.g., the use of soil preparation, planting and seeding, irrigation, application, and harvest equipment), and the storage and transport of applications.
- **Flows to the environment** as air, water, and soil emissions related to e.g., applications use and residue burning.

Figure 1. Data tiers, creamed corn example



Concerning the scope of the field crop unit process datasets, it is important to note that:

- **Data for the production of both crops and co-products are provided.** All field crop processes are multi-functional, with corn grain co-produced with silage, cotton lint co-produced with cottonseeds, and all crops co-produced with residues from previous crops (e.g., harvested for animal feed or other uses). This formulation provides the greatest flexibility for data use, allowing for example the practitioner to choose a basis for allocation (e.g., mass, energy, economic value) or to expand the LCA boundaries to include consideration of market changes as a result of co-product generation (as in a consequential LCA).

- **Although the amount of each application (seed, irrigation water, nutrients, pesticides, etc.) and related storage are included in the field crop unit process data, the fuel used and combusted and any disturbance related emissions by work processes/ equipment use are not[10].** This is intended to allow datasets to be used by multiple agricultural processes in the overall *LCA Digital Commons* database. For example, whereas the amount of fertilizer applied by broadcast equipment is included in the field crop data representing the production of soybeans in Iowa in 2006, the fuel used and combusted by the broadcast equipment will be estimated in the tier 3 unit process representing the broadcast equipment and used not only by the field crop data representing the production of soybeans in Iowa in 2006 but also by many of the other field crop production unit processes. Also, any losses during field crop storage will be considered in storage unit process datasets in "tier 1" to allow any final products the option of storing the feedstock or not.
- **In cases where the ARMS data are incomplete, such as when ARMS data has been omitted for privacy or specific ARMS variables do not represent 100% of the planted area, data are included in the field crop production unit processes as under the subcategory "services."** This is intended to ensure that missing data are represented as such and that ultimately data representing the range of possibly applicable practices are accessed in the related tier 2 dataset. Thus, tier 2 service datasets will include their own set of applications (e.g., the tier 2 unit process data flow named "nitrogenous fertilizer application service; unspecified rate" would include an estimation for the amount and types of nitrogen fertilizer used and any emissions associated with its use). Thus, all of the relevant applications and emissions are not included in the field crop data but will instead be in the tier 2 datasets. To be consistent with the data included in the crop production unit process datasets, service processes must include data representing equipment use and materials use, transport, and storage.
- **The scope of the data differ from that in other LCA databases in two key ways:**
    1. **The data achieve a mass balance.** The data balance the mass of biomass (crop, co-products, and residues) for select constituents (water, carbon, nitrogen, phosphorous, potassium, and the balance of dry matter) and the mass of water (irrigation, applied with manure, and applied with sewage sludge) and applications. This provides the data needed for a range of inventory cut-off rules (described by the ISO standards as a decision not to include select flows in an inventory, e.g., below a specified mass), which is not possible if the underlying unit process data are incomplete.

[10] Note that this is the same convention as used in ecoinvent crop unit process datasets.

2. **Flows to the environment are not based on any fate and transport modeling.** For flows to the environment, other LCA databases estimate some but not all fate and transport losses within the unit process data. When fate and transport considerations are included, the unit process data report only the remaining quantities as emitted to the environment as opposed to the amount that humans transform. For example in ecoinvent, fertilizers are applied and only the reaction products to air and water are included in the unit process data (e.g., for diammonium phosphate, ammonia, dinitrogen monoxide, nitrogen oxides, and nitrogen dioxide are emitted to air and phosphate and nitrate to water). The opposite is true for ecoinvent pesticides: pesticides are listed in the unit process data as emitted without biological or chemical transformation (e.g., atrazine is applied and emitted to soil as atrazine as opposed to quantifying degradates such as cyanuric acid; cyanurate salts; 2-chloro-4-hydroxy-6-amino-1,3,5-triazine; and any left over atrazine). The resulting data are possibly misused (e.g., some fate and transport considerations are included in some LCA impact characterization factors (e.g., USEtox™ [11]) thus offering the potential for double counting losses). Further and perhaps more importantly, the resulting data eliminate the opportunity for the use of the unit process data with a range of detailed fate, transport, and effect models (see Table 14).

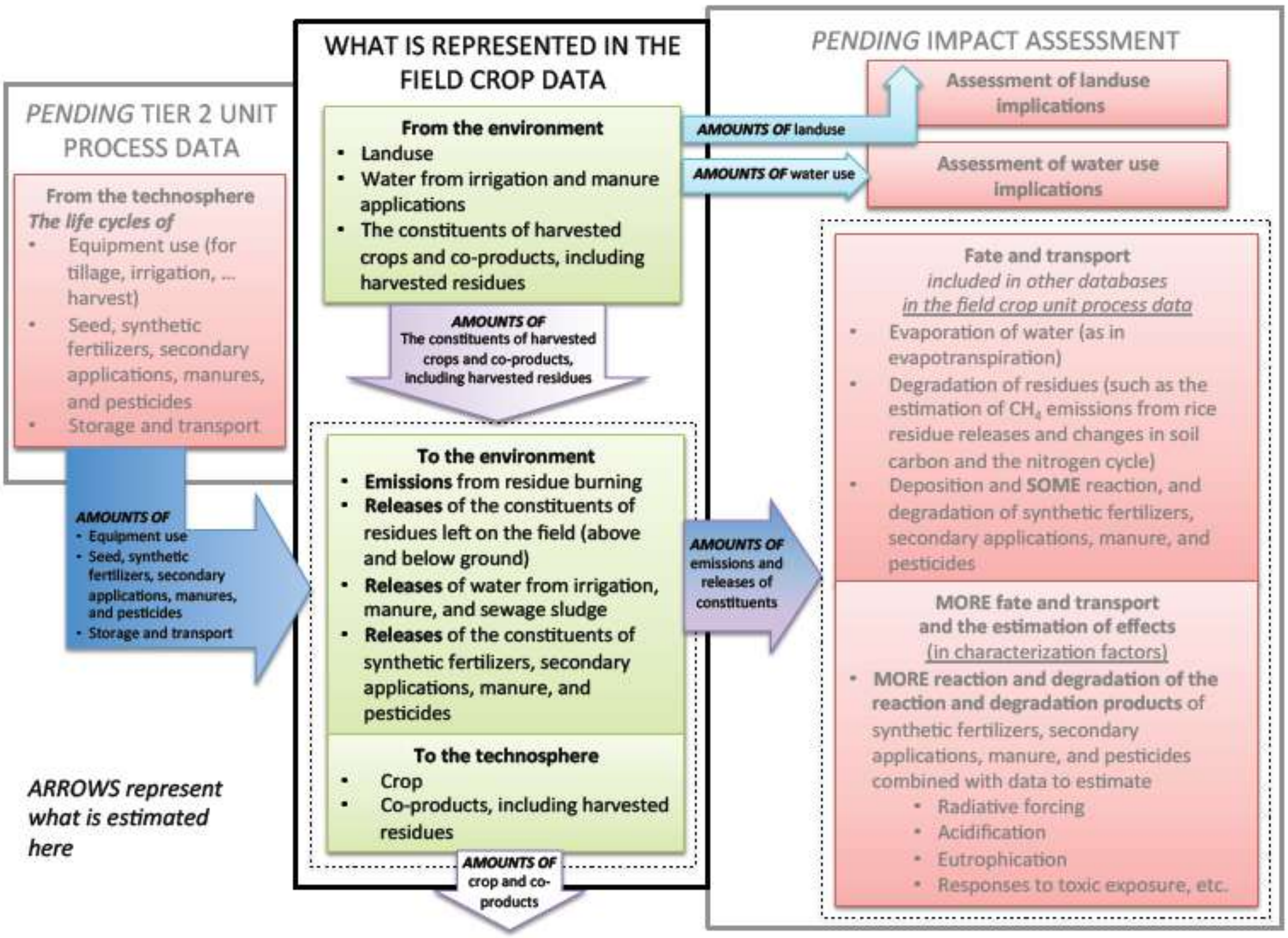
Within this context, Weidema, et al. (2011) note that it is difficult to determine an unambiguous and practicable boundary between life cycle inventory analysis (i.e., unit process data) and life cycle impact assessment. Here, the crop production unit process data have been prepared drawing a strict boundary not including any fate and transport losses, as depicted in Figure 2. Within this context, "emissions" are differentiated from "releases" to indicate that fate and transport has not been considered for releases. Specifically, the only emissions estimated are for residue burning and all other flows to the environment are releases, requiring further fate and transport modeling. To facilitate compatibility with other LCA databases and models, versions of the *LCA Digital Commons* crop production unit process data can be prepared using a range of fate and transport models (e.g., a dataset using the unit process data described here with fate and transport estimated using DayCent[12] or WIN-PST[13], etc.).

[11] See http://www.usetox.org/

[12] See http://www.nrel.colostate.edu/projects/daycent/

[13] See http://go.usa.gov/Kok

Figure 2. Data included in the crop production unit process datasets



1.3. Data formats

The Version 1 field crop production data were made available through the *LCA Digital Commons* in EcoSpold version 1 (v1)[14] format in June 2012 and are expected to be available in EcoSpold v2 and ILCD formats later in 2012. All three are data exchange formats based on XML (eXtended Markup Language) and related technologies (XSL, XSLT, Schema), are ISO/TS 14048 compliant (International Standards Organization (ISO) 2002), and are usable by a range of LCA software tools. Differences in the data formats include:

[14] See http://www.ecoinvent.org/database/EcoSpold-data-format/

- **Field character limitations.** In EcoSpold v1, data fields limit the amount of text that can be included in a flow name to 80 characters. As a result, abbreviations such as "unspec." for "unspecified" and the use of the shorter chemical names instead of the standard UNIPAC names are used in the EcoSpold v1 field crop production data (see Section 1.4). Note that e.g., EcoSpold v2 extends the limit to 120 characters.
- **Data fields dedicated to data quality information.** In ecoinvent's use of EcoSpold v1, data quality indicators are placed parenthetically in a general comment data field. This convention is also used in the EcoSpold v1 field crop production data. Alternatively, EcoSpold v2 provides specific fields for data quality information, although they differ in number and content from what is used here (see Section 1.6).
- **Accommodation of data parameterization.** Parameterization refers to the practice of presenting LCA data using raw data and formulas instead of computed numbers in unit process datasets within databases. As described by Cooper et al. (Cooper, Noon, and Kahn 2012), the benefits of data parameterization are transparency (the raw data and computations can be clearly documented and reviewed), enhancement of the potential to represent process variants (e.g., variations in load, process efficiency, etc. can be represented), and enhancement of interpretation capabilities (e.g., sensitivity analysis can be performed to the level of internal variables; results can be interpreted as a function of time). Whereas the EcoSpold v1 format does not allow parameterization, the EcoSpold v2 and ILCD formats do.

Given these, EcoSpold v1, EcoSpold v2, and the ILCD data format provide limited options for the specification of flow data uncertainty types/ descriptive statistics. Specifically, EcoSpold v1 and ILCD accommodate only undefined, normal, lognormal, triangular, and uniform distributions and EcoSpold v2 adds only beta, gamma, and binomial distributions. Much of the Version 1 field crop data are described by distributions not among those supported (see Section 1.5). Most notably, and as described by Cooper et al. (Cooper, Kahn, and Ebel 2012), because of the relatively small sample sizes of 15 or 30 used in the development of the ARMS means by ERS, a Student's t distribution is the appropriate representation of the probability density function and is not supported by the current and emerging formats.

The remedy here is to parameterize the Student's t distribution for use with the ARMS data and to parameterize the continuous probability distributions of data other than ARMS as needed. The method for parameterizing uncertainty distributions is described in Cooper et al. (Cooper, Noon, and Kahn 2012), using Smirnov transforms (a.k.a. inverse transform sampling).

1.4. Nomenclature, standard conventions, and inter-database compatibility

The nomenclature and standard conventions used are described in Appendix A: Standard conventions covering units of measure, location codes, technical scope, time frame, classifications, naming conventions, etc. Inter-database compatibility for tier 0 and tiers 2+ unit process data in other databases is to some extent provided by the use of classification systems. Specifically, each reference product, co-product, and technosphere flow is assigned United Nations Standard Products and Services Codes[15] (UNSPSC), the North American Industry Classification System[16] (NAICS), and International Standard Industrial Classification (ISIC) codes that also identify datasets in select other databases (e.g., NAICS is used by the US LCI Database and by ecoinvent v2). Also, the NAICS codes make the crop production data compatible with tiers 2+ economic-input-output life cycle data (e.g., using Carnegie Mellon's Economic Input-Output Life Cycle Assessment[17] (EIOLCA), the Comprehensive Environmental Data Archive[18] (CEDA), and Ohio State's Ecologically-Based Life Cycle Assessment[19] (Eco-LCA)). Matching codes between datasets allows supporting datasets to be identified and used in assessments.

Less compatible is the names of product, co-product, and technosphere flows and flows to and from the environment. The naming conventions described in Appendix A: Standard conventions are intended to facilitate future compatibility with existing LCA databases. The word "future" is used here because even when compatible with ISO14048, nomenclature is not consistent among existing databases (the US LCI database, ecoinvent, and ELCD) and does not take advantage of opportunities for the use of standard naming conventions. Thus, this places the names in the *LCA Digital Commons* data in the same place as data in other databases: as incompatible with other databases. However, so that the data can be used with tier 0 and tiers 2+ data in other databases, versions of each dataset will be prepared that match the nomenclature in other databases, as keyed to database-and-flow-specific universally unique identifiers (UUIDs). For example, a US LCI database version of each field crop unit process dataset, a version compatible with ecoinvent, and a version compatible with ILCD will be prepared.

1.5. Data uncertainty

As mentioned in Section 1.3, the field crop unit process data have been parameterized, such that raw data and formulas are presented in unit process datasets instead of computed numbers. Thus, uncertainty data are included for raw data as available, such that uncertainty propagates into the formulas in which the raw data are used. Ideally, if data are parameterized as such in unit process datasets throughout the life cycle, the inventory and impact assessments would represent uncertainty

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[15] See http://www..org

[16] See www.census.gov//

[17] See http://www.eiolca.net/

[18] See http://www.cedainformation.net

[19] See http://resilience.eng.ohio-state.edu/eco-lca/

propagated from the raw data through the LCA results, e.g., using a Monte Carlo simulation, and allowing uncertainty and sensitivity analysis to the raw data level.

For the raw data, the physical characteristics are made consistent with the mathematical boundaries of the distributions, such as ensuring physical properties are not sampled below zero (a negative amount of fertilizer is not applied) and fractions of a whole do not exceed 100% when multiple times over does not apply. A summary of the use of uncertainty types is presented in Table 3.

Table 3 Summary of uncertainty types

Uncertainty type	Raw data
Normal distribution	• Residue burning emission factors
Student's t distribution	• ARMS data (e.g., planted area, treated percent of planted area, treatment rates, etc.) • Fraction of liming materials that is limestone or dolomite • Growing period (fraction of the year)
Triangular distribution	• Biomass dry matter fractions • Below to above ground residue ratios • Fraction of manure type from each storage type • Nitrogen, phosphorous, and potassium contents except cotton residue • Pesticide active ingredient fractions • Residue burning area fraction
Uniform distribution	• Crop and residue carbon contents • Fraction of residue remaining on the field that is harvested • Manure as-applied moisture, volatiles, and nitrogen, phosphorous and potassium contents • Manure handling and storage loss fractions • Nitrogen, phosphorous, and potassium contents of cotton residue • Residue burning ash fraction and ash carbon fraction • Residue to crop ratios • Sewage sludge moisture and nitrogen, phosphorous and potassium contents • Storage time for applications • Synthetic fertilizer type fractions (e.g., % of nitrogen fertilizer that is urea), active ingredient fractions (e.g., % of urea that is nitrogen), and calcium carbonate equivalents

For the parameterized field crop unit process data, when the uncertainty data are among the types supported by the EcoSpold v1 and v2 and ILCD, data formats (as normal, triangular, and uniform distributions) the uncertainty information is presented as such. As noted in Table 3, there are 3 instances in which the uncertainty data is described by a Student's t distribution which does not to conform to the supported distributions: all ARMS data (used in the vast majority of the flows estimated), the fraction of liming materials that is limestone or dolomite, and the growing period for each crop (used to estimate land occupation in m^2-annually).

The method for parameterizing uncertainty distributions is described in Cooper et al. (Cooper, Noon, and Kahn 2012), using Smirnov transforms (a.k.a. inverse transform sampling). Essentially, probability density functions (pdfs) are converted to cumulative pdfs (cdfs) and inverted (to describe the inverse cdf (icdf)) that is then available for sampling in e.g., a Monte Carlo Analysis based on the generation of random numbers between zero and one. Given this, two methods are employed to represent the icdf: (1) if a relevant icdf was found in literature (e.g., the icdf described by Gleason (2000) to represent a Student's t distribution), then that icdf is used or (2) if no relevant icdf was found in literature, then a least squares fit of the icdf is generated and used.

For the ARMS data, Sommer et al. (1998) describe ARMS as a probability-based survey where each respondent represents a number of acres of similar size and type and the sample data are weighted and expanded to represent operations at the state level. Given these data, according to Kim et al. (2004) a delete-a-group jackknife is used to estimate the sample mean because the population mean is unknown. A predetermined set number of groups is used for the jackknife at a consistent sample size (*n*) of 15 prior to 2009 and 30 in 2009 and estimates the mean (*m*). Differences between the sample and population mean result from non-sampling errors (e.g., related to questionnaire design or data processing) and sampling errors (e.g., related to sample selection, estimation, or nonresponse adjustments). Whereas non-sampling errors cannot be measured directly, sampling error is represented in ARMS as the relative standard error (RSE) of the expected mean and is also called the coefficient of variation (CV). For the ARMS data, the RSE is defined as:

$$RSE = \frac{\left(s/\sqrt{n}\right)}{m}$$

Equation 1

where *s* = sample standard deviation.

The RSE for each ARMS mean can be used with the Student's t value to represent the distribution around each ARMS mean for uncertainty analysis. However, a t value must be generated within the unit process dataset for each instance, and is done so as described in Cooper et al. (Cooper, Noon, and Kahn 2012) using inverse transform sampling. To accomplish this, each ARMS variable is represented using 7 parameters: (1) a raw mean value *m*; (2) a raw RSE value; (3) the degrees of freedom (df) for the Student's t estimate (as n-1); (4) a probability *p* as a randomly generated uniform number between zero and one; (5) a standard normal *zp* at *p*; (6) the t value estimated as a function of *df*, *p*, and *zp*; and (7) the parameterized ARMS variable value estimated as a function of *m*, *RSE*, and *t*. Thus, during e.g., a Monte Carlo simulation, the generation of uniform random numbers between zero and one (i.e., the generation of p) allows the generation of t values which are used to represent the pdf of the mean ARMS data.

The ARMS RSE values are described and analyzed in Cooper et al. (Cooper, Kahn, and Ebel 2011). Although the vast majority of the data have a RSE less than 100%, values range from 0% to 1,600% such that uncertainty and data quality analyses for assessments using these data are very important. Note that the high RSE values most often occur with state estimates, with many states having a very low response rate, especially for certain practices, which contributes to high RSE values. The least precision was found in data collected between 2001 and 2002, in the production of corn and soybeans, and in synthetic and pesticide applications and irrigation data. The highest precision was seen in the production of durum wheat, rice, oats, and peanuts and in data representing previous crops and till and seed technology use.

Also, upwards of 20% of the data had 95% confidence intervals less than or exceeding actual limits, e.g., suggesting that the pdf at its tails includes a negative irrigation area or a fractional use of an irrigation method exceeding a total irrigated area. To account for these phenomena in the parameterized data, bounds are set on the parameterized ARMS variable value as applicable: physical values are set at a minimum of zero (such that the minimum area or application mass is treated as zero in an uncertainty analysis) and fractions are bounded by 0% and 100%. Further, when fractions are used together (e.g., to estimate the irrigated area using pressure systems and the irrigated area using gravity systems) balance relationships are parameterized using *successive if statements* to convert percentages (with in the field crop unit process data the parameter name starting with per_) to balance parameters (with the parameter name starting with Bal_) as described by Cooper et al. (Cooper, Noon, and Kahn 2012). Specifically, *successive if statements* balance the set of percentages to ensure the total does not exceed 100% as each data point is varied over its Student's t distribution. The balance parameters are then combined with the raw data to represent the final value of interest. It is very important to note that success of this formulation is dependent upon the use of a sufficient number of samples in e.g., a Monte Carlo simulation to ensure individual parameters are not biased.

Thus, it was found that in order to make uncertainty data for the ARMS and other raw data available to uncertainty and sensitivity analysis in LCAs using the unit process data required parameterization to be used in a new way. Beyond the relatively computationally intensive parameterization of balance relationships and probability distribution functions for the ARMS data, the fraction of the year during which each crop is grown, and the fraction of liming materials that is limestone or dolomite, the uncertainty in remaining data used are represented by normal, uniform, and triangular distributions or no uncertainty information when no such information was found.

It is also important to note that the uncertainty data presented here represents 'basic' uncertainty as opposed to 'additional' uncertainty as described by Weidema and Wesnæs (1996). Weidema and Wesnæs's additional uncertainty is related to the data not being of the optimal quality (e.g., differing in representativeness as described in Section 1.6) and is included in e.g., the ecoinvent database as the "square of the geometric standard deviation (95% interval – SDg95)." Commentary and alternative methods for considering the implications of varying data quality are discussed in Cooper and Kahn (2012).

1.6.Data quality

The ISO14044 states that "where a study is intended to be used in comparative assertions intended to be disclosed to the public, the [following] data quality requirements" *shall* be addressed: time-related coverage, geographic coverage, technology coverage, precision, completeness, representativeness (considering together time-related, geographic, and technology coverage), consistency, reproducibility, sources of the data, and uncertainty of the information. Among these, consistency (a qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis) is applicable to life cycle inventories as opposed to unit process data and completeness is interpreted here as at both the unit process and flow levels. The remaining requirements are at the level of each flow within a unit process dataset.

Cooper and Kahn (Cooper and Kahn 2012) explore issues with current data quality analysis methods, noting that amongst commonly applied methods there exists a need for improved repeatability and interpretability. As a result of this exploration of issues, a data quality analysis method has been developed for the crop production data, as follows.

1.6.1 Completeness at the unit process data

Herein, all datasets include data in the flow groups listed in Table 4. The actual flows in each dataset are specific flows in each flow group. For example, the group "fertilizer application (ha)" includes the application of nitrogenous, phosphoric, and potassium fertilizers each using no broadcast, broadcast with and without incorporation, and mixed methods.

All datasets include all flows, noting that as described in Section 1.2 missing data are represented as service processes (again, in cases where the ARMS data are incomplete, data are included in the field crop production unit processes as under the subcategory "services" to ensure that missing data are represented as missing from the dataset but not necessarily at a zero value). In general, service processes are used when rate data are not available in ARMS (e.g., the rate of nitrogenous fertilizer application is not reported). Like the data for which rate data are available, service processes include need to represent equipment use, the mass of the application, and the storage of the application. Also, service process datasets are tier 2 datasets and have yet to be prepared.

