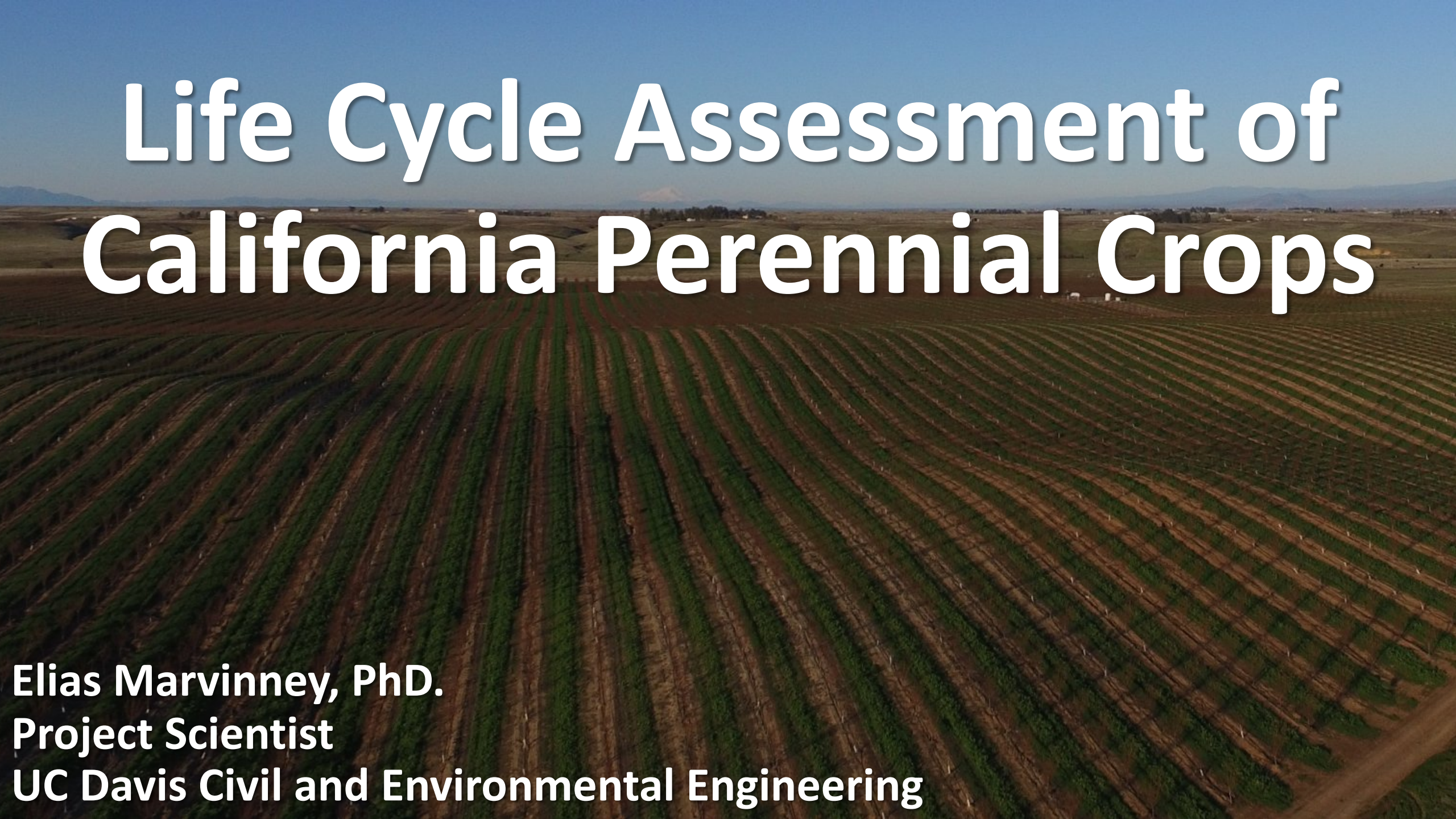
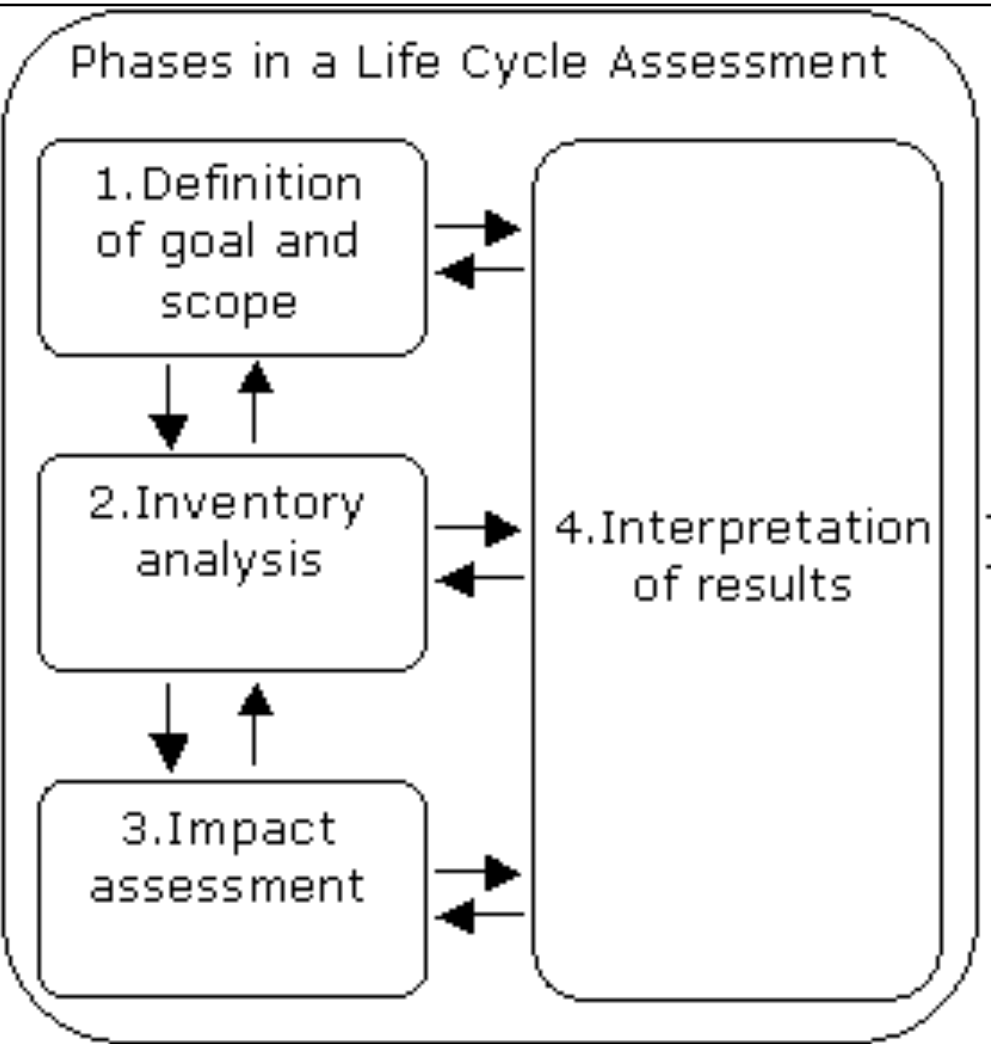
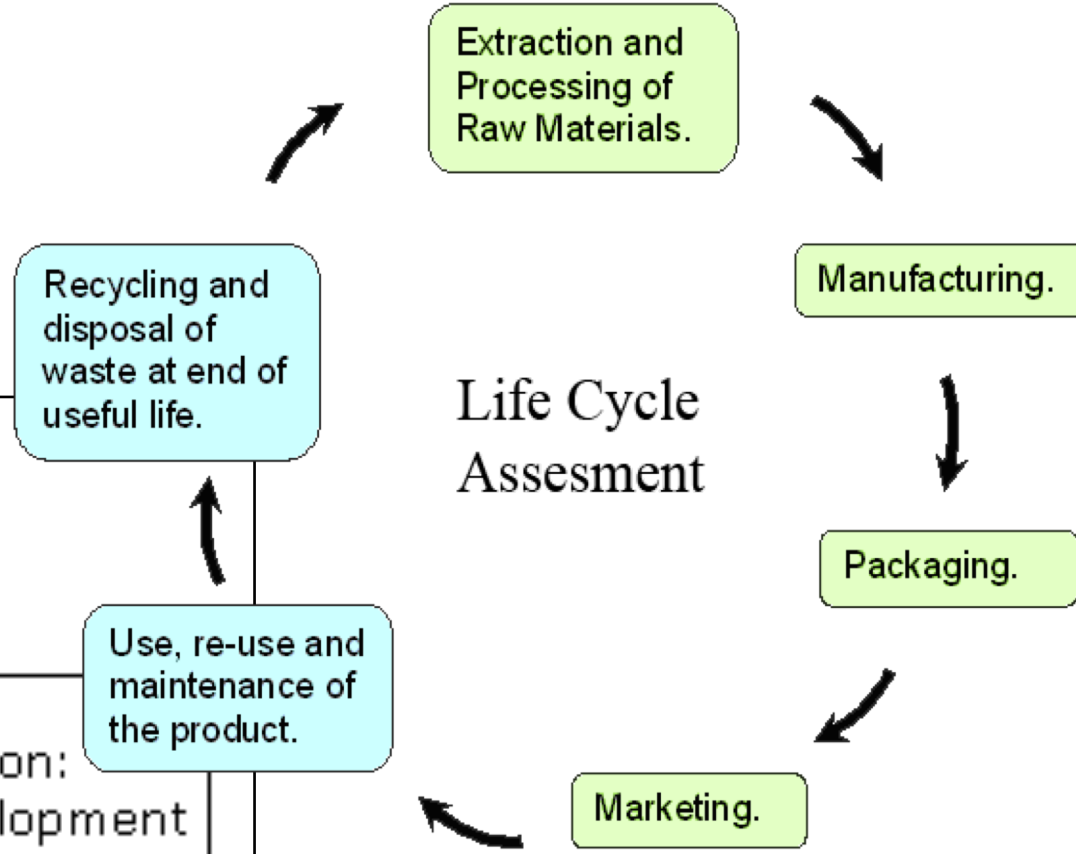


Life Cycle Assessment of California Perennial Crops

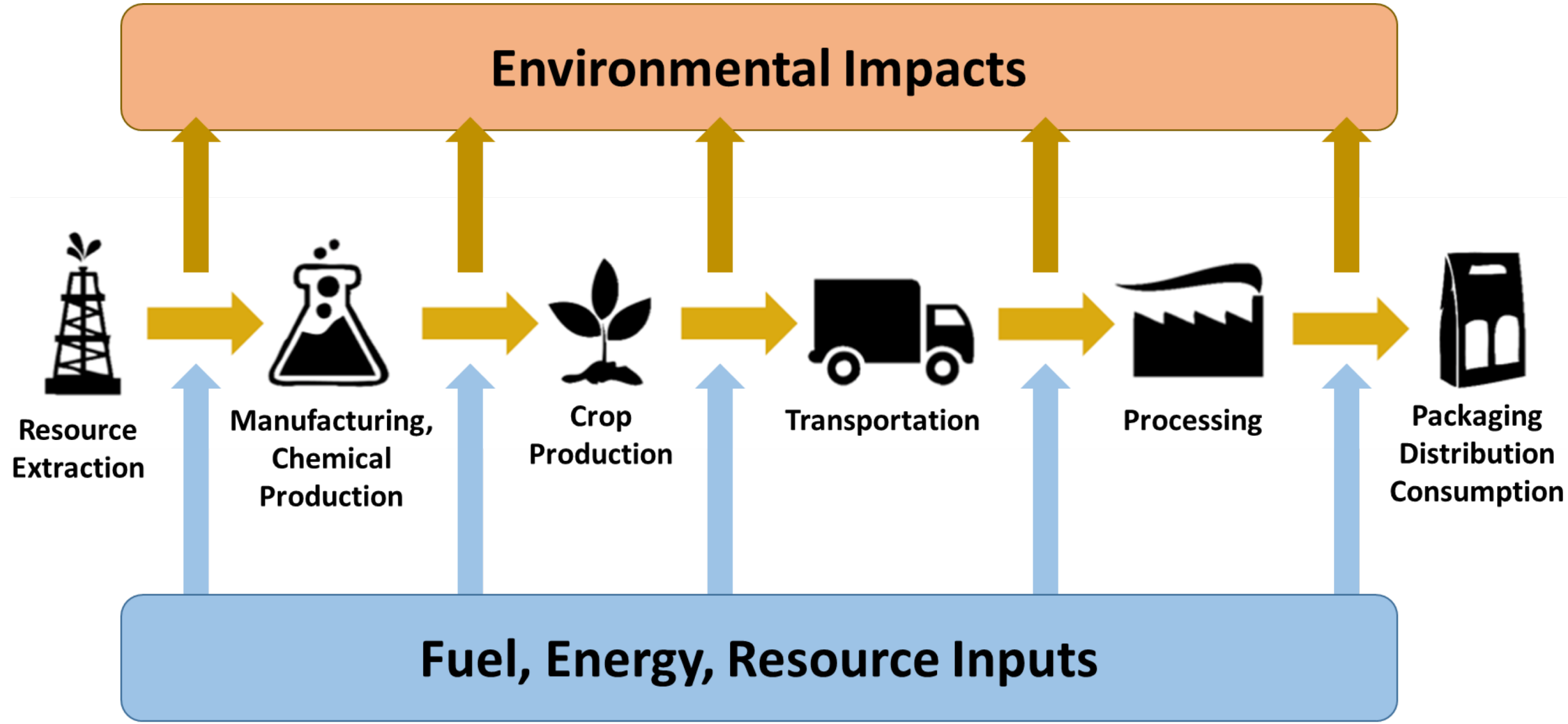
Elias Marvinney, PhD.
Project Scientist
UC Davis Civil and Environmental Engineering

What is life cycle assessment (LCA)?





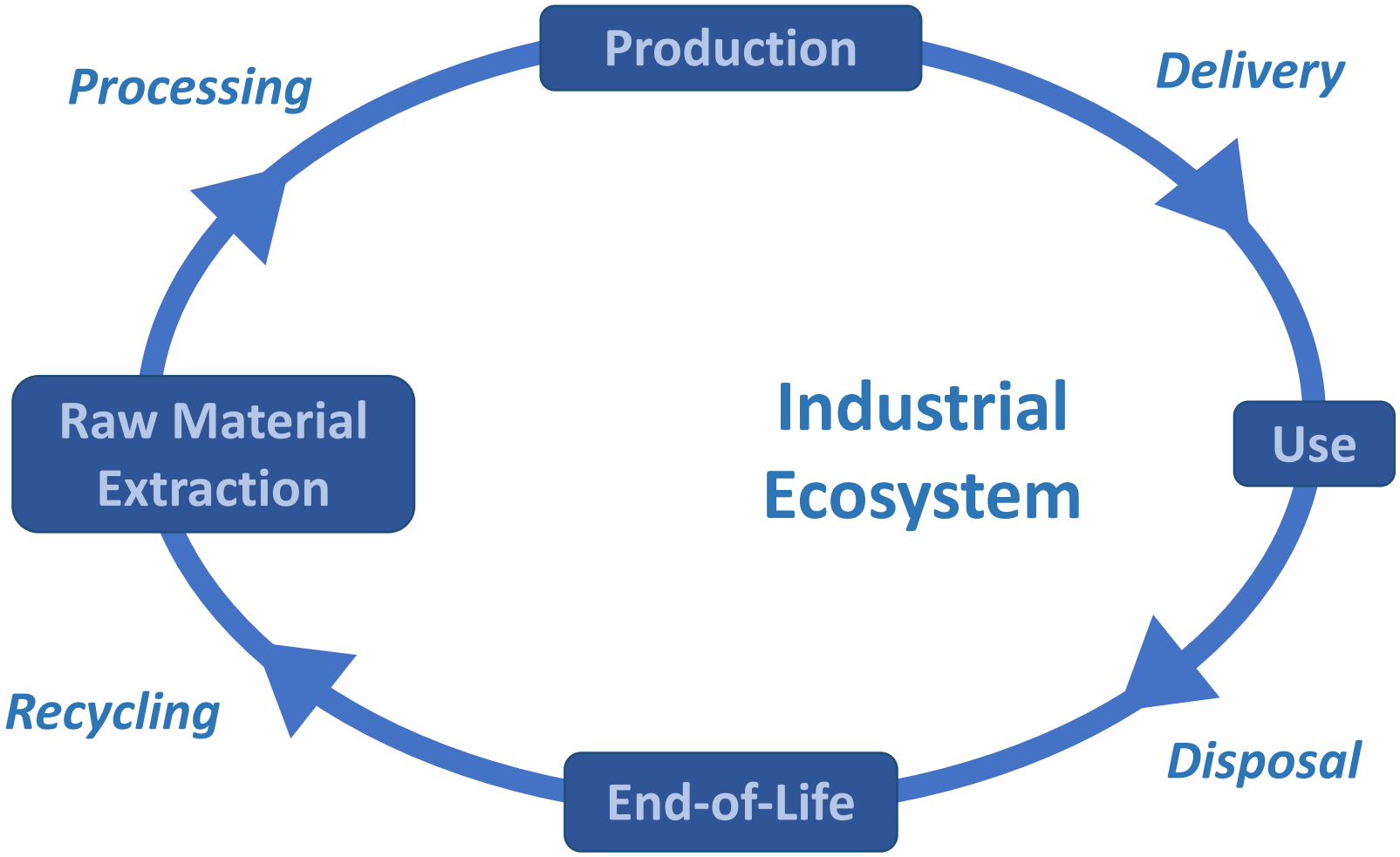
What can LCA tell us about agricultural sustainability?


Environmental Impacts
Resource Extraction
Manufacturing, Chemical Production
Crop Production
Transportation
Processing
Packaging Distribution Consumption
Fuel, Energy, Resource Inputs

Life Cycle Assessment

- Methodological toolset for understanding the impacts and benefits of industrial production systems

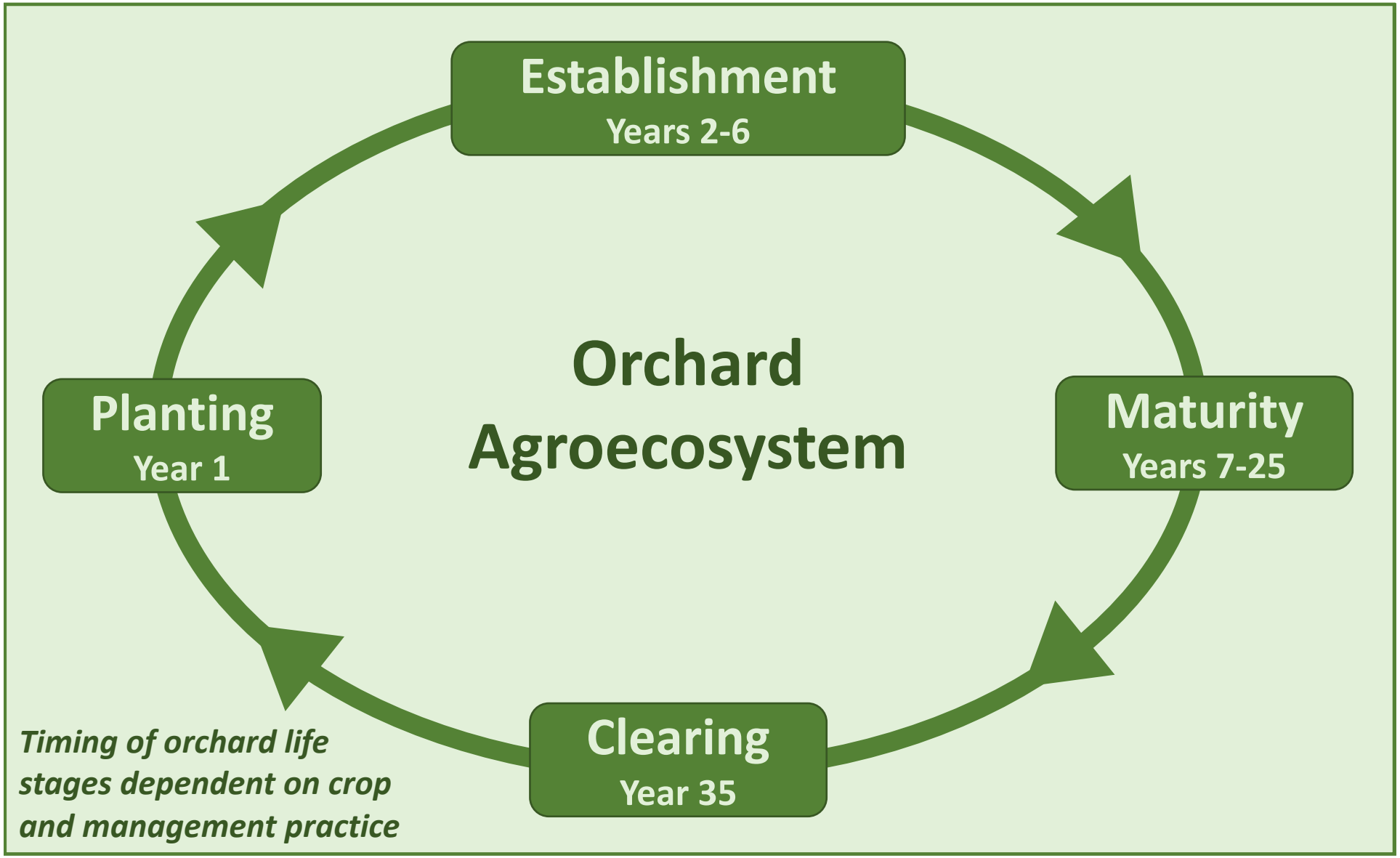
- Including industrial-scale agricultural production



- Phases of production: spatially and temporally separated
- Benefits and impacts occur at each phase

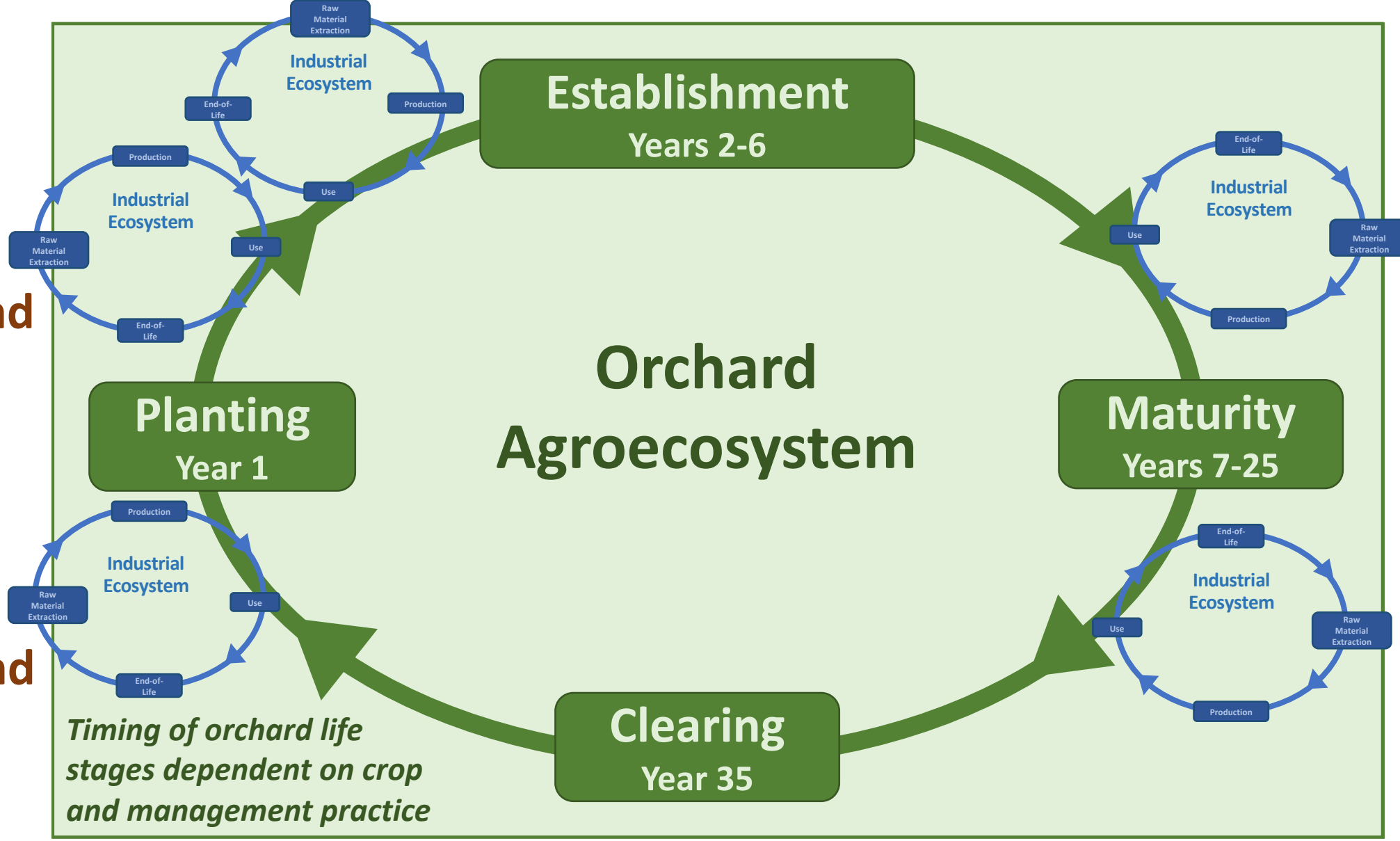
Orchard Life Cycle

- Industrial land use system



Orchard Life Cycle

- Industrial land use system
- Intersects with various industrial extraction and production systems

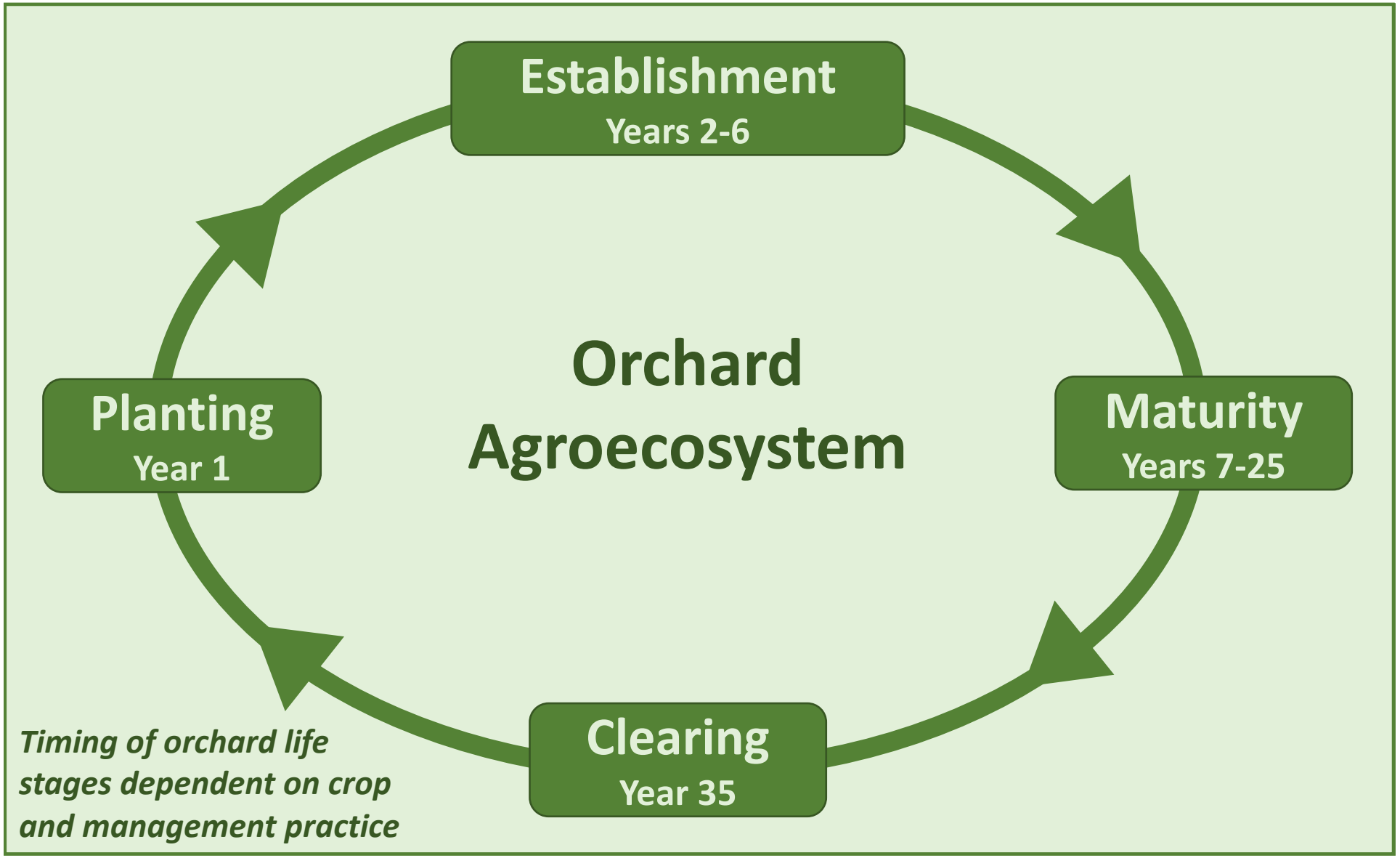


Application of LCA methodology to perennial cropping systems in California

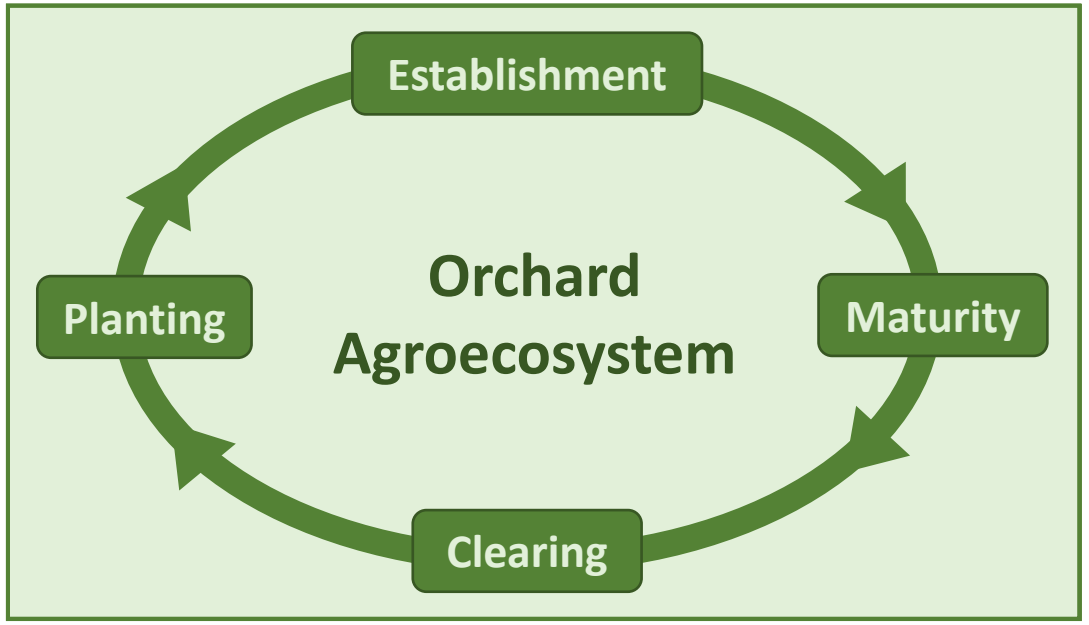
Orchard Life Cycle

Work to date:

- Almond
- Walnut
- Prune
- Pistachio
- Peach
- Citrus
- Beef
- Dairy
- Apiculture
- Mushrooms
- Cell Culture Products

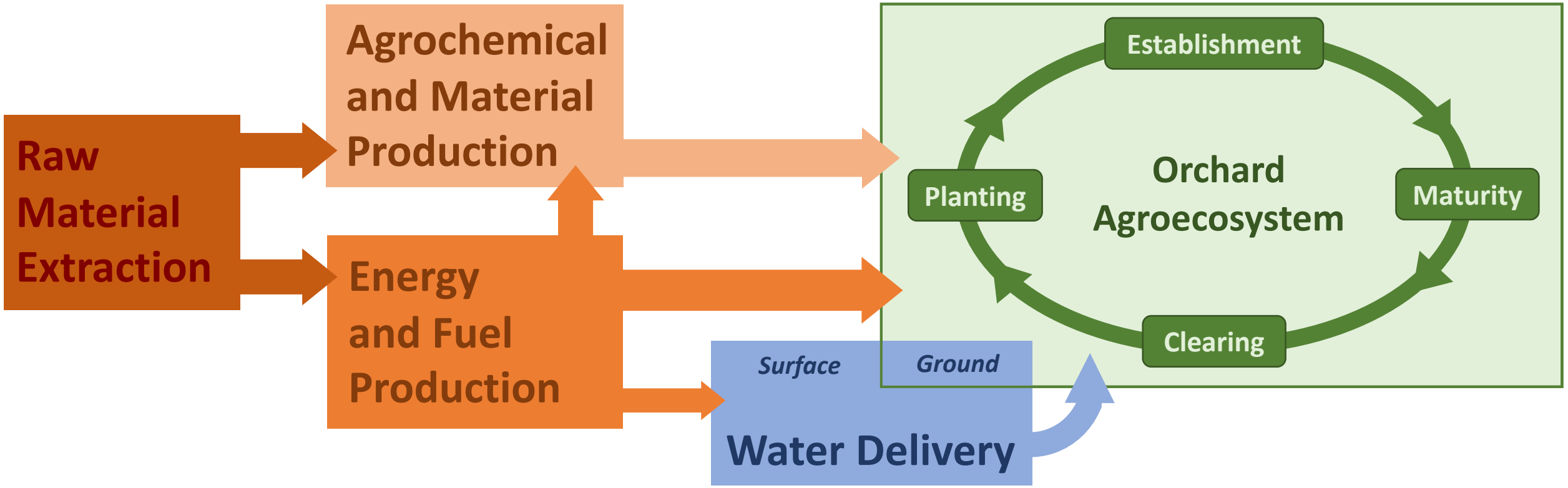


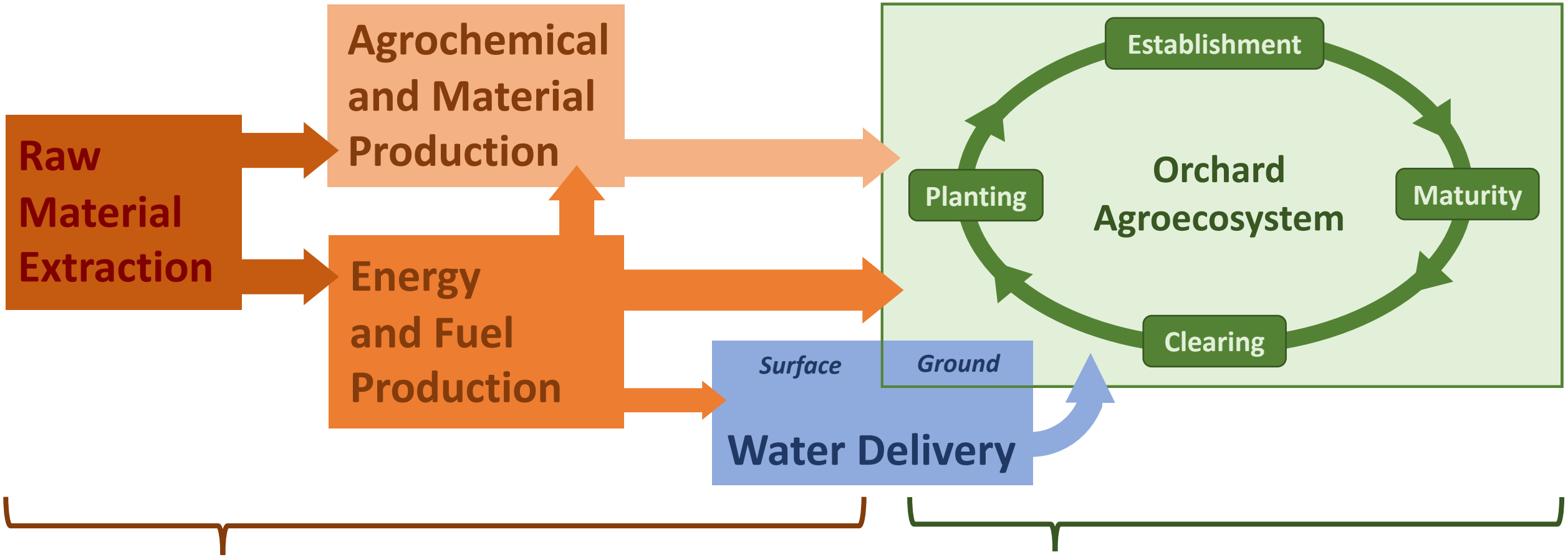
Orchard Life Cycle



Considerations for modeling:

- Productive lifespan and yield
- Biomass accumulation
- Soil emissions and C storage
- Management practices
- Input demand and fuel use
- Location relative to pedo-climatic zones, infrastructure


Raw Material Extraction
Agrochemical and Material Production
Energy and Fuel Production
Surface
Ground
Water Delivery
Establishment
Maturity
Clearing
Planting
Orchard Agroecosystem



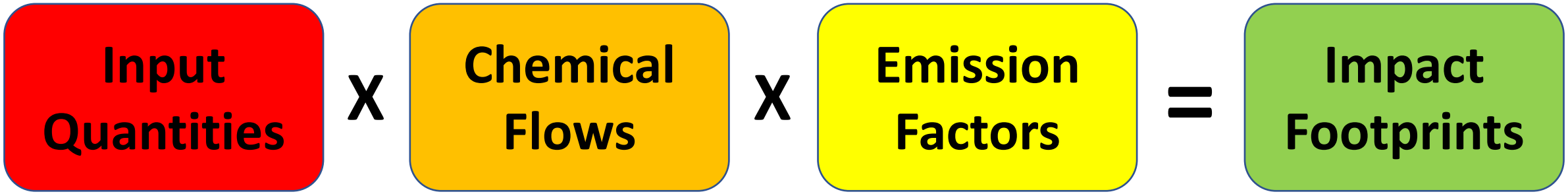
Off-site

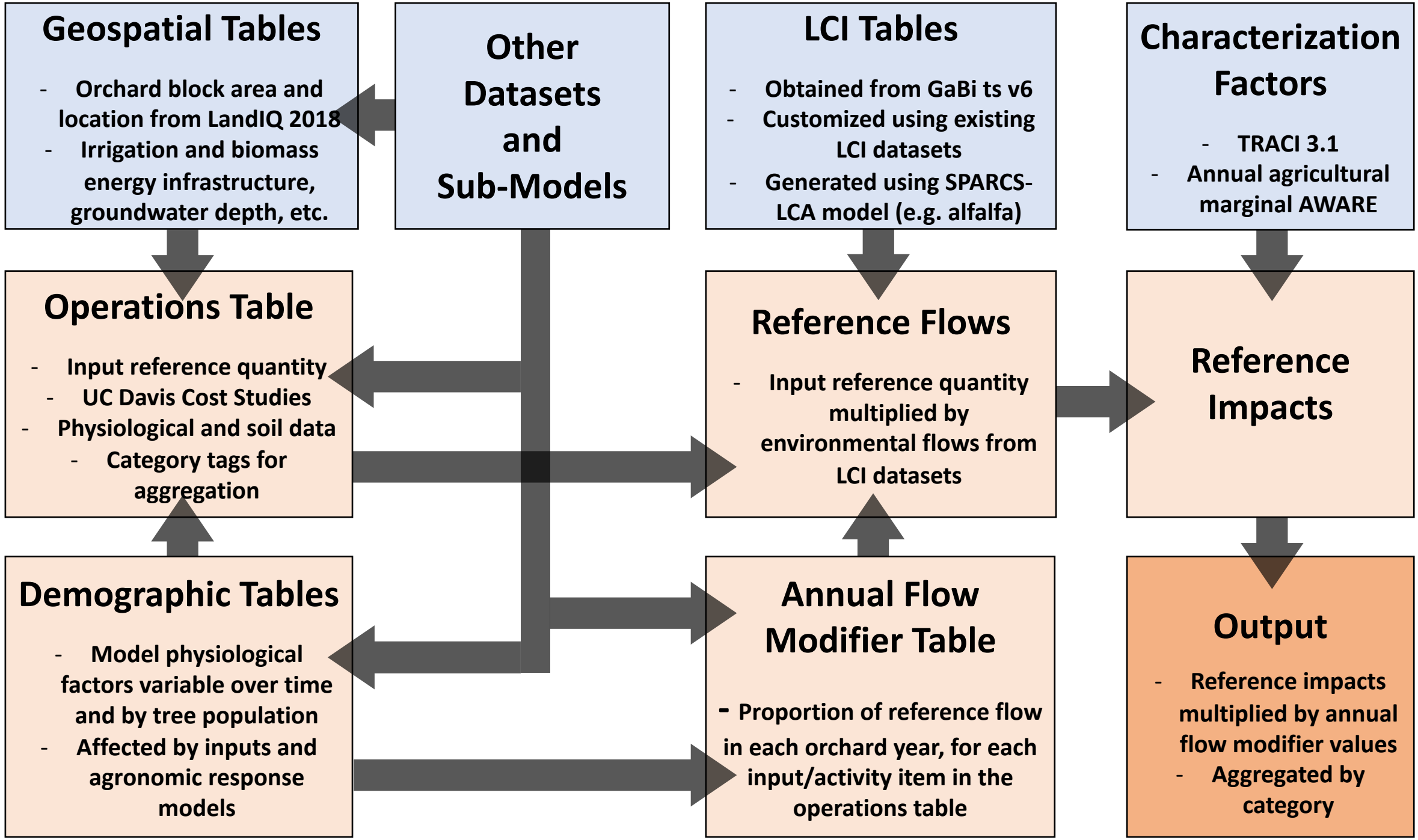
- Industrial production and transport impacts depend on points of origin

On-site

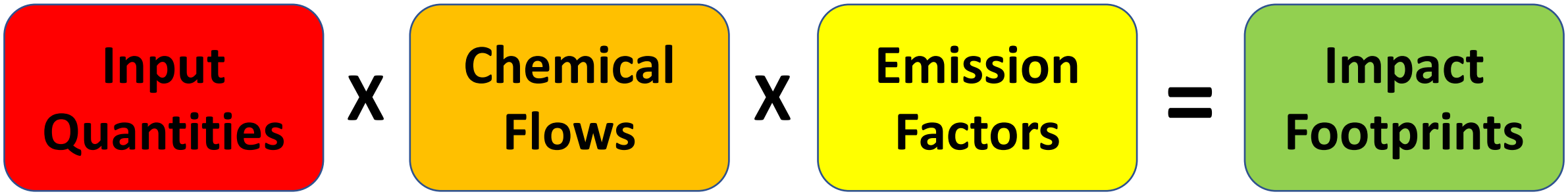
- Soil, climate, infrastructure and management determine input demand and yield

LCA Modeling Basics:

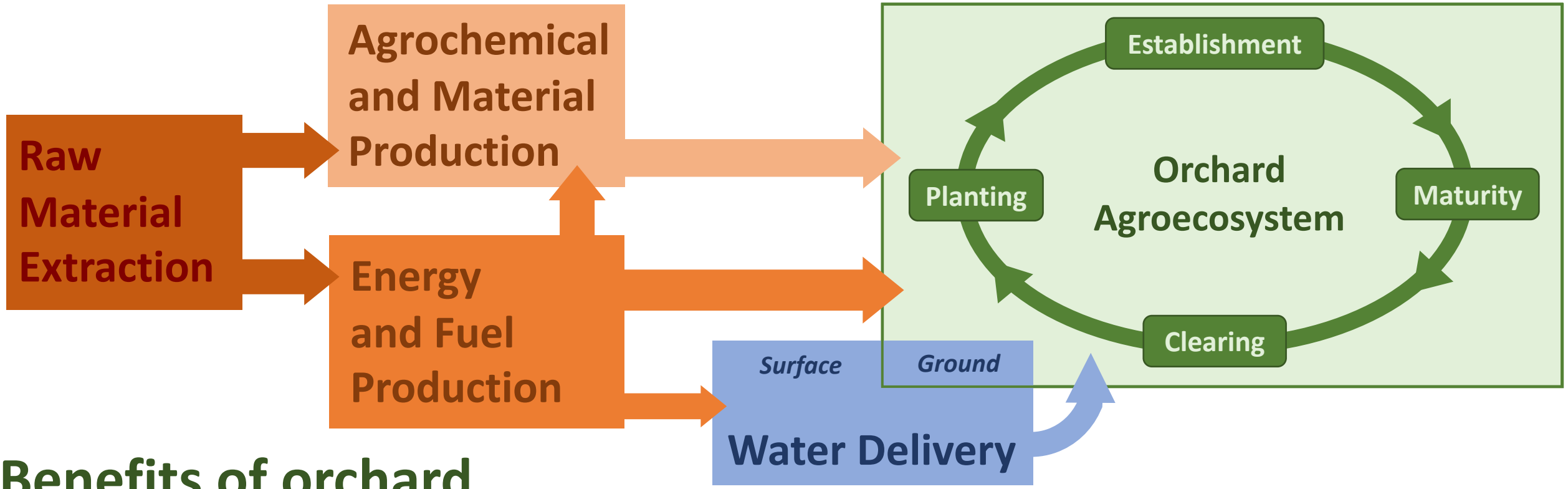



Geospatial Tables
- Orchard block area and location from LandIQ 2018
- Irrigation and biomass energy infrastructure, groundwater depth, etc.
Other Datasets and Sub-Models
LCI Tables
- Obtained from GaBi ts v6
- Customized using existing LCI datasets
- Generated using SPARCS-LCA model (e.g. alfalfa)
Characterization Factors
- TRACI 3.1
- Annual agricultural marginal AWARE
Operations Table
- Input reference quantity
- UC Davis Cost Studies
- Physiological and soil data
- Category tags for aggregation
Reference Flows
- Input reference quantity multiplied by environmental flows from LCI datasets
Reference Impacts
Demographic Tables
- Model physiological factors variable over time and by tree population
- Affected by inputs and agronomic response models
Annual Flow Modifier Table
- Proportion of reference flow in each orchard year, for each input/activity item in the operations table
Output
- Reference impacts multiplied by annual flow modifier values
- Aggregated by category

LCA Modeling Basics

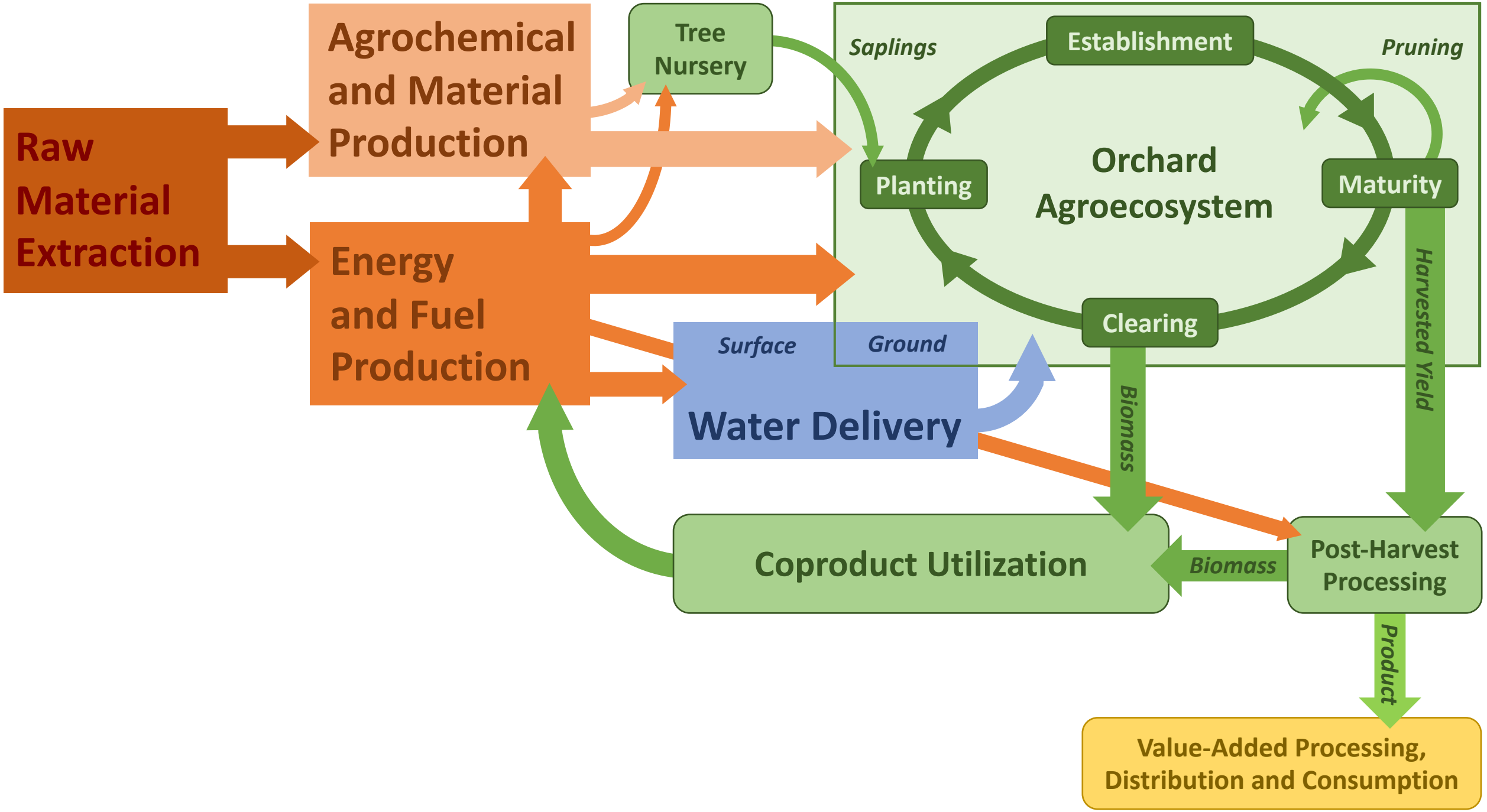


What about environmental *benefits*?



