Documentation of the WAEES Global Agricultural and Biofuels Partial Equilibrium Modeling System

THIS IS A WORKING DOCUMENT THAT CONTINUES TO EVOLVE WITH THE WAEES MODEL

PREPARED BY:

JOHN R. KRUSE, PHD

Website: www.waees-llc.com

Summer 2020

World Agricultural Economic and Environmental Services

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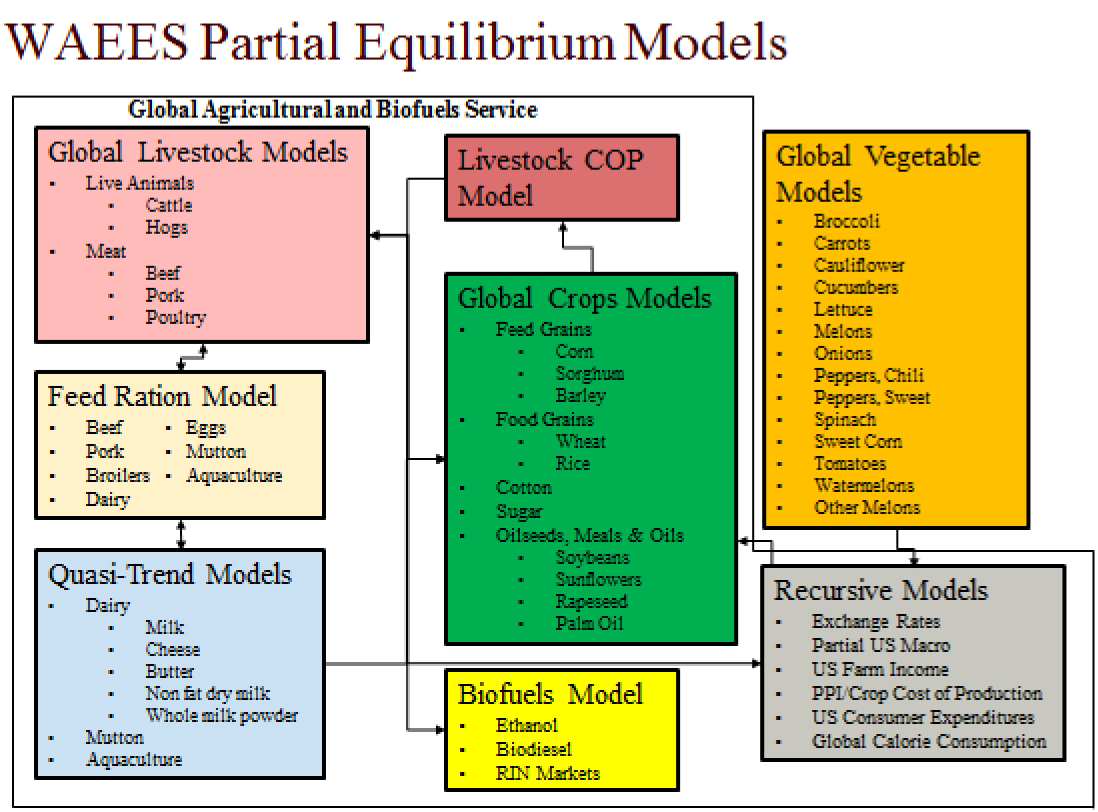
Introduction

This documentation is designed to discuss the non-proprietary portions of the WAEES Global Agricultural and Biofuel model. This documentation is intended to provide a general overview of the type of specifications used in the WAEES models. Some aspects of the model are discussed in detail while the proprietary portions of the model are not discussed. WAEES' researchers are always testing new specifications looking for models that simulate reality as close as possible so this documentation is continuously changing and often slips behind.

Commodity Coverage

The WAEES partial equilibrium modeling system is made up of a set of global econometric models emulating the behavior of the global agricultural sector. The partial equilibrium models can be broken down into crops, livestock and biofuels components encompassing feed grains, food grains, cotton, sugar, oilseeds, ethanol, biomass-based diesel, beef, pork, and poultry. Dairy and dairy products, mutton, and aquaculture are also covered in the global agricultural forecast but function as quasi-trend models rather than full partial equilibrium models.



Geographic Coverage

The WAEES models cover 48 countries/regions with an additional 12 regional aggregates including the world total. WAEES follows USDA's reported data coverage which may mean that a zero is reported for a particular commodity which USDA does not cover or has discontinued covering. USDA currently covers at least 90 percent of global production; therefore, the countries which are omitted represent a small portion of total global production. Specifically the WAEES model includes Canada, Mexico, the United States, Caribbean and Central America, Argentina, Brazil, Bolivia, Chile, Colombia, Paraguay, Uruguay, Other South America, the European Union 28, Other Europe, Kazakhstan, Russia, Ukraine, Uzbekistan, Other Former Soviet Union, Iran, Saudi Arabia, Turkey, Other Middle East, China, Japan, South Korea, Taiwan, Other East Asia, Bangladesh, India, Pakistan, Other South Asia, Indonesia, Malaysia, Myanmar, Philippines, Thailand, Vietnam, Other Southeast Asia, Australia, Other Oceania, Egypt, Morocco, Other North Africa, Kenya, Nigeria, South Africa, and Other Sub-Saharan Africa. WAEES also reports projections on crop area, yield and production for each of the EU-28 countries.

History of the WAEES Models

The WAEES global partial equilibrium model was first introduced in 2011 by Dr. John Kruse. Leveraging 20 years of previous modeling experience at the Food and Agricultural Policy Research Institute (FAPRI) and other employers, Dr. Kruse developed a new system of partial equilibrium models focused on agriculture and biofuels. Dr. Kruse's experience was heavily influenced by Dr. Abner Womack, Dr. Jimmy Mathews, Dr. Pat Westhoff, Dr. Gary Adams, Dr. Scott Brown, Dr. Jon Brandt, Dr. Ken Bailey, Dr. Willi Meyers, Dr. Steve Fuller, Dr. Abraham Subotnik, Dr. David Mandy, the work of Dr. James Houck, and the work of Dr. Vernon Roningen.

The WAEES team has had the privilege of previously working with many different types of models including the FAPRI system, the FAO's and OECD's Aglink – Cosimo model, a variety of USDA models, the IFPRI models, and several others. The experience with these systems and their capabilities influenced the design and development of the WAEES models.

Aside from the usual maintenance and updates of partial equilibrium model functionality, much of the WAEES model development has been driven by our private sector client priorities. Since 2011, some of the changes in the WAEES models include:

- expanding coverage from 40 to 48 countries and regions,
- enhanced capabilities to trace consumer expenditures on food and track calories, fats, proteins, and carbohydrates delivered to consumers,
- updates to changes in domestic and trade policies across the globe,
- enhanced biofuel models that track nearly all feedstock sources and distinguish methyl ester and renewable diesel sources,

- addition of the California Low Carbon Fuel Standard policy,
- addition of an enhanced livestock feed modeling system,
- improved solution algorithms that speed up the model solution process,
- the addition of fruit and vegetable commodities, and
- ongoing maintenance and update of equations' elasticities to ensure system performance.

The WAEES models are first and foremost economic models and are designed to serve the spirit of economic theory. Our emphasis is not econometric perfection, but ensuring the models can simulate the agricultural and biofuels sector well. We spend a lot of time and resources in continuously re-engineering the models and we maintain a very transparent model interface to facilitate the process. We spend as much time developing a complete understanding of the structure and functioning of a market as we do in assembling the data and developing the equations that emulate the market's behavior.

Data Sources

WAEES uses USDA's Production, Supply and Distribution (PSD) database for international data on quantities of supply and demand by type. The PSD database does not cover every commodity in every country, but captures at least 90 percent of global production for each commodity. PSD data is supplemented with data from the local country's Ministries of Agriculture (MOA) or their equivalent. For the most part, the MOA's are used to provide data on commodity prices, commodity costs of production, and agricultural policies. PSD data is also supplemented with data from the United Nations' Food and Agricultural Organization (FAO) which maintains a database called FAOSTAT. FAOSTAT is used to fill in data for countries where USDA reports zeros or has reported the same data values for a period of years. WAEES also uses some of the monthly spot commodity prices reported by FAO. Policy and tariff data are collected from the World Trade Organization, USDA's GAIN reports, and special OECD studies. International biofuels data is gathered from USDA's GAIN reports and local MOA's or local government statistical services.

Structure and Specification of the WAEES Models

General Overview of Model Structure

Partial equilibrium models function by solving for the commodity price that balances supply and demand. The WAEES models are structural in the sense that they are designed to emulate the structure of the markets they describe based on the data available. The structure of the market typically refers to the components that make up supply and demand subject to the biological lags in the production process. In the case of crops, the components of supply are typically production, imports, and beginning stocks with production calculated as the product of area and yield. The components of demand vary by crop commodity and may include food use, industrial use, feed and residual use, exports, and ending stocks. The typical market clearing condition determining price is then given by:

Beginning Stocks + Production + Imports = Food Use + Industrial Use + Feed & Residual Use + Exports + Ending Stocks

Some countries report more detailed breakouts of demand components for crops allowing more detailed analysis. For example, biofuels may be reported separately from other industrial uses. In the case of oilseeds, the meal and oil derivatives of the crushing process form important new commodities with their own market clearing conditions determining prices.

In the case of livestock, the market levels are more explicitly modeled with market clearing conditions at each level. Typically, the three levels are captured including the farm level (live animal or animal product production), the wholesale level (slaughter or processing facilities), and the retail level (consumer). Animals demanded for slaughter at the farm level become the supply of meat carcasses at the wholesale level. Wholesale carcass demand becomes the production of specific meat cuts at the retail level. The three market clearing conditions are given by:

Farm Level

Beginning Inventory + Production + Imports = Slaughter + Death Loss + Exports + Ending Inventory

Wholesale Level

Carcass Production = Carcass Demand

Retail Level

Beginning Stocks + Production + Imports = Consumption + Exports + Ending Stocks

Commodity prices are determined at each of the three levels based on supply and demand conditions. In the case of beef, the retail beef price represents the retail price, the price of boxed beef represents the wholesale price, and the price of steers and heifers represents the farm level price.

General Overview of Model Specifications

The structural models for each commodity are composed of behavioral (estimated) equations and identities. The behavioral equation specifications are theoretically derived based upon the behavioral postulates from the economic theories of firm profit maximization and consumer utility maximization. The model includes various domestic and international trade policies not detailed in the general specifications below.

In the specifications outlined below, the general specifications for each model module are presented. Each module includes identities, behavioral (estimated) equations, and a global market clearing condition which requires global supply to be equal to global demand. The identities are used to establish the relationship between the behavioral supply and demand equations with the end goal of constructing total supply and total demand. The behavioral equations are the key functional area of the model. These equations simulate how supply and demand for each commodity respond to changes in their key drivers. The structural specifications of these equations are derived from economic theory and consider "real world" constraints including biological constraints in the production process.

Detailed econometric equations capture the supply and demand components of each commodity in each country or region. The equations can be grouped into identities, behavioral equations, and market clearing equations. The basic structure and simplified specifications are outlined below by major commodity groups. In may be easier to understand why the equations are structured as they are if we describe the process using the concept of a residual supplier. One country is chosen to be the residual supplier. The choice of country to be the residual supplier does not technically matter but it is usually a large exporting country with minimal trade barriers. In the specifications below, one will notice that there are price linkage equations for the non-residual supplying countries that link to a world price which is technically the port price of the residual supplying country. The port price in the residual supplying country may have a linkage equation to a spot market or farm price. It is the spot market or farm price that the model solves for in the residual supplying country based on an initial assumption regarding net trade. The initial assumption is replaced by the aggregation of net trade positions across all other countries as the model iteratively solves for the price that balances supply and demand. Note that many of the specific nuances of the WAEES model are omitted in order to protect the proprietary details of the WAEES model.

Oilseeds, Oils, and Meals

Includes soybeans, soybean meal, soybean oil, sunflowers, sunflower meal, sunflower oil, rapeseed, rapeseed meal, rapeseed oil, palm oil.