Table 4 Unit process flow groups

Products and co-products	• Crop production (kg)	• Co-production (kg)
Flows from the environment	• Occupied area (m2a) • Transformed area (m2) • Water withdrawal (kg)	• Nutrients from air and soil (in crops, co-products, and above and belowground residues (kg)
Technosphere flows	• Field residue burning (kg) • Residue management (kg) • Soil preparation (ha) • Planting or sowing (ha) • Seed use (kg) and storage (kga) • Irrigation (ha) • Irrigation water use (kg) • Fertilizer application (ha) • Fertilizer active ingredient and filler use (kg) and storage (kga) • Lime application (ha) • Lime use (kg) and storage (kga)	• Secondary applications (gypsum, sulfur compounds, sulfuric acid, zinc compounds, sewage sludge) (ha) • Secondary and micronutrient use (kg) and storage (kga) • Manure application (ha) • Manure use (kg) and storage (kga) • Pesticide application (ha) • Pesticide active ingredient and formulation balance use (kg) and storage (kga) • Transport of applications (kg-km) • Harvest of crops and co-products (ha)
Flows to the environment	• Residue burning emissions (kg) • Releases of residue left on the field (above and below ground) (kg)	• Releases of water (in irrigation, with manure applications, in sewage sludge applied) (kg) • Releases of substances applied in fertilizers, manures, secondary applications, and pesticides (kg)

1.6.2 Flow level data quality indicators

At the flow level, the 2-tiered data quality analysis method is described in Cooper and Kahn (Cooper and Kahn 2012) as presented in Table 5. The “2-tiers” define flow data as either meeting a minimum criteria (receiving a score of A) or not (receiving a score of B). In each dataset, scores are listed presented parenthetically in the order presented in Table 5 (as e.g., (A,B,A,A,A,B,B) intended to represent a score of A for reliability and reproducibility, a score of B for flow data completeness, a score of A for temporal coverage, etc.) in a comment data field or in data quality dedicated data fields.

Table 5. *LCA Digital Commons* flow data quality scoring criteria

Category	**Requirements for a data quality score of A**
1. Reliability and reproducibility	The **flow data** were based on measurements using a specified and standardized measurement method **OR** the **flow data** were estimated using methods and data described in specified archival or other consistently publically available sources.
2. Flow data completeness	The **flow data** were collected over at least 3 years for agricultural (crop, livestock, forest, range) processes or other processes in which the data point varies for uncontrolled annual conditions (e.g., weather) **AND** the **flow data** balance the mass and energy in and out of the unit process.[20]
3. Temporal coverage	The **flow data** represent operations that occurred between the unit process start and end dates without forecasting.
4. Geographical coverage	The **flow data** represent operations that occurred within the location of the unit process, including non-agricultural process data that have been adapted to reflect logistics and market shares[21] for the unit process location.
5.Technological coverage	The **flow data** represent the process(es) and/or material(s) specified without surrogacy or aggregation with other technologies.
6. Uncertainty	The **flow data** either include estimates of the first quartile, mean, median, and third quartile values **OR** data or probability distribution from which these values can be estimated.
7. Precision[22]	The relative standard error of the **flow data** is less than or equal to 25% **OR** the interquartile range divided by the median is less than or equal to 50% **OR** for a triangular distribution, the minimum **flow data** value is ≥ 75% and maximum **flow data** value is ≤125% of the most likely value **OR** For a uniform distribution, the minimum **flow data** value is ≥ 75% and maximum **flow data** value is ≤125% of the average of the minimum and maximum values.

The crop production flow data quality scores are presented in Table 6. As shown, all flows obtain scores of (A,B,A,A,A,B,B) as meeting the requirements for reliability and reproducibility and temporal, geographical, and technological coverage except for select flows. Note that each individual crop-state-year dataset represents a single year of production and thus do not meet the completeness requirement. However, multi-year datasets combining at least 3 relevant crop-state-year datasets (when available) have been prepared to improve upon the completeness scoring criteria.

[20] An incomplete mass balance may represent either an incomplete unit process or an incomplete set of emissions factors, or both. In the case of a score of B e.g., for an incomplete set of emissions factors, the data quality analysis serves to highlight an opportunity to improve data quality through methodological or documentation improvement.
[21] Market shares, sometimes called mixer processes in LCA, reflect the technologies used in local markets. For example, market shares are used to represent the mix of technologies used in regional electricity generation (the percentage of coal, natural gas, nuclear, etc. per kWh) and the mix of waste management technologies (landfilling, waste-to-energy, etc.) locally available.
[22] In the precision category, percentages are intended to represent quartiles, as frequently used in descriptive statistics to represent a fourth of the population being sampled. Note also that for unit processes that balance in category 2, precision will apply as propagated to flows on both sides of the balance.

Table 6. Field crop production flow data quality scores

Category	**In the field crop unit process data, ALL flows not listed as EXCEPTIONS receive a score of:**
1. Reliability and reproducibility	A: Flow data were estimated using methods and data described in specified archival or other consistently publically available sources, as described in this document.
2. Flow data completeness	A: For flows in multi-year datasets. B: For flows in single year datasets, because a single year of agricultural production is represented, every flow does not meet the minimum criteria.
3. Temporal coverage	A: The flow data represent operations that occurred between the unit process start and end dates without forecasting. B: Flows representing field burning emissions are based on state-crop data from 2003-2007. B: The liming material adjustment factors are based on data from 1988-1995
4. Geographical coverage	A: The flow data represent operations that occurred within the location of the unit process. EXCEPTIONS B: All flows representing the specific types of fertilizer (e.g., ammonium nitrate as a nitrogen fertilizer) are based on US average data for each production year. B: All flows representing secondary applications except nitrogen inhibitors are based on US average data for each production year. B: Dolomite and limestone fractions are based on regional data.
5.Technological coverage	A: The flow data represent the processes and/or materials specified without surrogacy or aggregation with other technologies. EXCEPTIONS B: All flows representing service processes are surrogates for the processes and/or materials actually used. Note that the name of these flows includes the word “service.” B: All flows for which specific technologies are unspecified (e.g., the balance of a total in which some technologies are specified and some are not). Note that the name of these flows includes the word “unspecified.” B: All flows representing the specific types of fertilizer (e.g., ammonium nitrate as a nitrogen fertilizer) are based on US average data for each production year and are not crop specific. B: Fertilizer filler materials and the balance of pesticide formulations consist of an unknown group of materials. B: Applications of secondary applications except nitrogen inhibitors are not crop-specific, but in aggregate represent applications in a year. B: Residue burning emissions of non-methane volatile organic compounds (NMVOCs), particulate matter (PM2.5 and PM10), ash, and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) are not crop-specific. B: Residue burning emissions of carbon dioxide are estimated to balance, subtracting from the crop specific carbon uptake the non-crop specific carbon in ash and air emissions of particulate matter and NMVOCs. B: For flows to the environment, fertilizer, manure, and pesticide application methods have been assumed to apply to each type or constituent by the fraction of the planted area using the method.
6. Uncertainty	A: The flow data propagate uncertainty using probability distributions assigned to underlying parameters in the EcoSpold v2 and ILCD formats. B: In the EcoSpold v1 version of the crop production data, no uncertainty data are included.
7. Precision	A: In the EcoSpold v2 and ILCD versions of the crop production data, flow data that propagate precision to the stated criteria is assigned a score of A. B: In the EcoSpold v2 and ILCD versions of the crop production data, flow data that does not propagate precision to the stated criteria is assigned a score of B. B: In the EcoSpold v1 version of the crop production data, no uncertainty data are included. However, when the data are converted to the EcoSpold v2 and ILCD formats, parameterization will be used to propagate uncertainty, allowing an estimation of precision.

1.7.Critical review

Critical review of the field crop production unit process data engaged two panels of subject area and LCA experts. The first panel reviewed initial data formatting rules and field crop production flow data estimation methods in the spring and summer of 2011 with the panel members listed in Table 7. Given the benefit of input from the first panel, the data and documentation were updated. The second panel (Table 8), convened during March 2012, engaged additional crop production data experts in a re-review of the technical content of the new data. An additional panel will re-review data formatting, with an eye towards wide use in the preparation of data for the *LCA Digital Commons* and will convene later in 2012.

Table 7. Initial critical review panel (May 2011)

Panelist	**Organization**
Peter Arbuckle (Panel Chair)	National Institute of Food and Agriculture, USDA
Rob Anex	Biological Systems Engineering, University of Wisconsin - Madison
Rick Bergman	Forest Products Laboratory, USDA Forest Service
Bob Dubman	Economic Research Service, USDA
Jason Hill	Bioproducts and Biosystems Engineering, University of Minnesota
Jane Johnson	Agricultural Research Service, USDA
D.K. Lee	College of Agricultural, University of Illinois at Urbana-Champaign
Susan McCarthy (USDA Project Lead)	Agricultural Research Service, USDA
Shelie Miller	School of Natural Resources and Environment, University of Michigan
Greg Roth	College of Agricultural Sciences, Penn State
Greg Thoma	Chemical Engineering, University of Arkansas

Table 8. Second critical review panel (March, 2012)

Panelist	**Organization**
Rob Anex	Biological Systems Engineering, University of Wisconsin - Madison
Mike Edgerton	Monsanto
Jane Johnson	Agricultural Research Service, USDA
Tony Vyn	Agronomy Department, Purdue University
Marty Matlock	Department of Biological and Agricultural Engineering, University of Arkansas
David Muth	Biofuels and Renewable Energy, Idaho National Laboratory, USDOE
Robert Ebel	Economic Research Service, USDA
Andrew Lenssen	Agronomy Department, Iowa State University
Sangwon Suh	Bren School of Environmental Science and Management, University of California Santa Barbara

2. Field crop production unit process data estimation methods

2.1.Introduction

All raw data and all equations (i.e., the parameterization) used in the development of the crop production unit process data are listed in the MS Excel workbook called *Crop production data parameterization version 1.xlsx* that accompanies this document. Six worksheets list parameter names and descriptions, classification codes, EcoSpold v1 categories, CAS numbers, formulas, units of measure, data quality information, uncertainty information (uncertainty type, standard deviation, and most likely, minimum, and maximum values) and the mathematical relations:

- **Summary of input & output flows** lists the reference and co-products, technosphere flows, and flows to and from the environment as described in Table 3 and as the data appear in the EcoSpold v1 version of the crop production data.
- **Parameterization of reference and co-product flows** lists parameters for crop and co-product production, including harvested residues.
- **Parameterization of flows from the environment** lists parameters for land use (occupied and transformed areas), water withdrawals, and the uptake of nutrients from the air and soil.
- **Parameterization of technosphere flows** lists parameters for field operations and applications and logistics. There are 1,296 parameters related to technosphere flows.
- **Parameterization of flows to the environment** lists parameters for releases to the environment from residue burning, residues left on the field (above and below ground), water applied in irrigation, with manure, and with sewage sludge, and applications.
- **Parameterization of ARMS data** lists 135 raw data parameters and an example of how they are used with RSE values, probabilities, standard normals, and t values for the representation of the Student's t probability distributions.

For the data available through the LCA Digital Commons, the EcoSpold v1 data contains only the information on the "Summary of input & output flows" worksheet. Alternatively, the Version 1 crop production datasets in the EcoSpold v2 and ILCD formats will also imbed the parameterization on all worksheets in the MS Excel workbook in each dataset. Note also that converters are available to prepare EcoSpold v2 and ILCD XML files from EcoSpold v1 files, albeit without parameterization (thus only the resulting flow data transfers). The data sources and estimation methods are described as follows.

2.2.Reference products and co-products

All field crop data are presented on the basis of the production of a single kg wet mass of a reference field crop. Production data are primarily from NASS QuickStats (at http://quickstats.nass.usda.gov/) as described in Table 9. Note that QuickStats does not provide uncertainty data for measures of production or for the associated planted or harvested areas (i.e., the components of yield).

Table 9 What is harvested

	Reference product	**Co-products**
Corn grain	Grain (number of bushels reported by NASS QuickStats, assumed to be at the standard 56 lb/ bushel)	• Chopped silage (tons reported by NASS QuickStats) • Residue (estimated using the percent soil coverage reported in ARMS as “residue remaining on the field” as described by USDA Agricultural Handbook 703 (Renard et al. 1996))
Cotton	Lint (number of 480 lb bales reported by NASS QuickStats)	• Seeds (tons reported by NASS QuickStats) • Trash (leaves, burs, sticks, and dirt) harvested with lint and seeds, estimated as dependent on the harvest method, considering machine picked and stripped methods as described by the USEPA (US Environmental Protection Agency 1996)[23] • Residue (estimated using the percent soil coverage reported in ARMS as “residue remaining on the field” as described by USDA Agricultural Handbook 703 (Renard et al. 1996) and not harvested with the lint and seeds)
Oats	Grain (number of bushels reported by NASS QuickStats, assumed to be at 32 lb/ bushel)	• Residue (estimated using the percent soil coverage reported in ARMS as “residue remaining on the field” as described by USDA Agricultural Handbook 703 (Renard et al. 1996))
Peanuts	Seeds and shells[24] (number of pounds reported by NASS QuickStats)	• Residue (estimated using the percent soil coverage reported in ARMS as “residue remaining on the field” as described by USDA Agricultural Handbook 703 (Renard et al. 1996))
Rice	Grain (centum weight (cwt) reported in NASS QuickStats)	• Residue (estimated using the percent soil coverage reported in ARMS as “residue remaining on the field” as described by USDA Agricultural Handbook 703 (Renard et al. 1996))
Soybean	Beans without pods (number of bushels reported by NASS QuickStats, assumed to be at 60 lb/ bushel)	• Residue (estimated using the percent soil coverage reported in ARMS as “residue remaining on the field” as described by USDA Agricultural Handbook 703 (Renard et al. 1996))
Wheat	Grain (number of bushels reported by NASS QuickStats, assumed to be at 60 lb/ bushel)	• Residue (estimated using the percent soil coverage reported in ARMS as “residue remaining on the field” as described by USDA Agricultural Handbook 703 (Renard et al. 1996))

In addition to the crop produced, harvested co-products are also described in Table 9, as corn silage when the reference product is corn grain, as cottonseeds and trash harvested with lint and seeds when

[23] The USEPA (US Environmental Protection Agency 1996) states that machine picked cotton normally accounts for 70-80% of the total cotton harvested while machine stripped cotton normally accounts for 20-30%. Further, they list machine-picked cotton as typically at 34% lint and 9.5% trash and stripped at 23% lint and 35% trash.

[24] Peanuts are assumed to be in shells at harvest, based on a personal communication with Heping Zhu, USDA ARS (November 11, 2011)

the reference product is cotton lint, and as residue for each field crop. For corn grain, it is important to note that although farms can/will produce grain or silage, the related ARMS data are not separable as such (i.e., the ARMS data are presented for corn, which covers both grain and silage). For cotton trash, it has been assumed that 70-80% of the cotton is machine picked and the balance is machine stripped and that machine picked and stripped cotton is harvested at trash to lint ratios of 0.28 and 1.5 respectively (as in (US Environmental Protection Agency 1996)).

Crop residue is assumed to be a co-product (e.g., for use as animal feed, etc.) for all crops investigated, and in Table 9 it is noted that estimates use the percent soil coverage reported in ARMS as "residue remaining on the field" as described by USDA Agricultural Handbook 703 (Renard et al. 1996)[25]. Specifically, the ARMS variable "residue remaining after planting (%)" represents the percent soil coverage of *previous* crop residues. Previous crops covered by ARMS are corn, cotton, soybeans, small grains, other crops, and fallow such that here these data are interpreted such that "small grains" represent oats and wheat and "other crops" represent peanuts and rice. Given this interpretation, the ARMS data for each previous crop were collected for each state and previous year. Finding that this state-year data sparse due to ARMS data being collected in intermittent years and states (as listed in Table 1), data were then summarized for each previous crop by state for the period of 1996-2009 and for each previous crop for all states. The final data, presented in Appendix C: Data for the estimation of residue percent soil coverage, represent the mean and RSE for the percent soil coverage for each previous crop by state and for the nation when no state data were available.

Given estimates of the percent soil coverage, the mass of aboveground residue remaining on the field was estimated as described in the USDA Agricultural Handbook 703 (Renard et al. 1996). Specifically, Renard et al. provide an exponential function to convert ground cover (residue) weight to the portion of the soil surface that is covered:

$$S_p = (1 - \exp(-\alpha B_s)) * 100$$

Equation 2

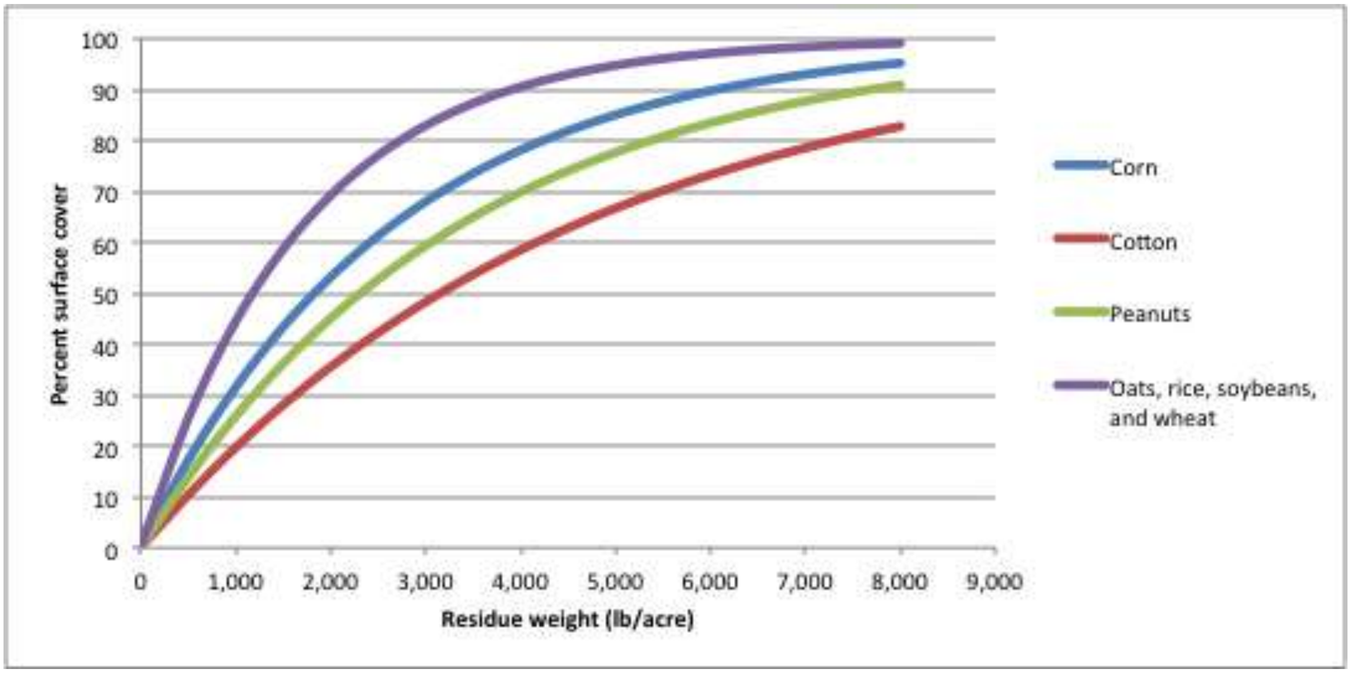
where S_p is percent residue cover, α is the ratio of the area covered by a piece of residue to the weight of that residue (acre/lb), and B_s is the dry weight of crop residue on the surface (lb/acre). Renard et al. provide typical values for α of 0.00038, 0.00022, and 0.00059 for corn; cotton; and oats, soybeans, and wheat respectively and here it is assumed that the value of 0.00059 also applies to rice. Figure 3 shows a plot of Equation 2 for each residue type. Since ARMS provides data for S_p, the final equation for the estimation of B_s is:

[25] See http://www.techtransfer.osmre.gov/NTTMainSite/Library/hbmanual/rusle703.htm

$$B_p = \frac{-ln\left(1 - \frac{S_p}{100}\right)}{\alpha}$$

Equation 3

Figure 3. Relationship of ground cover to residue dry weight



Finally, it is assumed that residue is harvested as a co-product is some fraction of the total aboveground residue produced less B_p. The amount of aboveground residue produced is estimated using the aboveground residue to crop ratios and dry matter fractions presented in Table 10 and the fraction harvested is modeled as a uniform distribution from zero to 1. To balance, aboveground residue not left on the field and not leaving as a co-product is assumed to be left to decay on the soil, incorporated or not. This formulation assumes it cannot be determined how the residue is actually managed: some fraction could be harvested as a residue co-product, some fraction could be left to decay on the soil surface, and/or some fraction could be incorporated into the soil and decay[26].

Table 10 Crop and residue characteristics

	Wet mass bushel conversion factors*	**Aboveground residue to crop ratios** (kg residue/ kg crop, triangular distributions except corn silage and peanuts)**			**Belowground to above ground residue ratios (kg below ground dry matter/ kg above ground dry matter, triangular distribution using the range provided by IPCC)*****	**Dry matter fraction** (triangular distributions except corn grain, oats, soybeans, and wheat)****		
		Minimum value	Most likely value	Maximum value	Values	Minimum value	Most likely value	Maximum value
Corn grain	25.4 kg/bushel (56 lb per bushel)	0.75	1.0	1.0	0.22 (+/- 26%)		0.85	
residue						0.22	0.64	0.91
Corn silage			0			0.22	0.28	0.34
residue						0.22	0.64	0.91
Cotton lint		1.0	1.0	3.3	0.21 (+/- 46%)	0.90	0.92	0.93
Seed						0.90	0.92	0.93
residue						0.80	0.86	0.92
Oats	14.5 kg/bushel (32 lb/bushel)	1.0	1.0	2.1	0.25 (+/- 120%)		0.86	
residue						0.85	0.89	0.93
Peanuts			1.0		0.20 (+/- 50%)	0.90	0.93	0.95
residue						0.85	0.90	0.92
Rice		1.0	1.0	1.5	0.16 (+/- 35%)	0.63	0.85	0.90
residue						0.90	0.91	0.93
Soybeans	27.2 kg/bushel (60 lb / bushel)	1.0	1.0	2.1	0.19 (+/- 45%)		0.87	
residue						0.88	0.90	0.94
Wheat, spring	27.2 kg/bushel (60 lb / bushel)	1.0	1.0	1.3	0.28 (+/- 26%)		0.87	
residue						0.83	0.86	0.90
Wheat, winter	27.2 kg/bushel (60 lb / bushel)	1.0	1.0	1.7	0.23 (+/- 41%)		0.87	
residue						0.83	0.86	0.90

* Wet weight bushel conversion factors are from (Hirning et al. 1987).

** Residue to crop ratios represent the range of values presented by the IPCC (1996, Table 4-17 on Page 4.85) and in the USDOE original "Billion-ton report" (Perlack et al. 2005) supplemented with data from Milbrandt (2005) for cotton, from Kiniry et al. (2005) for peanuts, and from a peer review communication from Vyn for corn. Note that the US DOE "Billion-ton-update" (US Department of Energy 2011) uses a baseline value of 1.0 representing a harvest index of 0.5 for all crops chosen as a result of substantial public comment on the original version of the report by Perlack et al. (2005). However, peer reviewers of the data presented here preferred a more crop-specific approach.

***Data are from the IPCC emission factor database (at http://www.ipcc-nggip.iges.or.jp/EFDB/) as the ratio of below-ground residues to above-ground biomass (RBG-BIO) from 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Table 11.2 (as IPCC EFIDs 417382, 417388, 417377, 417386, 417389, 417385, and 417384) except for the data for cotton. The cotton data represent the range of root to shoot ratios for over 25 genotypes and varying water stress from McMichael and Quisenberry (1991,Table 11).

******Dry matter fractions** are summarized from the USDA Natural Resources Conservation Service (NRCS) Crop Nutrient Database (US Department of Agriculture 2011a) and Lemunyon et al (1999) with cotton stalks data from Henry (1982) and corn silage data from a peer review communication with Vyn.

2.3.Flows from the environment

Table 15 in Appendix B: Parameterization of ARMS data summarizes the ARMS variables used. Data represent land occupation and transformation, water withdrawal, and nutrients up taken from air and soil as follows.

2.3.1 Land occupation and transformation

Land occupation and transformation are estimated in a manner similar to that described by Nemecek and Kägi (2007) for use in ecoinvent. Specifically, land occupation is estimated as the product of the planted area from NASS QuickStats and the fraction of the year during which each crop is grown (in m^2a, for square-meters-annual). The fraction of the year during which each crop is grown is estimated based on data from NASS representing usual planting and harvesting dates (US Department of Agriculture 2010). The raw NASS data are dates that indicate the periods in which crops are planted and harvested in most years based on 20 years of historical crop progress estimates and the knowledge of industry specialists. Eight dates are given by crop and state:

- Two *beginning dates* indicate when planting or harvesting is about 5% complete,
- Four *most active dates* indicate when between 15 and 85% of the crop is planted or harvested, and
- Two *ending dates* indicate when planting or harvesting are about 95% complete.