Benefits of orchard production systems:

- High nutritional yield
- Biomass co-product – displace fossil fuel-based production systems (e.g., energy, livestock feed)
- Ecosystem services: biodiversity, carbon storage, groundwater recharge, etc.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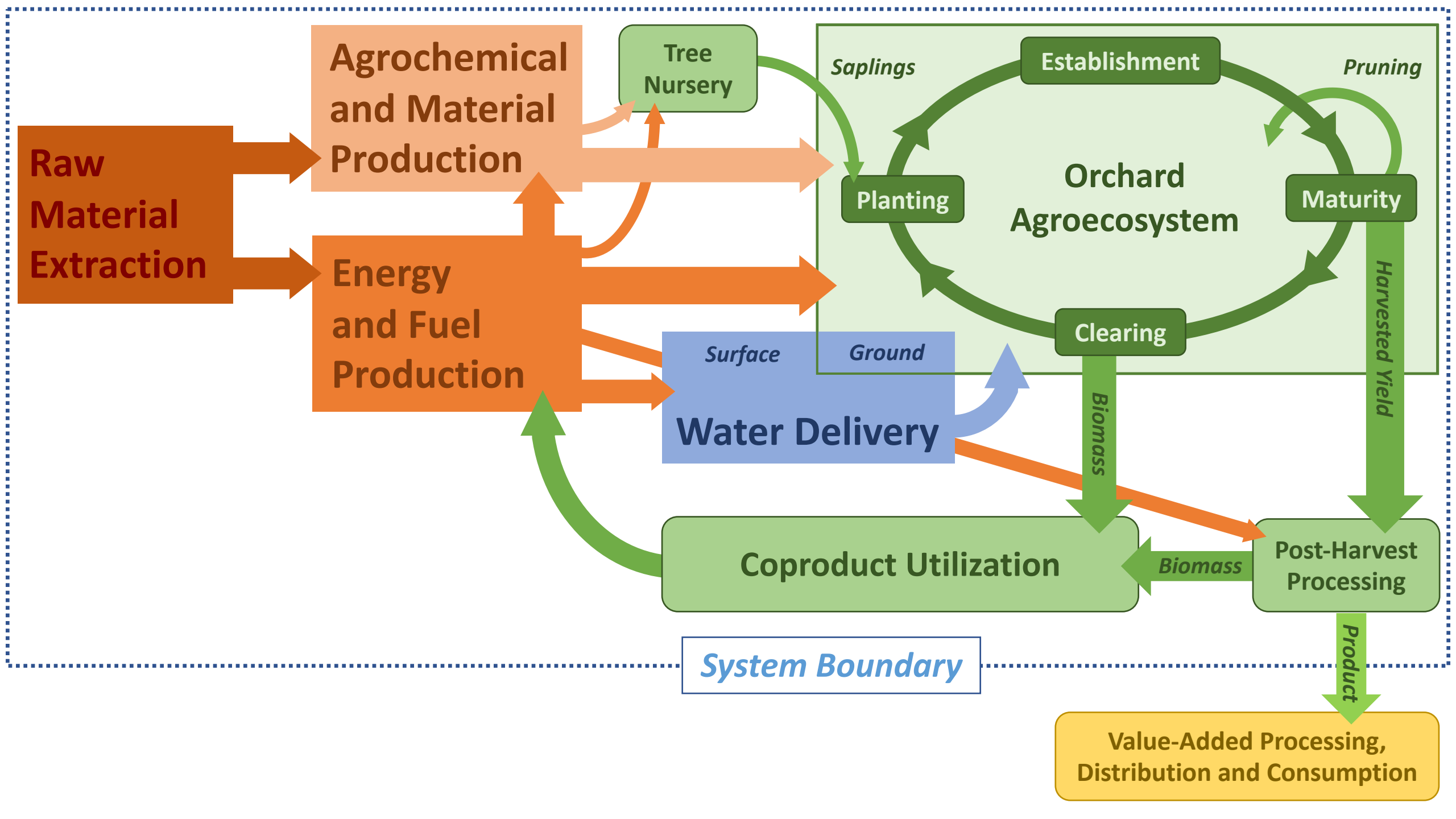
Coproduct Utilization
Biomass
Post-Harvest Processing
Product
Value-Added Processing, Distribution and Consumption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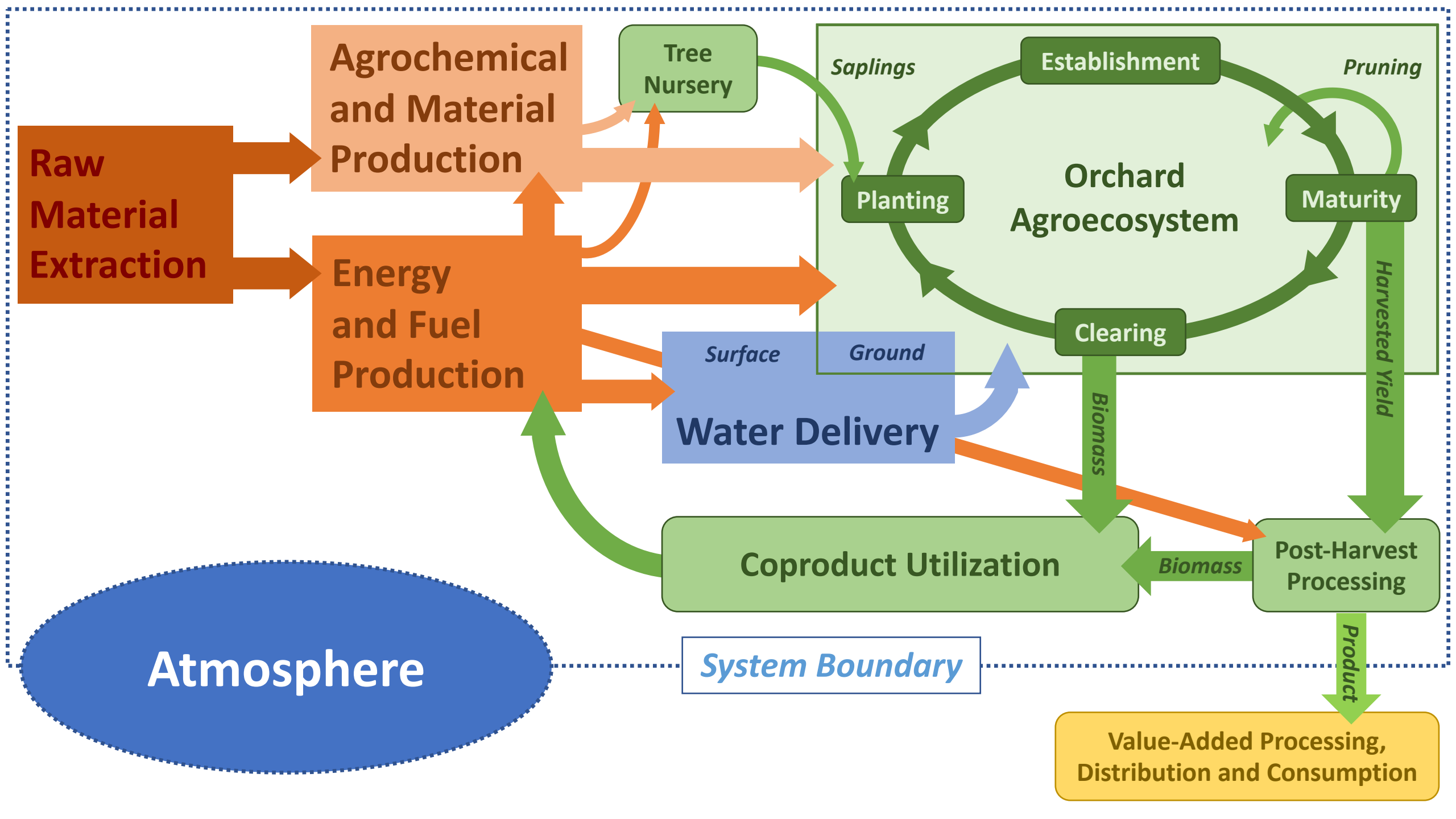
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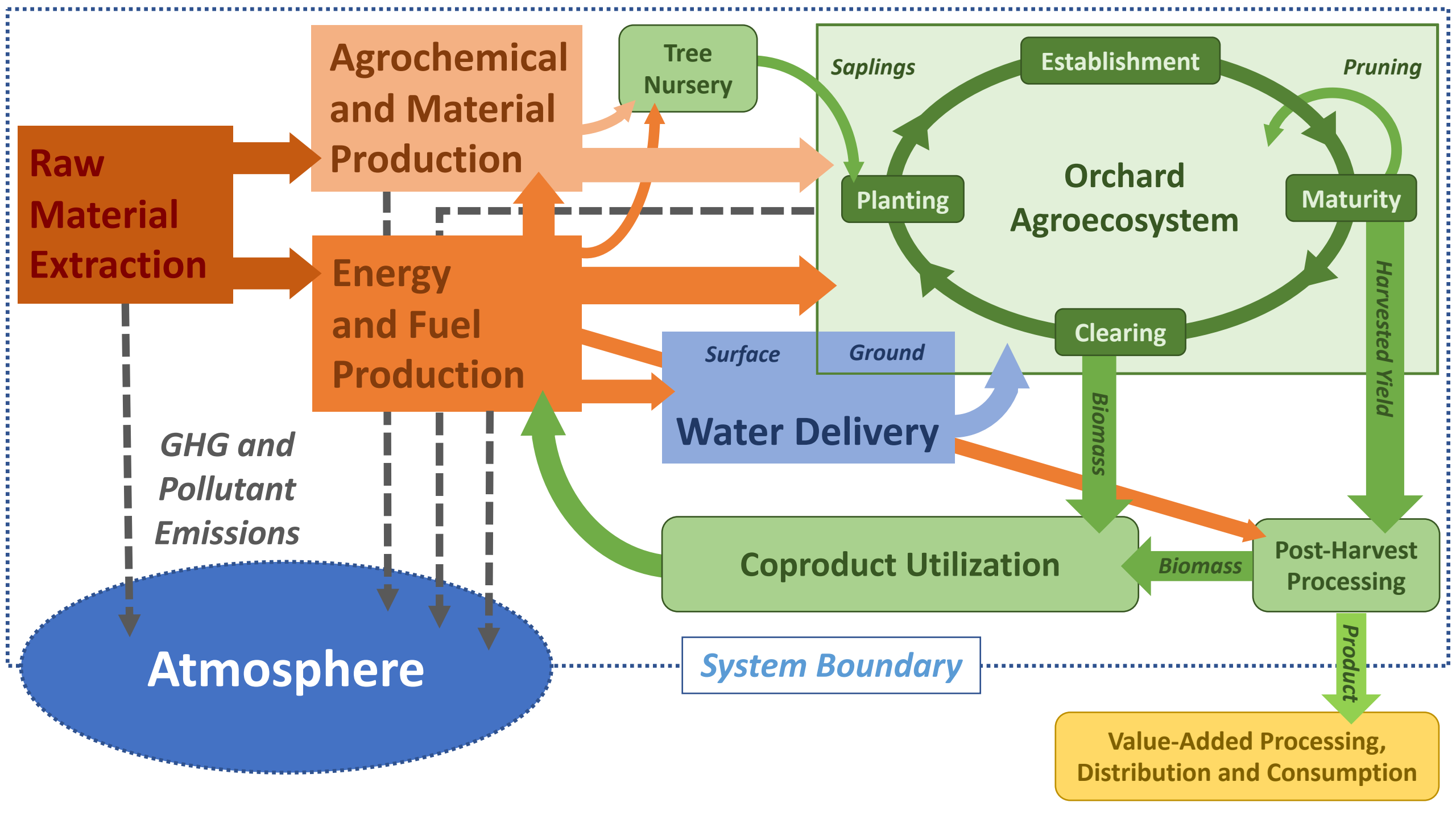
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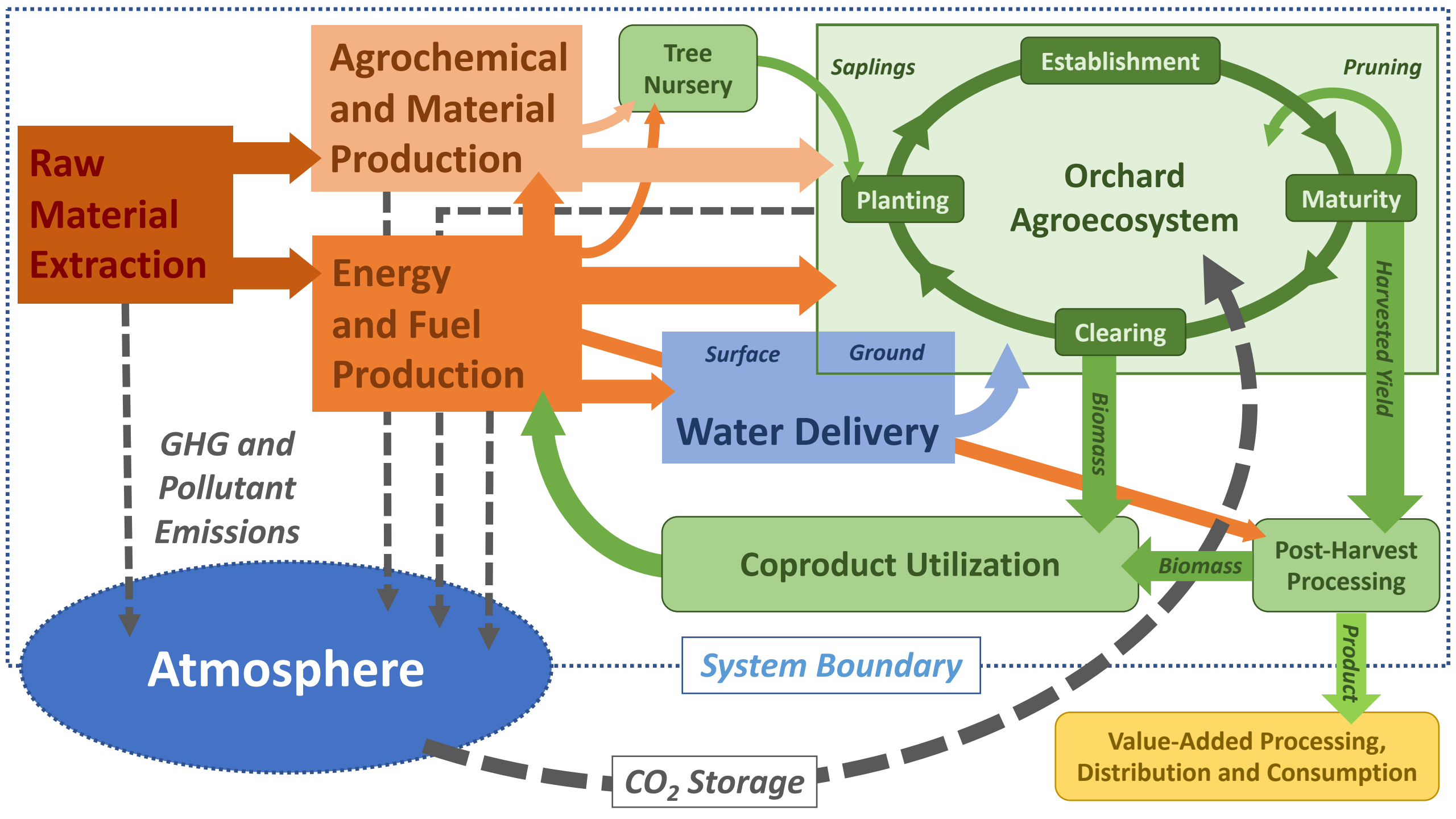
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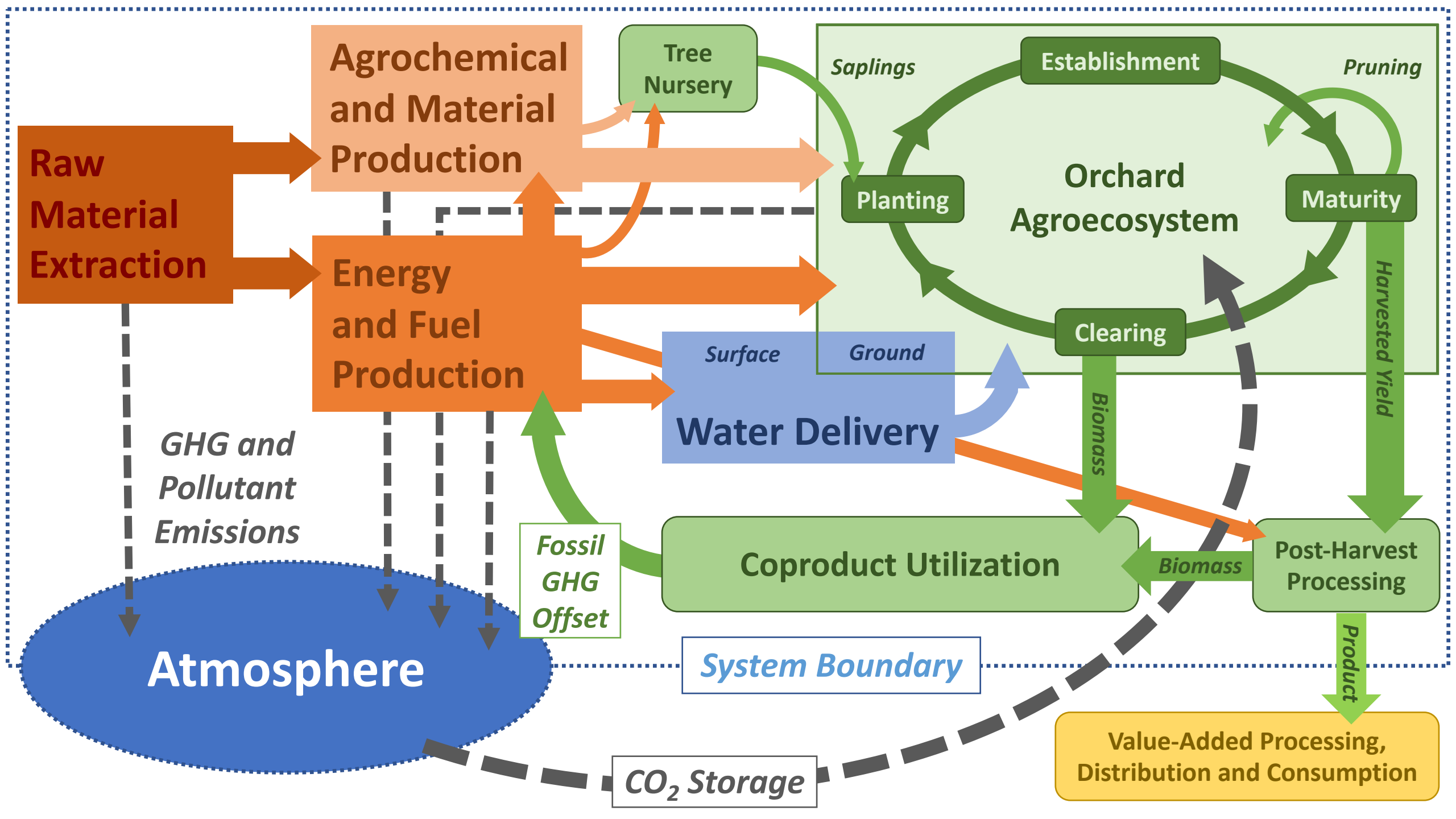
CO_2 Storage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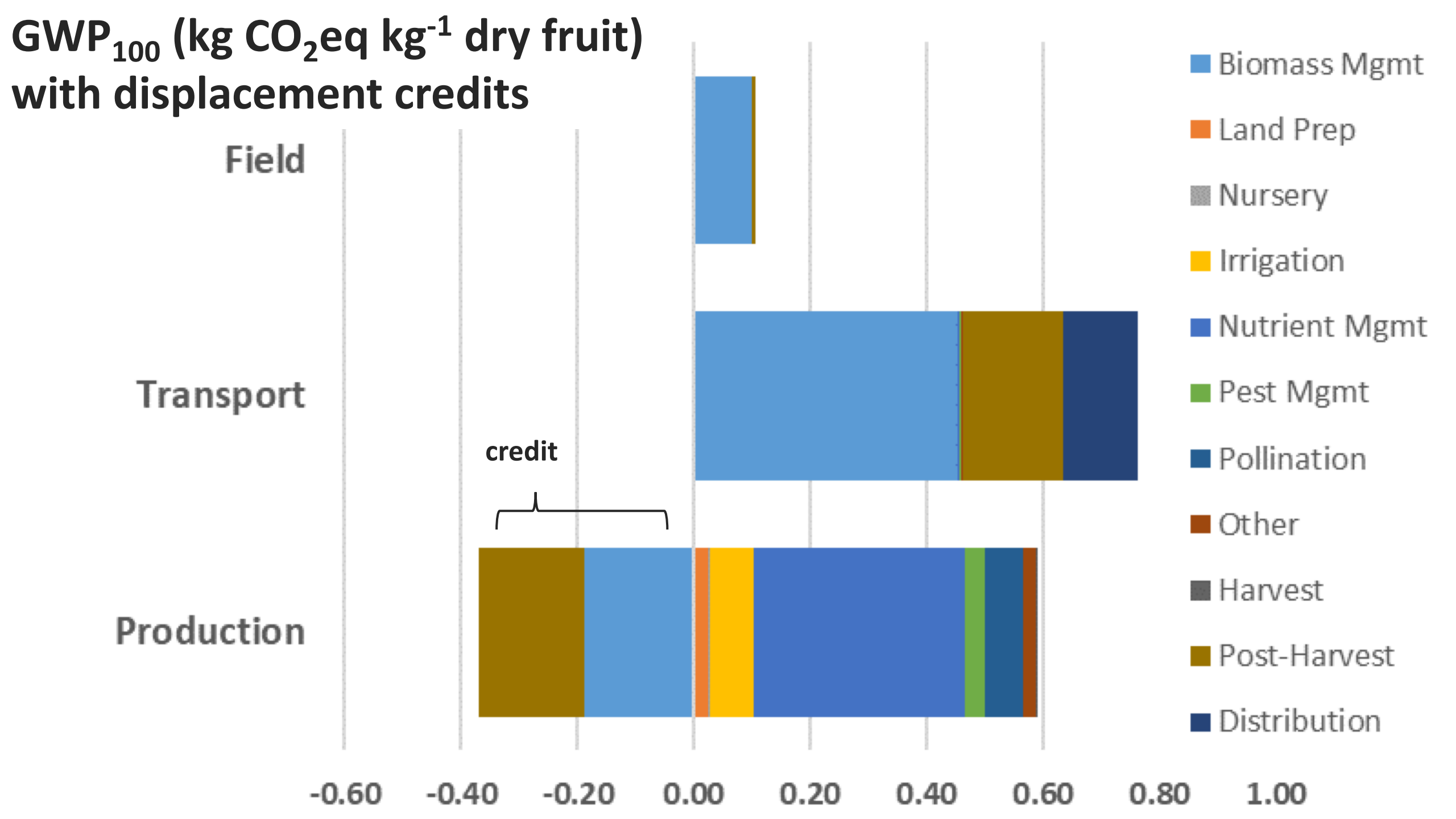
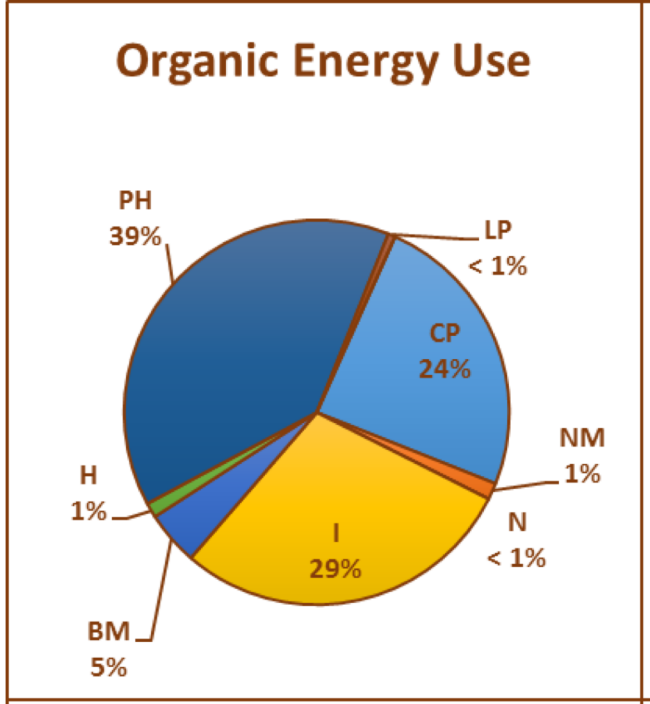
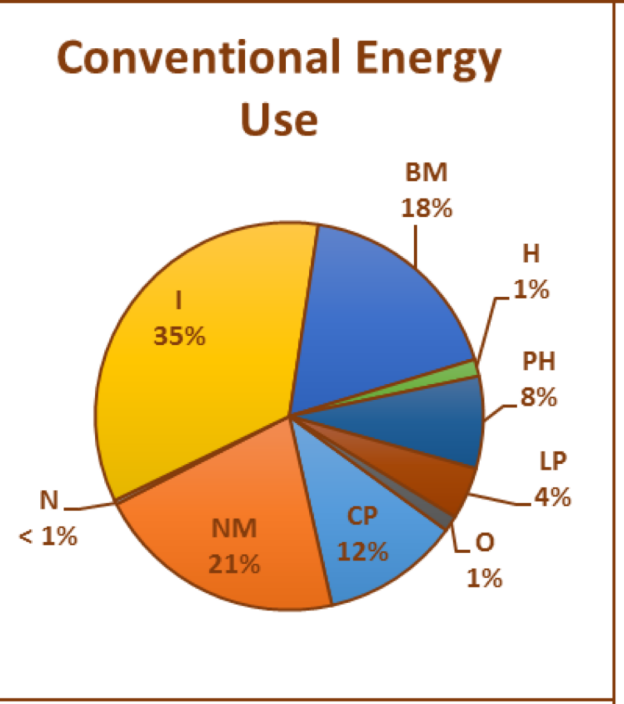
CO_2 Storage

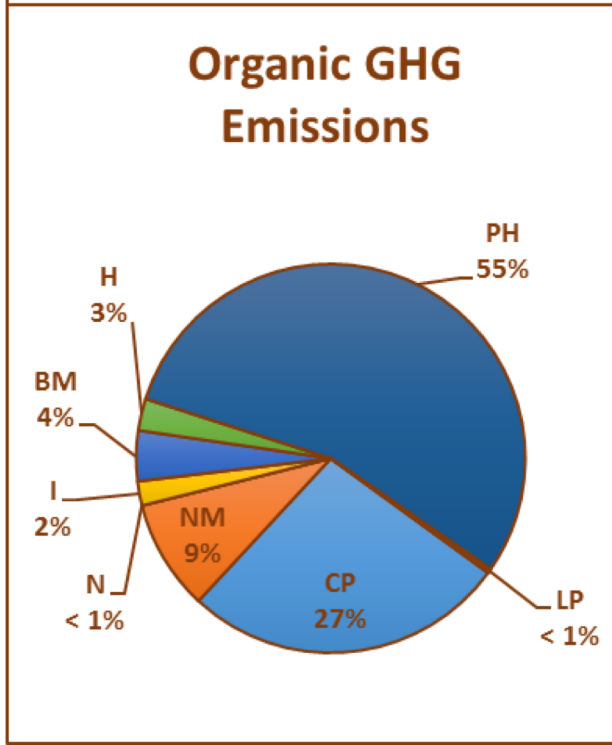
GWP_{100} (kg CO_2eq kg^{-1} dry fruit) with displacement credits

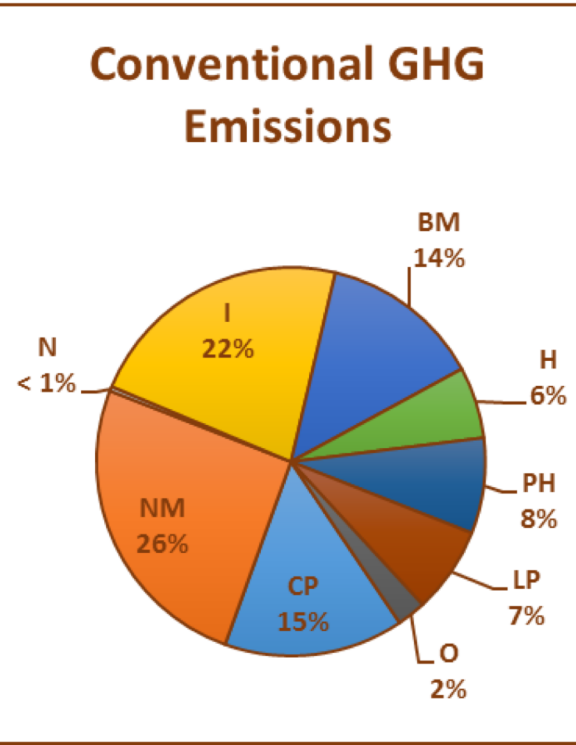


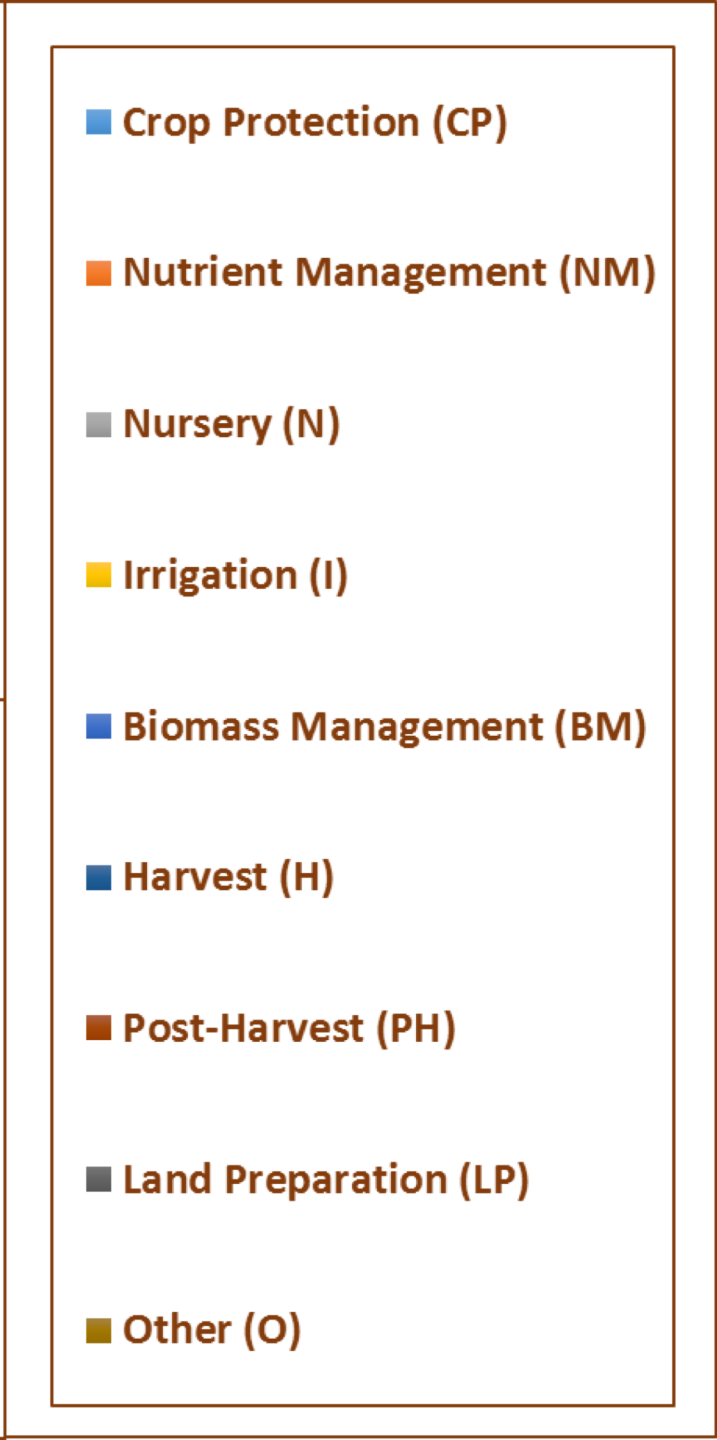
Walnut LCA Results: Categorical Breakdown



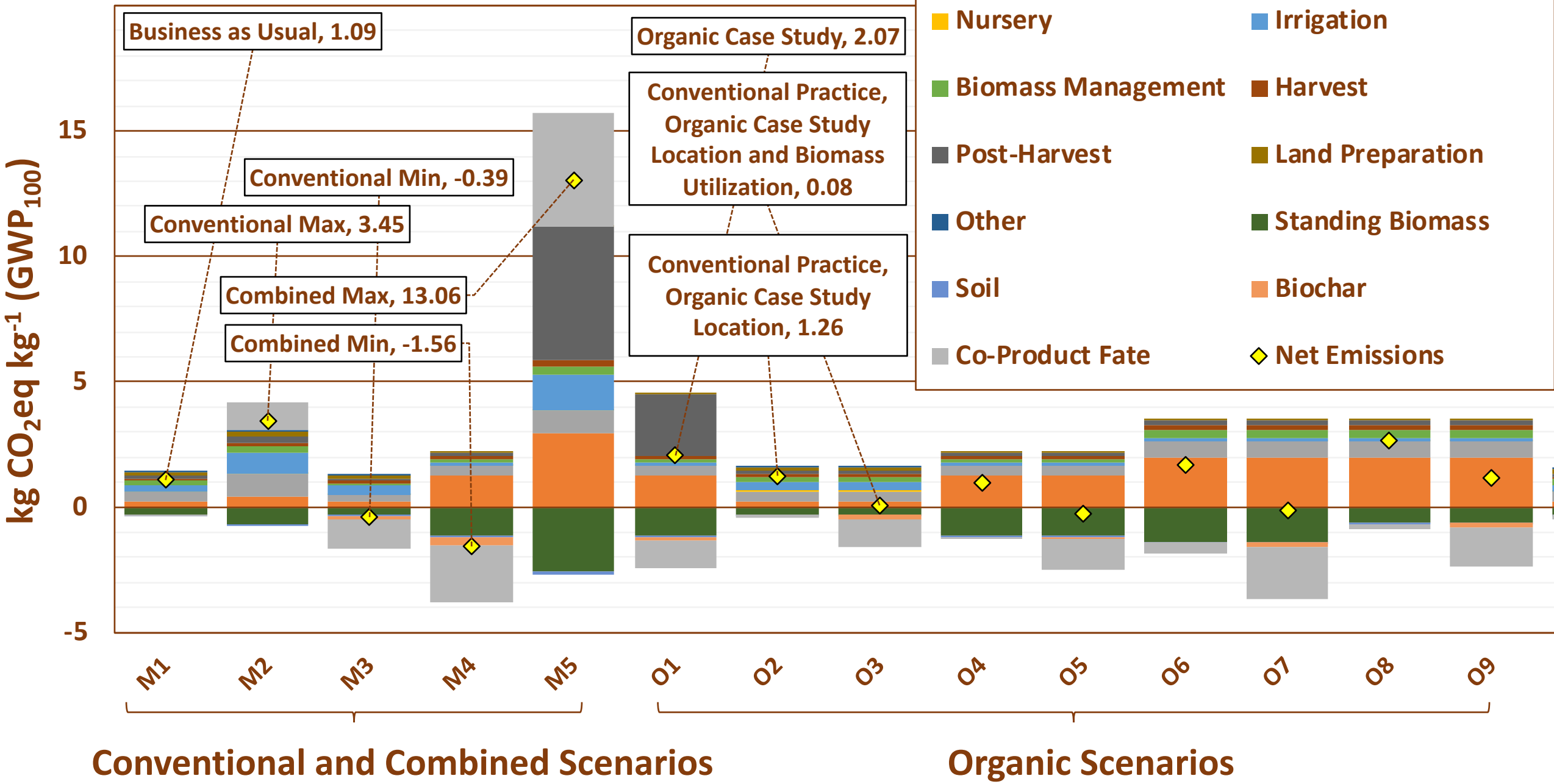






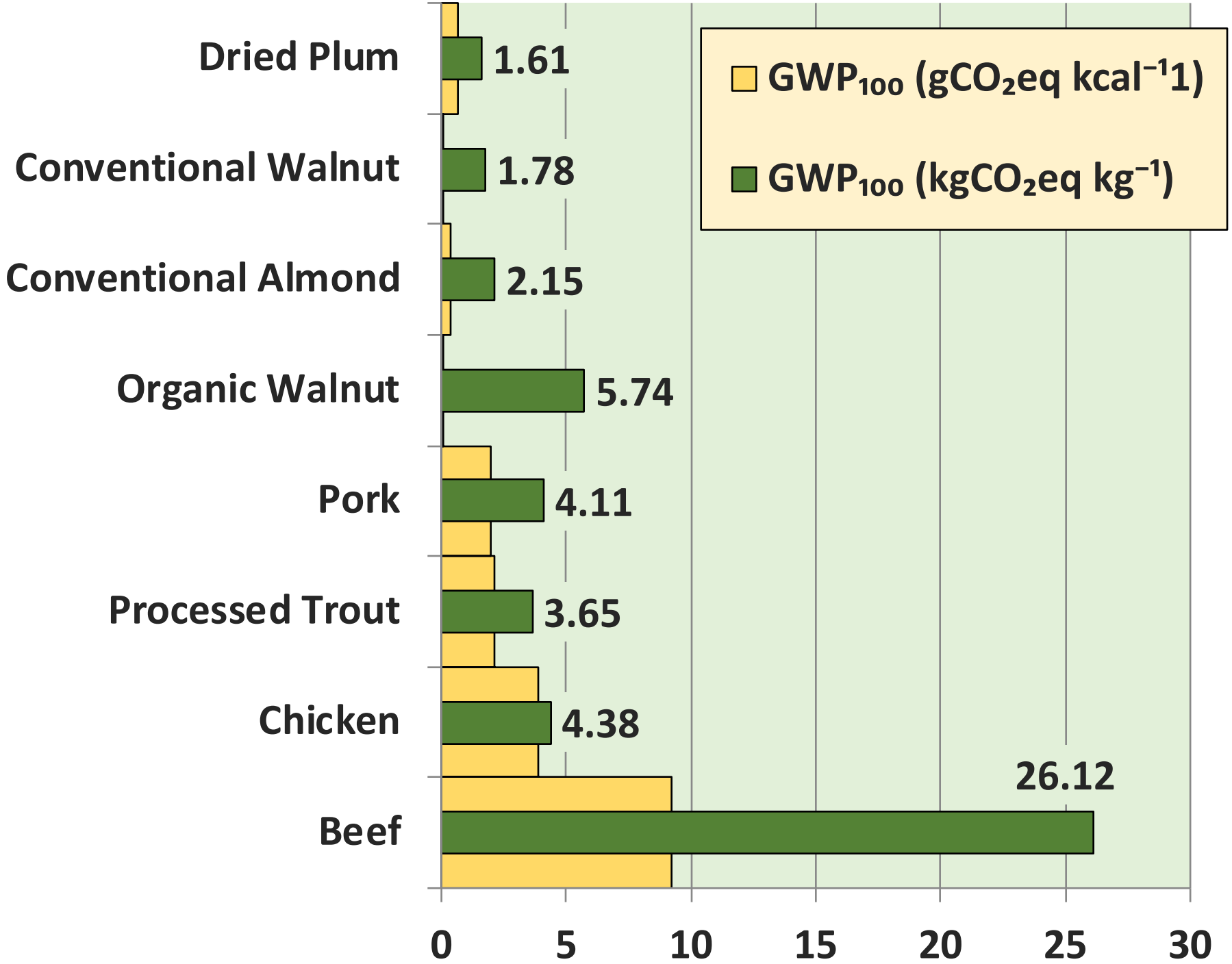


Walnut Emissions Scenario Results

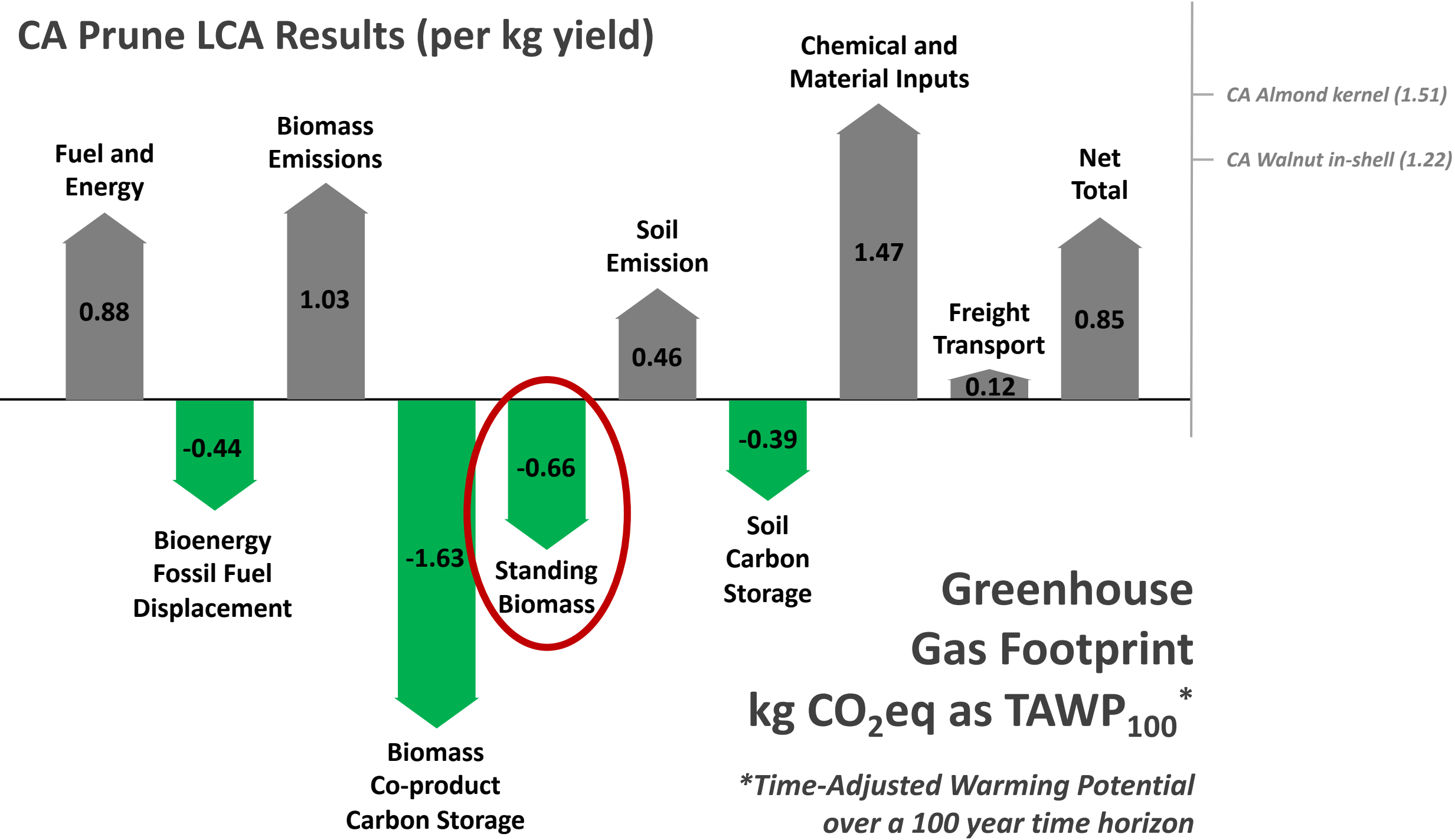


Prune LCA Findings:

Comparison with other agricultural products at postharvest gate



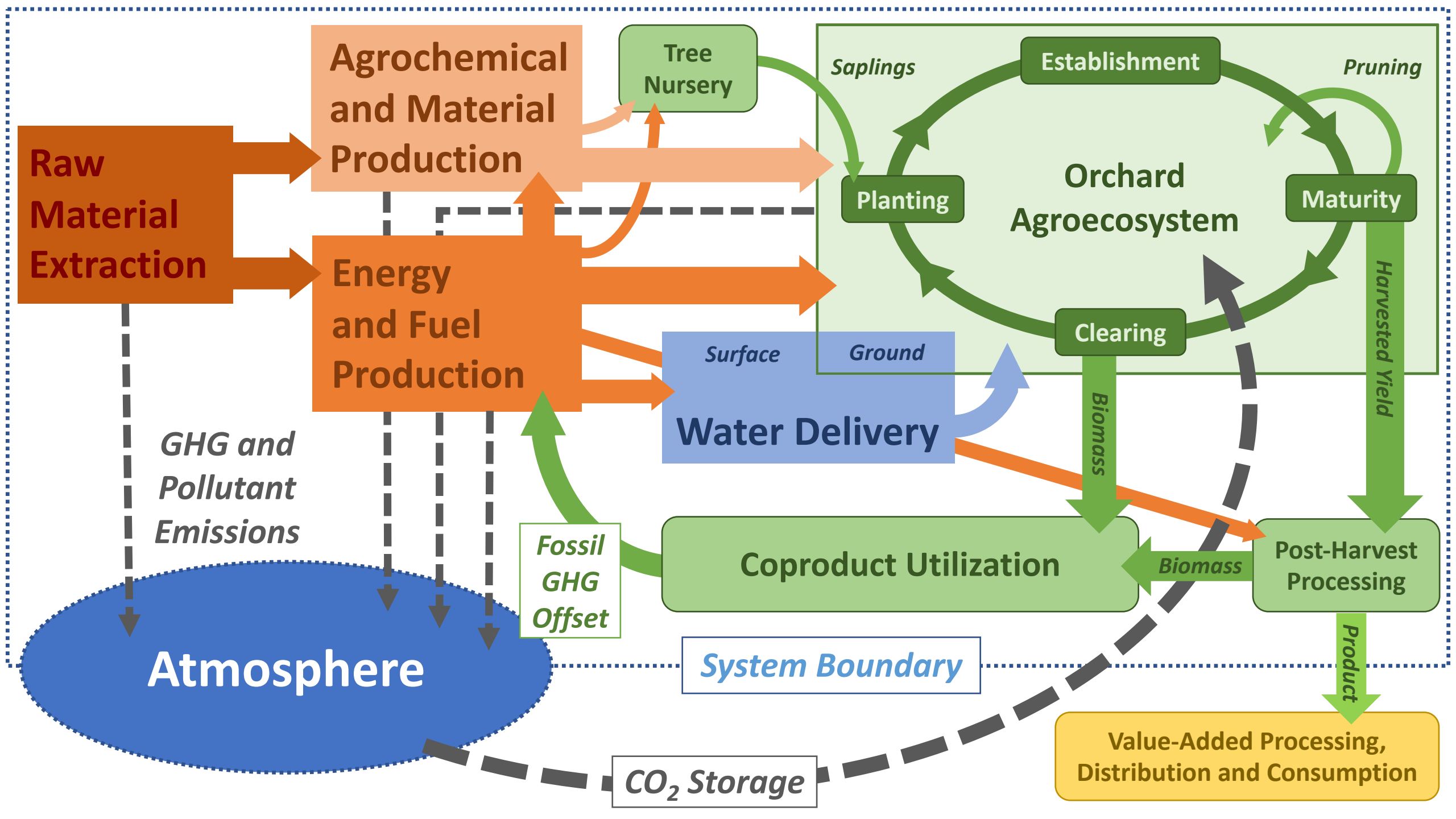
CA Prune LCA Results (per kg yield)



Greenhouse Gas Footprint

kg CO_2eq as $TAWP_{100}$*

**Time-Adjusted Warming Potential over a 100 year time horizon*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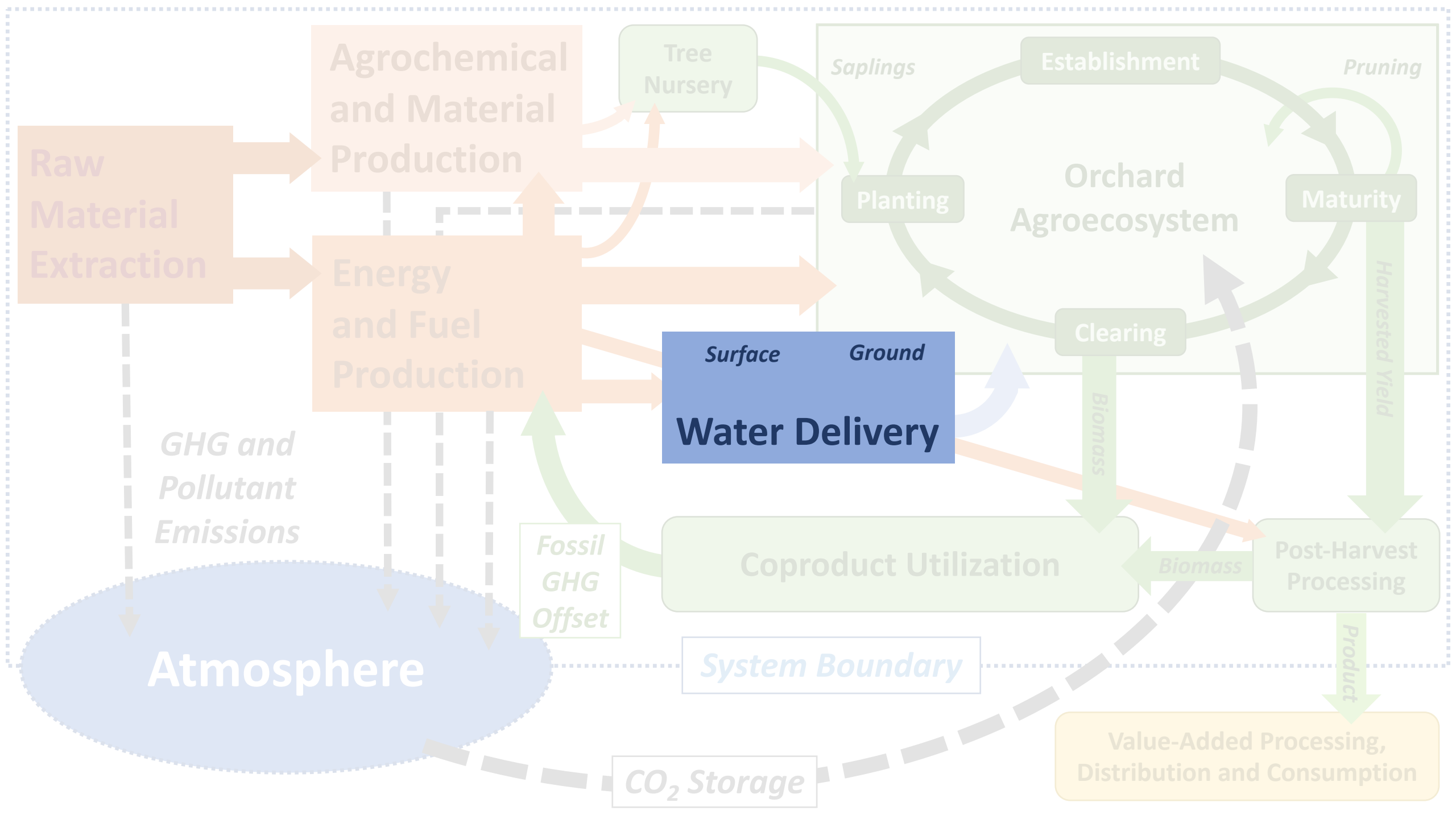
CO_2 Storage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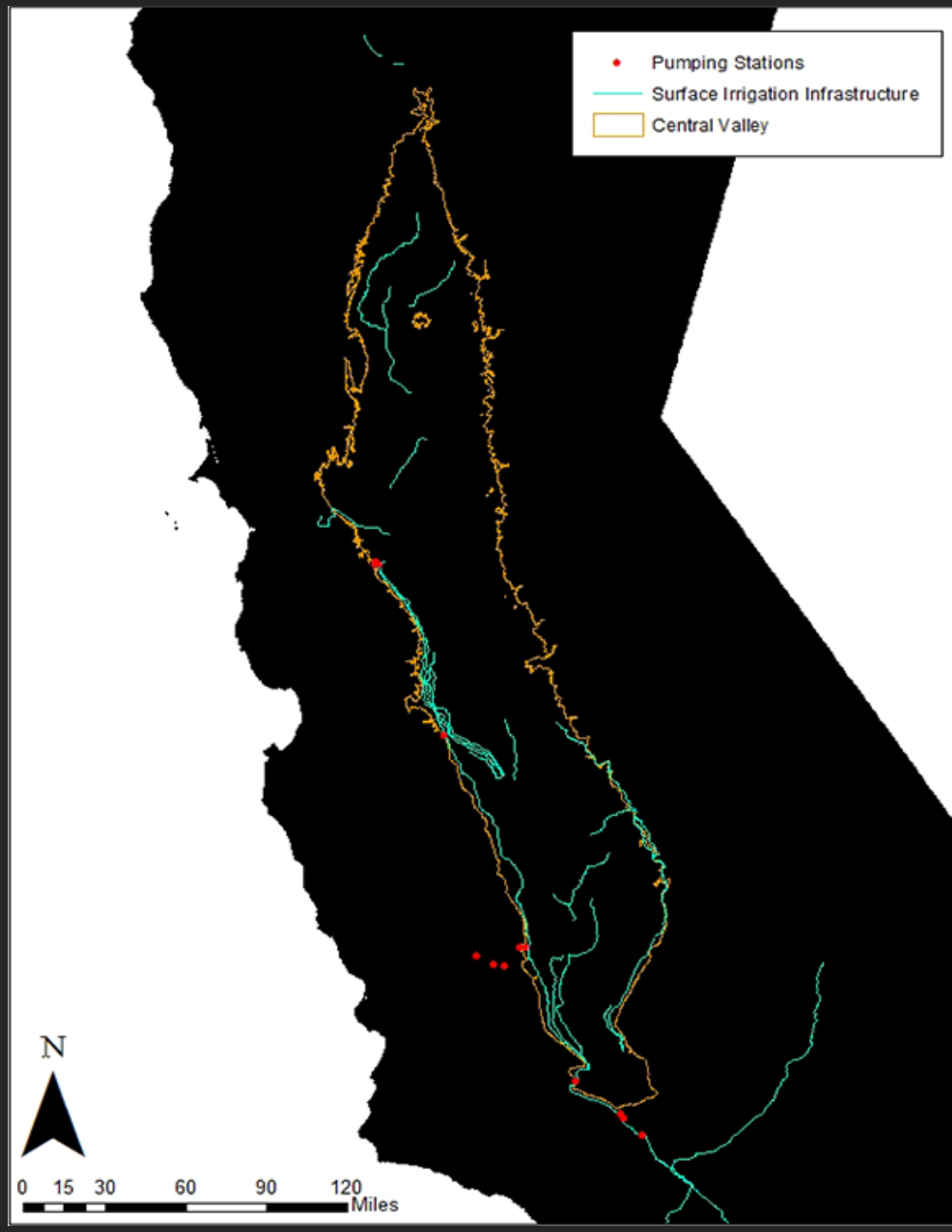
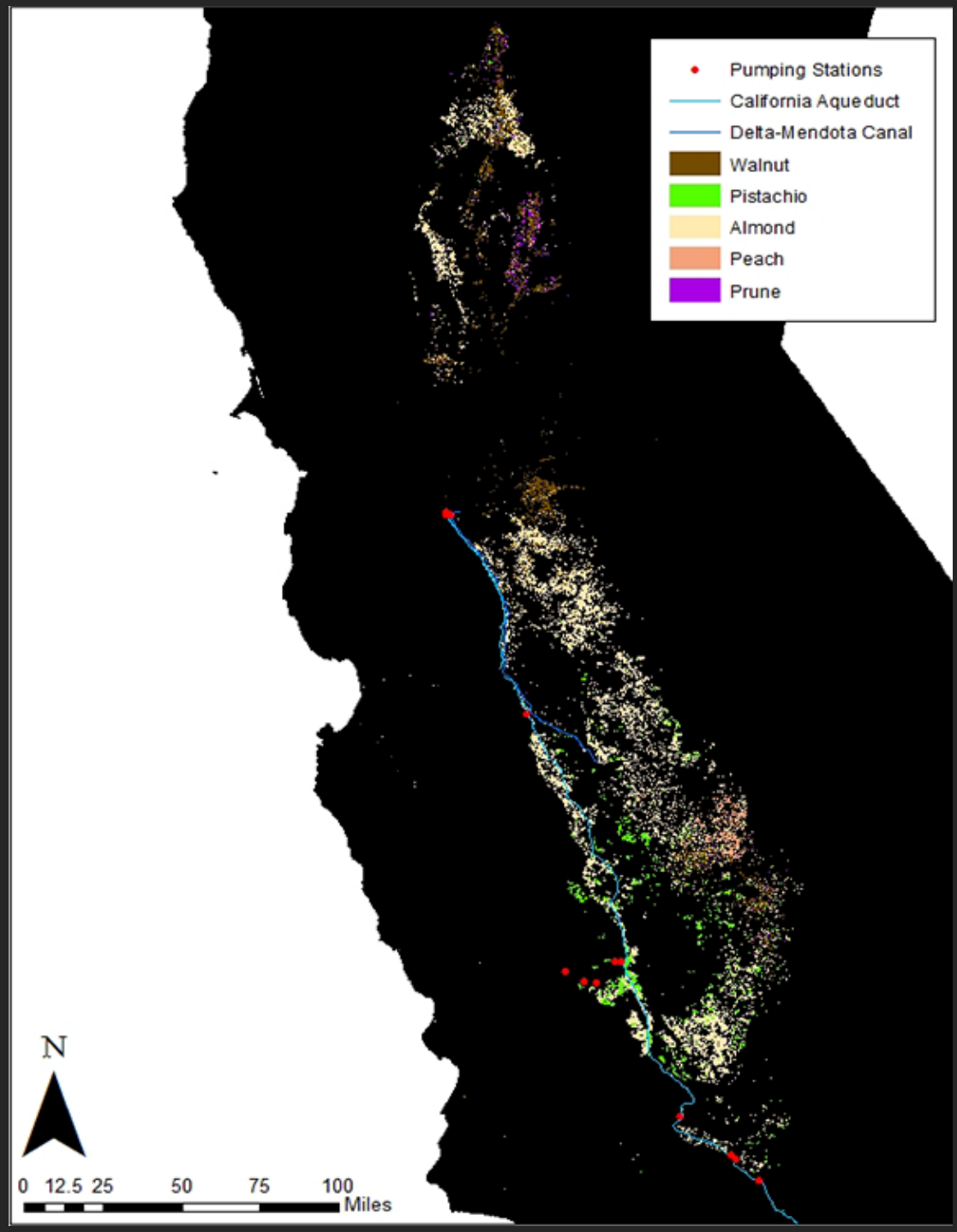
Major Irrigation Infrastructure

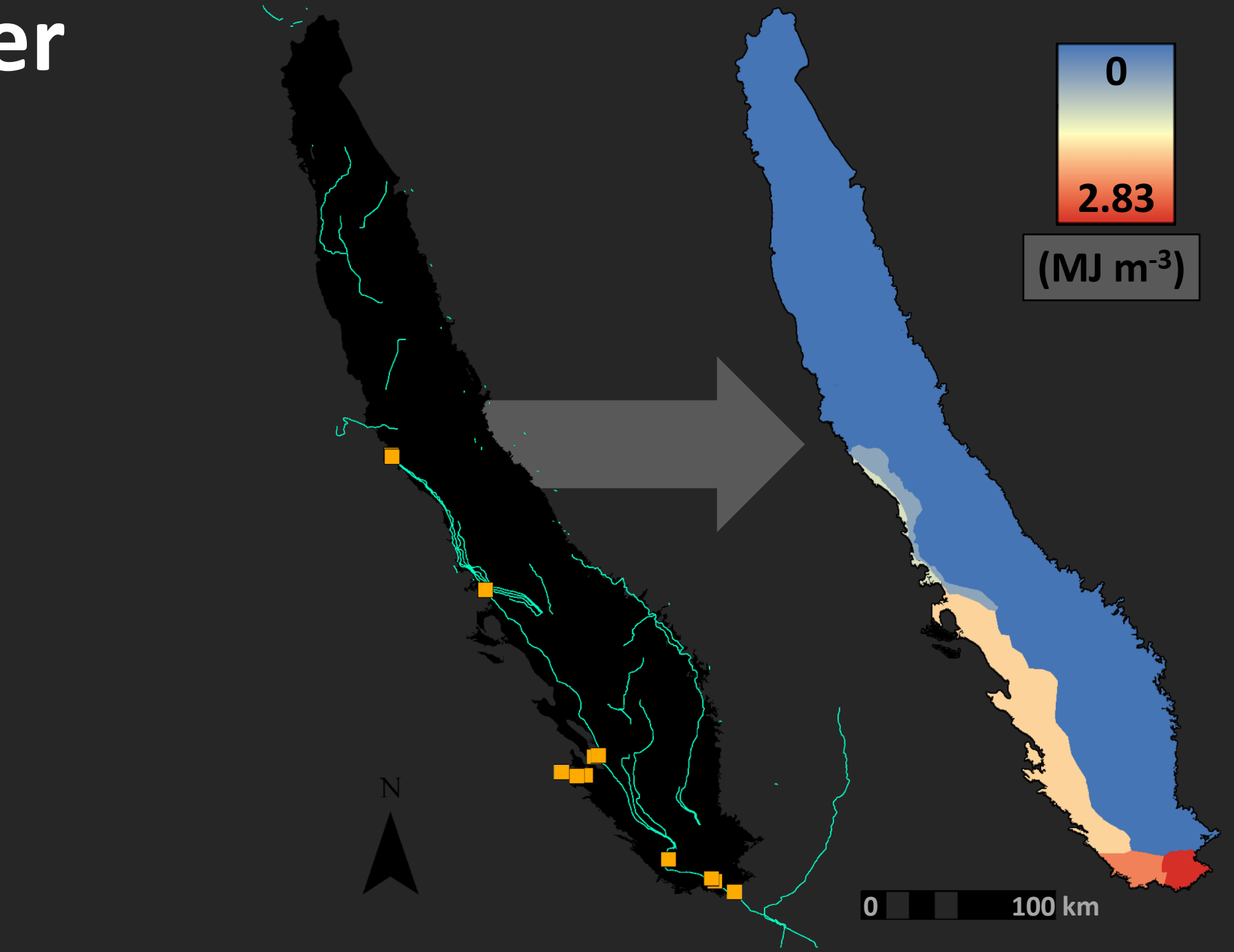


Major Irrigation Infrastructure and Tree Crops

- Bimodal distributions
  - North – south: Delta region
  - East – west: California Aqueduct

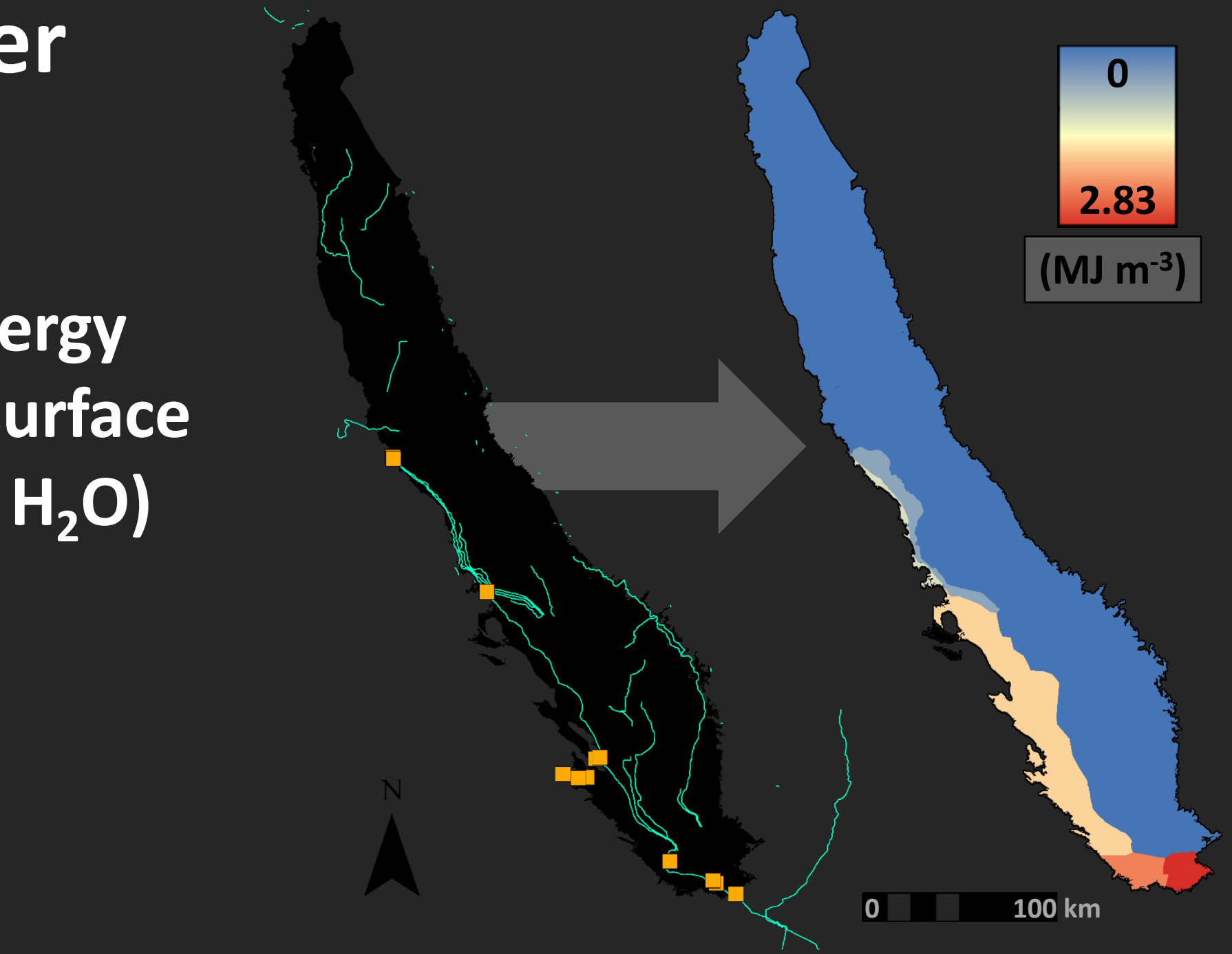


Surface Water Energy



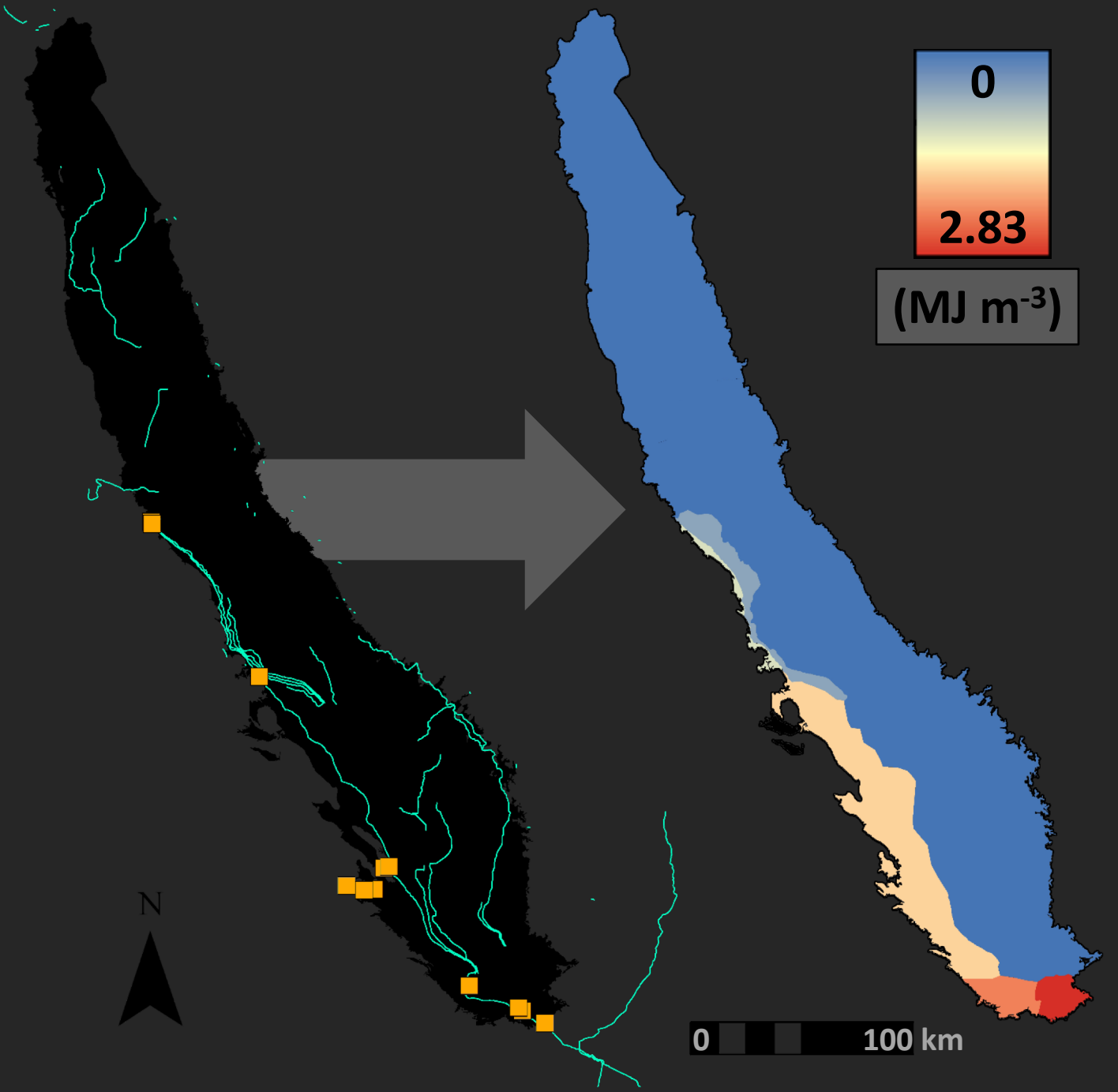
Surface Water Energy

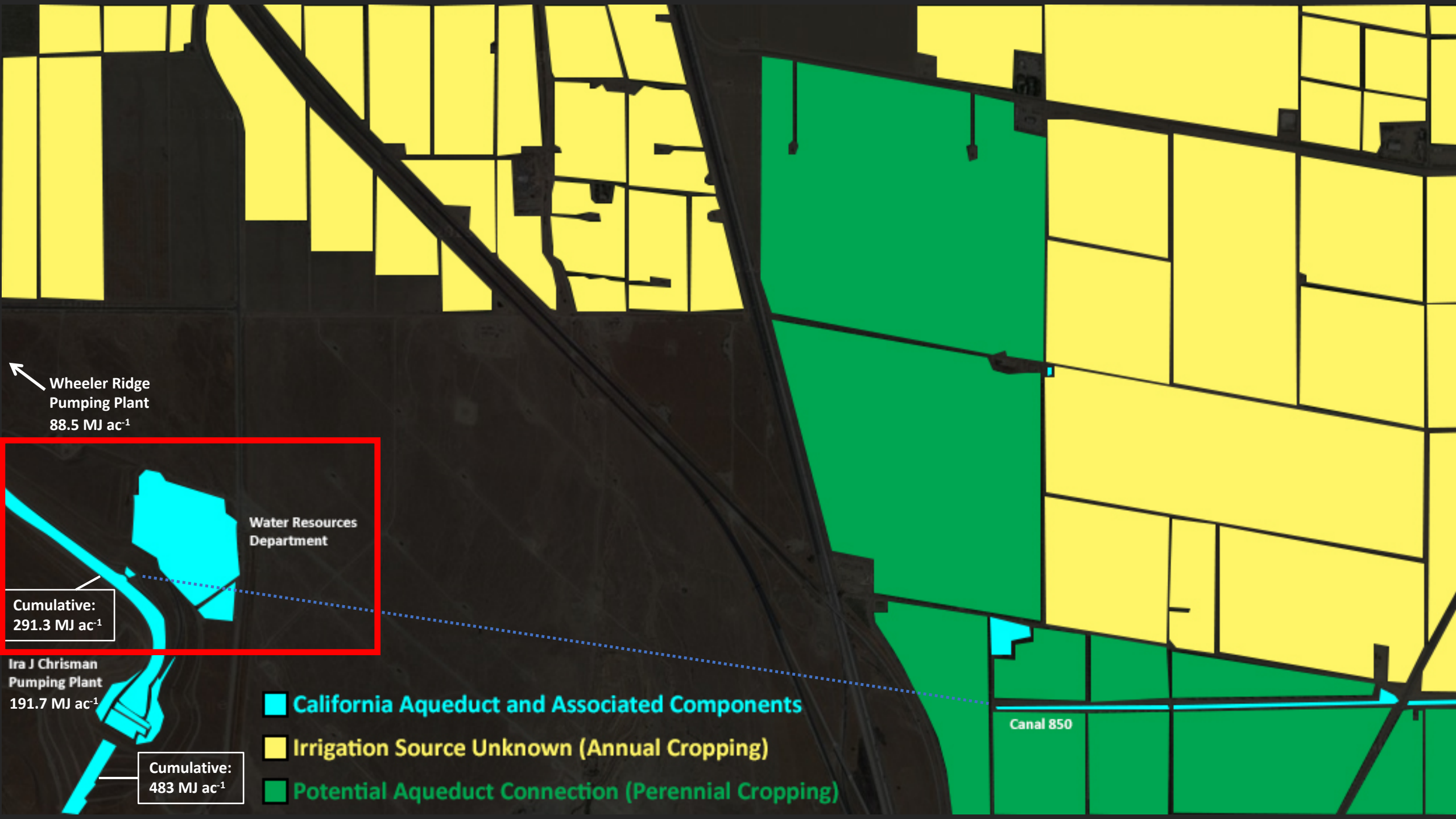
- 6 zones for energy embodied in surface water (MJ m^{-3} H_2O)

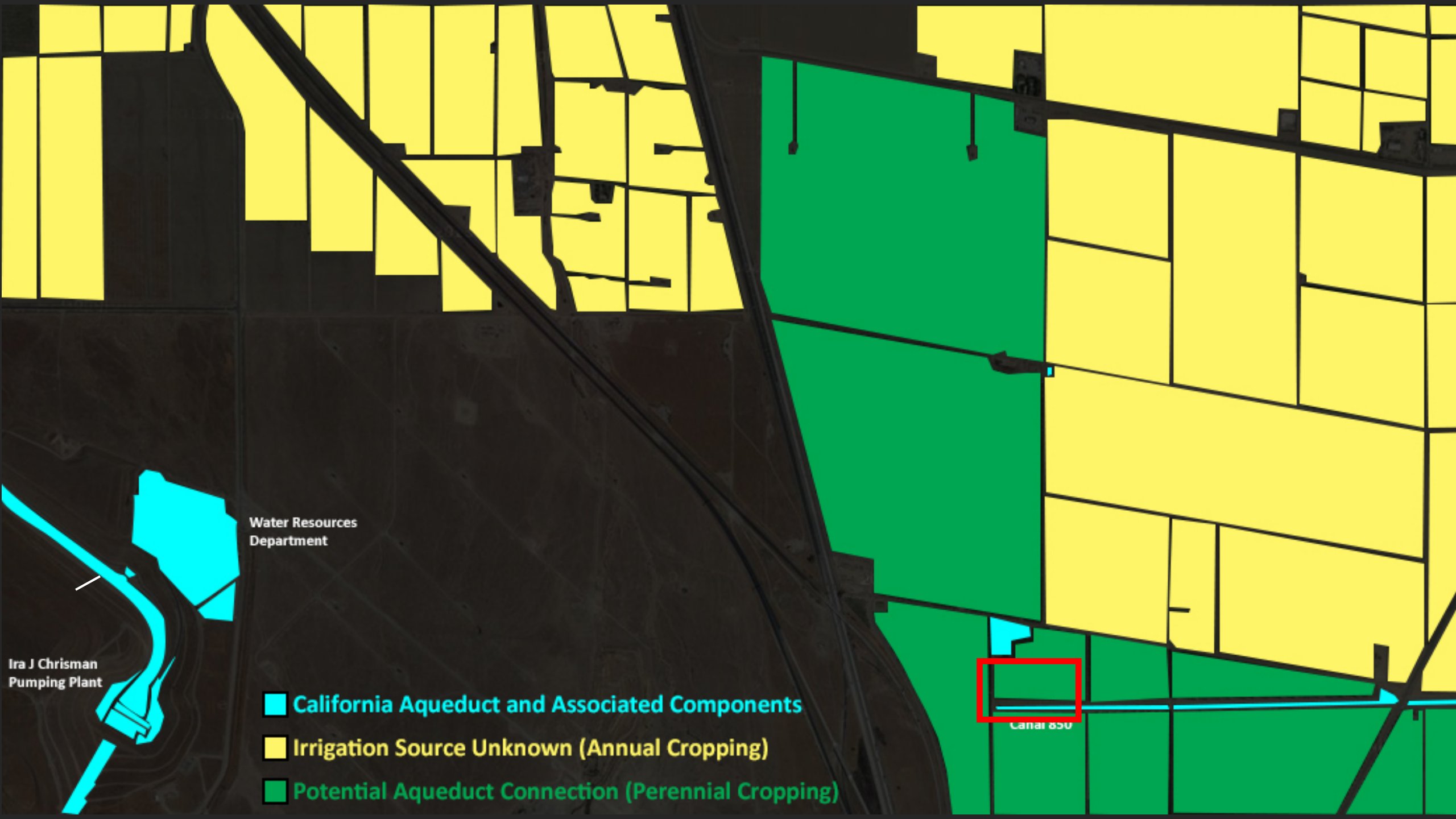


Surface Water Energy

- 6 zones for energy embodied in surface water (MJ m^{-3} H_2O)
- Aerial imagery and DWR GIS database used to relate crops and infrastructure




Wheeler Ridge
Pumping Plant
88.5 MJ ac-1
Water Resources
Department
Cumulative:
291.3 MJ ac-1
Ira J Chrisman
Pumping Plant
191.7 MJ ac-1
Cumulative:
483 MJ ac-1
California Aqueduct and Associated Components
Irrigation Source Unknown (Annual Cropping)
Potential Aqueduct Connection (Perennial Cropping)
Canal 850