Identities:

Beginning Stocks = Ending stocks $_{(t-1)}$ *(Oilseeds, Meals and Oils)*
*Production = Harvested Area * Yield* *(Oilseeds)*
*Production = Crush * Crushing Yield* *(Meals and Oils)*
Historical Crushing Yield = Product Production/Crush *(Meals and Oils)*
Projected Crushing Yield = Crushing Yield$_{t-1}$ *(Meals and Oils)*
Domestic Use = Crush + Food Use + Other Use *(Oilseeds)*
Domestic Use = Food Use + Feed Use + Industrial Use *(Meals and Oils)*
Total Supply = Beginning Stocks + Production + Imports *(Oilseeds, Meals and Oils)*
Total Demand = Domestic Use + Exports + Ending Stocks *(Oilseeds, Meals and Oils)*
For the non-Residual Supplying Countries
Net Exports = Ending Stocks$_{t-1}$ + Production + Imports – Domestic Demand – Ending Stocks *(Oilseeds, Meals and Oils)*

Behavioral Equations:

Preferred Approach:
Harvested Area = f(Deflated Expected Own Net Returns, Deflated Expected Cross Net Returns, Harvested Area$_{t-1}$) *(Oilseeds)*
Alternative Approaches:
Harvested Area = f(Deflated Expected Own Gross Returns, Deflated Expected Cross Gross Returns, Harvested Area$_{t-1}$) *(Oilseeds)*
Harvested Area = f(Deflated Own Price, Deflated Competing Crop Prices, Harvested Area$_{t-1}$) *(Oilseeds)*

Yield = f(Technology Trend) *(Oilseeds)*
Crush = f(Value of Meal and Oil Products, Value of Oilseed, Crush$_{t-1}$) *(Oilseeds)*
Feed, Seed, & Residual Use = f(Deflated Own Price, Soybean Production) *(Oilseeds)*
Feed Use = f(Deflated Own Price, Deflated Competing Prices, Livestock Protein Feed Requirement) *(Meals)*
Per Capita Food Use = f(Deflated Own Price, Real GDP Per Capita) *(Oilseeds, Meals)*
Per Capital Food Use = f(Deflated Own Price, Deflated Competing Prices, Real GDP Per Capita) *(Oils)*
Industrial Use = f(Deflated Own Price, Biodiesel Use, Trend) *(Oils)*
Ending Stocks = f(Deflated Own Price, Ending Stocks$_{t-1}$) *(Oilseeds, Meals, and Oils)*

For the non-Residual Supplying Countries
Price = f(World Price, Tariffs, Exchange Rates, etc.) *(Oilseeds, Meals, and Oils)*
Other price linkage equations
Farm or Spot Price = f(Port price, transportation costs, export tariffs) *(Oilseeds, Meals, and Oils)*

Global Market Clearing Condition

World Total Demand = World Total Supply *(Oilseeds, Meals, and Oils)*
Each crop has a global market clearing condition that determines world prices for soybeans, soybean meal, soybean oil, sunflowers, sunflower meal, sunflower oil, rapeseed, rapeseed meal, rapeseed oil, and palm oil.

Grains

Identities:

Beginning Stocks = Ending stocks $_{(t-1)}$ (All Grains)
*Production = Harvested Area * Yield (All Grains)*
Domestic Use = Feed Use + Food, Seed, & Industrial Use (Corn, Sorghum, Barley, Wheat)
Total Supply = Beginning Stocks + Production + Imports (All Grains)
Total Demand = Domestic Use + Exports + Ending Stocks (All Grains)
For the non-Residual Supplying Countries
Net Exports = Ending Stocks$_{t-1}$ + Production + Imports – Domestic Use – Ending Stocks (All Grains)

Behavioral Equations:

Preferred Approach:
Harvested Area = f(Deflated Expected Own Net Returns, Deflated Expected Cross Net Returns, Harvested Area$_{t-1}$) (All Grains)
Alternative Approaches:
Harvested Area = f(Deflated Expected Own Gross Returns, Deflated Expected Cross Gross Returns, Harvested Area$_{t-1}$) (All Grains)
Harvested Area = f(Deflated Own Price, Deflated Competing Crop Prices, Harvested Area$_{t-1}$) (All Grains)
Yield = f(Trend) (All Grains)
Feed Use = f(Deflated Own Price, Deflated Competing Prices, Livestock Energy Feed Requirement) (Corn, Sorghum, Barley, Wheat)
Per Capital Food, Seed, and Industrial Use = f(Deflated Own Price, Deflated Competing Prices, Ethanol Use, Real GDP Per Capita) (Corn, Sorghum, Barley, Wheat)
Per Capita Domestic Use = f(Deflated Own Price, Real GDP Per Capita) (Rice)
Ending Stocks = f(Deflated Own Price, Ending Stocks$_{t-1}$) (All Grains)

For the non-Residual Supplying Countries
Price = f(World Price, Tariffs, Exchange Rates, etc.) (All Grains)
Other price linkage equations
Farm or Spot Price = f(Port price, transportation costs, export tariffs) (All Grains)

Global Market Clearing Conditions

World Total Demand = World Total Supply (All Grains)
Each crop has a global market clearing condition that determines world prices for corn, sorghum, barley, wheat, and rice.

Cotton

Identities:

Beginning Stocks = Ending stocks $_{(t-1)}$
*Production = Harvested Area * Yield*
Domestic Use = Mill Use + Loss
Total Supply = Beginning Stocks + Production + Imports
Total Demand = Domestic Use + Exports + Ending Stocks

Behavioral Equations:

Preferred Approach:
Harvested Area = f(Deflated Expected Own Net Returns, Deflated Expected Cross Net Returns, Harvested Area$_{t-1}$)
Alternative Approaches:
Harvested Area = f(Deflated Expected Own Gross Returns, Deflated Expected Cross Gross Returns, Harvested Area$_{t-1}$)
Harvested Area = f(Deflated Own Price, Deflated Competing Crop Prices, Harvested Area$_{t-1}$)

Yield = f(Trend)
Per Capita Mill Use = f(Deflated Own Price, Deflated Synthetic Fiber Price, Real GDP Per Capita, Trend)
Loss = fixed value based on history
Ending Stocks = f(Deflated Own Price, Ending Stocks$_{t-1}$)

For the non-Residual Supplying Countries
Price = f(World Price, Tariffs, Exchange Rates, etc.)
Other price linkage equations
Farm or Spot Price = f(Port price, transportation costs, export tariffs)

Global Market Clearing Condition

World Total Demand = World Total Supply *(World Cotton Price)*

Sugarcane, Sugar beets, and Sugar

Identities:

Sugarcane & Sugar beets

*Production = Harvested Area * Yield*

Processing Use = Production – Other Food, Feed, Waste Use

Share of Processing Use used for Ethanol = 1 – Share of Processing Use used for Sugar

*Historical Data Extraction Rates: Sugar Production/(Processing Use*Share Used for Sugar)*

Projections of Extraction Rates: Extraction rate$_t$ = Extraction rate$_{t-1}$

Total Supply = Production

Total Demand = Other Food, Feed, Waste Use + Processing Use

Sugar

Domestic Sugar Production =

*Sugar Beets Used for Processing*Sugar Beet Share Used for Sugar*Sugar Beet Extraction Rate*

*+ Sugarcane Used for Processing*Sugarcane Share Used for Sugar*Sugarcane Extraction Rate*

Domestic Use = Domestic Consumption + Other Disappearance

Total Supply = Ending Stocks$_{t-1}$ + Production + Imports

Total Demand = Domestic Use + Exports + Ending Stocks

For the non-Residual Supplying Countries

Net Exports = Ending Stocks$_{t-1}$ + Production + Imports – Domestic Use – Ending Stocks

Behavioral Equations:

Harvested Area = f(Deflated Sugar Price, Deflated Sugar Price$_{t-1}$, Harvested Area$_{t-1}$,Trend)	*Sugarcane*
Harvested Area = f(Deflated Sugar Price$_{t-1}$, Harvested Area$_{t-1}$,Trend)	*Sugar beets*
Yield = f(Trend)	*Sugarcane & Sugar beets*
Other Food, Feed, Waste Use = f(Deflated Sugar Price, Ethanol Use, Trend)	*Sugarcane & Sugar beets*
Share of Processing Use used for Sugar = f(Deflated Sugar Price, Deflated Hydrous Ethanol Price, Share$_{t-1}$)	*Sugarcane & Sugar beets*
Domestic Consumption = f(Deflated Sugar Price, Real GDP Per Capita)	*Sugar*
Other Disappearance = f(Deflated Sugar Price, Trend)	*Sugar*
Ending Stocks = f(Deflated Sugar Price, Sugar Production, Ending Stocks$_{t-1}$)	*Sugar*

Global Market Clearing Condition

World Total Sugar Demand = World Total Sugar Supply *(World Sugar Price Equation)*

Cattle and Beef

The general structure of the international cattle and beef models are captured in the equations below. The US cattle and beef models are significantly more complex and are not presented here.

Identities:

Cattle
Beginning Inventory = Ending Inventory $_{(t-1)}$
Total Cow Inventory = Beef Cow Inventory + Dairy Cow Inventory
*Calf Crop = Total Cow Inventory * Calves Per Cow*
Total Slaughter = Calf Slaughter + Cow Slaughter + Steer & Heifer Slaughter
Total Cattle Ending Inventory = Cattle Beginning Inventory + Calf Crop + Imports – Total Slaughter – Death Loss - Exports
Beef
*Production = Total Slaughter * Average Slaughter Weight*
Total Supply = Ending Stocks$_{t-1}$ + Production + Imports
Total Demand = Domestic Consumption + Exports + Ending Stocks

Behavioral Equations:

Cattle
Beef Cow Inventory = f(Deflated Steer Price$_{(t-1\ \&\ t-2)}$, Deflated Feed Cost$_{(t-1\ \&\ t-2)}$, Beef Cow Inventory$_{t-1}$)
Dairy Cow Inventory = f(trend)
Calves Per Cow = f(trend)
Calf Slaughter = f(Deflated Steer Price, Deflated Feed Costs, Calf Crop)
Cow Slaughter = f(Deflated Steer Price, Deflated Feed Costs, Total Cow Inventory$_{t-1}$)
Steer & Heifer Slaughter = f(Deflated Steer Price, Deflated Feed Costs, Total Cattle Inventory$_{t-1}$)
Cattle Death Loss = f(Cattle Ending Inventory$_{t-1}$)
Beef
Average Slaughter Weight = f(trend)
Per Capita Beef Consumption = f(Deflated Retail Beef Price, Deflated Retail Pork Price, Deflated Retail Broiler Price, Real GDP Per Capita)

For the non-Residual Supplying Countries
Price = f(World Price, Tariffs, Exchange Rates, etc.)
Other price linkage equations
Farm or Spot Price = f(Port price, transportation costs, export tariffs)

Global Market Clearing Condition

Farm Market Animal Demand = Farm Market Animal Supply	*(determines market animal price)*
Wholesale Demand = Wholesale Supply	*(determines wholesale beef price)*
Retail Demand = Retail Supply	*(determines retail beef price)*

Swine and Pork

The general structure of the international swine and pork models are captured in the equations below. The US swine and pork models are significantly more complex and are not presented here.

Identities:

Swine
Beginning Inventory = Ending Inventory $_{(t-1)}$
*Pig Crop = Total Sow Inventory * Pigs Per Sow*
Total Slaughter = Sow Slaughter + Barrow & Gilt Slaughter
Total Swine Ending Inventory = Swine Beginning Inventory + Pig Crop + Imports – Total Slaughter – Death Loss - Exports
Pork
*Production = Total Slaughter * Average Slaughter Weight*
Total Supply = Ending Stocks$_{t-1}$ + Production + Imports
Total Demand = Domestic Consumption + Exports + Ending Stocks

Behavioral Equations:

Swine
Sow Inventory = f(Deflated Barrow & Gilt Price, Deflated Feed Costs, Sow Inventory$_{t-1}$)
Pigs Per Sow = f(trend)
Sow Slaughter = f(Deflated Barrow & Gilt Price, Deflated Feed Costs, Sow Inventory$_{t-1}$)
Barrow & Gilt Slaughter = f(Deflated Barrow & Gilt Price, Deflated Feed Costs, Pig Crop)
Swine Death Loss = f(Pig Crop)
Pork
Average Slaughter Weight = f(trend)
Per Capita Pork Consumption = f(Deflated Retail Beef Price, Deflated Retail Pork Price, Deflated Retail Broiler Price, Real GDP Per Capita)
Price = f(World Price, Tariffs, Exchange Rates, etc.)

Global Market Clearing Condition

Farm Market Animal Demand = Farm Market Animal Supply (determines market animal price)
Wholesale Demand = Wholesale Supply (determines wholesale pork price)
Retail Demand = Retail Supply (determines retail pork price)

Broilers

The general structure of the international broiler model is captured in the equations below. The US broiler models is more complex and is not presented here.

Identities:

Total Supply = Ending Stocks$_{t-1}$ + Production + Imports

Total Demand = Domestic Consumption + Exports + Ending Stocks

Behavioral Equations:

Broiler Production = f(Deflated Broiler Price, Deflated Feed Costs, Broiler Production$_{t-1}$, Trend)
Per Capita Broiler Consumption = f(Deflated Retail Beef Price, Deflated Retail Pork Price, Deflated Retail Broiler Price, Real GDP Per Capita)
Price = f(World Price, Tariffs, Exchange Rates, etc.)

Global Market Clearing Condition

Wholesale Demand = Wholesale Supply *(determines wholesale broiler price)*
Retail Demand = Retail Supply *(determines retail broiler price)*

The WAEES biofuels model specifications have been omitted from this documentation at this time. However, a general overview of these models is presented as an example at the end of this document.

Model Specification Details

Crop Area Specifications

WAEES analysts have found that crop acreage equations specified as a function of expected net returns among the relevant competing crops for the geography of concern generally perform the best under historical simulations and in forecasting crop area changes. The approach allows flexibility for explicitly simulating factors which affect the cost of production directly (especially new technology developments.) However, this approach is limited by the underlying quality and availability of the cost of production data which varies considerably across countries. The following sections describe several approaches to crop area specification that WAEES uses across its commodity models depending on the availability and quality of cost of production data.

Expected Net Returns Approach (Preferred)

The WAEES field crops modeling system captures corn, soybeans, sorghum, barley, wheat, rice, sunflowers, rapeseed, and cotton. Palm and sugarcane are also included in the WAEES system but they are modeled as perennial crops which involves a different approach. (Sugar beets are modeled independently of other crops responding only to sugar beet prices.)