The “usual planting dates” are the times when crops are usually planted in the fields. The “harvest dates” refer to the periods during which harvest of the crop actually occurs. Dates do not extend through any subsequent period in which some crops are stored in the field after harvest.

Given these dates, the growing period is represented as the fraction of the year between the planting and harvesting dates such that:

- 5% is assumed to grow during the period between the beginning planting and harvesting dates,
- 15% is assumed to grow during the period between the most active beginning planting and harvesting dates,
- 85% is assumed to grow during the period between the most active ending planting and harvesting dates, and
- 95% is assumed to grow during the period between the ending planting and harvesting dates.

Given the resulting year fractions for NASS data, because not all crop-state combinations were available the data were combined into their respective USDA crop regions by weighting each available state-crop data point by the harvested area (also provided in the NASS report). The results are presented in Appendix D: Data for the estimation of growing season length. As shown the data represent a cdf for the growth period, and are thus used as the basis for estimating a least squares fit of the icdf to the third order, in all cases with an R^2 of 1.00.

It is important to note that basing land occupation on the growing period fails to recognize the resources used for fallow and idle lands. Relevant data are available through USDA Census of Agriculture, which defines cropland to include 5 components: cropland harvested, crop failure, cultivated summer fallow, cropland used only for pasture, and idle cropland[27]. Ideally the resources for fallow and idle lands would be considered in any assessment of general agricultural operations, in which these resources are used for multiple crop types. Herein, no attempt has been made to allocate these resources to the production of each individual crop. However, resources associated with crop failure are included here, as estimates of land occupation are based on the planted as opposed to the harvested area.

Next, land transformation is estimated based on the ARMS planted area, presented with the identification of the previous crop. Note that Nemecek and Kägi (2007) also estimate the transformation from a previous crop or condition but use a fixed percentage for winter and spring crops (specifically, 71% from arable land and 29% from meadow for all winter crops; 100% from arable for all spring crops). Here, the ARMS data representing planted acres for each previous crop harvested are used instead of fixed percentages. For example, in 2007 in North Carolina, the production of cotton was preceded on a planted area basis by 43% cotton, 31% small grains, 12% soybeans, 11% other crops, and 3% corn. Because each fraction is uncertain (as described by its RSE), successive if statements are used to ensure the total planted area is represented (i.e., such that the percentages balance, as described in Section 0).

2.3.2 Water withdrawal

Water withdrawal represents that used for irrigation and that applied with manure. Withdrawal is explicitly included here, as opposed to presenting the result of subtracting from the withdrawal the amount that evaporates. The intent as depicted in Figure 2 is to keep fate and transport modeling out of the unit process data so that it can be modeled consistently and well using a variety of detailed computational models.

For irrigation water, withdrawal estimates are based on ARMS data, as the product of the irrigated area, the fraction of the irrigated area using ground and surface water sources, and the amount of water applied (in inches). When the fraction of the irrigated area to which ground and surface water was applied did not sum to 100%, the source is listed as unspecified. Note that there is also water

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[27] For definitions of the landuse types, see http://www.ers.usda.gov/data/majorlanduses/glossary.htm#idle

withdrawn in the irrigation related service processes, described in Section 2.4, and when the amount of water applied was not included in the ARMS data.

For water applied with manure, because data are not available by source, all withdrawals are added to the irrigation water from unspecified sources. The amount of water is estimated dependent upon the state of the manure at application, as either semi-dry or dry, lagoon liquid, or slurry liquid and the additional amount withdrawn is assumed to be zero when the manure is sprayed using irrigation systems.

2.3.3 Nutrients from air and soil

Nutrients from air and soil represent estimates of what has been taken up by crops, co-products, and above and belowground residues during growth. Their estimation forms the basis for the constituent mass balance, intended to facilitate a wide range of related data analyses (e.g., see Section 4).

As shown in Appendix E: Reference product, co-product, and residue c, carbon, nitrogen, phosphorous, and potassium to the extent data were identified are accounted, with all data on a dry matter basis and biomass moisture separately accounted. The intent of presenting constituents is to allow each to be balanced with the flows to the environment. For example, the crop production unit process data allow the nitrogen leaving the fields in biomass to be compared to that emitted or released to the environment. This feature is unique to the *LCA Digital Commons* crop production unit process data and when combined with data representing the timing of releases (e.g., nitrogen fertilizer applied in the fall or spring before planting, at planting, or after planting) and application methods (e.g., broadcast with or without incorporation) is intended to provide valuable data for fate and transport modeling and ultimately for impact assessment. More information about the balance capabilities of the field crop production data is provided in Section 4.

The dry matter fractions in the crop and co-products are presented in Table 10 and the ratio of below ground to above ground residue is estimated as presented in Appendix E: Reference product, co-product, and residue c. Note also that the uptake of carbon is listed as “carbon dioxide, kg C” such that the CO_2 uptake can be estimated by multiplying this value by 44/12 while still maintaining the goal of tracking the balance of carbon.

2.4 Flows from the technosphere

Flows from the technosphere represent resources used from the industrial sector and were developed beginning with the ARMS data for soil preparation, planting, and seeds; irrigation; application and quantities of synthetic fertilizer active ingredients; application, quantities, and storage of organic fertilizer; and pesticide applications. Table 16 in Appendix B: Parameterization of ARMS data summarizes the ARMS variables used. Data outside of ARMS used are as follows.

Note that constituents are not tracked in the technosphere flows. This is because the ratio of constituents in some applications is not constant. Specifically, whereas the ratio of nitrogen to phosphorous in e.g., diammonium phosphate might be considered constant, the ratio of nitrogen to phosphorous in manures and sewage sludge are not constant. To facilitate compatibility for life cycle inventory calculations, technosphere flows are represented as either an entire weight of material or as an active ingredient and the related water, filler or formulation balance.

2.4.1 Unit conversion for corn kernels

For the estimation of the mass of corn kernels applied as seed prior to 2002, ARMS presents data for corn seed use in kernels prior to 2002 and in pounds thereafter. Here it has been assumed here that there are 90,000 kernels per bushel (Lee and Herbeck 2005) at the standard bushel weight of 56 lb/bushel such that the weight of seeds can be estimated from the ARMS kernel data.

2.4.2 Synthetic fertilizer types and filler

ARMS presents data for synthetic fertilizers by the mass of N, P_2O_5, or K_2O applied. To convert these to the specific types of each (e.g., N fertilizer as anhydrous ammonia, urea, etc.), data from the ERS Fertilizer Use and Price summaries[28] representing US use by year (ultimately the data represent the mass % of each type of fertilizer used in a given year). As in AREI / Production Inputs (Taylor undated), the difference between primary nutrient tons and total fertilizer materials is assumed to be filler material. Related data are presented Appendix F: Fertilizer type data.

2.4.3 Applications of secondary nutrients

ARMS does not include data for the estimation of the quantities of secondary nutrients applied aside from nitrogen inhibitors. Data for secondary applications of gypsum, sulfur, sulfuric acid, zinc compounds, and sewage sludge are based on the data provided in ERS Fertilizer Use and Price summaries[29] representing US use by year. The data are presented in Appendix G: Secondary applications data. Specifically, the weight of each application in each year is divided by the planted area for all field crops from NASS QuickStats to provide a per area estimate use, which is then multiplied by the planted area for each crop in each state and year within the unit process parameterization. Therefore, the estimates are not crop or state-specific, but again consider these important applications to all crops in the US. Note also that no uncertainty data are included with the estimates as none were found.

[28] See Tables 3-5 at http://www.ers.usda.gov/Data/FertilizerUse/

[29] See Table 6 at http://www.ers.usda.gov/Data/FertilizerUse/

2.4.4 Applications of liming materials

ARMS also does not include data for the estimation of the quantities of lime, applied to neutralize acid production in agricultural soils that results from a range of sources including applications (e.g., nitrogen and sulfur containing fertilizers), product and co-product removals, nitrogen fixing, nitrate leaching, acid precipitation and the application of acidic irrigation waters, and changes in soil organic matter. Lime use in the production of corn, cotton, soybeans, and wheat was reported by the USDA for 1988-1995 in Taylor (Taylor undated), covering applications of lime and commercial fertilizers (NPK and sulfur) for the entire US. These data are presented as the percent of the planted areas treated and commensurate application rates. Because lime application on a given field will occur in intermittent years and in response to the variety of acidification sources and specific field conditions, it is assumed here that these data provide a broad estimate of the total application for the total planted area in a given year. Given this, combining Taylor's data with related yield data from NASS QuickStats, it was found that the following reasonably bounded the US lime use by crop (in kg lime per planted area) from 1988-1995 (as shown in Figure 4):

$$Lime_{applied} = \left(\frac{ECCE_{applications} + ECCE_{crop\ harvest} + ECCE_{nitrogen\ fixing}}{\eta_{liming\ materials}}\right) Adj_{crop\ i}$$

$$\text{with } ECCE_{applications} = \left(\sum CCE_{application\ j} M_{application\ j}\right)$$

$$ECCE_{crop\ harvest} = \left(CCE_{removed\ crop\ i} M_{crop\ i\ produced}\right)$$

$$ECCE_{nitrogen\ fixing} = \left(CCE_{Nfix\ crop\ i} M_{crop\ i\ produced}\right)$$

Equation 4

where:

- $ECCE_{applications}$ is the effective calcium carbonate equivalents (CCE in kg pure $CaCO_3$) needed to neutralize applications. $ECCE_{applications}$ is estimated as the product of the application CCE (at most likely, minimum, and maximum values of 1.48, 0.33, and 2.52 kg $CaCO_3$ to represent anhydrous ammonia[30], nitrogen solutions, and ammonia sulfate for nitrogen fertilizers; of 0.35, zero, and 0.70 kg $CaCO_3$ to represent at the diammonium phosphate at the high-end for phosphate fertilizers; and of 3 for sulfur as given in Table 11) and the mass of each application per planted area ($M_{application\ j}$). Using Taylor's data, $M_{application\ j}$ is estimated as the product of the mass of the active ingredient per treated area and the treated fraction of the planted area.

[30] Taylor states that anhydrous ammonia is the source of nearly all the nitrogen fertilizer.

- $ECCE_{crop\ harvest}$ is the effective CCE needed to neutralize removal of the crop and is estimated as the product of the minimum and maximum CCEs for each crop type given in Table 11 and the mass of each crop harvested per planted area provided by QuickStats (as $M_{crop\ i\ produced}$ in kg dry matter).
- $ECCE_{nitrogen\ fixing}$ is the effective CCE needed to neutralize nitrogen removed during fixing and is estimated as the product of the minimum and maximum CCEs for soybeans given in Table 11 and the mass of soybeans harvested per planted area provided by QuickStats.
- $\eta_{liming\_materials}$ is the efficiency of liming materials to provide $CaCO_3$ as a function of the liming material constituents, liming material fineness (the level to which the liming materials are ground/ sieved), and the depth to which the liming materials are incorporated. Mechanisms are described by Knudson (1984) and here it is assumed $\eta_{liming\_materials}$ is most likely 60%, at a minimum of 40%, and at a maximum of 100%.
- $Adj_{crop\ i}$ is a crop-specific adjustment factor estimated here to bring the average result to the average lime application rate provided by Taylor for all of the years for which Taylor provided data, at values of 25%, 18%, 46% and 13% for corn, cotton, soybeans, and wheat respectively.

Figure 4. Estimation of lime applications: comparison of estimated range to USDA US applications data for 1988-1995

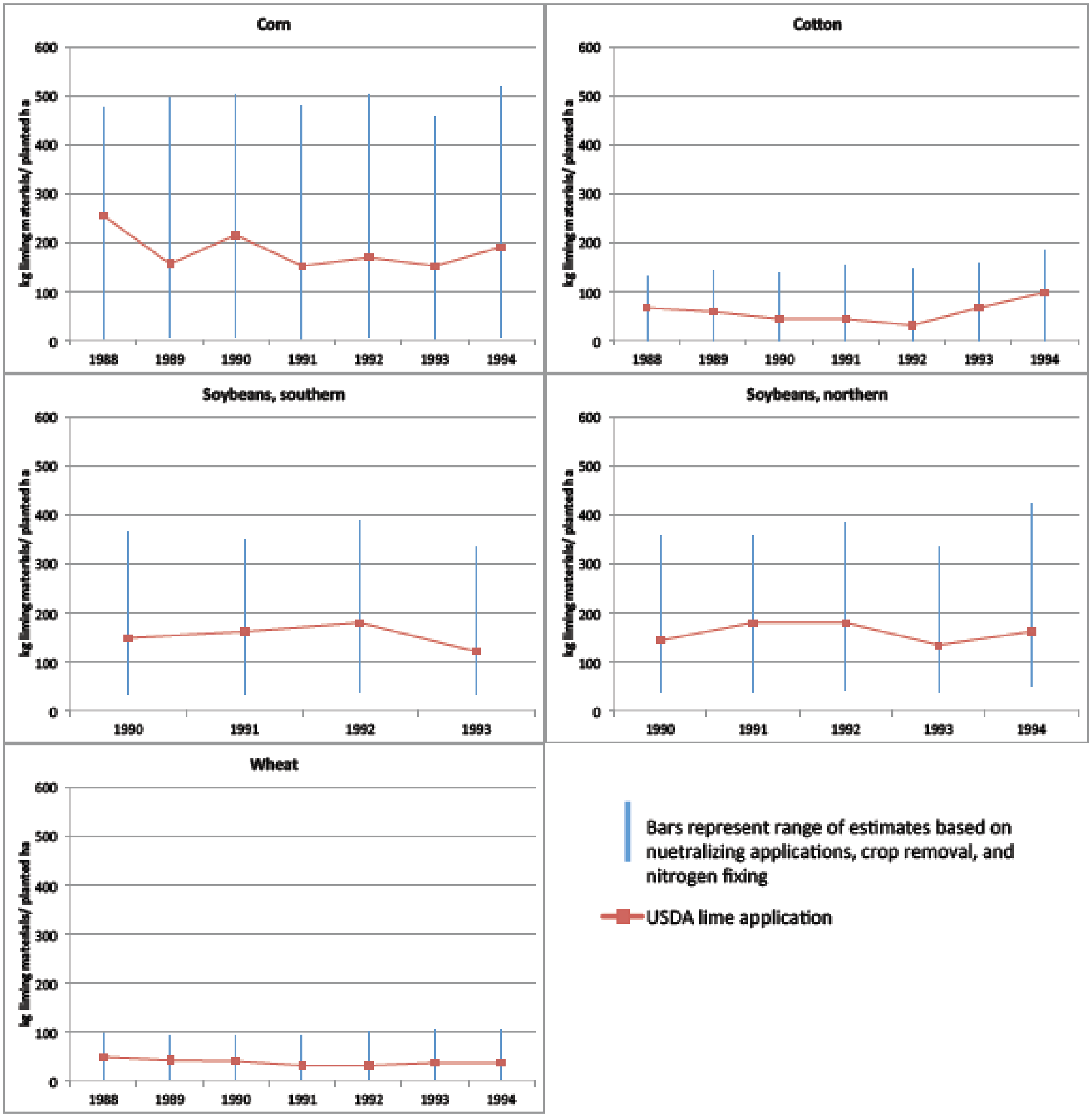

Table 11 Calcium carbonate equivalents (kg $CaCO_3$/kg material)

Applications[1] (in kg CCE/kg application)	Anhydrous ammonia	1.48
	Aqueous ammonia	0.36-0.54
	Ammonium nitrate	0.59
	Ammonium sulfate	1.09-2.52
	Nitrogen solutions	0.33-0.55
	Sodium nitrate	-0.29
	Urea	0.84
	Monoammonium phosphate (MAP)	0.65
	Diammonium phosphate (DAP)	0.70
	Sulfur	3.00
	Sulfuric acid	0.98
N fixation[2] (in kg CCE/kg dry biomass of crop harvested)	For peanuts and soybeans	0.036-0.059
Harvest[3] (in kg CCE/kg dry biomass of crop harvested)	For corn	0.0039 – 0.038
	For cotton	0.00054 – 0.014
	For oats	0.0028 – 0.038
	For peanuts	0.038 – 0.040
	For soybeans	0.005 – 0.072
	For wheat	0.010 – 0.037
Liming materials[4] (in kg CCE/kg liming material)	Pulverized limestone	0.90 – 0.98
	Dolomite limestone	1.08 – 1.09

1. **Nitrogen and phosphorous fertilizer data** are from Zublena et al. (1991) with the values for ammonium sulfate adjusted based on discussions by Chien (2010) and Gearhart and Collamer (2009).
2. **N fixation data** are estimated as the product of the acid production from Tang and Rengel (2003) in cmol per kg shoot and 0.5 grams $CaCO_3$ per cmol as noted by Tarkalson (2006).
3. **Harvest data** are a summary of data from several sources: Robarge (2008), Wortman et al. (2003), and as estimated as the product of the acid alkalinity cmol/kg biomass and 0.5 grams $CaCO_3$ per cmol with acid alkalinity data from Fargher (1926), McCall (1948), Rengel (2003), Yuan (2011), and Wang (2012).
4. **Liming material data** for limestone assumes a high-grade limestone is used at 90-98% $CaCO_3$ as described in Gazdik and Tagg (1957) and for dolomite assumes 54 - 58% $CaCO_3$ with the balance as MgCO3 as described by Walters (undated) and $MgCO_3$ contributes 1.2 kg $CaCO_3$ per kg as noted by Carey et al. (2006)

It is assumed here that the adjustment factor represents both farm-specific practices (specific farmers responding to specific yield changes) and the omitted but important contributions site-specific mechanisms such as acid tolerance of each crop, nitrate leaching, acid precipitation and the application of acidic irrigation waters, and changes in soil organic matter e.g., as a result of harvested residues and residues remaining on the field. Note that this method assumes lime applications track with changes in fertilizer applications and yield; is intended to allow gross acidification impacts of crop production to be assessed (as a function of the differences between acid produced and farm liming practices); and is not ideal. Noting that ARMS only provides data for the percent of planted acres on which have "ever treated with lime," which were not found useful here, an improved dataset for the representation of lime application rates are recommended for future work.

For the crop production data, using Equation 4, lime use is estimated for all crops except rice, because Wilson et al. (2001) note that lime applied during rice production is generally for the benefit of other crops in rotation. The application-specific CCE values given in Table 11 are used with each crop-state-year estimate of fertilizer and sulfur applications (for $M_{application\ j}$). Because oats and peanuts were not included in the USDA data in Taylor (Taylor undated), it is assumed that the adjustment factors are as estimated for wheat and soybeans respectively. Finally, lime use is divided between pulverized limestone and dolomite as:

$$M_{limestone} = \frac{Lime_{applied}}{CCE_{limestone} + R_{dolomite} CCE_{dolomite}}$$

Equation 5

and

$$M_{dolomite} = M_{limestone} R_{dolomite}$$

Equation 6

where $R_{dolomite}$ is the ratio of the mass of dolomite applied to the mass of limestone sold or used in each USDA farm production region from 2002-2009 as provided in the USGS Crushed Stone Minerals Year Book[31] as presented in Table 12 and the CCE values for limestone and dolomite are provided in Table 11. A Student's t distribution is assumed, given the values of RSE and degrees of freedom provided.

Table 12 Dolomite ratios by USDA farm production region

Region	Sample size	Average ratio of the mass of dolomite to the mass of limestone	RSE
Appalachia	16	0.14	15
Corn Belt	56	0.16	10
Delta	4	0.11	49
Lake States	30	0.22	17
Mountain	1	0.016	NA
Northeast	26	0.29	6
Northern Plains	1	0.058	NA
Pacific	15	0.026	32
Southeast	17	0.027	29
Southern Plains	5	0.079	29

[31] See http://minerals.usgs.gov/minerals/pubs/commodity/stone_crushed/

2.4.5 Pesticide applications

Although ARMS data for the application methods are used, ARMS data representing the type and quantity of pesticide applications is presented in chemical families[32], as opposed to as single chemicals. Because chemical families introduce substantial uncertainty into fate and transport modeling, pesticide active ingredient (AI) use data are from the NASS Agricultural Chemical Use Database[33]. Unspecified pesticide applications were estimated as the difference between the ARMS and NASS data. The balance of pesticide formulations (e.g., solvents and other ingredients) were estimated based on data representing the mass percent AI from the USEPA Pesticide Product Information System[34] (PPIS). Note that there are 204 pesticide active ingredients when all field crop production unit processes are considered, as listed with the respective active ingredient fractions in Appendix H: Pesticides applied.

2.4.6 Harvest operations

ARMS data do not specifically describe harvest operations, therefore in general harvest operations repeat the weight of crop or co-product (including harvested residues) harvested and specific technologies will be identified in the development of tier 2 data (see Figure 1). The exception to this is cotton harvesting, assumed to be split between machine picking and stripping as noted in Table 9 for the purpose of estimating the trash harvested with the lint and seeds. Industrial drying, and cleaning, sorting, and grading are assumed to be tier 0 data.

2.4.7 Applications transport

Applications transport (movement of seed, synthetic fertilizers, secondary applications, manure, and pesticides to the fields) is a function of the distance traveled and the weight of application moved. Whereas the weight of applications is estimated based on that in each year-state-crop dataset, the transport distances used are presented in Appendix I: Applications transport distances.

Manure transport distances are based on data from ARMS, specifically the variable "distance traveled by manure used." Sewage sludge transport is assumed to be the same as the manure transport distance. Both manure and sewage sludge are assumed to be transported at the moisture content at which they are applied to the field.

The remainder of the applications transport distances are based on those used in Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) (Wang 2009). Additional data will be brought into consideration in future versions of the crop production data, such as data from the Bureau of Transportation Statistics (BTS) Commodity Flow

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[32] See http://www.ers.usda.gov/Data/ARMS/Variables.htm

[33] See http://www.pestmanagement.info/nass/app_usage.cfm

[34] See http://www.epa.gov/opp00001/PPISdata/

Survey[35] as described by Cooper et al. (Cooper, Woods, and Lee 2008), data representing the locations of US fertilizer production sites from the Fertilizer Institute[36], and data representing pesticide production establishments as collected by the USEPA under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA).

2.5 Flows to the environment

Table 17 in Appendix B: Parameterization of ARMS data summarizes the ARMS variables used in the estimation of flows to the environment with additional information sources described as follows. Overall, data represent emissions from residue burning, and releases from aboveground and belowground residues left on the field, water applied in irrigation and with manure and sewage sludge, synthetic fertilizers, secondary applications, manures, and pesticides. Again, "emissions" are differentiated from "releases" to indicate that fate and transport has not been considered for releases (see Figure 2 and the related discussion). Like in the estimation of flows from the environment, flows to the environment are presented as constituents to facilitate analysis of balance, with more information about the balance capabilities provided in Section 4.

2.5.1 Emissions from residue burning

Data representing the area burned by crop and state were provided directly from McCarty for 2003-2007 and have been published in part and described by McCarty (2009a, 2009b, 2011). These data were created through a remote sensing method combined with a 30 m or 56 m Cropland Data Layer[37] and a land classification schema. Although the schema was found to correspond well with the USDA estimate of total cropland acreage in the contiguous US, some over and under estimation occurred[38], for example due to large pixel sizes with smaller field sizes and visa versa.

Here, McCarty's 2003-2007 data are combined with NASS QuickStats planted area data to provide an estimate of the fraction of the planted area burned. Specifically, McCarty's 2003-2007 data representing the burned areas for corn, cotton, rice, soybeans, and wheat were divided by commensurate crop-state-year NASS QuickStats planted area data. For oats and peanuts, McCarty's 2007 state data representing the burned areas for "other crops/fallow" were divided by NASS QuickStats state planted area data representing all field crops less the planted areas for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat and less the fallow area (only available in QuickStats for 2007 among the years studied by McCarty). Given these results, the field crop production datasets use

[35] See http://www.bts.gov/publications/commodity_flow_survey/index.html

[36] See http://www.tfi.org/industry-resources/fertilizer-economics/us-fertilizer-production-and-mining-facilities-glance

[37] See http://www.nass.usda.gov/research/Cropland/SARS1a.htm

[38] See Chapter 3 of McCarty (2009z) at http://drum.lib.umd.edu/handle/1903/9117

triangular distributions to represent the fraction of the planted area burned as presented in Appendix J: Residue burning data such that:

- Corn, cotton, rice, soybeans, and wheat use the commensurate 5-year average as the most-likely value, the maximum value used as the maximum value among the 5-years, and zero as the minimum value to account for incorrect classifications of crop types.
- Oats and peanuts use the 2007 value as the most-likely value, the maximum as the maximum for the state for all crops, and again zero as the minimum value.

