THE UNIVERSITY OF MAINE 1865

Center for Research on Sustainable Forests

Forest Carbon Accounting and Modeling Framework Alternatives

An Inventory, Assessment, and Application Guide

ADAM DAIGNEAULT, DANIEL HAYES

w/ IVAN FERNANDEZ,
AARON WEISKITTEL, MICHAEL PREMER

School of Forest Resources

University of Maine, Orono, ME

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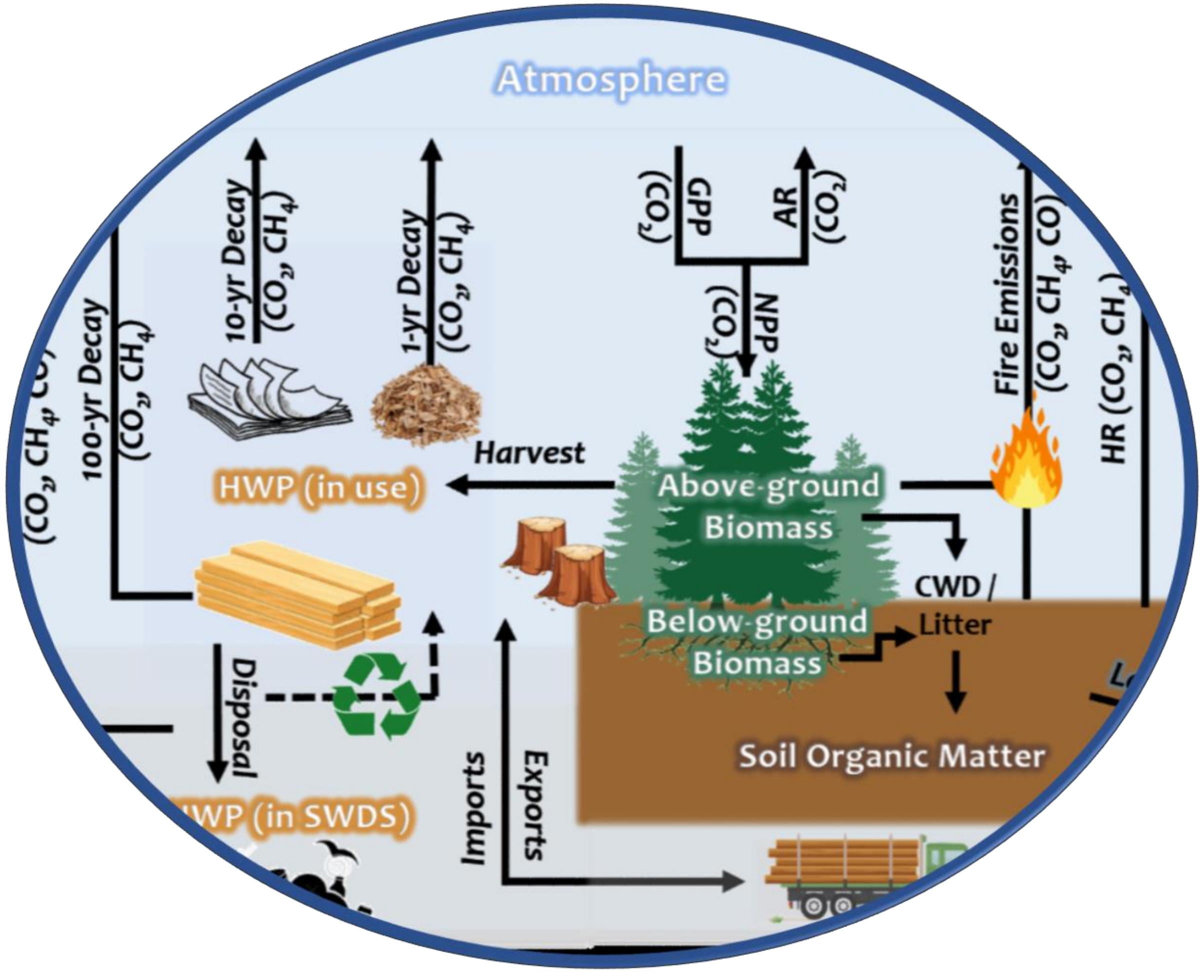
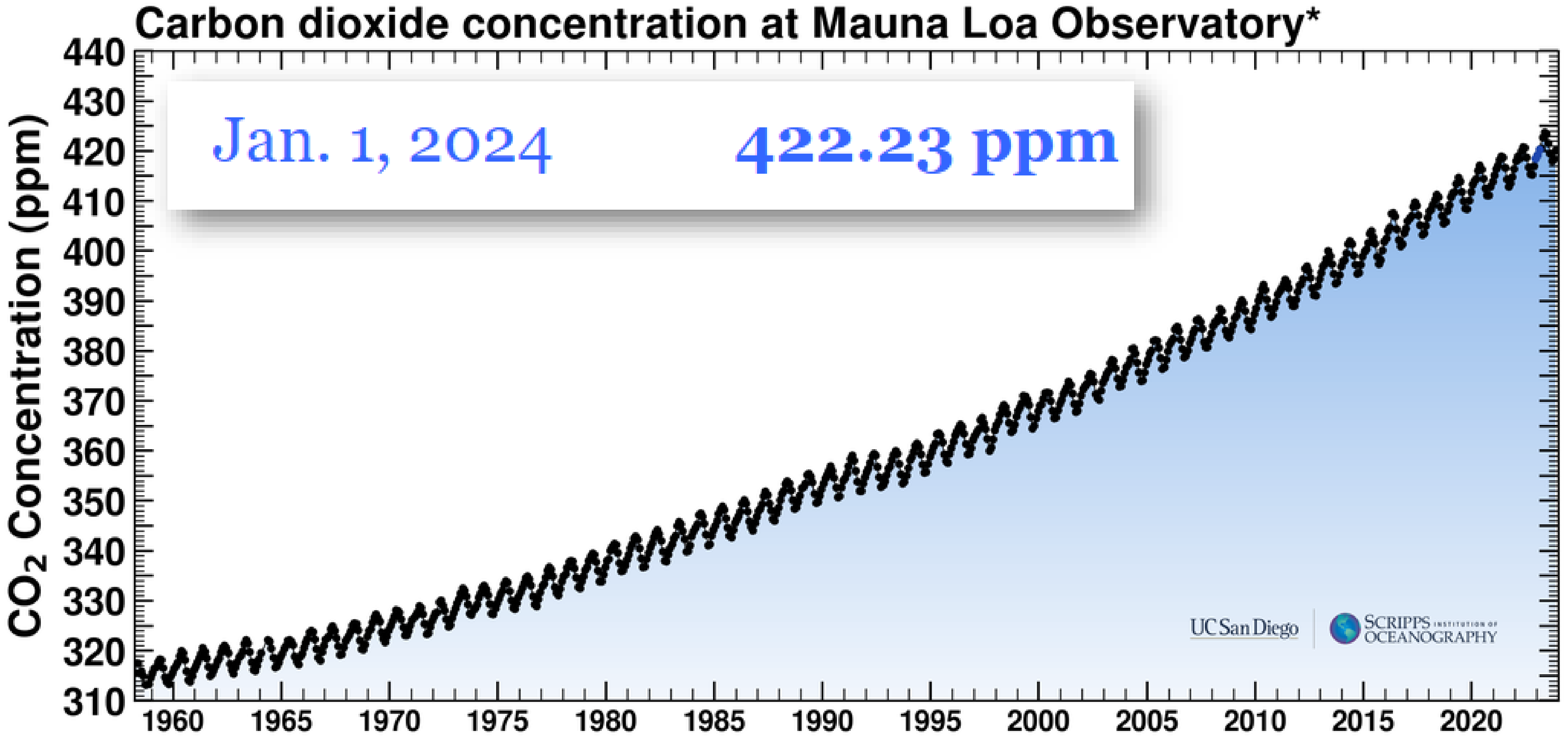


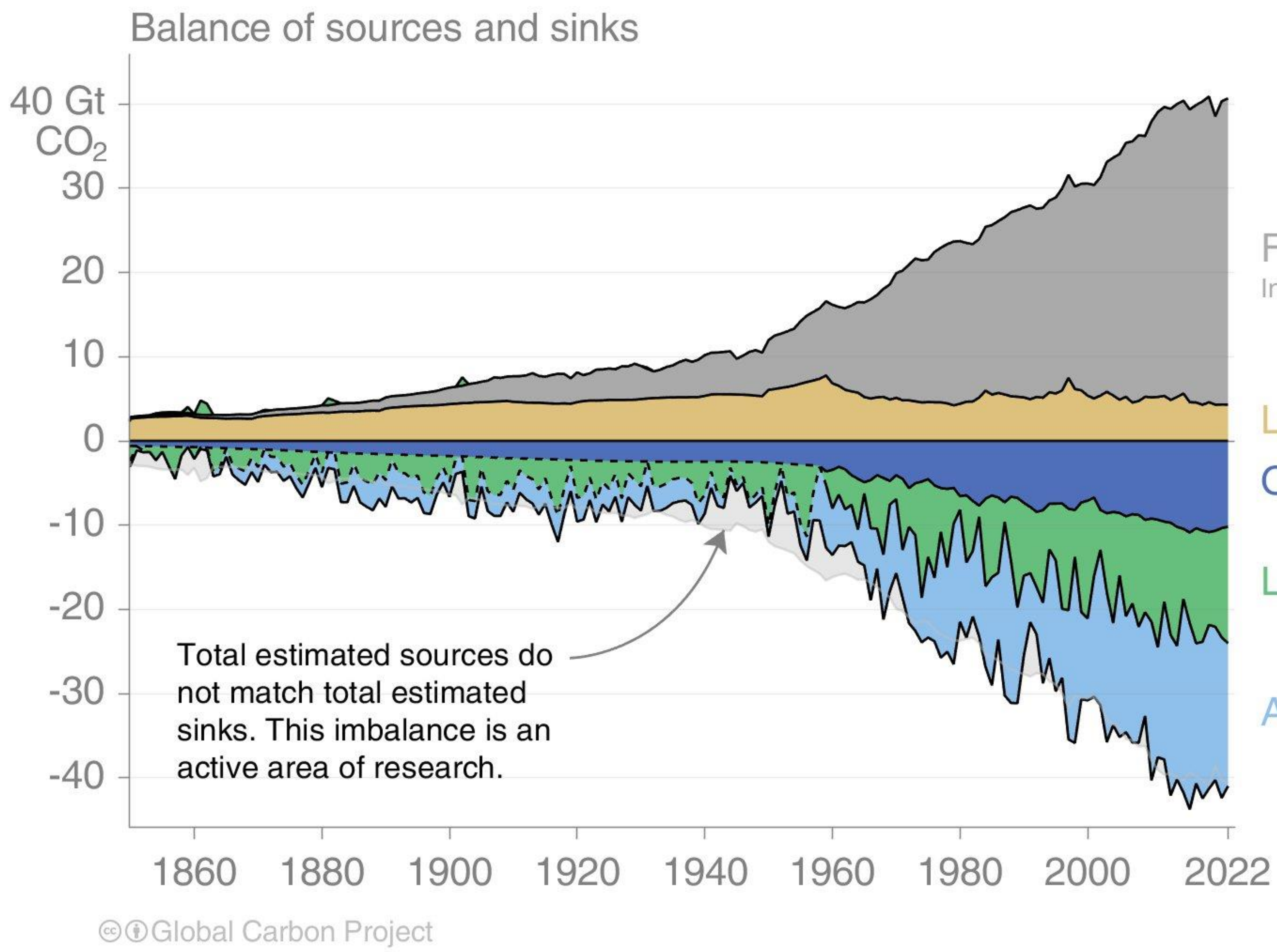
2023-24 FORESTS + CLIMATE LEARNING EXCHANGE SERIES

JANUARY 3rd, 2024

Forest Carbon and Climate Program
Department of Forestry
MICHIGAN STATE UNIVERSITY

