An Interactive Life Cycle Assessment (LCA) Model for U.S. Kelp Aquaculture Based on the Open-Source Platform openLCA

In addition to (and fully-integrated with) the financial planning modules, a Life Cycle Assessment (LCA) model was developed to generate a comprehensive assessment of the environmental impacts and benefits associated with the nursery and growout phases of a kelp aquaculture operation. The model includes assessments of the potential for both bioremediation (i.e., N and P removal) and negative CO_2 emissions resulting from the growout and harvesting of kelp. Although seaweed farming has long been touted as one of the most environmentally friendly forms of aquaculture, user-friendly tools aimed at the quantitative estimation of ecosystem service flows are lacking. The LCA model will allow users to estimate the environmental footprint of a kelp nursery/growout operation by fulfilling a few additional data requirements that build on the information already collected for the financial analysis.
Life Cycle Assessments use a standardized methodology to identify and quantify the environmental impacts of any given production system. In this context, a product could include any goods, technologies, and services. Impacts are quantified per the functional unit of the product system based on its output, i.e., one pound of wet kelp at harvest. The outputs of an LCA can be used to identify potential improvements in the production system with the overall aim to minimize environmental impacts such as resource depletion, global warming, (stratospheric) ozone depletion, acidification, eutrophication, etc.
Life Cycle Assessments are conducted more effectively through the use of specialized software, which guide users through the different stages of an LCA, from defining the scope and goals of the study to interpreting the results. The most popular software tools are Simapro, Gabi Sphera, Ecochain Mobius, OneClick LCA, OpenLCA, and Umberto. Out of these options, OpenLCA is the only free, open source software – the other tools require the payment of licensing fees. These instructions contain detailed explanations to conduct an LCA of kelp aquaculture operations. Three general steps are required:

1) The completion of the additional data requirements contained in the LCA-designated worksheets in the financial planning model.

2) The LCA worksheets will compute the material and energy requirements associated with the production of one foot of spool/seedstring (nursery worksheet) and one pound of fresh kelp at harvest (farm worksheet). These requirements are computed in specific cells and must be manually entered in the OpenLCA platform (to be downloaded free-of-charge from

https://www.openlca.org/).

3) OpenLCA will compute carbon emissions and N/P eutrophication produced by the nursery/farm operation. These estimates must be entered manually in the worksheet '2(b). Start up farm – LCA' in order to compute the additional revenue from negative CO_2 emissions and N and P removal (if any).
The following sections provide fully-detailed instructions on the three steps outlined above.

1) Additional Data Requirements (Financial Planning Model)

As mentioned previously, the LCA model requires the estimation of material and energy requirements involved in the production of one foot of spool (nursery phase) and one pound of fresh kelp at harvest (growout phase). These requirements are estimated in three different worksheets: "2(a). Start up nursery – LCA" (cells O45 : AC415); "2(b). Start up farm – LCA" (cells M68 : AA255); and "3. Operating Expenses – LCA" (cells Q57 : Y98). Many of these requirements are expressed in terms of the amount of dollars spent per foot of spool / pound of fresh kelp. These data are calculated automatically as the user enters the information required for the financial analysis in the worksheets "2(a). Start up nursery"; "2(b). Start up farm"; and "3. Operating Expenses", respectively. However, weight data (in kg) are needed for certain budget items:

i. Worksheet "2(a). Start up nursery – LCA": individual weights are required for 31 items (white cells in U column), if listed in the financial model. For example, cell U97 asks for the weight (in kg) of one individual bucket; cell U150 requires the approximate weight of the PVC pipe and fittings set used for the Seawater Filtration/Sterilization System; cell U215 asks for the weight of an individual cutting board (Nursery Tank Culture System). Notice that the reported weight values must correspond to the items whose average cost is listed in column D.

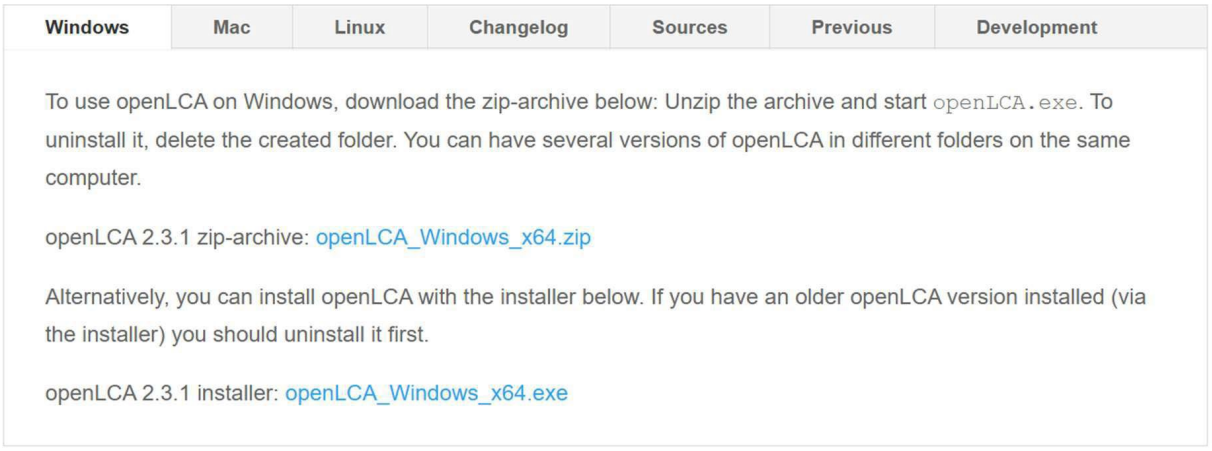
ii. Worksheet "2(a). Start up farm – LCA": individual weights are required for 25 items (white cells in S column), if listed in the financial model. For example, cells S90, S104 and S178 request the weight (in kg) of a steel anchor, a Styrofoam buoy, and a plastic container for holding longline, respectively.

iii. Worksheet "3. Operating Expenses – LCA": in order to compute energy and fuel requirements, the cost of one kWh must be entered in cells T69 and T97 while the average cost of fuel must be entered in cells W70 and W98.

2) OpenLCA Platform

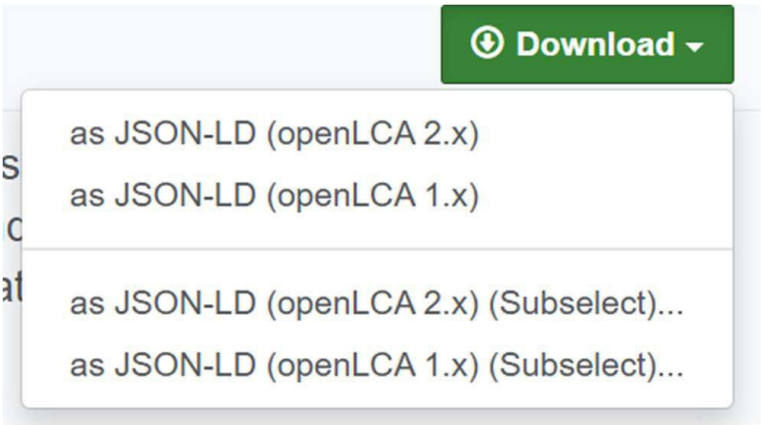
The steps indicated below must be followed to conduct the LCA within the OpenLCA platform.
i. Please download the latest version of OpenLCA from https://www.openlca.org/download/. Version 2.3.1 was released in September 2024 - newer versions are released on a frequent

basis.



ii. In order to operate OpenLCA, databases must be created and/or imported. Please download the following databases to a folder of your choosing in your computer.

- National Renewable Energy Laboratory/USLCI database: visit https://www.lcacommons.gov/lcacollaboration/National_Renewable_Energy_Laboratory/USLCI_Database_Public/datasets and click on the green 'Download' dropdown menu at the right portion of the page. Select the option 'as JSON-LD (openLCA 2.x)', which will download the zipped folder 'National_Renewable_Energy_Laboratory-USLCI_Database_Public'.

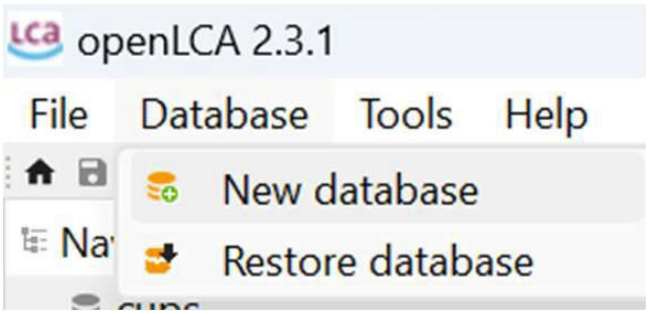


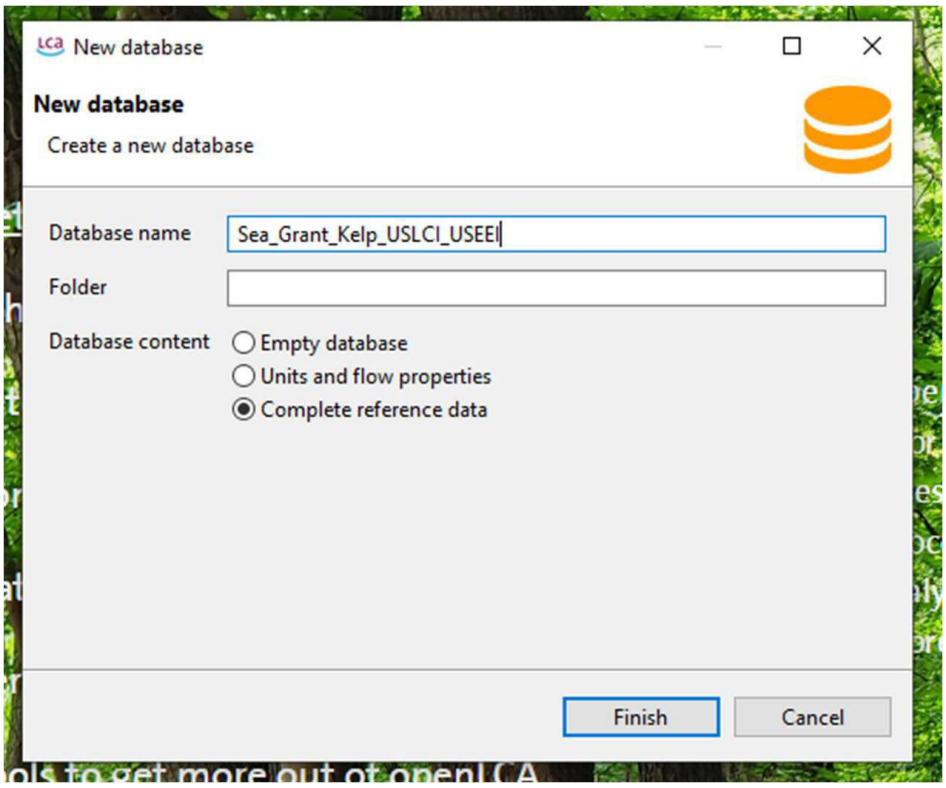
- US Environmental Protection Agency/USEEIO v2.0: visit https://www.lcacommons.gov/lcacollaboration/US_Environmental_Protection_Agency/USEEIO_v2/datasets and click on the green 'Download' dropdown menu at the right portion of the page. Select the option 'as JSON-LD (openLCA 2.x)', which will download the zipped folder 'US_Environmental_Protection_Agency-USEEIO_v2'.
- Federal LCA Commons/ReCiPe 2016 Impact Assessment Methods: visit https://www.lcacommons.gov/lcacollaboration/