Water Resources
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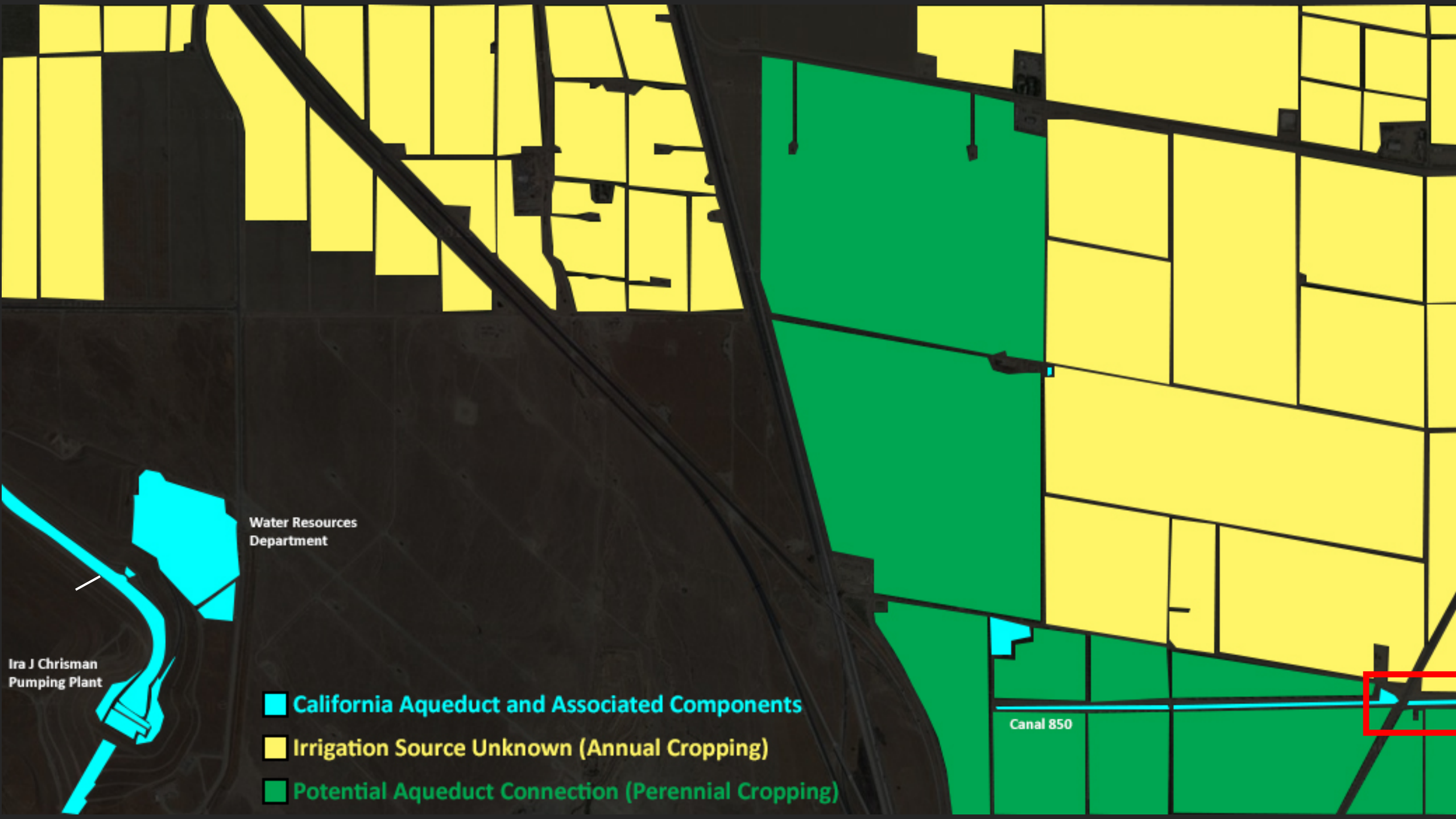
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Ira J Chrisman Pumping Plant
Canal 850
California Aqueduct and Associated Components
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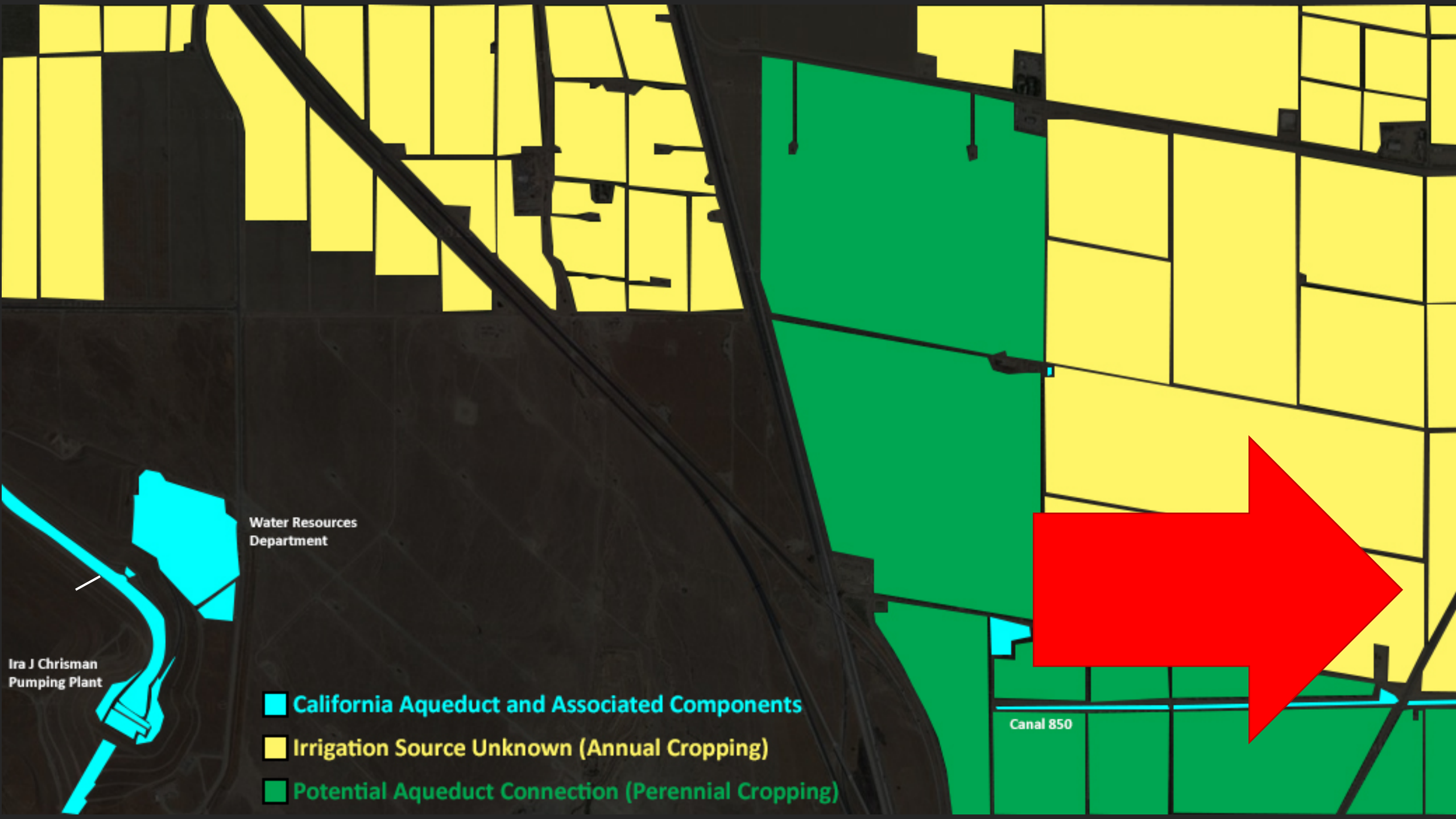
S Wheeler Ridge Rd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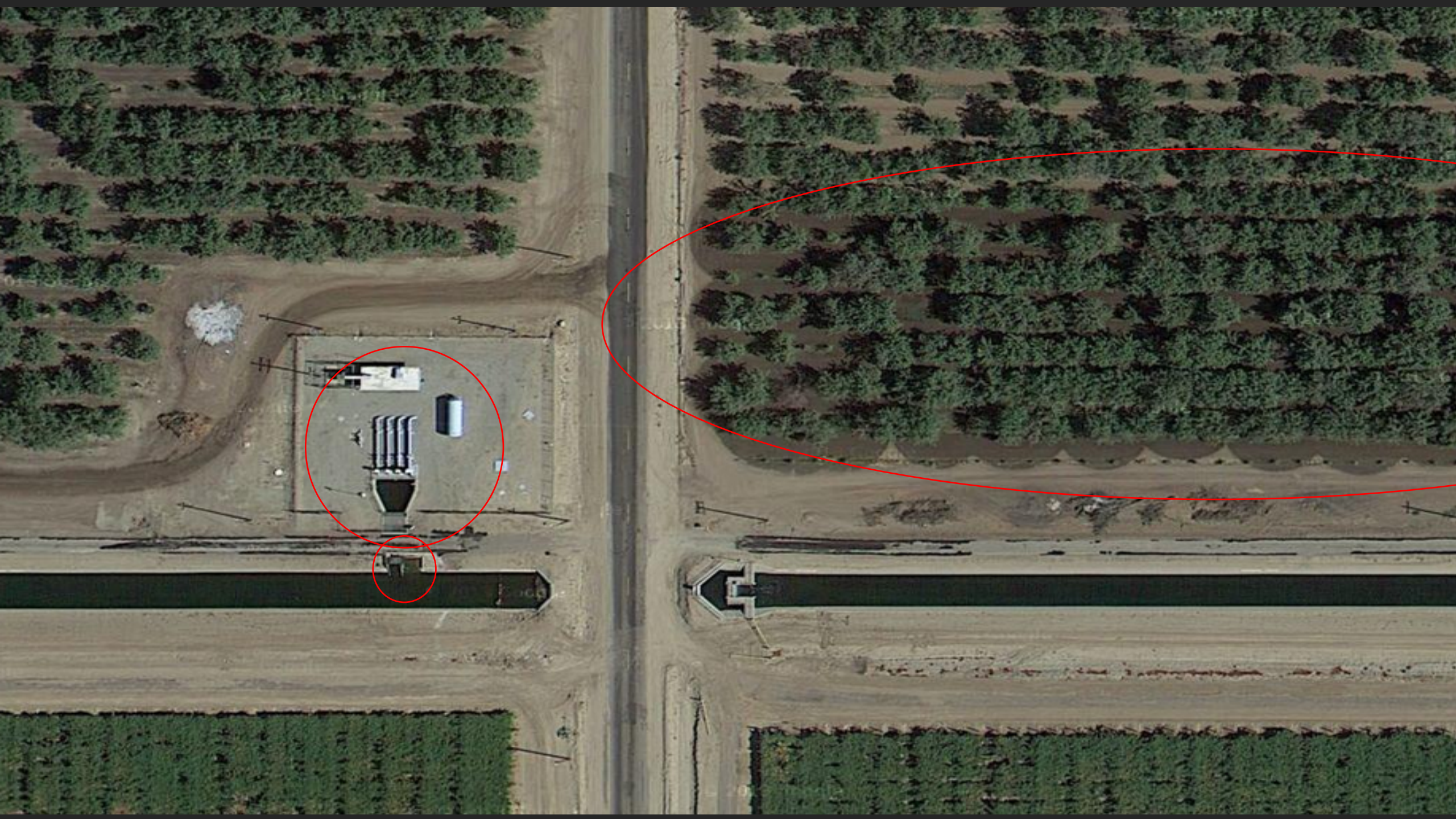
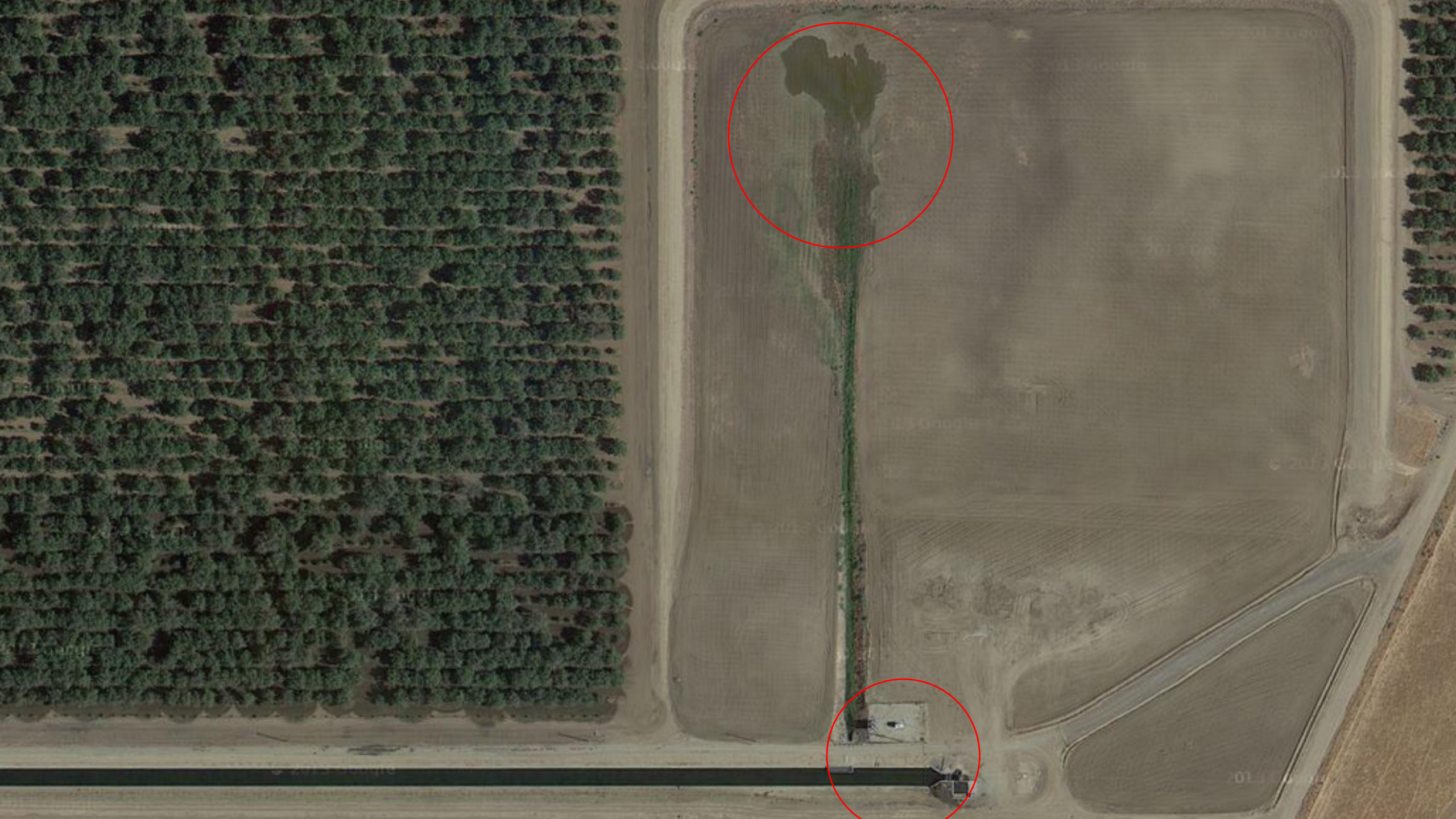
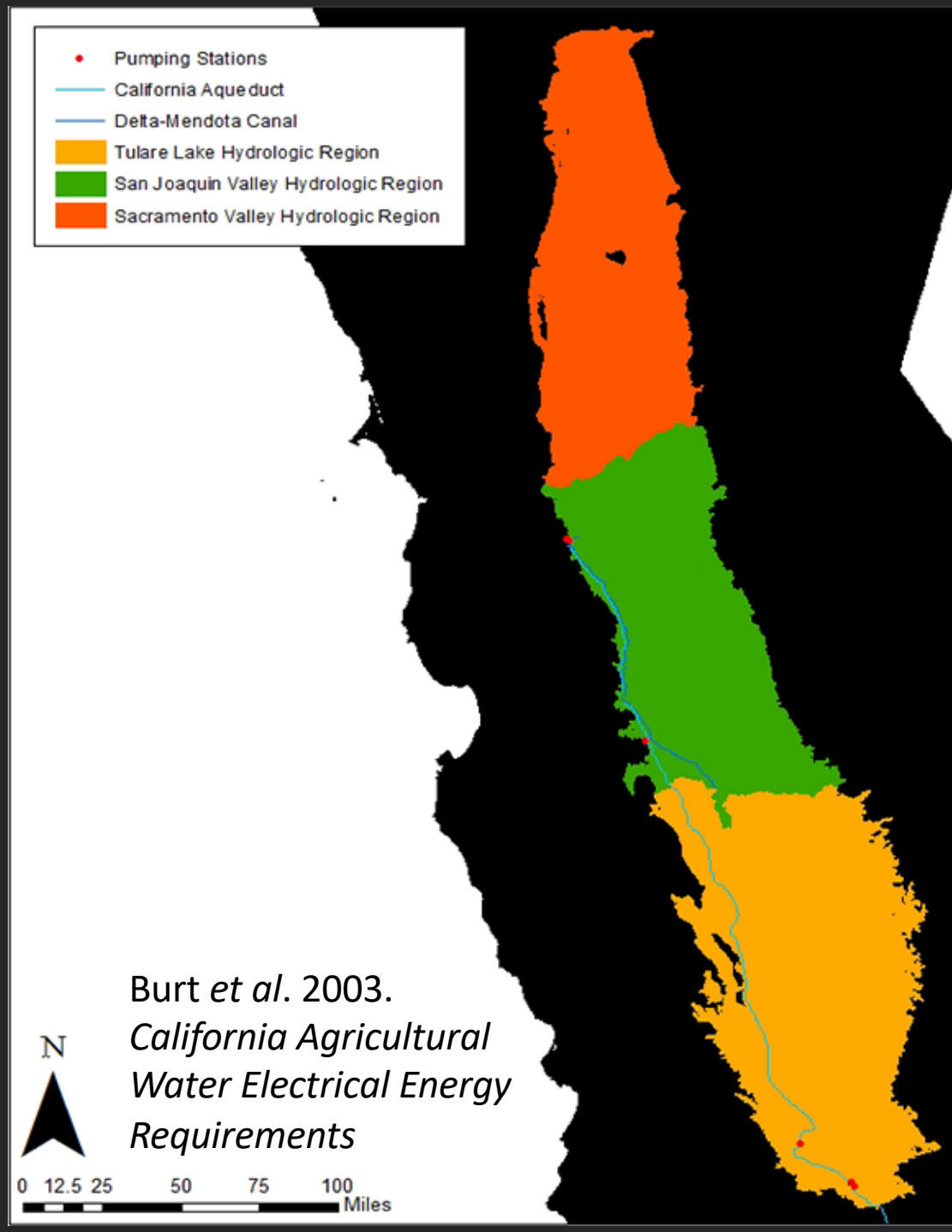




Hydrologic Regions and Groundwater Depth

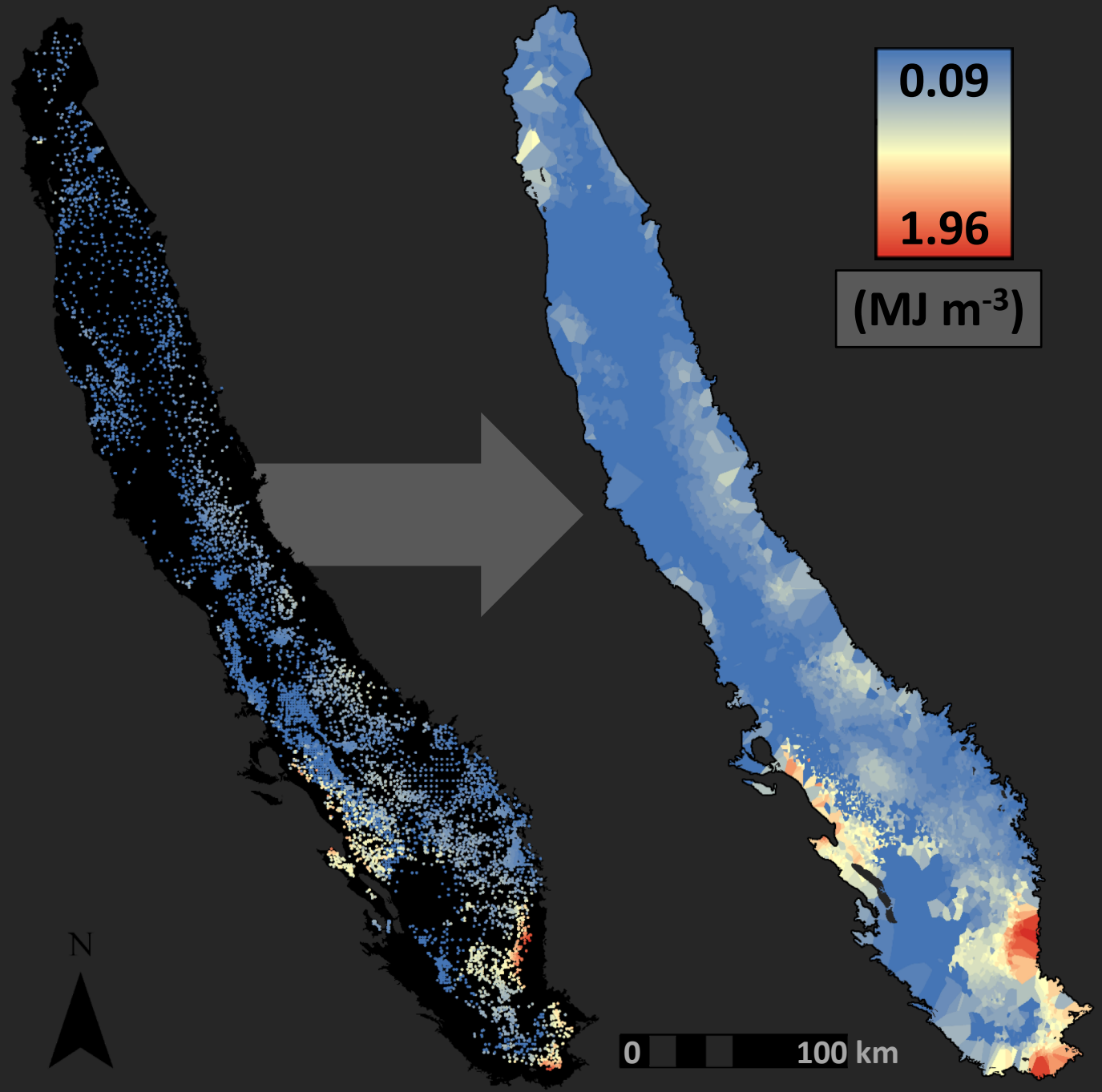
- Mean groundwater pumping energy requirement (MJ m^{-3})

  Sacramento River: 0.53
  San Joaquin River: 0.67
  Tulare Lake: 1.14



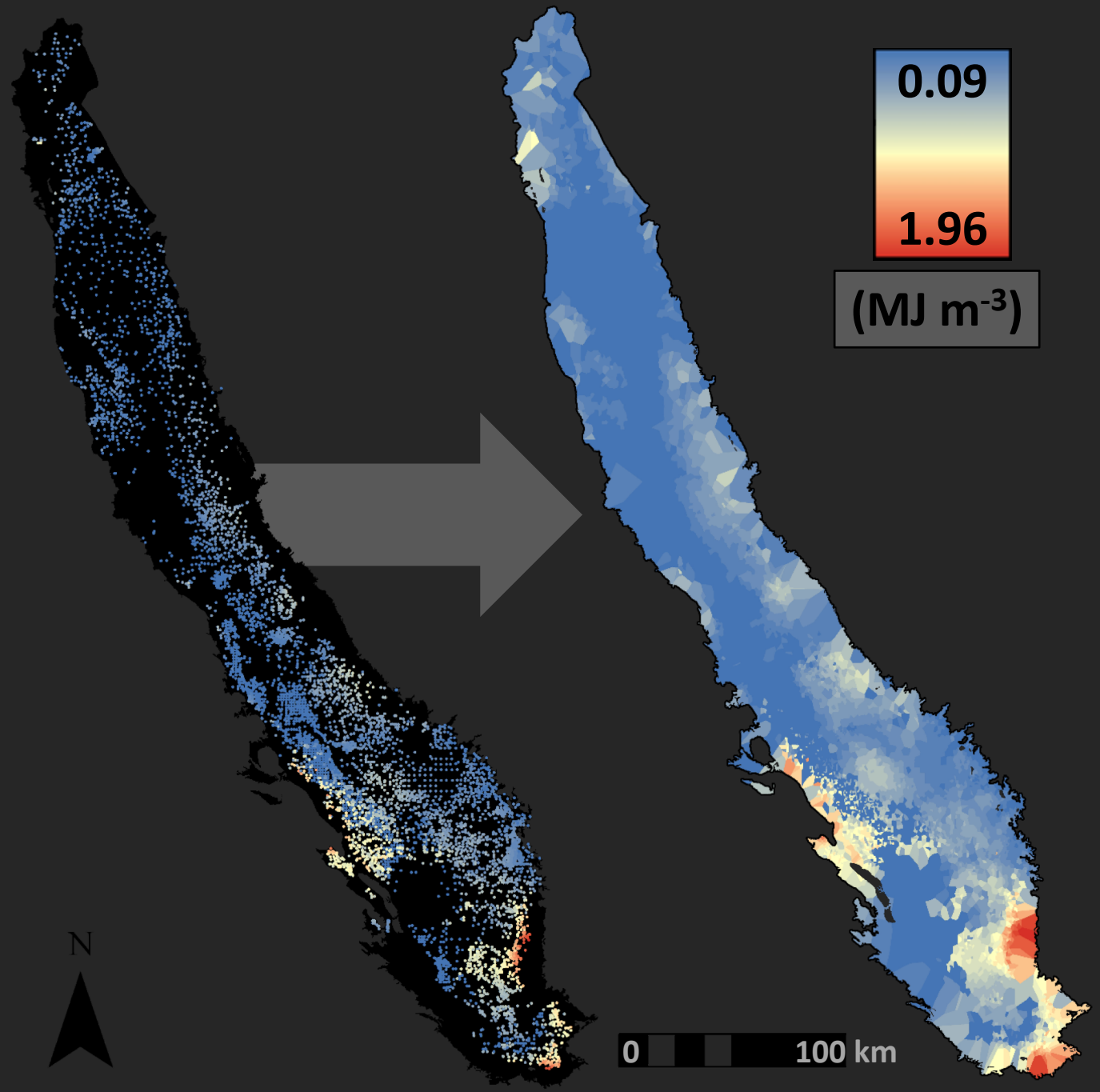
Burt *et al*. 2003. *California Agricultural Water Electrical Energy Requirements*

Hydrologic Regions and Groundwater Depth



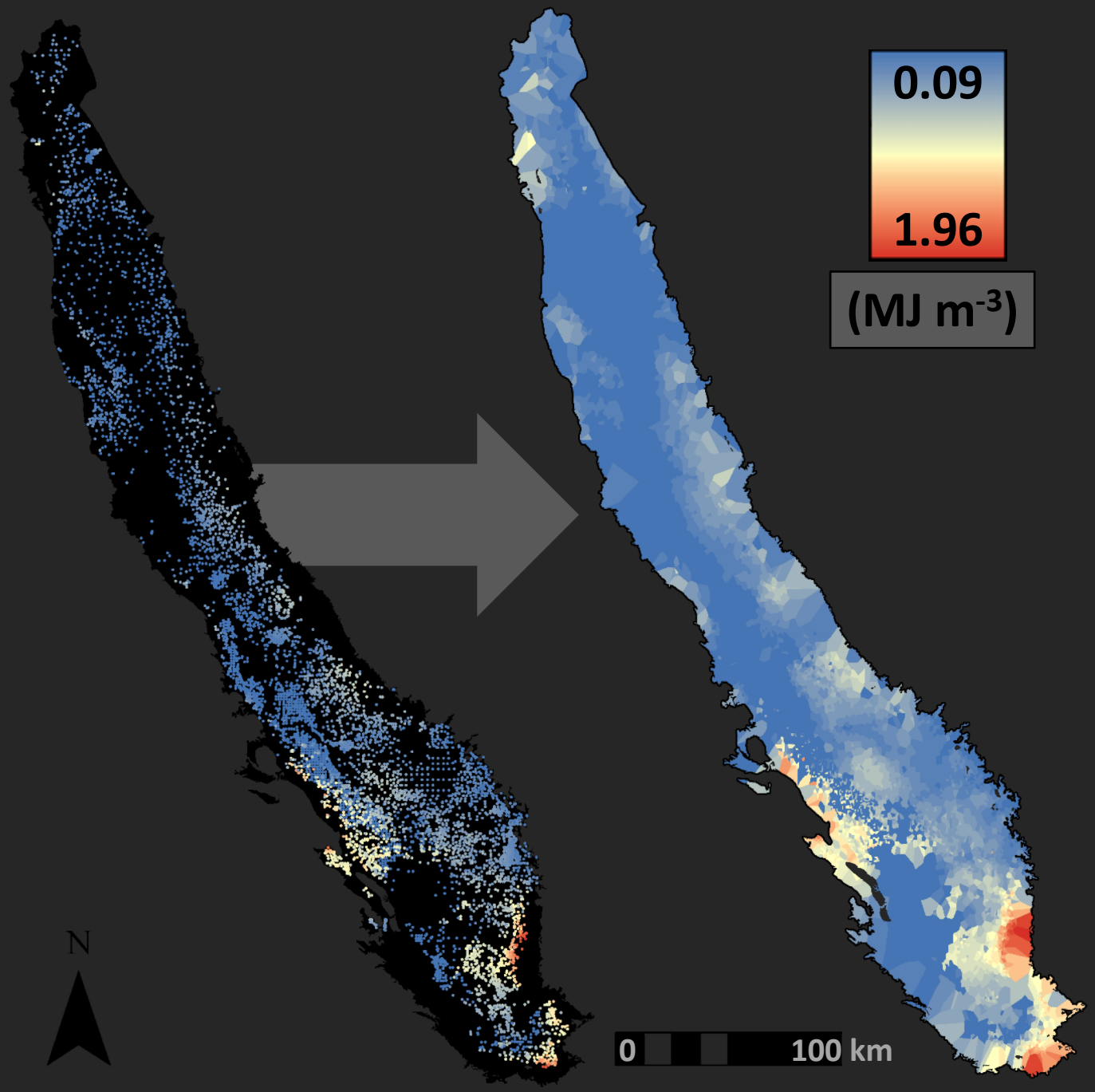
Hydrologic Regions and Groundwater Depth

- Test well depths used to calculate static head and energy needed for extraction

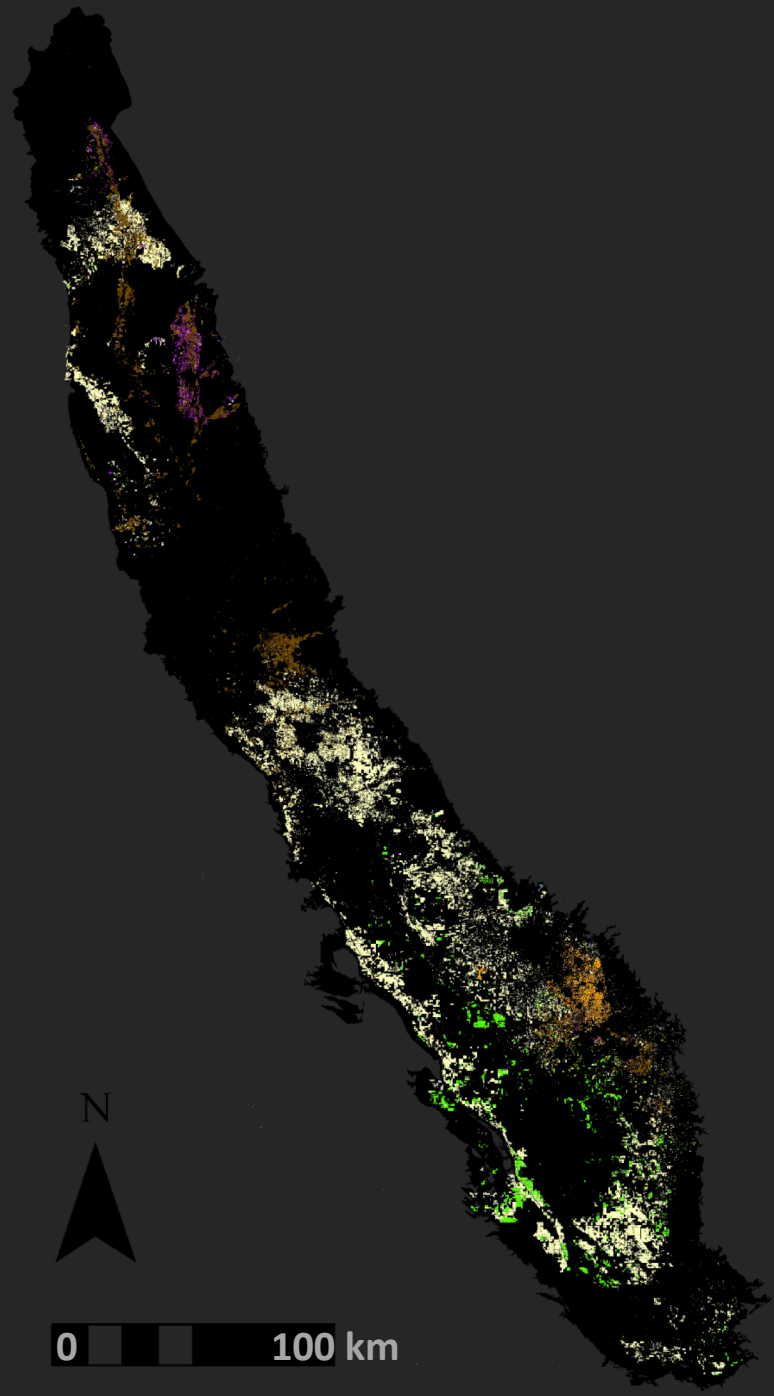


Hydrologic Regions and Groundwater Depth

- Test well depths used to calculate static head and energy needed for extraction
- Thiessen polygons for groundwater zones



Irrigation Energy for Major Tree Crops

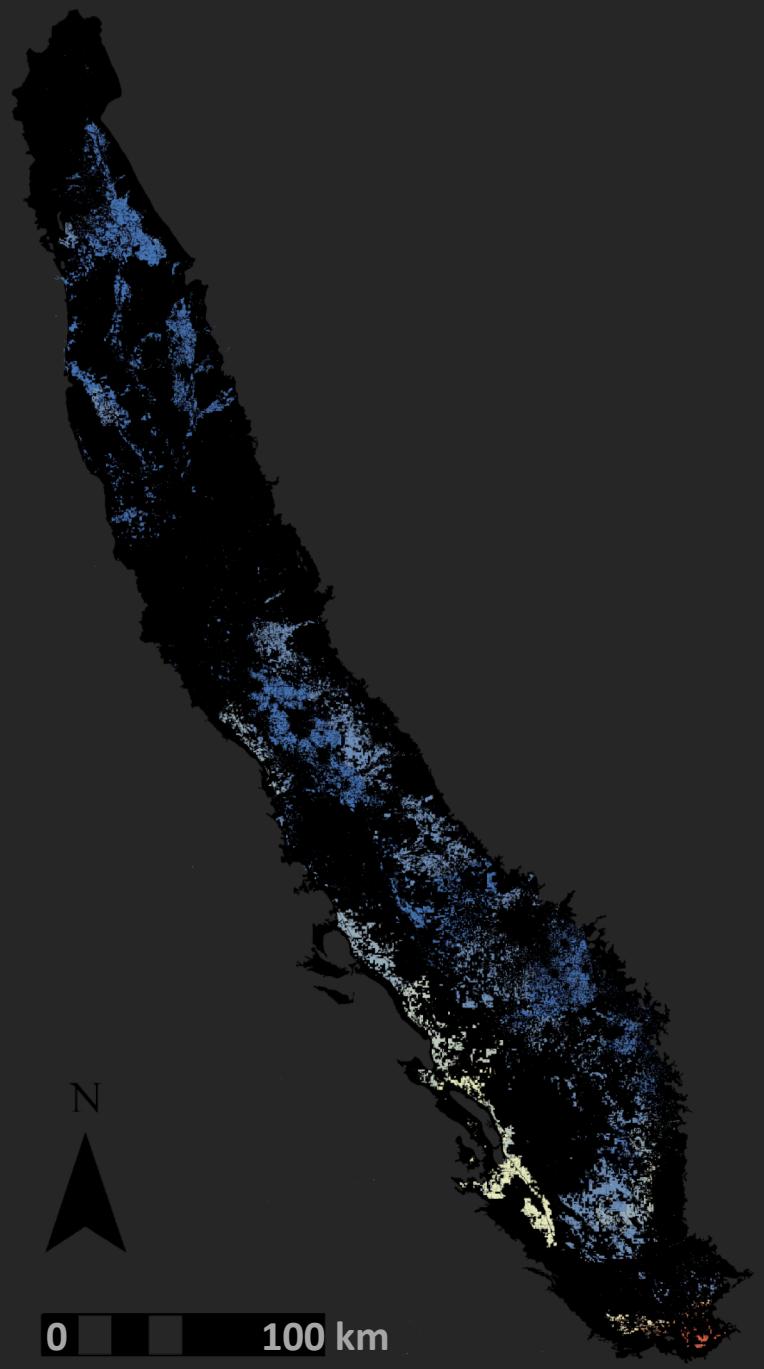


0
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25

(MJ m^{-3})

Irrigation Energy for Major Tree Crops

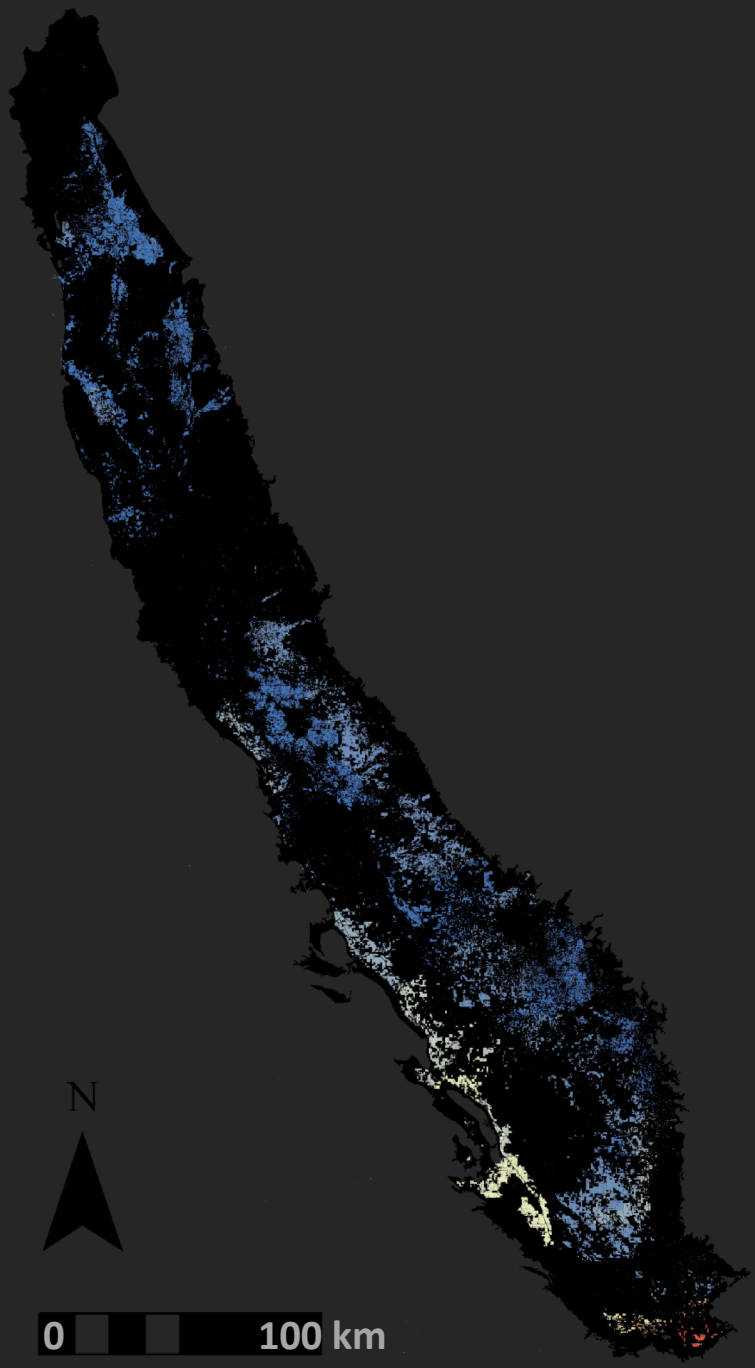
- Ground and surface water, irrigation system usage statistics from Almond Board Sustainability reports and farm advisor interviews



0
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
(MJ m^{-3})

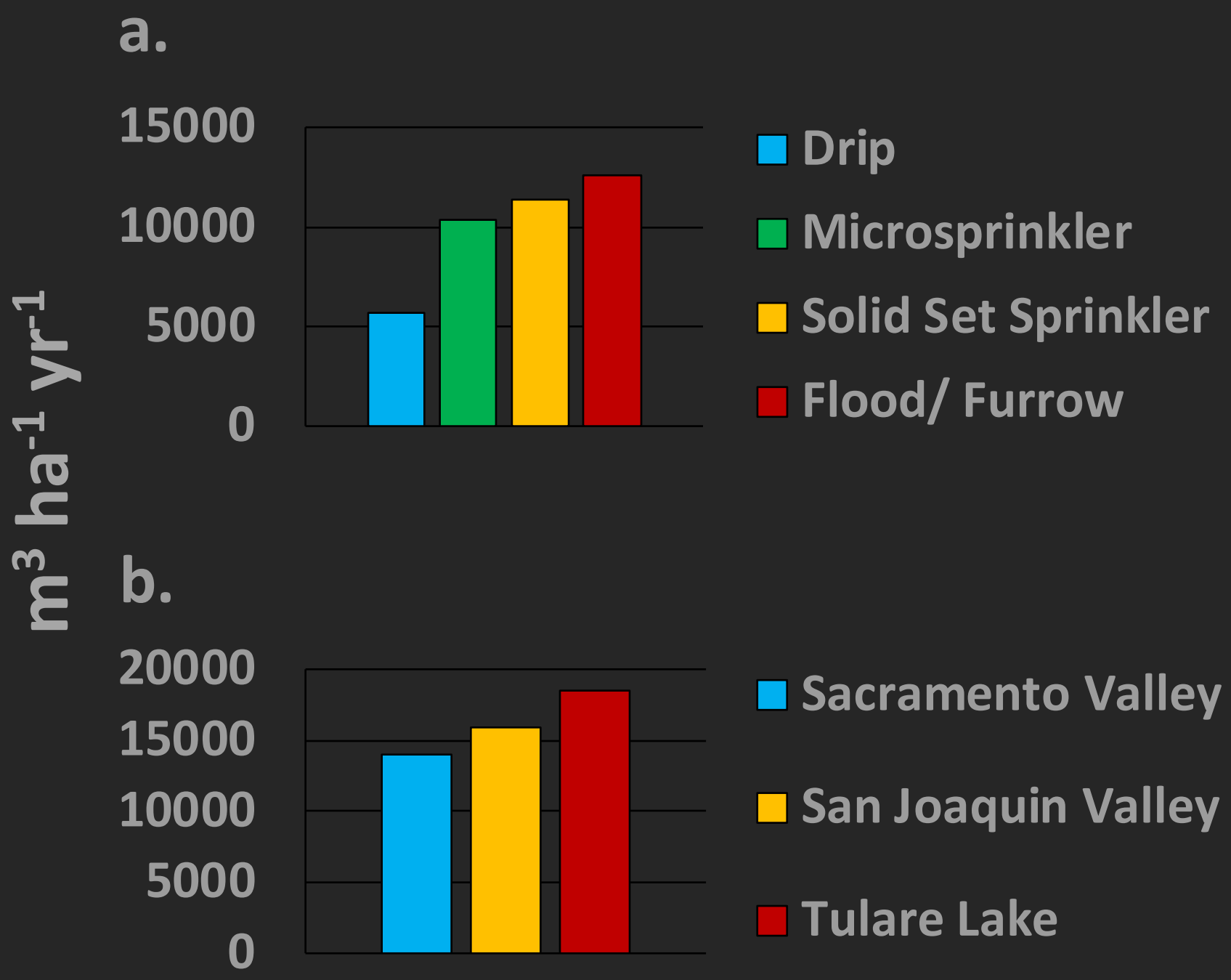
Irrigation Energy for Major Tree Crops

- Ground and surface water, irrigation system usage statistics from Almond Board Sustainability reports and farm advisor interviews
- Regional water use from UC Davis Cost/ Return Studies

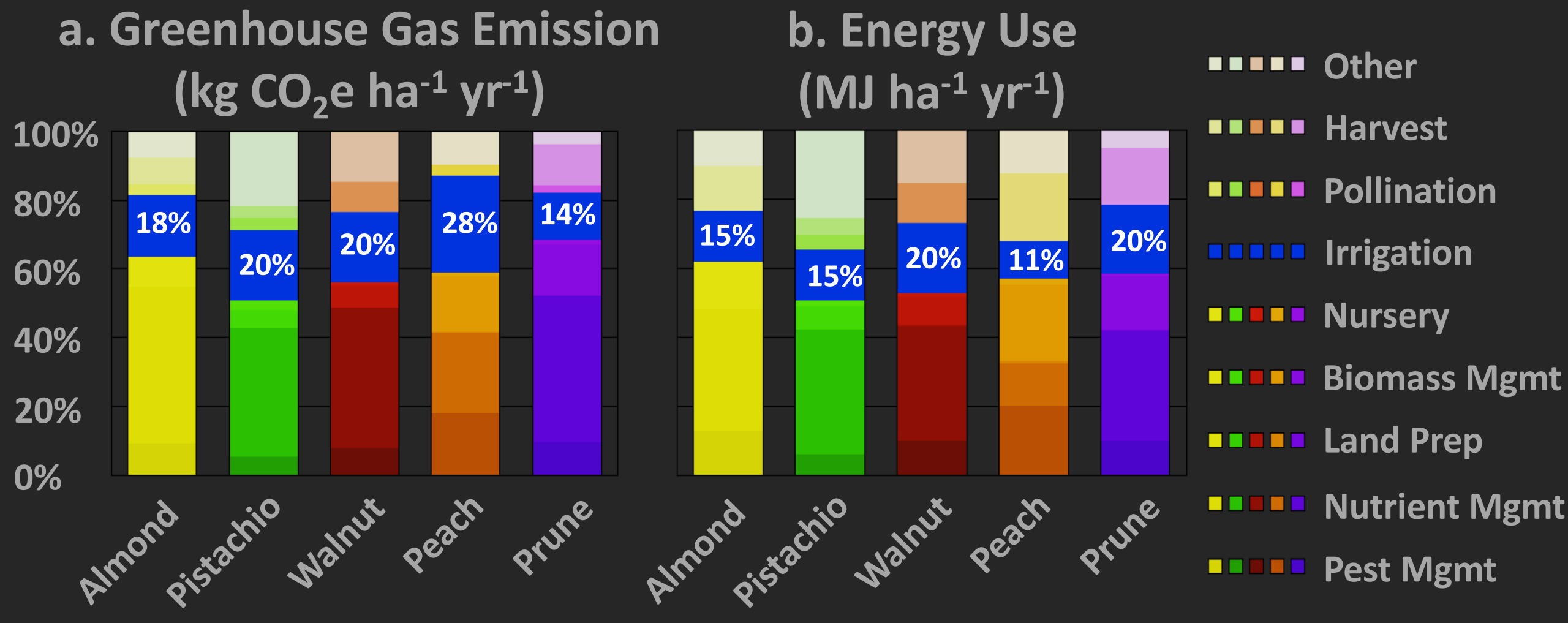


0
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
2.25
(MJ m^{-3})