SAF

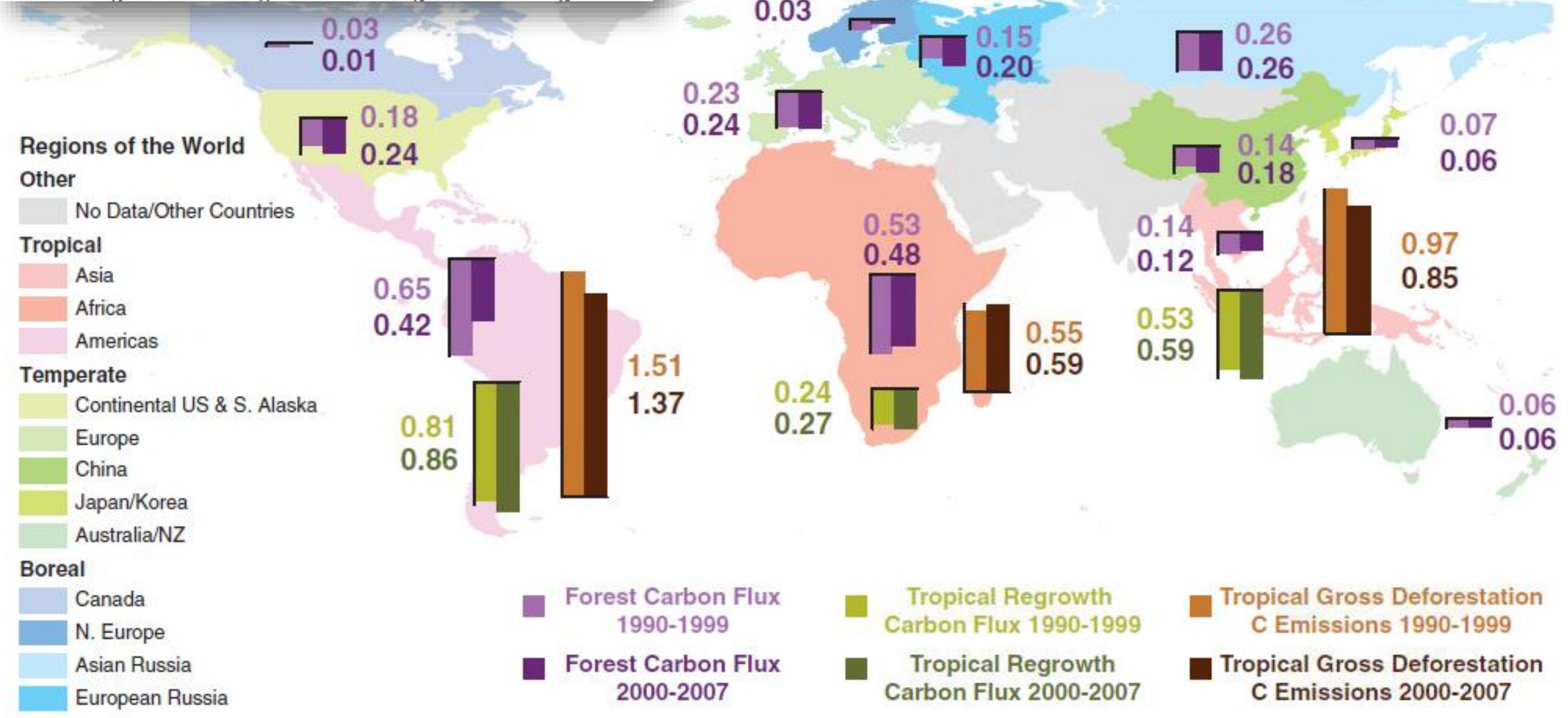

Carbon dioxide concentration at Mauna Loa Observatory*
Jan. 1, 2024
422.23 ppm
CO_2 Concentration (ppm)
440
430
420
410
400
390
380
370
360
350
340
330
320
310
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
UC San Diego
SCRIPPS INSTITUTION OF OCEANOGRAPHY


Balance of sources and sinks
40 Gt CO_2
30
20
10
0
-10
-20
-30
-40
1860
1880
1900
1920
1940
1960
1980
2000
2022
Fossil carbon
Includes carbonation sink
Land-use change
Ocean sink
Land sink
Atmosphere
Total estimated sources do not match total estimated sinks. This imbalance is an active area of research.
Global Carbon Project

A Large and Persistent Carbon Sink in the World's Forests

Yude Pan,[1*] Richard A. Birdsey,[1] Jingyun Fang,[2,3] Richard Houghton,[4] Pekka E. Kauppi,[5]
Werner A. Kurz,[6] Oliver L. Phillips,[7] Anatoly Shvidenko,[8] Simon L. Lewis,[7] Josep G. Canade

19 AUGUST 2011 VOL 333 SCIENCE www.sciencemag.org



Carbon Monitoring, Reporting and Verification (MRV)

- International agreements on climate change mitigation (i.e., the United Nations Framework Convention on Climate Change, or UNFCCC)
- Forest conservation incentive programs (e.g., REDD+)
- State-level climate goals (e.g., “Maine Won’t Wait”)
- Carbon trading markets (e.g., California Air Resources Board)

Ameriflux Tower Site at the Howland Research Forest
U.S. Forest Service and University of Maine

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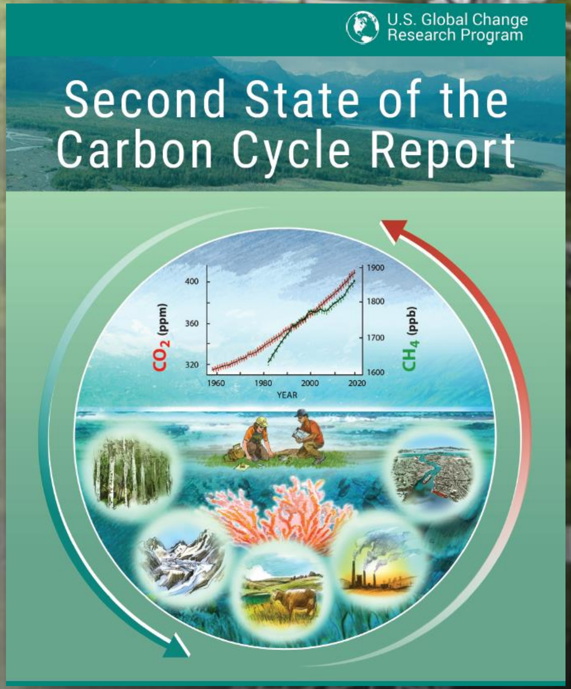
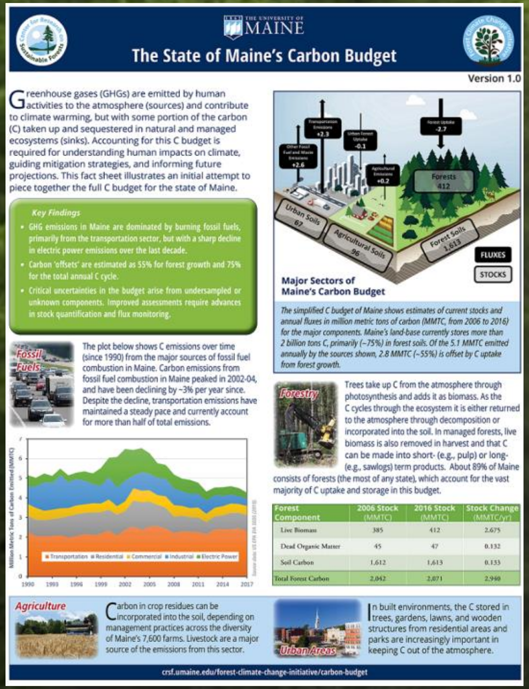
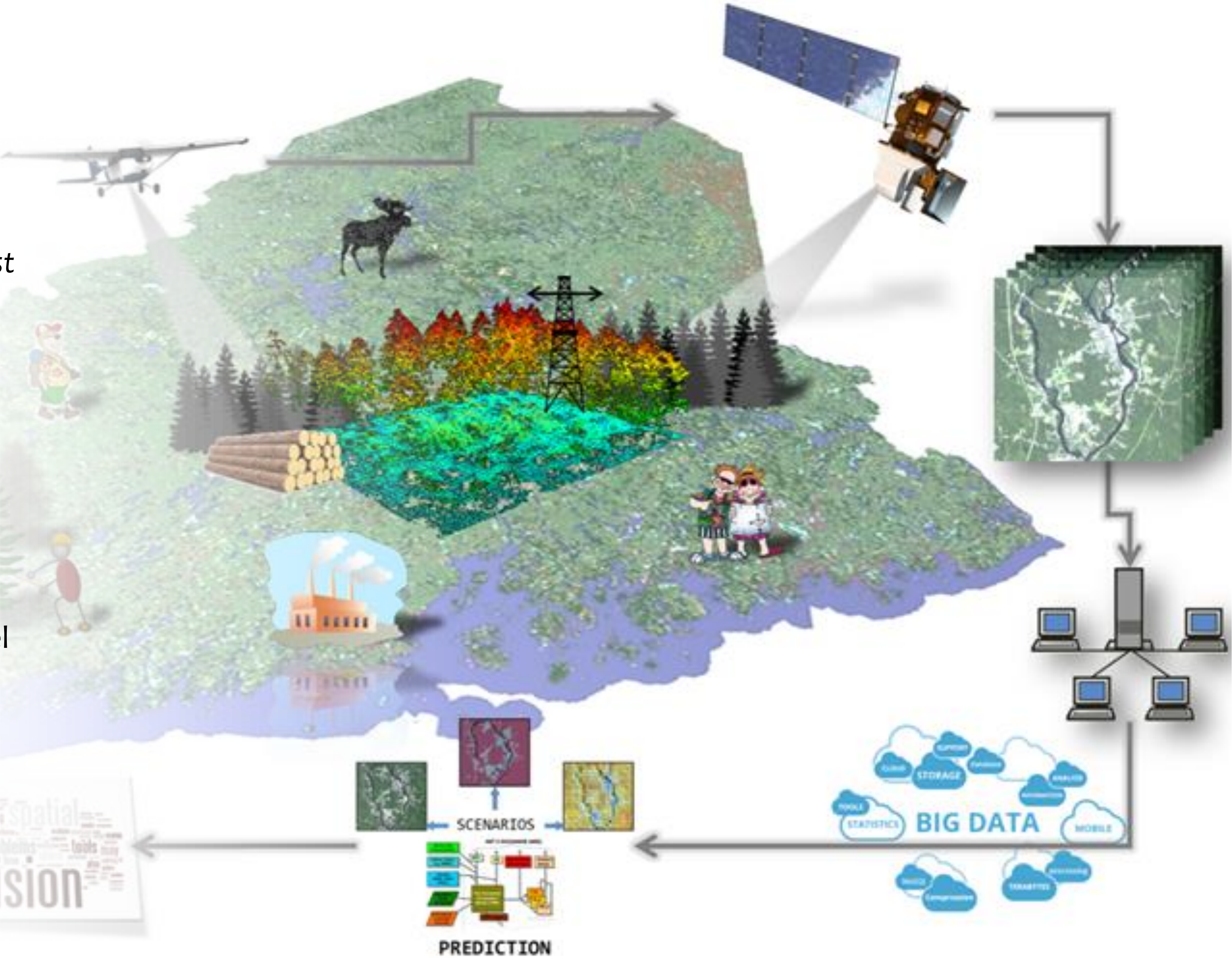