Federal_LCA_Commons/ReCiPe/datasets and click on the green 'Download' dropdown menu at the right portion of the page. Select the option 'as JSON-LD (openLCA 2.x)', which will download the zipped folder 'Federal_LCA_Commons-ReCiPe'.

- Kelp farming LCA model: visit https://seaweedhub.extension.uconn.edu/resources/business/ and download the zipped folder 'Kelp_USLCI_USEEIO'.

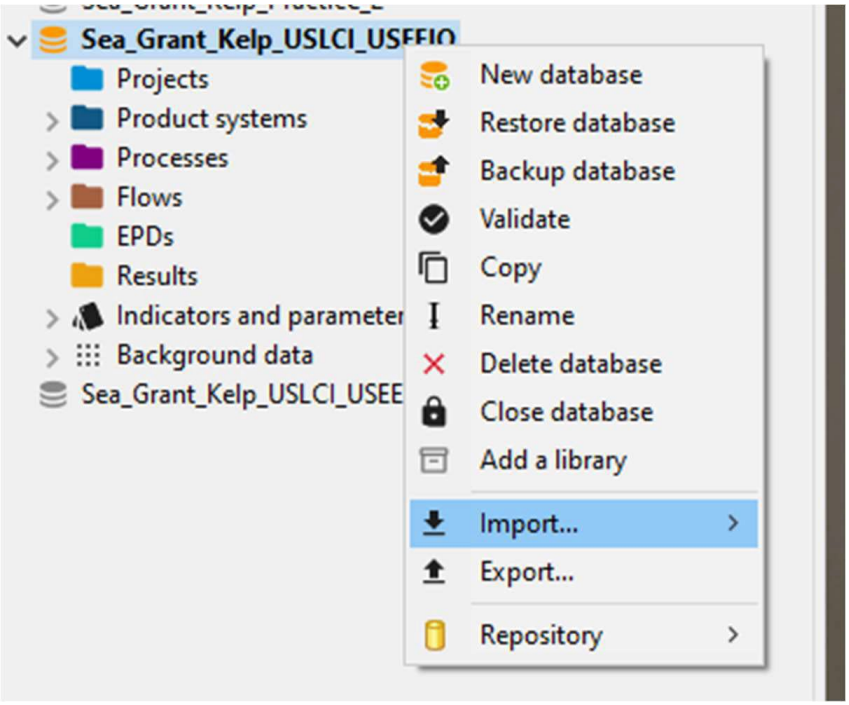
iii. The next step is to create a database in OpenLCA that can be used to import the databases downloaded in ii). Once you open the platform, click on 'Database' (upper left menu) and then click on 'New Database'. You can type 'Sea_Grant_Kelp_USLCI_USEEIO' as the Database Name. Click 'Finish'.

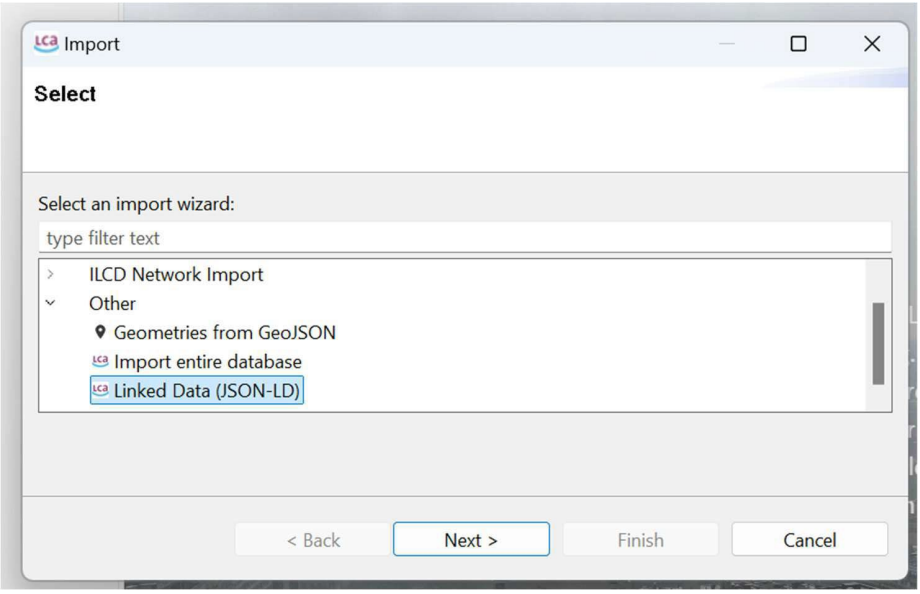




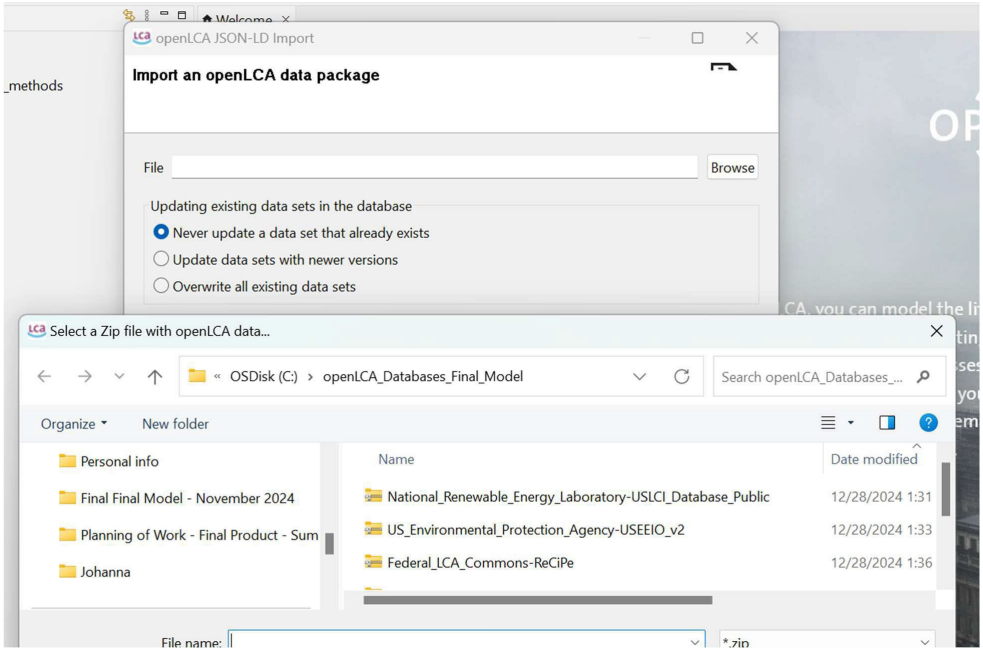
iv. Once the database is created, the zipped folders 'National_Renewable_Energy_Laboratory-USLCI_Database_Public', 'US_Environmental_Protection_Agency-USEEIO_v2',

'Federal_LCA_Commons-ReCiPe', and 'Kelp_USLCI_USEEIO' can be imported. Make sure the newly created database is active (it appears highlighted in colors – if not, click on it with the right mouse button and select 'Open database' in the dropdown menu). After this is done, click on the title with the right mouse button and select 'Import' > 'Other' > 'Linked Data (JSON-LD) > Next.

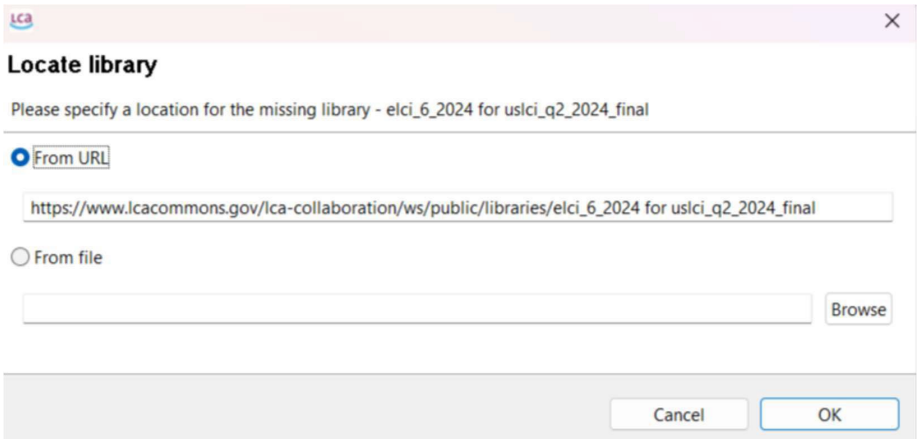




v. The window 'Import an openLCA data package' will appear on the screen. Click on 'Browse' and select the zipped folder 'National_Renewable_Energy_Laboratory-USLCI_Database_Public'. Click on 'Finish'.



vi. openLCA may ask for a supporting library from the LCA Commons website. Click on OK. The Import process will take a few minutes.