Note also that McCarty continues to improve these data, using the Crop Data Layer in its native resolution as it is produced for the contiguous US starting and is compiling a single IDL code that can be transferred to C or ArcPy easily. As McCarty completes this work, it will be available for integration into the field crop unit process data and for other uses in the larger scientific community.

Given estimates of the fraction of the planted area burned, combustion completeness data are from McCarty (2011) and emissions are estimated with dry matter divided among ash, air emissions of methane (CH_4), carbon monoxide (CO), nitrogen dioxide (NO_2), dinitrogen monoxide (N_2O), sulfur dioxide (SO_2), particulate matter (PM2.5 and PM10), and non-methane volatile organic compounds (NMVOCs), and air and land emissions of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/F) and water released according to the residue moisture content.

The overall emission factor data are presented in Appendix J: Residue burning data including constituents of the particulate matter and the NMVOCs. Constituent breakdown for the residue burning emissions varies, with a focus primarily on capturing the carbon so that the CO_2 emissions can be estimated as the balance of uptake (although the PCDD/Fs were not included in the balance). Whereas the carbon content of the CH_4 and CO and the specified NMVOCs are estimated from their molecular formulas, the carbon in the ash, particulate matter, and unspecified NMVOCs required further investigation. Specifically, the ash fraction is estimated at 9.1 – 30% of the dry matter at a carbon fraction uniformly distributed between 7.4 and 19% based on the overall range of data from Jenkins (1996) for corn, rice, and wheat (thus assumed here to apply to all crops). The crop-specific particulate matter emission factors are from McCarty (McCarty 2011) and the carbon fraction again from Jenkins (1996) for corn, rice, and wheat at 31-62% and 27-63% for PM2.5 and PM10 respectively. The unspecified NMVOCs were estimated as in Akagi et al. [39] (2011) assuming like Akagi et al. that they are equal in weight to the specified NMVOC emissions and “mostly of high molecular weight NMVOCs.” Here, Akagi et al.’s generalization “mostly of high molecular weight NMVOCs” were

[39] Note that the data in Akagi et al. were based on 2 studies, one of 6 fires of unspecified crops in Mexico and one representing 3 rice straw fires. Clearly improved data are needed to better represent crop-specific emissions.

assumed to be $C_{20}H_{12}$, as the molecular weight of some key polycyclic aromatic hydrocarbons (PAHs). Finally, the PCDD/F emissions to air and land are from UNEP (United Nations Environment Programme 2001) at 30 ug TEQ/t to air and 10 ug TEQ/t to land, however noting that Black et al. question the general applicability of these factors in an un-archived work[40]. Improved crop-specific data are recommended for future work.

2.5.2 Releases from field residues

Releases from field residues include aboveground biomass not harvested and belowground biomass. Constituents are estimated as those for each crop residue in Table 10 however it is recognized that these data are not ideal. Specifically, studies have evaluated differences in root constituents as compared to above ground residues, e.g., as presented by Johnson et al. (2007). However, no data beyond the carbon/nitrogen ratios for corn and soybeans were found. Thus, improved crop-specific data are recommended for future work.

2.5.3 Applied water

Applied water in irrigation, with manure, and in sewage sludge are summarized and reported without losses such as evapotranspiration, etc.

2.5.4 Releases from synthetic fertilizers, secondary applications, manure, and pesticides

Data for releases from synthetic fertilizers summarize that applied as divided among the application timing (e.g., in the fall or spring before planting) and method (e.g., broadcast with incorporation). Although the data are reported without fate and transport considerations, they are reported by constituent (N, P, and K) and by the time of application (as in the fall or spring before planting, at planting, or after planting) and the application method. For secondary applications except sewage sludge, releases are also a summary of what was applied. Zinc compounds are assumed to be at a range from 0% to 100% zinc oxide (ZnO) and commensurately from 100% to 0% zinc sulfate ($ZnSO_4$). Sewage sludge constituents are listed in Appendix K: Sewage sludge constituents and are the range of values from Lerch et al. (1992), assumed here to follow a uniform distribution. Limestone and dolomite releases are reported as the fractions of C, calcium, magnesium, and oxygen applied. For manure applications, releases are a summary of what was applied, in the form applied (as semi-solid or solid manure, liquid slurry, or lagoon liquid at moisture contents of 80-88%, 90-92%, and 93-95% respectively as in the Integrated Farm System model[41]), by animal (beef cattle, dairy cattle, hogs, poultry, or other) and like the synthetic fertilizer data uses ARMS data to represent application timing

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[40] See http://www.scribd.com/doc/48311728/Emission-From-Forest-and-Crop-Fires

[41] See http://www.ars.usda.gov/main/docs.htm?docid=8519

(as in the fall or spring before planting) and application methods. Manure constituents are estimated starting from the constituents excreted and subsequently the constituents applied to the fields are estimated given housing and storage losses (see the data in Appendix L: Manure data). Note that it is anticipated that the parameterization of the reduction in constituents from excretion the application may be moved to the tier 2 datasets for manure management in subsequent data versions. Finally, pesticide applications are a summary of what was applied and the application method.

In all cases, data representing the fraction of each application using a specific application method are from ARMS and actually represent the fraction of the treated area using the application method. This construct was chosen to provide an indication of the method of application as useful information for fate and transport assessment. Improved data are recommended for future work.

3 Multi-year field crop production unit process datasets

Table 2 lists 70 multi-year datasets. Referring to Table 5 and Table 6, an implication of the use of the data quality score for *flow data completeness* is that any field crop production unit process dataset that represents a single year of production will receive a score of B (indicating lower data quality) in the temporal coverage category for all flow data. This *appropriately* recognizes that a single year of crop production data does not capture the variability in e.g., yield, irrigation, and nutrient applications that come from differences in weather from year to year. As a result, the *LCA Digital Commons* also contains data that combine years for a single crop and state where such data are available. These datasets, which receive a data quality score of A in the temporal coverage category, are intended to represent a higher level of quality in this category. However, a secondary result of combining datasets is a commensurate combining of the flow error, which may or may not impact the score in the precision data quality category in the EcoSpold v2 and ILCD versions of the data.

4 Mass balance information

As described, flow constituents are tracked in a way that allows an overall accounting of biomass, water, carbon, and other constituents to and from the environment. Specifically, the balance of biomass can be followed from uptake for crops and co-products through burn emissions and releases of above and belowground residue left on the fields and the balance of nitrogen can similarly be followed with additional inputs from synthetic fertilizers, manure, and sewage sludge. Table 13 presents details of each constituent balance/ account (i.e., presenting what is considered).

Table 13 Elements of balance

	Into the unit process		**Out of the unit process**	
	From the tech.	**From the environment**	**To the technosphere**	**To the environment**
Biomass		Uptake by the harvested crop	Leaves, stems, branches, cobs, pods, and /or stalk on harvested crop	
		Uptake by the harvested non-residue co-products	Leaves, stems, branches, cobs, pods, and /or stalk on harvested non-residue co-products	
		Uptake by above-ground residues	Leaves, stems, branches, cobs, pods, and /or stalk on harvested above-ground residues	Above ground residues not harvested return to the environment (burned or left on the field)
		Uptake by below-ground residues		Below ground residues return to the environment
C		As in biomass balance		
	Applied as manure			What was applied as manure is sent to the environment
	Applied as sewage sludge			What was applied as sewage sludge is sent to the environment
	Applied as lime			What was applied as lime is sent to the environment
NPK		As in biomass balance		
	Applied as manure			What was applied as manure is sent to the environment
	Applied as sewage sludge (except K)			What was applied as sewage sludge is sent to the environment
	Applied as synthetic fertilizer			What was applied as synthetic fertilizer is sent to the environment
Water		As in biomass balance		
	Applied as sewage sludge			What was applied as sewage sludge is sent to the environment
		Withdrawn for irrigation		What was withdrawn for irrigation is sent to the environment
		Withdrawn to aid in manure application		What was withdrawn to aid in manure application is sent to the environment
Pesticide	Applied as 204 varieties			What was applied as 204 varieties (to air & soil) is sent to the environment
	Applied as the balance of formulation			What was applied as the balance of formulation (to air & soil) is sent to the environment

5 Fate and transport and impact assessment

According to the ISO standard, elementary flows cross from and to the environment in a completed LCA with elementary flows defined as drawn from the environment without previous human transformation and as released into the environment without subsequent human transformation. Consideration of transformations in the environment (i.e., fate and transport considerations) is needed for impact assessment and thus the fate and transport of releases must be estimated. As noted, the data here have been prepared to allow flexibility in the fate, transport, and ultimately the impact assessment models that can be used. Within this context, Table 14 provides a list of example models that can be used, noting that whereas some will use the final unit process exchange data as inputs, others will pull details from the parameterization. These models bring detailed data and algorithms for environmental conditions (temperature, precipitation, wind conditions, soil types and conditions, vicinity of ground and surface waters, etc.) and although they will require that careful attention be paid to representing variations to the state level, the variability will be less than data aggregated to the national level (e.g., all corn production in the US in 2005).

The vision for the *LCA Digital Commons* is to prepare parameterized fate and transport data files (currently being called *crosswalk files*) using a range of fate and transport models for flows to and from the environment to estimate emissions for impact assessment. These would result in versions of the crop production data with a full set of emissions, as opposed to releases prior to fate and transport considerations. Once accomplished, data will be compatible with select characterization factors, typically used in LCA for impact assessment. Characterization factors, also called equivalency factors, essentially represent a screening-level risk assessment as a single factor used to translate unit process or inventory flows to and from the environment to their contribution to specific impacts.

Resource related characterization factors for flows from the environment that cover issues of scarcity do not require fate and transport considerations. Emissions related characterization factors include some results of generalized fate, transport, and effects modeling for emissions, so care must be taken to ensure they are used without double counting losses based on the considerations in a given crosswalk. As an example, the IPCC global warming potentials (GWPs) are emissions related characterization factors in the climate change category that when multiplied by the mass of greenhouse gas emissions to the environment provide an estimate of the contribution to climate change with CO_2 as the reference substance (i.e., the unit of category result is in CO_2-equivalents).

Table 14. Example fate and transport calculations for impact assessment

	Example environmental processes and emissions	**Example models for representing fate, transport, and impact***
Land transformation, tillage methods, residue management, irrigation, and all applications	Changes in/ cycling of soil carbon, nitrogen, phosphorous, sulfur, etc. as well as emissions typically considered in crop production data prepared for LCA: • CH_4 emissions to air from flooded rice cultivation (for both primary and ratooned crops) • CO_2 emissions to air from manure applications • CO_2 emissions to air from urea applications • CO_2 emitted from lime applications • Metals runoff • N_2O (direct and indirect) emissions to air from applications, volatilization/ deposition, and leaching/ runoff • NH_3 emissions to air from applications • NO_3-leaching • PO_4^{-3} leaching	ARS's Integrated Farm System Model (IFSM) Colorado State University's DayCent (and Century) IPCC data and equations (IPCC 2006) NRCS's Geospatial Nutrient Tool (GNT) NRCS's Nitrate Leaching and Economic Analysis Package (NLEAP)
Water withdrawal and application specifically	Water budget and leaching	Colorado State University's Century
Erosion specifically		NRCS's RUSLE2 and WEPS
Releases from pesticide applications specifically	Pesticide movement/drift, partitioning, reaction, and degradation	IPCC's data and equations NRCS's WIN-PST PestLCI ((Birkved and Hauschild 2006) and (Birkved and Heijungs 2011)) USEPA's aquatic models (GENEEC, FIRST, KABAM, PRZM, EXAMS, EXPRESS, SWAMP, SCIGROW, SWIMODEL, Tier I Rice Model), terrestrial models (SIP, STIR, T-REX, TIM, T-HERPS, TerrPlant), and atmospheric models (AgDRIFT, AgDISP, PERFUM, SOFEA, FEMS) USEPA's Pesticide Fate Database (identifies degradates) USEtox™[42]

* See

- ARS's Integrated Farm System Model (IFSM) http://www.ars.usda.gov/main/docs.htm?docid=8519
- Colorado State University's DayCent (and Century) http://www.nrel.colostate.edu/projects/daycent/ and http://www.nrel.colostate.edu/projects/century/
- IPCC data and equations e.g., (IPCC 2006)
- NRCS's Geospatial Nutrient Tool (GNT) http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/tools/?&cid=stelprdb1044746
- NRCS's Nitrate Leaching and Economic Analysis Package (NLEAP) http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/tools/?&cid=stelprdb1044740
- NRCS's RUSLE2 and WEPS http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/landuse/crops/erosion/?&cid=nrcs143_023947
- NRCS's WIN-PST http://go.usa.gov/Kok
- PestLCI ((Birkved and Hauschild 2006) and (Birkved and Heijungs 2011))
- USEPA's aquatic models (GENEEC, FIRST, KABAM, PRZM, EXAMS, EXPRESS, SWAMP, SCIGROW, SWIMODEL, Tier I Rice Model), terrestrial models (SIP, STIR, T-REX, TIM, T-HERPS, TerrPlant), and atmospheric models (AgDRIFT, AgDISP, PERFUM, SOFEA, FEMS) described at http://www.epa.gov/pesticides/science/models_db.htm
- USEPA's Pesticide Fate Database http://cfpub.epa.gov/pfate/home.cfm
- USEtox™ http://www.usetox.org/

[42] Note that the USEtox™ model is currently under review by the UNEP SETAC Life Cycle Initiative with the perspective of a global recommendation as the preferred model for characterization modeling of human and ecotoxic impacts in LCA.

Also, characterization factors for pesticides do not cover the range of pesticides used and do not consider degradates (e.g., ReCiPe[43] characterization factors based in part on the USES-LCA model (developed by the Dutch National Institute for Public Health and the Environment (RIVM), Universiteit Leiden Institute of Environmental Sciences (CML), PRé Consultants, Radboud Universiteit Nijmegen and CE Delft), the IMPACT 2002[44] characterization factor database (developed by the University of Michigan Risk Science Center), the TRACI[45] characterization factor database (developed by the US Environmental Protection Agency (USEPA)), and the USEtox™ [46] characterization factor database and model (developed by the USEtox Team representing Ecole Polytechnique Montreal, RIVM, the Radboud University Nijmegen, the Technical University of Denmark, the University of California-Berkeley, and the University of Michigan). Further, only some allow provide the capability to modify default environmental conditions (e.g., ReCiPe and USEtox™ characterization models have been developed for a default but editable environments).

6 Next steps

In addition to the release of the Version 1 crop production data in EcoSpold v2 and ILCD formats, plans for 2012 and beyond include the development of:

- Tier 2 unit process data based on the USEPA NONROAD model,
- Tier 2 unit process data representing irrigation processes,
- Tier 2 unit process data representing manure management processes,
- Crosswalks to unit process in the US LCI database, and
- Crosswalks to select impact characterization systems.

All of this work, as well as the unit process datasets described herein, will be available at the *LCA Digital Commons* at http://www.lcacommons.gov/.

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[43] See http://www.lcia-recipe.net/

[44] See http://www.sph.umich.edu/riskcenter/jolliet/impact2002+.htm

[45] Described at http://www.epa.gov/nrmrl/std/sab/traci/

[46] See http://www.usetox.org/

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Appendix A: Standard conventions

1. Quantification of reference flows	As suggested by Carpenter, et al (2010) and is the convention in LCA databases, reference flows are expressed using a unitary measure. Specifically, for each field crop dataset the reference flow is 1 kg of field crop.
2. Units of measure	Units of measure follow the International System of Units (SI) following ISO 80000-1:2009 to the extent possible.
3. Location codes	Whereas ISO14048 states that ISO 3166-1 country codes (Alpha-2 (Two Letter)) be used, here the ISO 3166-2 Subdivision/State Code without including the country code are used. In subsequent versions, the intent is to use the entire code, that begins with the ISO 3166-1 country code, followed by a hyphen, followed by the ISO 3166-2 Subdivision/State Code (e.g., US-NJ for New Jersey). Further, location information will include longitude and latitude, hydrologic unit code (HUC), and GIS binary shapefiles[47].
4. Technical scope	ISO 14048 Section 7.3(b) suggests the following options to describe the technical scope: • GATE-TO-GATE - A process where all production stages occur within one site. The site may be geographically specified, or in the case of e.g. average data, the geographical specification may be more general. Processes outside the defined gates are not included. • CRADLE-TO-GATE - A process starting with resource extraction, which may include some manufacturing or service operations but excluding all subsequent stages. • GATE-TO-GRAVE - A process that includes the distribution, the use and the final disposal of the product. • CRADLE-TO-GRAVE - A process starting with resource extraction to the final disposal of the product. All the field crop datasets described here have a gate-to-gate technical scope.
5. Time frame	As is the convention in ecoinvent, time frame is conveyed as the startDate and the endDate as either 0000 (year) or 0000-00 (year-month).
6. Coding of reference products, co-products, and flows from the technosphere	United Nations Standard Products and Services Codes (UNSPSC), the North American Industry Classification System (NAICS), and International Standard Industrial Classification (ISIC) codes are used for identifying technosphere flows. In the ecospold v1 version, all codes are placed in the local name field, separated by semicolons.
7. EcoSpold v1 categories/ subcategories for reference products, co-products, and	For the EcoSpold v1 data, ecoinvent categories are used with two exceptions: ○ **The category/subcategory *agricultural means of production/ storage*** has been added for seed and applications storage. Storage is measured in kga (representing mass and year). Further, it is anticipated that equipment storage will be included in the respective tier 2 unit process data (e.g., based on swath width) and that crop storage processes will be developed in the short term.

[47] See http://www.esri.com/

flows from the technosphere	○ **The category/subcategory *agricultural means of production/ service*** includes flows intended to ensure that missing data are accounted (as described in Section 1.2). Flows in this group represent irrigation, seed and nutrient application, and the application of lime and gypsum, compost, sewage sludge, and pesticides. In all cases, service processes are designated using the UNSPSC segment "Farming and Fishing and Forestry and Wildlife Contracting Services." Note that the categories/subcategories used in the ILCD format are different, and that the use of categories/subcategories is eliminated in EcoSpold v2 and replaced with parent-child relationships.
8. Names for reference products, co-products, and flows from the technosphere	Three things are important to the assignment of names for reference products, co-products, and flows from the technosphere: **(1) EcoSpold v1 has an 80-character limit on names.** This limits the information that can be provided in EcoSpold v1 format, noting that the limit is increased in EcoSpold v2 and the ILCD formats. **(2) An interest in communicating needed information concerning the flow.** ILCD provides a convention of interest. Specifically, in their guidance for structuring flow names (European Commission - Joint Research Centre - Institute for Environment and Sustainability 2010c), ELCD/ILCD applies the following rule: <"Base name"; "Treatment, standards, routes"; "Mix type and location type"; "Quantitative flow properties"> where "Treatment, standards, routes" and "Mix type and location type" applies only to energy and materials flows (i.e., not activities or services) and: • The "base name" provides a general descriptive name of the flow, • "Treatment, standards, routes" provides qualitative information about energy and materials flows such as treatment received, standard fulfilled, product quality, use information, production route name, educt name, designation as a primary or secondary material, etc., • "Mix type and location type" defines the energy and materials flows as representing a production or consumption mix, location type of availability (e.g. "at farm" or "at regional storage"), and • "Quantitative flow properties" provides quantitative information such as the amount of residue associated with tillage operations or the pesticide active ingredient content, etc. In addition, because of the focus herein on constituent balance, when a flow is measured by one of its constituents or by an active ingredient, the balance of the application is provided in a separate flow or flows. **(3) An interest in communicating the availability of technosphere process data in the *LCA Digital Commons*.** Specifically, when data have yet to be provided in the Commons, "CUTOFF" precedes the flow name. Given these three things, the naming convention used for the EcoSpold v1 data is: <CUTOFF (if applicable) "Base name"; "Routes"; "Location type"; "Quantitative flow properties"> and removal of the character limitation allows greater information to be provided in the other formats.
9. Names for flows to and from the	The names of flows in the EcoSold v1 version to and from the environment either ○ Follow the ecoinvent convention for land occupation and transformation, but add

environment.	identification of the previous and current crop types ○ Use shorter chemical names to meet the character limitation with the intent in subsequent data versions to use the standard UNIPAC names
10. Inclusion of Chemical Abstracts Service (CAS) registry numbers	**Chemical Abstracts Service (CAS) registry numbers are included for the flows to and from the environment for which they exist.** CAS numbers are entered as 9-digit numbers with the final and previous 2 digits preceded by hyphens (e.g., 000124-38-9 is the CAS number of CO_2)
11. Inclusion of chemical formulas for the flows to and from the environment	**Chemical formulas for the flows to and from the environment** based on those provided in the US National Library of Medicine's ChemID database with hyphens removed.
12. Inclusion of IUPAC International Chemical Identifier (InChI™) codes for the flows to and from the environment	**IUPAC International Chemical Identifier (InChI™) codes for the flows to and from the environment** based on those provided in the US National Library of Medicine's ChemID database. InChI codes[48] are intended to be unique to a chemical structure (as an improvement over SMILES notation) and have been developed to enable linking of diverse data compilations and both visual and computational analyses of chemical structures. The intent for including the InChI codes here is to make available a wide range of visualization and automated chemical analyses in future versions of the *LCA Digital Commons*. Note that the InChI codes have been entered in the generalComment field for EcoSpold v1, with other information such as that related to data quality) and with the intent of identifying a superior data field in subsequent dataset versions.
13. EcoSpold v1 categories/ subcategories for flows to and from the environment	**Categories/subcategories for flows to and from the environment** follow the ecoinvent v1 convention.

[48] See http://www.iupac.org/inchi/

Appendix B: Parameterization of ARMS data

The ARMS variables listed in Table 15 - Table 17 are parameterized to allow the Student's t distribution for each to be represented. For example, the parameterization of the irrigated area is represented in the crop production datasets using 9 parameters:

Parameter description	Parameter name	Uncertainty type	min value	max value	Mathematical relation
Sample size for ARMS jackknife estimate of variance	Sample_size				
Degrees of freedom	df				Sample_size-1
Approximation g(df)	g_df				(df-1.5)/(df-1)^2
Raw data for Irrigated acres (1,000 acres)	Raw_IRRACRS				
RSE for IRRACRS (Percent)	RSE_Raw_IRRACRS				
Probability for t_ IRRACRS	p_t_IRRACRS	uniform	0	1	
Standard normal at p for t_ IRRACRS	zp_t_IRRACRS				SQRT(2)*(IF((2*p_t_IRRACRS-1)<0,-1,IF((2*p_t_IRRACRS-1)>0,1,0))*SQRT(SQRT((2/(PI()*0.140012289)+LN(1-(2*p_t_IRRACRS-1)^2)/2)^2-LN(1-(2*p_t_IRRACRS-1)^2)/0.140012289)-(2/(PI()*0.140012289)+LN(1-(2*p_t_IRRACRS-1)^2)/2)))
Student's t for IRRACRS	t_IRRACRS				IF(p_t_IRRACRS<0.5,-SQRT(df*EXP(zp_t_IRRACRS^2*g_df)-df),SQRT(df*EXP(zp_t_IRRACRS^2*g_df)-df))
Irrigated acres (1,000 acres)	IRRACRS		0	100	Raw_IRRACRS*(1+t_IRRACRS*RSE_Raw_IRRACRS/100)

For content accessibility to Appendix B parameter table, contact National Agricultural Library staff at (301) 504-5510.