The general approach within the WAEES models for a specific geography is the following:

$$Corn\ Area = \alpha_1 + \beta_{11}\frac{ENR_{CRN}}{Deflator} + \beta_{12}\frac{ENR_{SBN}}{Deflator} + \cdots + \beta_{1n}\frac{ENR_{COT}}{Deflator}$$
$$Soybean\ Area = \alpha_2 + \beta_{21}\frac{ENR_{CRN}}{Deflator} + \beta_{22}\frac{ENR_{SBN}}{Deflator} + \cdots + \beta_{2n}\frac{ENR_{COT}}{Deflator}$$
$$\vdots$$
$$Cotton\ Area = \alpha_n + \beta_{n1}\frac{ENR_{CRN}}{Deflator} + \beta_{n2}\frac{ENR_{SBN}}{Deflator} + \cdots + \beta_{nn}\frac{ENR_{COT}}{Deflator}$$

Where the variables are defined as:

ENR: Expected Net Returns
CRN: Corn
SBN: Soybeans
… : all other crops
COT: Cotton

Symmetry is imposed upon the matrix of slopes with respect to expected net returns. The importance of this constraint relates to how the model performs under simulation. Without this constraint, a simulation which increases one commodities price relative to other commodities could result in significant gain or loss in crop area for that geography. Mathematically this constraint is imposed as:

$$\beta_{ij} = \beta_{ji} \; \forall \; i \neq j$$

WAEES also generally imposes the restriction that the slope on the own price coefficient should be larger in absolute value than the sum of the cross price slopes. This suggests that if all prices increase, total crop area will also increase and vice versa. In some situations this restriction is not appropriate because in some countries, the area planted for a crop with a relatively small area base may be more affected by changes in the price of a crop with a relatively large area base. Mathematically, imposing this restriction looks like the following:

$$\beta_{ii} \geq \left| \sum_{j=1}^{n} \beta_{ij} \right| \forall \; i \neq j$$

Critical to the success of this specification, is the definition of expected net returns. WAEES defines this to be:

Expected Net Returns = Expected Price * Expected Yield – Variable Cost of Production

Expected prices are defined differently in the model depending on the geography. The specification of expected prices in the US models uses an adaptive expectations approach whereby the expectation of price in the coming crop year is adjusted by the yield realized in the previous crop year versus the expected yield. This approach acknowledges that farmers generally know that years with low yields resulting in high commodity prices are not likely to be repeated under normal yield situations in the new crop year. In other northern hemisphere countries, naive expectations are often used for price expectations. In southern hemisphere countries, the September – January planting horizon allows these producers to see prices not only from the previous marketing year but also prices from the current marketing year. Typically the expected prices for these countries use half of the previous marketing year and half of the current marketing year (on a northern hemisphere marketing year basis.) This allows countries such as Brazil and Argentina to adjust their crop planting based on the commodity price reaction to the size of the northern hemisphere crops.

In recent years, domestic support policies in many countries have moved away from supporting crop area through direct production subsidies. There are a few countries which still support price by offering procurement or minimum prices at which the government will buy production to support prices at that level. These types of subsidies are captured within the expected prices using specifications such as:

Expected farm price = max(farm price$_{t-1}$, minimum procurement price)

Another example is the cast of export tariffs imposed in Argentina. In this situation, the farm price is lower than the port price by the amount of the export tariff. Accounting for being a southern hemisphere country, the specification for expected price is:

Argentina expected corn farm price = (0.5*port price$_{t-1}$*(1-Argentina corn export tariff$_{t-1}$) +0.5*port price$_t$*(1-Argentina corn export tariff$_t$))

Some countries have more complicated subsidies involving deficiency payments and/or input subsidies. A large subset of literature has been written on policy inducing prices which detail the various approaches to including government subsidies directly within the specification. WAEES attempts to capture the majority of these policies, but there is always room for improvement.

Expected yields are modeled as a function primarily of technology trends but occasionally include explicit adjustments capturing new varieties or a GMO event.

Variable cost of production data are modeled for each major cost category including seed, fertilizer, crop protection chemicals, hired labor, services, etc. These equations primarily reflect changes in input pricing and do not generally assume large shifts in the quantity of input used unless a new technology causes a shift. Specifically, the WAEES models include costs of production data for the US, Brazil, Argentina, China, and India. WAEES continues to monitor the consistency of this data in other countries and may utilize this approach for those areas in the future.

In some countries such as Brazil, the area of land devoted to crops is increasing. While WAEES has developed a variety of approaches to measuring this expansion, there is considerable difficulty finding even annually updated time series on the key drivers of acreage expansion such as new highways and rail lines that are not only built but also operational. In countries where land area expansion is occurring, WAEES uses historical based trends to capture future expansion in crop area subject to port capacity constraints. This is accomplished by adding specific trends to each of the equations above.

Gross Returns and Variable Costs Approach

In some countries, the data on gross returns and variable costs do not appear to be consistent, in that the differences in returns and costs are consistently negative through time, exhibit large variance, or may be exceedingly positive through time. In some of these cases, WAEES has separated expected net returns into deflated expected gross returns and deflated variable costs or expected gross returns deflated by variable costs. This allows the user to still explicitly include variable cost of production as a driver while avoiding problems with consistently negative expected net returns. There are some theoretical implications of this approach including that the elasticity of crop area with respect to gross returns should be greater than the absolute value of the elasticity of crop area with respect to variable costs.

Gross Returns Approach

When no reliable variable cost of production data is available, WAEES uses the gross returns approach which is similar to the Expected Net Returns Approach except that no variable cost data is included.

The gross returns approach within the WAEES models for a specific geography is the following:

$$Corn\ Area = \alpha_1 + \beta_{11}\frac{EGR_{CRN}}{Deflator} + \beta_{12}\frac{EGR_{SBN}}{Deflator} + \cdots + \beta_{1n}\frac{EGR_{COT}}{Deflator}$$
$$Soybean\ Area = \alpha_2 + \beta_{21}\frac{EGR_{CRN}}{Deflator} + \beta_{22}\frac{EGR_{SBN}}{Deflator} + \cdots + \beta_{2n}\frac{EGR_{COT}}{Deflator}$$
$$\vdots$$
$$Cotton\ Area = \alpha_n + \beta_{n1}\frac{EGR_{CRN}}{Deflator} + \beta_{n2}\frac{EGR_{SBN}}{Deflator} + \cdots + \beta_{nn}\frac{EGR_{COT}}{Deflator}$$

Where the variables are defined as:

EGR: Expected Gross Returns
CRN: Corn
SBN: Soybeans
… : all other crops
COT: Cotton

Similar symmetry conditions are imposed as discussed in the expected net returns approach.

Price Approach

Derived directly from economic theory where no technology changes are forthcoming, this approach is the traditional approach to estimating crop area.

$$Corn\ Area = \alpha_1 + \beta_{11}\frac{EP_{CRN}}{Deflator} + \beta_{12}\frac{EP_{SBN}}{Deflator} + \cdots + \beta_{1n}\frac{EP_{COT}}{Deflator}$$
$$Soybean\ Area = \alpha_2 + \beta_{21}\frac{EP_{CRN}}{Deflator} + \beta_{22}\frac{EP_{SBN}}{Deflator} + \cdots + \beta_{2n}\frac{EP_{COT}}{Deflator}$$
$$\vdots$$
$$Cotton\ Area = \alpha_n + \beta_{n1}\frac{EP_{CRN}}{Deflator} + \beta_{n2}\frac{EP_{SBN}}{Deflator} + \cdots + \beta_{nn}\frac{EP_{COT}}{Deflator}$$

Where the variables are defined as:

EP: Expected Price
CRN: Corn
SBN: Soybeans
… : all other crops
COT: Cotton

Similar symmetry conditions are imposed as discussed in the expected net returns approach.

Other Specification Additions

In some countries, it may be possible that producers cannot fully adjust the crop area to commodity prices within one year. Marc Nerlove published a journal article in 1958 describing the partial adjustment model. The quick summary of his theory capturing this possibility is that the lagged dependent variable must be added to the crop acreage equation. The coefficient on the lagged dependent variable reflects how long of an adjustment period is necessary for the producer to fully respond. In general, when used, WAEES restricts these parameters to be less than 0.3 which prevents lagged crop area from "driving" the equation and limits the long run elasticity to be 1.42 times the short run elasticity. There are some developing countries where inclusion of this term significantly improves equation performance.

Food Demand Specifications

All food demands in the WAEES models are specified as per capita equations ensuring that food consumption increases proportionally with population unless other drives such as own and cross prices or per capita income cause changes in demand. In general, the per capita food demand equations are specified as a function of the deflated own and cross prices as well as real per capita income. In some foods, the cross prices are highly collinear and a weighted average of the prices is used instead of specifying them separately.

Some food products such as vegetable oils are highly substitutable for consumers. These closely related food products are specified as a grouped subset of food consumption following

$$\frac{Soy\ Oil\ Consumption}{Population} = \alpha_1 + \beta_{11}\frac{Price_{SBO}}{Deflator} + \beta_{12}\frac{Price_{SFO}}{Deflator} + \cdots + \beta_{1n}\frac{Price_{PAO}}{Deflator} + \gamma_1\frac{Real\ GDP}{Population}$$

$$\frac{Sun\ Oil\ Consumption}{Population} = \alpha_2 + \beta_{21}\frac{Price_{SBO}}{Deflator} + \beta_{22}\frac{Price_{SFO}}{Deflator} + \cdots + \beta_{2n}\frac{Price_{PAO}}{Deflator} + \gamma_2\frac{Real\ GDP}{Population}$$

$$\vdots$$

$$\frac{Palm\ Oil\ Consumption}{Population} = \alpha_n + \beta_{n1}\frac{Price_{SBO}}{Deflator} + \beta_{n2}\frac{Price_{SFO}}{Deflator} + \cdots + \beta_{nn}\frac{Price_{PAO}}{Deflator} + \gamma_n\frac{Real\ GDP}{Population}$$

Where the variables are defined as:

SBO: Soybean oil
SFO: Sunflower oil
… : all other vegetable oils
PAO: Palm oil

Economic theory produces a set of regularity conditions that apply to consumer demands under specific assumptions. Under the assumption that vegetable oils are separable from other consumer purchases, then the interrelationship among the price elasticities is given by:

$$e_{ij} = w_j(\eta_j - \eta_i) + e_{ji}\frac{w_j}{w_i}$$

Where the variables are defined as:

e_{ij}: Price elasticity of oil i with respect the price of oil j
w_i: Share of income spent on oil i
η_i: Income elasticity of oil i

In the situation that $\eta_i = \eta_j$ then the equation reduces to:

$\frac{\partial x_i}{\partial p_j} = \frac{\partial x_j}{\partial p_i}$ or in other words, the slopes become symmetric

$$\beta_{ij} = \beta_{ji} \ \forall \ i \neq j$$

Regardless of which formula applies to a specific circumstance, the importance of this characteristic shows up under simulation so that the overall slopes of the cross price terms are close to symmetric.

Feed Demand Specifications

Animal feeds can be generally broken down into feedstuffs that provide sources of energy, i.e. grains, animal fats, and vegetable oils, and feedstuffs that provide sources of protein, i.e. protein meals and pulses. Feedstuffs are generally substitutable although they are not exactly equivalent in nutritional value. In the WAEES model we reflect the difference in nutritional value putting all of our feedstuffs on either a corn equivalent or soybean equivalent basis.