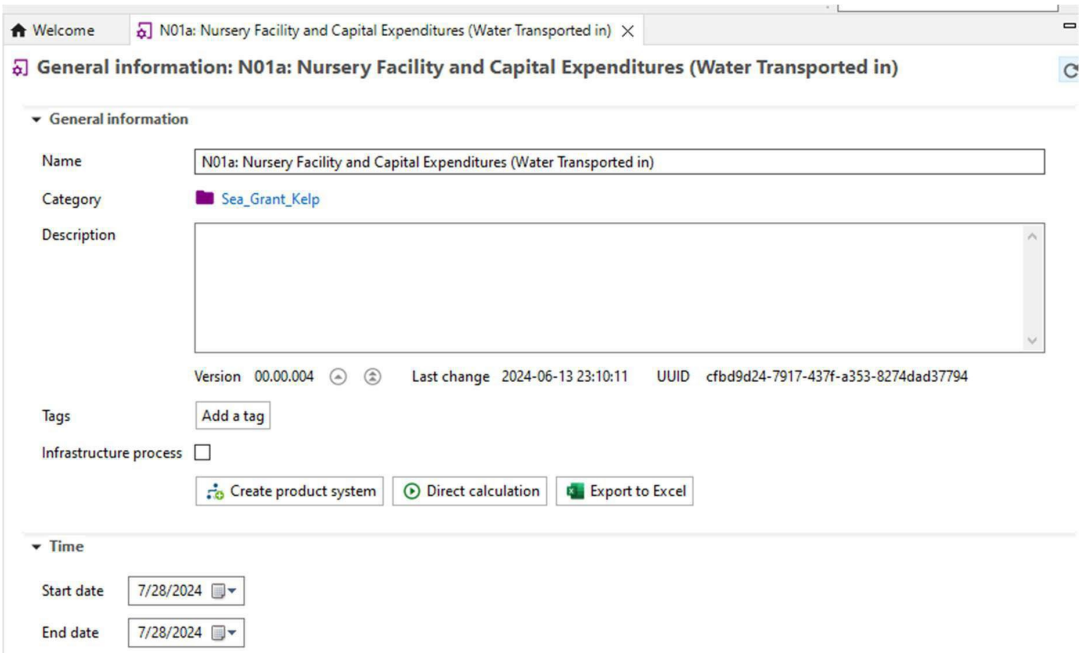


vii. Repeat the above steps to import the zipped folders 'US_Environmental_Protection_Agency-USEEIO_v2', 'Federal_LCA_Commons-ReCiPe', and 'Kelp_USLCI_USEEIO'.

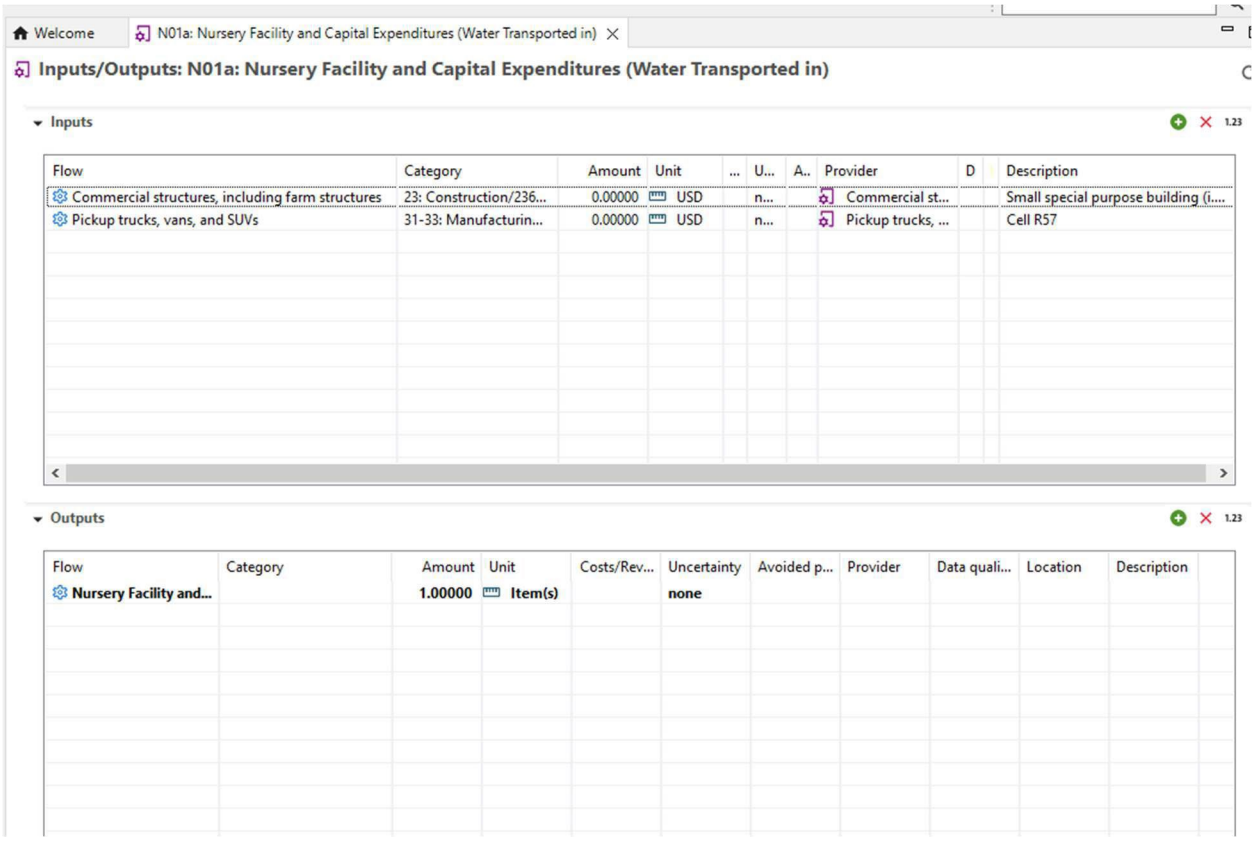
viii. Click to expand the 'Sea_Grant_Kelp_USLCI_USEEIO' database after the zipped folders have been imported. You will find a number of folders (Projects, Product Systems, Processes, Flows and other supporting folders). The LCA model is found in the subfolder 'Sea_Grant_Kelp' within the folder 'Processes'.

ix. By expanding ‘Sea_Grant_Kelp’, you will find that the model contains 30 different processes. The processes ‘N01a’ through ‘N12’ and ‘G02a’ through ‘G12’ correspond to the nursery and growout phases, respectively. The process ‘AA: Seed Spool’ compiles the information from the nursery processes while “BB: Harvested Kelp” does the same for the growout processes.

x. The nursery and growout processes in openLCA are modeled after the tables in the Excel worksheets “2(a). Start up nursery – LCA” (cells O45 : AC415); “2(b). Start up farm – LCA” (cells M68 : AA255); and “3. Operating Expenses – LCA” (cells Q57 : Y98). In order to run the LCA model, the material and energy requirements computed in the worksheets must be transcribed into its corresponding process in OpenLCA. As an example, double-click on the process ‘N01a’ (Nursery Facility and Capital Expenditures (Water Transported in)). The following window will display:



xi. Click on the tab 'Inputs/Outputs' in the lower portion of the window. This is the tab that will be used to enter the requirements computed in the worksheets.



xii. This process is defined by only two openLCA flows: 'Commercial structures" and 'Pickup trucks, vans, and SUVs'. The corresponding information is found in the worksheet 'Start

up nursery – LCA', cells O51: T57. The Process name is indicated in column P.

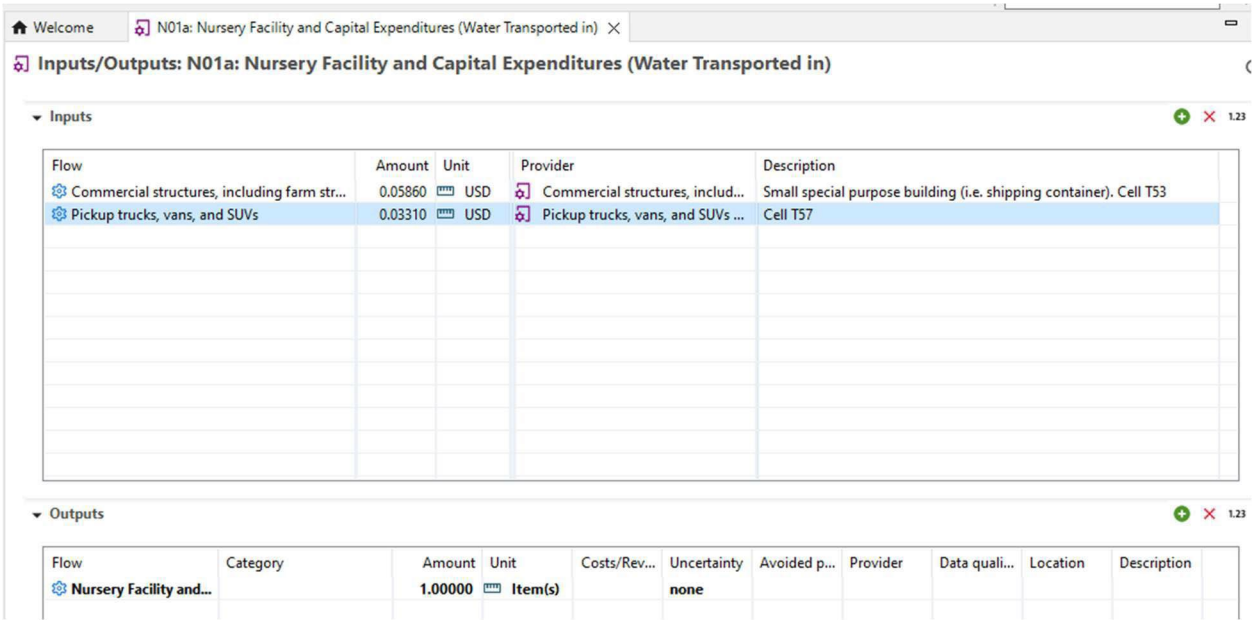
openLCA Flow			Amount		
Name	Process	Unit	Current USD per foot of spool	Adjustment Factor	2012 USD per foot of spool
Commercial structures	N01a	2012 USD	8.33E-02	0.704	5.86E-02
Pickup trucks, vans, and SUVs	N01a	2012 USD	4.44E-02	0.745	3.31E-02

xiii. For demonstration purposes, it has been assumed that the following capital expenditures have been made for the nursery: 1) $50,000 for a small special-purpose building (cells C53 : J53 in worksheet '2(a). Start up nursery', useful life of 20 years); and 2) $20,000 for a pick-up truck (cells C57: J57 in worksheet '2(a). Start up nursery', useful life of 15 years).
It is also assumed that the nursery produces 30,000 feet of seedstring. The corresponding LCA table in the worksheet 'Start up nursery – LCA', cells O51: T57 indicates that the capital expenditure in the building amounts to $0.0833 per foot of spool (nominal dollars) and $0.0586 (2012 dollars). The table also indicates that this budget item is modeled as the flow 'Commercial Structures' under process 'N01a' in OpenLCA.