Table 15. ARMS variables used: flows from the environment

ARMS variable description	Parameter name	Use
Area previously corn (1,000 acres)	PCORN_thouAC	transformed area
Area previously soybeans (1,000 acres)	PSOY_thouAC	transformed area
Area previously cotton (1,000 acres)	PCOTTON_thouAC	transformed area
Area previously small grains (1,000 acres)	PSMALLG_thouAC	transformed area
Area previously other crops (1,000 acres)	POTHER_thouAC	transformed area
Area previously fallow (1,000 acres)	PFALLOW_thouAC	transformed area
Irrigated acres (1,000 acres)	IRRACRS	water withdrawal
Water applied per irrigated acre (Inches)	IRRWAT	water withdrawal
Surface water source (Percent of irrigated acres)	SRFW	water withdrawal
Ground water source (Percent of irrigated acres)	GNDW	water withdrawal
Gravity irrigated acres (1,000 acres)	GIRRACRS	water withdrawal

Table 16. ARMS variables used: flows from technosphere

ARMS variable description	Parameter name	Use
Planted acres (1,000 acres)***	PLACREStwelve	fertilizer use
Acres treated with N (Percent of planted acres)	NITACtwelve	fertilizer use
No N broadcast (Percent of acres with N)	NITHOXone_twelve	fertilizer use
All N broadcast with incorp. (Percent of acres with N)	NITHOXtwo_twelve	fertilizer use
All N broadcast without incorp. (Percent of acres with N)	NITHOXthree_twelve	fertilizer use
Mixed N application method, with incorp. (Percent of acres with N)	NITHOXfour_twelve	fertilizer use
Mixed N application method, without incorp. (Percent of acres with N)	NITHOXfive_twelve	fertilizer use
Acres treated with P2O5 (Percent of planted acres)	PHOACtwelve	fertilizer use
No P2O5 broadcast (Percent of acres with P)	PHOHOXone_twelve	fertilizer use

ARMS variable description	Parameter name	Use
All P2O5 broadcast with incorp. (Percent of acres with P)	PHOHOXtwo_twelve	fertilizer use
All P2O5 broadcast without incorp. (Percent of acres with P)	PHOHOXthree_twelve	fertilizer use
Mixed P2O5 application method, with incorp. (Percent of acres with P)	PHOHOXfour_twelve	fertilizer use
Mixed P2O5 application method, without incorp. (Percent of acres with P)	PHOHOXfive_twelve	fertilizer use
Acres treated with K2O (Percent of planted acres)	POTACtwelve	fertilizer use
No K2O broadcast (Percent of acres with K)	POTHOXone_twelve	fertilizer use
All K2O broadcast with incorp. (Percent of acres with K)	POTHOXtwo_twelve	fertilizer use
All K2O broadcast without incorp. (Percent of acres with K)	POTHOXthree_twelve	fertilizer use
Mixed K2O application method, with incorp. (Percent of acres with K)	POTHOXfour_twelve	fertilizer use
Mixed K2O application method, without incorp. (Percent of acres with K)	POTHOXfive_twelve	fertilizer use
Total N applied (Pounds per treated acre)	NITLBeleven	fertilizer use
Acres treated with N (Percent of planted acres)	NITACeleven	fertilizer use
Total P2O5 applied (Pounds per treated acre)	PHOLBeleven	fertilizer use
Acres treated with P2O5 (Percent of planted acres)	PHOACeleven	fertilizer use
Total K2O applied (Pounds per treated acre)	POTLBeleven	fertilizer use
Acres treated with K2O (Percent of planted acres)	POTACeleven	fertilizer use
Planted acres (1,000 acres)	PLACRESeleven	fertilizer use
Irrigated acres (1,000 acres)	IRRACRS	irrigation
Water applied per irrigated acre (Inches)	IRRWAT	irrigation
Surface water source (Percent of irrigated acres)	SRFW	irrigation
Ground water source (Percent of irrigated acres)	GNDW	irrigation
Gravity irrigated acres (1,000 acres)	GIRRACRS	irrigation
Gravity water applied per irrigated acre (Inches)	GIRRWAT	irrigation
Gravity surface water source (Percent of irrigated acres)	GSRFW	irrigation
Gravity ground water source (Percent of irrigated acres)	GGNDW	irrigation
Pressure irrigated acres (1,000 acres)	PIRRACRS	irrigation
Pressure water applied per irrigated acre (Inches)	PIRRWAT	irrigation
Pressure surface water source (Percent of irrigated acres)	PSRFW	irrigation
Pressure ground water source (Percent of irrigated acres)	PGNDW*	irrigation
No irrigation system irrigated acres (1,000 acres)	NIRRACRS	irrigation
No irrigation system water applied per irrigated acre (Inches)	NIRRWAT	irrigation
No irrigation system surface water source (Percent of irrigated acres)	NSRFW	irrigation
No irrigation system ground water source (Percent of irrigated acres)	NGNDW	irrigation
Planted acres (1,000 acres)	PLACRESeighteen	manure use
Tons Applied (Tons per treated acre)	MANAPPeighteen	manure use
Pct acres treated with manure (Percent of planted acres)	MANACRSeighteen	manure use
Broadcast or Sprayed with incorporation (Application Method Pct of Manured acres)	MANMBIeighteen	manure use
Broadcast w/out Incorporation (Application Method Pct of Manured acres)	MANMBSeighteen	manure use
Injected/knifed in (Application Method Pct of Manured acres)	MANMIIeighteen	manure use
Sprayed using irrigation systems (Application Method Pct of Manured acres)	MANMISeighteen	manure use
Beef cattle (Manure Type Pct of Treated acres)	MANSBCeighteen	manure use
Dairy cattle (Manure Type Pct of Treated acres)	MANSDCeighteen	manure use
Hogs (Manure Type Pct of Treated acres)	MANSHOeighteen	manure use
Poultry (Manure Type Pct of Treated acres)	MANSPOeighteen	manure use
Other (Manure Type Pct of Treated acres)	MANSOTeighteen	manure use
Lagoon liquid (Manure State Pct of Treated acres)	MANSLLeighteen	manure use
Semi-dry or Dry (Manure State Pct of Treated acres)	MANSSDeighteen	manure use
Slurry Liquid (Manure State Pct of Treated acres)	MANSSLeighteen	manure use
Planted acres (1,000 acres)	PLACRESeleven	nitrogen inhibitor use
Nitrogen inhibitor used (Percent of planted acres)	NINHBTReleven	nitrogen inhibitor use
Planted acres (1,000 acres)	PLACRES_one	pesticide use
Treatment rate with any pesticide (Pounds a.i. per treated acre)	PSTQT_one	pesticide use

ARMS variable description	Parameter name	Use
Acres treated with any pesticide (percent of planted acres)	PSTACT_one**	pesticide use
Treatment rate with herbicide (Pounds a.i. per treated acre)	HRBQT_one	pesticide use
Acres treated with herbicide (percent of planted acres)	HRBACT_one	pesticide use
Treatment rate with insecticide (Pounds a.i. per treated acre)	INSQT_one	pesticide use
Acres treated with insecticide (percent of planted acres)	INSACT_one	pesticide use
Herbicide acre-treatments (1,000 Acres, for use with application methods)	HRBACtwentytwo_fifteen	pesticide use
Banded/side-dressed (Percent of herbicide acre-treatments)	HRBHWseven_fifteen	pesticide use
Broadcast by air (Percent of herbicide acre-treatments)	HRBHWthree_fifteen	pesticide use
Broadcast with incorp. (Percent of herbicide acre-treatments)	HRBHWone_fifteen	pesticide use
Broadcast without incorp. (Percent of herbicide acre-treatments)	HRBHWtwo_fifteen	pesticide use
Chiseled/injected/knifed in (Percent of herbicide acre-treatments)	HRBHWsix_fifteen	pesticide use
Foliar or directed spray (Percent of herbicide acre-treatments)	HRBHWeight_fifteen	pesticide use
In irrigation water (Percent of herbicide acre-treatments)	HRBHWfive_fifteen	pesticide use
In seed furrow (Percent of herbicide acre-treatments)	HRBHWfour_fifteen	pesticide use
Insecticide acre-treatments (1,000 Acres, for use with application methods)	INSACnine_sixteen	pesticide use
Banded/side-dressed (Percent of insecticide acre-treatments)	INSHWseven_sixteen	pesticide use
Broadcast by air (Percent of insecticide acre-treatments)	INSHWthree_sixteen	pesticide use
Broadcast with incorp. (Percent of insecticide acre-treatments)	INSHWone_sixteen	pesticide use
Broadcast without incorp. (Percent of insecticide acre-treatments)	INSHWtwo_sixteen	pesticide use
Chiseled/injected/knifed in (Percent of insecticide acre-treatments)	INSHWsix_sixteen	pesticide use
Foliar or directed spray (Percent of insecticide acre-treatments)	INSHWeight_sixteen	pesticide use
In irrigation water (Percent of insecticide acre-treatments)	INSHWfive_sixteen	pesticide use
In seed furrow (Percent of insecticide acre-treatments)	INSHWfour_sixteen	pesticide use
Planted acres (1,000 acres)	PLACRES_five	seed use
Average seeding rate (Kernels (corn 2001 and earlier) or pounds (all other crops) per acre)	SEEDQTY_four	seed use
GMO herbicide resistant seed (Percent of planted acres)	GMOR_five	seed use
Non-GMO herbicide resistant seed (Percent of planted acres)	NGMOR_five	seed use
Area using no-till (1,000 acres)	NO_TILL_thouAC	soil prep., planting and sowing
Area using ridge till (1,000 acres)	RIDGE_TILL_thouAC	soil prep., planting and sowing
Area using mulch till (1,000 acres)	MULCH_TILL_thouAC	soil prep., planting and sowing
Area using reduced till (1,000 acres)	REDUCED_TILL_thouAC	soil prep., planting and sowing
Area using conventional till (1,000 acres)	CONV_TILL_thouAC	soil prep., planting and sowing
Area using tillage practice not determined (1,000 acres)	UNSPEC_TILL_thouAC	soil prep., planting and sowing
Distance traveled by manure used	DISALNUM_eighteen	transport

Table 17. ARMS variables used: flows to the environment

ARMS variable description	Parameter name	Use
Planted acres (1,000 Acres)	PLACRES_thirteen	fertilizer constituents to the environment
Acres treated with N (percent of planted acres)	NITAC_thirteen	fertilizer constituents to the environment
N applied in fall before planting (Pounds per treated acre)	NITLBone_thirteen	fertilizer constituents to the environment
N applied in spring before planting (Pounds per treated acre)	NITLBtwo_thirteen	fertilizer constituents to the environment
N applied at planting (Pounds per treated acre)	NITLBthree_thirteen	fertilizer constituents to the environment
N applied after planting (Pounds per treated acre)	NITLBfour_thirteen	fertilizer constituents to the environment
N in Fall before planting (Percent of acres with N)	NITWHNone_thirteen	fertilizer constituents to the environment
N in Spring before planting (Percent of acres with N)	NITWHNtwo_thirteen	fertilizer constituents to the environment
N at planting (Percent of acres with N)	NITWHNthree_thirteen	fertilizer constituents to the environment
N after planting (Percent of acres with N)	NITWHNfour_thirteen	fertilizer constituents to the environment
Acres treated with P2O5 (percent of planted acres)	PHOAC_thirteen	fertilizer constituents to the environment
P2O5 applied in fall before planting (Pounds per treated acre)	PHOLBone_thirteen	fertilizer constituents to the environment
P2O5 applied in spring before planting (Pounds per treated acre)	PHOLBtwo_thirteen	fertilizer constituents to the environment
P2O5 applied at planting (Pounds per treated acre)	PHOLBthree_thirteen	fertilizer constituents to the environment

ARMS variable description	Parameter name	Use
P2O5 applied after planting (Pounds per treated acre)	PHOLBfour_thirteen	fertilizer constituents to the environment
P2O5 in Fall before planting (Percent of acres with P)	PHOWHNone_thirteen	fertilizer constituents to the environment
P2O5 in Spring before planting (Percent of acres with P)	PHOWHNtwo_thirteen	fertilizer constituents to the environment
P2O5 at planting (Percent of acres with P)	PHOWHNthree_thirteen	fertilizer constituents to the environment
P2O5 after planting (Percent of acres with P)	PHOWHNfour_thirteen	fertilizer constituents to the environment
Acres treated with K2O (percent of planted acres)	POTAC_thirteen	fertilizer constituents to the environment
K2O in fall before planting (Pounds per treated acre)	POTLBone_thirteen	fertilizer constituents to the environment
K2O in spring before planting (Pounds per treated acre)	POTLBtwo_thirteen	fertilizer constituents to the environment
K2O at planting (Pounds per treated acre)	POTLBthree_thirteen	fertilizer constituents to the environment
K2O after planting (Pounds per treated acre)	POTLBfour_thirteen	fertilizer constituents to the environment
K2O in Fall before planting (Percent of acres with K)	POTWHNone_thirteen	fertilizer constituents to the environment
K2O in Spring before planting (Percent of acres with K)	POTWHNtwo_thirteen	fertilizer constituents to the environment
K2O at planting (Percent of acres with K)	POTWHNthree_thirteen	fertilizer constituents to the environment
K2O after planting (Percent of acres with K)	POTWHNfour_thirteen	fertilizer constituents to the environment
Percent of manure applied in the fall before planting	MANTPF_eighteen	manure constituents to the environment
Percent of Manure applied in the spring before planting	MANTPS_eighteen	manure constituents to the environment
Percent of manure applied after planting	MANTPA_eighteen	manure constituents to the environment

*Note that ARMS data for 2009 Washington spring and winter wheat were removed, they were greater than 100% and assumed to be in error.

**Note that ARMS data for 1999 Indiana corn and 2000 Mississippi cotton were removed, they were greater than 100% and assumed to be in error.

*** Note that ARMS provides planted area estimates by data group and that these values are not consistent throughout the entire database but instead represent the area assessed for each data group.

Appendix C: Data for the estimation of residue percent soil coverage

Crop	Year	State	Percent soil coverage	RSE
corn	1996	Illinois	43	76
corn	1996	Indiana	43	83
corn	1996	Iowa	36	58
corn	1996	Kansas	34	135
corn	1996	Kentucky	48	113
corn	1996	Michigan	31	121
corn	1996	Minnesota	22	91
corn	1996	Missouri	36	116
corn	1996	Nebraska	42	86
corn	1996	North Carolina	29	163
corn	1996	Ohio	42	75
corn	1996	Pennsylvania	21	157
corn	1996	South Carolina	25	60
corn	1996	South Dakota	38	114
corn	1996	Texas	15	229
corn	1996	Wisconsin	23	74
corn	1997	Illinois	43	76
corn	1997	Indiana	43	83
corn	1997	Iowa	36	58
corn	1997	Michigan	31	121
corn	1997	Minnesota	22	91
corn	1997	Missouri	36	116
corn	1997	Nebraska	42	86
corn	1997	Ohio	42	75
corn	1997	South Dakota	38	114
corn	1997	Wisconsin	23	74
corn	1998	Colorado	28	131
corn	1998	Illinois	43	76
corn	1998	Indiana	43	83
corn	1998	Iowa	36	58
corn	1998	Kansas	34	135
corn	1998	Kentucky	48	113
corn	1998	Michigan	31	121
corn	1998	Minnesota	22	91
corn	1998	Missouri	36	116
corn	1998	Nebraska	42	86
corn	1998	North Carolina	29	163
corn	1998	Ohio	42	75
corn	1998	Pennsylvania	21	157
corn	1998	South Dakota	38	114
corn	1998	Texas	15	229
corn	1998	Wisconsin	23	74
corn	1999	Colorado	28	131
corn	1999	Illinois	43	76
corn	1999	Indiana	43	83
corn	1999	Iowa	36	58
corn	1999	Kansas	34	135
corn	1999	Kentucky	48	113
corn	1999	Michigan	31	121
corn	1999	Minnesota	22	91
corn	1999	Missouri	36	116
corn	1999	Nebraska	42	86
corn	1999	North Carolina	29	163
corn	1999	Ohio	42	75
corn	1999	South Dakota	38	114
corn	1999	Texas	15	229
corn	1999	Wisconsin	23	74
corn	2000	Colorado	28	131
corn	2000	Illinois	43	76
corn	2000	Indiana	43	83
corn	2000	Iowa	36	58
corn	2000	Kansas	34	135

Crop	Year	State	Percent soil coverage	RSE
corn	2000	Kentucky	48	113
corn	2000	Michigan	31	121
corn	2000	Minnesota	22	91
corn	2000	Missouri	36	116
corn	2000	Nebraska	42	86
corn	2000	New York	4.1	67
corn	2000	North Carolina	29	163
corn	2000	North Dakota	24	164
corn	2000	Ohio	42	75
corn	2000	Pennsylvania	21	157
corn	2000	South Dakota	38	114
corn	2000	Texas	15	229
corn	2000	Wisconsin	23	74
corn	2001	Colorado	28	131
corn	2001	Georgia	34	73
corn	2001	Illinois	43	76
corn	2001	Indiana	43	83
corn	2001	Iowa	36	58
corn	2001	Kansas	34	135
corn	2001	Kentucky	48	113
corn	2001	Michigan	31	121
corn	2001	Minnesota	22	91
corn	2001	Missouri	36	116
corn	2001	Nebraska	42	86
corn	2001	New York	4.1	67
corn	2001	North Carolina	29	163
corn	2001	North Dakota	24	164
corn	2001	Ohio	42	75
corn	2001	Pennsylvania	21	157
corn	2001	South Dakota	38	114
corn	2001	Texas	15	229
corn	2001	Wisconsin	23	74
corn	2005	Colorado	28	131
corn	2005	Georgia	34	73
corn	2005	Illinois	43	76
corn	2005	Indiana	43	83
corn	2005	Iowa	36	58
corn	2005	Kansas	34	135
corn	2005	Kentucky	48	113
corn	2005	Michigan	31	121
corn	2005	Minnesota	22	91
corn	2005	Missouri	36	116
corn	2005	Nebraska	42	86
corn	2005	New York	4.1	67
corn	2005	North Carolina	29	163
corn	2005	North Dakota	24	164
corn	2005	Ohio	42	75
corn	2005	Pennsylvania	21	157
corn	2005	South Dakota	38	114
corn	2005	Texas	15	229
corn	2005	Wisconsin	23	74
cotton	1996	Arizona	15	58
cotton	1996	Arkansas	7.1	20
cotton	1996	California	0.57	15
cotton	1996	Georgia	17	19
cotton	1996	Louisiana	6.8	18
cotton	1996	Mississippi	9.3	10
cotton	1996	Tennessee	26	6.7
cotton	1996	Texas	12	41
cotton	1997	Alabama	21	13
cotton	1997	Arizona	15	58
cotton	1997	Arkansas	7.1	20
cotton	1997	California	0.57	15
cotton	1997	Georgia	17	19

Crop	Year	State	Percent soil coverage	RSE
cotton	1997	Louisiana	6.8	18
cotton	1997	Mississippi	9.3	10
cotton	1997	Missouri	11	24
cotton	1997	North Carolina	23	13
cotton	1997	South Carolina	22	12
cotton	1997	Tennessee	26	6.7
cotton	1997	Texas	12	41
cotton	1998	Alabama	21	13
cotton	1998	Arizona	15	58
cotton	1998	Arkansas	7.1	20
cotton	1998	California	0.57	15
cotton	1998	Georgia	17	19
cotton	1998	Louisiana	6.8	18
cotton	1998	Mississippi	9.3	10
cotton	1998	North Carolina	23	13
cotton	1998	Tennessee	26	6.7
cotton	1998	Texas	12	41
cotton	1999	Alabama	21	13
cotton	1999	Arizona	15	58
cotton	1999	Arkansas	7.1	20
cotton	1999	California	0.57	15
cotton	1999	Georgia	17	19
cotton	1999	Louisiana	6.8	18
cotton	1999	Mississippi	9.3	10
cotton	1999	North Carolina	23	13
cotton	1999	Tennessee	26	6.7
cotton	1999	Texas	12	41
cotton	2000	Alabama	21	13
cotton	2000	Arizona	15	58
cotton	2000	Arkansas	7.1	20
cotton	2000	California	0.57	15
cotton	2000	Georgia	17	19
cotton	2000	Louisiana	6.8	18
cotton	2000	Mississippi	9.3	10
cotton	2000	Missouri	11	24
cotton	2000	North Carolina	23	13
cotton	2000	Tennessee	26	6.7
cotton	2000	Texas	12	41
cotton	2003	Alabama	21	13
cotton	2003	Arizona	15	58
cotton	2003	Arkansas	7.1	20
cotton	2003	California	0.57	15
cotton	2003	Georgia	17	19
cotton	2003	Louisiana	6.8	18
cotton	2003	Mississippi	9.3	10
cotton	2003	Missouri	11	24
cotton	2003	North Carolina	23	13
cotton	2003	South Carolina	22	12
cotton	2003	Tennessee	26	6.7
cotton	2003	Texas	12	41
cotton	2007	Alabama	21	13
cotton	2007	Arkansas	7.1	20
cotton	2007	California	0.57	15
cotton	2007	Georgia	17	19
cotton	2007	Louisiana	6.8	18
cotton	2007	Mississippi	9.3	10
cotton	2007	Missouri	11	24
cotton	2007	North Carolina	23	13
cotton	2007	South Carolina	22	12
cotton	2007	Tennessee	26	6.7
cotton	2007	Texas	12	41
oats	2005	Illinois	45	88
oats	2005	Iowa	25	95
oats	2005	Kansas	40	141

Crop	Year	State	Percent soil coverage	RSE
oats	2005	Michigan	22	153
oats	2005	Minnesota	23	217
oats	2005	Nebraska	49	149
oats	2005	New York	39	520
oats	2005	North Dakota	41	89
oats	2005	Pennsylvania	19	280
oats	2005	South Dakota	49	105
oats	2005	Texas	23	188
oats	2005	Wisconsin	29	41
peanuts	1999	Alabama	4.7	72
peanuts	1999	Georgia	24	83
peanuts	1999	North Carolina	15	111
peanuts	1999	Texas	13	124
peanuts	2004	Alabama	4.7	72
peanuts	2004	Florida	2.7	21
peanuts	2004	Georgia	24	83
peanuts	2004	North Carolina	15	111
peanuts	2004	Texas	13	124
rice	2006	Arkansas	12	103
rice	2006	California	4.1	52
rice	2006	Louisiana	6.9	118
rice	2006	Mississippi	19	129
rice	2006	Missouri	28	147
rice	2006	Texas	13	124
soybeans	1996	Arkansas	14	111
soybeans	1996	Illinois	29	92
soybeans	1996	Indiana	31	72
soybeans	1996	Iowa	28	84
soybeans	1996	Louisiana	12	195
soybeans	1996	Minnesota	17	80
soybeans	1996	Mississippi	19	74
soybeans	1996	Missouri	28	94
soybeans	1996	Nebraska	34	79
soybeans	1996	Ohio	36	133
soybeans	1996	Tennessee	33	90
soybeans	1997	Arkansas	14	111
soybeans	1997	Illinois	29	92
soybeans	1997	Indiana	31	72
soybeans	1997	Iowa	28	84
soybeans	1997	Kansas	26	117
soybeans	1997	Kentucky	36	78
soybeans	1997	Louisiana	12	195
soybeans	1997	Michigan	26	77
soybeans	1997	Minnesota	17	80
soybeans	1997	Mississippi	19	74
soybeans	1997	Missouri	28	94
soybeans	1997	Nebraska	34	79
soybeans	1997	North Carolina	27	133
soybeans	1997	Ohio	36	133
soybeans	1997	Pennsylvania	30	84
soybeans	1997	South Dakota	33	98
soybeans	1997	Tennessee	33	90
soybeans	1997	Wisconsin	25	220
soybeans	1998	Arkansas	14	111
soybeans	1998	Illinois	29	92
soybeans	1998	Indiana	31	72
soybeans	1998	Iowa	28	84
soybeans	1998	Kansas	26	117
soybeans	1998	Kentucky	36	78
soybeans	1998	Louisiana	12	195
soybeans	1998	Michigan	26	77
soybeans	1998	Minnesota	17	80
soybeans	1998	Mississippi	19	74
soybeans	1998	Missouri	28	94