OVERVIEW

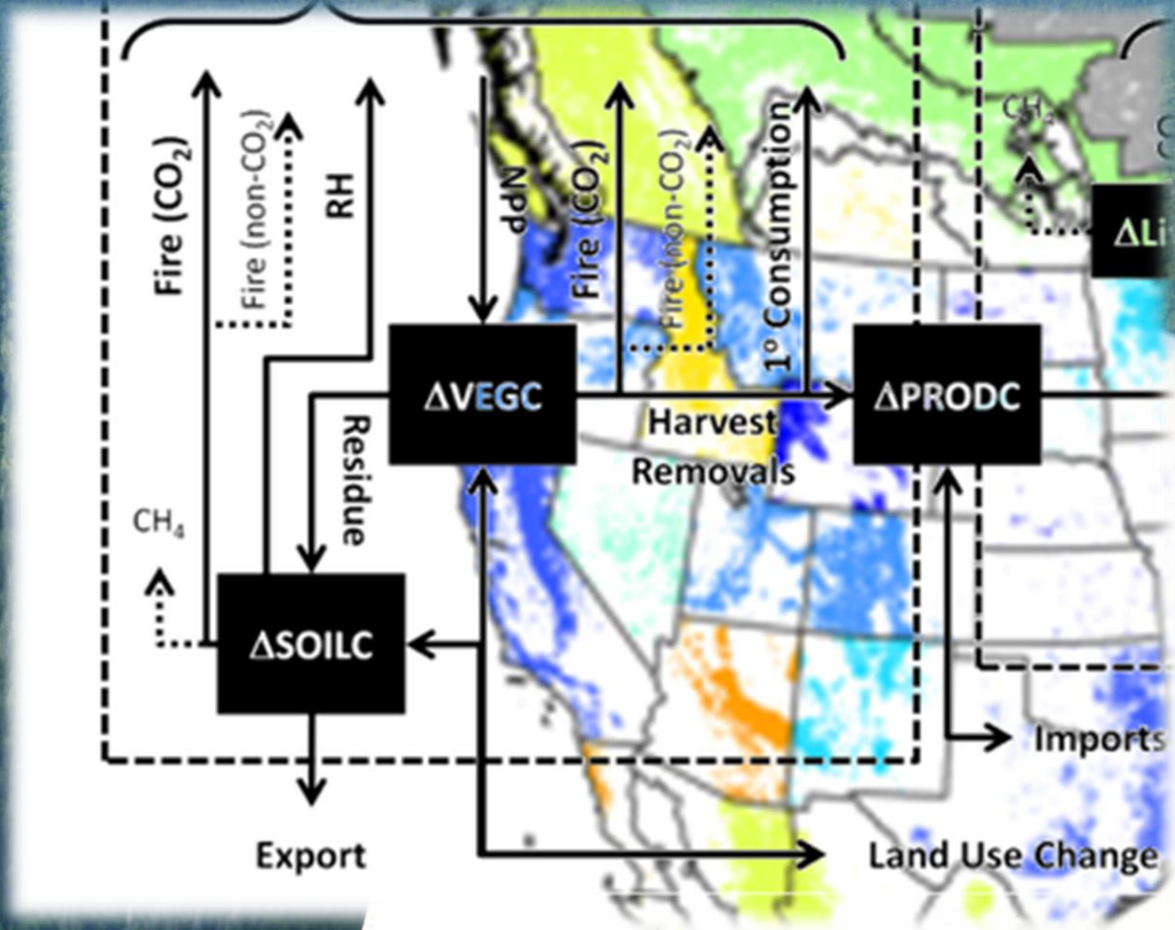
1) *A qualitative analysis and summary of forest carbon modeling* that
   - describes how models work
   - explains the differences between various model types
   - highlights the advantages and caveats in their use for a range of applications
2) *A carbon modeling decision support framework* that can be used for
   - determining which forest carbon model may be best suited for an application
   - considering agency information needs and capacity
   - working with agency staff and/or contractor support

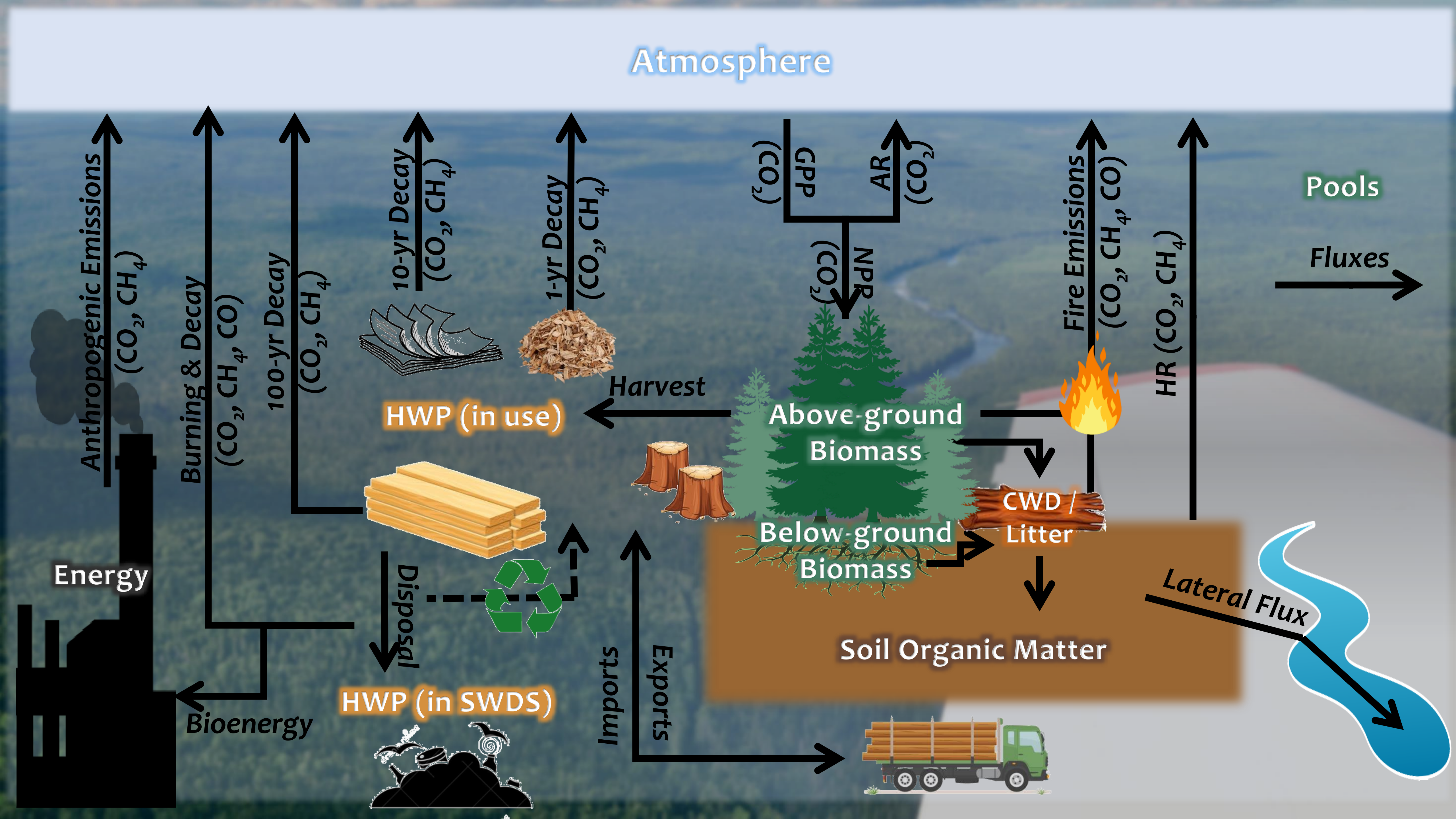


PART 1. The Role of Modeling in Forest Carbon Assessment

(a) What are the Major Components of the Forest Sector Carbon Budget? and

(b) How do we measure and model them?