Feed demand is a derived demand from the theoretical economic behavioral postulate of profit maximization. In the case of livestock, biological lags in production and production response to additions suggest some rigidity in how quickly herd sizes can be adjusted. As a result, the generalized specification includes not only the inflation adjusted feed prices but also a measure of the livestock herd feed requirement which is reflected in the livestock energy feed requirement in the equations below. As available, the deflated index of livestock prices is also included as an explanatory variable. The relatively close substitutability in grains results in the equation system depicted below that includes certain characteristic based on economic theory:

$$Corn\ Feed\ Demand = \alpha_1 + \beta_{11}\frac{Price_{Crn}}{Deflator} + \beta_{12}\frac{Price_{Srg}}{Deflator} + \cdots + \beta_{1n}\frac{Price_{Wht}}{Deflator} + \gamma_1 \text{LEFR} + \delta_1\frac{LPI}{Deflator}$$

$$Sorghum\ Feed\ Demand = \alpha_2 + \beta_{21}\frac{Price_{Crn}}{Deflator} + \beta_{22}\frac{Price_{Srg}}{Deflator} + \cdots + \beta_{2n}\frac{Price_{Wht}}{Deflator} + \gamma_2 \text{LEFR} + \delta_2\frac{LPI}{Deflator}$$

$$\vdots$$

$$Wheat\ Feed\ Demand = \alpha_n + \beta_{n1}\frac{Price_{Crn}}{Deflator} + \beta_{n2}\frac{Price_{Srg}}{Deflator} + \cdots + \beta_{nn}\frac{Price_{Wht}}{Deflator} + \gamma_n \text{LEFR} + \delta_n\frac{LPI}{Deflator}$$

Where the variables are defined as:

Crn: Corn
Srg: Sorghum
… : all other grains (primarily barley)
Wht: Wheat
LEFR: Livestock Energy Feed Requirement
LPI: Livestock Price Index

Symmetry is imposed upon the matrix of slopes with respect to feed grain prices. The importance of this constraint relates to how the model performs under simulation. Without this constraint, a simulation which increases one feed price relative to other feed prices could result in significant gain or loss in feed demand for that geography. Mathematically this constraint is imposed as:

$$\beta_{ij} = \beta_{ji}\ \forall\ i \neq j$$

WAEES also generally imposes the restriction that the slope on the own price coefficient should be larger in absolute value than the sum of the cross price slopes. This suggests that if all prices increase, total grain feed demand will decline and vice versa. Mathematically, imposing this restriction looks like the following:

$$\beta_{ii} \geq \left|\sum_{j=1}^{n}\beta_{ij}\right|\ \forall\ i \neq j$$

In addition WAEES imposes the condition that the elasticity with respect to grain consuming animal units be 1, suggesting that a 1% increase in Livestock Energy Feed Requirement results in a 1% increase in feed demand all else equal. This means that:

$$\varepsilon^{\textbf{Grain Feed Demand}}_{\textbf{Livestock Energy Feed Requirement}} = \mathbf{1}$$

A similar structure is used in estimating protein meal demands. A similar structure is used for protein meals:

$$\begin{aligned}&\mathit{Soybean\ Meal\ Feed\ Demand}\\&\quad= \alpha_1 + \beta_{11}\frac{Price_{SBM}}{Deflator} + \beta_{12}\frac{Price_{RSM}}{Deflator} + \cdots + \beta_{1n}\frac{Price_{SFM}}{Deflator} + \gamma_1 \mathrm{LPFR} + \delta_1\frac{LPI}{Deflator}\end{aligned}$$

$$\begin{aligned}&\mathit{Rapeseed\ Meal\ Feed\ Demand}\\&\quad= \alpha_2 + \beta_{21}\frac{Price_{SBM}}{Deflator} + \beta_{22}\frac{Price_{RSM}}{Deflator} + \cdots + \beta_{2n}\frac{Price_{SFM}}{Deflator} + \gamma_2 \mathrm{LPFR} + \delta_2\frac{LPI}{Deflator}\end{aligned}$$

$$\vdots$$

$$\begin{aligned}&\mathit{Sunflower\ Meal\ Feed\ Demand}\\&\quad= \alpha_n + \beta_{n1}\frac{Price_{SBM}}{Deflator} + \beta_{n2}\frac{Price_{RSM}}{Deflator} + \cdots + \beta_{nn}\frac{Price_{SFM}}{Deflator} + \gamma_n \mathrm{LPFR} + \delta_n\frac{LPI}{Deflator}\end{aligned}$$

Where the variables are defined as:

SBM: Soybean Meal
RSM: Rapeseed Meal
… :   all other protein sources
SFM: Sunflower Meal
LPFR: Livestock Protein Feed Requirement
LPI: Livestock Price Index

Symmetry is imposed upon the matrix of slopes with respect to protein prices. The importance of this constraint relates to how the model performs under simulation. Without this constraint, a simulation which increases one feed price relative to other feed prices could result in significant gain or loss in feed demand for that geography. Mathematically this constraint is imposed as:

$$\beta_{ij} = \beta_{ji}\ \forall\ i \neq j$$

WAEES also generally imposes the restriction that the slope on the own price coefficient should be larger in absolute value than the sum of the cross price slopes. This suggests that if all prices increase, total protein meal demand will decline and vice versa.   Mathematically, imposing this restriction looks like the following:

$$\beta_{ii} \geq \left| \sum_{j=1}^{n} \beta_{ij} \right| \forall\ i \neq j$$

In addition WAEES imposes the condition that the elasticity with respect to livestock protein feed requirements be 1, suggesting that a 1% increase in Livestock Protein Feed Requirement results in a 1% increase in feed demand all else equal. This means that:

$$\boldsymbol{\varepsilon_{Livestock\ Energy\ Feed\ Requirement}^{Protein\ Feed\ Demand} = 1}$$

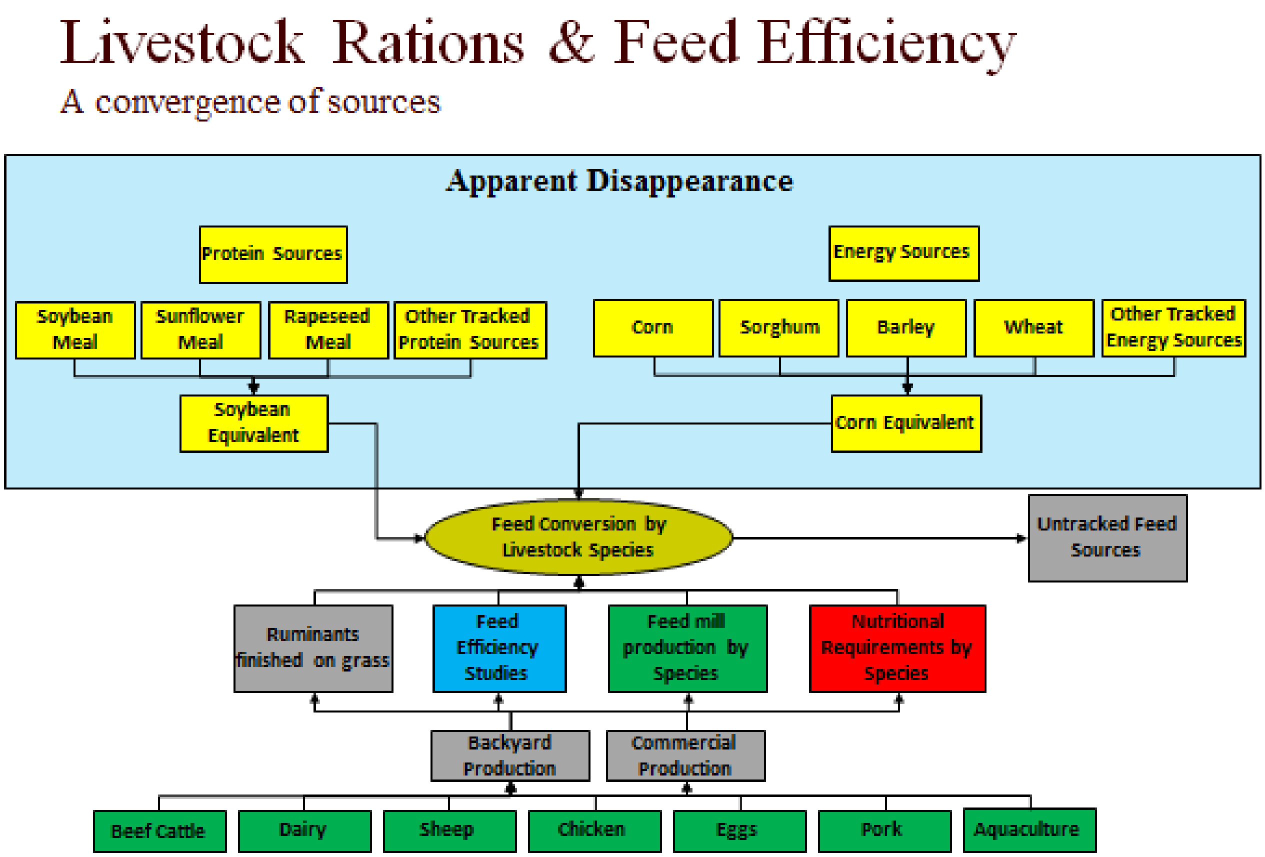
Calculating Livestock Energy and Protein Feed Requirements

There is a wealth of studies published on feeding trial results of specific livestock rations and numerous textbooks that detail the most efficient nutritional profiles by livestock species. But there is often a considerable gap between what is actually done and the best management practices. The WAEES models attempt to reconcile apparent feed disappearance with meat and livestock product production.

In some ways this analysis is similar to putting together a puzzle where not all pieces fit perfectly together and some of the pieces are missing all together. In an ideal world, the feed efficiencies would be based on annually surveyed data reflecting the entire lifespan of the animal as well as the supporting breeding animals. In addition, ideally feed use would be annually surveyed for by livestock species and the product of feed efficiency and meat or livestock product production would match feed utilization. Unfortunately, most of these pieces are either not precisely measured or missing in their entirety.

Estimating Feed Efficiency

Measuring aggregate feed efficiency for each livestock species at a regional or country level is rarely done by any country on an annual basis. Therefore, the first piece of the puzzle is to determine nutritional guidelines for each livestock species. The National Academy of Sciences has released a set of minimal nutritional guidelines by livestock species that provides details on the quantity of feed required for each stage of the animal's life. In addition to the National Academy of Sciences research, the literature is full of specific species feed studies that frequently report feed efficiencies. The table below presents a range of feed efficiencies, crude protein guidelines, and dressing percentages reported by various studies. This data provides a guideline for where the derived feed efficiencies should fall.



Feed efficiency, protein content, and dressing percentages, 2014 practices

	Feed Efficiency*		Crude Protein %		Dressing
	Range	Median	Range	Median	Percentage
Ruminants (grain fed)					
Beef Cattle	4.4-5.6	5.25	10-14%	11.0%	62%
Sheep	4.0-8.0	5.00	17-19%	18.0%	50%
Dairy	0.4-0.6	0.50	14-20%	17.5%	NA
Swine	4.8-5.7	5.55	12-14%	13.0%	72%
Poultry					
Broilers	2.1-3.3	2.67	14-23%	18.0%	71%
Eggs	1.9-3.0	1.95	14-18%	16.0%	NA
Aquaculture**	1.0-3.0	1.10	30-50%	40.0%	40%-93%

* Feed efficiency is defined as kg of energy and protein feeds (excluding forages) per kg of carcass weight or animal product produced including breeding animal overhead.

** There is considerable variance in aquaculture data on feed efficiency, protein requirements, and dressing percentages by fish species and production method.

The next piece of the puzzle is the data reported by the feed milling industry and/or the country Ministries of Agriculture. Nearly every major country has estimates of the quantity of feed produced for each livestock species. Some of the data reported combines livestock species. For example, data for broilers and layers is often combined as well as the ruminants: beef, dairy and sheep. Data reported by the feed milling industry often excludes farm prepared feeds. Finally, the feed data is reported on an "as fed" basis rather than on a corn or soybean equivalent basis.

The final piece of the puzzle is the data from USDA and FAO on feed and residual use by feedstuff. This data when converted to a corn and soybean meal equivalent basis suggests the overall level of feed use, but does not provide insights on use by species.

Through the combination of dietary guidelines; feed milling and ministry of agriculture data; and the total apparent feedstuff disappearance one can triangulate a reasonable approximation of livestock feed efficiencies by species. The process begins by comparing the total milling industry feed production (and/or results from a special national study) with the total feed and residual disappearance on an as fed basis. This provides an approximate measure of how much of the feed disappearance is actually supplied by the milling industry and how much is based on farm prepared feeds. Using the actual livestock production data, one can then derive an estimate of the total feed required per unit of livestock production adjusted for the ratio of feed & residual use versus total milled feed use. This is calculated according to the following formula:

$$"As\ Fed"\ Feed\ Efficiency_i = \frac{Milled\ Feed\ for\ Species_i}{Total\ Meat\ or\ Product\ Produced_i} * \frac{Total\ Feed\ \&\ Residual\ Use}{Total\ Milled\ Feed}$$

where:

i = beef, pork, poultry, fluid milk, mutton, and aquaculture
As Fed Feed Efficiency: total units of feed per unit of production on an as fed basis
Milled feed for species: quantity of milled feed report for species i
Total meat or product produced: quantity of meat or livestock product produced
Total feed & residual use: quantity of feed & residual use summed across all feed grains
Total milled feed: total quantity of feed milled for all species

Implied in this methodology is the assumption that the proportion of feed that is milled is the same for each species. This assumption is not necessarily true and must be adjusted in some countries because the resulting feed efficiencies are not consistent with nutritional guidelines. Typically, the swine sector has a disproportionate share of farm produced feed relative to other livestock species based on very low feed efficiencies implied from milling feed data.

The next step is to determine the share of the feed that is allocated to energy feed stuffs versus protein feedstuffs. The median crude protein guidelines in Table 3 provide a starting point for the initial shares of energy versus protein feedstuffs in the livestock rations. Using the initial shares and adjusting to a corn or soybean meal equivalency, the energy and protein feed efficiency can be derived from the as fed feed efficiency. This is calculated according to the following formula:

$$Energy\ Feed\ Efficiency_i = As\ Fed\ Feed\ Efficiency_i * Ration\ Share\ of\ Energy\ Feeds_i * \frac{Total\ Energy\ Feed\ \&\ Residual\ Use, Corn\ Equivalent\ Basis}{Total\ Energy\ Feed\ \&\ Residual\ Use, As\ Fed\ Basis}$$

$$Protein\ Feed\ Efficiency_i = As\ Fed\ Feed\ Efficiency_i * Ration\ Share\ of\ Protein\ Feeds_i * \frac{Total\ Protein\ Feed\ \&\ Residual\ Use, Soybean\ Meal\ Equivalent\ Basis}{Total\ Protein\ Feed\ \&\ Residual\ Use, As\ Fed\ Basis}$$

The final step in the process in the calibration of feed efficiencies with the actual feed disappearance and nutritional guidelines. Minimum nutritional guidelines set the floor for energy and protein feedstuff use. Feed conversion rates can be significantly higher especially if feed quality is questionable or a more inefficient production process is used. Energy or protein shares can be further adjusted within nutrition guideline ranges for each species to more closely align reported energy feedstuff use and protein feedstuff use with simulated energy feed use.