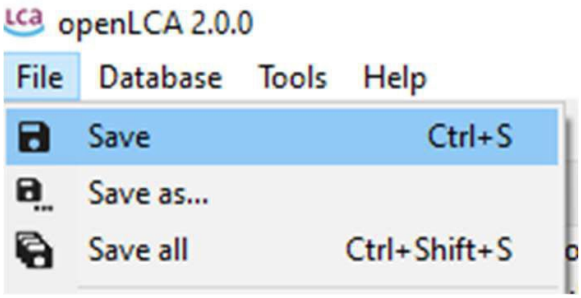
xiv. As implied in ii), flows in the 'Sea_Grant_Kelp_USLCI_USEEIO' database were obtained from two different sources: the Unit & System Life Cycle Inventory (USLCI) database maintained by the National Renewable Energy Laboratory (NREL), and the U.S. Environmentally-Extended Input-Output Model (USEEIO v2.0) produced by the Environmental Protection Agency (EPA). The combined databases provide a comprehensive set of goods and services for the U.S. economy that can be used for life cycle assessment and related applications. Notice that the functional units of USLCI and USEEIO processes are kg and 2012 U.S. Dollars, respectively.

xv. Because 'Commercial structures' and 'Pickup trucks, vans, and SUVs' are USEEIO processes, the material requirements need to be expressed in terms of 2012 USD per foot of spool. In other words, 2012 $0.0586 in commercial structures need to be spent per foot of spool (these computations consider the life expectancy of the building). The environmental impact of the special-purpose building is then scaled relative to this expenditure amount.
xvi. The material and energy requirements for each openLCA flow is formatted in bold, brown fonts – see for example cells T53 and T57 in '2(a). Start up nursery – LCA'. These estimates need to be entered manually in the openLCA processes, under the column 'Amounts'. This is how openLCA is instructed that the production of one foot of spool requires an expenditure of 2012 $0.0586 in commercial structures and 2012 $0.0331 in pickup trucks. Notice that the 'Description' column refers to the specific cells in the

worksheet (T53 and T57) that compute the Amount value to be entered in openLCA.

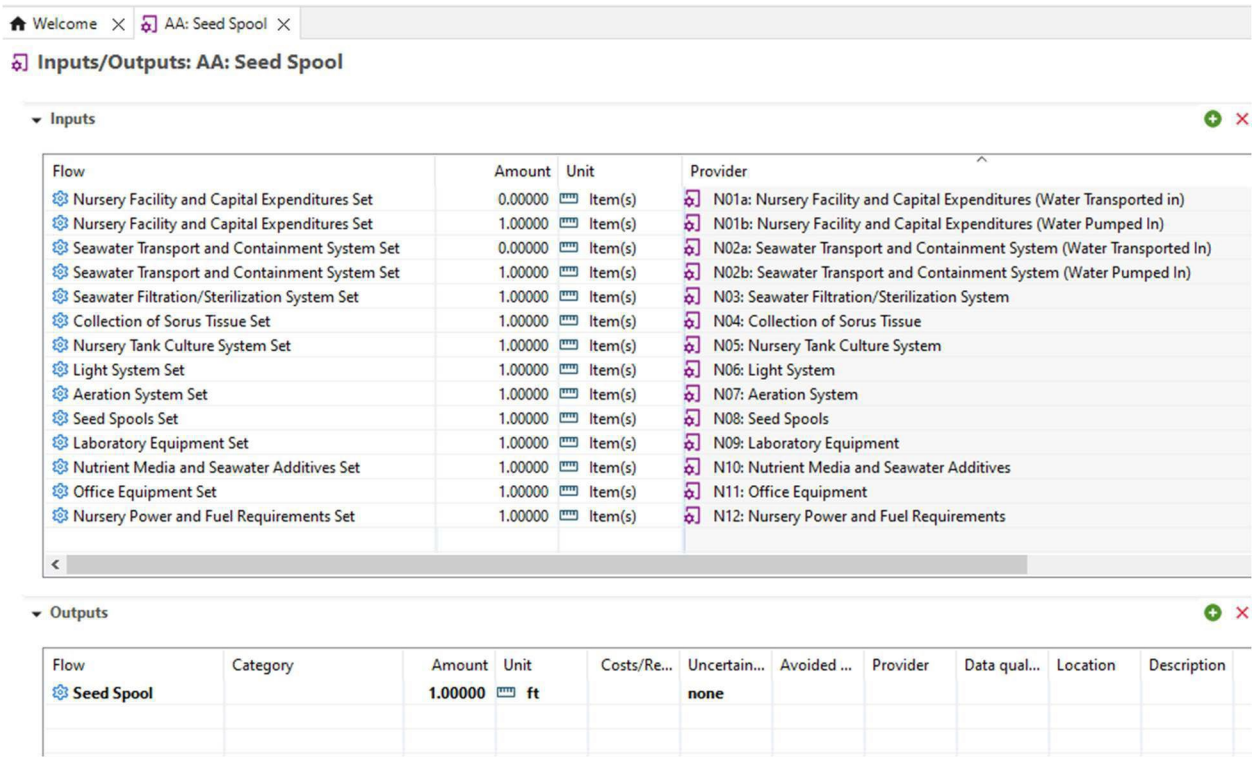


xvii. Please save changes to the Process right after entering the 'Amount' values.



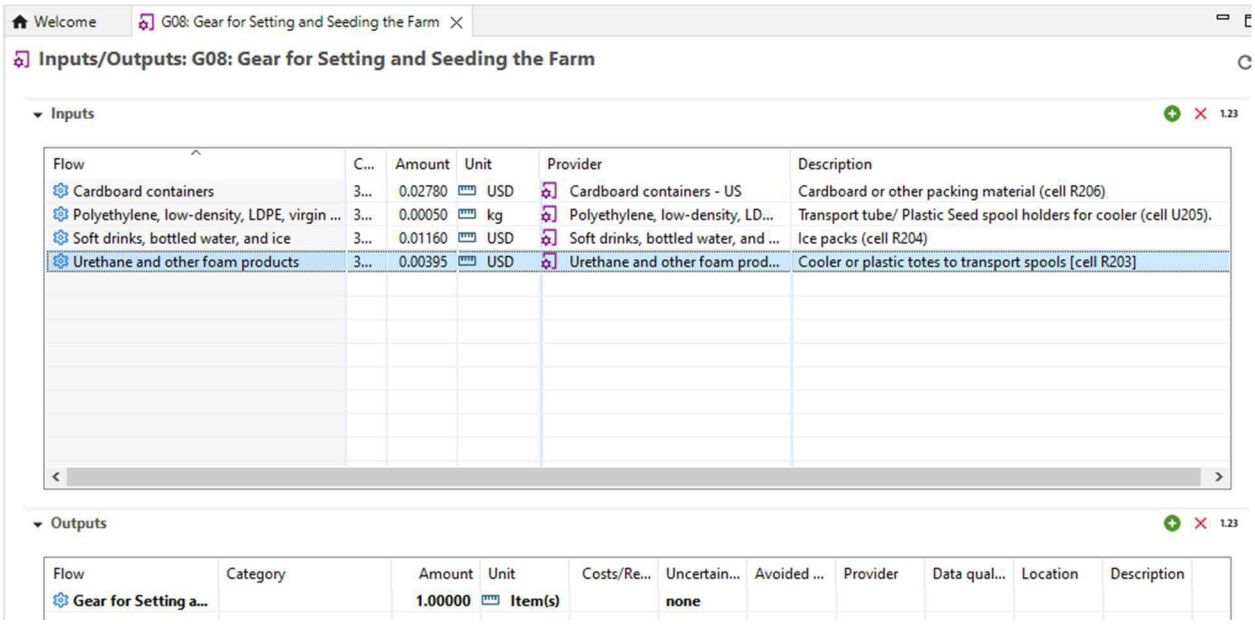
xviii. Follow the same procedure to enter all material and energy requirements for processes 'N01b' through 'N12'. The Excel tables for processes 'N01a' through "N11' are found in the worksheet '2(a). Start up nursery – LCA' (cells O45 : AC415) while process 'N12: Nursery Power and Fuel Requirements' is found in the worksheet '3. Operating Expenses – LCA' (cells Q69: Y70).

xix. The process 'AA: Seed Spool' compiles all requirements listed in processes 'N01a' through 'N12'. Open this process and click on the header 'Provider' to order the flows by process number. The 'Amount' values for processes 'N03' through 'N12' should be 1.00 (i.e., one "unit" of each process is considered in the analysis). Please notice that only one of the processes 'N01a' and 'N01b' can be assigned an 'Amount' of 1.00, depending on whether water is transported in or pumped in. The same applies to processes 'N02a' and 'N02b'. The 'Output' of process 'AA: Seed Spool' is one foot of spool.