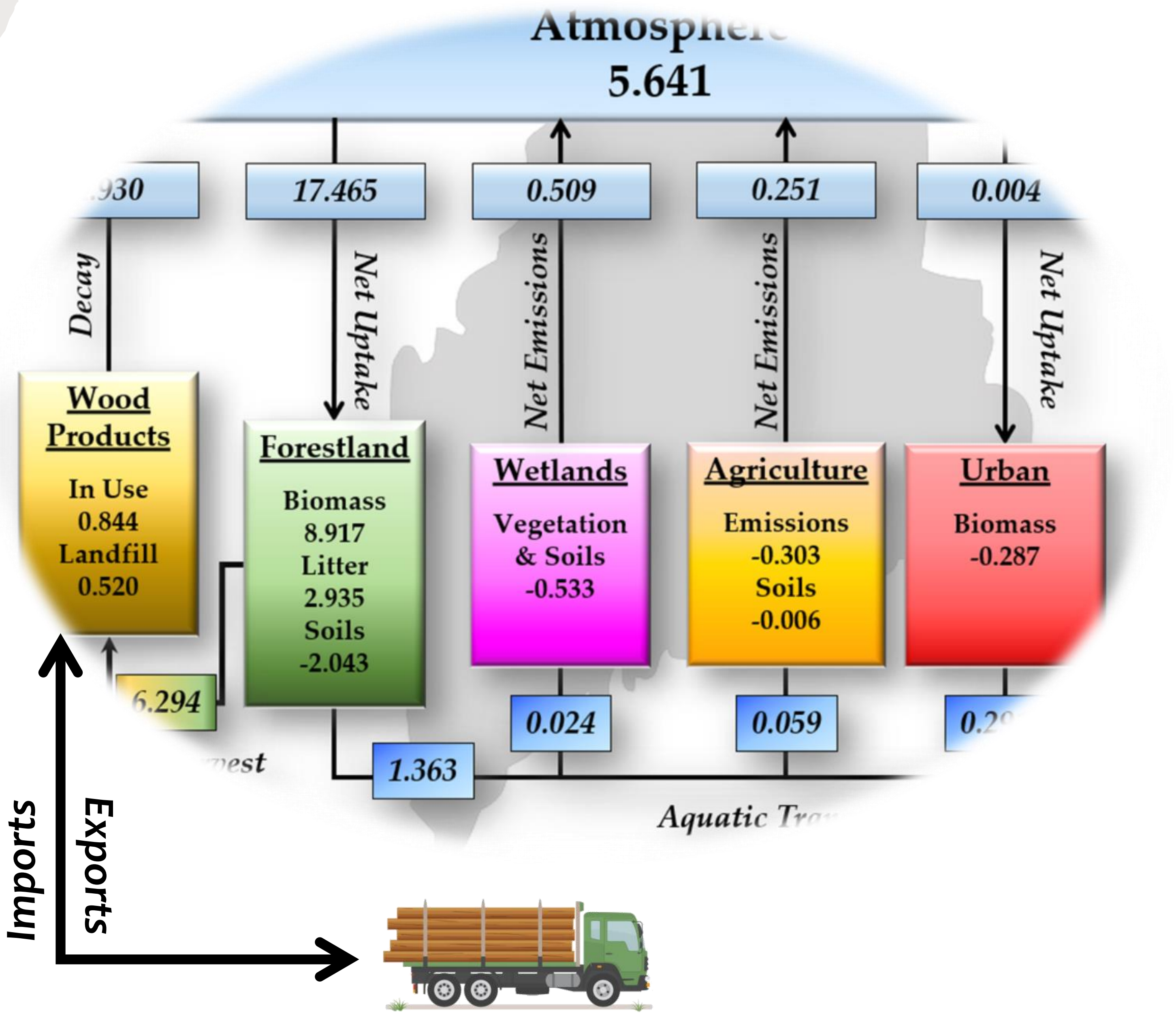


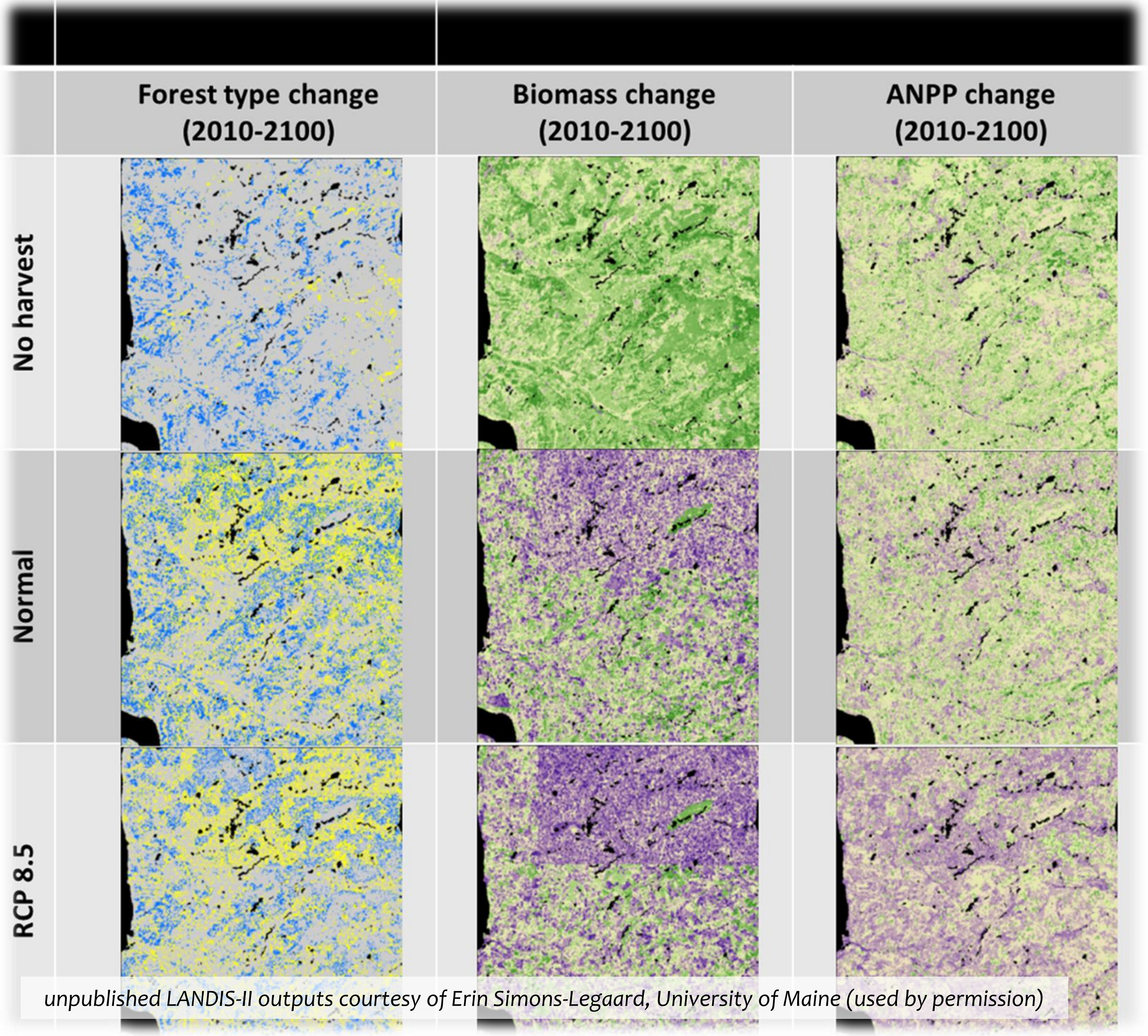


Atmosphere
Anthropogenic Emissions (CO_2, CH_4)
Burning & Decay (CO_2, CH_4, CO)
100-yr Decay (CO_2, CH_4)
10-yr Decay (CO_2, CH_4)
1-yr Decay (CO_2, CH_4)
GPP (CO_2)
AR (CO_2)
NPP (CO_2)
Fire Emissions (CO_2, CH_4, CO)
HR (CO_2, CH_4)
Pools
Fluxes
Harvest
HWP (in use)
Above-ground Biomass
Below-ground Biomass
CWD / Litter
Soil Organic Matter
Lateral Flux
Energy
Disposal
Bioenergy
HWP (in SWDS)
Imports
Exports

Carbon Accounting

- What is a forest?
  - LULUCF categories
- What is the boundary?
  - the default approach
  - the production approach
  - the atmospheric flow approach
- Where is the boundary?
  - the “managed land proxy”





unpublished LANDIS-II outputs courtesy of Erin Simons-Legaard, University of Maine (used by permission)

The role of modeling in forest carbon assessment

PROCESS AND POLICY

- Models are used to understand forest carbon processes and what controls them.
- Models are used to understand how these processes may respond to future stressors and management actions.
- Models are used to estimate the potential impacts of specific policy or management strategy.
- Models are used to inform the policy design by investigating alternative courses of action.

Modeling Approaches

- Statistical, Empirical

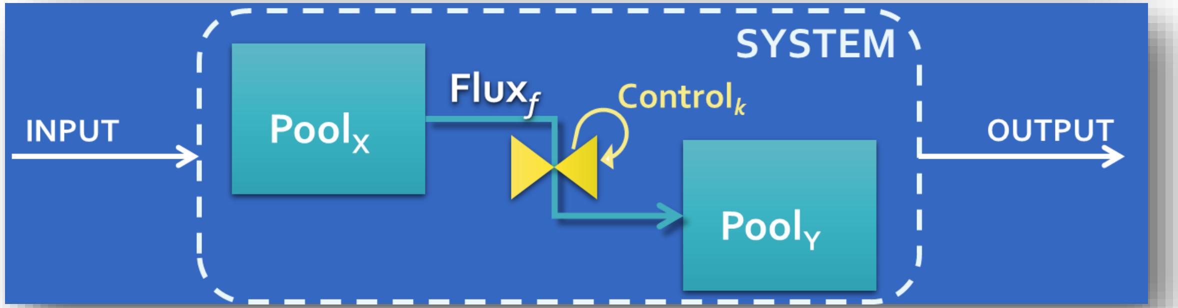
$$Y = ax + b$$

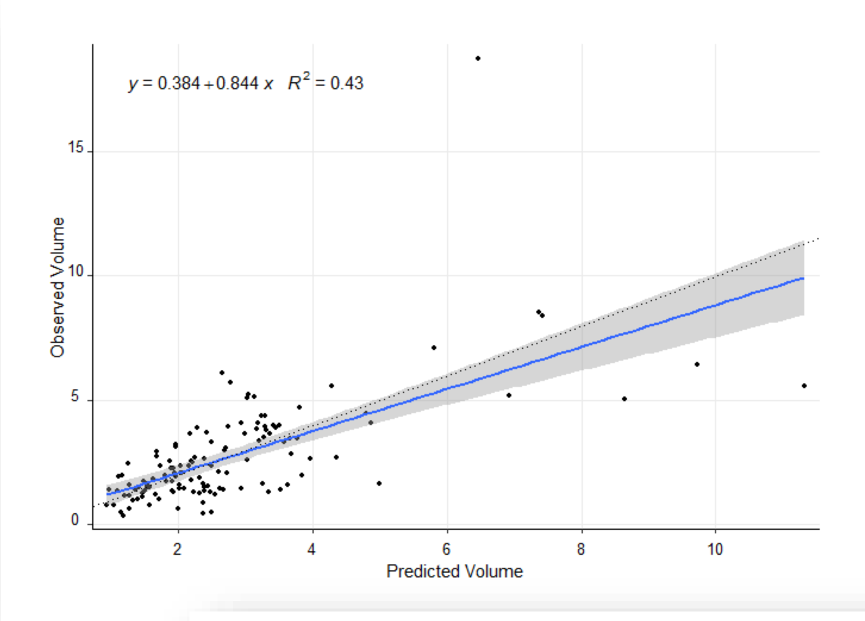
$$V = a_0 \times k^{(b0-b1)} \times D^{b1} \times H^c$$

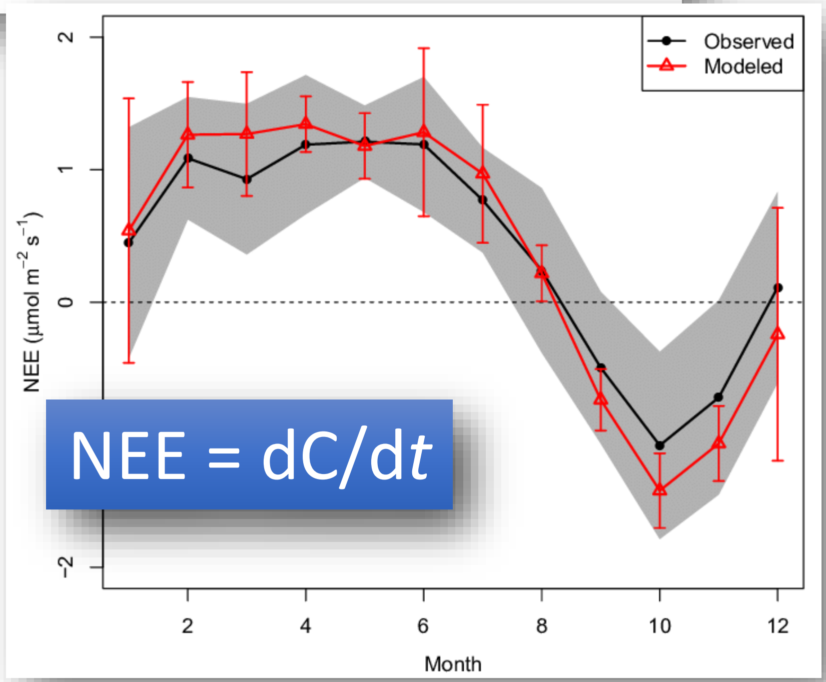
$$\Delta C = C_{t2} - C_{t1}$$

- Numerical simulation, "Process-based"

$$dx/dt = \Sigma(INPUTS) - \Sigma(OUTPUTS)$$



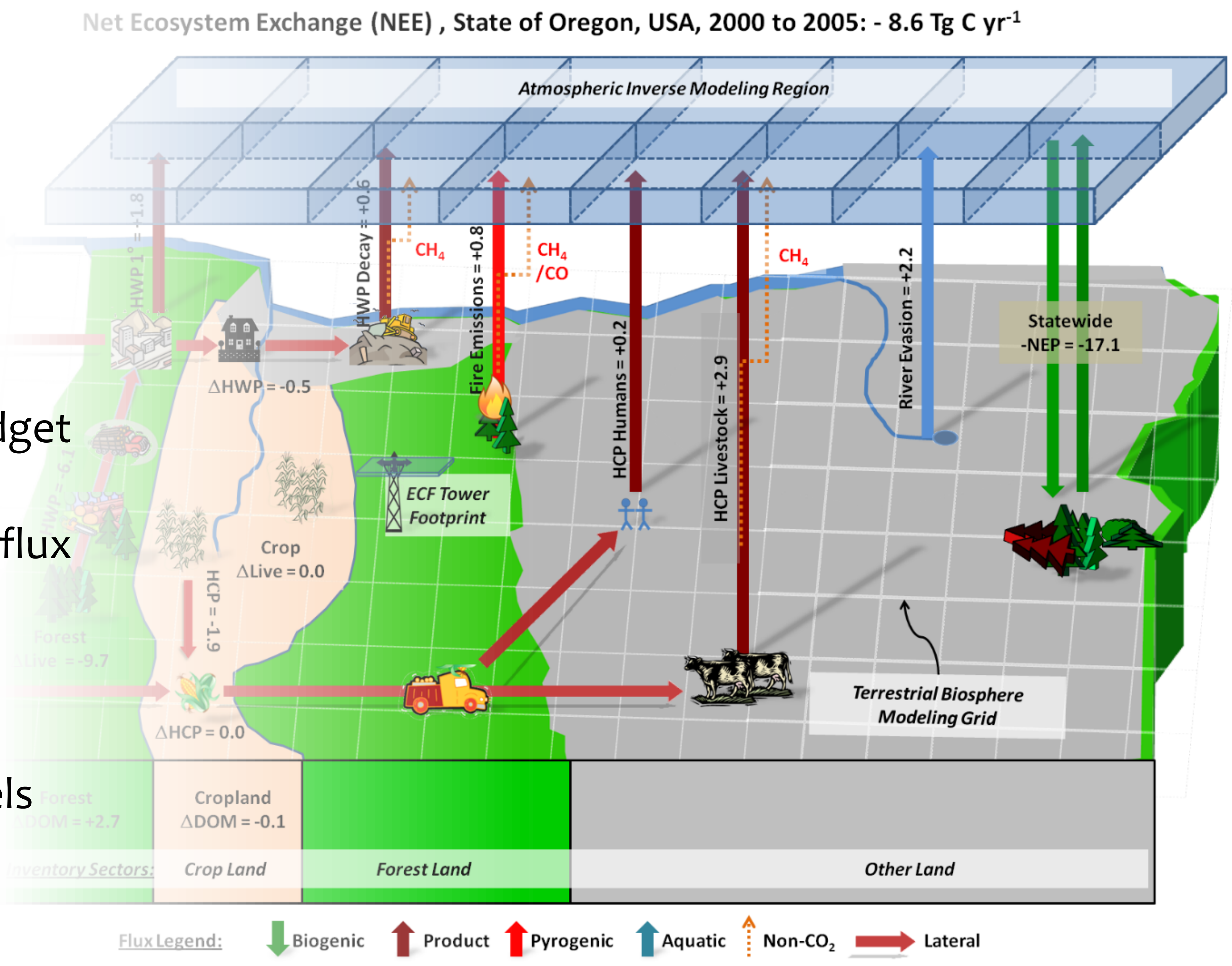




$$NEE = dC/dt$$

Modeling Approaches

- “Top-down”
  - Atmospheric Budget
  - Inverse Models
  - Eddy-covariance flux
- “Bottom-up”
  - Inventories
  - Bookkeeping
  - Ecosystem Models