Crop	Year	State	Percent soil coverage	RSE
soybeans	1998	Nebraska	34	79
soybeans	1998	North Carolina	27	133
soybeans	1998	Ohio	36	133
soybeans	1998	South Dakota	33	98
soybeans	1998	Tennessee	33	90
soybeans	1999	Arkansas	14	111
soybeans	1999	Illinois	29	92
soybeans	1999	Indiana	31	72
soybeans	1999	Iowa	28	84
soybeans	1999	Kansas	26	117
soybeans	1999	Kentucky	36	78
soybeans	1999	Louisiana	12	195
soybeans	1999	Michigan	26	77
soybeans	1999	Minnesota	17	80
soybeans	1999	Mississippi	19	74
soybeans	1999	Missouri	28	94
soybeans	1999	Nebraska	34	79
soybeans	1999	North Carolina	27	133
soybeans	1999	Ohio	36	133
soybeans	1999	Pennsylvania	30	84
soybeans	1999	South Dakota	33	98
soybeans	1999	Tennessee	33	90
soybeans	2000	Arkansas	14	111
soybeans	2000	Illinois	29	92
soybeans	2000	Indiana	31	72
soybeans	2000	Iowa	28	84
soybeans	2000	Kansas	26	117
soybeans	2000	Kentucky	36	78
soybeans	2000	Louisiana	12	195
soybeans	2000	Michigan	26	77
soybeans	2000	Minnesota	17	80
soybeans	2000	Mississippi	19	74
soybeans	2000	Missouri	28	94
soybeans	2000	Nebraska	34	79
soybeans	2000	North Carolina	27	133
soybeans	2000	North Dakota	20	113
soybeans	2000	Ohio	36	133
soybeans	2000	South Dakota	33	98
soybeans	2000	Tennessee	33	90
soybeans	2000	Wisconsin	25	220
soybeans	2002	Arkansas	14	111
soybeans	2002	Illinois	29	92
soybeans	2002	Indiana	31	72
soybeans	2002	Iowa	28	84
soybeans	2002	Kansas	26	117
soybeans	2002	Kentucky	36	78
soybeans	2002	Louisiana	12	195
soybeans	2002	Maryland	26	175
soybeans	2002	Michigan	26	77
soybeans	2002	Minnesota	17	80
soybeans	2002	Mississippi	19	74
soybeans	2002	Missouri	28	94
soybeans	2002	Nebraska	34	79
soybeans	2002	North Carolina	27	133
soybeans	2002	North Dakota	20	113
soybeans	2002	Ohio	36	133
soybeans	2002	South Dakota	33	98
soybeans	2002	Tennessee	33	90
soybeans	2002	Virginia	45	109
soybeans	2002	Wisconsin	25	220
soybeans	2006	Arkansas	14	111
soybeans	2006	Illinois	29	92
soybeans	2006	Indiana	31	72
soybeans	2006	Iowa	28	84

Crop	Year	State	Percent soil coverage	RSE
soybeans	2006	Kansas	26	117
soybeans	2006	Kentucky	36	78
soybeans	2006	Louisiana	12	195
soybeans	2006	Michigan	26	77
soybeans	2006	Minnesota	17	80
soybeans	2006	Mississippi	19	74
soybeans	2006	Missouri	28	94
soybeans	2006	Nebraska	34	79
soybeans	2006	North Carolina	27	133
soybeans	2006	North Dakota	20	113
soybeans	2006	Ohio	36	133
soybeans	2006	South Dakota	33	98
soybeans	2006	Tennessee	33	90
soybeans	2006	Virginia	45	109
soybeans	2006	Wisconsin	25	220
wheat	1996	Colorado	46	61
wheat	1996	Delaware	39	520
wheat	1996	Idaho	22	106
wheat	1996	Kansas	40	141
wheat	1996	Minnesota	23	217
wheat	1996	Montana	43	64
wheat	1996	Nebraska	49	149
wheat	1996	North Dakota	41	89
wheat	1996	Oklahoma	22	51
wheat	1996	Oregon	27	71
wheat	1996	South Dakota	49	105
wheat	1996	Texas	23	188
wheat	1996	Washington	29	93
wheat	1997	Colorado	46	61
wheat	1997	Idaho	22	106
wheat	1997	Illinois	45	88
wheat	1997	Kansas	40	141
wheat	1997	Minnesota	23	217
wheat	1997	Missouri	38	106
wheat	1997	Montana	43	64
wheat	1997	Nebraska	49	149
wheat	1997	North Dakota	41	89
wheat	1997	Ohio	35	122
wheat	1997	Oklahoma	22	51
wheat	1997	Oregon	27	71
wheat	1997	Pennsylvania	19	280
wheat	1997	South Dakota	49	105
wheat	1997	Texas	23	188
wheat	1997	Washington	29	93
wheat	1998	California	26	57
wheat	1998	Colorado	46	61
wheat	1998	Georgia	38	88
wheat	1998	Idaho	22	106
wheat	1998	Illinois	45	88
wheat	1998	Kansas	40	141
wheat	1998	Louisiana	38	50
wheat	1998	Minnesota	23	217
wheat	1998	Mississippi	49	43
wheat	1998	Missouri	38	106
wheat	1998	Montana	43	64
wheat	1998	Nebraska	49	149
wheat	1998	North Carolina	48	97
wheat	1998	North Dakota	41	89
wheat	1998	Ohio	35	122
wheat	1998	Oklahoma	22	51
wheat	1998	Oregon	27	71
wheat	1998	South Dakota	49	105
wheat	1998	Texas	23	188
wheat	1998	Washington	29	93

Crop	Year	State	Percent soil coverage	RSE
wheat	2000	Arkansas	41	106
wheat	2000	Colorado	46	61
wheat	2000	Idaho	22	106
wheat	2000	Illinois	45	88
wheat	2000	Kansas	40	141
wheat	2000	Kentucky	63	48
wheat	2000	Minnesota	23	217
wheat	2000	Missouri	38	106
wheat	2000	Montana	43	64
wheat	2000	Nebraska	49	149
wheat	2000	North Carolina	48	97
wheat	2000	North Dakota	41	89
wheat	2000	Ohio	35	122
wheat	2000	Oklahoma	22	51
wheat	2000	Oregon	27	71
wheat	2000	South Dakota	49	105
wheat	2000	Texas	23	188
wheat	2000	Washington	29	93
wheat	2004	Colorado	46	61
wheat	2004	Idaho	22	106
wheat	2004	Illinois	45	88
wheat	2004	Kansas	40	141
wheat	2004	Michigan	22	153
wheat	2004	Minnesota	23	217
wheat	2004	Missouri	38	106
wheat	2004	Montana	43	64
wheat	2004	Nebraska	49	149
wheat	2004	North Dakota	41	89
wheat	2004	Ohio	35	122
wheat	2004	Oklahoma	22	51
wheat	2004	Oregon	27	71
wheat	2004	South Dakota	49	105
wheat	2004	Texas	23	188
wheat	2004	Washington	29	93
wheat	2009	Colorado	46	61
wheat	2009	Idaho	22	106
wheat	2009	Illinois	45	88
wheat	2009	Kansas	40	141
wheat	2009	Michigan	22	153
wheat	2009	Minnesota	23	217
wheat	2009	Missouri	38	106
wheat	2009	Montana	43	64
wheat	2009	Nebraska	49	149
wheat	2009	North Dakota	41	89
wheat	2009	Ohio	35	122
wheat	2009	Oklahoma	22	51
wheat	2009	Oregon	27	71
wheat	2009	South Dakota	49	105
wheat	2009	Texas	23	188
wheat	2009	Washington	29	93

Appendix D: Data for the estimation of growing season length

Table 18. Growing season lengths (fraction of year)

Crop	Region	Growing complete for 5%	Growing complete for 15%	Growing complete for 85%	Growing complete for 95%	Inverse cdf 3rd order coeff	Inverse cdf 2nd order coeff	Inverse cdf 1st order coeff	Inverse cdf 0th order coeff
Corn grain	Appalachia	4.0E-01	4.1E-01	4.3E-01	4.4E-01	1.1E-01	-1.6E-01	9.9E-02	4.0E-01
	Corn Belt	4.2E-01	4.3E-01	4.6E-01	4.8E-01	3.1E-01	-4.5E-01	2.2E-01	4.1E-01
	Delta	3.9E-01	4.0E-01	4.1E-01	4.2E-01	1.9E-01	-3.0E-01	1.5E-01	3.9E-01
	Lake States	4.2E-01	4.5E-01	4.8E-01	4.9E-01	4.3E-01	-7.4E-01	4.0E-01	4.0E-01
	Mountain	4.4E-01	4.5E-01	4.8E-01	4.9E-01	-2.8E-02	2.7E-02	4.6E-02	4.4E-01
	Northeast	4.2E-01	4.3E-01	4.5E-01	4.6E-01	8.3E-02	-1.2E-01	8.4E-02	4.2E-01
	Northern Plains	4.1E-01	4.3E-01	4.8E-01	4.9E-01	1.9E-01	-3.0E-01	2.0E-01	4.1E-01
	Pacific	4.7E-01	4.9E-01	4.0E-01	4.0E-01	4.9E-01	-8.3E-01	2.8E-01	4.6E-01
	Southeast	3.9E-01	4.0E-01	4.2E-01	4.2E-01	9.1E-02	-2.6E-01	2.1E-01	3.8E-01
	Southern Plains	3.9E-01	4.0E-01	4.3E-01	4.7E-01	7.0E-01	-8.8E-01	3.1E-01	3.7E-01
Corn silage	Appalachia	3.4E-01	3.4E-01	3.5E-01	3.5E-01	-8.7E-03	-4.3E-02	6.1E-02	3.4E-01
	Corn Belt	3.3E-01	3.4E-01	3.3E-01	3.0E-01	-2.7E-01	1.6E-01	6.6E-02	3.3E-01
	Delta	3.2E-01	3.2E-01	3.4E-01	3.6E-01	1.5E-01	-9.1E-02	-1.4E-02	3.2E-01
	Lake States	3.6E-01	3.6E-01	3.8E-01	3.8E-01	-9.2E-02	1.0E-01	4.0E-03	3.6E-01
	Mountain	3.7E-01	3.7E-01	3.7E-01	3.9E-01	3.5E-01	-4.4E-01	1.4E-01	3.6E-01
	Northeast	3.5E-01	3.5E-01	3.4E-01	3.4E-01	-1.5E-01	2.5E-01	-1.3E-01	3.6E-01
	Northern Plains	3.3E-01	3.4E-01	3.6E-01	3.5E-01	1.1E-02	-1.2E-01	1.3E-01	3.3E-01
	Pacific	3.4E-01	3.4E-01	2.7E-01	3.1E-01	7.1E-01	-8.6E-01	1.5E-01	3.3E-01
	Southeast	2.5E-01	2.4E-01	2.6E-01	2.8E-01	-6.0E-02	2.8E-01	-1.9E-01	2.6E-01
	Southern Plains	3.5E-01	3.3E-01	3.5E-01	3.8E-01	1.1E-01	8.6E-02	-1.6E-01	3.6E-01
Cotton	Appalachia	4.3E-01	4.3E-01	4.8E-01	5.1E-01	2.9E-01	-2.7E-01	8.8E-02	4.3E-01
	Corn Belt	4.1E-01	4.1E-01	4.7E-01	4.9E-01	2.5E-01	-2.7E-01	1.3E-01	4.0E-01
	Delta	4.1E-01	4.2E-01	4.5E-01	4.6E-01	1.8E-01	-2.3E-01	1.2E-01	4.0E-01
	Mountain	5.0E-01	5.2E-01	5.4E-01	6.1E-01	1.2E+00	-1.5E+00	4.7E-01	4.8E-01
	Northern Plains	4.3E-01	4.3E-01	5.0E-01	5.1E-01	-8.1E-02	2.1E-01	-3.9E-02	4.3E-01
	Pacific	5.1E-01	5.0E-01	4.9E-01	5.2E-01	2.2E-01	-1.1E-01	-9.4E-02	5.2E-01
	Southeast	4.2E-01	4.4E-01	4.9E-01	5.1E-01	3.9E-01	-5.3E-01	2.6E-01	4.1E-01
	Southern Plains	3.9E-01	4.3E-01	5.4E-01	5.6E-01	5.0E-01	-9.0E-01	6.1E-01	3.6E-01
Oats	Alaska	3.3E-01	3.1E-01	3.4E-01	3.5E-01	-1.8E-01	4.5E-01	-2.5E-01	3.4E-01
	Appalachia	6.8E-01	6.6E-01	6.1E-01	6.4E-01	2.8E-01	-1.4E-01	-1.8E-01	6.9E-01
	Corn Belt	2.9E-01	2.9E-01	2.6E-01	2.5E-01	-6.7E-02	6.5E-03	1.5E-02	2.9E-01
	Delta	6.6E-01	6.5E-01	5.8E-01	5.8E-01	3.3E-02	5.4E-02	-1.8E-01	6.7E-01
	Lake States	2.8E-01	2.7E-01	2.8E-01	2.8E-01	-1.2E-01	2.1E-01	-8.7E-02	2.8E-01
	Mountain	3.1E-01	3.1E-01	3.0E-01	3.1E-01	1.7E-01	-2.1E-01	4.9E-02	3.1E-01
	Northeast	2.9E-01	3.0E-01	3.1E-01	2.8E-01	-2.6E-01	2.0E-01	3.9E-02	2.9E-01
	Northern Plains	2.9E-01	2.9E-01	2.8E-01	2.8E-01	8.1E-03	-1.2E-02	-7.8E-03	2.9E-01
	Pacific	7.3E-01	7.6E-01	5.9E-01	5.8E-01	8.2E-01	-1.5E+00	5.1E-01	7.1E-01
	Southeast	6.6E-01	6.5E-01	5.9E-01	5.6E-01	-4.1E-01	4.8E-01	-2.0E-01	6.7E-01
	Southern Plains	6.0E-01	6.0E-01	5.6E-01	5.4E-01	-2.1E-01	2.4E-01	-1.1E-01	6.1E-01
Peanuts	Appalachia	4.0E-01	4.2E-01	4.2E-01	4.5E-01	6.2E-01	-8.0E-01	2.6E-01	3.9E-01
	Delta	4.1E-01	4.0E-01	4.2E-01	4.1E-01	-3.4E-01	4.6E-01	-1.4E-01	4.1E-01
	Mountain	3.9E-01	4.1E-01	4.3E-01	4.4E-01	2.0E-01	-2.9E-01	1.6E-01	3.9E-01
	Southeast	3.9E-01	3.9E-01	4.3E-01	4.4E-01	8.1E-02	-1.1E-01	9.7E-02	3.8E-01
	Southern Plains	4.0E-01	4.2E-01	4.5E-01	4.6E-01	2.9E-01	-4.7E-01	2.6E-01	3.9E-01

Crop	Region	Growing complete for 5%	Growing complete for 15%	Growing complete for 85%	Growing complete for 95%	Inverse cdf 3rd order coeff	Inverse cdf 2nd order coeff	Inverse cdf 1st order coeff	Inverse cdf 0th order coeff
Rice	Corn Belt	4.1E-01	4.0E-01	4.2E-01	4.3E-01	6.0E-02	3.0E-02	-6.3E-02	4.1E-01
	Delta	3.9E-01	3.9E-01	3.9E-01	3.9E-01	8.0E-02	-1.4E-01	6.5E-02	3.8E-01
	Pacific	3.8E-01	3.8E-01	4.4E-01	4.2E-01	-5.5E-01	7.3E-01	-1.6E-01	3.8E-01
	Southern Plains	3.7E-01	3.8E-01	3.6E-01	3.6E-01	2.6E-01	-4.0E-01	1.5E-01	3.6E-01
Soybeans	Appalachia	4.1E-01	4.3E-01	4.1E-01	4.0E-01	2.1E-01	-4.2E-01	2.1E-01	4.0E-01
	Corn Belt	3.9E-01	4.0E-01	3.9E-01	3.8E-01	4.9E-02	-1.1E-01	5.3E-02	3.9E-01
	Delta	3.9E-01	3.9E-01	4.0E-01	3.9E-01	-1.6E-01	1.8E-01	-1.8E-02	3.9E-01
	Lake States	3.9E-01	3.9E-01	3.9E-01	3.9E-01	4.0E-02	-6.2E-02	2.4E-02	3.9E-01
	Northeast	4.0E-01	4.0E-01	4.0E-01	3.9E-01	-7.7E-02	3.7E-02	2.4E-02	4.0E-01
	Northern Plains	3.8E-01	3.8E-01	3.8E-01	3.9E-01	7.9E-02	-7.3E-02	1.1E-02	3.8E-01
	Southeast	4.3E-01	4.4E-01	4.5E-01	4.6E-01	4.2E-01	-6.7E-01	3.0E-01	4.1E-01
	Southern Plains	4.0E-01	4.0E-01	3.9E-01	4.0E-01	1.1E-01	-1.3E-01	2.3E-02	4.0E-01
Wheat, spring, durum	Mountain	3.4E-01	3.4E-01	3.4E-01	3.2E-01	-1.6E-01	1.5E-01	-1.6E-02	3.4E-01
	Northern Plains	2.9E-01	2.9E-01	3.1E-01	3.3E-01	5.8E-03	7.6E-02	-4.3E-02	2.9E-01
	Pacific	6.5E-01	6.4E-01	5.3E-01	5.0E-01	-2.7E-01	2.4E-01	-1.5E-01	6.6E-01
Wheat, spring (excl durum)	Lake States	2.9E-01	2.8E-01	3.0E-01	3.1E-01	-1.6E-02	1.4E-01	-1.1E-01	3.0E-01
	Mountain	3.3E-01	3.2E-01	3.3E-01	3.3E-01	-5.4E-02	1.1E-01	-6.0E-02	3.3E-01
	Northern Plains	3.0E-01	2.9E-01	3.0E-01	3.0E-01	3.1E-02	1.2E-02	-3.1E-02	3.0E-01
	Pacific	3.7E-01	3.5E-01	3.4E-01	3.2E-01	-4.5E-01	6.6E-01	-2.8E-01	3.8E-01
Wheat, winter	Appalachia	7.0E-01	6.7E-01	6.2E-01	6.1E-01	-3.3E-01	5.9E-01	-3.7E-01	7.1E-01
	Corn Belt	7.3E-01	7.2E-01	7.0E-01	6.9E-01	-1.9E-01	2.3E-01	-9.9E-02	7.3E-01
	Delta	6.4E-01	6.3E-01	5.7E-01	5.7E-01	-9.8E-02	2.0E-01	-1.9E-01	6.5E-01
	Lake States	8.1E-01	8.0E-01	8.0E-01	8.0E-01	-8.9E-02	1.7E-01	-1.0E-01	8.1E-01
	Mountain	8.5E-01	8.4E-01	8.3E-01	8.2E-01	-1.9E-01	2.8E-01	-1.4E-01	8.6E-01
	Northeast	7.7E-01	7.6E-01	7.4E-01	7.2E-01	-4.4E-01	6.3E-01	-2.7E-01	7.9E-01
	Northern Plains	7.8E-01	7.8E-01	7.4E-01	7.3E-01	7.7E-02	-1.5E-01	1.8E-02	7.8E-01
	Pacific	8.3E-01	8.3E-01	7.9E-01	7.7E-01	-1.5E-01	1.5E-01	-7.1E-02	8.3E-01
	Southeast	6.1E-01	5.7E-01	5.4E-01	5.2E-01	-6.5E-01	1.1E+00	-6.0E-01	6.4E-01
	Southern Plains	7.3E-01	7.2E-01	6.7E-01	6.5E-01	-3.3E-01	4.2E-01	-2.0E-01	7.4E-01

Appendix E: Reference product, co-product, and residue characterization

Table 19. Reference product, co-product, and residue carbon (% dry matter)

	C % (min)	C % (max)
Corn grain	3.8E-01	5.1E-01
Corn residue	3.9E-01	5.3E-01
Corn silage	3.9E-01	5.3E-01
Cotton lint	4.4E-01	5.9E-01
Cotton seed	4.2E-01	5.7E-01
Cotton residue	3.9E-01	5.2E-01
Oat grain	3.8E-01	5.2E-01
Oat residue	3.8E-01	5.1E-01
Peanut fruit	4.1E-01	5.5E-01
Peanut residue	4.1E-01	5.5E-01
Rice grain	3.4E-01	4.6E-01
Rice residue	3.2E-01	4.4E-01
Soybean grain	4.2E-01	5.7E-01
Soybean residue	3.9E-01	5.2E-01
Wheat durum grain	3.9E-01	5.3E-01
Wheat spring grain	3.9E-01	5.3E-01
Wheat winter grain	3.9E-01	5.3E-01
Wheat residue	3.9E-01	5.3E-01

- Data are from (Adam et al. 1994) accessed through the USDOE EERE Biomass Program, Biomass Feedstock Composition and Property Database (http://www.afdc.energy.gov/biomass/progs/); (Agricultural Utilization Research Institute 2008); (Balkcom et al. 2007); (Bostrom et al. 2009); (Brooks 1898); (Ebeling and Jenkins 1985); (Energy Research Centre of the Netherlands (ECN) 2011) at http://www.ecn.nl/phyllis/search.asp; (IPCC 2011); (Johnson et al. 2007); (Korenaga et al. 2010); (Latshaw and Miller 1924); (Lee and Herbeck 2005); (Loomis and Lafitte 1987); (National Cottonseed Products Association 2011); (Richard 2011); (US Department of Agriculture 2011b); and (Vamvuka 2011)
- Variation represents the greater of range found in literature and +/-15% as in (National Research Council 1982)

Table 20. Reference product, co-product, and residue nitrogen, phosphorous, and potassium (% dry matter)

	N % (most likely)	N % (min)	N % (max)	P % (most likely)	P % (min)	P % (max)	K % (most likely)	K % (min)	K % (max)
Corn grain	1.8E-02	1.6E-02	2.0E-02	3.4E-03	3.0E-03	4.5E-03	3.4E-03	2.4E-03	4.5E-03
Corn residue	1.1E-02	7.8E-03	1.3E-02	1.0E-03	7.0E-04	1.3E-03	1.5E-02	1.1E-02	2.0E-02
Corn silage	1.3E-02	1.2E-02	1.5E-02	3.0E-03	1.8E-03	7.9E-03	1.2E-02	9.9E-03	1.6E-02
Cotton lint	1.7E-02	1.9E-03	3.6E-02	4.1E-03	2.9E-03	5.3E-03	4.9E-03	3.4E-03	6.4E-03
Cotton seed	3.8E-02	3.6E-02	4.0E-02	7.3E-03	7.1E-03	7.6E-03	1.2E-02	1.1E-02	1.2E-02
Cotton residue		1.2E-02	2.3E-02		1.5E-03	2.9E-03		1.5E-03	1.9E-03
Oat grain	1.9E-02	1.6E-02	2.2E-02	3.7E-03	3.3E-03	4.3E-03	4.6E-03	4.2E-03	4.8E-03
Oat residue	1.5E-02	1.1E-02	2.2E-02	2.6E-03	1.8E-03	3.4E-03	1.6E-02	1.1E-02	2.1E-02
Peanut fruit	4.3E-02	3.8E-02	4.9E-02	3.5E-03	3.5E-03	3.5E-03	5.6E-03	5.6E-03	5.6E-03
Peanut residue	2.0E-02	1.7E-02	2.3E-02	1.7E-03	1.4E-03	2.3E-03	1.2E-02	9.2E-03	1.4E-02
Rice grain	1.6E-02	1.3E-02	2.6E-02	3.2E-03	1.1E-03	5.0E-03	4.6E-03	3.3E-03	5.7E-03
Rice residue	7.2E-03	6.5E-03	8.1E-03	8.8E-04	5.5E-04	1.3E-03	1.3E-02	7.9E-03	2.0E-02
Soybean grain	6.6E-02	6.1E-02	6.8E-02	6.7E-03	6.3E-03	7.3E-03	1.5E-02	9.3E-03	1.8E-02
Soybean residue	2.6E-02	2.0E-02	3.0E-02	3.0E-03	2.1E-03	3.9E-03	9.9E-03	6.9E-03	1.3E-02
Wheat durum grain	2.4E-02	2.3E-02	2.5E-02	4.2E-03	4.1E-03	4.5E-03	5.0E-03	5.0E-03	5.1E-03
Wheat spring grain	2.7E-02	2.6E-02	2.8E-02	4.3E-03	4.2E-03	4.4E-03	4.1E-03	2.9E-03	5.3E-03
Wheat winter grain	2.1E-02	1.8E-02	2.4E-02	3.9E-03	3.3E-03	4.7E-03	4.8E-03	4.4E-03	5.1E-03
Wheat residue	1.3E-02	1.1E-02	1.5E-02	2.0E-03	1.4E-03	2.6E-03	1.2E-02	8.4E-03	1.6E-02

- Data are from (Lemunyon et al 1999) and USDA NRCS Crop Nutrient Database (US Department of Agriculture 2011a)
- Variation as in USDA NRCS Crop Nutrient Database (US Department of Agriculture 2011a) or +/- 30% as in (National Research Council 1982)

Appendix F: Fertilizer type data

Composition data are from USDA ERS Fertilizer Imports/Exports: Documentation (at http://www.ers.usda.gov/Data/FertilizerTrade/documentation.htm), Ullmann's Agrochemicals (volume 1), and the USDA NRCS Nitrogen Fertilizer Guide (at http://www.nm.nrcs.usda.gov/technical/handbooks/iwm/NM_IWM_Field_Manual/Section09/9e-Nitrogen_Fertilizer_Guide.pdf).