Often the feed milling data reported by livestock type does not cover every historical year. WAEES primarily focuses on the data reported since 2010, but includes older data if reported by the sources considered. The table below presents some of the sources of feed milling data used by WAEES. Since feed milling data is not available for every year, implied feed efficiencies cannot be calculated in those years. Instead, observed trends in historical feed efficiencies in combination with actual feedstuff disappearance are used to extrapolate feed efficiencies to the years in which no feed milling data is reported.   Livestock feeding studies published in the literature and the occasional survey of feed efficiencies also provide guidance in extrapolating feed efficiencies.

Feed milling data availability by selected country

Country	Source
Canada	International Feed Industry Federation Annual Report
Mexico	International Feed Industry Federation Annual Report
Brazil	Sindiracoes
Mexico	International Feed Industry Federation Annual Report
Argentina	International Feed Industry Federation Annual Report
Chile	International Feed Industry Federation Annual Report
Colombia	International Feed Industry Federation Annual Report
Bolivia	International Feed Industry Federation Annual Report
Paraguay	International Feed Industry Federation Annual Report
Uruguay	International Feed Industry Federation Annual Report
European Union	European Feed Manufacturers' Federation (FEFAC)
China	International Feed Industry Federation Annual Report
Taiwan	Taiwan Council of Agriculture, Statistics, Material for Agricultural Production
Japan	International Feed Industry Federation Annual Report
Thailand	Thai Feed Mill Association
India	International Feed Industry Federation Annual Report
Australia	Stock Feed Manufacturers' Council of Australia, Info Centre, FGP Feed Grain S&D Report
South Africa	Animal Feed Manufacturers Association, Chairman's Report, National Statistics

Feed Equivalency

There is a wide variety in feedstuffs fed to livestock globally. Each of these feedstuffs is unique in its composition of energy and protein as well as the amino acids that make up the protein profile.

Feed equivalency values are different for each livestock species based on their specific nutritional needs. Livestock nutrition guidelines suggested by extension personnel and livestock nutrition books suggest that with respect to energy, the critical factor affecting feed value for ruminants is total digestible nutrients (Mehren, 2014), while for swine and poultry, the critical factor is metabolizable energy (U.S. Pork Center of Excellence, 2010), (National Research Council, 1994). From a protein perspective, the critical factor affecting feed value for ruminants is the overall level of crude protein. For swine, the amino acid lysine is the most critical factor affecting feed value of protein feedstuffs (U.S. Pork Center of Excellence, 2010). For poultry, a combination of amino acids is critical for protein feedstuffs. Based on the advice of Dr. Gary Allee (Allee, 2002), the key amino acids for poultry production are lysine, methionine, and cysteine with a rough weighting of 50%, 25%, and 25%, respectively.

In order to determine the actual energy and protein delivered, each feedstuff must be converted to a common basis of measurement. Since corn and soybean meal are the dominant energy and protein sources, respectively, they are used as the common basis of measurement. This means that all other feedstuffs are compared to corn and soybean meal. An energy feedstuff with an 89% feed equivalency value (as fed) would be assumed to deliver 89% of the feed value of corn. One important note is that the feed equivalency values used in this study are based on an "as fed" basis because the quantities of the feedstuffs as feed demand are reported on an as fed basis rather than a dry matter basis.

$$Energy\ feed\ equivalency\ (as\ fed), ruminants = \frac{Feedstuff\ TDN\ (as\ fed)}{Corn\ TDN\ (as\ fed)}$$

Where the variables are defined as:

- TDN: Total digestible nutrients
- % DM: Percent dry matter

In the case of pork and poultry

$$Energy\ feed\ equivalency\ (as\ fed), swine\ \&\ poultry = \frac{Feedstuff\ Metabolizable\ Energy\ (as\ fed)}{Corn\ Metabolizable\ Energy\ (as\ fed)}$$

If(maximum(FEV Ruminants, FEV Swine, FEV Poultry)-minimum (FEV Ruminants, FEV Swine, FEV Poultry)) > 0.20

Then

Overall energy feed equivalency = maximum(FEV Ruminants, FEV Swine, FEV Poultry)

Else

Overall energy feed equivalency = average(FEV Ruminants, FEV Swine, FEV Poultry)

$$Protein\ feed\ equivalency, ruminants = \frac{Feedstuff\ CP\ (as\ fed)}{SBM\ CP\ (as\ fed)}$$

Where the variables are defined as:

- CP: Crude protein
- SBM: Soybean meal
- % DM: Percent dry matter

$$Protein\ feed\ equivalency, swine = \frac{Feedstuff\ Lysine\ Content\ (available, as\ fed)}{SBM\ Lysine\ Content\ (available, as\ fed)}$$

$$Protein\ feed\ equivalency, poultry = \frac{(FS\ Lysine\ Content * .5 + FS\ Methionine\ Content * .25 + FS\ Cysteine\ Cotent * .25)}{(SBM\ Lysine\ Content * .5 + SBM\ Methionine\ Content * .25 + SBM\ Cysteine\ Cotent * .25)}$$

Where the variables are defined as:

- FS: Feedstuff
- SBM: Soybean meal

Since specific feedstuff disappearance is not tracked by livestock species in most countries, it is not precisely known how much of a particular feedstock is consumed by a specific livestock species. Without this information, a possible simplifying assumption is to use the average feed equivalency across livestock species. The problem with this assumption is that some feedstuffs are clearly more superior for some livestock species. In this analysis the simple average assumption is modified so if the feed equivalency difference among livestock species is greater than 20%, the maximum feed equivalency value is used arguing that the feedstuff will be dominantly fed to the livestock species where it is best suited.

If(maximum(FEV Ruminants, FEV Swine, FEV Poultry)-minimum FEV Ruminants, FEV Swine, FEV Poultry) > 0.20

Then

Overall feed equivalency = maximum(FEV Ruminants, FEV Swine, FEV Poultry)

Else

Overall feed equivalency = average(FEV Ruminants, FEV Swine, FEV Poultry)

The tables below present the overall results of the feed equivalence for the feedstuffs considered in the WAEES models. In the case of energy feed equivalence, grains are the dominant source of feed but other milling products, starch roots, fats and oils, even fruits and sugar based products are fed. In the case of proteins, oilseed meals are the dominant source but whole oilseed feeding, milling products and pulses are also used. Notably, the feedstuffs listed are not all of the possible sources, but consumption of these feedstuffs is tracked by USDA and/or FAO.

Apparent Feed Consumption

Both USDA and FAO report the amount of major commodities that is consumed as feed. However, it is important to remember that this consumption is technically feed and residual use. In general this means that feed demand is derived from the following identity:

Feed Demand = Beginning Stocks + Production + Imports
– Food & Industrial Use – Exports – Ending Stocks

The main reason this approach is used is that data on trade, production, food & industrial use, and stocks is often explicitly tracked via survey while feed demand is not. This implies that errors in measuring any of the other categories are compounded in the feed category and subsequently, the category is typically referred to as feed and residual use. Analyzing the US data suggests that production measurement errors can be quite large and that these errors typically get compounded in feed use. For example, overestimating the crop size leads to higher feed demand use. In addition, especially large production years can result in increased residual use because of outside storage issues that result in waste in addition to decreasing feed quality. Possible year to year errors in feed demand measurement because of the inclusion of the residual suggests that one should limit expectations of a perfect relationship between calculated livestock feed demands based on meat and livestock production and apparent feed consumption based on derived feed and residual use by feedstuff.

Total energy and protein feed use in corn and soybean equivalents, respectively, can be calculated by multiplying feed and residual use as reported by feedstuff by the overall feed equivalency value (FEV) for each feedstuff. This allows more accurate summation of the feedstuffs across types and allows for comparison with estimated livestock feed demands expressed on a corn/soybean meal ration basis.

Energy feed equivalence to corn by livestock species

Feedstuff	Source	Ruminants		Swine		Poultry		Overall
		TDN*	FEV-As Fed**	ME/LB***	FEV-As Fed	ME/LB	FEV-As Fed	FEV-As Fed
Corn	**FS**	**80%**	**100%**	**1,520**	**100%**	**1,530**	**100%**	**100%**
Grains								
Barley	FS	74%	93%	1,305	86%	1,250	82%	87%
Millet	FS	69%	86%	1,310	86%	1,470	96%	90%
Oats	FS	68%	85%	1,215	80%	1,160	76%	80%
Rice, unmilled	FS	71%	89%	1,075	71%	1,335	87%	82%
Rye	FS	76%	95%	1,230	81%	1,230	80%	85%
Sorghum	FS	71%	89%	1,470	97%	1,505	98%	95%
Triticale	FS			1,430	94%	1,430	93%	94%
Wheat, hard grain	FS	76%	95%	1,465	96%	1,440	94%	95%
Wheat, soft grain	FS	79%	99%	1,550	102%	1,460	95%	99%
Other cereals	FS	79%	98%	1,285	85%	1,200	78%	98%
Grain milling products								
Brans	FS	62%	78%	1,055	69%	590	39%	78%
Corn gluten feed	FS	75%	94%	1,090	72%	795	52%	94%
Cottonseed hulls	FS	47%	59%					59%
DDGs corn	FS	79%	99%	1,460	96%	910	59%	99%
Oat hulls	FS	37%	46%	340	22%	160	10%	46%
Rice bran, unextracted	FS	60%	75%	1,000	66%	925	60%	67%
Rice hulls	FCT	14%	17%					19%
Soybean hulls	FCT/NRCS	81%	101%	839	55%			101%
Wheat bran	FS	62%	78%	1,055	69%	590	39%	78%
Wheat middlings	FS	81%	101%	1,000	66%	950	62%	101%
Starchy roots and vegetables								
Cassava tuber meal	FS	68%	85%	1,510	99%	1,325	87%	91%
Cocoa beans and products	FPD	39%	49%	278	18%			49%
Potatoes and products	FPD	13%	16%	164	11%			13%
Roots & tubers, dry equivalent	FPD	13%	16%	164	11%			13%
Sweet potatoes	FPD	30%	37%	465	31%			34%
Tomatoes and products	FPD	6%	7%					7%
Other vegetables	FPD	11%	11%	163	11%			12%
Yams	FPD			420	28%			28%
Vegetable oils and animal fat								
Coconut oil	FET/BJP			3,660	241%	3,538	231%	236%
Corn oil	NRCS			3,820	251%			251%
Cottonseed oil	FET/NRCS			3,746	246%			246%
Olive oil	NRCS			3,803	250%			250%
Palm oil	BJP			3,629	239%	3,629	237%	238%
Palm kernel oil	BJP			3,629	239%	3,629	237%	238%
Peanut oil	FET/NRCS			3,803	250%			250%
Rape and mustard oil	NRCS			3,823	252%	4,178	273%	273%
Sesameseed oil	FS			3,810	251%			251%
Soybean oil	NRCS			3,818	251%	3,799	248%	250%
Sunflowerseed oil	FET/NRCS			3,814	251%	4,381	286%	286%
Animal fat	NRCC/NRCS	177%	221%	3,608	237%	3,608	236%	231%
Fruits								
Bananas	FPD	21%	26%	327	22%			24%
Dates	FPD	78%	97%	1,292	85%			91%
Grapefruit and products	FPD	14%	17%	188	12%			15%
Grapes and products	FPD	35%	43%	489	32%			38%
Oranges and mandarines	FPD	15%	18%	221	15%			16%
Sugar and Sweetners								
Molasses	FPD/NRCS	68%	85%	1,044	69%	1,028	67%	73%
Sugar beet	FPD	20%	25%	267	18%			21%
Sugar cane	FPD	17%	21%	164	11%			16%
Sugar non-centrifugal	FPD			1,618	106%			106%

*TDN: Total digestible nutrients
**FEV: Feed equivalency value to corn
***ME/LB: Metabolizable energy per pound
Sources: FS is Feedstuffs Ingredient Analysis Table: 2014 Edition, FPD is FAO's Feedipedia available at www.feedipedia.org
FCT is Beef Magazine's 2009 Feed Composition Tables, NRCS is the National Research Council, Nutrient Requirements for Swine
BJP is the Brazilian Journal of Poultry Science, NRCC is the National Research Council's, Nutrient Requirements for Cattle
FET is Feed Energy Topic: Swine Diets by Feed Energy Company available at www.feedenergy.com.