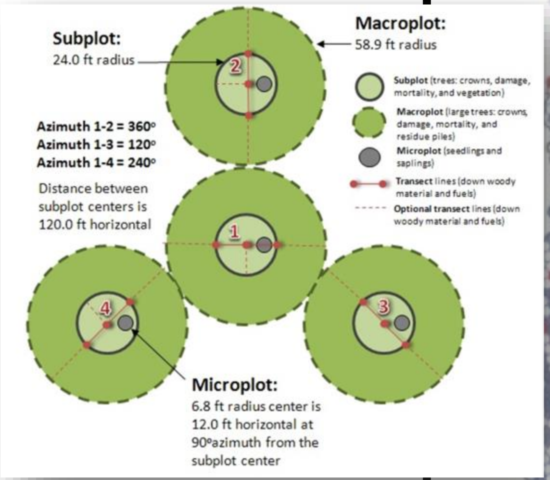
Forest Inventory Models

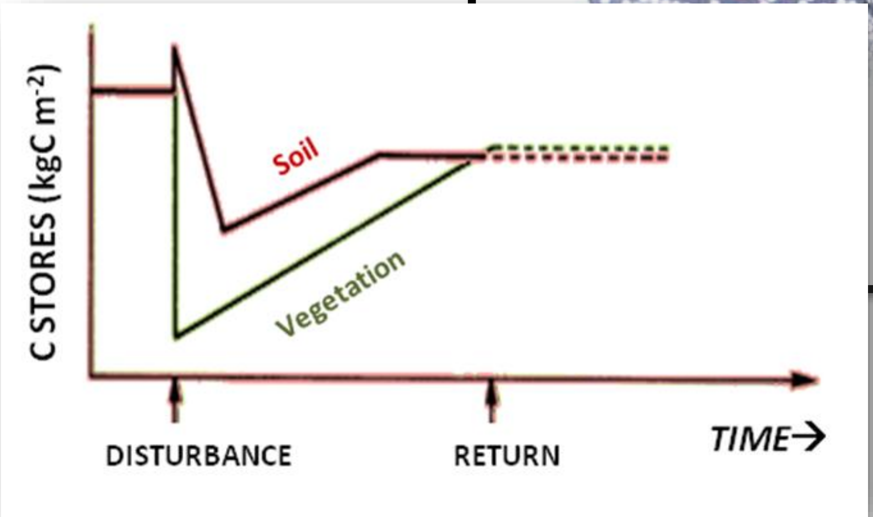
- “Stock Change” approach (e.g., US FIA)

$$\Delta C = C_{t2} - C_{t1}$$

- “Gain-Loss” approach (e.g., Canada’s NFI)

$$C_{t2} = C_{t1} + \Delta C$$

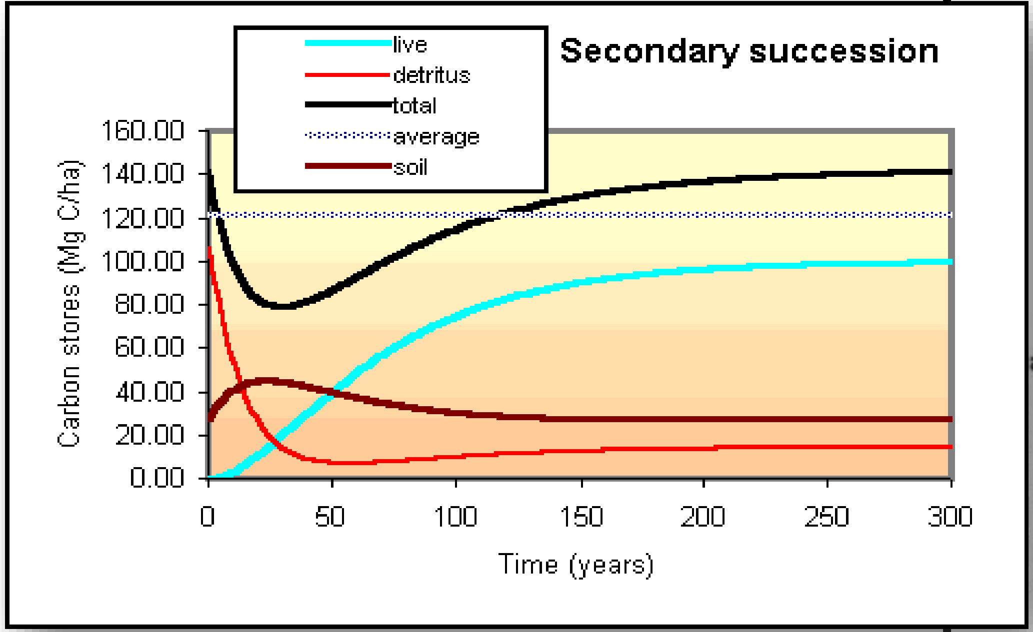




Bookkeeping Models

1. “Measure & Multiply”
2. Update land use changes
3. Track disturbances

LU/LC Class	Carbon in biomass Mg C ha^{-1} (U%; N)
CF	47 (11%; 627)
CFsec	15 (23%; 325)
CBF	41 (6%; 1448)
CBFsec	18 (14%; 524)
BF	31 (10%; 1073)
BFsec	13 (15%; 571)
THF	52 (7%; 1126)
THFsec	19 (14%; 438)
TDF	19 (5%; 1134)
TDFsec	15 (10%; 503)
MG	ND[b]
MGsec	ND
SL[c]	19 (8%; 1334)
SLsec	6 (20%; 177)
GR	11 (20%; 1515)
WT	ND
Palms	ND
Others	ND
IAPF	ND