Table 21. Breakdown of nitrogen fertilizer types

Year	Anhydrous Ammonia	Aqua Ammonia	Ammonium Nitrate	Ammonium Sulfate	Nitrogen solutions	Sodium nitrate	Urea	Di ammonium phosphate	Mono ammonium phosphate
1996	0.37 - 0.39	0.0073 - 0.0086	0.066 - 0.067	0.020 - 0.021	0.26 - 0.29	0.00046 - 0.00049	0.17 - 0.17	0.065 - 0.072	0.013 - 0.013
1997	0.36 - 0.39	0.0044 - 0.0052	0.060 - 0.062	0.024 - 0.025	0.28 - 0.30	0.00049 - 0.00052	0.16 - 0.17	0.065 - 0.072	0.013 - 0.014
1998	0.33 - 0.35	0.0052 - 0.0062	0.061 - 0.063	0.021 - 0.023	0.28 - 0.30	0.00058 - 0.00061	0.19 - 0.20	0.065 - 0.071	0.014 - 0.014
1999	0.35 - 0.37	0.0067 - 0.0079	0.058 - 0.059	0.021 - 0.022	0.28 - 0.30	0.00051 - 0.00054	0.19 - 0.20	0.054 - 0.060	0.013 - 0.013
2000	0.33 - 0.35	0.0066 - 0.0078	0.053 - 0.054	0.022 - 0.023	0.28 - 0.31	0.00039 - 0.00041	0.20 - 0.21	0.056 - 0.062	0.015 - 0.016
2001	0.30 - 0.32	0.0071 - 0.0084	0.053 - 0.054	0.024 - 0.025	0.28 - 0.30	0.00041 - 0.00043	0.23 - 0.24	0.061 - 0.067	0.017 - 0.018
2002	0.31 - 0.32	0.0055 - 0.0065	0.052 - 0.053	0.021 - 0.023	0.27 - 0.29	0.00041 - 0.00043	0.24 - 0.24	0.063 - 0.070	0.019 - 0.021
2003	0.30 - 0.32	0.0079 - 0.0094	0.050 - 0.051	0.023 - 0.024	0.27 - 0.29	0.00027 - 0.00029	0.24 - 0.25	0.058 - 0.065	0.019 - 0.021
2004	0.29 - 0.31	0.0097 - 0.0114	0.045 - 0.047	0.023 - 0.024	0.29 - 0.31	0.00024 - 0.00025	0.23 - 0.24	0.060 - 0.066	0.021 - 0.023
2005	0.30 - 0.31	0.0083 - 0.0098	0.045 - 0.046	0.023 - 0.025	0.29 - 0.31	0.00032 - 0.00034	0.22 - 0.23	0.060 - 0.066	0.023 - 0.024
2006	0.30 - 0.32	0.0081 - 0.0096	0.031 - 0.032	0.025 - 0.026	0.29 - 0.31	0.00026 - 0.00028	0.24 - 0.25	0.055 - 0.061	0.025 - 0.026
2007	0.30 - 0.32	0.0068 - 0.0081	0.031 - 0.032	0.025 - 0.027	0.31 - 0.33	0.00018 - 0.00019	0.23 - 0.24	0.047 - 0.052	0.025 - 0.027
2008	0.32 - 0.34	0.0084 - 0.0100	0.027 - 0.027	0.025 - 0.026	0.29 - 0.31	0.00022 - 0.00023	0.23 - 0.23	0.044 - 0.049	0.027 - 0.029
2009	0.32 - 0.34	0.0090 - 0.0106	0.025 - 0.026	0.024 - 0.026	0.31 - 0.33	0.00029 - 0.00031	0.23 - 0.24	0.034 - 0.037	0.022 - 0.023
Mass fraction N	0.82	0.20 – 0.25	0.33 – 0.34	0.21	0.28 – 0.32	0.16	0.45 – 0.46	0.18 – 0.21	0.11

Table 22. Breakdown of phosphorous and potassium fertilizer types

	Fraction of P2O5 applied					Fraction of K2O applied	
	Superphosphate grades 22% and under	**Superphosphate grades over 22%**	**Other single phosphates**	**Di ammonium phosphate**	**Mono ammonium phosphate**	**Potash: Potassium chloride**	**Potash: Other single nutrient**
1996	0.0021 - 0.0022	0.074 - 0.081	0.010 - 0.020	0.65 - 0.67	0.23 - 0.25	0.0021 - 0.0022	0.074 - 0.081
1997	0.0033 - 0.0034	0.063 - 0.069	0.013 - 0.028	0.64 - 0.67	0.25 - 0.26	0.0033 - 0.0034	0.063 - 0.069
1998	0.0033 - 0.0034	0.060 - 0.066	0.013 - 0.028	0.64 - 0.66	0.25 - 0.27	0.0033 - 0.0034	0.060 - 0.066
1999	0.0058 - 0.0059	0.065 - 0.072	0.017 - 0.036	0.61 - 0.64	0.27 - 0.28	0.0058 - 0.0059	0.065 - 0.072
2000	0.00086 - 0.00087	0.057 - 0.064	0.021 - 0.045	0.59 - 0.62	0.30 - 0.31	0.00086 - 0.00087	0.057 - 0.064
2001	0.00122 - 0.00123	0.056 - 0.063	0.020 - 0.041	0.58 - 0.61	0.30 - 0.32	0.00122 - 0.00123	0.056 - 0.063
2002	0.00125 - 0.00126	0.051 - 0.057	0.017 - 0.036	0.57 - 0.59	0.33 - 0.35	0.00125 - 0.00126	0.051 - 0.057
2003	0.00153 - 0.00155	0.042 - 0.046	0.011 - 0.022	0.56 - 0.59	0.35 - 0.37	0.00153 - 0.00155	0.042 - 0.046
2004	0.00135 - 0.00137	0.031 - 0.035	0.012 - 0.026	0.55 - 0.58	0.37 - 0.39	0.00135 - 0.00137	0.031 - 0.035
2005	0.00102 - 0.00103	0.029 - 0.032	0.012 - 0.026	0.54 - 0.57	0.39 - 0.41	0.00102 - 0.00103	0.029 - 0.032
2006	0.00062 - 0.00062	0.027 - 0.031	0.012 - 0.024	0.50 - 0.53	0.43 - 0.45	0.00062 - 0.00062	0.027 - 0.031
2007	0.00057 - 0.00057	0.021 - 0.024	0.014 - 0.028	0.46 - 0.49	0.48 - 0.49	0.00057 - 0.00057	0.021 - 0.024
2008	0.00035 - 0.00036	0.019 - 0.021	0.014 - 0.029	0.43 - 0.46	0.51 - 0.52	0.00035 - 0.00036	0.019 - 0.021
2009	0.00062 - 0.00063	0.0152 - 0.017	0.023 - 0.047	0.40 - 0.44	0.52 - 0.53	0.00062 - 0.00063	0.0152 - 0.017
Mass fraction P2O5 or K2O	0.18 – 0.22	0.46 – 0.50	0.13 – 0.33	0.46 – 0.53	0.48 – 0.61	0.4 – 0.6	0.44

Table 23. Fertilizer filler ratios

Year	Fertilizer filler ratio*
1996	24%
1997	14%
1998	14%
1999	20%
2000	25%
2001	37%
2002	37%
2003	45%
2004	28%
2005	26%
2006	29%
2007	33%
2008	35%
2009	40%

Appendix G: Secondary applications data

Table 24. Secondary applications (lb/ acre)

Year	Gypsum	Sulfur	Sulfuric Acid	Zinc compound	Sewage Sludge
1996	0.0048	0.00036	0.00040	0.00011	0.00030
1997	0.0074	0.00048	0.00013	0.00014	0.00017
1998	0.0086	0.00051	0.00010	0.00014	0.00025
1999	0.0049	0.00062	0.00016	0.00016	0.00025
2000	0.0043	0.00051	0.00014	0.00015	0.00046
2001	0.0044	0.00049	0.00014	0.00013	0.00072
2002	0.0036	0.00054	0.00032	0.00010	0.00028
2003	0.0040	0.00053	0.00032	0.00012	0.00033
2004	0.0046	0.00095	0.00043	0.00014	0.00018
2005	0.0047	0.00075	0.00035	0.00013	0.00037
2006	0.0049	0.00069	0.00037	0.00021	0.00027
2007	0.0044	0.00076	0.00034	0.00016	0.00030
2008	0.0047	0.0019	0.00020	0.00013	0.00027
2009	0.0044	0.00048	0.00023	0.00010	0.00056

Appendix H: Pesticides applied

Table 25. Pesticides applied

CAS number	Average active ingredient mass %	Minimum active ingredient mass %	Maximum active ingredient mass %	Systematic name	Name used (for ecospold v1, name must be 36 characters or less to fit with the balance of name)
000009-47-7	22	0	100	2,4-D	2,4-D
000192-84-4	35	0	97	Acetic acid, (2,4-dichlorophenoxy)-, 2-ethylhexyl ester	2,4-D, 2-ethylhexyl ester
000200-83-1	19	0	97	Acetic acid, (2,4-dichlorophenoxy)-, compd. with N-methylmethanamine (1:1)	2,4-D, dimethylamine salt
000009-48-6	87	51	98	4-(2,4-Dichlorophenoxy)butyric acid	4-(2,4-Dichlorophenoxy)butyric acid
000275-84-1	22	1	27	Butoxone	Butoxone
005340-43-3	7	0	50	Dimethylamine 2-(2,4-dichlorophenoxy)propionate	Dichlorprop-dimethylammonium
010409-84-8	10	0	24	3-Pyridinecarboxylic acid, 2-(4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl)-5-methyl-, monoammonium salt, (.+-.)-	Imazapic
007175-14-2	13	0	98	Abamectin	Abamectin
003056-01-1	60	0	99	Acephate	Acephate
000008-68-2	21	0	98	1-Naphthaleneacetamide	1-Naphthaleneacetamide
013541-02-7	19	0	100	Acetamiprid	Acetamiprid
003425-68-1	48	7	97	Acetochlor	Acetochlor
005059-46-6	50	0	100	Acifluorfen	Acifluorfen
001597-26-8	31	0	96	Alachlor	Alachlor
000011-60-3	18	5	96	Aldicarb	Aldicarb
000083-41-8	64	0	98	Ametryn	Ametryn
003308-96-1	36	2	100	Amitraz	Amitraz
000191-22-9	37	8	97	Propachlor	Propachlor
000008-65-0	19	0	94	Azinphos-Methyl	Azinphos-Methyl
013186-03-8	18	0	96	Azoxystrobin	Azoxystrobin
000010-12-9	16	12	22	Barban	Barban
008305-59-6	20	0	99	Benzoic acid, 2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]methyl]-methyl ester	Bensulfuron-methyl
002505-78-0	99	99	99	Bentazon	Bentazon
000006-58-0	11	0	100	Benzoic acid	Benzoic acid

CAS number	Average active ingredient mass %	Minimum active ingredient mass %	Maximum active ingredient mass %	Systematic name	Name used (for ecospold v1, name must be 36 characters or less to fit with the balance of name)
008265-70-3	8	0	99	Bifenthrin	Bifenthrin
012540-19-5	71	18	98	Benzoic acid, 2,6-bis[(4,6-dimethoxy-2-pyrimidinyl)oxy]-, sodium salt	Bispyribac-sodium
000168-98-5	53	11	98	Bromoxynil	Bromoxynil
005663-49-8	32	2	97	Bromoxynil octanoate	Bromoxynil octanoate
000168-99-2	32	2	97	Bromoxynil octanoate	Bromoxynil octanoate
006932-77-0	55	25	99	4H-1,3,5-Thiadiazin-4-one, 2-{(1,1-dimethylethyl)imino}tetrahydro-3-(1-methylethyl)-5-phenyl-	Buprofezin
000009-48-4	56	1	99	2,4-dichlorophenoxyacetic acid, butyl ester	2,4-D-butyl
000007-56-5	5	0	65	Cacodylic acid	Cacodylic acid
000006-32-2	13	0	99	Carbaryl	Carbaryl
000156-36-2	19	0	95	Carbofuran	Carbofuran
012863-90-1	11	0	90	Benzenepropanoic acid, .alpha.-2-dichloro-5-{4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1H-1,2,4-triazol-1-yl}-4-fluoro-, ethyl ester	Carfentrazone-ethyl
005459-38-8	20	2	88	Chlorethoxyfos	Chlorethoxyfos
012245-37-0	21	1	97	1H-Pyrrole-3-carbonitrile, 4-bromo-2-(4-chlorophenyl)-1-(ethoxymethyl)-5-(trifluoromethyl)-	Chlorfenapyr
009098-23-4	20	3	98	Benzoic acid, 2-(((((4-chloro-6-methoxy-2-pyrimidinyl)amino)carbonyl)amino)sulfonyl)-, ethyl ester	Chlorimuron-ethyl
000189-74-6	41	0	99	Chlorothalonil	Chlorothalonil
000292-18-2	10	0	100	Chlorpyrifos	Chlorpyrifos
006490-27-3	52	9	98	Chlorsulfuron	Chlorsulfuron
009912-92-2	32	13	96	Clethodim	Clethodim
010551-20-9	42	6	98	Propanoic acid, 2-{4{(5-chloro-3-fluoro-2-pyridinyl)oxy}phenoxy}-, 2-propynyl ester	Clodinafop-propargyl
008177-78-1	31	3	90	Clomazone	Clomazone
000170-21-6	26	0	98	Clopyralid	Clopyralid
014715-03-4	58	8	98	Benzoic acid, 3-chloro-2-{{(5-ethoxy-7-fluoro{1,2,4}triazolo{1,5-c}pyrimidin-2-yl)sulfonyl}amino}-, methyl ester	Cloransulam-methyl
002042-75-2	36	0	96	Copper hydroxide	Copper hydroxide
000775-89-7	11	2	26	Copper sulfate (anhydrous)	Copper sulfate (anhydrous)
002172-54-2	61	10	97	Cyanazine	Cyanazine
011313-67-9	19	2	99	Cyclopropanecarboxylic acid, 1-(((2,4-dichlorophenyl)amino)carbonyl)-	Cyclanilide

CAS number	Average active ingredient mass %	Minimum active ingredient mass %	Maximum active ingredient mass %	Systematic name	Name used (for ecospold v1, name must be 36 characters or less to fit with the balance of name)
006835-93-5	10	0	99	beta-Cyfluthrin	beta-Cyfluthrin
012200-88-9	28	2	97	Cyhalofop-butyl	Cyhalofop-butyl
005231-50-8	27	0	99	Cypermethrin	Cypermethrin
005291-86-5	5	0	100	Cyclopropanecarboxylic acid, 3-(2,2-dibromoethenyl)-2,2-dimethyl-, cyano(3-phenoxyphenyl)methyl ester, (1R-(1.alpha.(S*),3.alpha.))-	Deltamethrin
000191-80-9	7	0	100	Dicamba	Dicamba
000230-06-5	9	0	100	Dimethylamine 3,6-dichloro-o-anisate	Dimethylamine 3,6-dichloro-o-anisate
001000-78-9	20	0	97	Benzoic acid, 3,6-dichloro-2-methoxy-, potassium salt	Dicamba-potassium
000198-26-0	55	23	92	Benzoic acid, 3,6-dichloro-2-methoxy-, sodium salt	Dicamba-sodium
005133-82-3	53	20	99	Diclofop-methyl	Diclofop-methyl
014570-12-9	91	84	97	(1,2,4)Triazolo(1,5-c)pyrimidine-2-sulfonamide, N-(2,6-dichlorophenyl)-5-ethoxy-7-fluoro-	Diclosulam
000011-53-2	11	0	95	Dicofol	Dicofol
000014-16-2	62	9	86	Dicrotophos	Dicrotophos
004986-68-7	50	0	100	Difenzoquat	Difenzoquat
003536-73-5	36	0	99	Diflubenzuron	Diflubenzuron
010929-39-3	35	17	93	3-Pyridinecarboxylic acid, 2-{1-{{{(3,5-difluorophenyl)amino}carbonyl}hydrozono}ethyl}-, monosodium salt	Diflufenzopyr-sodium
008767-46-8	55	25	97	Dimethenamid	Dimethenamid
016351-51-8	43	1	97	Acetamide,2-chloro-N-(2,4-dimethyl-3-thienyl)-N-(2-methoxy-1-methylethyl)-,(S)-	Dimethenamid-p
005529-06-7	50	22	98	Dimethipin	Dimethipin
000006-05-5	34	0	98	Dimethoate	Dimethoate
000029-80-4	6	0	98	Disulfoton	Disulfoton
000033-05-1	37	0	99	Diuron	Diuron
000014-42-8	27	1	81	Arsonic acid, methyl-, disodium salt, hexahydrate	Disodium methanearsonate
015556-99-8	30	0	97	Emamectin benzoate	Emamectin benzoate
000011-52-7	17	0	96	Endosulfan	Endosulfan
000014-57-3	25	7	80	Endothall	Endothall
000075-99-4	46	0	99	EPTC	EPTC
006623-00-4	4	0	99	Esfenvalerate	Esfenvalerate

CAS number	Average active ingredient mass %	Minimum active ingredient mass %	Maximum active ingredient mass %	Systematic name	Name used (for ecospold v1, name must be 36 characters or less to fit with the balance of name)
005528-36-6	46	10	96	Ethalfluralin	Ethalfluralin
001667-28-0	40	0	87	Ethephon	Ethephon
015323-39-1	43	5	97	Oxazole, 2-(2,6-difluorophenyl)-4-{4-(1,1-dimethylethyl)-2-ethoxyphenyl}-4,5-dihydro-	Etoxazole
000259-31-9	22	1	100	Benzene, pentachloronitro-	Benzene, pentachloronitro-
011315-84-0	50	0	100	Fenoxaprop P	Fenoxaprop P
006644-12-4	24	5	93	Fenoxaprop-ethyl	Fenoxaprop-ethyl
003951-54-8	36	1	92	Fenpropathrin	Fenpropathrin
012006-83-3	18	0	99	1H-Pyrazole-3-carbonitrile, 5-amino-1-(2,6-dichloro-4-(trifluoromethyl)phenyl)-4-((trifluoromethyl)sulfinyl)-	Fipronil
007924-14-6	8	0	93	Propanoic acid, 2-(4-((5-(trifluoromethyl)-2-pyridinyl)oxy)phenoxy)-, butyl ester, (R)-	Fluazifop-p-butyl
007962-25-6	68	40	97	2-Pyridinamine, 3-chloro-N-(3-chloro-2,6-dinitro-4-(trifluoromethyl)phenyl)-5-(trifluoromethyl)-	Fluazinam
018127-41-9	52	4	93	1H-1,2,4-Triazole-1-carboxamide,4,5-dihydro-3-methoxy-4-methyl-5-oxo-N-[[2-(trifluoromethoxy)phenyl]sulfonyl]-,sodium salt	Flucarbazone-sodium
009896-74-9	27	1	98	(1,2,4)Triazolo(1,5-a)pyrimidine-2-sulfonamide, N-(2,6-difluorophenyl)-5-methyl-	Flumetsulam
008754-61-7	39	1	99	Flumiclorac pentyl ester	Flumiclorac pentyl ester
010336-10-7	39	0	98	Flumioxazin	Flumioxazin
000216-41-2	65	13	97	Fluometuron	Fluometuron
006937-78-7	10	9	10	Acetic acid, ((4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy)-	Fluroxypyr
008140-63-3	20	0	99	Acetic acid, ((4-amino-3,5-dichloro-6-fluoro-2-pyridinyl)oxy)-, 1-methylheptyl ester	Fluroxypyr-meptyl
006633-29-5	51	2	98	Benzamide, N-(3-(1-methylethoxy)phenyl)-2-(trifluoromethyl)-	Flutolanil
007217-80-0	39	16	95	Sodium bentazon	Sodium bentazon
015806-26-0	53	23	98	Flonicamid	Flonicamid
000094-42-9	17	0	93	Phosphonodithioic acid, ethyl-, O-ethyl S-phenyl ester	Dyphonate
017315-95-4	37	2	99	N,N-Dimethyl-2-?3-(4,6-dimethoxypyrimidin-2-yl)ureidosulfonylU-4-formylaminobenzamide	Foramsulfuron
007670-36-3	11	0	99	gamma-Cyhalothrin	gamma-Cyhalothrin
007718-28-2	18	1	95	Butanoic acid, 2-amino-4-(hydroxy-methylphosphinyl)-, monoammonium salt	Glufosinate-ammonium
000107-18-6	70	1	99	Glyphosate	Glyphosate
006925-44-6	31	28	34	Glycine, N-(phosphonomethyl)-, diammonium salt	Glyphosate diammonium salt
003864-19-0	30	0	84	Glyphosate-isopropylammonium	Glyphosate-isopropylammonium

CAS number	Average active ingredient mass %	Minimum active ingredient mass %	Maximum active ingredient mass %	Systematic name	Name used (for ecospold v1, name must be 36 characters or less to fit with the balance of name)
007090-11-1	40	2	58	Glycine, N-(phosphonomethyl)- potassium salt	Glyphosate potassium salt
010078-42-1	52	0	99	1H-Pyrazole-4-carboxylic acid, 3-chloro-5-(((((4,6-dimethoxy-2-pyrimidinyl)amino)carbonyl)amino)sulfonyl)-1-methyl-, methyl ester	Halosulfuron-methyl
008140-58-8	61	27	90	Benzoic acid,2-(4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl)-4(or 5)-methyl-, methyl ester	Imazamethabenz
011431-13-9	31	3	97	3-Pyridinecarboxylic acid, 2-(4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl)-5-(methoxymethyl)-	Imazamox
008133-43-1	42	0	99	Imazapyr	Imazapyr
008133-53-7	26	1	98	Imazaquin	Imazaquin
008133-57-5	27	1	99	Imazethapyr	Imazethapyr
013826-14-3	22	0	100	Imidacloprid	Imidacloprid
017358-44-6	11	0	94	Indoxacarb	Indoxacarb
014111-22-0	31	3	98	Methanone,(5-cyclopropyl-4-isoxazolyl){2-(methylsulfonyl)-4-(trifluoromethyl)phenyl}-	Isoxaflutole
014570-12-1	14	0	99	[1,2,4] Triazolo [1,5-c] pyrimidine-2-sulfonamide, N-(2,6-difluorophenyl)-8- fluoro-5-methoxy-	Florasulam
007750-16-4	43	24	95	Lactofen	Lactofen
009146-50-6	11	0	98	Cyclopropanecarboxylic acid, 3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethyl-, cyano(3-phenoxyphenyl)methyl ester, {1.alpha.(S*),3.alpha.(Z)}-(.+-.)-	Lambda-cyhalothrin
000033-05-2	33	0	99	Linuron	Linuron
000012-17-5	28	0	100	Malathion (NO INERT USE)	Malathion
000009-47-6	48	0	97	MCPA	MCPA
000203-94-5	26	0	96	MCPA, dimethylamine salt	MCPA, dimethylamine salt
002945-04-1	53	0	98	Acetic acid, (4-chloro-2-methylphenoxy)-, 2-ethylhexyl ester	MCPA-2-ethylhexyl
002654-42-7	56	34	74	Acetic acid, (4-chloro-2-methylphenoxy)-, isooctyl ester	MCPA-isooctyl
000365-34-3	23	22	24	MCPA, sodium salt	MCPA, sodium salt
007063-01-0	16	0	97	D-Alanine, N-(2,6-dimethylphenyl)-N-(methoxyacetyl)-, methyl ester	Metalaxyl-M
002430-72-4	34	2	99	1,1-Dimethylpiperidinium chloride	1,1-Dimethylpiperidinium chloride
024573-59-4	10	10	10	Boric acid (H5B5O10), ion(1-), 1,1-dimethylpiperidinium (9CI)	Mepiquat pentaborate
020846-52-8	15	2	96	Mesosulfuron-methyl	Mesosulfuron-methyl
036540-01-9	19	2	99	Methanone, (5-hydroxy-1,3-dimethyl-1H-pyrazol-4-yl) [2-(methylsulfonyl)-4-(trifluoromethyl) phenyl]-	Pyrasulfotole