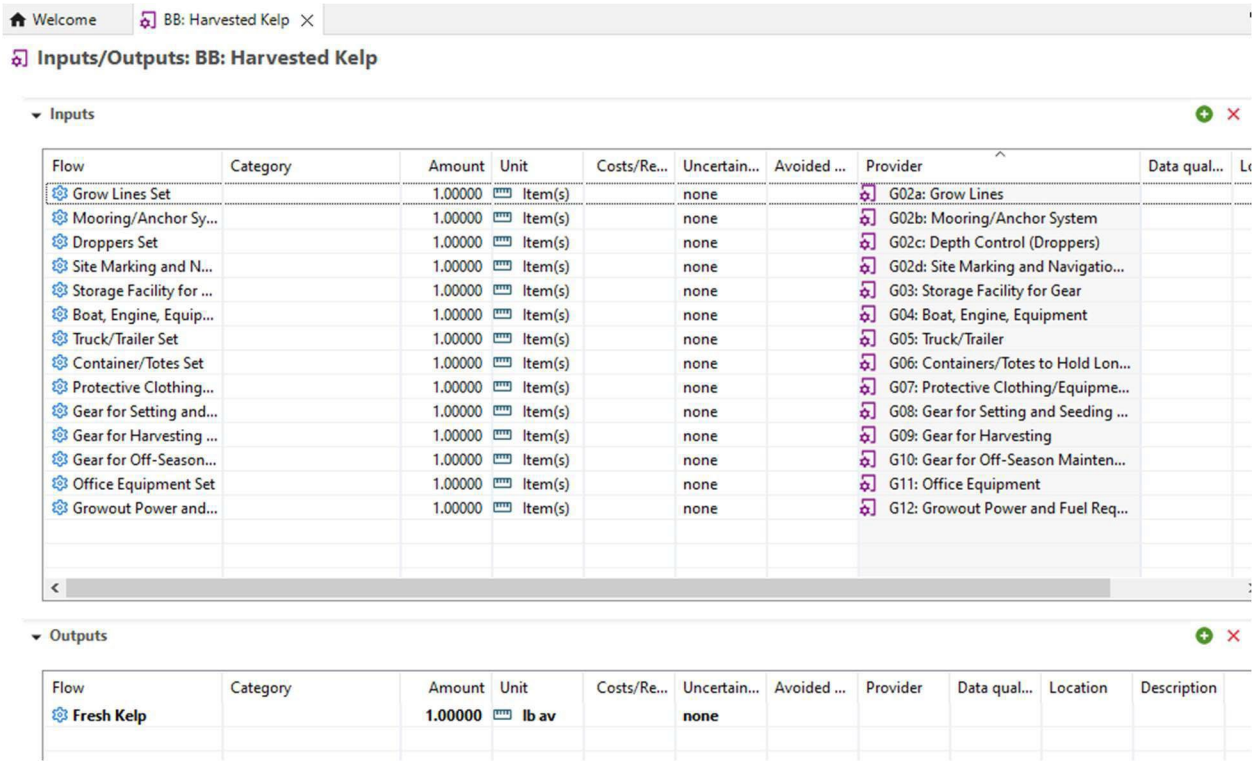


xx. The same procedure is used to enter the material and energy requirements from the worksheets “2(b). Start up farm – LCA” (cells M68 : AA255); and “3. Operating Expenses – LCA” (cells Q97 : Y98) into the processes ‘G02a’ through ‘G12’. The ‘Description’ column in each process refers to the specific cell in the worksheets computing the material requirement per pound of fresh kelp at harvest. These values are then entered into the ‘Amount’ column for each process. See the example below for process ‘G08: Gear for Setting and Seeding the Farm’.

openLCA Flow			Amount			Amount		
Name	Process	Unit	Current USD per lb of harvested kelp	Adjustment Factor	2012 USD per lb of harvested kelp	kg per individual item	kg - all items	kg per lb of harvested kelp
Urethane and other foam products	G08	2012 USD	1.00E-02	0.395	3.95E-03			
Soft drinks, bottled water, and ice	G08	2012 USD	2.50E-02	0.466	1.16E-02			
Polyethylene, LDPE	G08	kg				5.00	5.00	5.00E-04
Cardboard containers	G08	2012 USD	5.00E-02	0.557	2.78E-02			



xxi. The process ‘BB: Harvested Kelp’ compiles all requirements listed in processes ‘G02a’ through ‘G12’. Open this process and click on the header ‘Provider’ to order the flows by process number. The value listed in the ‘Amount’ column should be 1.00 for each process. The ‘Output’ of process ‘BB: Harvested Kelp’ is one pound of fresh kelp at harvest.

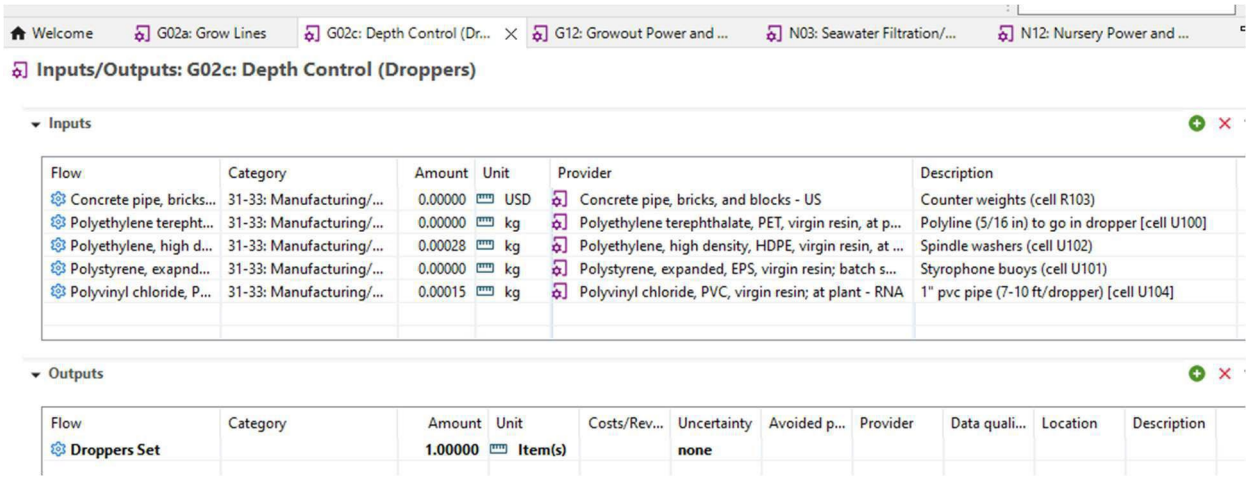


xxii. A simplified example is provided below to demonstrate how the simulation is run. Assume that the production of one pound of fresh kelp at harvest involves only the following

(hypothetical) amounts, which will be entered directly into openLCA:

Offshore Farm: Two 200-ft grow lines, with five pounds of usable harvest per foot of line		
Item	**Unit**	**Value**
Output: Reference Flow		
Fresh kelp	lb	1
Inputs: Materials		
Seedstring	ft	0.2
Fuel	gallon	0.006
Aluminum, primary	kg	0.00076
Steel, stainless	kg	0.00234
Polypropylene (PP)	kg	1.375E-6
Polyethylene, high density (HDPE)	kg	0.00028
Polyvinyl chloride (PVC)	kg	0.00015

In turn, only the UV sterilizer and electricity consumption will be considered for the production of one foot of spool (seedstring):



ft Welcome @ G02a: Grow lines @ G02c: Depth Control (Dr... @ G12: Growout Power and... X &.] N03: Seawater Filtration/... @ N12: Nursery Power and ...

@ Inputs/Outputs:G12: Growout Power and Fuel Requirements

... Inputs 0 x

Flow	Category	Amount	Unit	Provider	Description
® Electricity, at grid· R...	22: Utilities/2211: Electr...	0.00000	El kWh	@ Electricity, Eastern US, 2014 • US	Cell V97.
$ Gasoline,. combusted...	22: Utilities/2213: Water...	0.00600	El gal (US fl)	@ Gasoline,.combusted in equipment - RNA	Cell Y98.

• Outputs 0 X

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided p...	Provider	Data quali...	Location	Description
$ Growout Power an...		1.00000	El Item(s)		none					

• Welcome @ G02a: Grow lines @ G02c: Depth Control(Dr... @ G12: Growout Power and ... @ N03: Seawater Filtration/.., X @ N12: Nursery Power and ..,

@ Inputs/Outputs: N03: Seawater Filtration/Sterilization System

... Inputs 0 X

Flow	Category	Amount	Unit	Provider	Description
@ Fluid meters and counti...	31-33: Manufactur...	0.00000	El USO	@ Fluid meters and counting devices· US	Digital flow meters (cell R154).
Eel Irradiation apparatuses	31-33: Manufactur...	0.05785	El USO	@ Irradiation apparatuses.• US	UV rterilizer (cell R151).
$ Polyethylene, high densi...	31-33: Manufactur...	0.00000	El kg	@ Polyethylene, high density, HOPE, virgin r...	Storage reservoir/tank/structure (cell U144).
!el Polyethylene, high densi...	31-33: Manufactur...	0.00000	El kg	@ Polyethylene, high density, HOPE, virgin r...	5-Gal plastic carboys/jugs (cell U1S8).
@ Polypropylene, PP, virgi...	31-33: Manufactur...	0.00000	El kg	@ Polypropylt!!ne., PP, virgin resin, at plant· ...	Filter cartridges (cell U148).
$ Polypropylene, PP, virgi..,	31-33: Manufactur,..	0.00000	El kg	@ Polypropylene. PP, virgin resin, at plant· ..,	Filters (fine) • cell U149.
$ Polyvinyl chloride, PVC, ...	31-33: Manuf actur...	0.00000	El kg	@ Polyvinyl chloride, PVC, virgin resin; at pl...	PVC pipe and fittings/pipe supports (cell U147).
!el Polyvinyl chloride, PVC, ...	31-33: Manufactur...	0.00000	El kg	@ Polyvinyl chloride, PVC, virgin resin; at pl...	PVC pipe and fittings (cell U153).
$ Polyvinyl chloride, PVC, ...	31-33: Manufactur...	0.00000	El kg	@ Polyvinyl chloride,. PVC, virgin resin; at pl...	PVC pipe and fittings (cell Ul50).
$ Polyvinyl chloride, PVC, ...	31-33: Manufactur...	0.00000	El kg	@ Polyvinyl chloride, PVC, virgin resin; at pl...	Freshwater inflow/PVC pipe/fittings (cell U156).
$ Pumps and pumping eq...	31-33: Manufactur...	0.00000	El USO	@ Pumps and pumping equipment - US	Peri5taltic pump/tubing/valves (cell R145).
$ Rubber and plastic belts...	31-33: Manufactur...	0.00000	El USO	@ Rubber and plastic belts and hoses· US	Hose (cell R157).
t§l Sand, gravel, clay, phosp...	21: Mining, Quarry...	0.00000	El USO	@ Sand, gravel, clay, phosphate, other non..,	Sand filters (poolfilters)• cell R146.
$ Shelving and lockers	31-33: Manufactur...	0.00000	El USO	@ Shelving and lockers· US	Racks/table (cell R155).