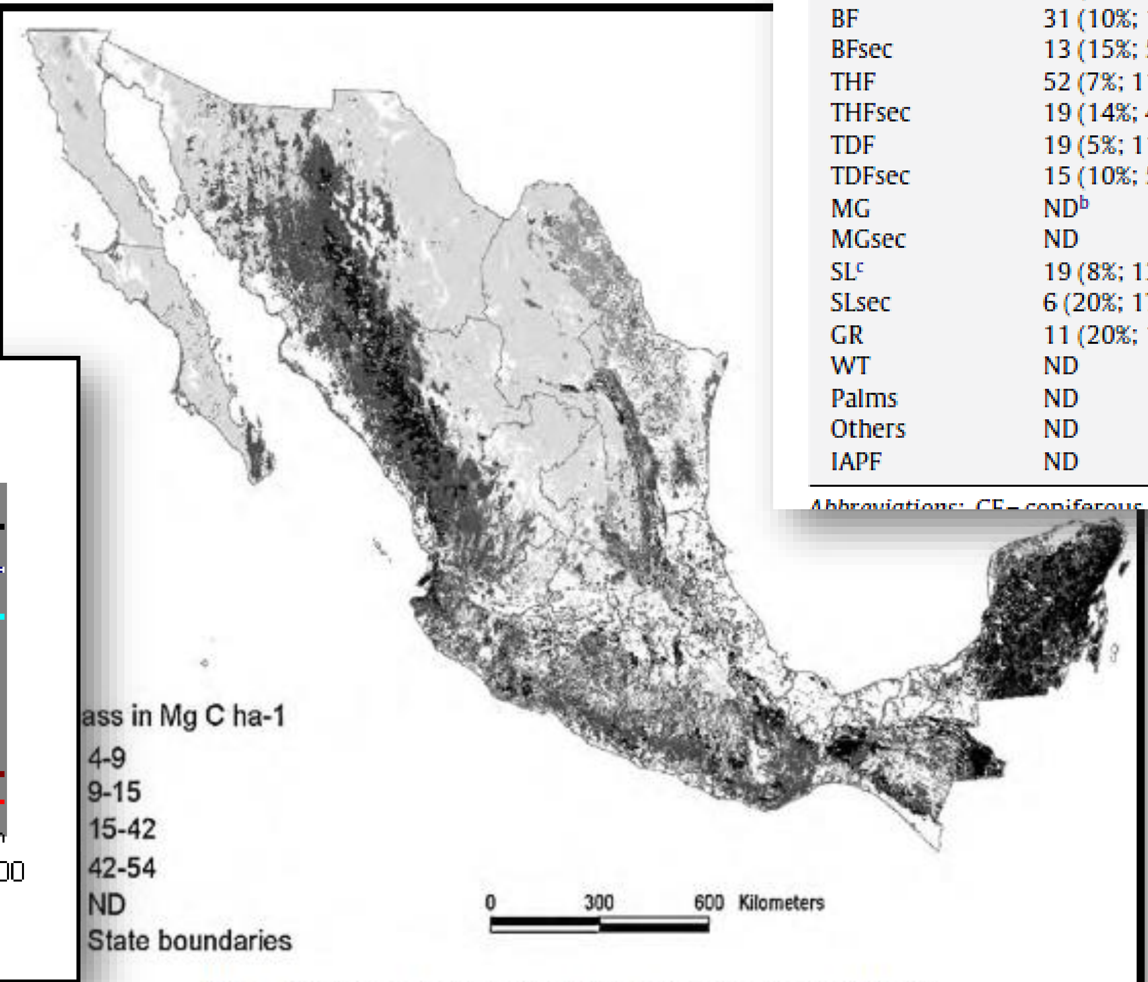
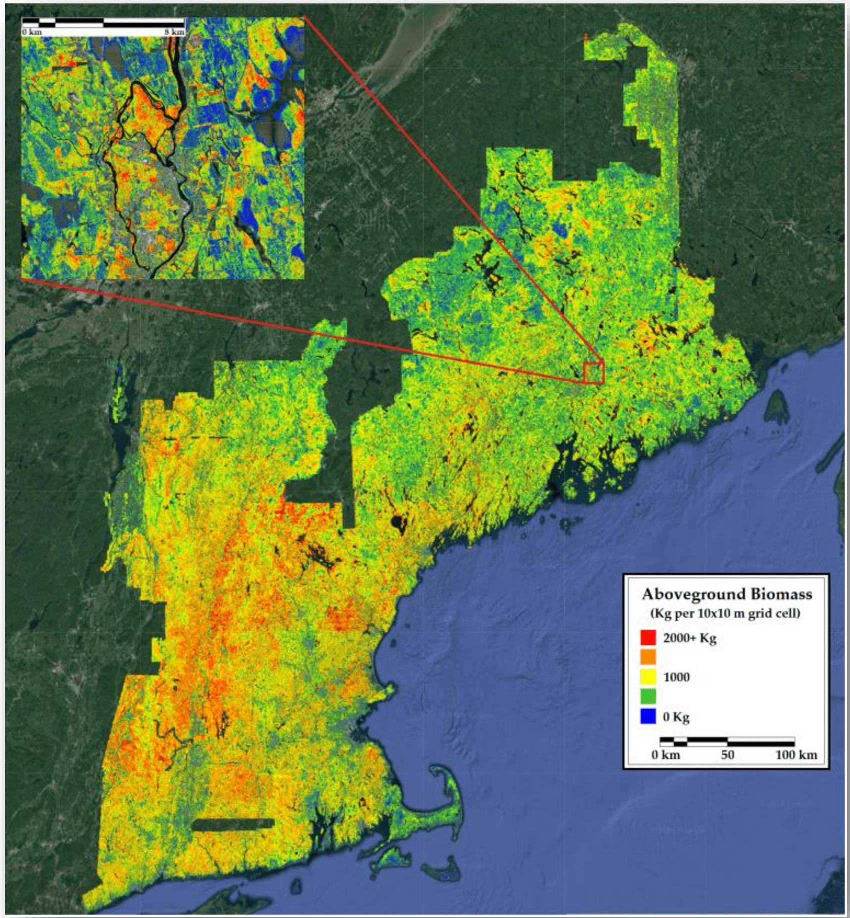
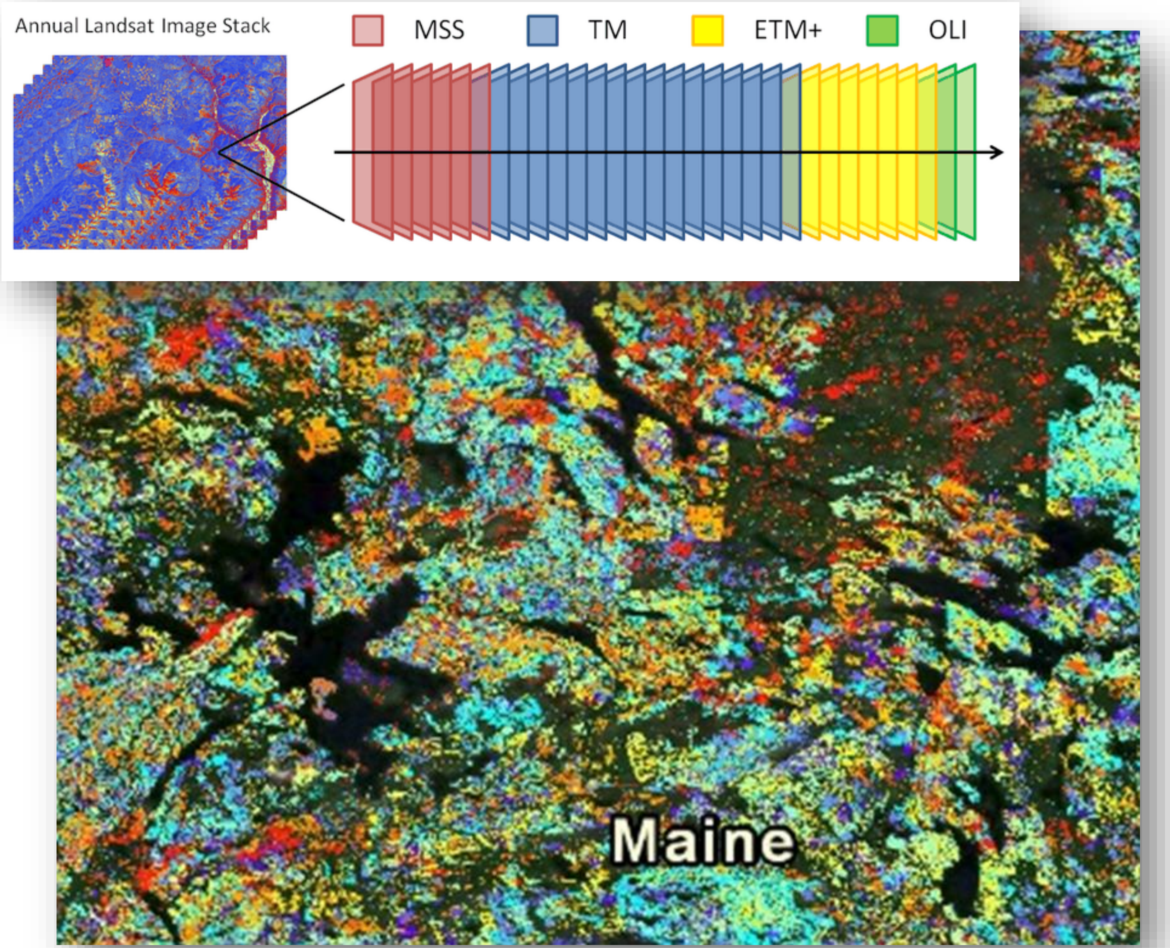


Fig. 4. Biomass carbon stocks in terrestrial ecosystems of Mexico.