Protein feed equivalence to soybean meal by livestock species

		Ruminants		Swine		Poultry				Overall
Feedstuff	Source	% CP*	FEV-As Fed**	% Lysine	FEV-As Fed	% Lysine	% Methionine	% Cysteine	FEV-As Fed	FEV-As Fed
amino acid weighting				100%		50%	25%	25%		
Soybean meal	**FS**	**48%**	**100%**	**2.75**	**100%**	**2.75**	**0.64**	**0.58**	**100%**	**100.0%**
Oilseed Meals										
Canola meal	FS	38%	79%	1.60	58%	1.60	0.69	0.71	68%	82.2%
Coconut meal (copra)	FS	22%	46%	0.31	11%	0.31	0.27	0.10	15%	48.6%
Corn gluten meal	FS	60%	126%	0.88	32%	0.88	1.84	0.95	68%	128.4%
Cottonseed meal	FS	41%	86%	1.70	62%	1.70	0.51	0.62	67%	87.7%
Fish meal, Peruvian anchovy	FS	65%	136%	4.90	178%	4.90	1.90	0.60	183%	183.0%
Palm kernel meal	FPD	15%	32%	0.48	18%	0.48	0.30	0.20	22%	25.2%
Peanut meal, solvent	FS	47%	98%	1.29	47%	1.29	0.44	0.47	52%	100.6%
Sesameseed meal	FS	42%	88%	1.21	44%	1.21	1.39	0.49	64%	87.9%
Sunflower meal, expeller	FS	41%	86%	2.00	73%	2.00	1.60	0.80	95%	95.2%
Oilseeds										
Cottonseed	FS	23%	48%							49.8%
Palm kernels	FPD	9%	18%	0.33	12%	0.33	0.20	0.00	13%	15.2%
Peanuts	FPD	26%	54%							61.8%
Rape and Mustardseed	FPD	19%	40%	1.30	47%	1.30	0.42	0.52	53%	48.5%
Sesameseed	FPD	23%	48%							54.3%
Soybeans (cooked)	FS	38%	79%	2.34	85%	2.34	0.52	0.55	86%	83.2%
Sunflowerseed	FPD	15%	32%	0.65	24%	0.65	0.37	0.30	29%	29.8%
Milling products										
DDGs, corn	FS	27%	56%	0.90	33%	0.90	0.45	0.32	38%	59.1%
Pulses										
Dry beans	FS	26%	54%	1.52	55%	1.52	0.25	0.14	51%	50.7%
Peas	FS	22%	46%	1.20	44%	1.20	0.20	0.30	43%	44.8%

* CP: Crude Protein (As Fed)
** FEV: Feed equivalency value to soybean meal
Sources: FS is Feedstuffs Ingredient Analysis Table: 2014 Edition, FPD is FAO's Feedipedia available at http://www.feedipedia.org/

Calculating Livestock Feed Requirements

Drawing on the initial designs developed by USDA in their Static World Policy Simulation Modeling Framework (SWOPSIM), livestock feed demand can be broken down into the feed required per unit of meat or livestock product produced. The feed needed can be subdivided into energy and protein components. The SWOPSIM model included feedstuffs tracked by USDA in their Production, Supply, and Disposition database (United States Department of Agriculture, Foreign Agricultural Service, 2014). In this analysis, data from the feed milling industry, along with livestock nutritional guidelines, and available country data on reported feed use by livestock species is used to triangulate estimates of the underlying feed efficiency by livestock type and the energy and protein components. Conceptually, total livestock feed requirements can be found by the following formula:

$$Livestock\ Feed\ Requirement = \sum_{i=1}^{6} Feed\ Efficiency_i * Production_i$$

where:

i = beef, pork, poultry, fluid milk, mutton, and aquaculture
Feed efficiency: units of feed per unit of carcass weight or livestock product
Production: units of meat production (carcass weight basis) or units of livestock product

Livestock feed requirements are further broken down into energy and protein feeds resulting in the following formulas:

$$Livestock\ Energy\ Feed\ Requirement = \sum_{i=1}^{6} Energy\ Feed\ Efficiency_i * Production_i$$

$$Livestock\ Protein\ Feed\ Requirement = \sum_{i=1}^{6} Protein\ Feed\ Efficiency_i * Production_i$$

where:

i = beef, pork, poultry, fluid milk, mutton, and aquaculture
Energy feed efficiency: units of energy feed required per unit of carcass weight or livestock product, energy feeds are expressed on a corn equivalent basis
Protein feed efficiency: units of protein feed required per unit of carcass weight or livestock product, protein feeds are express on a protein equivalent basis
Production: units of meat production (carcass weight basis) or units of livestock product

Note that both formulas measure feed efficiency as feed per unit of carcass weight or livestock production implicitly including the live weight to carcass weight conversion as well as breeding herd feed costs. The units of feed required per unit of meat produced under this methodology will be significantly higher than frequently quoted feed efficiencies that are based on units of feed per unit of live weight over the fattening period of the animal's life.

Feed Efficiency Data

Few countries directly survey livestock producers for feed efficiency data. In the US, USDA captures some of this data for swine in their ARMS survey conducted in 1992, 1998, 2004, and 2009 (Key & McBride, 2007). In Europe, the United Kingdom keeps very detailed records on feed conversions rations for the poultry sector through time based on the DEFRA Harcheries and Poultry Slaughterhouse Surveys and Integrated Poultry Unit Survey (DEFRA, 2014).

The premise of the methodology used in this study is to match apparent feedstuff consumption with the quantity of meat and animal products produced subject to nutritional guideline constraints. The basic nutritional guidelines are broken down by species into energy and protein requirements to produce a pound of meat (carcass weight basis) or animal product.

Livestock production systems have a strong influence on the degree of feed efficiency obtained; therefore a range of feed efficiencies for each livestock species is used rather than one fixed number. The bottom of the range (least amount of feed per pound of gain) represents the most efficient livestock producers and also sets the minimum feed requirement. In some countries, such as China, their reported feed efficiencies when multiplied by livestock production result in feed utilization exceeding the quantities of feedstuffs reported suggesting the use of untracked feedstuffs or alternatively that meat and livestock product production is overstated. At the top of the range are the least efficient livestock producers which may be influenced by the actual quality of the feedstuffs they are using in addition to the livestock production system they are using.

Measuring Feed Efficiency

Many of the feed efficiency numbers discussed by livestock producers and published in feed trials are quoted as pounds of feed per pound of live animal weight produced and typically represent the fattening phase of livestock production. It is basic nutritional theory that larger animals require more pounds of feed per pound of gain because more energy is used for maintenance in large animals than in small animals. This means that small animals such as fish or poultry are able to attain greater levels of feed efficiency than large animals such as swine or cattle. In addition, this also means that animals fed to heavier weights will be less feed efficient. For example, hogs fed to 240 pounds are more feed efficient than hogs fed to 280 pounds.

In this context, we are interested in the overall feed efficiency by species accounting for the feed supporting the breeding herd as well as slaughter efficiency. The measure of feed efficiency used in this analysis is kilograms of feed per kilogram of meat or animal product produced. This means that the feed efficiencies quoted in this study will be less efficient because they are quoted on carcass weight basis rather than a live weight basis and they reflect the feed fed to the breeding animals to support production as well. For the purpose of brevity, the feed efficiencies used in the study are referred to a feed efficiency, carcass weight basis.

The goal of this analysis is not to isolate the best feed efficiency but rather to establish the possible range of feed efficiencies by livestock species to help guide the estimation of apparent feed disappearance. The species specific discussion that follows uses largely US examples to pinpoint feed efficiency and trends in feed efficiency, but the process followed for the US is also utilized for other countries. Essentially the process involves four steps: determining if there are any reports of feed efficiency, comparing reported feed efficiency with apparent feed disappearance, using feed milling data to calculate feed efficiency and comparing milling feed production with apparent feed consumption, and finally arriving at livestock rations that stay within nutritional guides but emulate the historical feed disappearance well.

Feed Efficiency by Species

Ruminants

The US dominates the grain fed beef industry. Other major producers of beef such as Argentina and Australia promote their grass fed beef systems although there is a small amount of grain fed beef in each country. With the large focus on grain fed beef in the US, the state of the art in feed efficiency is set in the United States.

Historical studies document the gains in US beef production. In studies by Loy, he estimated a gain in feed efficiency of 0.047 lbs/year over the 1978-1992 period and a gain of 0.033 lbs/year over the 1988-2002 period. But based on yearly closeout summaries from Land O'Lakes/Purina Feeds, Shike points out that data over the 2001-2011 period shows no gain in feed efficiency for beef cattle in the United States (Shike, 2012). Given recent history this analysis assumes no growth in beef feed efficiency for the 2014-2030 period for the United States.

As scientists began to better understand the crude protein requirements of ruminants, protein inclusion in ruminant rations has gradually increased. In the mid-1980's it was already well documented by livestock nutritionists that ruminant rations should include more protein. But change at the farm level reflects gradual adjustment. WAEES estimates that protein levels in dairy rations increased from around 12 percent in 1990 to approximately 16% by 2013. The grain and meal portion of beef cattle rations continue to reflect about 10 percent protein content.

Swine

USDA reports swine feed efficiency in the US for farrow-to-finish and feeder-to-finish operations based on the Farm Costs and Returns Survey and Agricultural Resource management surveys. The surveys capture all large producing states and are the most representative aggregate measure of feed to pork conversion. (The large pork producing states such as Iowa and Illinois also report feed efficiencies based on their producer swine enterprise record programs. The state data sample sizes are often small so the samples may not be reliable.) The USDA surveys are conducted about every 6 years. The data from the past 4 surveys is presented in the table below (Key & McBride, 2007), (McBride & Key, 2013). The surveys report both farrow to finish and feeder to finish feed efficiencies. As expected the farrow-to-finish feed efficiencies are larger because they reflect the carrying cost of the breeding herd for those operations which is a more accurate representation of the total feed per pound of pork produced. The reported farrow to finish feed efficiencies per kilogram of live weight are converted to feed efficiencies on a carcass weight basis by dividing by the average dressing percentage of 72% for swine.

An analysis of life cycle nutrition for swine by Iowa State University based on 1994 data, suggests that approximately 28 percent more feed is needed above the amount used over the growing period in order to support breeding herd (Holden, Ewan, Jurgens, Stahy, & Zimmerman, 2009). Adjusting for improved growing feed conversions and increased pigs per sow, suggests an extra 28 percent for the breeding herd is still accurate, but it is 28 percent of a smaller quantity of grower feed needed. The percentage differences in the USDA survey data between farrow-to-finish and feeder-to-finish suggest a range of 9 to 65 percent different which may indicate that they are not comparable.

U.S. swine feed efficiency

	1992	1998	2004	2009
kilograms of feed per kilogram of liveweight production				
Farrow-to-Finish	4.16	3.74	3.54	3.00
Feeder-to-Finish	3.83	2.82	2.14	2.07
kilograms of feed per kilogram of carcass weight production				
Farrow-to-Finish	5.78	5.19	4.92	4.17

Source: USDA FCRS surveys, ARMS surveys and WAEES calculations.

Unfortunately, the USDA survey data does not fully agree with USDA's evaluation of grain consumption by livestock type. Using USDA's Economic Research Service (ERS) data on grain consuming animal units (GCAU's), hogs account for 28.4 percent of the grain consuming animal units. At a feed efficiency of 5.08 kilograms of feed per kilogram of carcass weight produced in 2013, swine consumed approximately 27.4 percent of apparent energy feed disappearance, lower than USDA's estimated share but significantly higher than the 4.17 feed efficiency. In addition at a feed efficiency of 5.08, swine consumed approximately 22.5 percent of apparent protein feeds. By comparison, USDA's high protein consuming animal units (HPAU's) for hogs represent 23.1 percent of total high protein animal consumption in 2013.

The third piece of the puzzle is the quantity of swine feed produced by the feed milling industry. For 2012, the feed millers report 23.59 million metric tons (mmt) of swine feed produced which would imply a pork feed efficiency of 2.59, considerably lower than even the USDA surveyed feed efficiencies. It is clear that some feeds are milled directly on the farm and it is likely that relative simplicity of hog feed production makes it likely that a significant share of hog feeds are produced on farm. This makes this piece of the puzzle less useful in determining the feed efficiency for swine.

The progression in US swine feed efficiency is documented in the table above. Over the 1992 to 1998 period, farrow-to-finish swine operations feed efficiency improved from 4.16 to 3.74 kilograms of feed per kilogram of live weight produced, improving -0.07 kilograms per year. Improvements over the 1999 to 2004 period were slower at -0.03 kilograms per year, but then accelerated over the 2004 to 2009 period to -0.11 kilograms per year. The literature discusses many different reasons for the progression in feed efficiency including better nutrition, increased use of confinement housing, and larger and more efficient swine operations (McBride & Key, 2013). In the US, swine total feed efficiency is assumed to improve -0.04 kilograms of feed per kilogram of live weight per year over the 2014 to 2030 period. The reason a lower rate of feed efficiency growth is used over the forecast period is that the majority of swine production now occurs within confinement housing systems in larger operations, so feed efficiency gains from conversion to these types of systems are expected to be minimal.

As in the case of ruminants, the protein content of swine rations has increased through time. Although more of the recent nutrition research focus is on the specific amino acid lysine, this study continues to measure crude protein since quantities of feedstuffs are not tracked in this manner and data on synthetic lysine use by livestock species is not publicly available.

Broilers

In the US, the National Chicken Council and USDA report estimates of broiler feed efficiency. The broiler feed efficiency table below presents the estimates reported by the National Chicken Council for feed efficiency on a live weight basis. The carcass weight estimates are calculated by WAEES using a dressing percentage of 71 percent. The 2011 USDA ARMS survey (MacDonald, 2014) found a feed efficiency of 1.89 on a live weight basis, very similar to the National Chicken Council’s estimate of 1.92. By comparison, since 2000, Brazil’s feed efficiencies are reported to be slightly better than US levels.