• Outputs 0 X

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided p...	Provider	Data quali...	Location	Description
@ Seawater Filtration/ ..•		**1.00000**	El **Item(s)**							

l'- Welcome @ G02a: Grow lines @ G02c: Depth Control (Dr... @ G12: Growout Power and ... @ N03: Seawater Filtration/... @ N12: Nursery Power and ... X

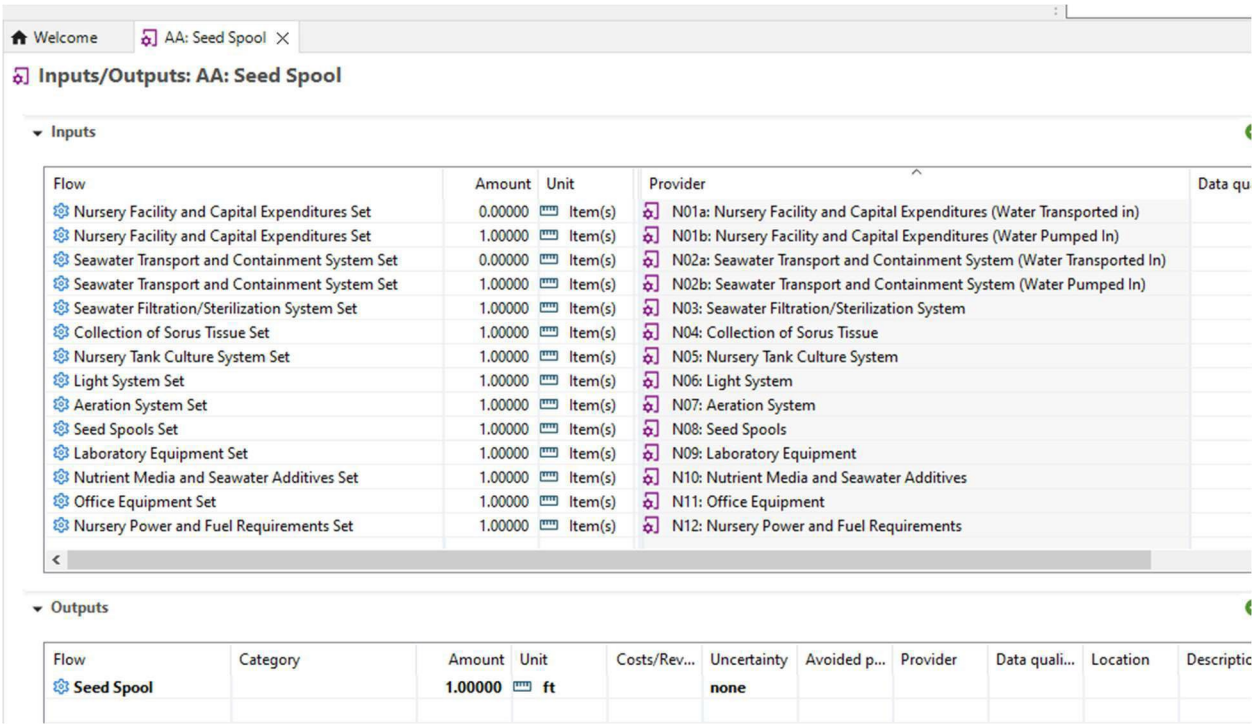
@ Inputs/Outputs: N12: Nursery Power and Fuel Requirements

... Inputs Ox

Flow	Category	Amount	Unit	Provider	Description
@ Electricity, at grid • RNA	22: Utilities/...	0.01100	El kWh	@ Electricity, Eastern US, 2014 • US	Cell V69.
$ Gasoline., combu5ted in equipment...	22: Utilities/...	0.00000	El gal (US...	@ Gasoline, combusted in equipm...	Cell Y70.

Outputs 0 x

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided p...	Provider	Data quali...	Location	Description
$ Nursery Power and ...		1.00000	El Item(s)		none					



Welcome | AA: Seed Spool

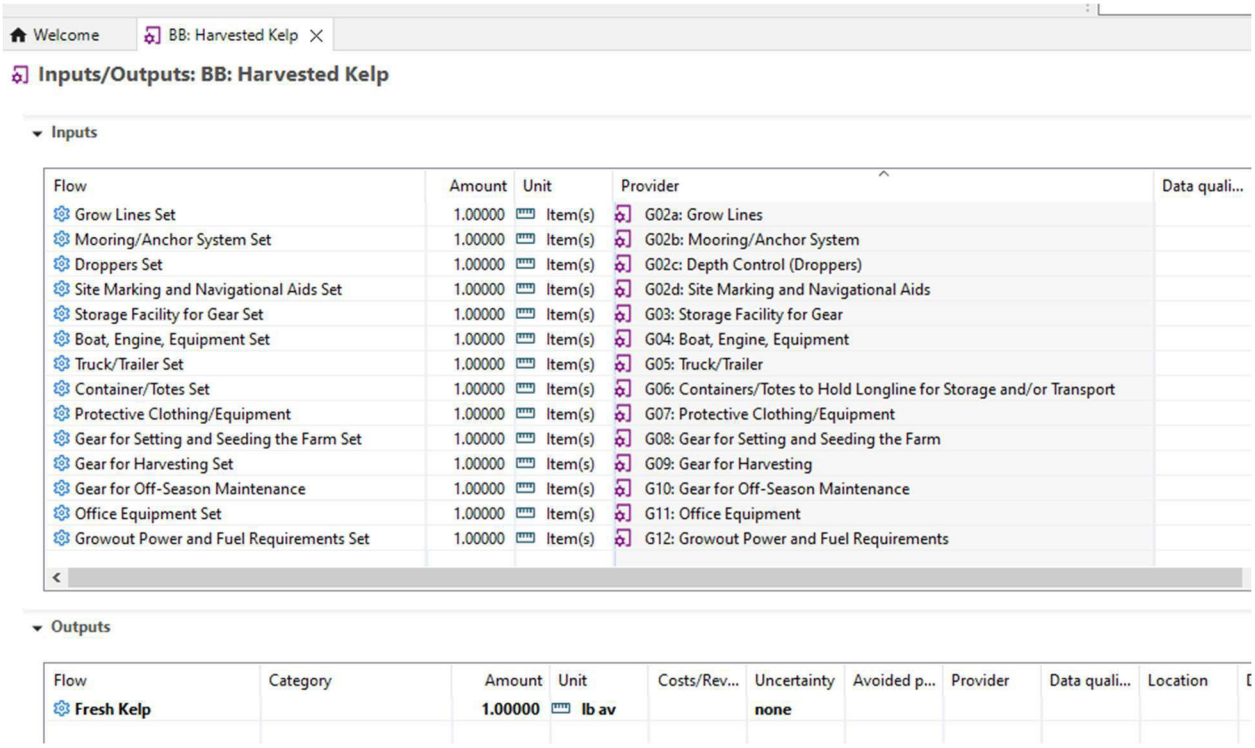
Inputs/Outputs: AA: Seed Spool

Inputs

Flow	Amount	Unit	Provider	Data qu
Nursery Facility and Capital Expenditures Set	0.00000	Item(s)	N01a: Nursery Facility and Capital Expenditures (Water Transported in)	
Nursery Facility and Capital Expenditures Set	1.00000	Item(s)	N01b: Nursery Facility and Capital Expenditures (Water Pumped In)	
Seawater Transport and Containment System Set	0.00000	Item(s)	N02a: Seawater Transport and Containment System (Water Transported In)	
Seawater Transport and Containment System Set	1.00000	Item(s)	N02b: Seawater Transport and Containment System (Water Pumped In)	
Seawater Filtration/Sterilization System Set	1.00000	Item(s)	N03: Seawater Filtration/Sterilization System	
Collection of Sorus Tissue Set	1.00000	Item(s)	N04: Collection of Sorus Tissue	
Nursery Tank Culture System Set	1.00000	Item(s)	N05: Nursery Tank Culture System	
Light System Set	1.00000	Item(s)	N06: Light System	
Aeration System Set	1.00000	Item(s)	N07: Aeration System	
Seed Spools Set	1.00000	Item(s)	N08: Seed Spools	
Laboratory Equipment Set	1.00000	Item(s)	N09: Laboratory Equipment	
Nutrient Media and Seawater Additives Set	1.00000	Item(s)	N10: Nutrient Media and Seawater Additives	
Office Equipment Set	1.00000	Item(s)	N11: Office Equipment	
Nursery Power and Fuel Requirements Set	1.00000	Item(s)	N12: Nursery Power and Fuel Requirements	

Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided p...	Provider	Data quali...	Location	Descriptic
Seed Spool		**1.00000**	**ft**		**none**					