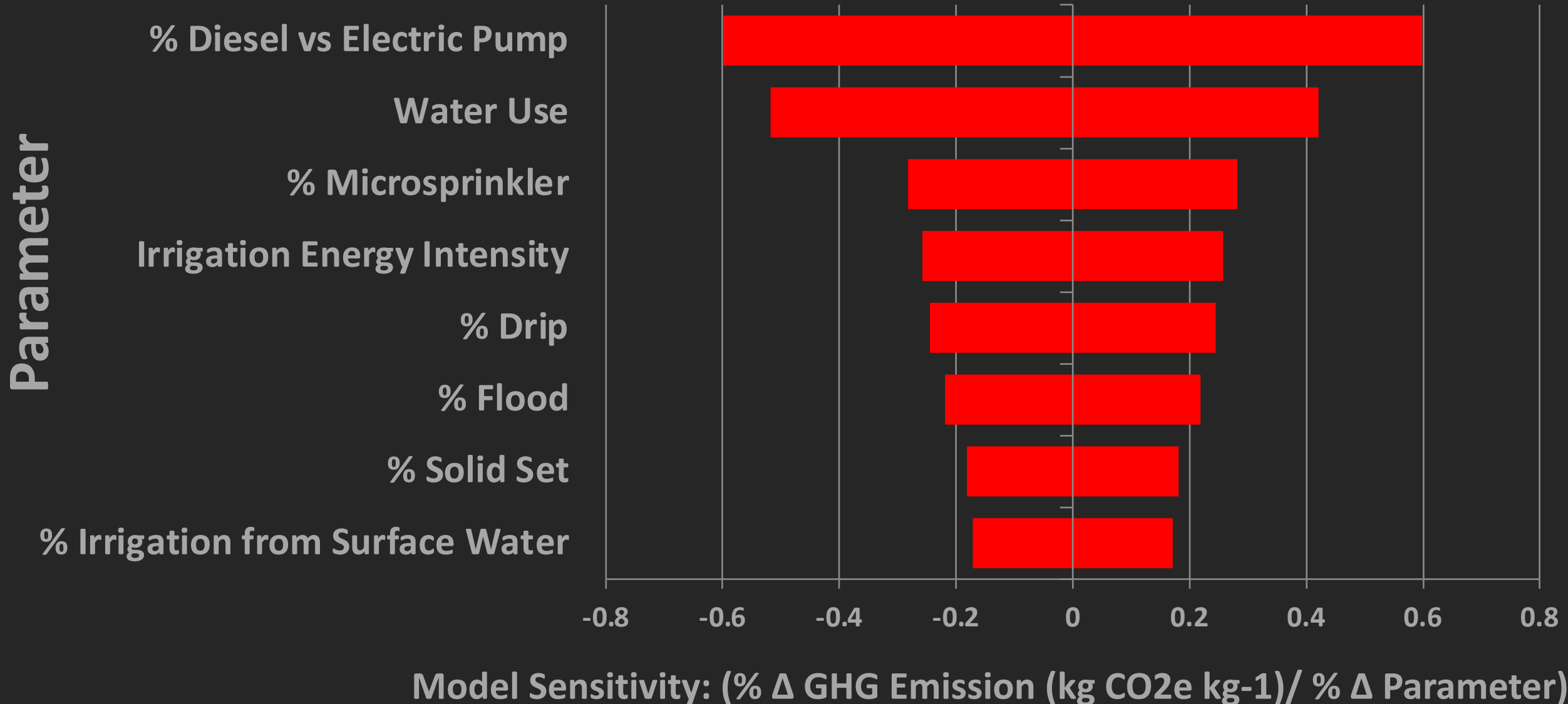
Water Use by Irrigation System (a) and Hydrologic Region (b)

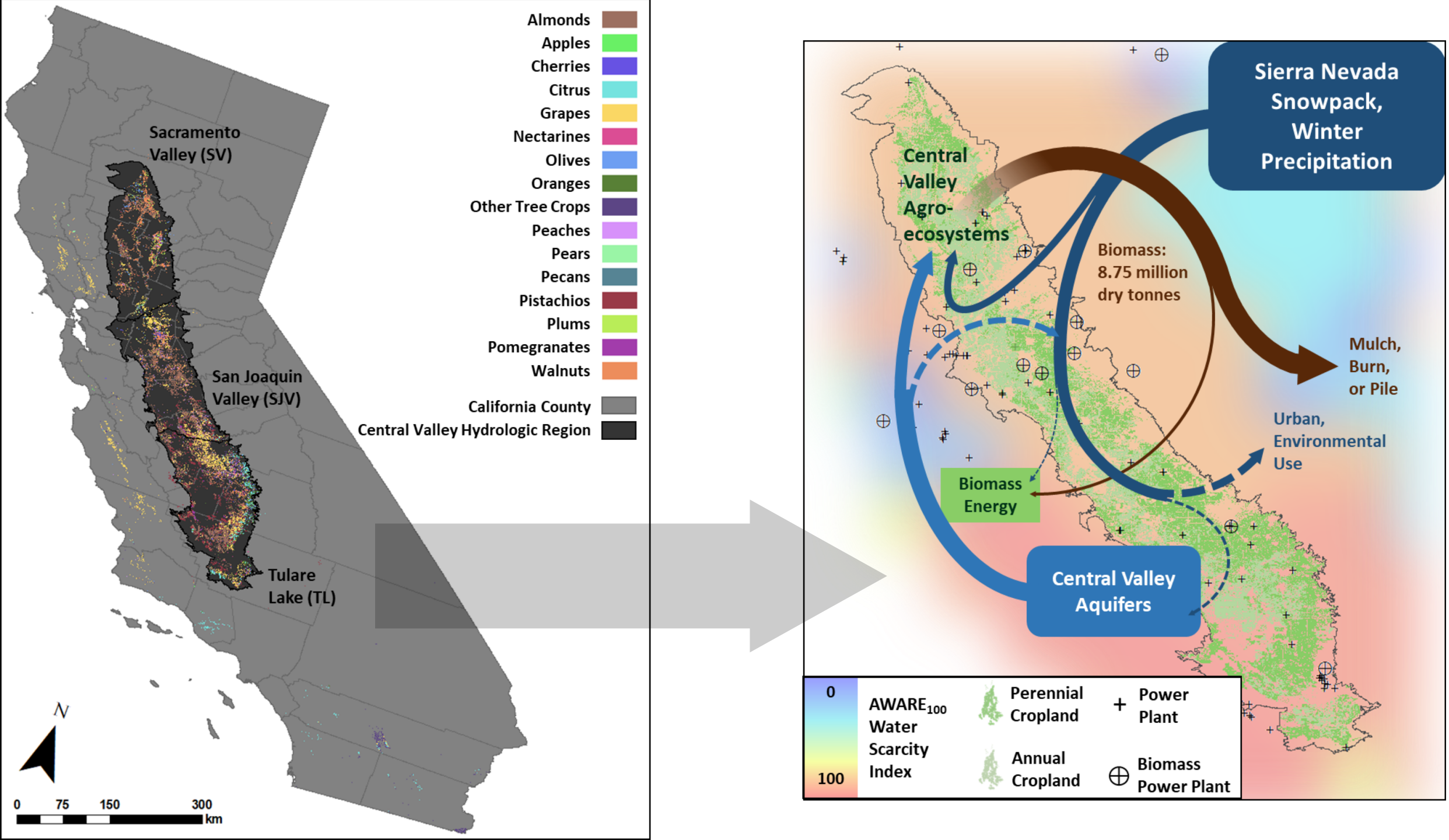


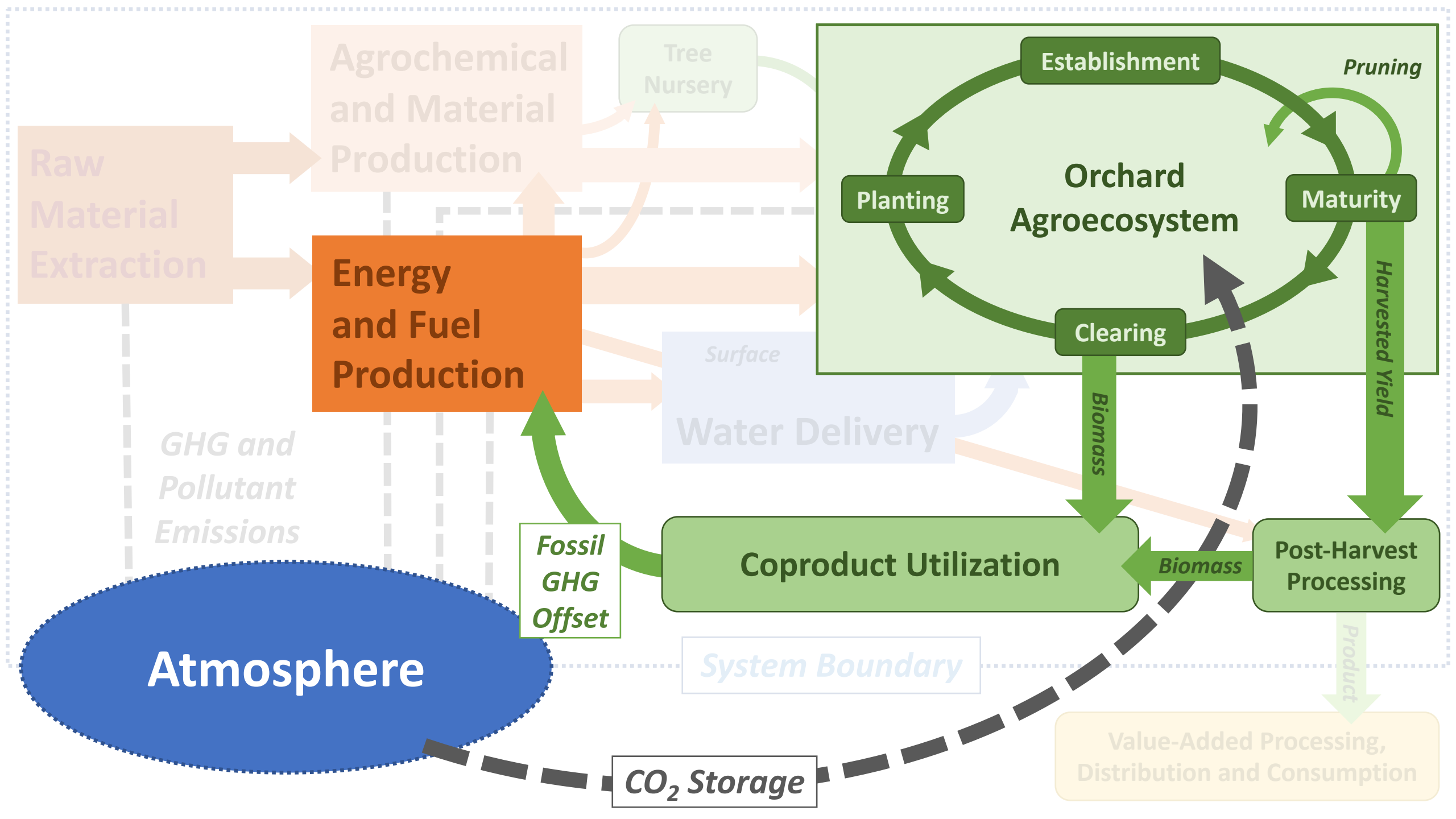
Contribution of Irrigation to Orchard GHG Emission (a) and Energy Use (b)



Sensitivity Analysis: Almond Production



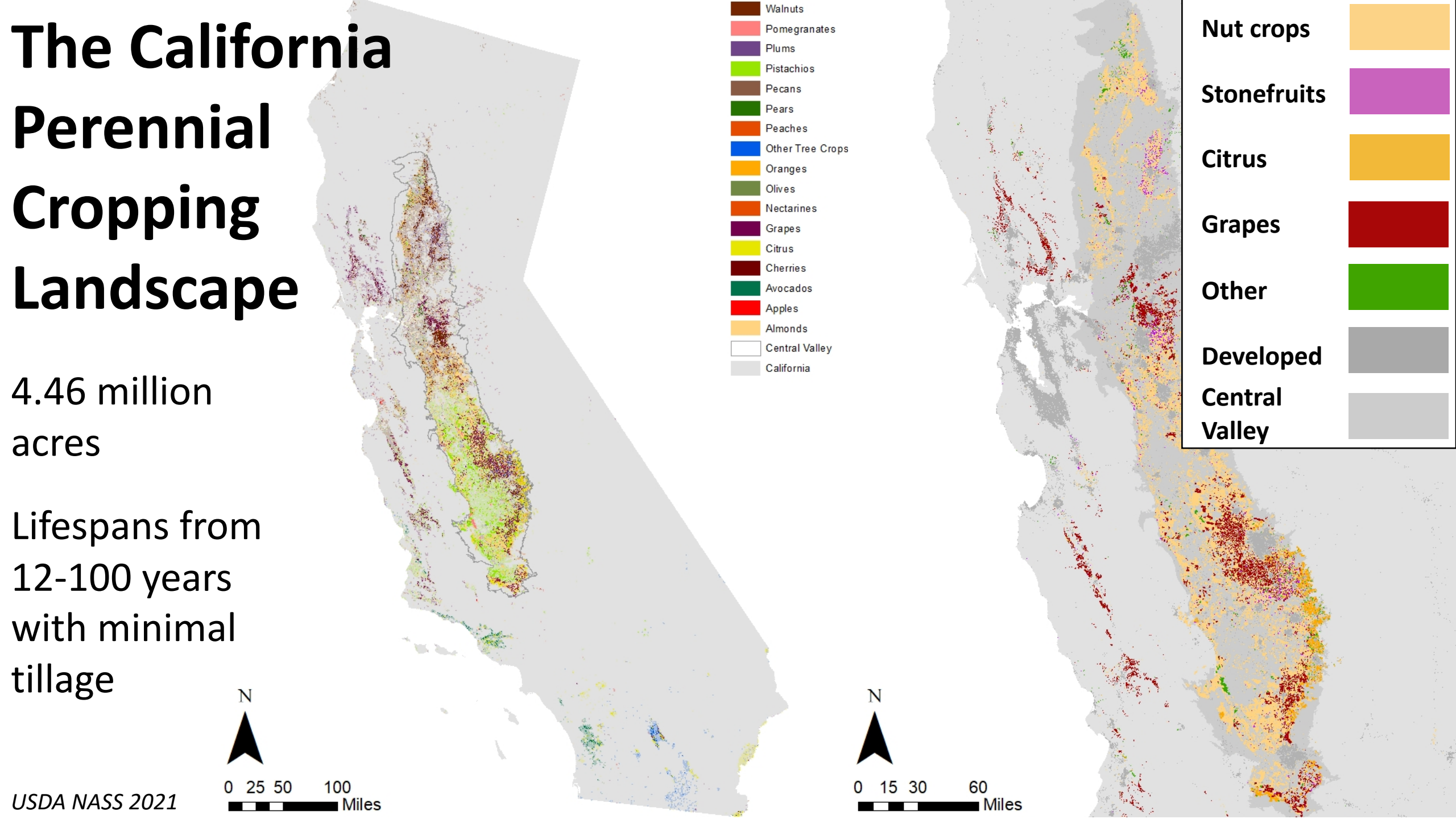

Almonds
Apples
Cherries
Citrus
Grapes
Nectarines
Olives
Oranges
Other Tree Crops
Peaches
Pears
Pecans
Pistachios
Plums
Pomegranates
Walnuts
California County
Central Valley Hydrologic Region
Sacramento Valley (SV)
San Joaquin Valley (SJV)
Tulare Lake (TL)
N
0 75 150 300
km
Sierra Nevada Snowpack, Winter Precipitation
Central Valley Agro-ecosystems
Biomass: 8.75 million dry tonnes
Mulch, Burn, or Pile
Urban, Environmental Use
Biomass Energy
Central Valley Aquifers
0
100
AWARE100 Water Scarcity Index
Perennial Cropland
Annual Cropland
Power Plant
Biomass Power Plant


Agrochemical and Material Production
Tree Nursery
Raw Material Extraction
Energy and Fuel Production
Establishment
Pruning
Planting
Orchard Agroecosystem
Maturity
Clearing
Harvested Yield
Surface
Water Delivery
Biomass
GHG and Pollutant Emissions
Fossil GHG Offset
Coproduct Utilization
Biomass
Post-Harvest Processing
Atmosphere
System Boundary
Product
Value-Added Processing, Distribution and Consumption
CO_2 Storage

The California Perennial Cropping Landscape

4.46 million acres

Lifespans from 12-100 years with minimal tillage

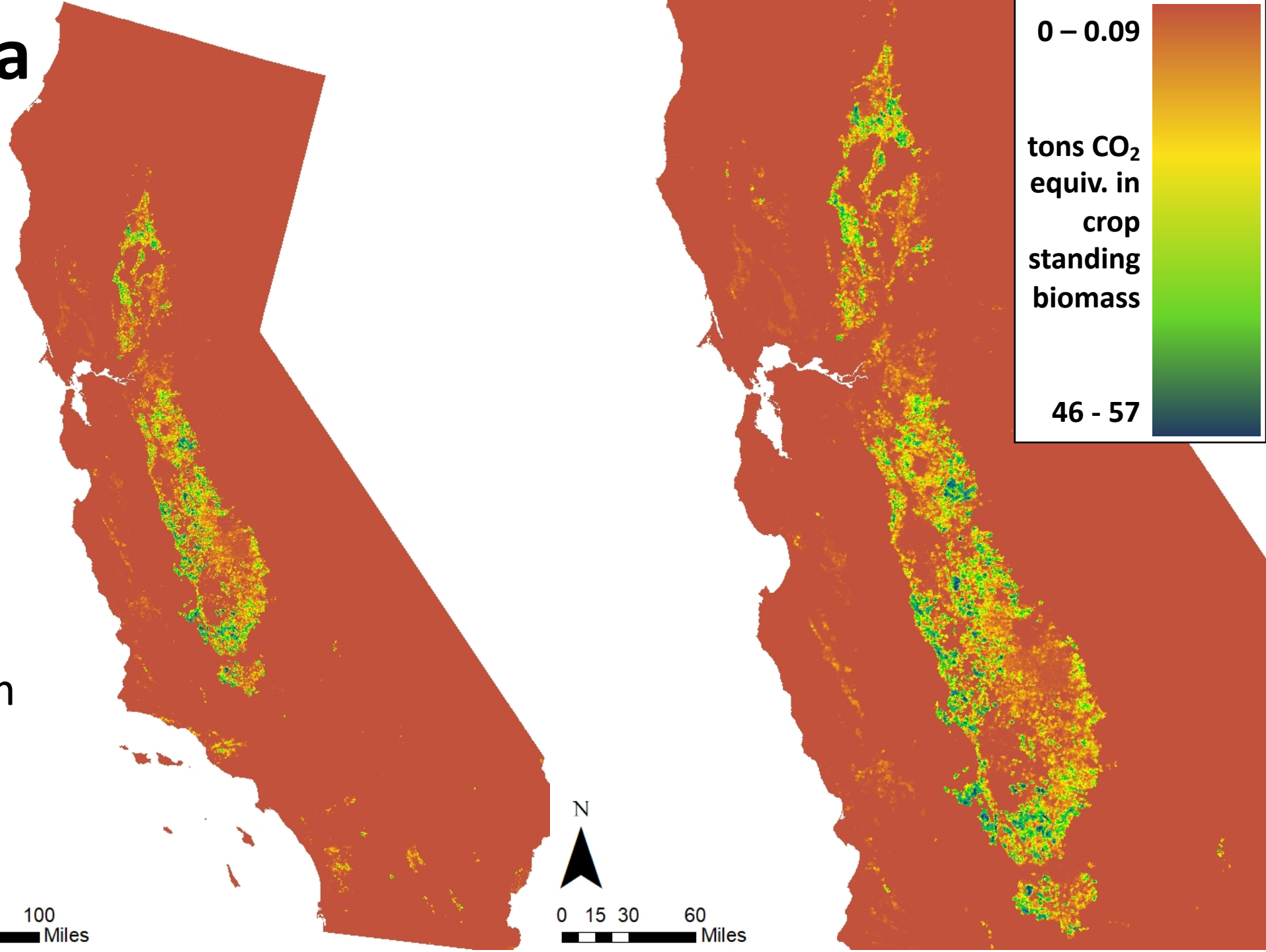


USDA NASS 2021

The California Perennial Cropping Landscape

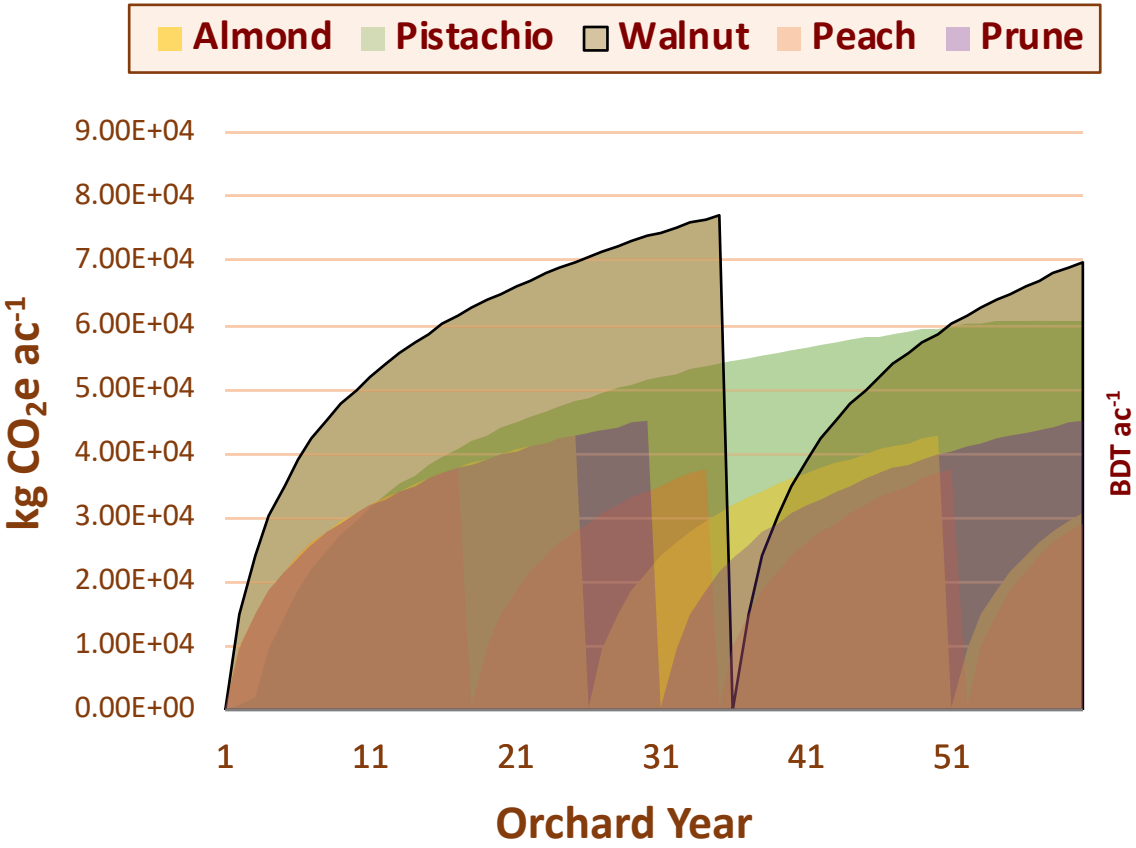
Up to 110 million bone dry tons

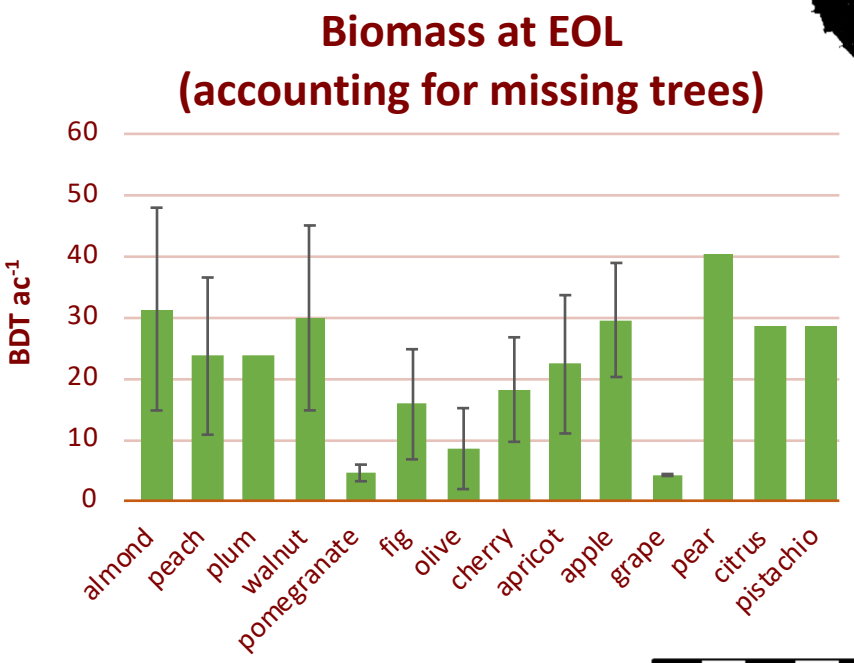
Equivalent to 205 million tons CO_2 from the atmosphere

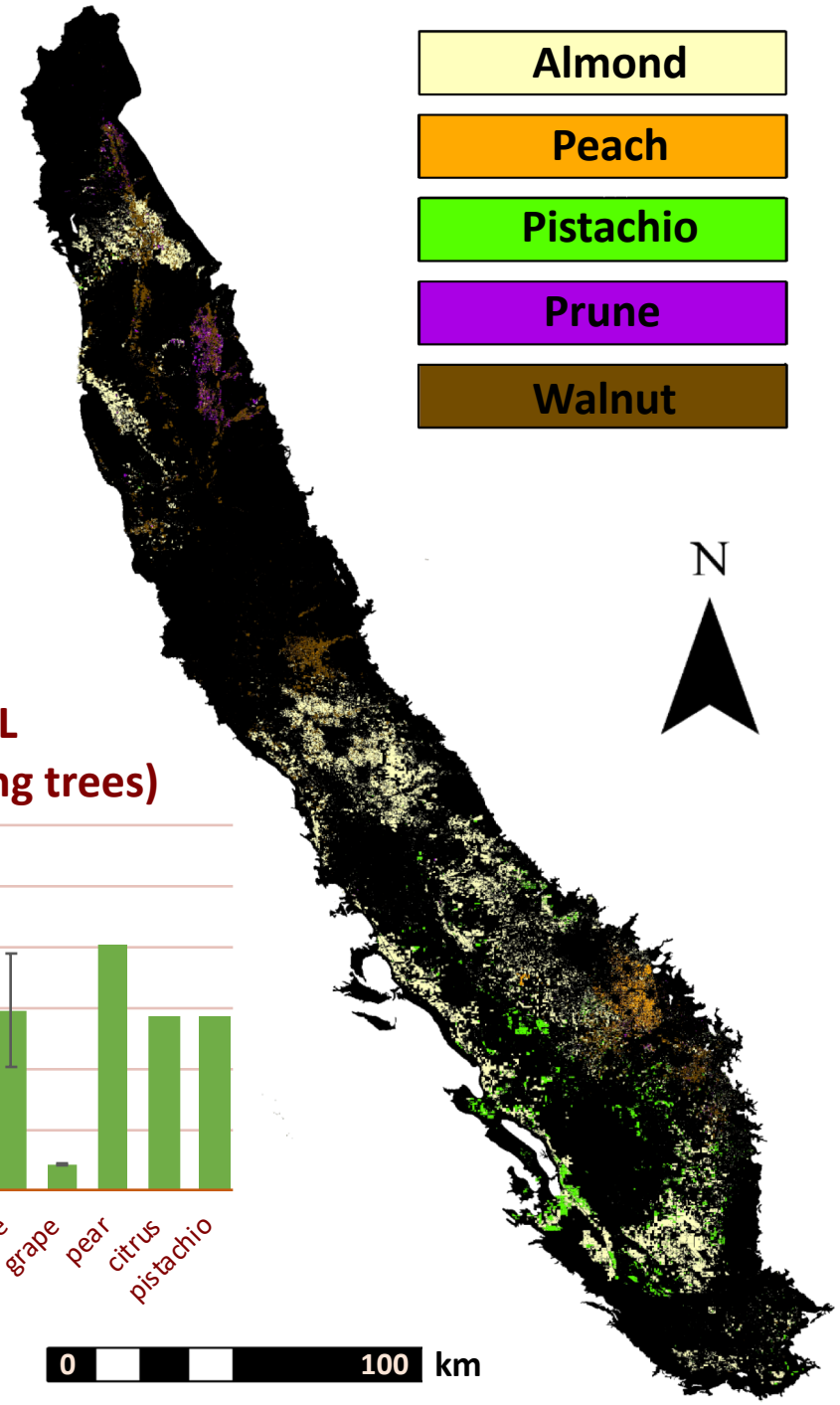


Biomass Plants as "Gatekeepers" for Avoided Fossil Fuel Use GHG Credit

- Accounting for competition from other biomass feedstock sources

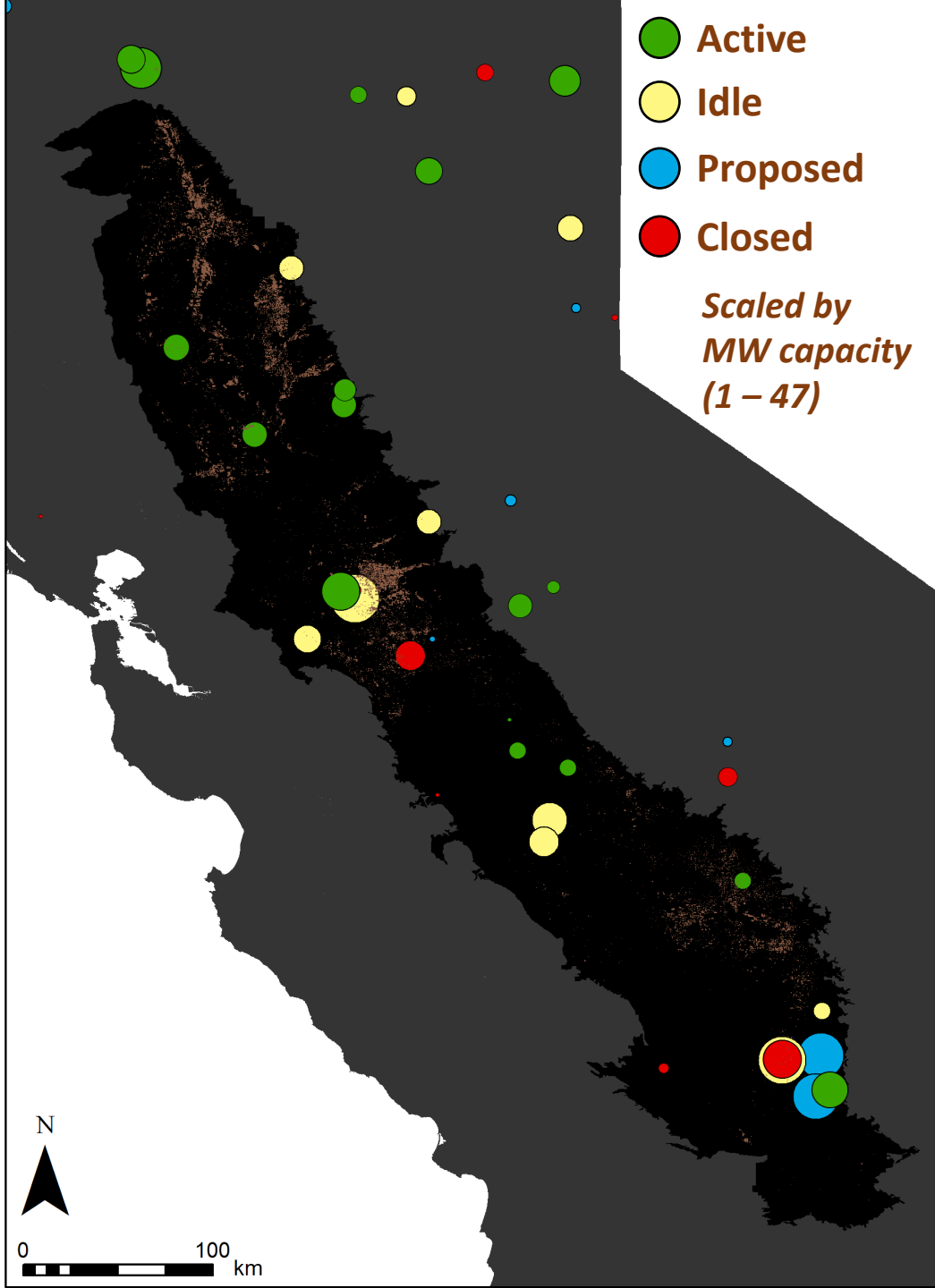






Walnut orchards and California biomass energy infrastructure

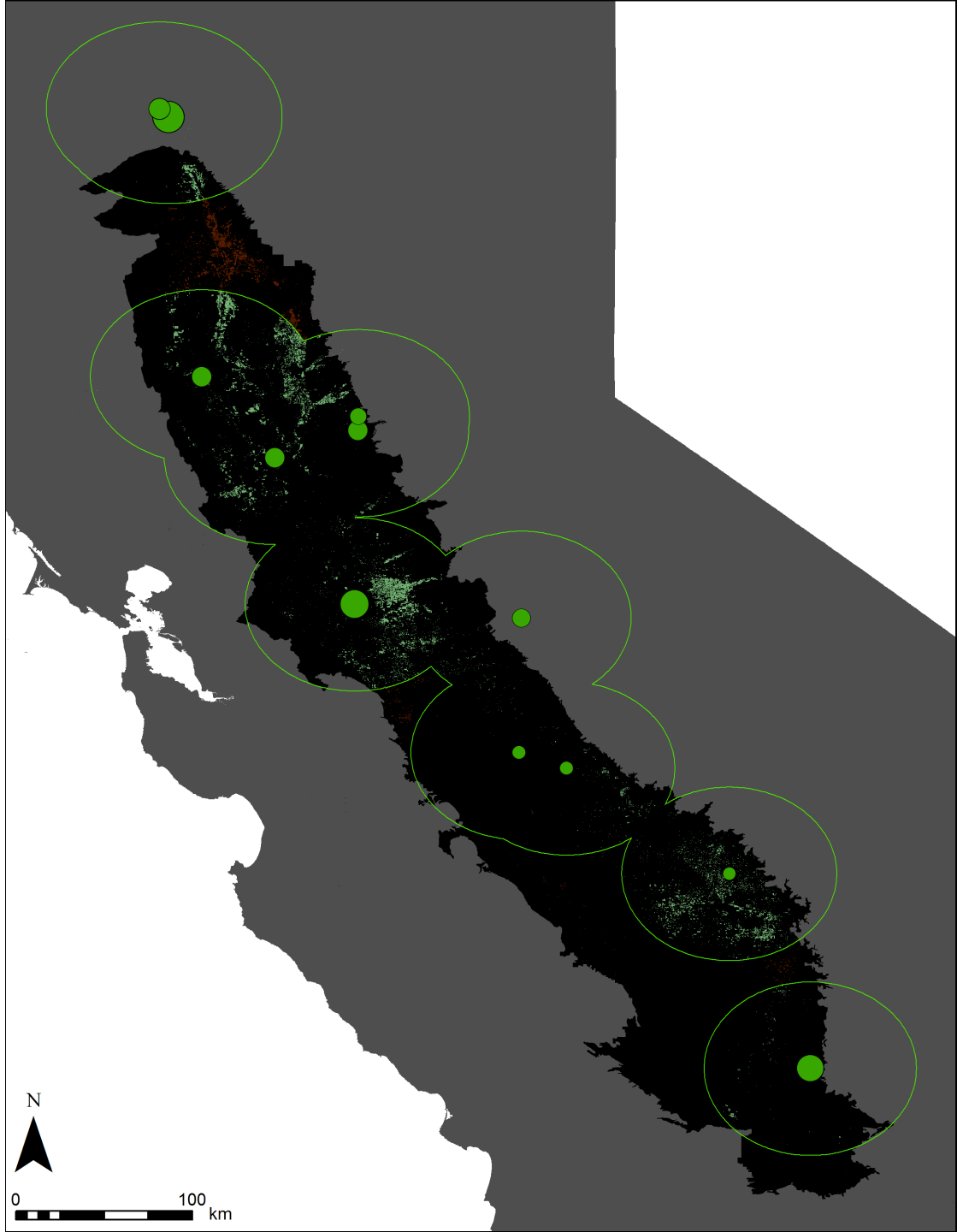
- Recent and ongoing plant closure and idling are changing orchard EOL management options
- Alternative EOL biomass options are needed (orchard recycling, etc)



Walnut orchards and California biomass energy infrastructure

% within average transport range of a power plant:

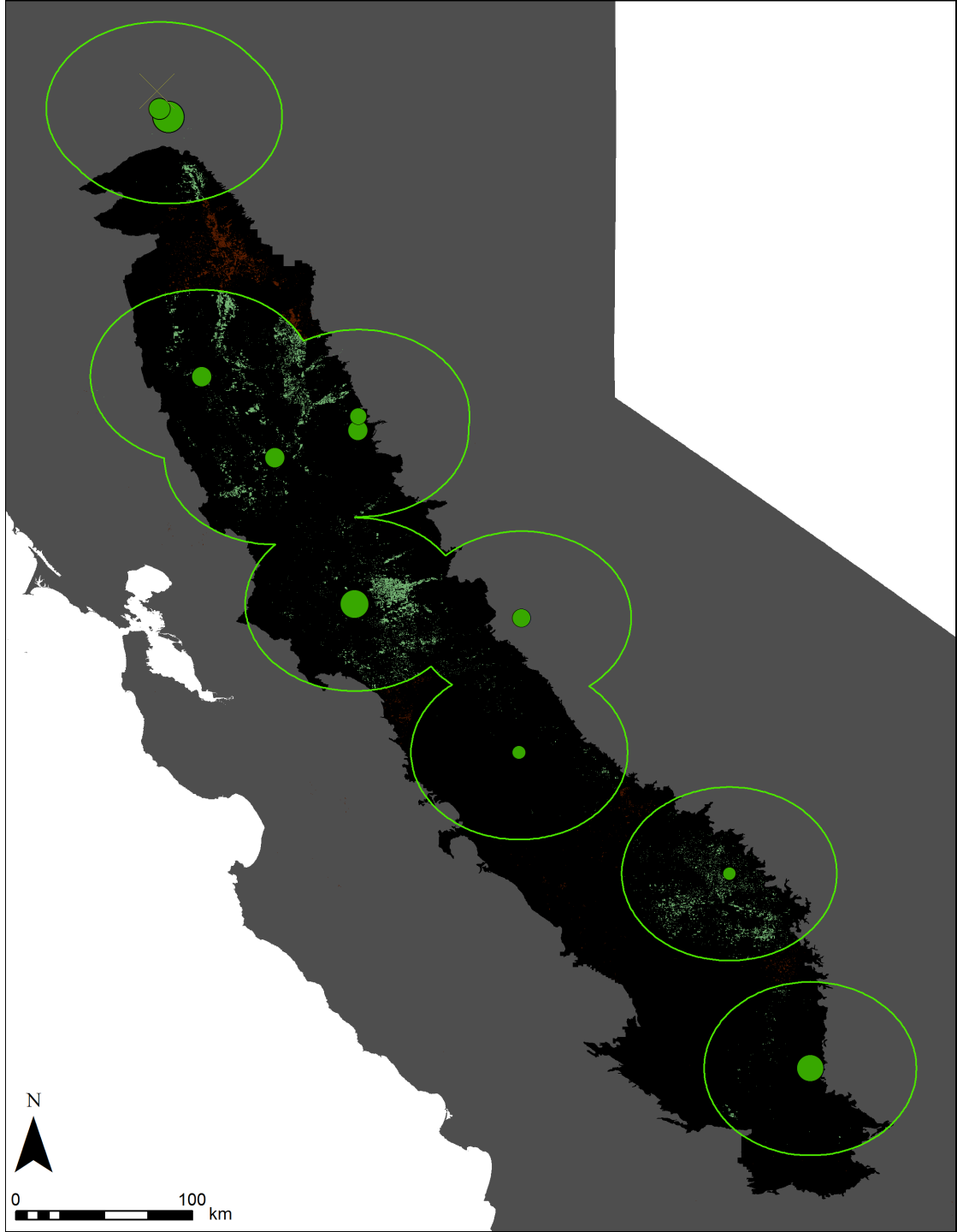
79



Walnut orchards and California biomass energy infrastructure

% within average transport range of a power plant:

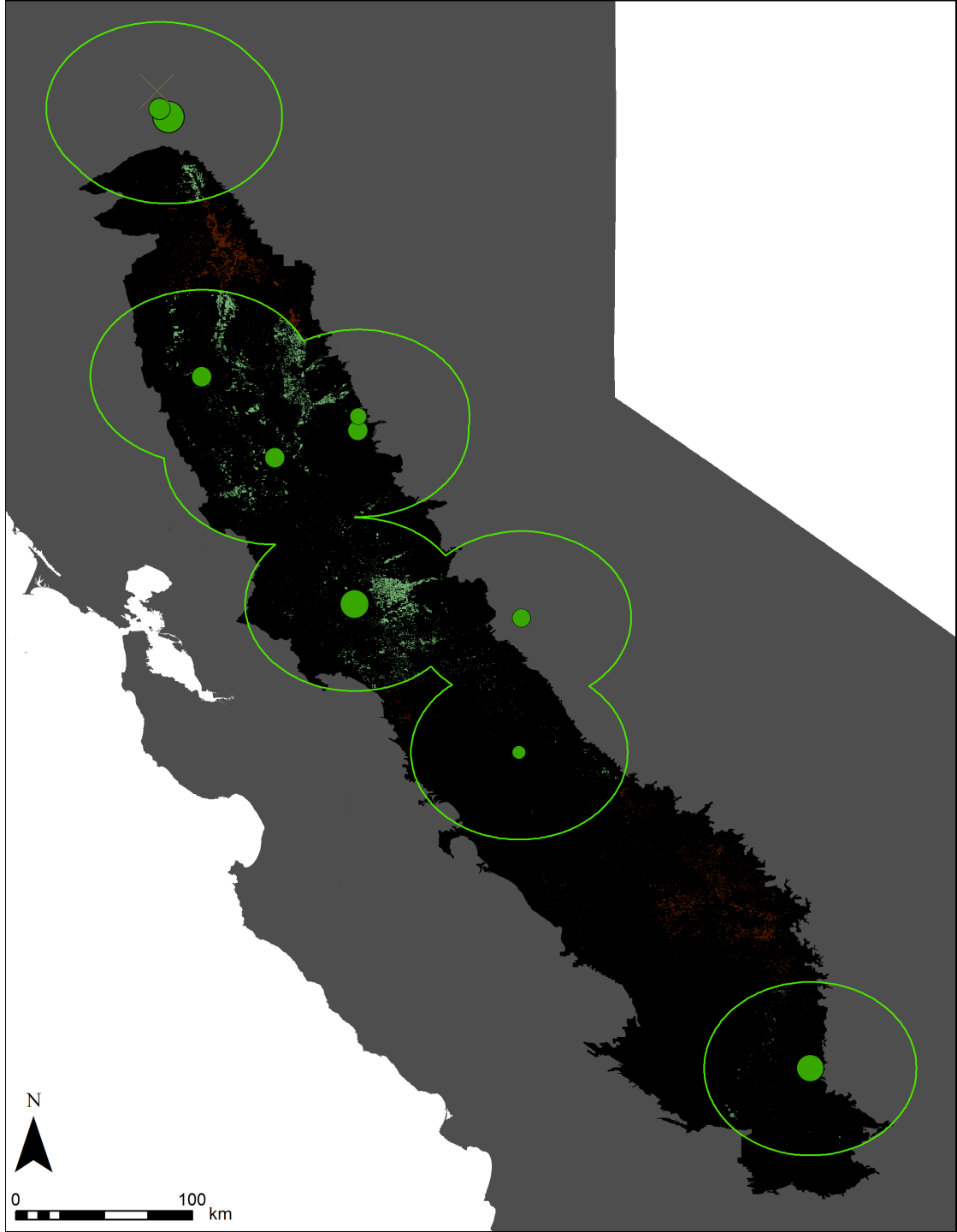
78



Walnut orchards and California biomass energy infrastructure

% within average transport range of a power plant:

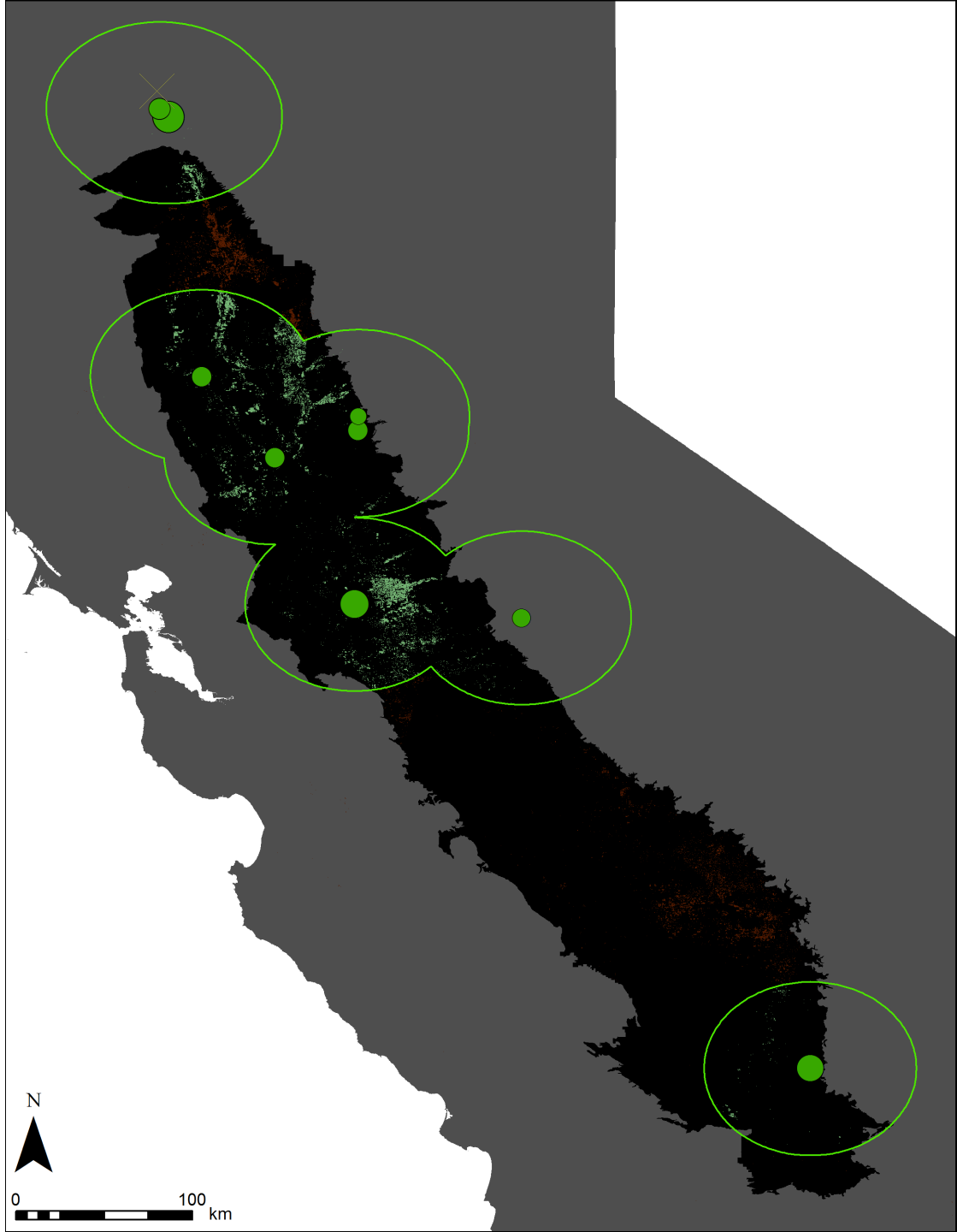
62



Walnut orchards and California biomass energy infrastructure

% within average transport range of a power plant:

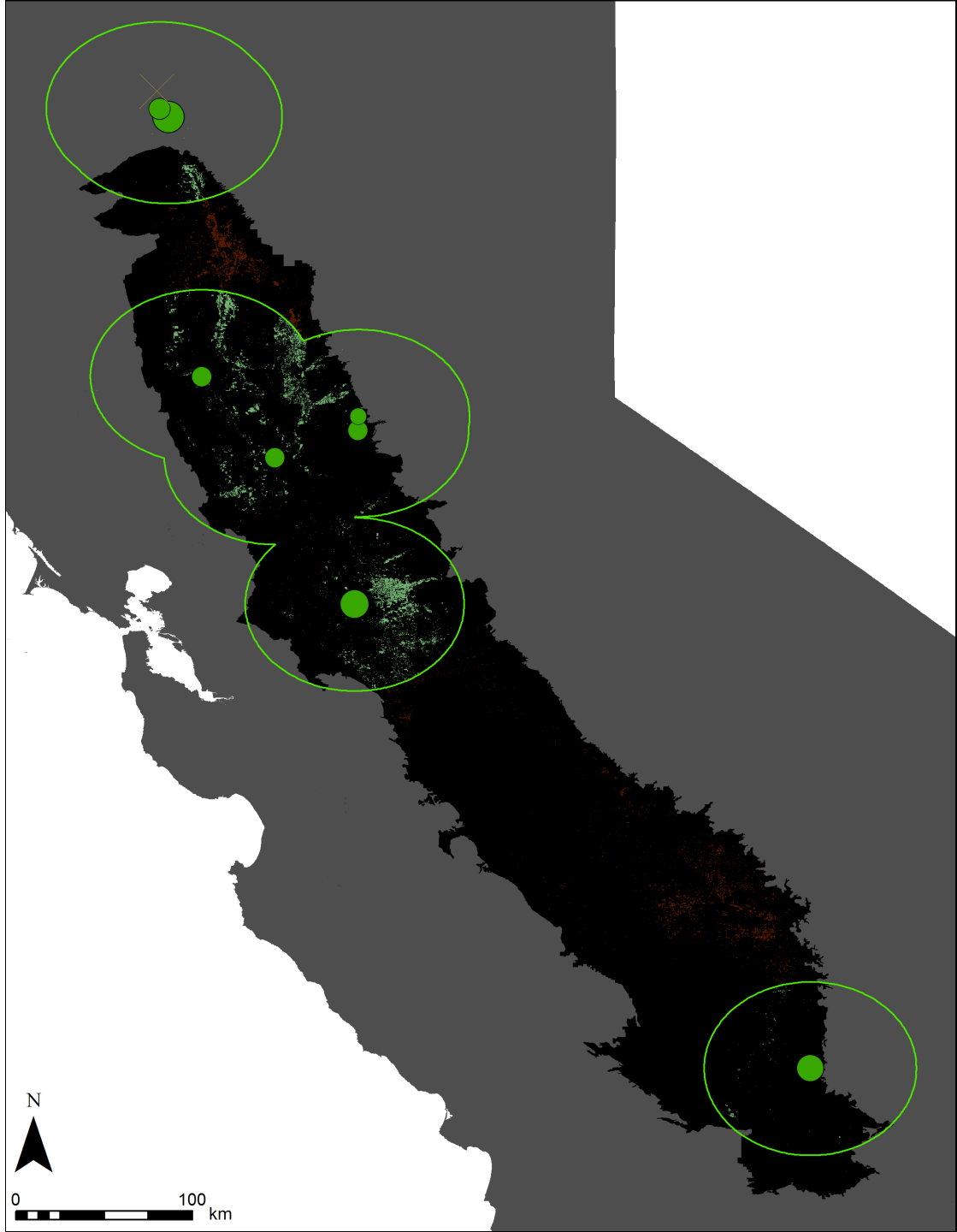
61



Walnut orchards and California biomass energy infrastructure

% within average transport range of a power plant:

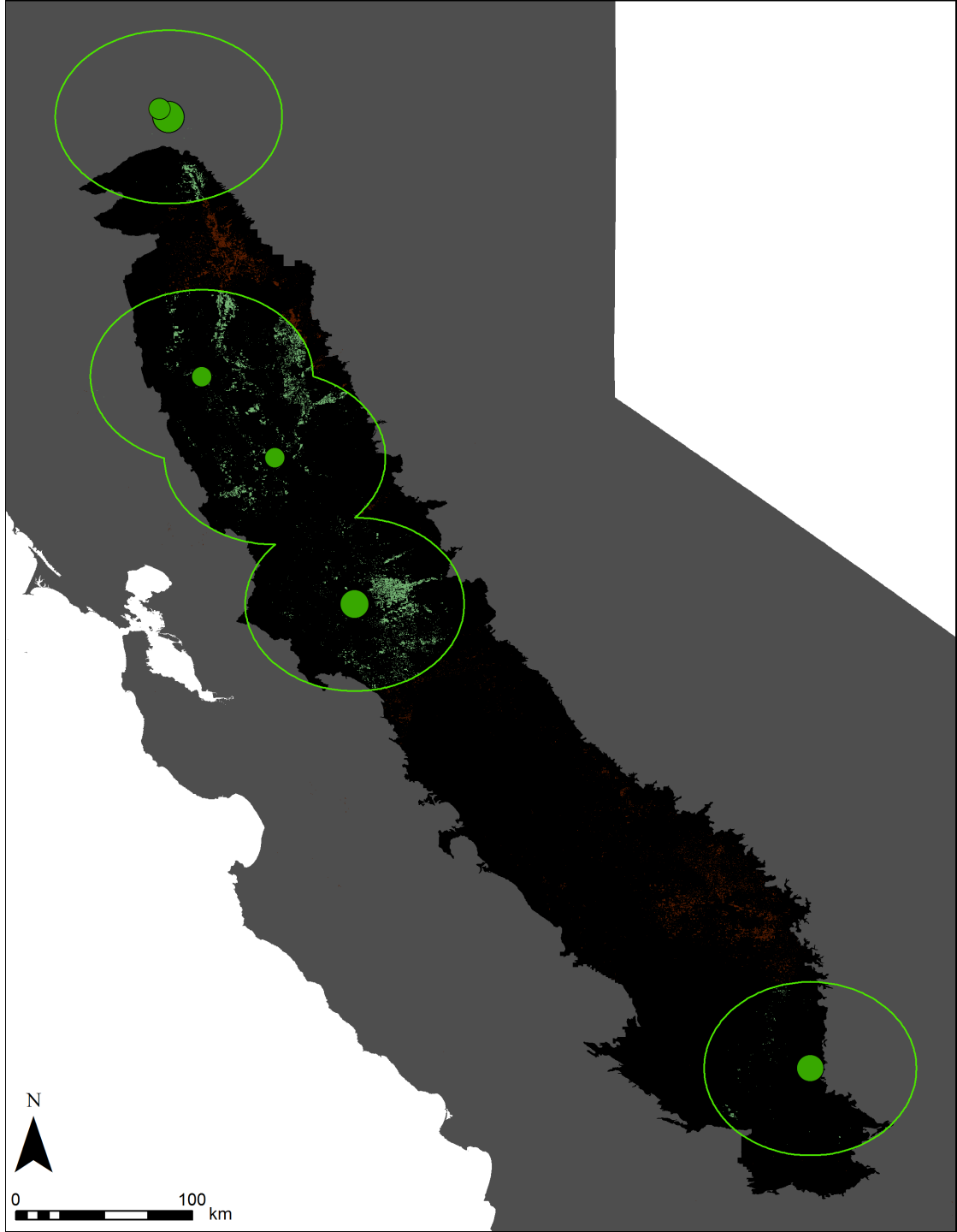
60



Walnut orchards and California biomass energy infrastructure

% within average transport range of a power plant:

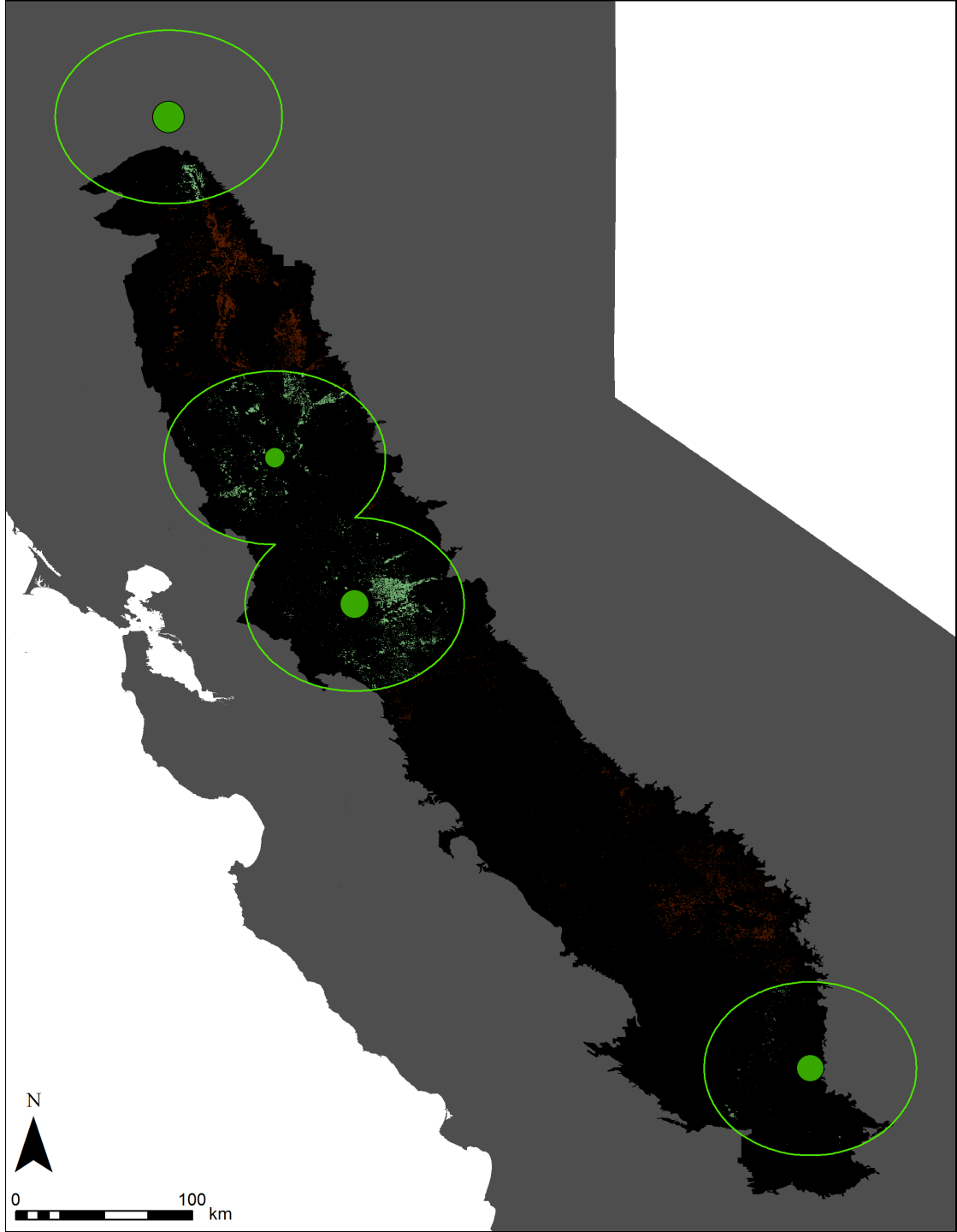
60



Walnut orchards and California biomass energy infrastructure

% within average transport range of a power plant:

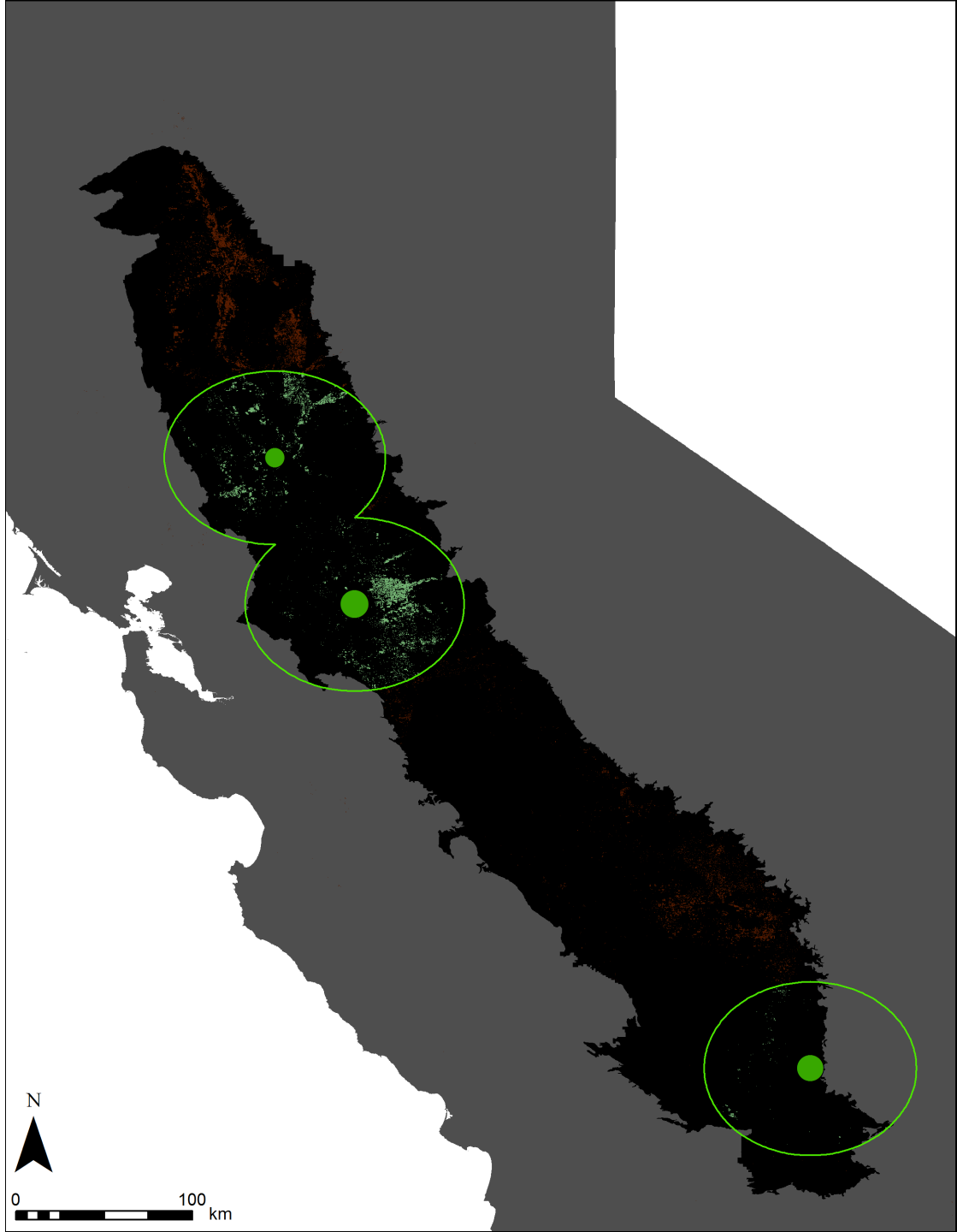
43



Walnut orchards and California biomass energy infrastructure

% within average transport range of a power plant:

40



Walnut orchards and California biomass energy infrastructure

% within average transport range of a power plant:

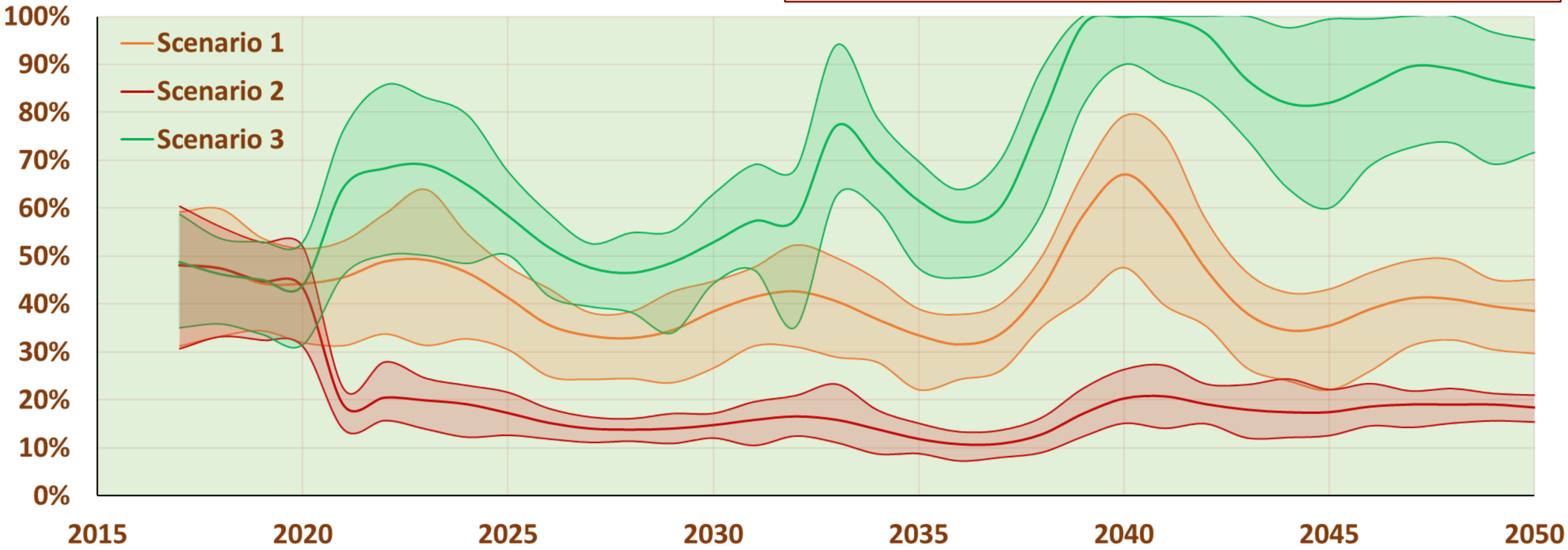
24

Estimated Almond Biomass to Energy (Central Valley)

Scenario 1: currently active power plants maintained through 2050

Scenario 2: Most currently active BMPPs closed by 2020, only new projects/ proposals active through 2050

Scenario 3: Current plants maintained through 2050, plus currently idled BMPPs returned to active status starting in 2020 (2 reactivated every 5 years)

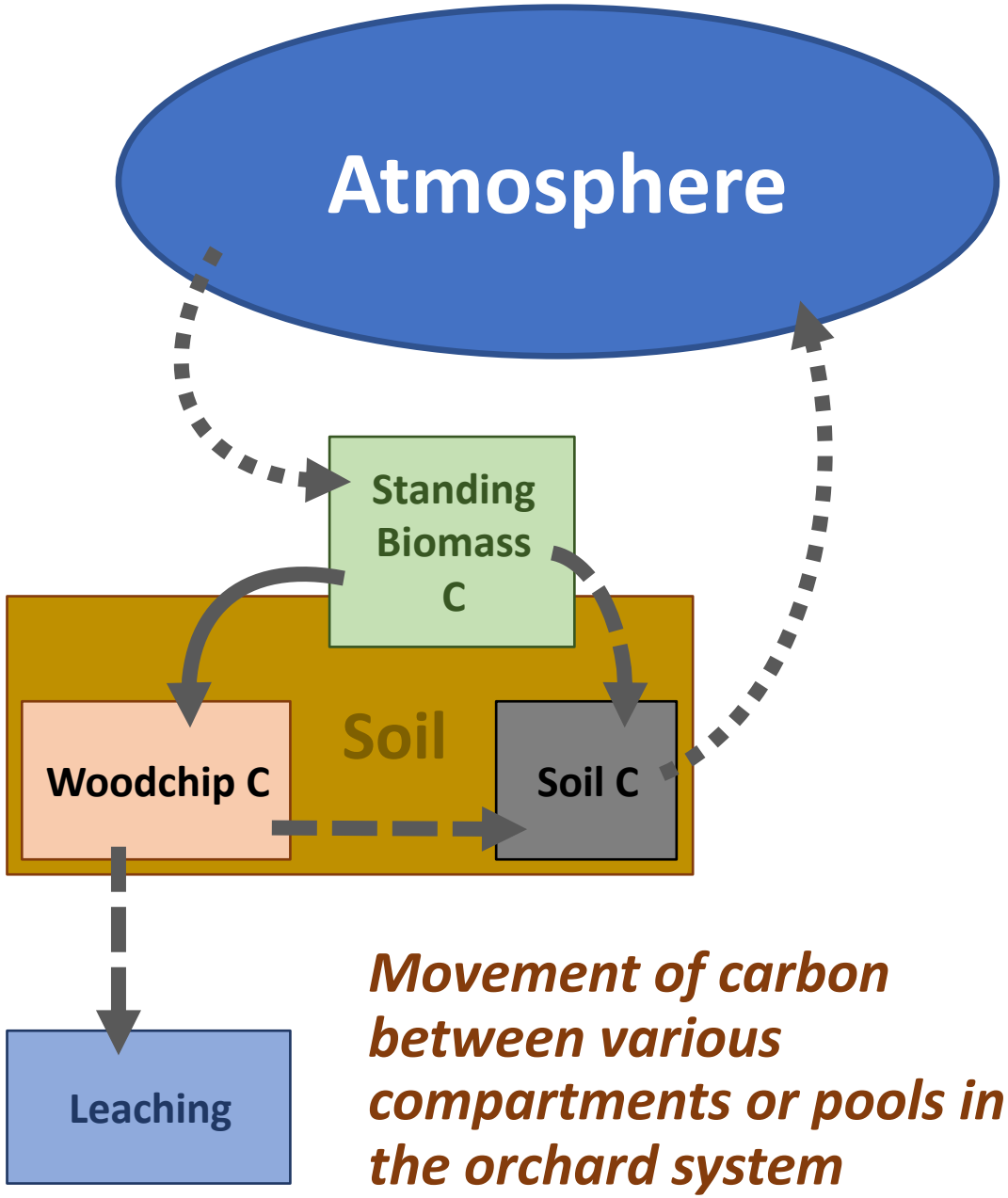


Alternative to Biomass-based Energy Production: "Orchard Recycling"

Returning biomass directly to orchard soil

Alternative to Biomass-based Energy Production: "Orchard Recycling"

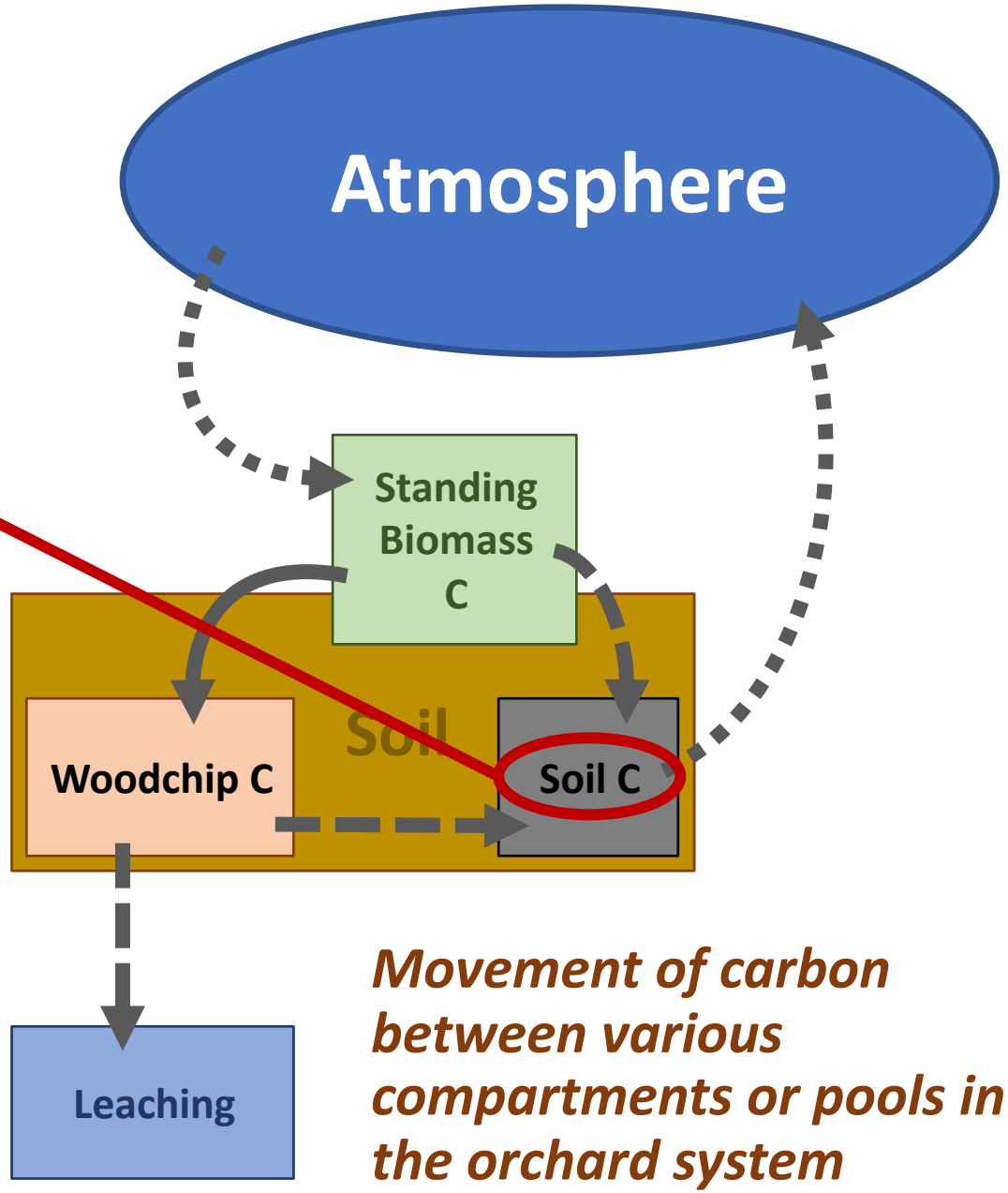
- 17 years of data from barrel experiments in with almond chips
- Basis for estimates of potential soil carbon storage under different management practices and orchard systems



Movement of carbon between various compartments or pools in the orchard system

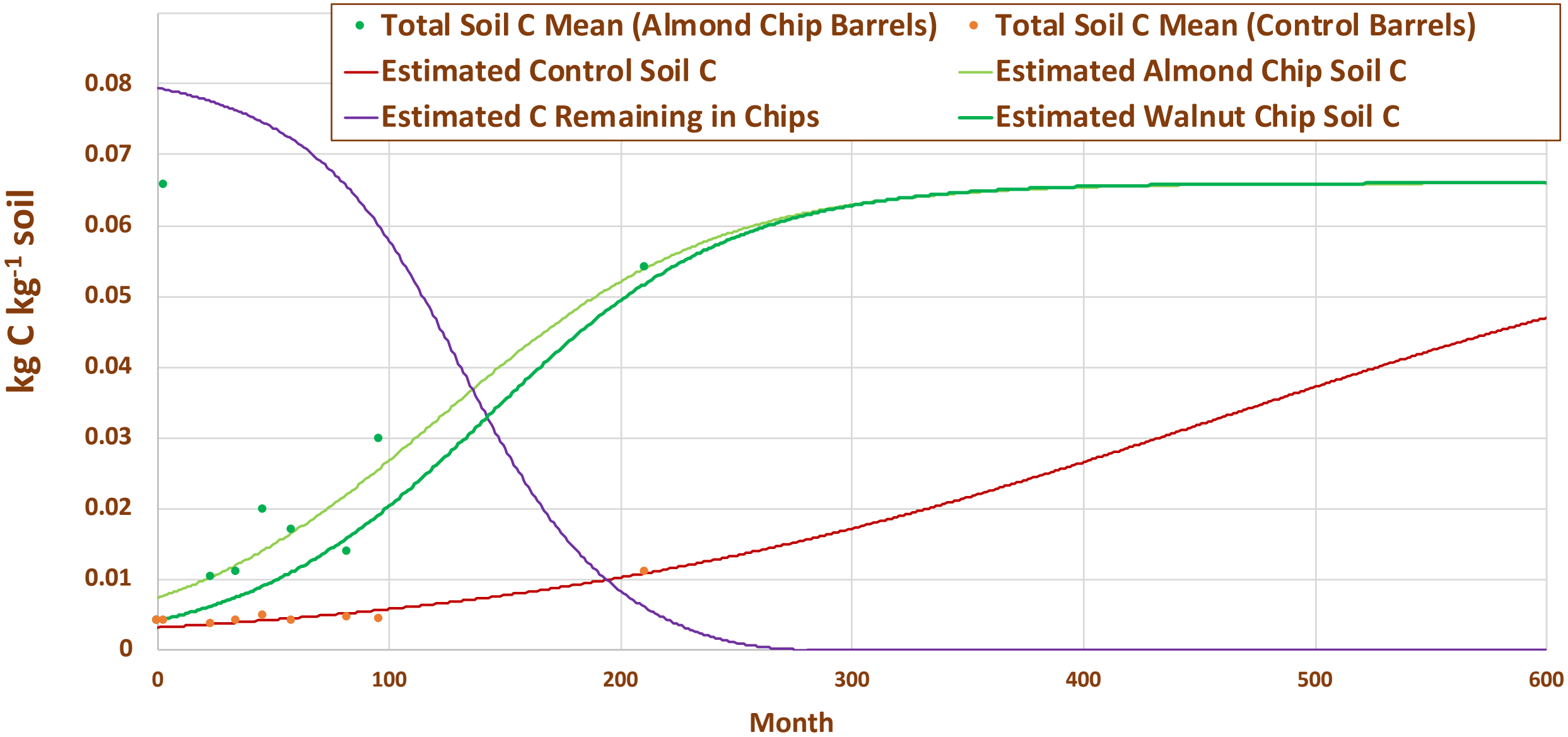
Alternative to Biomass-based Energy Production: "Orchard Recycling"

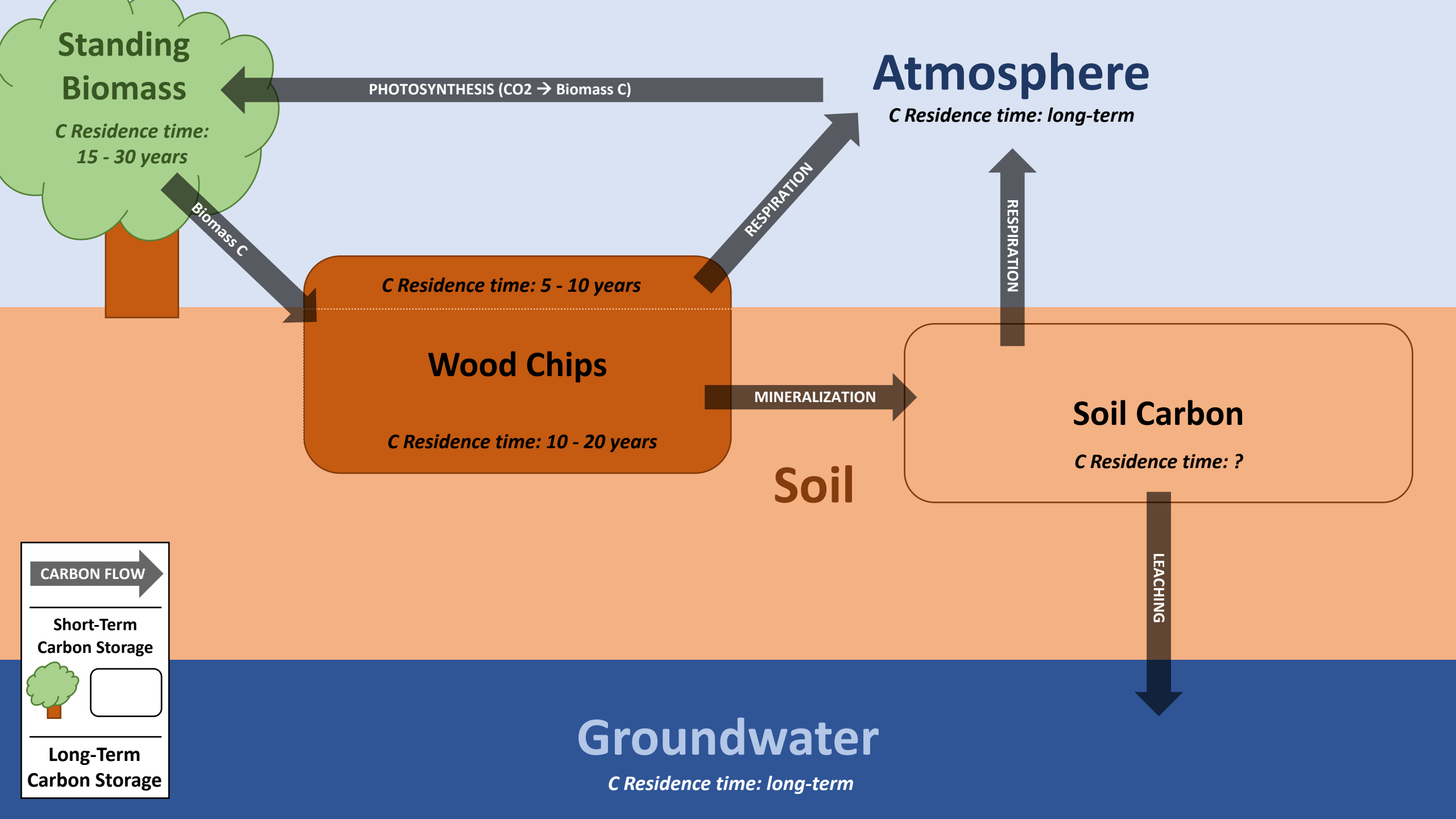
- 17 years of data from barrel experiments in with almond chips
- Basis for estimates of potential soil carbon storage under different management practices and orchard systems



Movement of carbon between various compartments or pools in the orchard system

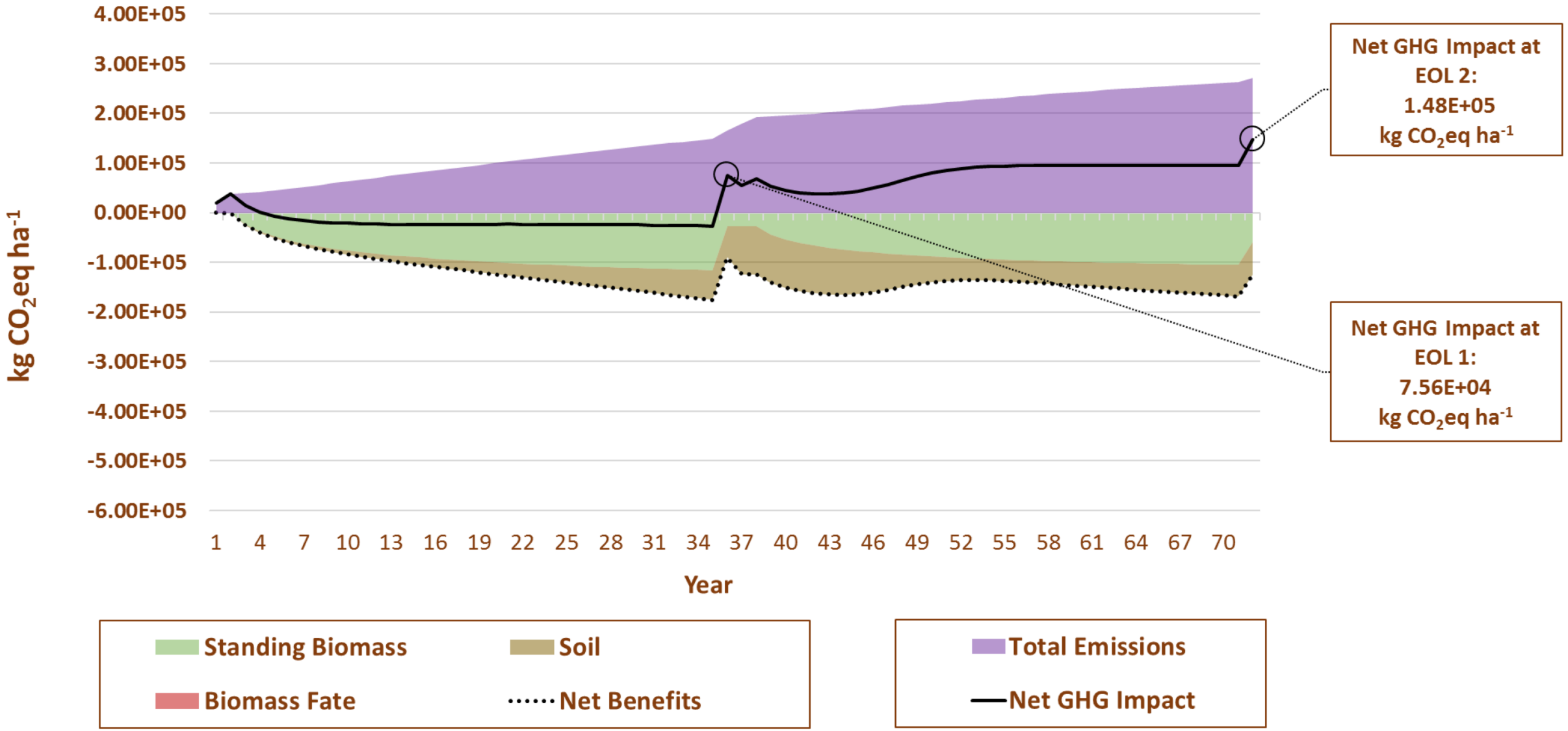
Alternative to Biomass-based Energy Production: "Orchard Recycling"




Standing Biomass
C Residence time: 15 - 30 years
PHOTOSYNTHESIS (CO2 → Biomass C)
Atmosphere
C Residence time: long-term
Biomass C
RESPIRATION
RESPIRATION
C Residence time: 5 - 10 years
Wood Chips
C Residence time: 10 - 20 years
MINERALIZATION
Soil Carbon
C Residence time: ?
Soil
LEACHING
CARBON FLOW
Short-Term Carbon Storage
Long-Term Carbon Storage
Groundwater
C Residence time: long-term

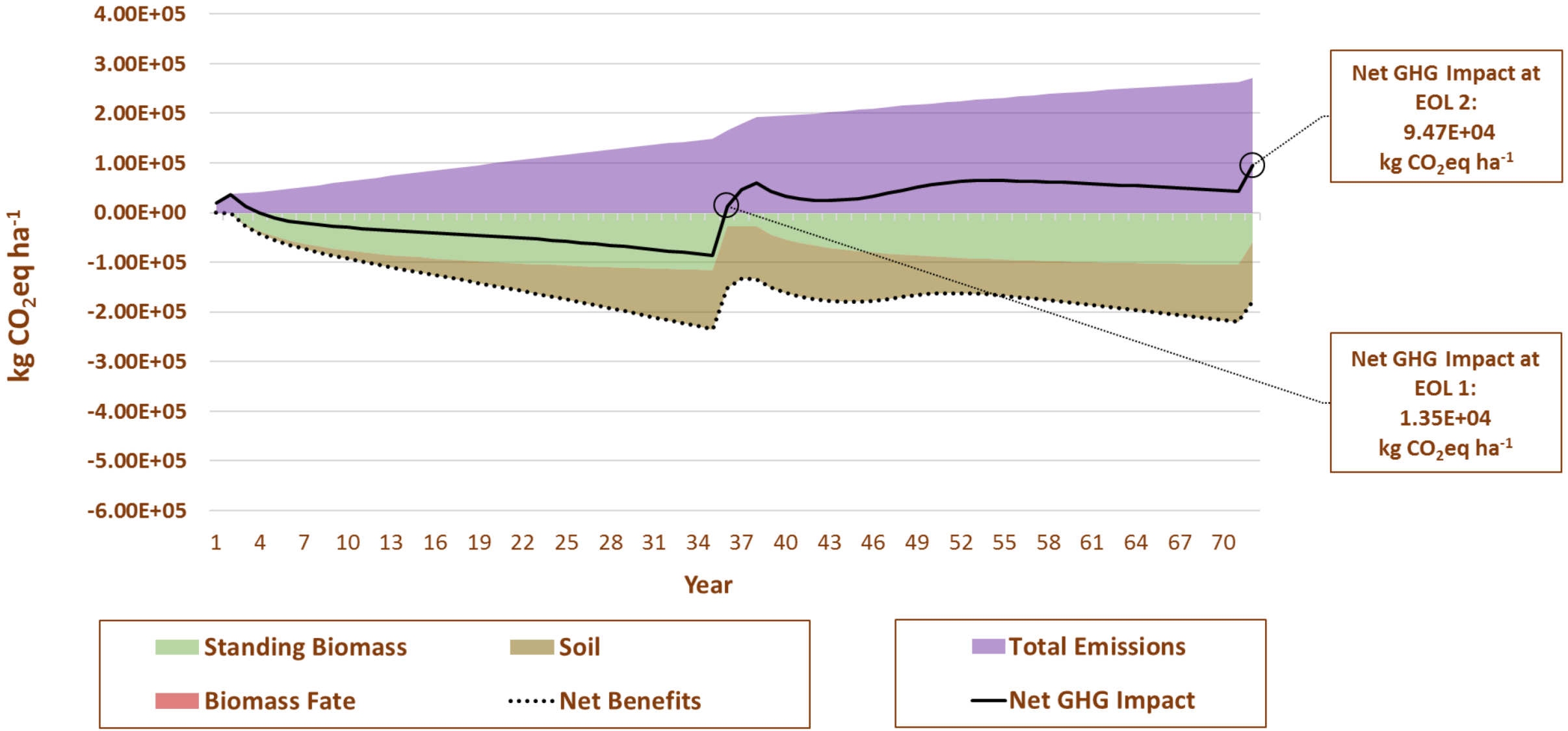
GHG Impacts under Various Management Scenarios