However, the National Chicken Council also reports that in 2011, 55 million tons of feed were used in the broiler industry to produce 18.5 million tons (37 billion pounds) of broilers on a carcass weight basis. This translates into a feed efficiency of 2.97 compared with 2.66 reported above. The feed efficiency numbers from the National Chicken Council and USDA capture only broiler grow-out farms and feed used to support the broiler breeder farms are not included whereas breeder feed is included in the 55 million tons number. This implies 0.31 pounds of feed is attributed to breeding broilers per pound of carcass weight produced or an additional 11.6 percent. The feed consumption attributed to broiler breeders is assigned to the egg sector since total egg production includes hatching eggs.

Broiler Feed Efficiency

	United States		Brazil	
Year	Live Weight Basis	Carcass Weight Basis*	Live Weight Basis	Carcass Weight Basis*
1980	2.05	2.89		
1985	2.00	2.82		
1990	2.00	2.82	2.06	2.90
1995	1.95	2.75	1.99	2.81
2000	1.95	2.75	1.94	2.73
2005	1.95	2.75	1.86	2.62
2006	1.96	2.76	1.86	2.62
2007	1.95	2.75	1.85	2.60
2008	1.93	2.72	1.83	2.57
2009	1.92	2.70	1.84	2.59
2010	1.92	2.70		
2011	1.92	2.70		
2012	1.90	2.68		
2013	1.88	2.65		
2014	1.89	2.66		

Sources: US data: National Chicken Council
Brazil Data: Brazilian Journal of Poultry Science, Dec 2012

Broiler feed efficiencies have improved significantly averaging -0.0075 kilograms of feed per kilogram of broiler meat production over the 1980 to 2013 period.

Turkeys

In 2002, turkey feed efficiency was reported to range between 2.8 and 3.2 pounds per pound of turkey on a live weight basis (Porter, 2002). The National Turkey Federation reports a feed efficiency range of 2.5 to 2.7 for turkeys on a live weight basis (National Turkey Foundation, 2013).

Eggs

The Egg Industry Center (EIC) at Iowa State University monitors the profitably of the US egg industry. Included in their measurements are measurements of feed conversion for eggs. The data is sourced to industry surveys and indicates that as of 2013 the US egg industry had an average feed conversion of 3.33 pounds of feed per dozen eggs produced (Ibarburu & Bell, 2015). WAEES inquiry with Ibarburu indicates that the feed conversions are just for layer eggs for human consumption excluding eggs for hatching. Penn State University reports 3 pounds of feed per dozen of white eggs produced and 3.5 pounds of feed per dozen of brown eggs produced which is in the same range as the EIC estimates. Eggs hatched for broiler production have a higher feed conversion because the breeds used for meat production produce less eggs per hen per year and have more muscle tone and bulkiness requiring more feed for maintenance. In a Penn State poultry management guide, hatching eggs are reported to require 7.2 lbs of feed per dozen eggs produced or 0.6 lbs per egg (Muir, Keene, & Jorday, 1983). Slightly more current sources suggest this may be as low as 6.5 lbs per dozen eggs produced (Eckroade, Davison, & Ziegler, 1999). In 2013, USDA reports that approximately 12% of the eggs produced were used for hatching. A simple weighted average of hatching (6.5 lbs per dozen) and layer eggs (3.33 lbs per dozen) suggests an average feed conversion of 3.71 pounds of feed per dozen eggs.

Aquaculture

The diversity of fish species contributes to a wide range of reported feed efficiencies. There also appears to be less standardization in the weight at which the fish are slaughtered resulting in more variance in feed efficiencies. For example, in one study of catfish response to variable protein levels, feed efficiencies are reported to range from 1.35-1.47 pounds of feed per pound of live weight produced for a 1 pound catfish, but range from 1.83-1.94 for a 3.7 pound catfish (Li & Lovell, 1992). By comparison, salmon are reported to have a feed efficiency of 1.2 kilograms of feed per kilogram of live weight produced (The Fish Site, 2011). Shrimp feed efficiencies range from 1.2 to 1.4 (Ray, 2014), (Samocha, 2012).

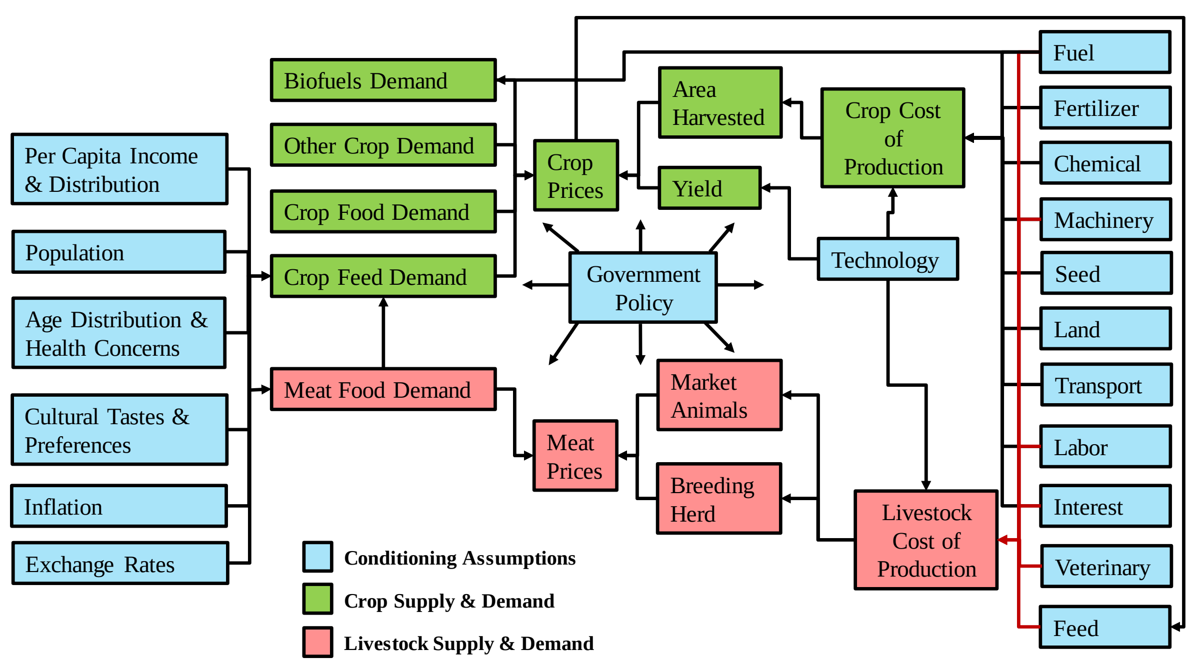
Further complicating the situation is that animal wastes and by products from other production processes are often fed to fish reducing apparent feed consumption because these quantities are not tracked. Some of the countries do not even report an aquaculture breakout in the feed milling statistics. While there are some guidelines on feed efficiency by species the quantity of untracked waste feed stuffs results in only a portion of the feed requirement being met with tracked feedstuffs. Where possible, data from the milling industry is used to derive an apparent feed efficiency recognizing that this feed efficiency may understate the actual level. If no data is available a 1:1 feed conversion ratio is assumed allowing room for feeding of wastes.

Conceptual Overview of How WAEES Models Work

The diagram below illustrates the inter-linkages of the crops and livestock model. In the diagram, the blue boxes represent the key drivers (conditioning assumptions) of the agricultural sector including income, population, culture, inflation, exchange rates, domestic and trade policy, technology and input costs. The green boxes are an aggregate approximation of the crops sector. As relevant, each box represents an equation for each commodity covered. For example, there are specific feed demand equations for corn, sorghum, barley, soybean meal, sunflower meal, etc. The pink boxes are an aggregate approximation (within the diagram) of the detailed livestock sector model encompassing beef, pork and broilers. The diagram illustrates how income, population, and other factors drive food demand for crops and meats. Crude oil prices (and policies) drive the demands for biofuels. As demand increases, crop prices increase providing an incentive for production expansion. Technology growth drives yield expansion providing much of the needed production. Crop area may also grow to meet demand needs although in developed countries this often amounts to tradeoffs among crops. Ultimately supply and demand are balanced via commodity prices. If demand is stronger than supply, commodity prices increase until demand growth is slowed and supply growth is increases enough for supply and demand to balance.

Partial Equilibrium Modeling System

(Conceptual Framework Representation for One Country)



Price Equilibrium

There are several advanced solution algorithms that can be used to solve partial equilibrium models, Gauss-Seidel, Newton, Picard, etc. These approaches have been used by WAEES but they are somewhat complex to explain. In order to simplify the concept, the paragraphs below describe the equilibration method that is often used in our Excel versions of the model. It is a very intuitive approach and somewhat easier to follow.

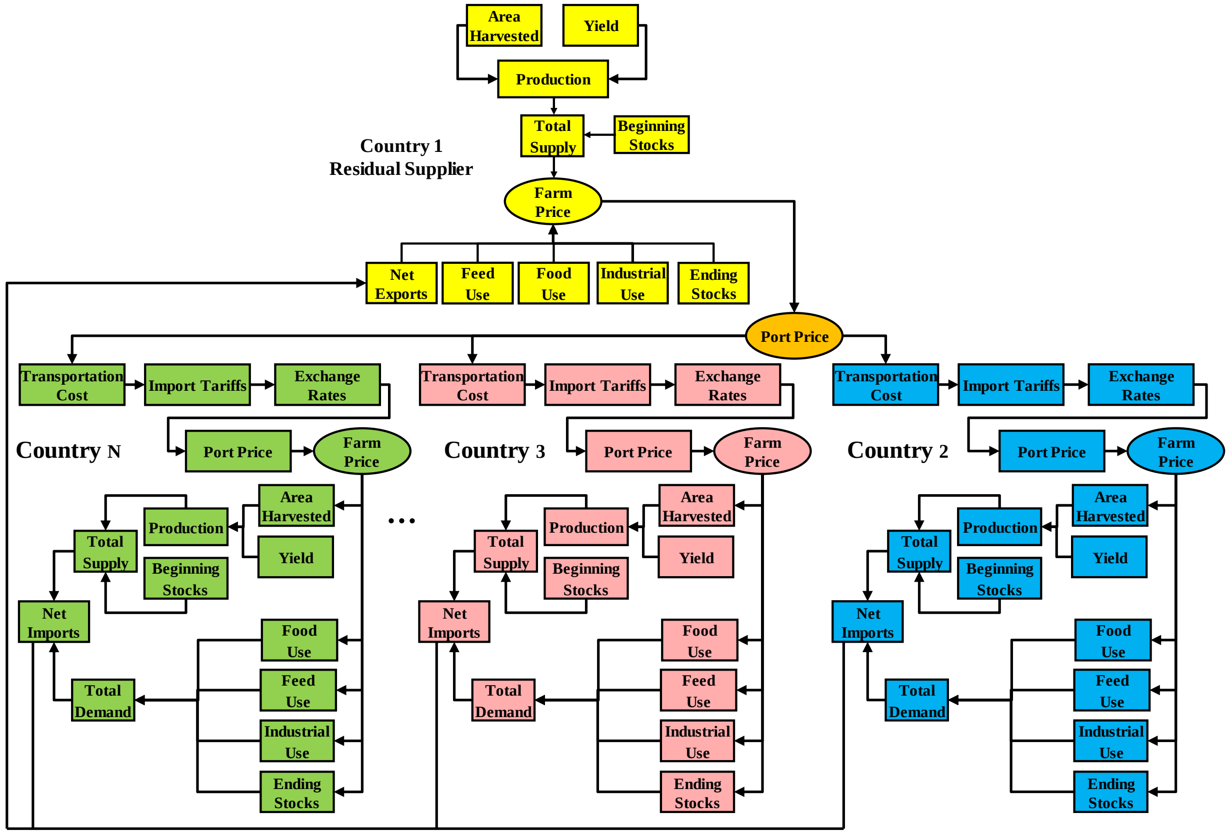
The Global Equilibrium Concept

The WAEES partial equilibrium models solve iteratively for the level of price that balances global supply and demand across all commodities simultaneously. This occurs at the individual country level for each commodity. Most countries are at least somewhat open to trade albeit with tariffs. The trade diagram below illustrates conceptually how global supply and demands are balanced within a "global" price equilibrium solution. Typically a large exporting country is chosen as the residual supplier for the world. The choice of this country does not affect the solution. The commodity price in the residual supplying country is solved for by assuming an initial level of exports. This price is then transferred to other countries through trade barriers, transportation costs, and exchange rates. Based on a given price level, each country determines how much it is willing to supply or demand at that price and subsequently how much it wants to import or export. While not depicted in the diagram below, occasionally a country has tariffs high enough that no trade will occur or only a fixed amount of trade will occur at the lower tariff level. Note that in those countries internal prices may not reflect the world level of prices because supply and demand must be balanced from domestic sources. After the supply and demand in each country is determined and the implied trade position, these trade positions are summed to find the new level of exports for the residual supplying country replacing the initial assumption. The process then repeats itself until prices adjust to balance global supply and demand. For example, if the sum of trade across all other countries is lower than the initial starting assumption for the residual supplying country, the price level in the residual supplying country will fall to balance supply and demand. This lower price level will then get transferred to all other countries affecting their supply and demand and ultimately net trade positions and of course replace the exports again in the residual supplying country. This process continues until global supply and demand balance.