CAS number	Average active ingredient mass %	Minimum active ingredient mass %	Maximum active ingredient mass %	Systematic name	Name used (for ecospold v1, name must be 36 characters or less to fit with the balance of name)
010420-68-8	23	0	96	Mesotrione	Mesotrione
005783-71-1	15	0	99	Metalaxyl	Metalaxyl
000013-74-8	35	18	45	Sodium N-methyldithiocarbamate	Sodium N-methyldithiocarbamate
001026-59-6	46	3	72	Methamidophos	Methamidophos
001675-27-5	15	0	99	Methomyl	Methomyl
000029-80-0	30	0	84	Methyl parathion	Methyl parathion
005121-84-2	51	0	98	Propazine	Propazine
002108-76-9	49	0	98	1,2,4-Triazin-5(4H)-one, 4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-	Metribuzin
007422-36-6	44	0	99	Metsulfuron-methyl	Metsulfuron-methyl
000221-26-1	30	1	96	Molinate	Molinate
002135-13-3	73	59	79	Urea, sulfate (1:1)	Urea, sulfate
000216-38-6	38	0	59	Arsonic acid, methyl-, monosodium salt	MSMA
000030-07-5	20	0	95	Naled	Naled
011199-10-4	55	1	98	Nicosulfuron	Nicosulfuron
002731-41-2	62	5	98	Norflurazon	Norflurazon
011671-44-6	15	0	99	Benzamide, N-[[[3-chloro-4-[1,1,2-trifluoro-2-(trifluoromethoxy)ethoxy]phenyl]amino]carbonyl]-2,6-difluoro-	Novaluron
002313-52-0	20	10	42	Oxamyl	Oxamyl
004287-40-3	25	0	99	Oxyfluorfen	Oxyfluorfen
000191-04-5	29	0	46	1,1'-Dimethyl-4,4'-bipyridinium dichloride	Paraquat dichloride
000008-26-8	22	1	100	Benzene, pentachloronitro-	Benzene, pentachloronitro-
004048-74-1	24	0	97	Pendimethalin	Pendimethalin
005264-55-1	8	0	99	Permethrin, mixed cis,trans	Permethrin, mixed cis,trans
000800-20-9	59	0	100	Aliphatic petroleum hydrocarbons	Aliphatic petroleum hydrocarbons
000029-80-2	15	0	95	Phorate	Phorate
000191-80-1	47	0	97	Picloram	Picloram
024397-32-8	22	5	98	Propanoic acid, 2,2-dimethyl-, 8-(2,6-diethyl-4-methylphenyl)-1,2,4,5-tetrahydro-7-oxo-7H-pyrazolo[1,2-d] [1,4,5]oxadiazepin-9-yl ester	Pinoxaden
008620-95-0	55	8	99	Primisulfuron-methyl	Primisulfuron-methyl
004119-	75	60	91	Profenofos	Profenofos

CAS number	Average active ingredient mass %	Minimum active ingredient mass %	Maximum active ingredient mass %	Systematic name	Name used (for ecospold v1, name must be 36 characters or less to fit with the balance of name)
80-7					
000728-71-6	64	8	97	Prometryn	Prometryn
000070-99-8	51	10	99	Propanil	Propanil
000231-23-8	47	3	95	Propargite	Propargite
006020-79-1	24	0	99	1H-1,2,4-Triazole, 1-((2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl)methyl)-	Propiconazole
018127-41-7	42	5	95	Benzoic acid, 2-[[[(4,5-dihydro-4-methyl-5-oxo-3-propoxy-1H-1,2,4-triazol-1-yl)carbonyl]amino]sulfonyl]-,methyl ester, sodium salt	Propoxycarbazone-sodium
009412-53-5	39	2	96	Benzenesulfonamide, N-(((4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino)carbonyl)-2-(3,3,3-trifluoropropyl)-	Prosulfuron
017892-87-6	21	1	98	3H-1,2,4-Triazole-3-thione, 2-[2-(1-chlorocyclopropyl)-3-(2-chlorophenyl)-2-hydroxypropyl]-1,2-dihydro-	Prothioconazole
017501-31-0	20	0	98	Carbamic acid, [2-[[[1-(4-chlorophenyl)-1H-pyrazol-3-yl]oxy]methyl]phenyl]methoxy-, methyl ester	Pyraclostrobin
012963-01-9	12	0	98	Pyraflufen-ethyl	Pyraflufen-ethyl
005551-23-9	59	44	91	Pyridate	Pyridate
015011-47-9	49	2	95	2-Pyridinecarboxylic acid, 4-amino-3,6-dichloro-	Aminopyralid
009573-76-1	3	0	99	Pyridine, 2-(1-methyl-2-(4-phenoxyphenoxy)ethoxy)-	Pyriproxyfen
012334-31-8	54	2	97	Pyrithiobac-sodium	Pyrithiobac-sodium
008408-70-4	31	0	98	8-Quinolinecarboxylic aicd, 3,7-dichloro-	Quinclorac
007657-81-8	50	0	100	Use code no. 128711	Quizalofop, ethyl
012293-14-0	27	1	99	Rimsulfuron	Rimsulfuron
008739-21-9	49	16	96	S-Metolachlor	S-Metolachlor
007405-18-2	20	11	50	Sethoxydim	Sethoxydim
000012-23-9	29	0	46	1,1'-Dimethyl-4,4'-bipyridinium dichloride	Simazine
000777-50-9	31	2	100	Sodium chlorate	Sodium chlorate
016831-69-8	16	0	90	2-{(6-Deoxy-2,3,4-tri-O-methyl-alpha-L-mannopyranosyl)oxy}-13-{{5-(dimethylamino)tetrahydro-6-methyl-2H-pyran-2-yl}oxy}-9-ethyl-2,3,3a,5a,5b,6,9,10,11,12,13,14,16a,16b-tetradecahydro-14-methyl-1H-as-Indaceno{3,2-d}oxacyclododecin-7,15-dione,(Cont'd Qual	Spinosad
012283-63-5	16	0	91	Sulfentrazone	Sulfentrazone
008159-18-3	51	40	58	Glycine, N-(phosphonomethyl)-, ion(1-), trimethylsulfonium	Glyphosate-trimesium
014177-63-1	62	24	98	Imidazol{1,2-a}pyridine-3-sulfonamide, N-{{(4,6-dimethoxy-2-pyrimidinyl)amino}carbonyl}-2-(ethylsulfonyl)-	Sulfosulfuron

CAS number	Average active ingredient mass %	Minimum active ingredient mass %	Maximum active ingredient mass %	Systematic name	Name used (for ecospold v1, name must be 36 characters or less to fit with the balance of name)
000770-43-9	55	0	100	Sulfur	Sulfur
010753-49-3	28	0	99	1H-1,2,4-Triazole-1-ethanol, .alpha.-(2-(4-chlorophenyl)ethyl)-.alpha.-(1,1-dimethylethyl)-, (+-),	Tebuconazole
011241-02-8	54	23	99	Tebufenozide	Tebufenozide
009618-25-5	21	2	93	Phosphorothioic acid, O-{2-(1,1-dimethylethyl)-5-pyrimidinyl} O-ethyl O-(1-methylethyl) ester	Tebupirimfos
007953-83-2	25	2	94	Tefluthrin	Tefluthrin
001307-17-9	36	15	89	Terbufos	Terbufos
015371-92-4	21	0	99	4H-1,3,5-Oxadiazin-4-imine, 3-[(2-chloro-5-thiazolyl)methyl]tetrahydro-5-methyl-N-nitro-	Thiamethoxam
005170-75-2	46	8	99	Thidiazuron	Thidiazuron
007922-72-3	42	0	98	Thifensulfuron methyl	Thifensulfuron methyl
002824-97-6	43	10	97	Thiobencarb	Thiobencarb
005966-92-0	47	2	95	Thiodicarb	Thiodicarb
008782-08-0	60	35	84	2-Cyclohexen-1-one, 2-{1-(ethoxyimino)propyl}-3-hydroxy-5-(2,4,6-trimethylphenyl)-	Tralkoxydim
006684-12-6	5	0	100	Cyclopropanecarboxylic acid, 3-(2,2-dibromoethenyl)-2,2-dimethyl-, cyano(3-phenoxyphenyl)methyl ester, (1R-(1.alpha.(S*),3.alpha.))-	Tralomethrin
000230-31-5	33	10	96	S-(2,3,3-Trichloroallyl) diisopropylthiocarbamate	Tri-allate
008209-75-5	58	9	92	Benzenesulfonamide, 2-(2-chloroethoxy)-N-(((4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino)carbonyl)-	Triasulfuron
010120-04-0	38	2	98	Tribenuron-methyl	Tribenuron-methyl
000007-84-8	78	71	100	Easy Off-D	Tribufos
005533-50-3	76	29	99	Triclopyr	Triclopyr
014151-72-7	20	0	98	Benzeneacetic acid,.alpha.-(methoxyimino)-2-{{{{1-{3-(trifluoromethyl)phenyl}ethylidene}amino}oxy}methyl}-, methyl ester, (E,E)-	Trifloxystrobin
029033-21-4	61	1	94	2-Pyridinesulfonamide, N-[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]-3-(2,2,2-trifluoroethoxy)-, monosodium salt, monohydrate	Trifloxysulfuron-sodium
000158-20-8	21	0	99	Trifluralin	Trifluralin
000192-97-7	37	1	96	Carbamothioic acid, dipropyl-, S-propyl ester	Vernolate
137497-61-1	7	0	88	Zeta-Cypermethrin	Zeta-Cypermethrin

* When no active ingredient data were found, the range was assumed to be 0-100%

Appendix I: Applications transport distances

Table 26. Applications transport distances

	Parameter description	**Distance (miles)**
international vessel transport; average fuel	N fertilizer	3522
	P fertilizer	4200
	K fertilizer	3900
	pesticide and secondary applications (except lime and gypsum)	4000
domestic barge transport; average fuel	synthetic fertilizer, pesticide, and secondary applications (except lime and gypsum)	400
bulk cargo rail transport; diesel	synthetic fertilizer, pesticide, and secondary applications (except lime and gypsum)	750
regional or national trucking; class 8, average fuel	seed transport	50
	synthetic fertilizer, pesticide, and secondary applications (except lime and gypsum)	50
	lime and gypsum	50
	pesticide and other secondary applications transport, regional truck (miles)	50
local area trucking; class 6, average fuel	manure and sewage sludge	Estimated from ARMS by dataset
	synthetic fertilizer, pesticide, and secondary applications (except lime and gypsum)	30

Appendix J: Residue burning data

Table 27. Fraction of planted area burned

		Average area burned/ planted area	Maximum area burned/ planted area
Corn	Colorado	1.8E-03	6.6E-03
	Georgia	2.4E-03	3.8E-03
	Illinois	6.9E-04	1.2E-03
	Indiana	1.1E-03	2.0E-03
	Iowa	1.2E-03	2.0E-03
	Kansas	3.0E-04	5.6E-04
	Kentucky	4.8E-04	1.4E-03
	Michigan	2.2E-03	4.8E-03
	Minnesota	1.3E-03	2.9E-03
	Missouri	3.6E-03	7.6E-03
	Nebraska	2.3E-03	3.4E-03
	New York	2.8E-03	6.6E-03
	North Carolina	1.0E-03	2.8E-03
	North Dakota	3.5E-03	6.9E-03
	Ohio	1.3E-03	2.9E-03
	Pennsylvania	1.5E-03	3.0E-03
	South Carolina	6.0E-04	1.2E-03
	South Dakota	4.6E-03	1.6E-02
	Texas	2.9E-03	5.8E-03
	Wisconsin	2.3E-03	4.0E-03
Cotton	Alabama	2.4E-03	5.3E-03
	Arizona	3.9E-02	4.8E-02
	Arkansas	3.5E-02	6.7E-02
	California	9.7E-03	1.7E-02
	Georgia	1.4E-03	2.3E-03
	Louisiana	1.1E-02	2.6E-02
	Mississippi	4.5E-03	1.6E-02
	Missouri	7.1E-03	1.7E-02
	North Carolina	3.4E-03	6.1E-03
	South Carolina	3.3E-03	5.9E-03
	Tennessee	6.6E-04	1.6E-03
	Texas	7.1E-03	1.6E-02
Oats	Illinois	0.0E+00	2.2E-02
	Iowa	6.3E-04	3.7E-01
	Kansas	4.1E-03	1.3E-02

		Average area burned/ planted area	**Maximum area burned/ planted area**
Oats (cont.)	Michigan	9.6E-03	1.7E-02
	Minnesota	1.7E-04	1.8E-02
	Nebraska	3.2E-04	3.4E-03
	New York	1.6E-03	9.3E-03
	North Dakota	7.3E-03	1.0E-02
	Pennsylvania	6.0E-04	1.6E-02
	South Dakota	1.8E-03	2.9E-02
	Texas	9.4E-04	4.4E-01
	Wisconsin	0.0E+00	2.4E-02
Peanuts	Alabama	2.8E-03	1.1E-01
	Florida	3.2E-02	1.0E+00
	Georgia	9.3E-04	3.6E-02
	North Carolina	5.5E-03	2.0E-02
	Texas	9.4E-04	4.4E-01
Rice	Arkansas	6.4E-02	1.2E-01
	California	1.7E-01	2.9E-01
	Louisiana	2.3E-02	3.3E-02
	Mississippi	2.6E-02	5.1E-02
	Missouri	3.6E-02	7.0E-02
	Texas	2.7E-01	4.4E-01
Soybeans	Arkansas	3.3E-03	7.6E-03
	Illinois	6.7E-04	1.3E-03
	Indiana	1.7E-03	2.5E-03
	Iowa	1.3E-03	2.7E-03
	Kansas	4.0E-03	1.1E-02
	Kentucky	1.3E-03	2.3E-03
	Louisiana	3.6E-03	1.7E-02
	Maryland	2.0E-03	3.1E-03
	Michigan	3.4E-03	6.7E-03
	Minnesota	1.3E-03	2.2E-03
	Mississippi	5.9E-03	1.2E-02
	Missouri	3.6E-03	8.1E-03
	Nebraska	1.7E-03	3.3E-03
	North Carolina	6.7E-04	1.6E-03
	North Dakota	2.2E-04	5.2E-04
	Ohio	2.0E-03	3.5E-03
	Pennsylvania	5.1E-03	9.7E-03
	South Dakota	1.6E-03	3.0E-03
	Tennessee	3.5E-03	6.0E-03

		Average area burned/ planted area	**Maximum area burned/ planted area**
Soybeans (cont.)	Virginia	2.6E-03	3.3E-03
	Wisconsin	6.8E-03	1.3E-02
Wheat	Arkansas	1.9E-01	4.0E-01
	California	1.3E-01	2.0E-01
	Colorado	1.8E-02	2.3E-02
	Delaware	1.0E-02	3.2E-02
	Georgia	2.2E-02	3.6E-02
	Idaho	1.2E-01	2.0E-01
	Illinois	1.1E-02	2.2E-02
	Kansas	9.1E-03	1.3E-02
	Kentucky	5.1E-03	9.1E-03
	Louisiana	1.5E-01	2.3E-01
	Michigan	6.6E-03	1.7E-02
	Minnesota	7.6E-03	1.8E-02
	Mississippi	9.9E-02	1.6E-01
	Missouri	3.2E-02	5.3E-02
	Montana	9.4E-03	1.3E-02
	Nebraska	1.6E-03	2.5E-03
	North Carolina	1.5E-02	2.0E-02
	North Dakota	7.0E-03	1.0E-02
	Ohio	1.0E-02	2.0E-02
	Oklahoma	1.3E-02	2.0E-02
	Oregon	5.1E-02	7.5E-02
	Pennsylvania	5.1E-03	1.6E-02
	South Dakota	1.7E-02	2.9E-02
	Texas	1.2E-02	1.7E-02
	Washington	6.3E-02	1.1E-01

Table 28. Residue burning emission factors

		corn		cotton		oats		peanuts		rice		soybeans		wheat	
		mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev	mean	stdev
Methane (CH4)*	g/kg	2.2	0.49	3.3	1.0	2.8	1.5	2.8	1.5	2.1	0.94	3.2	1	2.1	1.2
Carbon monoxide (CO)*	g/kg	53	24	73	15	64	26	64	26	53	28	69	25	55	22
PM2.5*	g/kg	5.0	0.93	6.2	3.2	6.2	3.1	6.2	3.1	5.8	4.8	6.2	3.2	4.0	1.5
PM10*	g/kg	11	10	8.9		8.5	4.9	8.5	4.9	3.3	0.22	8.9		6.6	3.0
Nitrogen Dioxide (NO2)*	g/kg	2.3	1.6	3.4	1.6	2.8	1.3	2.8	1.3	3.1	1.3	3.2	1.4	2.0	0.83
Sulfur dioxide (SO2)*	g/kg	1.2	1.9	1.6	2.1	1.2	1.4	1.2	1.4	1.4	1.7	1.6	2.1	0.44	0.040
Dinitrogen monoxide (N2O)**	g/kg	0.07 for all crops													
NMVOC, identified***	g/kg	Mean of 26 and stdev of 9.8 for all crops													
NMVOC, unidentified ***	g/kg	Mean of 26 and stdev of 9.8 for all crops													
PCDD/F****	ug TEQ/t to air	30 for all crops													
PCDD/F****	ug TEQ/t to land	10 for all crops													

* From (McCarty 2011)

** From (IPCC 2006)

*** From (Akagi et al. 2011)

****From (United Nations Environmental Programme 2001)

Table 29. Residue burning NMVOC constituents (all crops)

	Mean (g/kg)	stdev
Ethylene (C2H4)	1.5E+00	5.9E-01
Ethane (C2H6)	9.1E-01	4.9E-01
Acetic Acid (CH3COOH)	5.6E+00	2.6E+00
Formaldehyde (HCHO)	2.1E+00	8.4E-01
Methanol (CH3OH)	3.3E+00	1.4E+00
Acetaldehyde (CH3CHO)	1.2E+00	2.8E-01
Formic Acid (HCOOH)	1.0E+00	4.9E-01
Acetylene (C2H2)	2.7E-01	7.9E-02
Phenol (C6H5OH)	5.2E-01	1.4E-01
Acetol (C3H6O2)	3.8E+00	9.1E-01
Glycolaldehyde (C2H4O2)	2.0E+00	3.8E-01
Propylene (C3H6)	6.8E-01	3.7E-01
Methyl Vinyl Ether (C3H6O)	7.6E-02	1.2E-02
Furan (C4H4O)	1.1E-01	4.2E-02
Acetone (C3H6O)	4.5E-01	7.1E-02
Benzene (C6H6)	1.5E-01	3.5E-02
Toluene (C6H5CH3)	1.9E-01	6.2E-02
Propane (C3H8)	2.8E-01	1.5E-01
1,3 Butadiene (C4H6)	1.5E-01	7.2E-02
1-Butene (C4H8)	1.3E-01	6.0E-02
Isoprene (C5H8)	3.8E-01	1.6E-01
i-Butane (C4H10)	2.5E-02	1.3E-02
n-Butane (C4H10)	7.2E-02	3.6E-02
trans-2-Butene (C4H8)	5.7E-02	3.0E-02
cis-2-Butene (C4H8)	4.3E-02	2.3E-02
i-Butene (C4H8)	1.2E-01	6.0E-02
i-Pentane (C5H12)	2.0E-02	1.2E-02
n-Pentane (C5H12)	2.5E-02	1.2E-02
Cyclopentane (C5H10)	1.9E-03	1.2E-03
Hydrogen Cyanide (HCN)	2.9E-01	3.8E-01
Ammonia (NH3)	2.2E+00	1.3E+00
Acetonitrile (CH3CN)	2.1E-01	6.2E-02
Propenenitrile (C3H3N)	3.4E-02	1.8E-03
Propanenitrile (C3H5N)	6.2E-02	1.8E-03

Appendix K: Sewage sludge constituents

Table 30. Sewage sludge constituents (all crops)

	minimum DM%	**maximum DM%**
nitrogen	4%	20%
phosphorous	0.31%	2.5%
carbon	77%	94%

Appendix L: Manure data

Table 31. Constituents of excreted manure (kg/kg TS)

	Moist. Fract.	VS	N	P	K
MIN.					
Beef	8.8E-01	8.1E-01	2.9E-02	6.7E-03	2.1E-02
Dairy	8.3E-01	9.0E-01	3.2E-02	5.4E-03	1.2E-02
Poultry	7.4E-01	5.9E-01	3.6E-02	1.2E-02	1.8E-02
Hog	9.0E-01	8.0E-01	6.4E-02	1.4E-02	3.3E-02
MAX.					
Beef	9.2E-01	8.9E-01	6.9E-02	9.3E-03	4.8E-02
Dairy	9.6E-01	9.2E-01	1.3E-01	3.8E-02	1.7E-01
Poultry	7.5E-01	8.0E-01	7.3E-02	2.2E-02	2.8E-02
Hog	as min	9.0E-01	8.5E-02	2.6E-02	4.6E-02

Data are from the American Society of Agricultural and Biological Engineers (ASABE, 2010), the North Carolina State University (at http://www.bae.ncsu.edu/programs/extension/manure/awm/program/barker/a&pmp&c/content.htm) and Kirchmann and Witter (1992).

Table 32. Manure housing and storage losses

Loss	single value	minimum value	maximum value
cattle N loss in housing facilities		2.0%	90%
poultry N loss in housing facilities		4.0%	70%
hog N loss in housing facilities		15%	60%
unspecified animal N loss in housing facilities		2.0%	90%
cattle N losses for solid or semi-solid storage		10%	50%
hog N losses for solid or semi-solid storage		10%	50%
poultry N losses for solid or semi-solid storage		5.0%	50%
unspecified animal N losses for solid or semi-solid storage		5.0%	50%
N losses in slurry tanks		2.0%	35%
N losses in anaerobic lagoon		50%	99%
N storage losses unspecified manure form		2.0%	99%
P and K losses from excretion to field	5.0%		
cattle anaerobic C losses from excretion to field	20%		
poultry anaerobic C losses from excretion to field	44%		
hog anaerobic C losses from excretion to field	26%		
unspecified animal C losses from excretion to field		20%	58%
cattle aerobic C losses from excretion to field	28%		
poultry aerobic C losses from excretion to field	58%		
hog aerobic C losses from excretion to field	51%		

Data are from Rotz (Rotz 2004), Borton et al. (1995), and the Integrated Farm System Model (IFSM at http://www.ars.usda.gov/main/docs.htm?docid=851)