Welcome | BB: Harvested Kelp

Inputs/Outputs: BB: Harvested Kelp

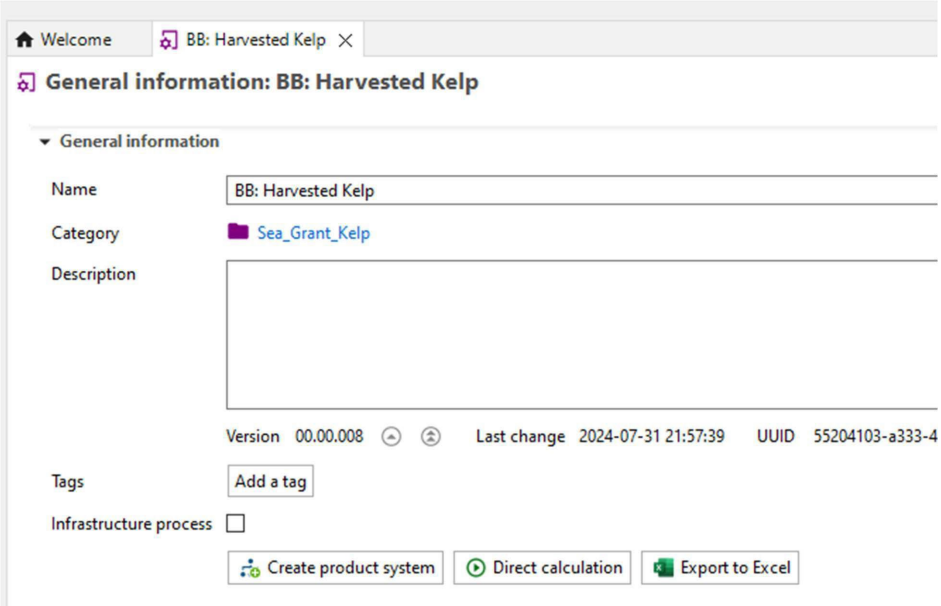
Inputs

Flow	Amount	Unit	Provider	Data quali...
Grow Lines Set	1.00000	Item(s)	G02a: Grow Lines	
Mooring/Anchor System Set	1.00000	Item(s)	G02b: Mooring/Anchor System	
Droppers Set	1.00000	Item(s)	G02c: Depth Control (Droppers)	
Site Marking and Navigational Aids Set	1.00000	Item(s)	G02d: Site Marking and Navigational Aids	
Storage Facility for Gear Set	1.00000	Item(s)	G03: Storage Facility for Gear	
Boat, Engine, Equipment Set	1.00000	Item(s)	G04: Boat, Engine, Equipment	
Truck/Trailer Set	1.00000	Item(s)	G05: Truck/Trailer	
Container/Totes Set	1.00000	Item(s)	G06: Containers/Totes to Hold Longline for Storage and/or Transport	
Protective Clothing/Equipment	1.00000	Item(s)	G07: Protective Clothing/Equipment	
Gear for Setting and Seeding the Farm Set	1.00000	Item(s)	G08: Gear for Setting and Seeding the Farm	
Gear for Harvesting Set	1.00000	Item(s)	G09: Gear for Harvesting	
Gear for Off-Season Maintenance	1.00000	Item(s)	G10: Gear for Off-Season Maintenance	
Office Equipment Set	1.00000	Item(s)	G11: Office Equipment	
Growout Power and Fuel Requirements Set	1.00000	Item(s)	G12: Growout Power and Fuel Requirements	

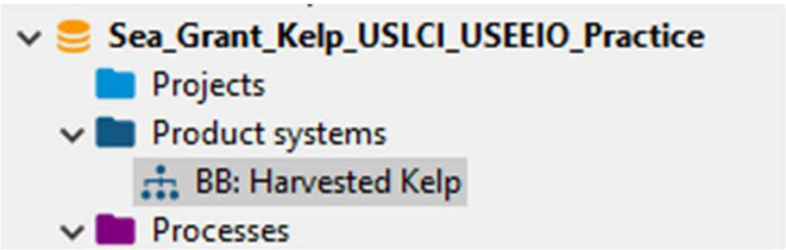
Outputs

Flow	Category	Amount	Unit	Costs/Rev...	Uncertainty	Avoided p...	Provider	Data quali...	Location
Fresh Kelp		**1.00000**	**lb av**		**none**				

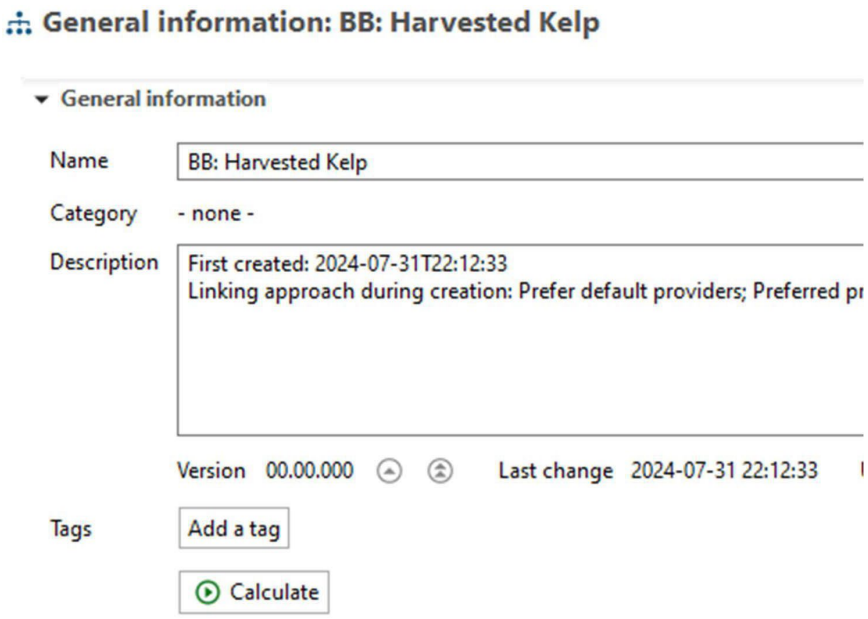
xxiv. The next step is to create a Product System that integrates all the information from the model processes to compute the environmental impact assessment associated with one pound of fresh kelp. This is done by clicking the tab ‘General Information’ in the process ‘BB: Harvested Kelp’.



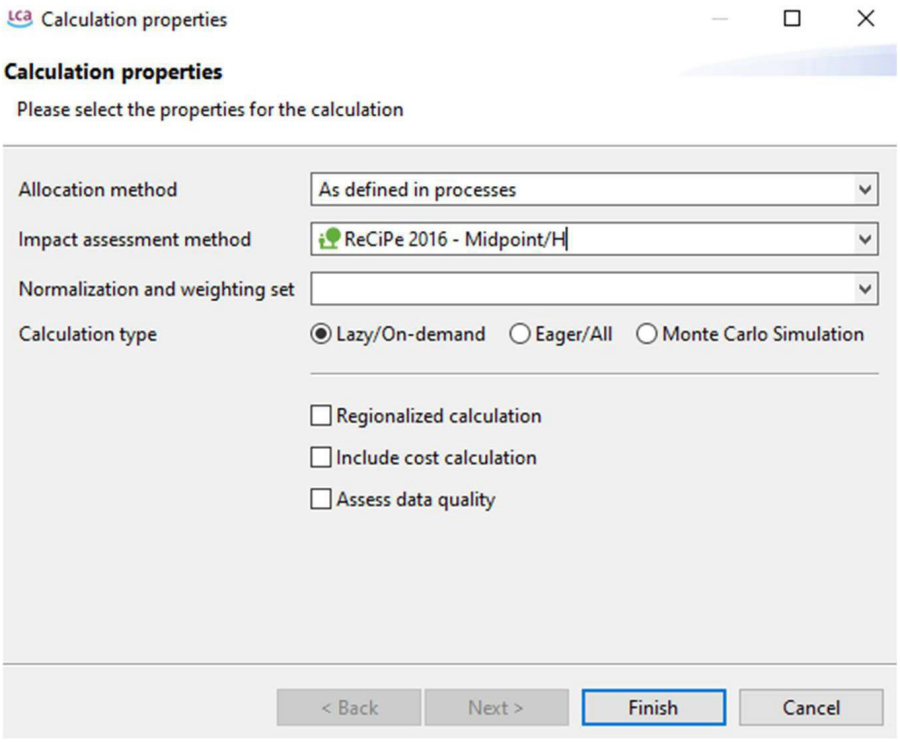
xxv. The new Product System will automatically be labeled as 'BB: Harvested Kelp'. There is no need to change any other options. Click on 'Finish' to create the system, which will be stored in the folder 'Product systems'.



xxvi. A 'Calculate' button will be found in the 'General Information' tab of the Product System. Click on it.



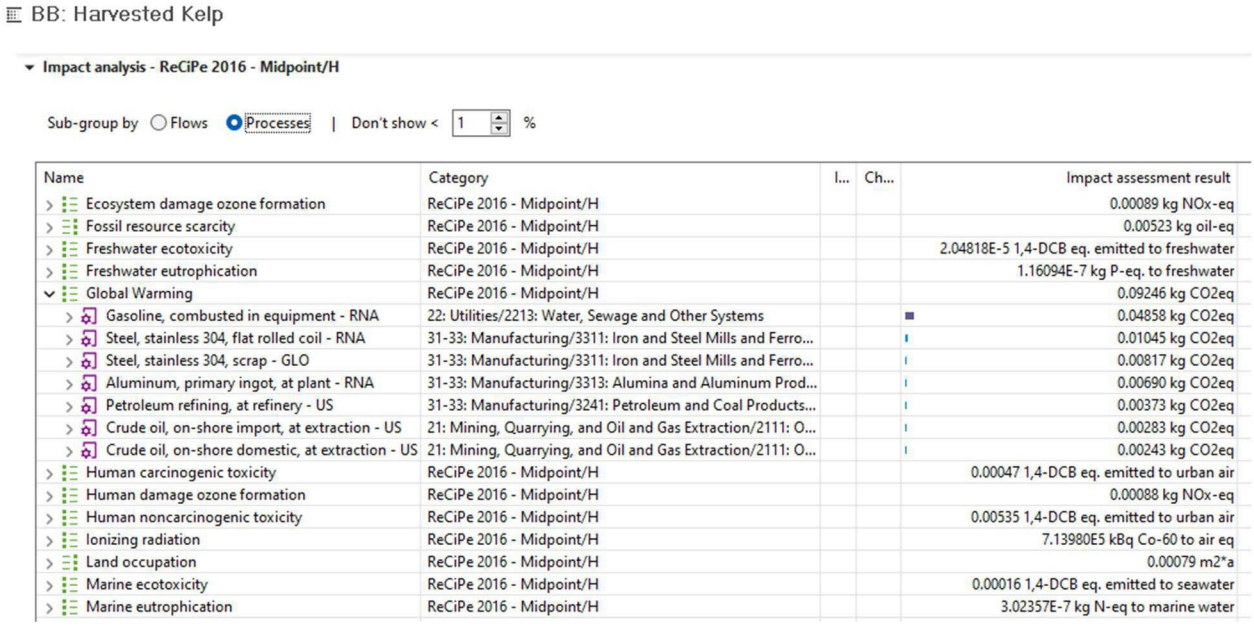
xxvii. The default options in the 'Calculation Properties' window will suffice for the analysis. 'ReCiPe 2016 – Midpoint/H' can be selected as the Impact Assessment Method. Click on 'Finish'.



xxviii. A Results panel with nine different tabs will be generated by openLCA. To obtain a quick summary of the results, click on the tab 'Impact Analysis'. This tab presents the results of 18 different impact categories. According to the assumptions used in the example, the production of one pound of fresh kelp releases 0.092 kg CO_2-eq (Global Warming) and

3.024E-7 kg N-eq to marine water (Marine Eutrophication).