The Method of Equilibration

Following on the description of attaining global equilibrium above, the method of equilibration involves the creation of price equilibrators which is essentially an iterative approach for the model to make better and better guesses regarding the price that balances global supply and demand. The global equilibrium approach described the first step in solving for prices in the residual supplying country as making an assumption about the level of net trade so that one could simultaneously solve for prices. We could have just as easily started by making a guess

WAEES Structural Partial Equilibrium Models



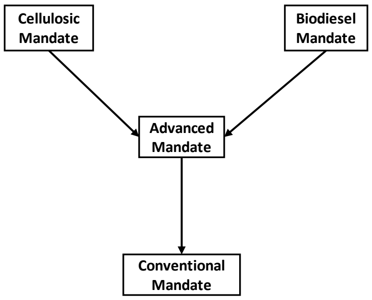
about the level of price that would balance global supply and demand and then checked to see how much we were off by looking at the difference in global supply and demand. Note that we really only have to check the difference in supply and demand in the residual supplying country because all the other countries determine their net trade positions based on the determination of their domestic supply and demand relative to the level of the initial price guess. All of the non-residual supplying countries supply and demand balance by default. It is when the net trade positions are summed across all the non-residual supplying countries to determine the net trade position for the residual supplier that supply and demand in the residual supplying country may not balance. One can easily calculate the difference between supply and demand in the residual supplying country and make a new price guess to reduce the difference between supply and demand. If supply is greater than demand, then the original price guess must fall. Alternatively, if demand is greater than supply, the original price guess must increase. In Excel, equations capture the difference between supply and demand and then multiply it by a negative dampening factor to suggest how much the price guess should change by in order to bring supply and demand closer to equilibrium. The dampening factor sets the pace of how fast the model converges but if it is set too large it can also cause the solution to diverge. The original price guess is added to the suggested price change to create a new price guess. Within

Excel, the original price guess is linked to the new price guess creating a circular reference. In order to solve the model in Excel, iterative calculations must be turned on. This can become quite complex with multiple commodities solving simultaneously for the global supply and demand equilibrium.

An Example of the US Partial Equilibrium Model for the Biofuels Sector

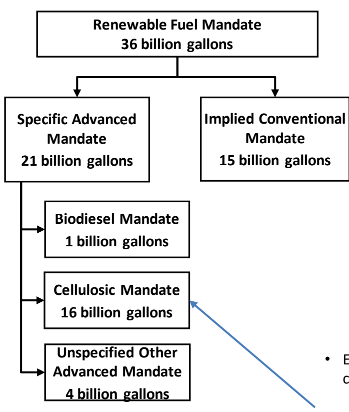
Within the WAEES model, the US ethanol and biodiesel sectors are set up as partial equilibrium models with supply and demand equations and an endogenous ethanol and biodiesel price. The structure of the model has its roots in the ethanol specifications documented by John Kruse, Patrick Westhoff, Seth Meyer, and Wyatt Thompson in a 2007 journal article in AgBioForum entitled, "Economic impacts of not extending biofuel subsidies." With the second Renewable Fuel Standard, these original specifications have been updated to reflect the hierarchical system of mandates. The biofuels mandates require compliance with each specific mandate type including biodiesel, cellulosic, advanced and the overall renewable fuel mandate. The rationale for different mandates in the legislation was to encourage biofuel producers to move towards feed stocks that provided the greatest level of greenhouse gas (GHG) reductions compared with conventional petroleum. The term "advanced biofuels" was used to describe biofuels that reduced GHG emissions by at least 50 percent compared with a 20 percent reduction requirement for conventional feed stocks. Cellulosic derived biofuels must reduce GHG emissions by 60 percent. Compliance with the mandates by the obligated parties is enforced by the EPA through as system of Renewal Identification Numbers (RINS) assigned to each type of biofuel produced. Obligated parties must demonstrate that they have met their assigned obligations through the number of RINS they have for each type of fuel. Theoretically there could be a specific RIN value for each type of mandate – cellulosic, biodiesel, advanced, and conventional, if each mandate was binding. Mandates are binding when the market is forced by policy to produce more than what normal economic conditions would suggest.

Hierarchical RINS Modeling



- Theoretically there can be 4 different RIN prices specific to each mandate if all the mandates are binding.
- Mandates are binding when the market is forced by policy to produce more than what normal economic conditions would suggest.
- Given the hierarchy of the mandates, it must be the case that RIN values for biodiesel are greater than or equal to advanced RIN values and advanced RIN values must be greater than or equal to conventional RINS. This is because biodiesel RINS can be used as advanced RINS and advanced RINS can be used as conventional RINS. (This process is referred to as demotion.)
- Biodiesel RINS can have the same value as advanced RINS if the biodiesel mandate is less binding than the advanced mandate.

US Biofuels Mandates in 2022



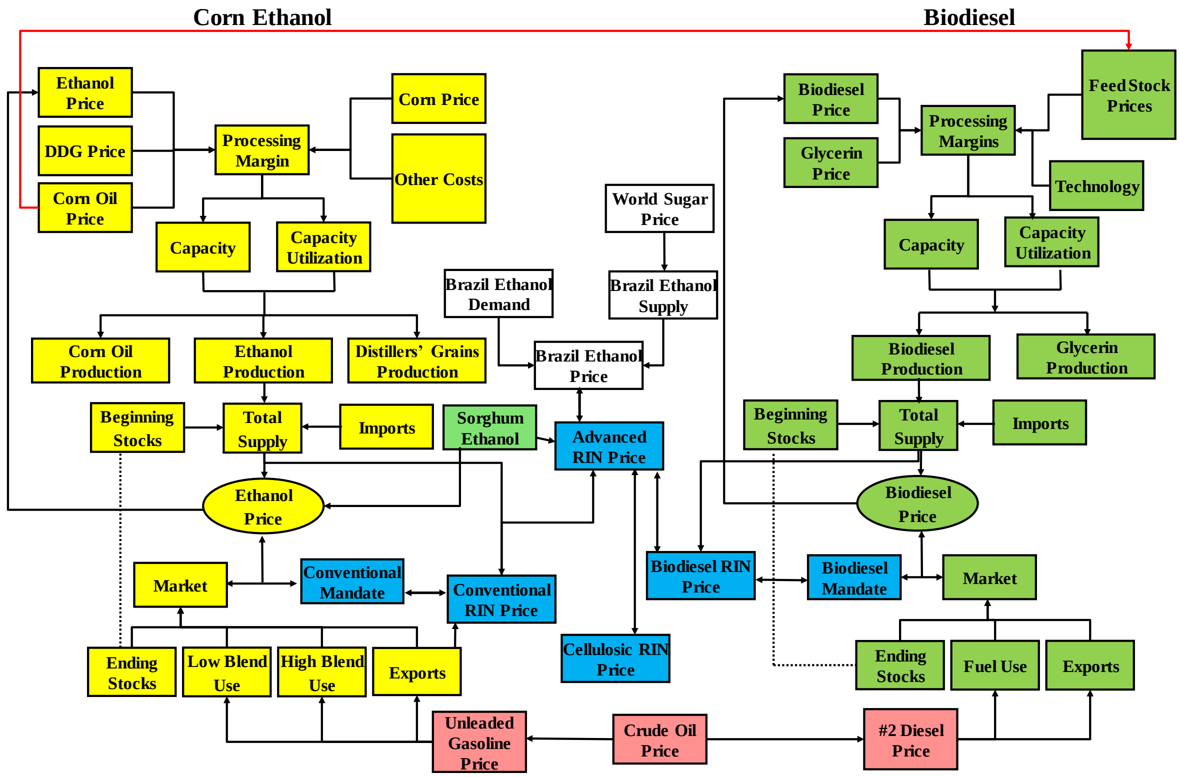
- EPA has waived the cellulosic mandate in 2011 and 2012 because cellulosic biofuels are still very expensive to produce.
- While the cellulosic mandates has been waived, the overall advanced mandate continues to be retained forcing more demand for other advanced fuel feed stocks such as biodiesel and sugarcane ethanol.

A simplified diagram of the US biofuels model is presented below. The supply of biofuels is driven by the profit margins of the biofuel plants. Profit margins are derived by subtracting the cost of the feed stocks and other variable costs of production from the value of the products. In the case of ethanol, the value of the ethanol plus the value of the byproducts including corn oil and distiller's grains form the gross returns. The cost of ethanol is composed of the feed stock cost, primarily corn, and the other inputs. Ethanol demand is determined by the greater of market demand or the ethanol volume obligation set by EPA. Market demand is influenced by the unleaded gasoline price. Low blend use represents E10 or lower blends. High blend use includes E15 and higher blends. Ethanol price is solved for in the model by balancing ethanol supply and demand. Note that ethanol supply includes ethanol imports (primarily Brazilian sugarcane ethanol) and the small amount of cellulosic ethanol produced which is currently a fixed assumption.

In the case of biodiesel, the value of biodiesel and the byproduct glycerin form the gross returns. The cost of producing biodiesel is composed of the feed stock costs such as vegetable oils, waste oils, corn oil and other inputs. The respective margins for ethanol and biodiesel drive capacity expansion in the longer term and capacity utilization in the short term for each sector. Equilibrium between biodiesel supply and demand is found by solving for the biodiesel price.

The model also captures the supply and demand of RINs (not depicted in the diagram in detail). The RIN prices are solved for based on the supply and demand of each type of RIN. California's Low Carbon Fuel Standard (LCFS) requirements are included and the model solves for feedstock required to meet the LCFS requirements.

US Biofuels Partial Equilibrium Models



The WAEES Global Modeling Process

Forecast Assumptions

WAEES begins each semi-annual forecast by developing a set of conditioning assumptions that will be used for the forecast. These assumptions include the critical domestic and trade policies affecting agriculture and biofuels in each country; macroeconomic conditions such as per capita income growth, population growth, inflation rates, and exchange rates; technology assumptions such as crop yield growth; and key cost of production drivers such as interest rates, petroleum prices, wage rates, and other trends in tastes and preferences. Infrastructure constraints and land area expansion assumptions are also outlined in this process. These assumptions are direct inputs into the WAEES global agricultural partial equilibrium models.

Historical Data

The second step in the process is updating all historical data to the latest numbers. A large portion of the historical supply and demand data is drawn from USDA's Production, Supply, and Disposition (PSD) database. Historical data on crop area, yield, and production for each of the EU-28 countries is taken from Eurostat and supplemented with data from each of the country Ministries of Agriculture as needed. Some historical data such as sugarcane and sugar beet area harvested is taken from FAOSTAT, but the data is reviewed for consistency prior to being used in the models. Historical data on commodity prices are taken from a variety of sources including the respective Ministries of Agriculture (or equivalent) in each country, USDA, FAO, and many others. Historical government policy information is gathered from USDA Gain Reports, the WTO, OECD, FAO, and the respective Ministries of Agriculture (or equivalent) in each country.

The timing of historical data releases determines when the WAEES forecasts are completed. The critical updates for PSD's global livestock data occur in April and October. The global crops data is updated more frequently throughout the year. Since the size of the southern hemisphere crops are generally available in April/May and the size of plantings in the northern hemisphere crops are generally known, WAEES conducts the first of the semiannual forecasts over the month of May targeting the beginning of June for release of the forecast numbers. The second forecast is typically done over the month of November targeting the beginning of December for a release of the forecast numbers. At this time of the year, the northern hemisphere crop sizes and the southern hemisphere plantings are generally known.

Model Development and Equation Updates

The WAEES global partial equilibrium models are in a constant state of review to ensure that the equations are performing adequately, the model structure is adapted to changes in the marketplace, changes in data sources captured, and new coverage is added as necessary.

While WAEES does not keep an exact count on the number of equations in the system, it now exceeds 20,000 equations. The performance of the behavioral equations within the system are continuously monitored within the system based on their percent root mean square errors, consistency with market behavior, and their recent pattern of historical errors. Prior to each forecast, the equations are reviewed and replaced as needed.

Model Calibration and Adjustment

After the historical data has been updated, each equation is recalibrated to the updated historical data. After reviewing the equation performance as per the description above, the model adjustment factors are set for the first forecast year. These adjustments are set based on a weighted average of the equation errors over the previous 3-5 years in the model. In 99.5% of the equations this adjustment factor is held constant over the forecast horizon of 2020 through 2030. There are a few equations, particularly in the livestock sector, where adjustments are used to generate the livestock cycles.

Generating the forecast

After capturing the forecast assumptions, updating the historical data, reviewing the model equations, and calibrating the model, the model is then solved to generate a global forecast of commodity prices that balances supply and demand within each country and around the world. Since the commodities are highly interrelated within the model sometimes the forecast assumptions generate unexpected results and/or push the model into a region outside the experience based on historical data. The global solution is carefully reviewed and the equation results are evaluated based on direction and magnitude of response, and if necessary, the model equations are adjusted and the model is re-solved for a new global solution. These corrections are usually small or not needed, but some scenarios can push the model into untested ranges.

Reporting the Forecast Results

Each model with the WAEES global modelling system includes a master data block capturing the historical and forecast data. These data blocks are combined from the various models and used to generate a standard set of world tables and country supply and demand tables for each commodity. Currently these tables are reported in one Excel file with an index including hyperlinks that facilitate location of the different table types. WAEES creates a set of PowerPoint slides summarizing the forecast and/or changes from the previous forecast. Finally, a written report is generated documenting the key assumptions, results, and key sensitivities for the forecast.

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