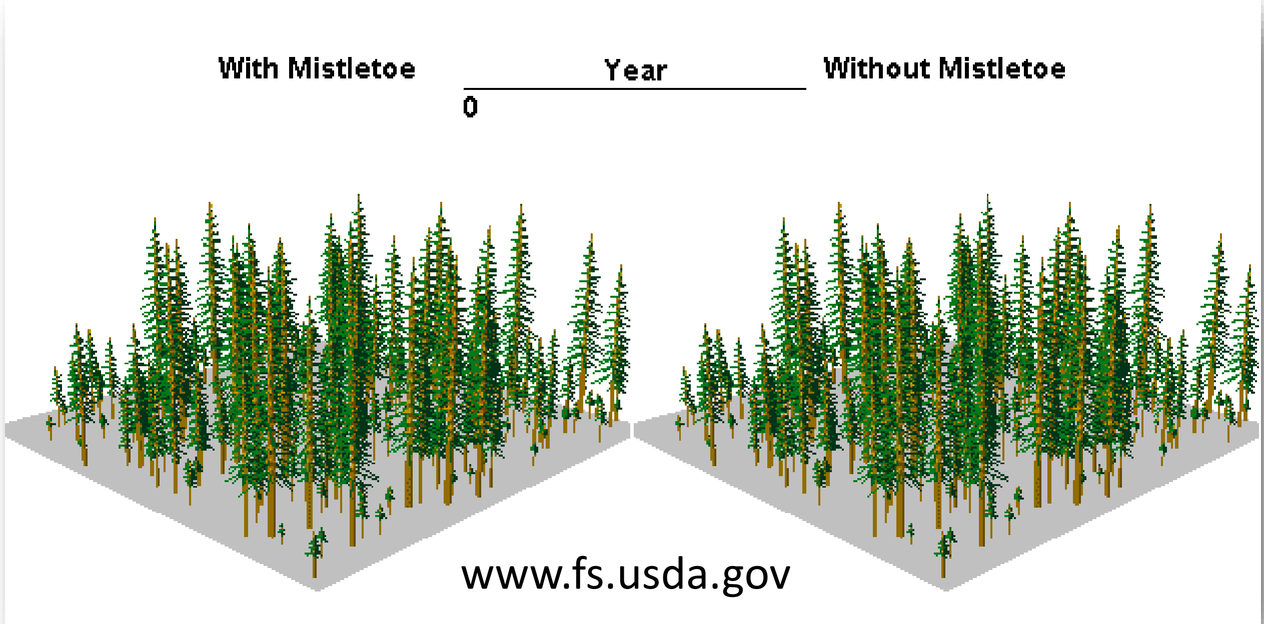
Remote Sensing & Upscaling

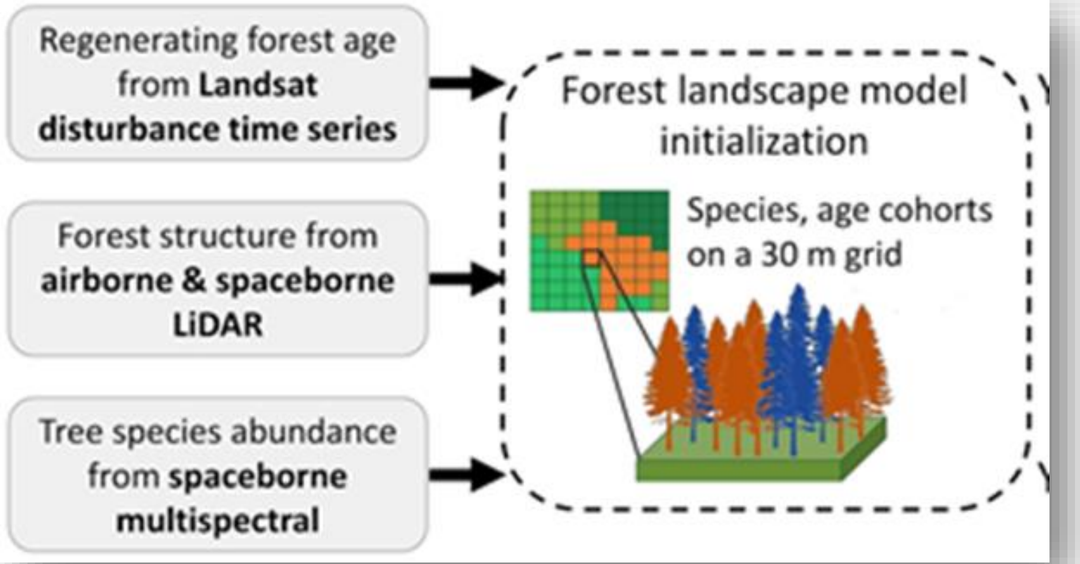




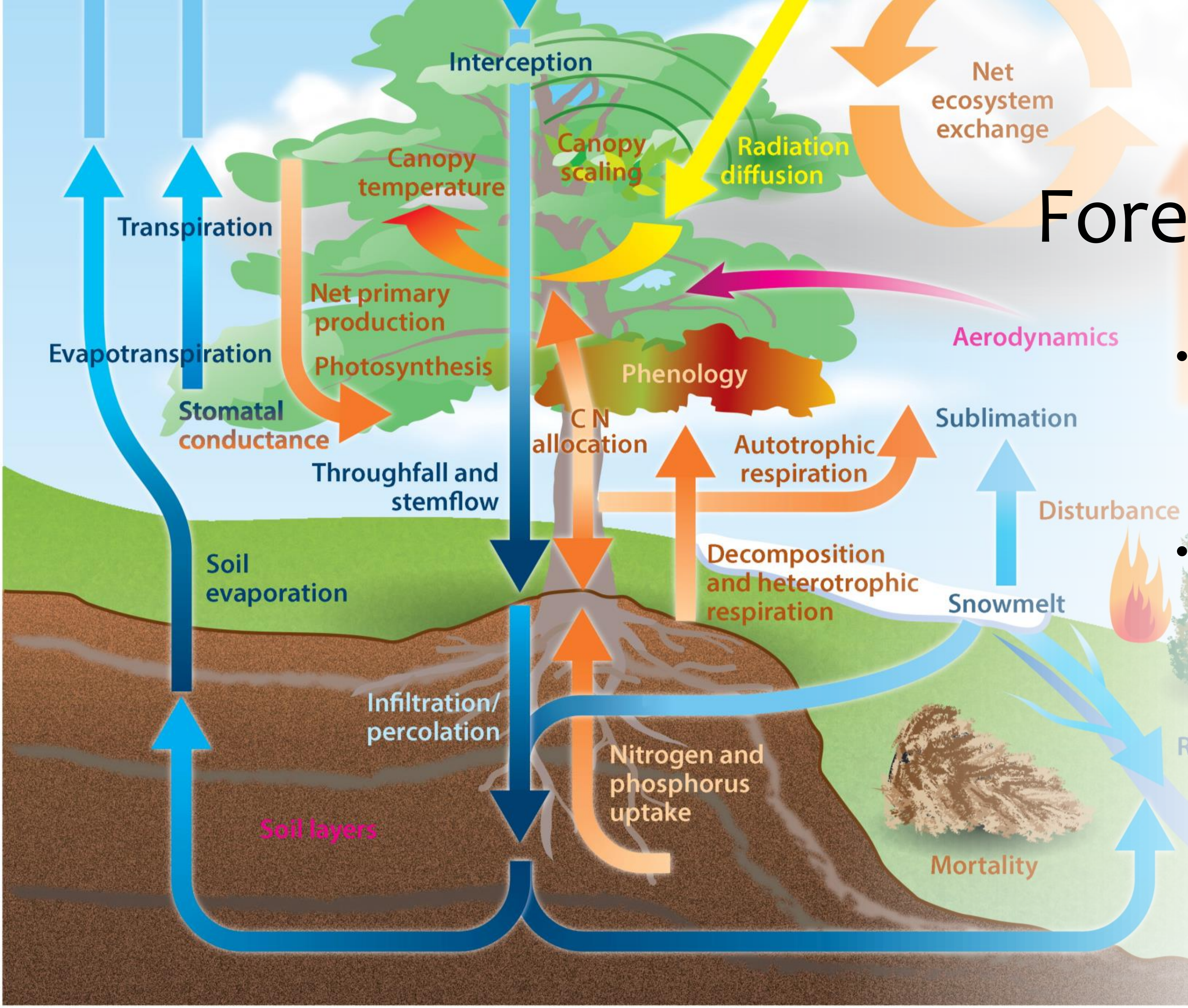
Mechanistic Models

- Forest Gap Models
  - Plot / stand level vegetation dynamics
  - Plant-to-community succession and resource competition
- Forest Landscape Models
  - Simulate broader-scale forest dynamics through time with spatially-referenced data



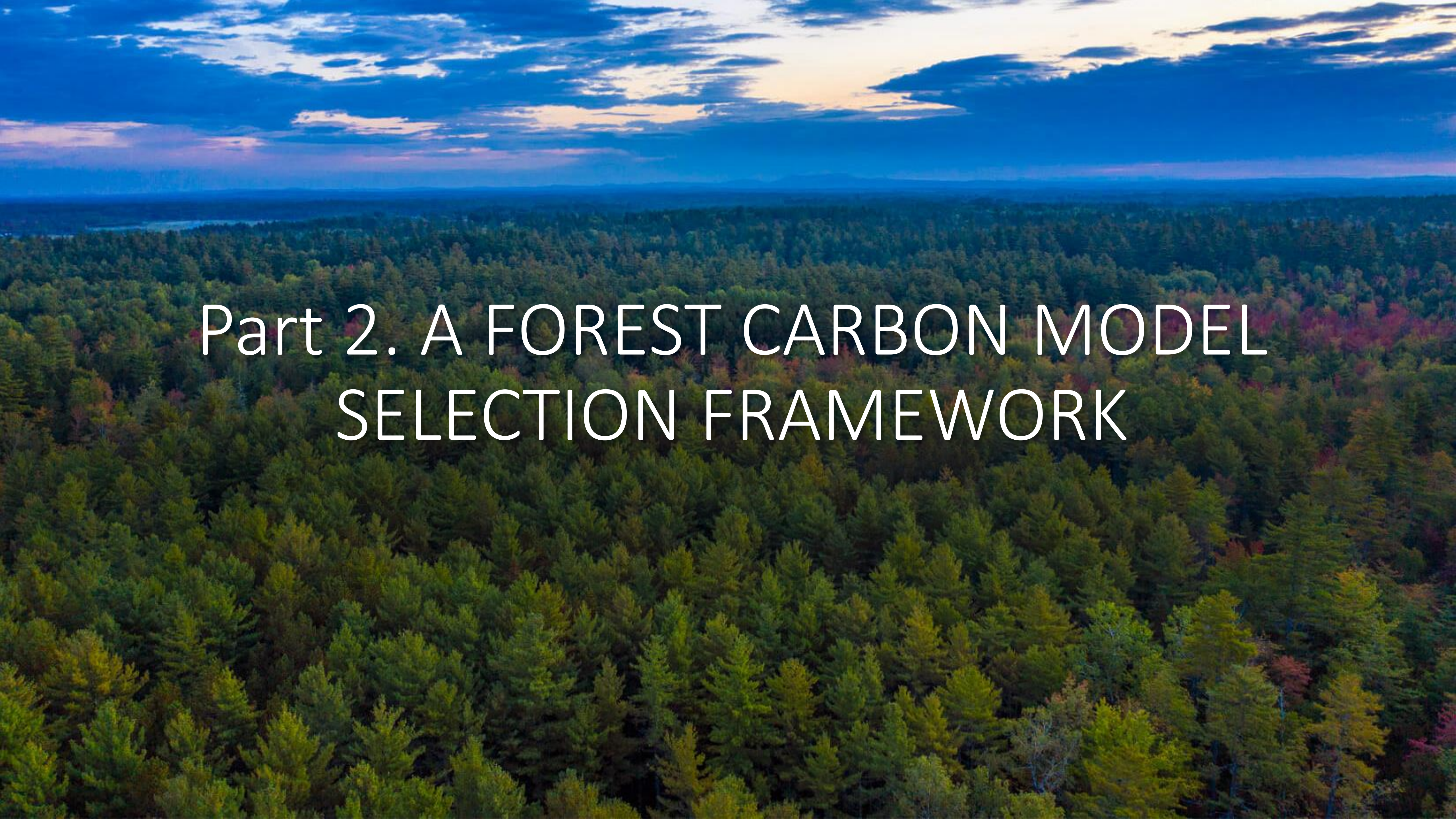


Forest Ecosystem Models



- Terrestrial Biosphere (TBMs) and Land Surface Models (LSMs) in Earth System / Climate (ESMs) and Integrated Assessment Models
- Numerical simulation of climate-driven ecological processes
  - Coupled Plant-Soil-Water-Energy
  - Prognostic (EK) or Diagnostic (LUE)
  - Big Leaf or Dynamic Vegetation (DVMs) and Ecosystem Demography Models

Fisher JB, et al. 2014.



Part 2. A FOREST CARBON MODEL SELECTION FRAMEWORK

How do we select which model(s) to use?

- Multiple models and frameworks available to model forest carbon
- Needs and complexity vary:
    - Carbon pools
    - Stocks and flows
    - Spatial and temporal scales
    - Forest management
    - Forest products / demand
    - Land use / land cover change
    - Climate change
    - Pest, disease, fire impacts

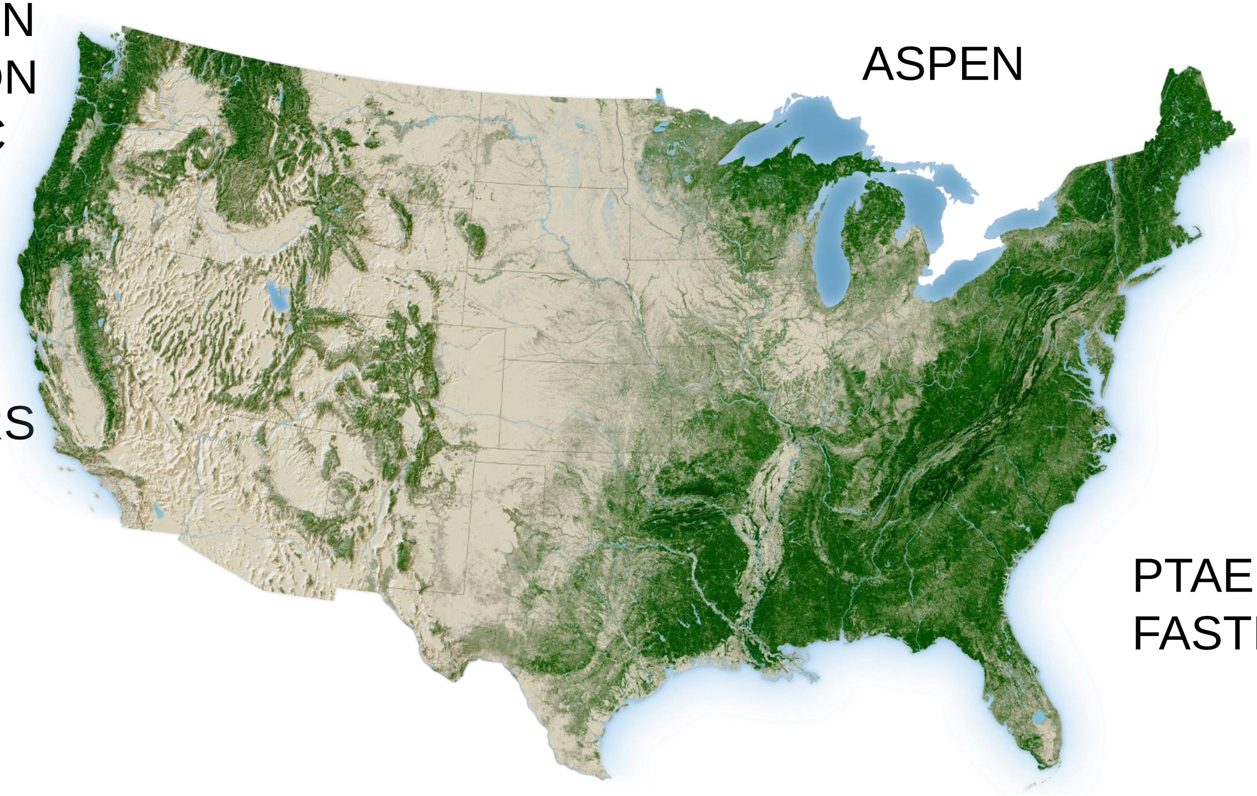
“Which forest model *should be used to*….. generate yield curves?”

Each region has a rich history of growth and yield studies and associated models specific to the dominant commercial species – multiple internal models exist that are confidential and proprietary

ORGANON
CIPSANON
SMC PYC
FPS
DF SIM
TASS
CACTOS
CONIFERS

ASPEN

OSM



PTAEDA
FASTLOB

FVS

National Forest Inventory Systems - FIA

Increased Applications of CFS-CBM

American Forests
NIACS

Forest Carbon and Climate Program
Department of Forestry
MICHIGAN STATE UNIVERSITY

Impact of Forest Management and Wood Utilization on Carbon Sequestration and Storage in Pennsylvania and Maryland