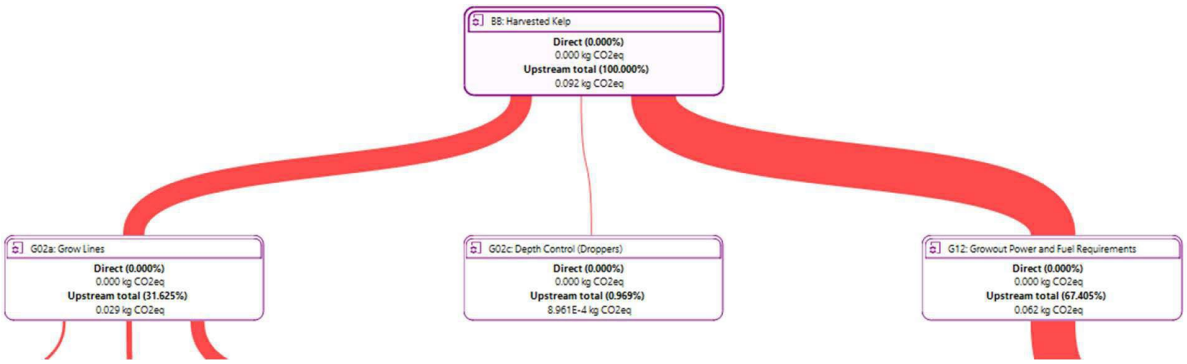
xxix. Notice that impacts can be sub-grouped by flows or processes (upper portion of the panel). Check the radio button for Processes and expand the Global Warming category. The different processes contributing carbon emissions will be listed in descending order of importance. The process 'Gasoline, combusted in equipment – RNA' contributed over 50% (0.04858 kg CO_2-eq) of total emissions.



Name	Category	I...	Ch...	Impact assessment result
Ecosystem damage ozone formation	ReCiPe 2016 - Midpoint/H			0.00089 kg NOx-eq
Fossil resource scarcity	ReCiPe 2016 - Midpoint/H			0.00523 kg oil-eq
Freshwater ecotoxicity	ReCiPe 2016 - Midpoint/H			2.04818E-5 1,4-DCB eq. emitted to freshwater
Freshwater eutrophication	ReCiPe 2016 - Midpoint/H			1.16094E-7 kg P-eq. to freshwater
Global Warming	ReCiPe 2016 - Midpoint/H			0.09246 kg CO2eq
Gasoline, combusted in equipment - RNA	22: Utilities/2213: Water, Sewage and Other Systems			0.04858 kg CO2eq
Steel, stainless 304, flat rolled coil - RNA	31-33: Manufacturing/3311: Iron and Steel Mills and Ferro...			0.01045 kg CO2eq
Steel, stainless 304, scrap - GLO	31-33: Manufacturing/3311: Iron and Steel Mills and Ferro...			0.00817 kg CO2eq
Aluminum, primary ingot, at plant - RNA	31-33: Manufacturing/3313: Alumina and Aluminum Prod...			0.00690 kg CO2eq
Petroleum refining, at refinery - US	31-33: Manufacturing/3241: Petroleum and Coal Products...			0.00373 kg CO2eq
Crude oil, on-shore import, at extraction - US	21: Mining, Quarrying, and Oil and Gas Extraction/2111: O...			0.00283 kg CO2eq
Crude oil, on-shore domestic, at extraction - US	21: Mining, Quarrying, and Oil and Gas Extraction/2111: O...			0.00243 kg CO2eq
Human carcinogenic toxicity	ReCiPe 2016 - Midpoint/H			0.00047 1,4-DCB eq. emitted to urban air
Human damage ozone formation	ReCiPe 2016 - Midpoint/H			0.00088 kg NOx-eq
Human noncarcinogenic toxicity	ReCiPe 2016 - Midpoint/H			0.00535 1,4-DCB eq. emitted to urban air
Ionizing radiation	ReCiPe 2016 - Midpoint/H			7.13980E5 kBq Co-60 to air eq
Land occupation	ReCiPe 2016 - Midpoint/H			0.00079 m2*a
Marine ecotoxicity	ReCiPe 2016 - Midpoint/H			0.00016 1,4-DCB eq. emitted to seawater
Marine eutrophication	ReCiPe 2016 - Midpoint/H			3.02357E-7 kg N-eq to marine water

xxx. The tab 'Sankey Diagram' offers another useful way to visualize the results. Click on the upper left-hand icon to select the impact category Global Warming.

xxxi. The Sankey Diagram reveals how different processes in the model contribute to the impact category, Global Warming in this case. 'G02a: Grow Lines' contributes about 32% of emissions while 'G12: Growout Power and Fuel Requirements' accounts for 67% of emissions. The impact of 'G02c: Depth Control' is much lower (about 1%). 'Gasoline, combusted in equipment' directly contributes most of the emissions to 'G12' but upstream processes release some emissions as well. Regarding 'G02a: Grow Lines', most emissions are accounted for by 'Steel, stainless' (20% of total). Under the assumptions made, the nursery phase ('AA: Seed Spool') contributes relatively few emissions (4% of total).



3) Estimation of Ecosystem Services – Carbon Sequestration and Nutrient Removal.

The results from the openLCA model can be used to estimate potential revenue streams from ecosystem services such as carbon sequestration and nutrient removal. To this end, the user needs to refer back to the '2(b). Start up farm – LCA' worksheet, cells AE68 : AN101.

i. Carbon Sequestration: The openLCA Global Warming impact category in the preceding example revealed that 0.09246 kg CO_2-eq per pound of fresh kelp were released by the hypothetical farm. This value is to be entered in cell AF97. The remaining cells in the module estimate the amount of CO_2 that is exported from the farm and sequestered in sediments. This amount is separate from the carbon incorporated to the kelp biomass through photosynthesis; in other words, the carbon removed through harvest is not included in the sequestration calculations.

The parameters used in the model will vary according to the type of substrate in the farm: muddy or coarse. This distinction is made as muddy substrates are associated with sheltered locations and a higher rate of sediment deposition. The user is asked to indicate the choice of sediment in cell AG72.

The amount of carbon sequestration is contrasted with the positive emissions from the farm in order to estimate net CO_2 emissions. If negative (i.e., sequestration exceeds positive emissions), an additional revenue flow is computed in cells AF101 : AH101, which assumes a carbon price of $30 per ton of CO_2-eq.

ii. Nutrient Removal: this module computes the amount of N and P removed through the harvesting of kelp and compares it to the amounts of N and P eutrophication resulting from the LCA model. In the previous example, Marine Eutrophication was estimated at 3.02357E-7 kg N-eq while Freshwater Eutrophication was found to be 1.16094E-7 kg P-eq.

BB: Harvested Kelp

Impact analysis - ReCiPe 2016 - Midpoint/H

Sub-group by ○ Flows ● Processes | Don't show < 1 %

Name	Category	Invent...	Characte...	Impact assessment result
Ecosystem damage ozone formation	ReCiPe 2016 - Midpoint/H			0.00089 kg NOx-eq
Fossil resource scarcity	ReCiPe 2016 - Midpoint/H			0.00523 kg oil-eq
Freshwater ecotoxicity	ReCiPe 2016 - Midpoint/H			2.04818E-5 1,4-DCB eq. emitted to freshwater
Freshwater eutrophication	ReCiPe 2016 - Midpoint/H			1.16094E-7 kg P-eq. to freshwater
Global Warming	ReCiPe 2016 - Midpoint/H			0.09246 kg CO2eq
Human carcinogenic toxicity	ReCiPe 2016 - Midpoint/H			0.00047 1,4-DCB eq. emitted to urban air
Human damage ozone formation	ReCiPe 2016 - Midpoint/H			0.00088 kg NOx-eq
Human noncarcinogenic toxicity	ReCiPe 2016 - Midpoint/H			0.00535 1,4-DCB eq. emitted to urban air
Ionizing radiation	ReCiPe 2016 - Midpoint/H			7.13980E5 kBq Co-60 to air eq
Land occupation	ReCiPe 2016 - Midpoint/H			0.00079 m2*a
Marine ecotoxicity	ReCiPe 2016 - Midpoint/H			0.00016 1,4-DCB eq. emitted to seawater
Marine eutrophication	ReCiPe 2016 - Midpoint/H			3.02357E-7 kg N-eq to marine water
Mineral resource scarcity	ReCiPe 2016 - Midpoint/H			0.00160 kg Cu-eq
Particulate matter formation	ReCiPe 2016 - Midpoint/H			0.00015 kg PM2.5-eq
Stratospheric ozone depletion	ReCiPe 2016 - Midpoint/H			2.87750E-8 kg CFC11-eq
Terrestrial acidification	ReCiPe 2016 - Midpoint/H			0.00046 kg SO2-eq
Terrestrial ecotoxicity	ReCiPe 2016 - Midpoint/H			0.24594 1,4-DCB eq. emitted to industrial soil
Water consumption	ReCiPe 2016 - Midpoint/H			0.05896 m3

These values are to be entered in cells AL83 and AL84, respectively. If the amount of nutrient removal exceeds the nutrient releases from the LCA model, additional revenue streams are computed in cells AL89 : AN90. The N and P prices are estimated at $20/kg and $4/kg, respectively.

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