Whole Orchard Recycling at 1% Max Soil C



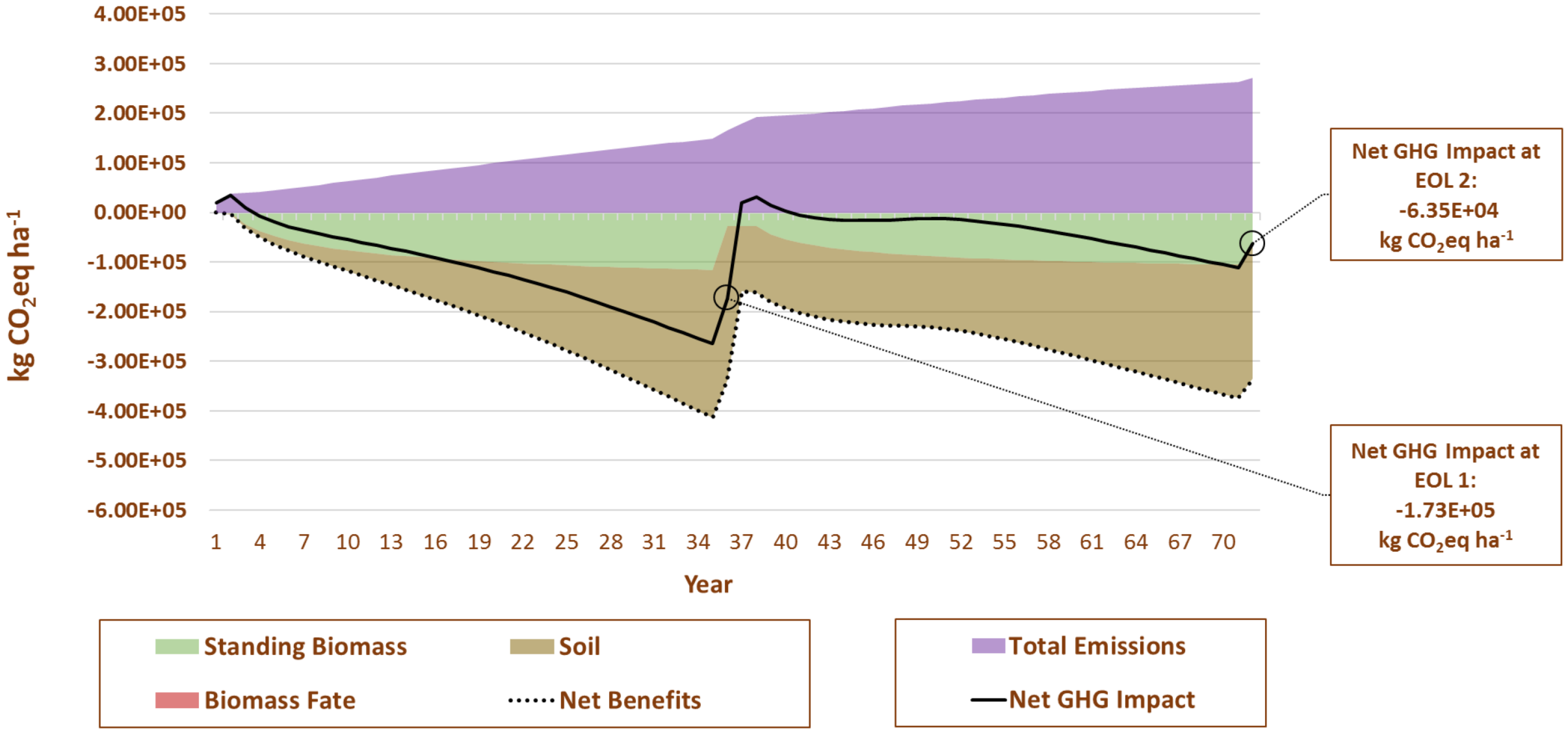
GHG Impacts under Various Management Scenarios

Whole Orchard Recycling at 2% Max Soil C



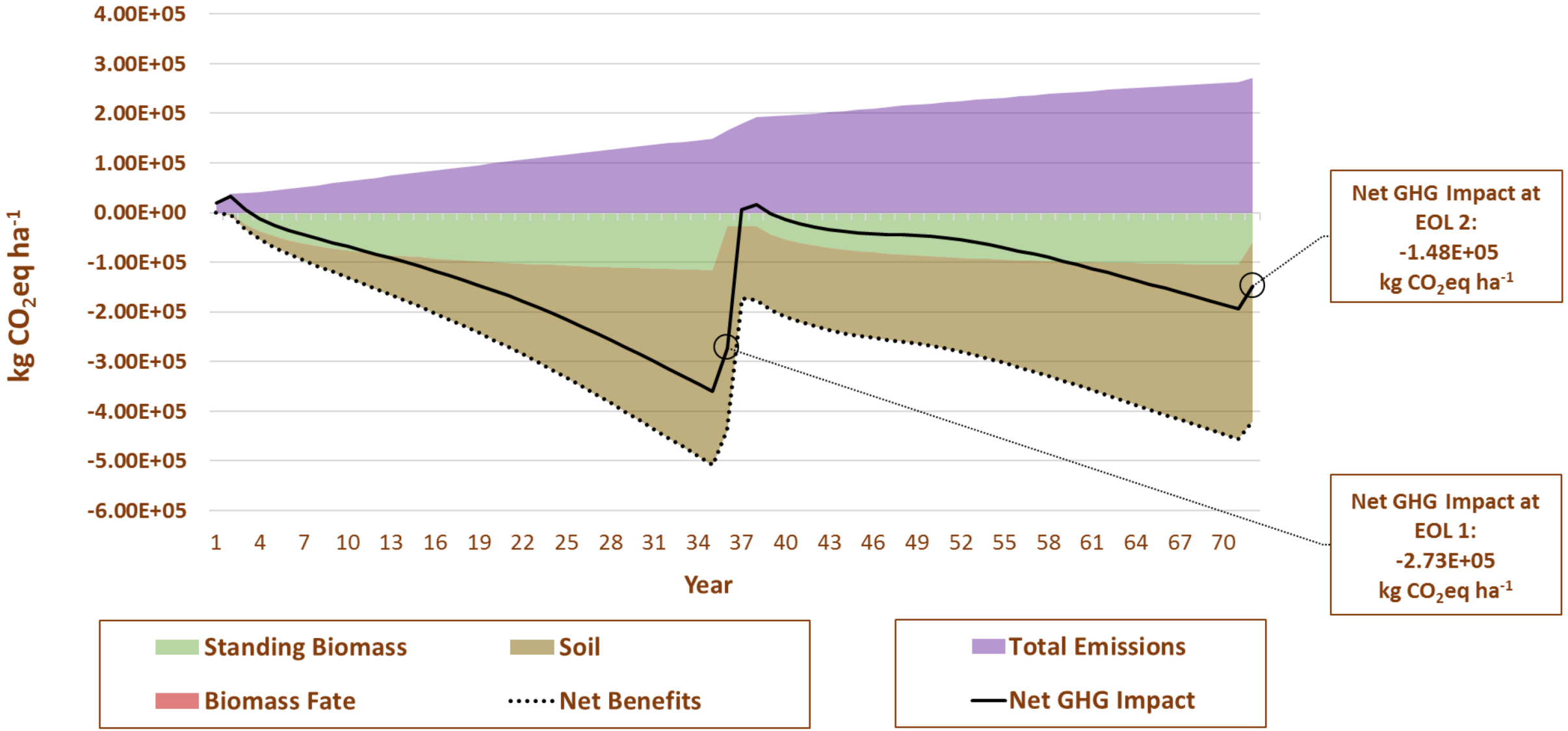
GHG Impacts under Various Management Scenarios

Whole Orchard Recycling at 5% Max Soil C

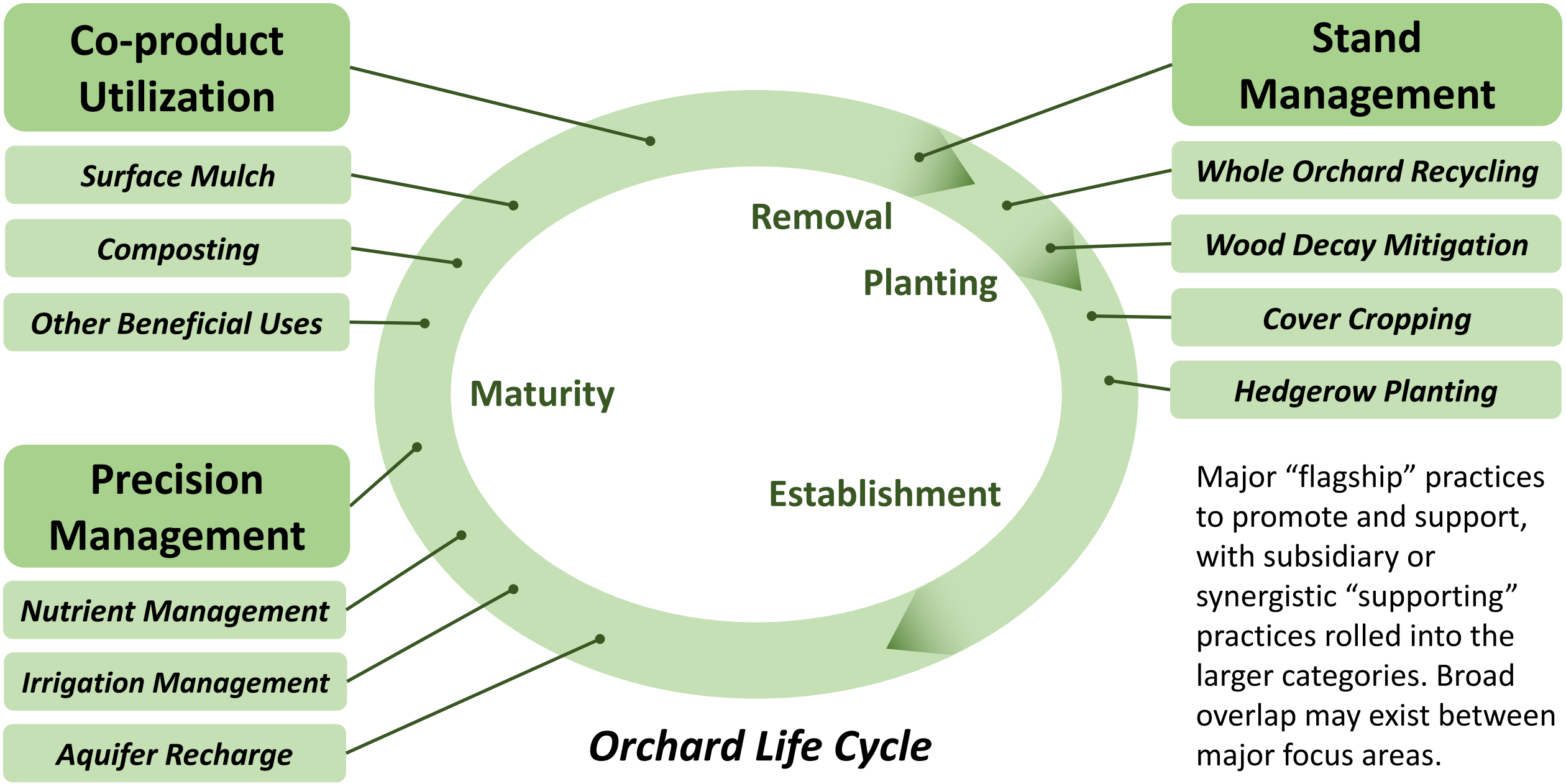


GHG Impacts under Various Management Scenarios

Whole Orchard Recycling at 6.6% Max Soil C



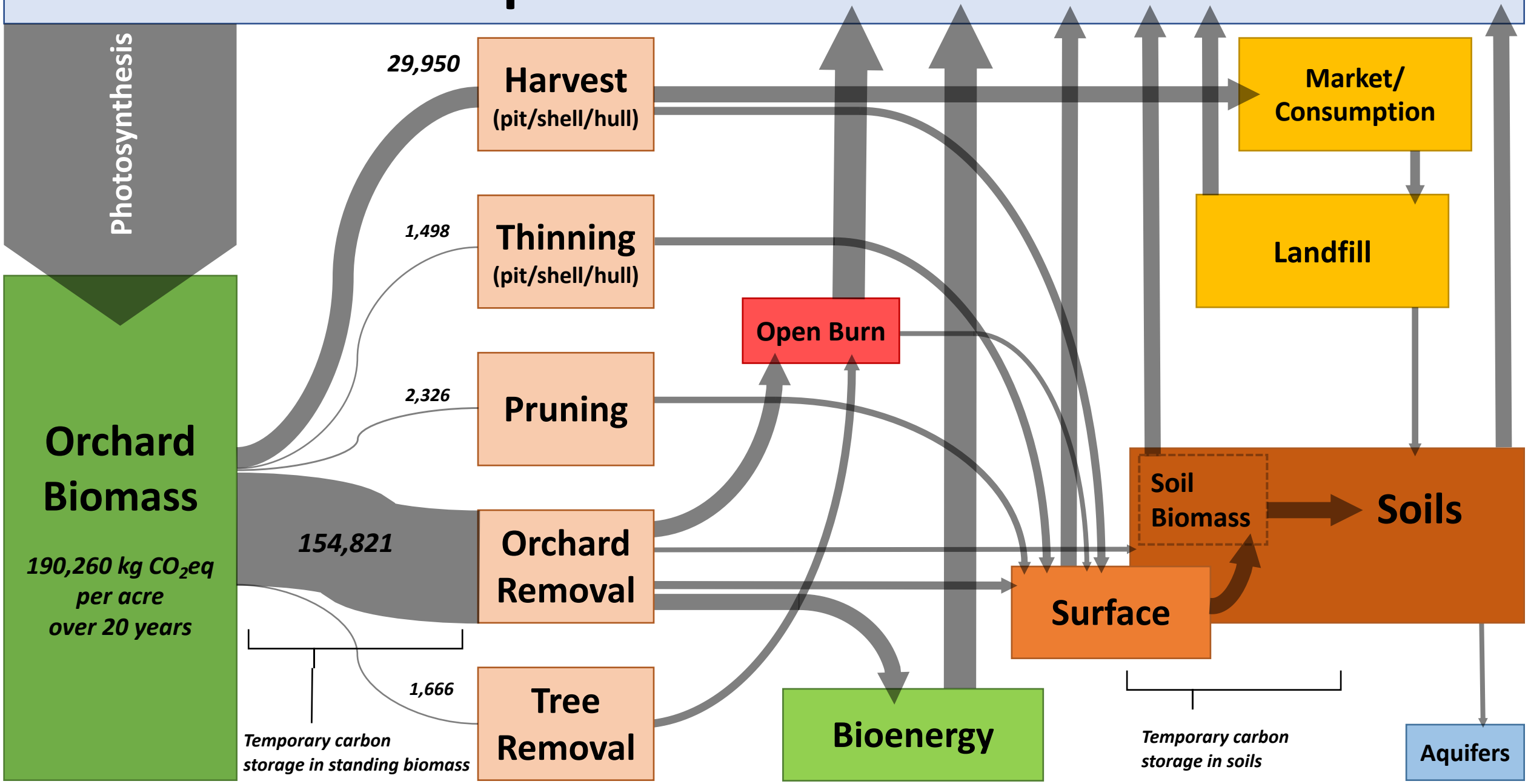
Climate Smart Practices for California Perennial Crops

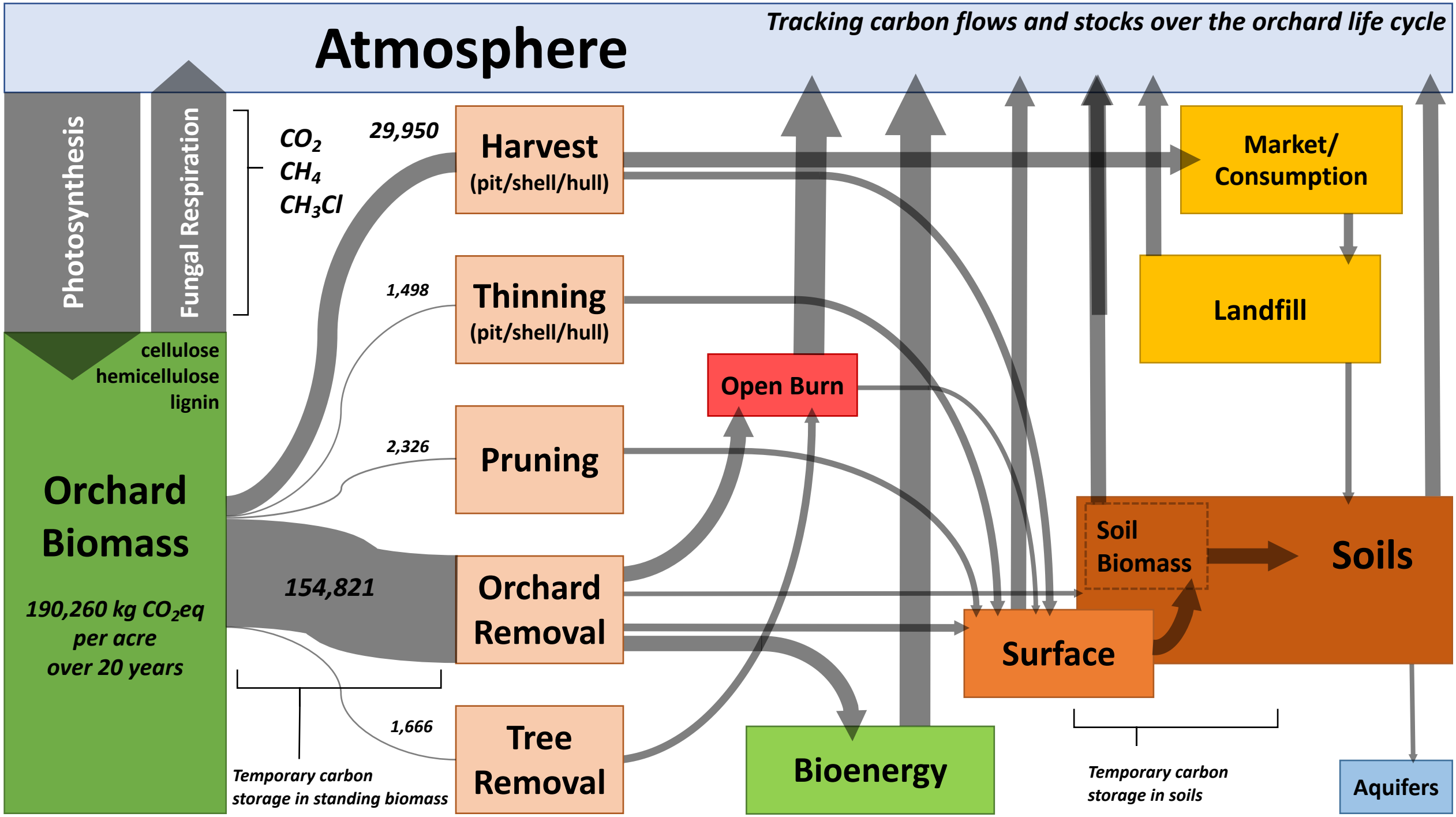


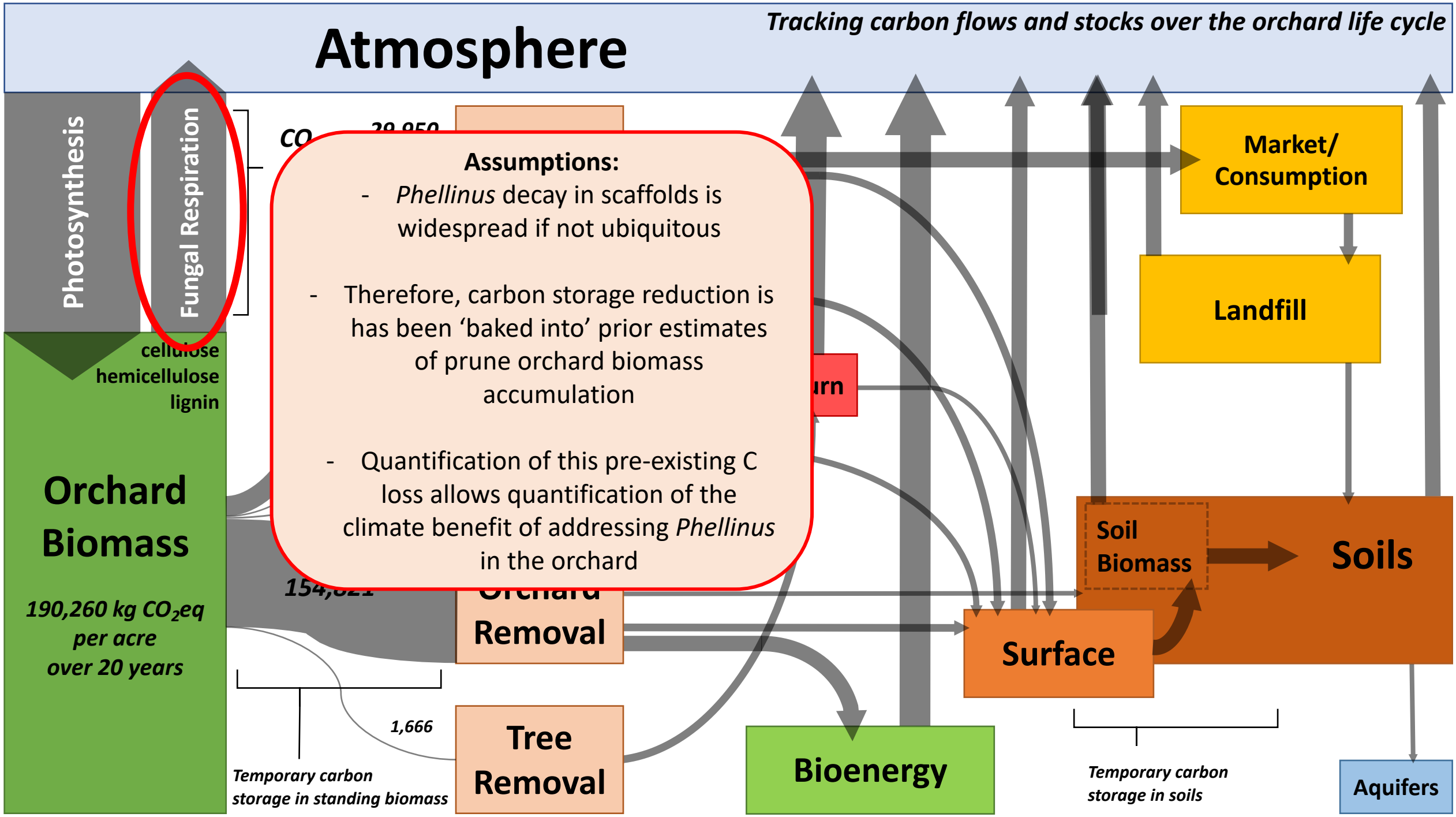
Major “flagship” practices to promote and support, with subsidiary or synergistic “supporting” practices rolled into the larger categories. Broad overlap may exist between major focus areas.

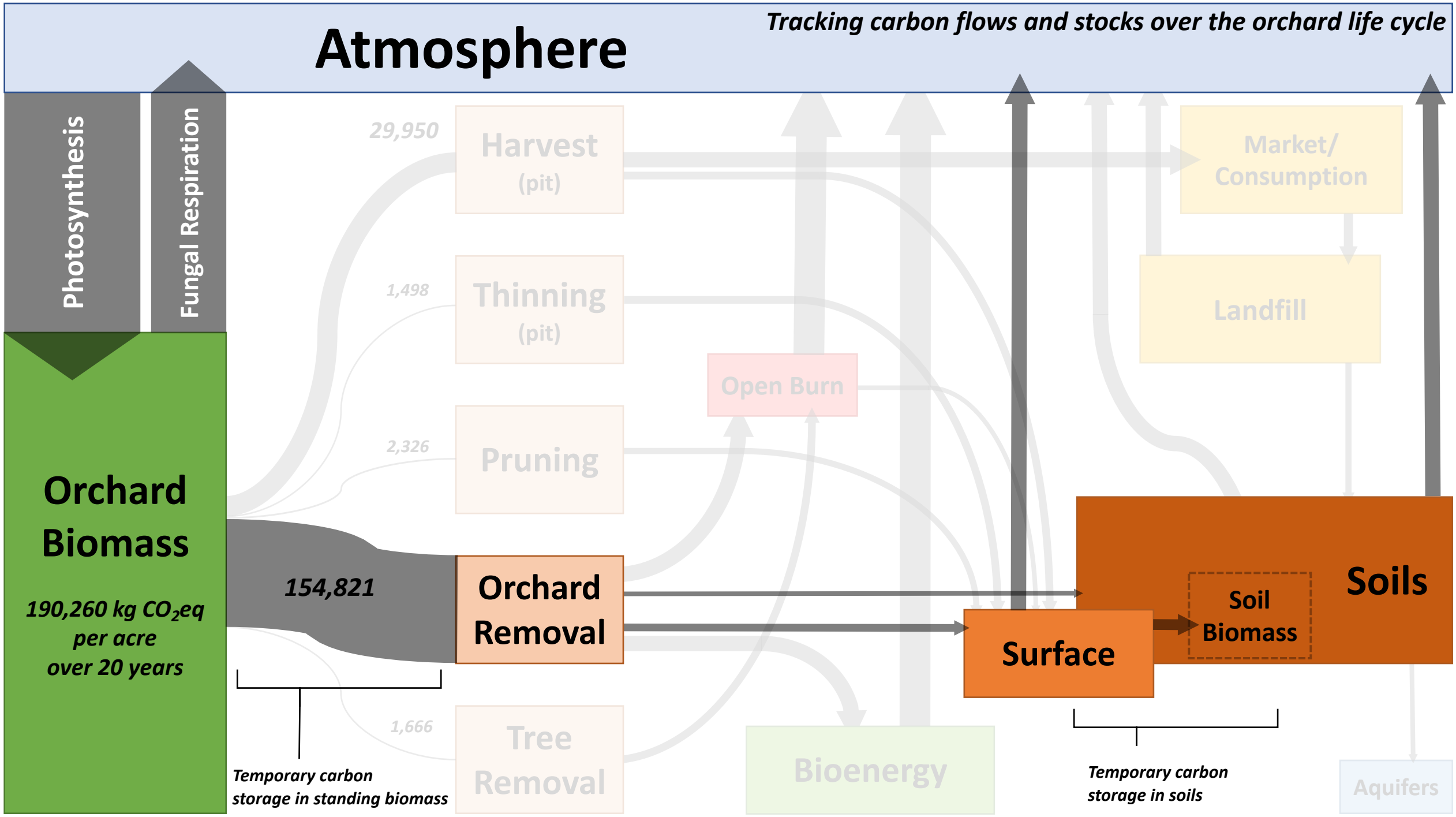
Atmosphere

Tracking carbon flows and stocks over the orchard life cycle




Atmosphere
Tracking carbon flows and stocks over the orchard life cycle
Photosynthesis
Fungal Respiration
CO_2
CH_4
CH_3Cl
cellulose
hemicellulose
lignin
Orchard Biomass
190,260 kg CO_2eq per acre over 20 years
29,950
1,498
2,326
154,821
1,666
Harvest (pit/shell/hull)
Thinning (pit/shell/hull)
Pruning
Orchard Removal
Tree Removal
Temporary carbon storage in standing biomass
Open Burn
Bioenergy
Market/ Consumption
Landfill
Soil Biomass
Soils
Surface
Temporary carbon storage in soils
Aquifers


Atmosphere
Tracking carbon flows and stocks over the orchard life cycle
Photosynthesis
Fungal Respiration
CO
cellulose
hemicellulose
lignin
Orchard Biomass
190,260 kg CO2eq per acre over 20 years
Assumptions:
- Phellinus decay in scaffolds is widespread if not ubiquitous
- Therefore, carbon storage reduction is has been 'baked into' prior estimates of prune orchard biomass accumulation
- Quantification of this pre-existing C loss allows quantification of the climate benefit of addressing Phellinus in the orchard
154,821
Orchard Removal
1,666
Tree Removal
Temporary carbon storage in standing biomass
Market/ Consumption
Landfill
Soil Biomass
Soils
Surface
Bioenergy
Temporary carbon storage in soils
Aquifers


Atmosphere
Tracking carbon flows and stocks over the orchard life cycle
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190,260 kg CO2eq per acre over 20 years
29,950
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1,498
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2,326
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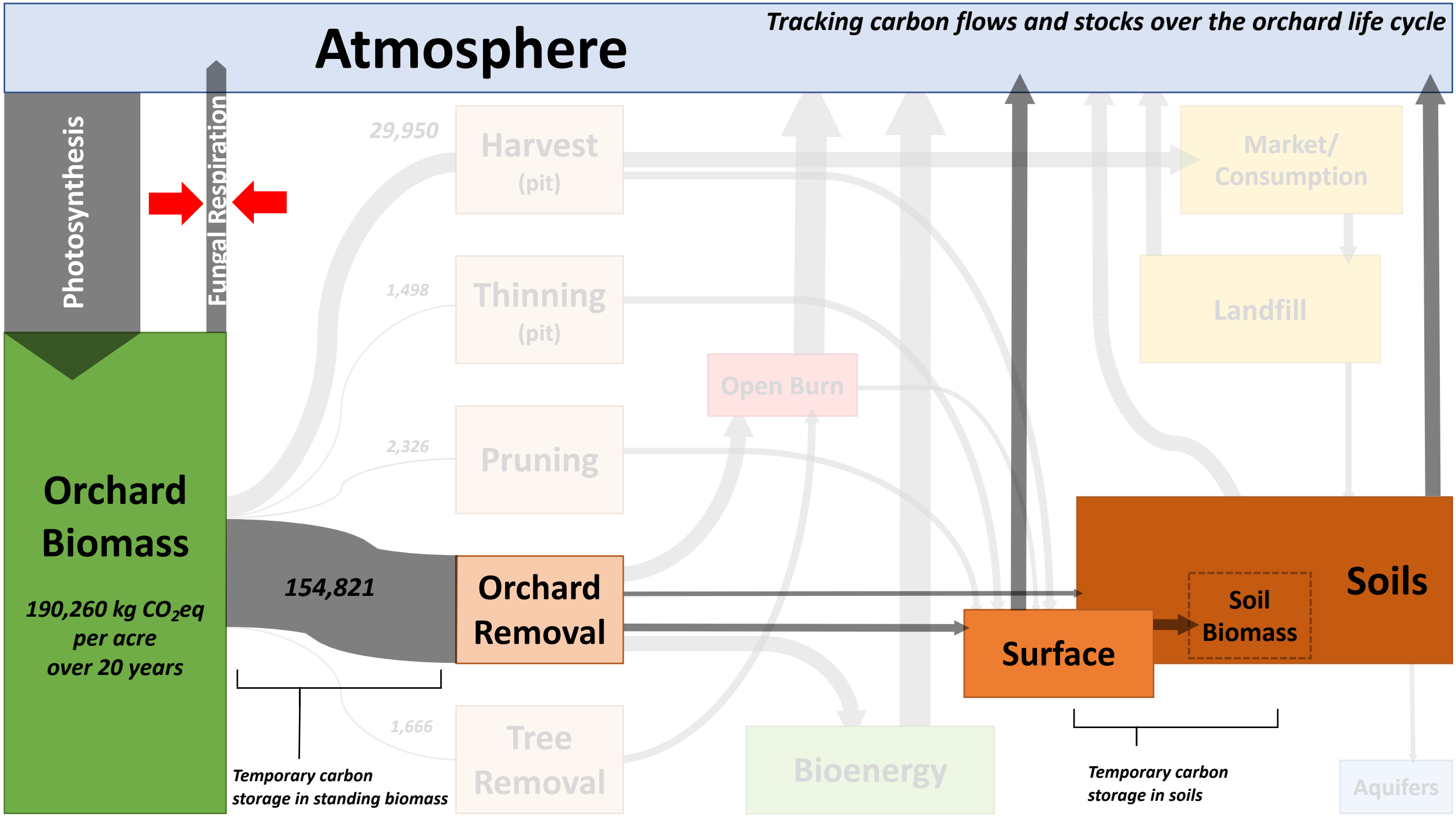
Temporary carbon storage in standing biomass
Temporary carbon storage in soils


Atmosphere
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Soils
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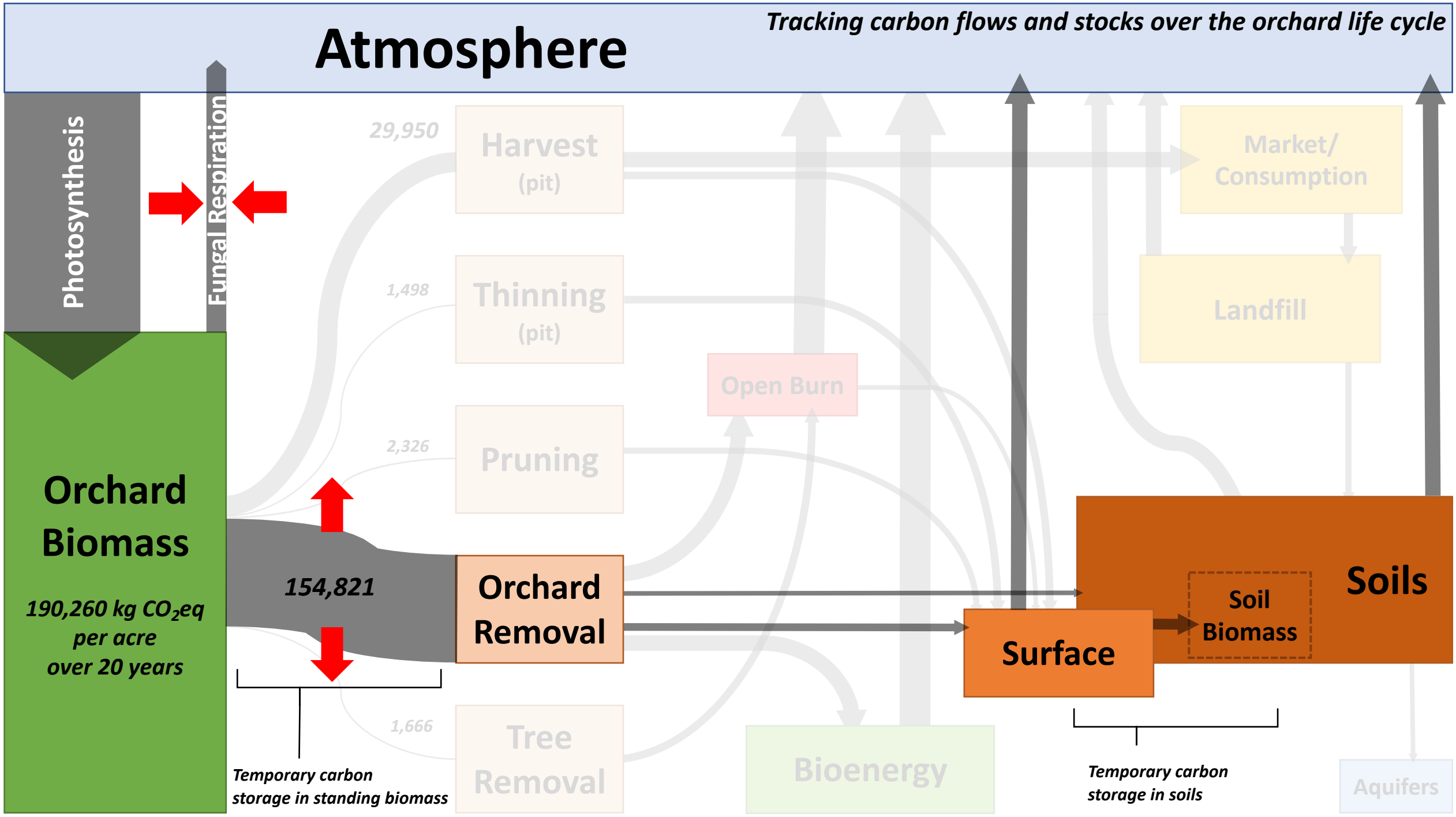
Surface
Temporary carbon storage in soils
Aquifers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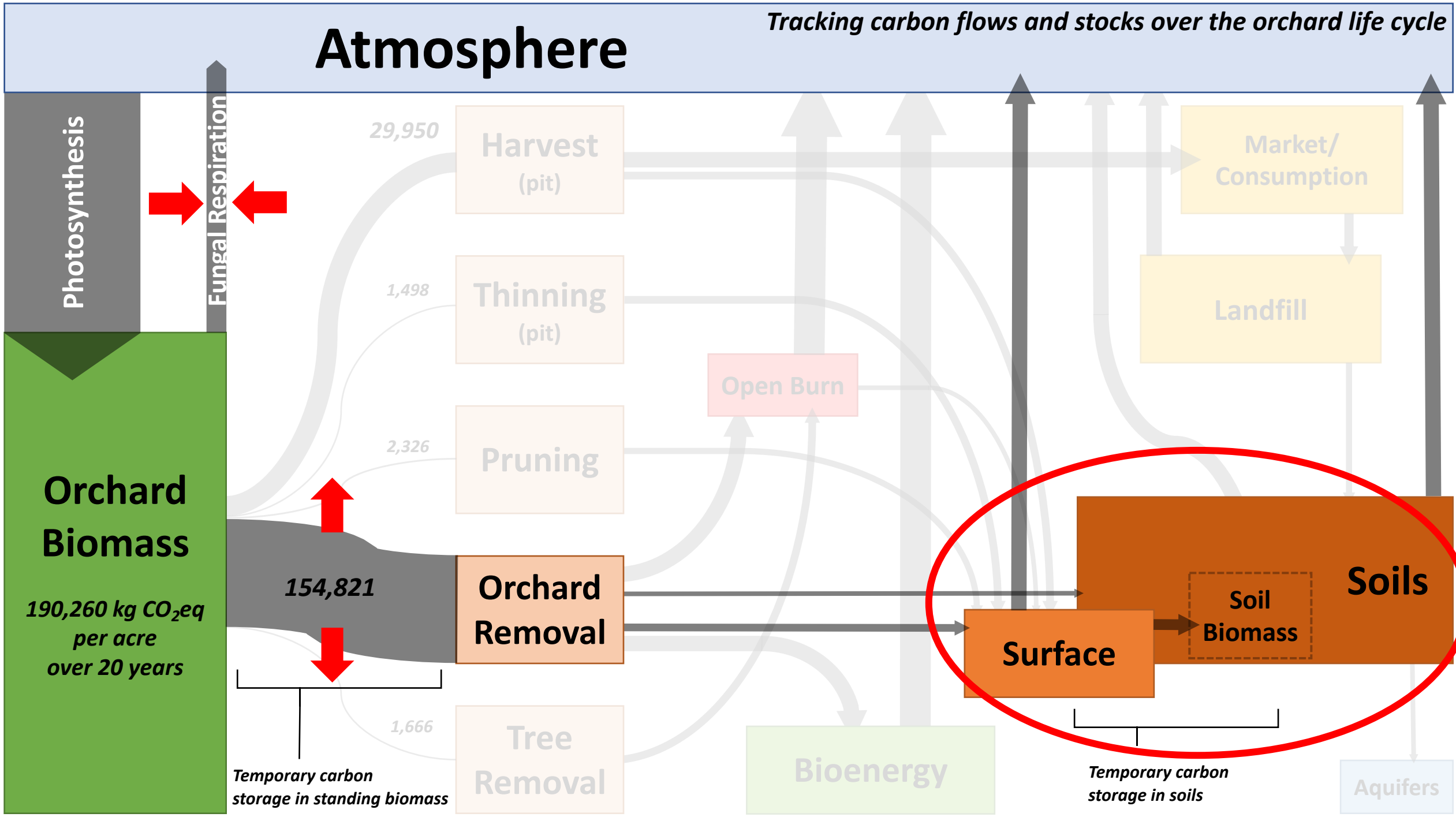
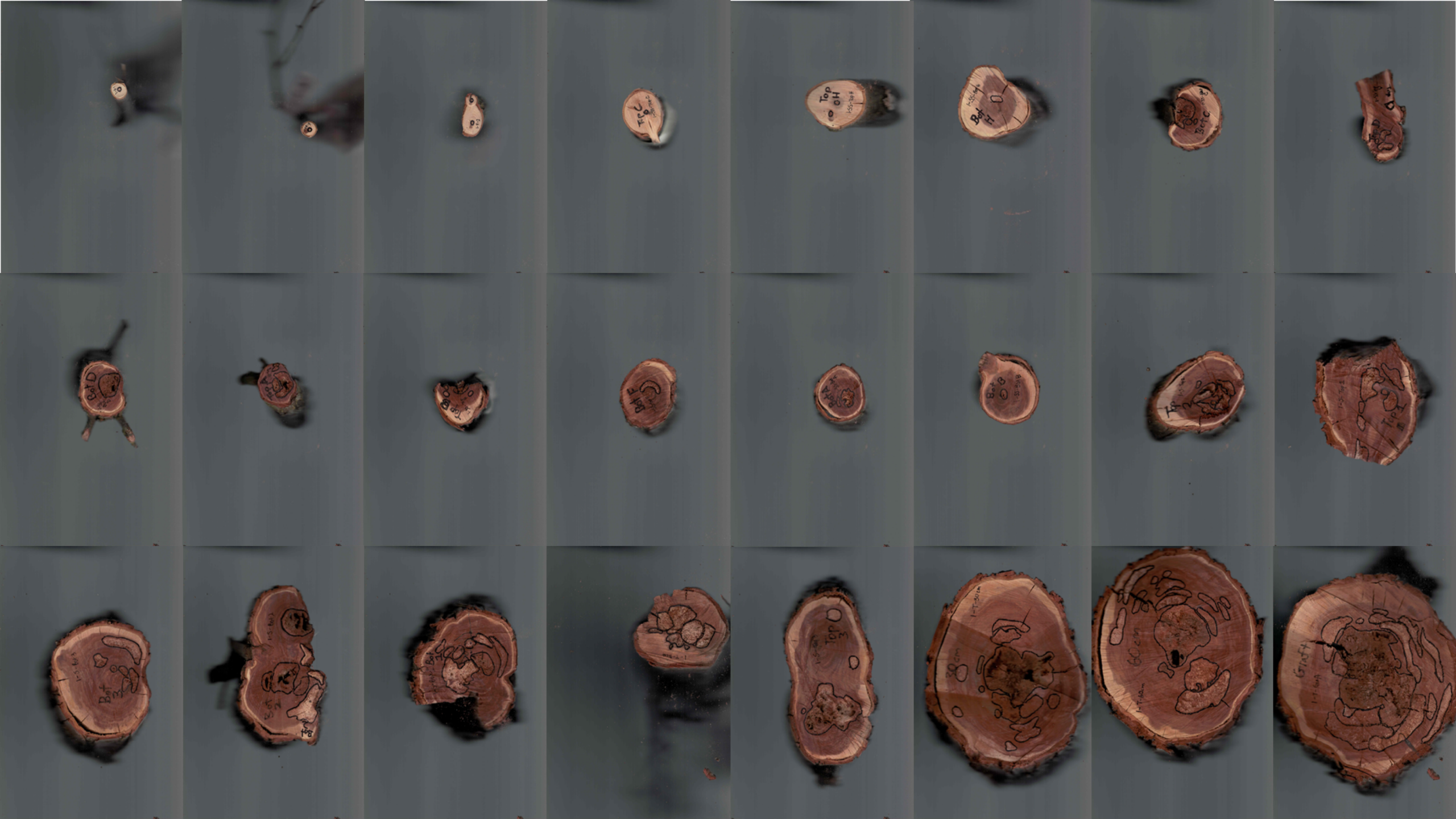
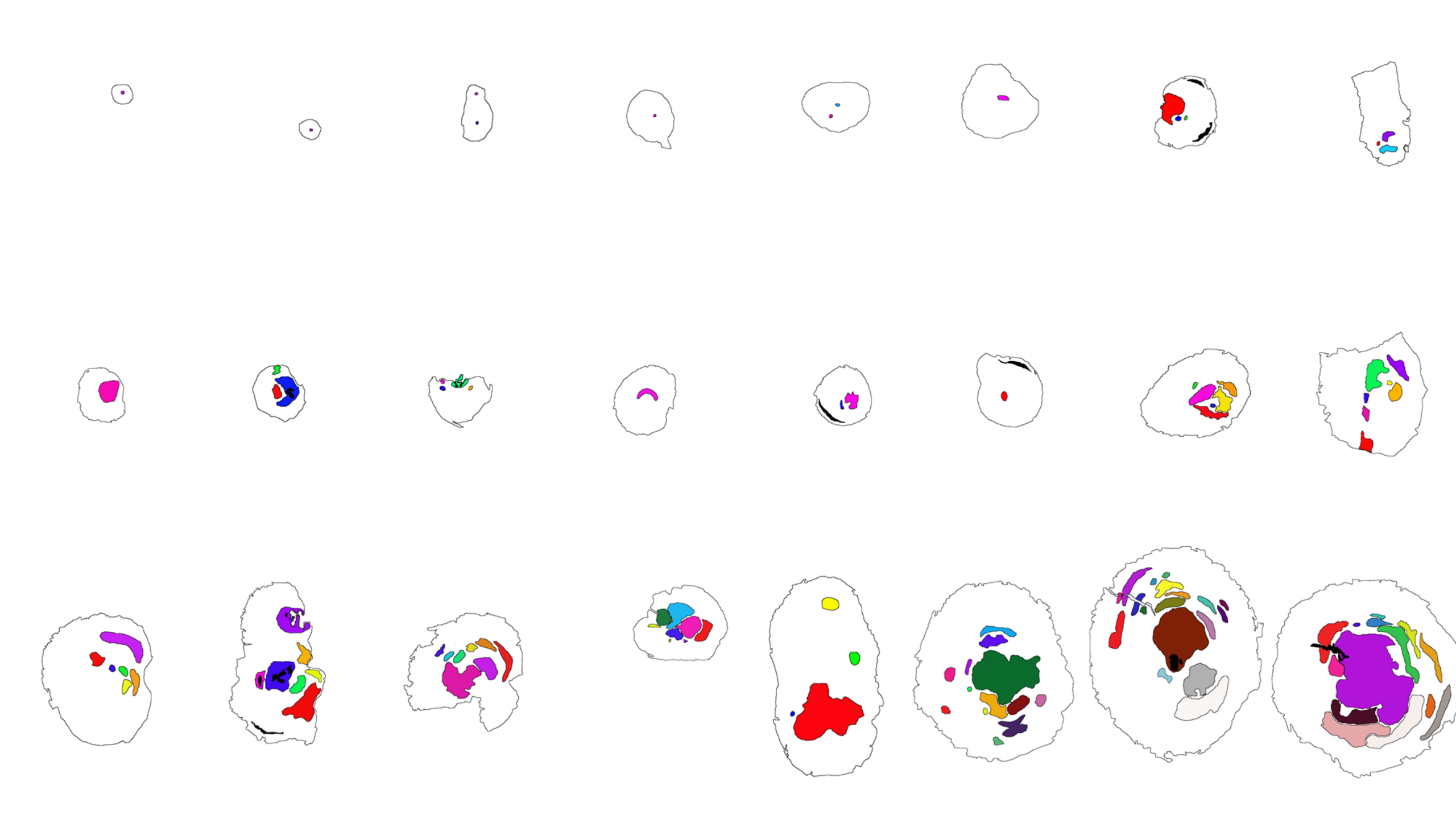
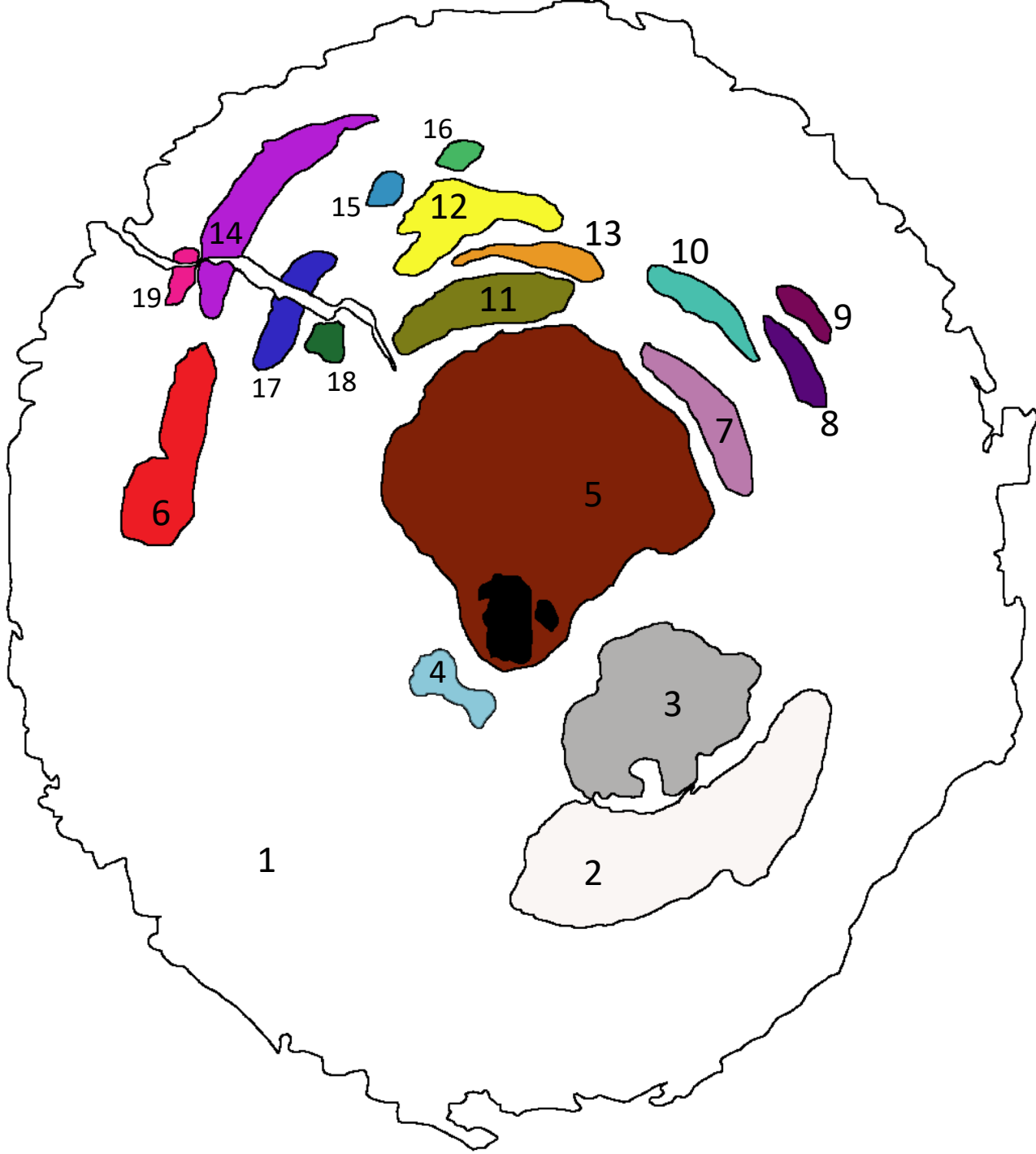
Temporary carbon storage in standing biomass
Temporary carbon storage in soils

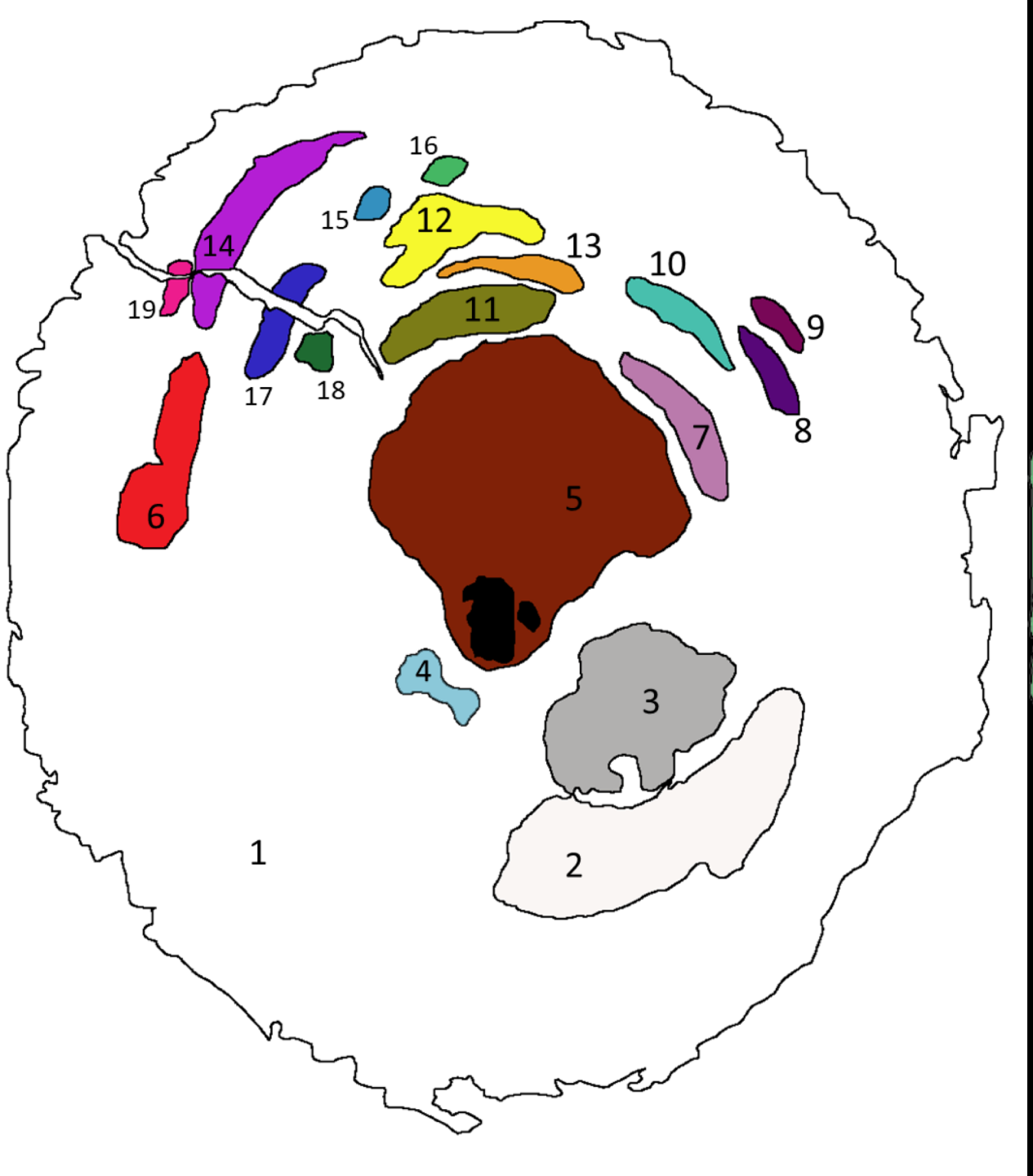

Atmosphere
Tracking carbon flows and stocks over the orchard life cycle
Photosynthesis
Fungal Respiration
Orchard Biomass
190,260 kg CO2eq per acre over 20 years
29,950
Harvest (pit)
1,498
Thinning (pit)
2,326
Pruning
1,666
Tree Removal
154,821
Orchard Removal
Open Burn
Market/ Consumption
Landfill
Soils
Soil Biomass
Surface
Bioenergy
Aquifers
Temporary carbon storage in standing biomass
Temporary carbon storage in soils





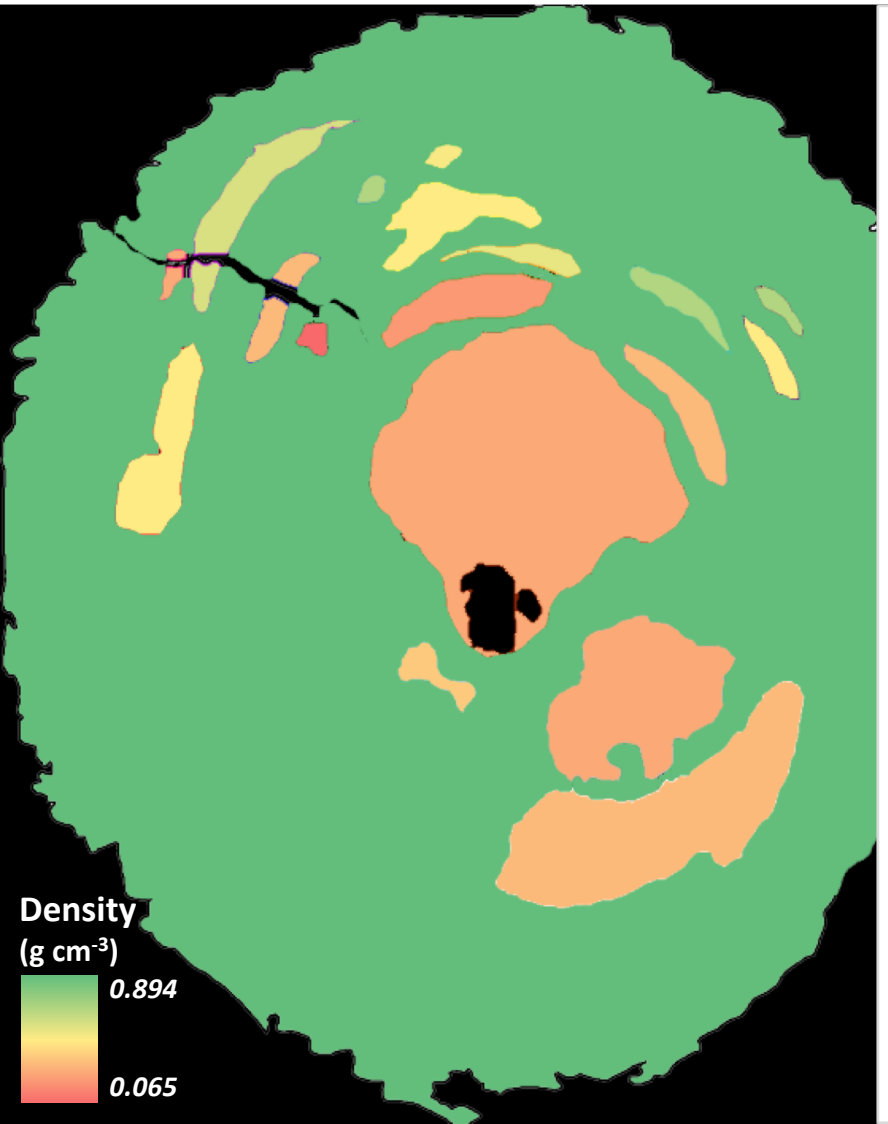

1-T-60cm

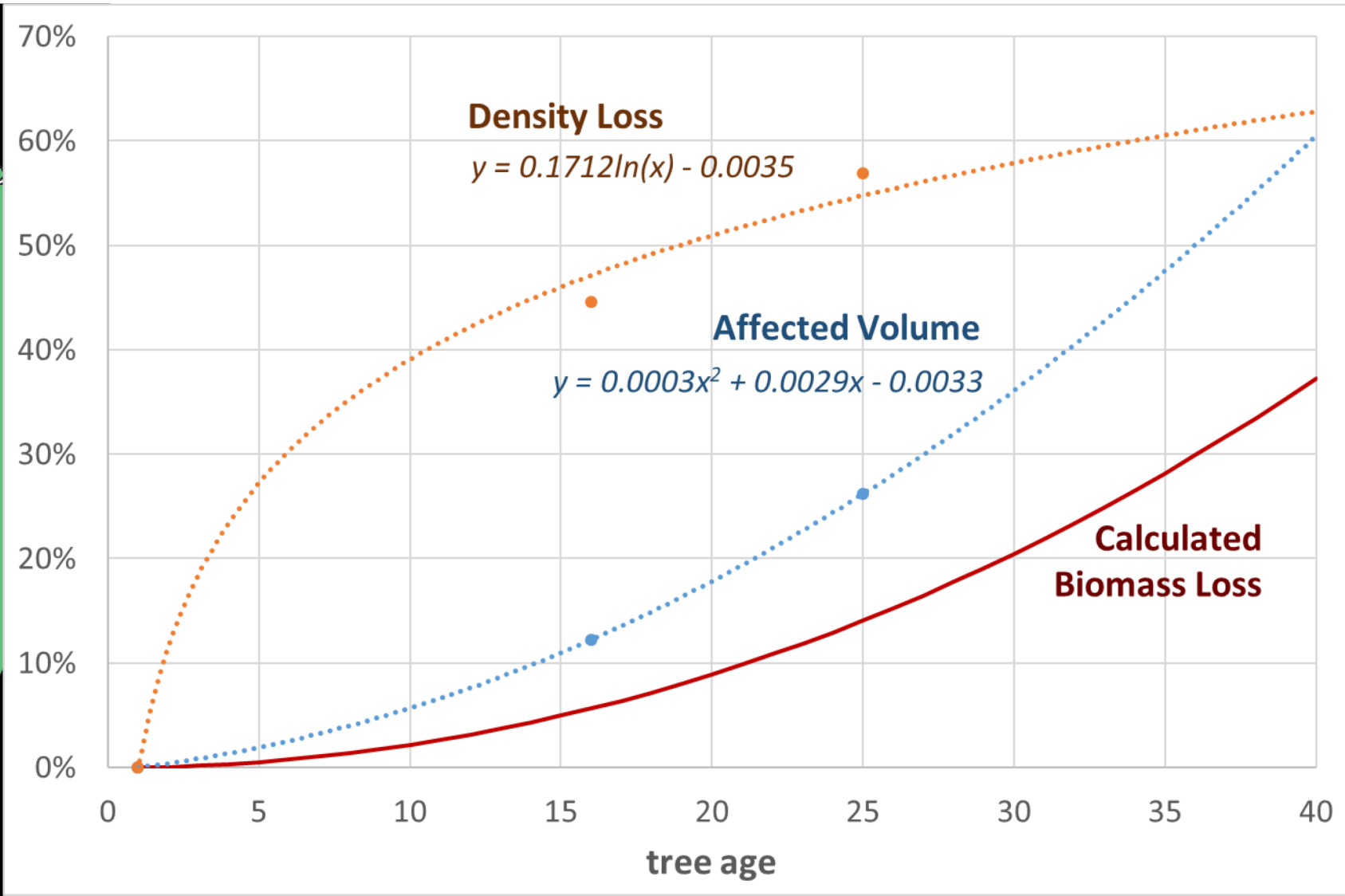

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19


16
15
12
14
13
10
19
11
9
17
18
8
7
6
5
4
3
1
2

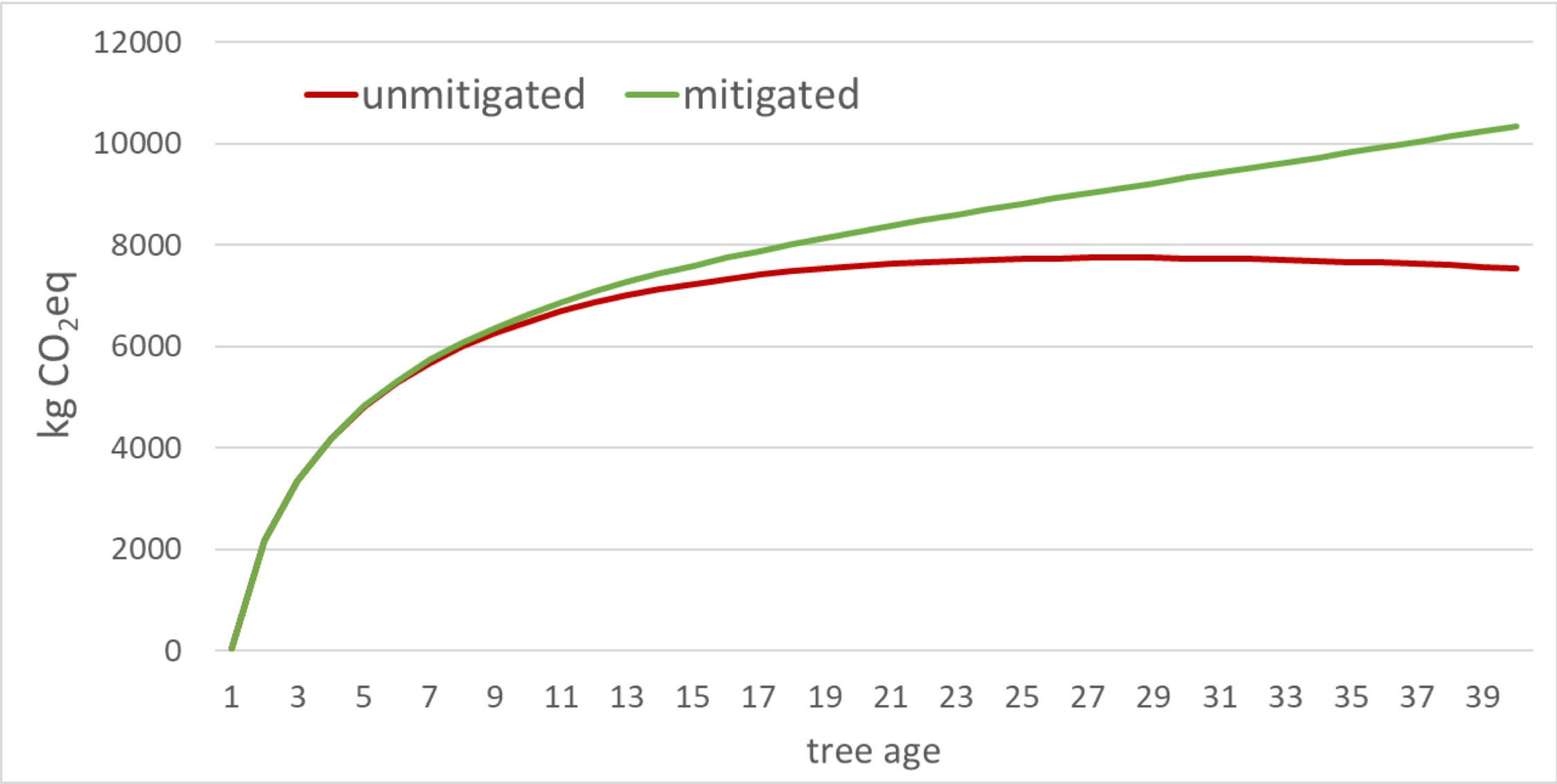

Penetrometer
Pressure
Maximum
(no penetration)
0.0

Ongoing work:
Density loss and affected volume over time

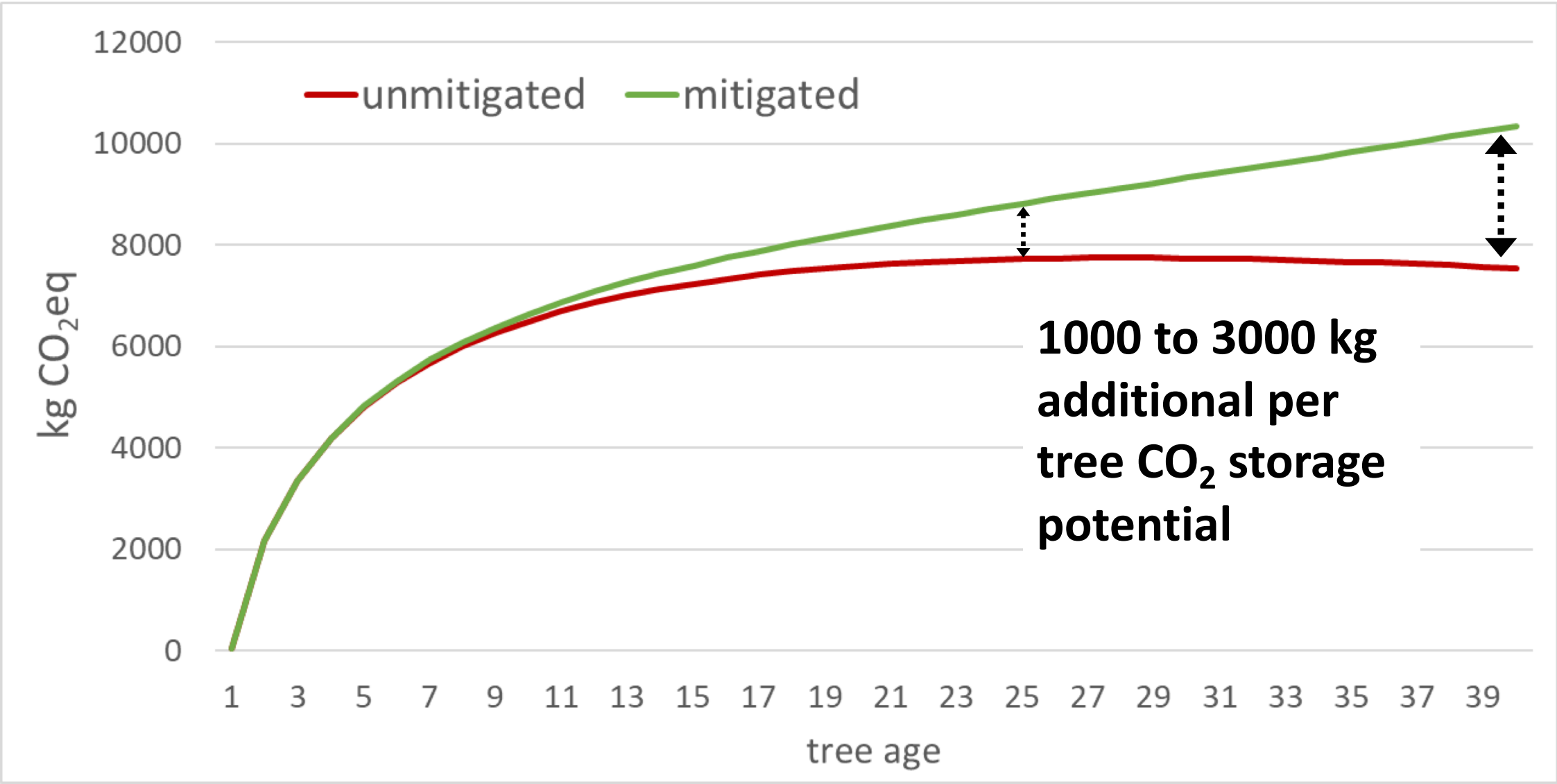




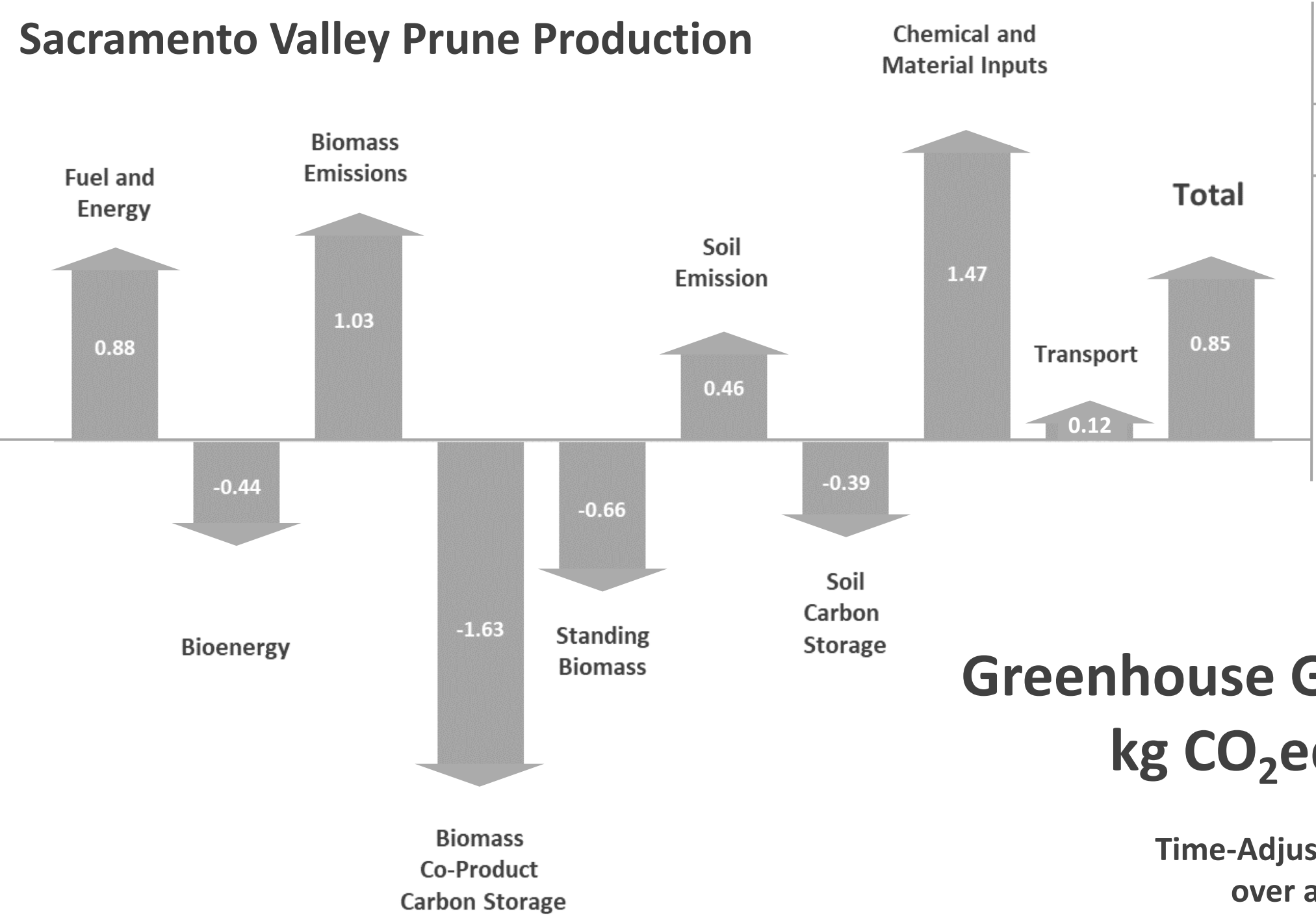
Ongoing work:
Hypothetical wood decay mitigation effect on biomass



Ongoing work:
Hypothetical wood decay mitigation effect on biomass



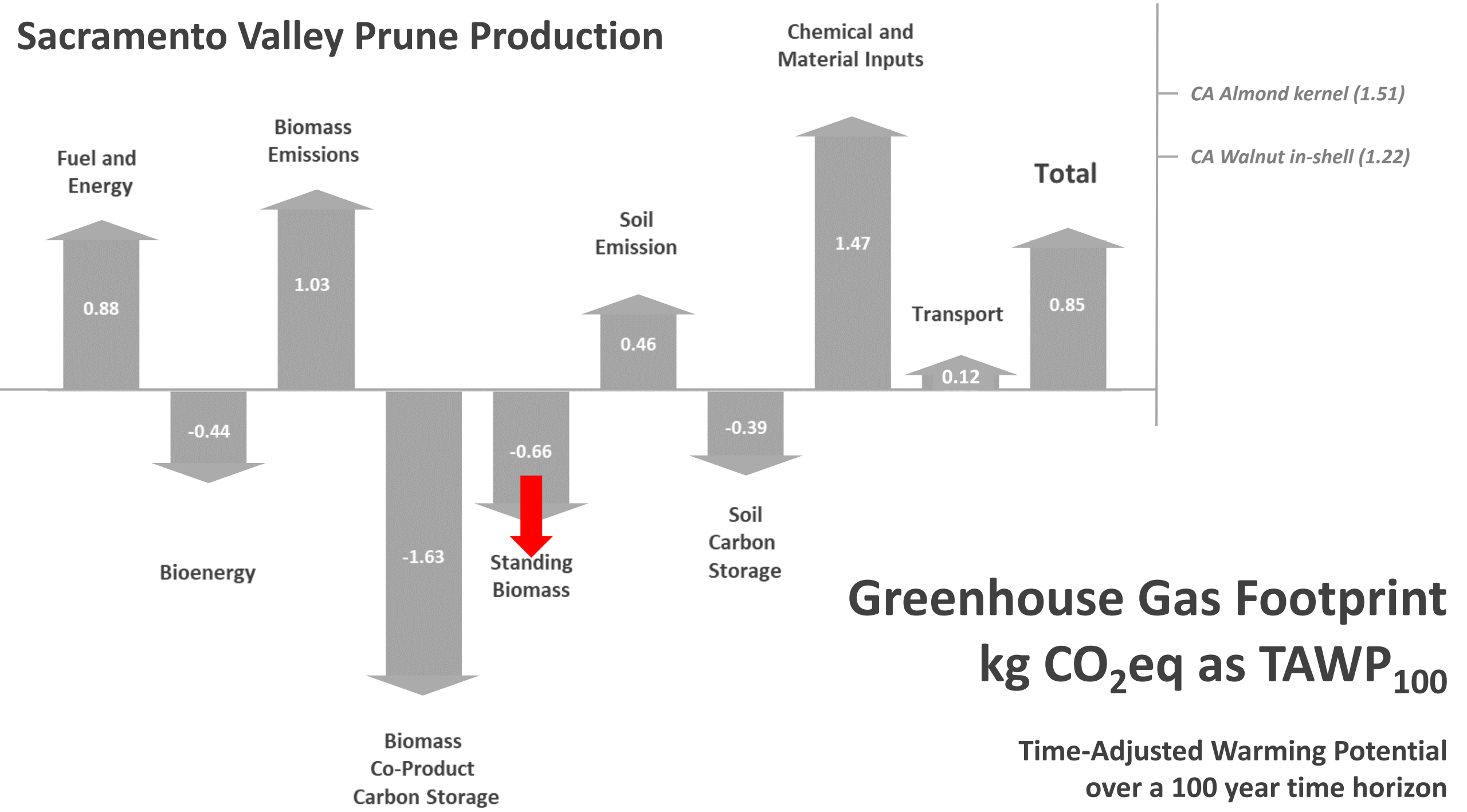
Sacramento Valley Prune Production



Greenhouse Gas Footprint
kg CO_2eq as $TAWP_{100}$

Time-Adjusted Warming Potential over a 100 year time horizon

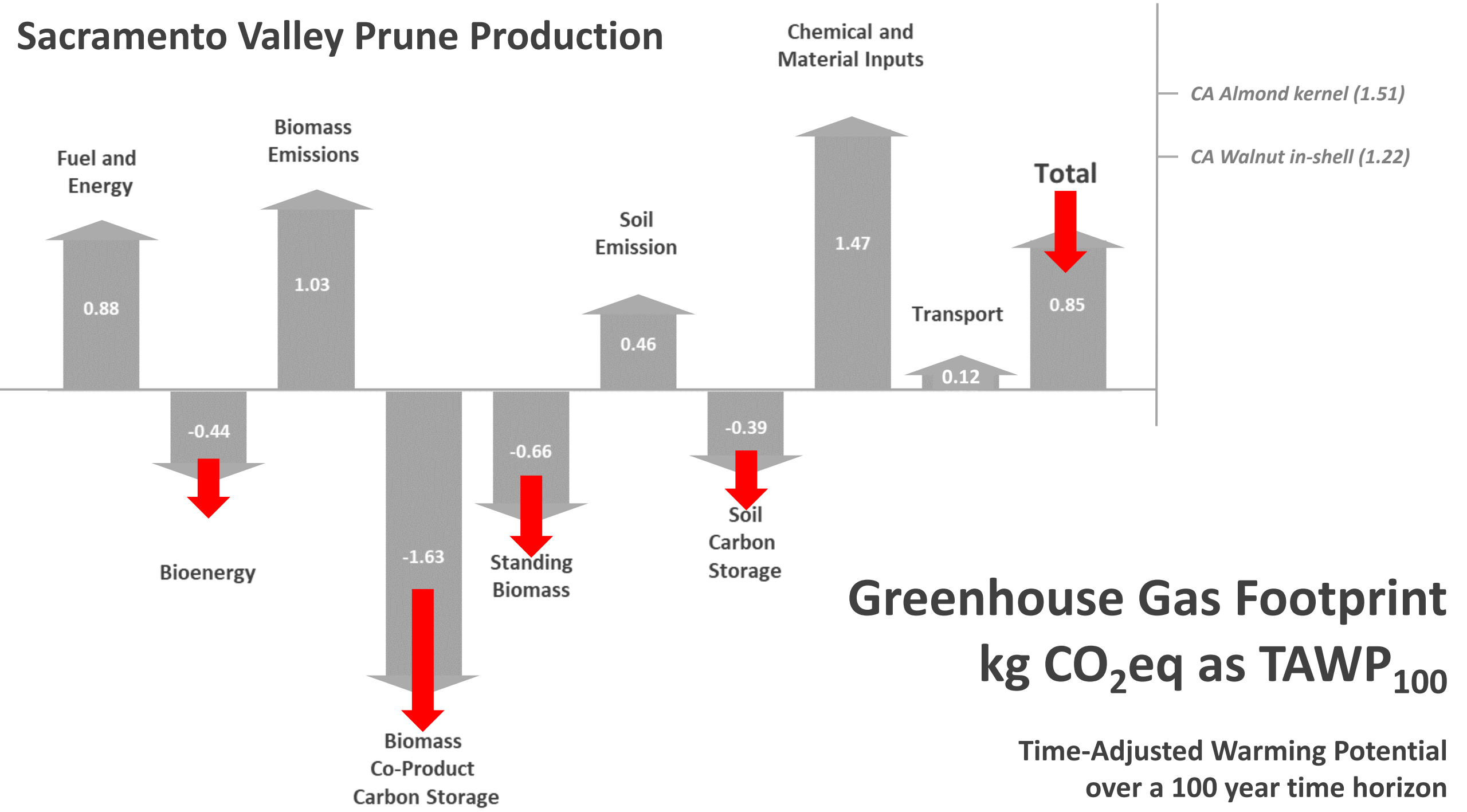
Sacramento Valley Prune Production



Greenhouse Gas Footprint
kg CO_2eq as $TAWP_{100}$

Time-Adjusted Warming Potential over a 100 year time horizon

Sacramento Valley Prune Production



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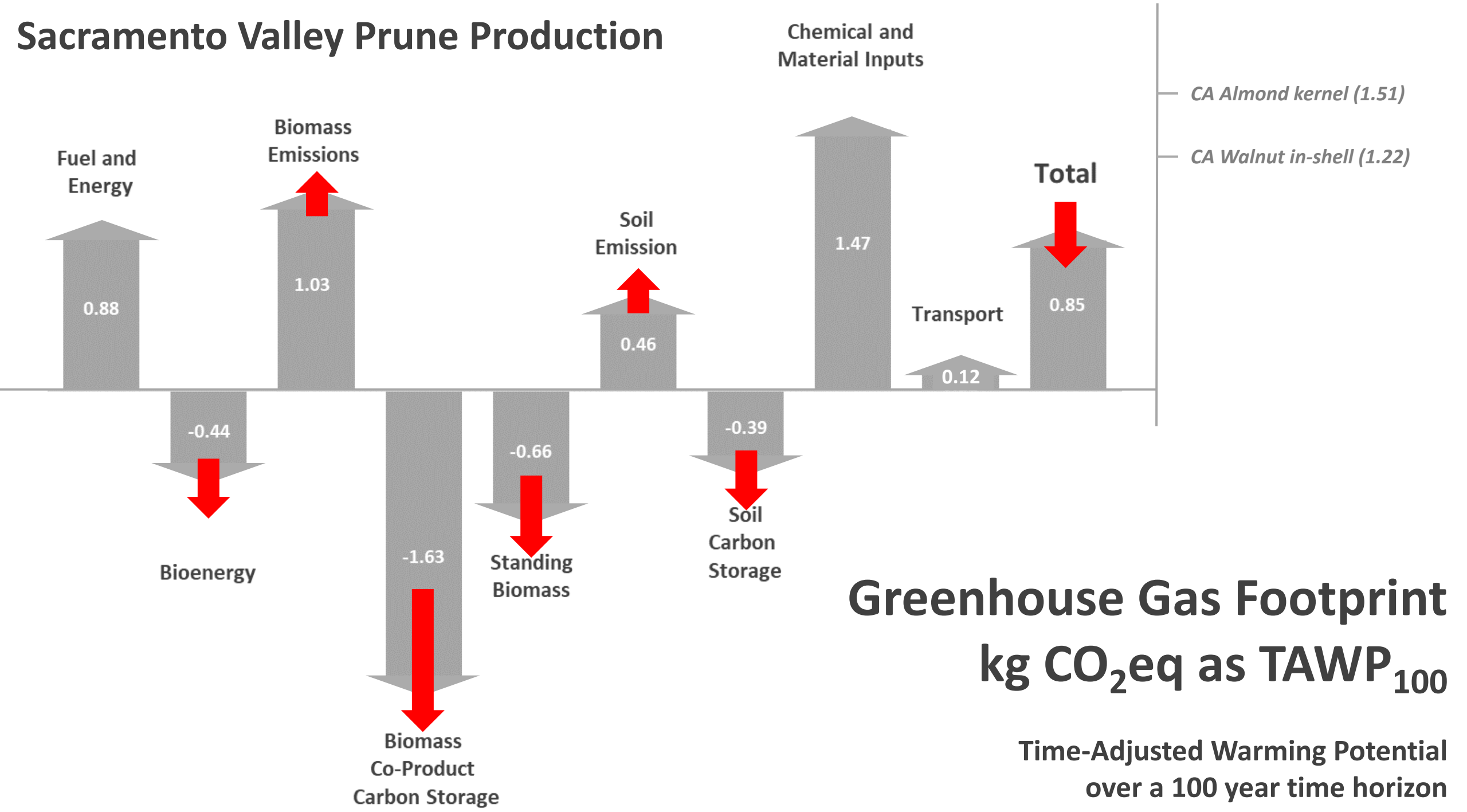
kg CO_2eq as $TAWP_{100}$

Time-Adjusted Warming Potential over a 100 year time horizon

Sacramento Valley Prune Production



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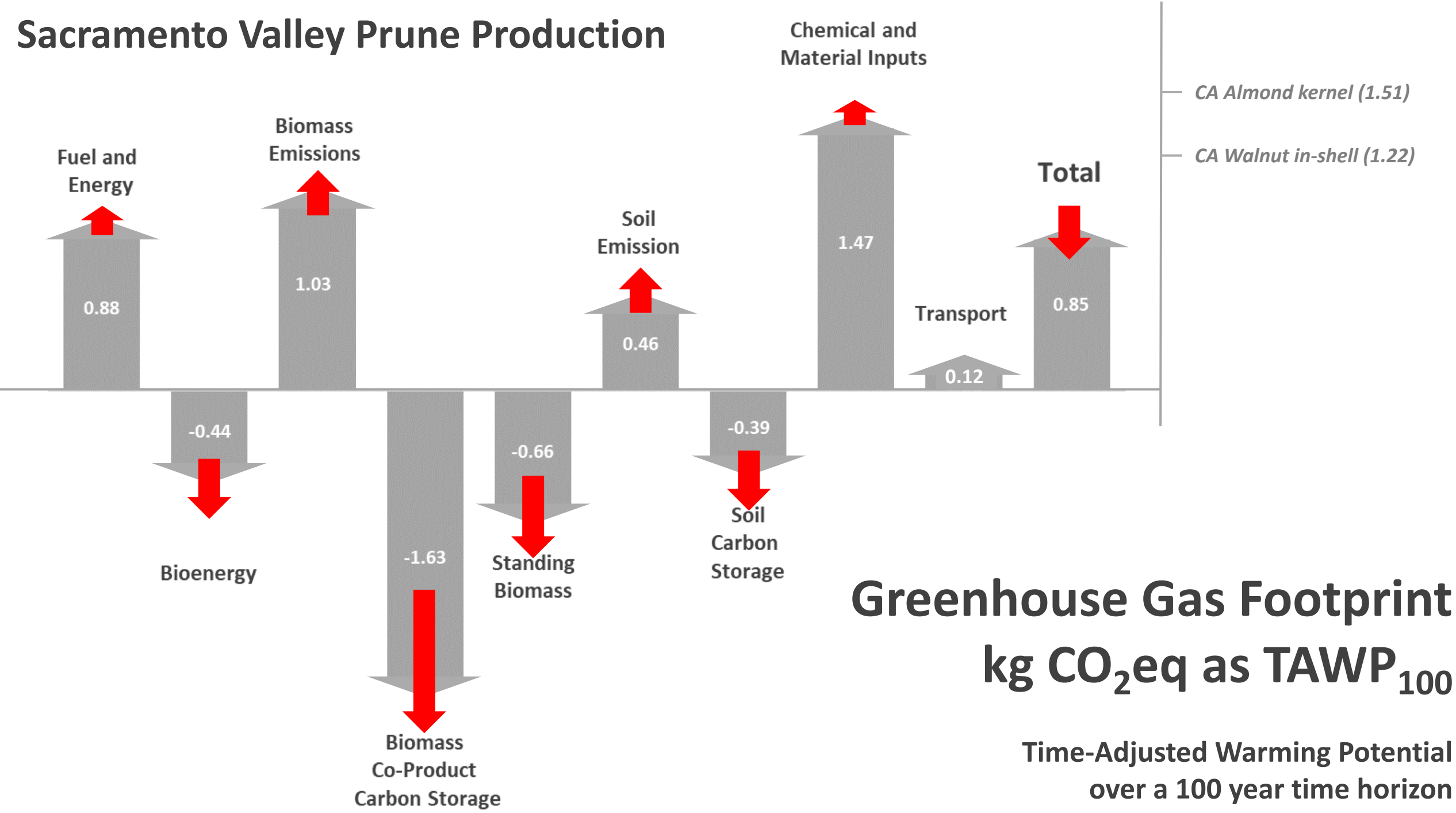
Sacramento Valley Prune Production



Greenhouse Gas Footprint
kg CO_2eq as $TAWP_{100}$

Time-Adjusted Warming Potential over a 100 year time horizon

Elias Marvinney, PhD.
emarvinney@ucdavis.edu