Results for

State of Pennsylvania

Kendall DeLyser

Chad Papa

Kylie Clay

Daphna Gadoth-Goodman

Lauren Cooper

Todd Ontl

December 23, 2022

CBM CFS3

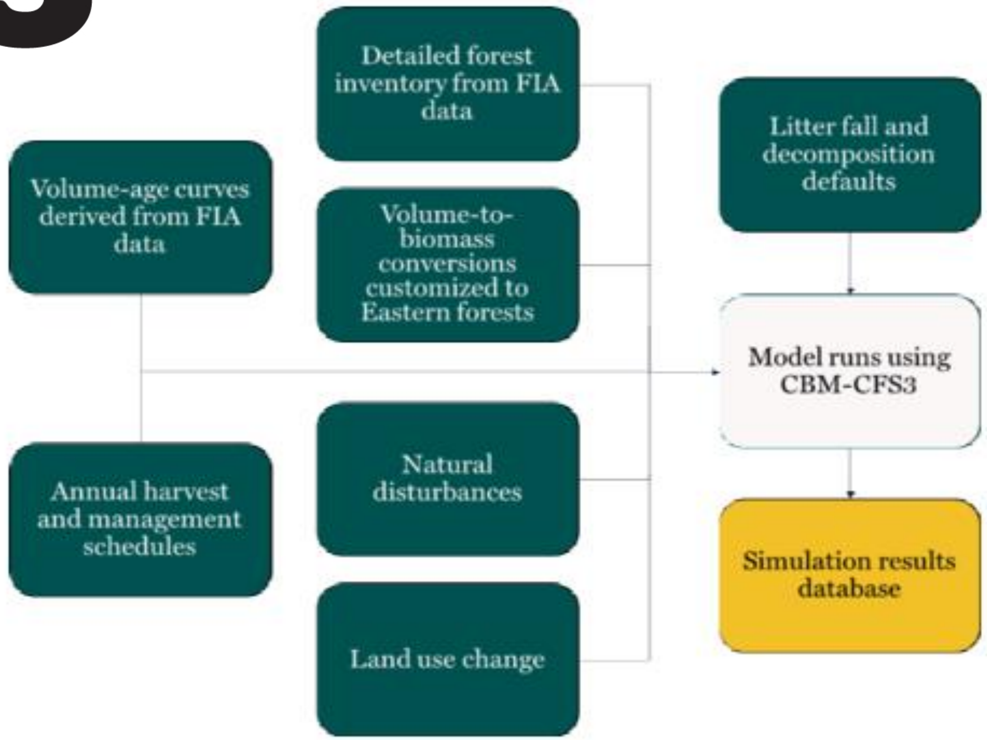


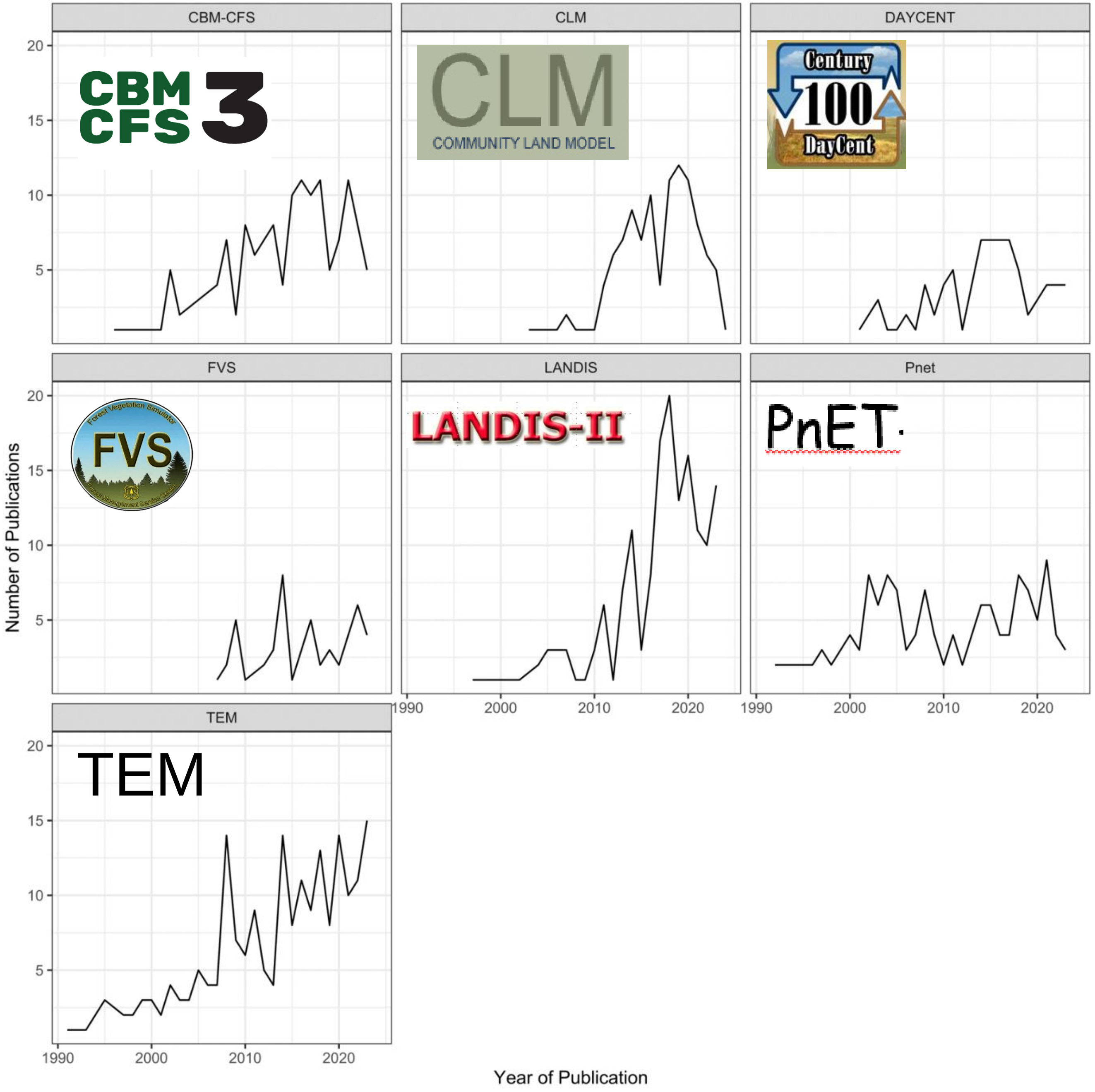
Figure 2. Modeling inputs and process for CBM-CFS3. Adapted from Kull et al. 2019.

CFS-CBM is processed based, and relies on strong national inventories like FIA

Web of Science returned a total of 857 manuscripts using the 15 forest carbon models we considered (1990-2023)

Most common models:

CBM-CFS3
DAYCENT/CENTURY
LANDIS
TEM
FVS
PnET
TEM



Questions to Consider When Selecting a Forest Carbon Model

1. What **forest carbon pools** (e.g., aboveground, belowground, harvested wood products) does the model account for?
2. At what **spatial scale** (e.g., pixel, plot, stand, parcel, county, state, etc.) does the model simulate ecosystem carbon stocks and fluxes?
3. At what **time step** (e.g., daily, annual, decadal, etc.) does the model estimate forest carbon dynamics?
4. Can the model incorporate **policy relevant management alternatives** (e.g., silvicultural systems, best management practices) of interest to decision makers?
5. How does the model incorporate **ecosystem disturbances** to accommodate the policy objectives?
6. How does the model account for carbon stored in **harvested wood products**?
7. How does **model parameterization** compare to the **available data** for an intended use, and Are there realistic options to enhance data availability to result in successful utilization of the model?

More questions to consider…

8. How **sensitive is model** parameterization to measurement methodologies or other user-based inputs and assumptions?
9. What are the levels of **uncertainty in the output** of any of the models compared to the goals of the user?
10. For applications where total atmospheric greenhouse gas reductions are a primary goal, how does the model accommodate **non-CO_2 greenhouse gases** (e.g., CH_4, N_2O, etc.)?
11. To what extent does the model incorporate **socioeconomic drivers** (e.g., market demand, land use change, etc.) on forest carbon stocks and fluxes?
12. Does the model account for other **potential impacts** (e.g., leakage) outside of the geographic area of interest?
13. What **software licenses** and **computer resources** are required to run the model?
14. What **level of skill and resources** are required to use the model and how does that compare to the quality and utility of the model output to inform decision making?

Key components of forest carbon models with LANDIS-II example

Table 1. Key components of forest carbon models with LANDIS-II example

Component	Description	Example using LANDIS-II
Statement of purpose	What model is primarily developed to do	Designed to model custom disturbance and succession for large landscapes. Most common models examine seed dispersal, carbon dynamics, forest management, and climate change impacts.
Model Type	Main model category (bookkeeping, economic, etc.) and characteristics (e.g., landscape, stand)	Landscape, ecological
Model methodology	Primary model approach (simulation, optimization, etc.)	Simulation
Simulation Mode	Temporal focus of the model (i.e., past, present, future)	Future / prognostic
Temporal Resolution	Resolution that model is parameterized at	Annual
Temporal Extent	Typical time steps that model output is produced at	Decadal to multi-century timesteps
Spatial Resolution	Geographical resolution of model	User-defined stands and cohorts (resolution varies)
Spatial Extent	Typical geographical extent of model	Landscape, hundreds to millions of acres
Carbon Pools	Carbon pools included in model accounted	Aboveground growing stock
Forest Ecosystems	Forest ecosystems / species included in default model	User-defined
Other key outputs	Other key outputs besides carbon pools that are captured in the model	Harvested biomass
Silvicultural Practices	How the model accounts for silvicultural practices / forest management	User-defined (e.g., clearcut, partial removal, thinning, etc.)
Disturbance	Whether model accounts for ecological disturbances like fire, pest, and disease.	Yes
Climate Sensitivity	Whether the model accounts climate change	Yes, with user-defined climate projections
Deterministic v. Stochastic Process	Stochastic: includes a random component that uses a distribution as one of the inputs and can produce a distribution for the output. Deterministic: uses numbers as inputs and produces numbers as outputs.	Quasi-stochastic
Data Requirements	Key user-provided data required to parameterize and run model	plot/polygon level vegetation information; optional: climate data, soil data
Accessibility	Software and licensing requirements	Open source, available via model website
Computing Requirements	Other computing requirements to parameterize and run model	text file reader; optional: GIS software (for raster data)
Primary user	Personnel model primarily developed to be used by (e.g., ecologists, economists, computer scientist, etc.).	Forest ecologist, computer scientist
Customizability	The extent to which the model can be customized for a specific geographical area, driver, policy, etc.	Highly customizable; several model extensions; varying spatial scales and resolutions,
Learning time	Likely amount of time required to learn how to use model	Months
State policy utility	Utility of the model for state-level policymaking	High, but could require significant resources to parameterize and calibrate, especially if interested in complex silvicultural systems.
Latest model version	Latest version of the model, and when last updated.	v7.0 (2018)
Relevant Applications	Examples of where model has been applied in the Eastern US	Northern Maine, Vermont
Model Documentation	Link to website with more details	https://www.landis-ii.org/

Model Criteria / Scoring Rubric

- 15 Total Criteria divided into 3 sub-criteria:
  - Usability
  - Complexity
  - Analytical capability
- Each individual criteria were then scored on a scale of 0-10
  - 0 = no capability to meet that criterion
  - 10 = very high capability
- Scores averaged within and across criteria for Total Model Score (0-10)

#	Model Name	Model Type
1	3PG	Empirical, physiological
2	Biome-BGC	Ecosystem process
3	CBM-CFS3	Empirical, stock and change
4	CLM5 / CLM-FATES	Global climate model
5	ED2	Cohort, dynamic vegetation
6	FASOM	Economic, optimization
7	ForGATE	Stand-Regional C calculator
8	FVS	Forest stand simulator
9	GTM	Economic, optimization
10	LANDIS-II	Landscape, ecological simulation
11	LURA	Economic, optimization
12	Open Stand Model	Forest stand simulator
13	PnET	Empirical, physiological
14	TEM6	Regional, ecosystem simulation
15	Woodstock / REMSOFT	Landscape, optimization

Forest Carbon Model Selection Criteria

Criteria	Category	Options / Components in Criteria Scoring
Accessibility	Usability	Open Source; Software; License
Learning Curve	Usability	Low; Medium; High
Data requirements	Usability	Low; Medium; High
Spatial resolution	Complexity	Pixel; Plot; Stand; Landscape; Regional
Spatial extent	Complexity	Varies
Temporal resolution	Complexity	Daily; Monthly; Annual; Greater than annual
Temporal extent	Complexity	Daily; Monthly; Annual; Greater than annual
Silvicultural systems supported	Complexity	Yes / No
Forest Ecosystem Carbon Pools	Complexity; Analytics	Aboveground; Belowground; Soil; Coarse woody debris
Timber Harvest	Complexity	Yes / No
Harvested wood products pools	Complexity; Analytics	Yes / No
Scenario analysis	Analytics	Yes / No
Economic drivers	Analytics	Yes / No
Climate sensitivity	Analytics	Yes / No
Fire, pest, disease sensitivity	Analytics	Yes / No

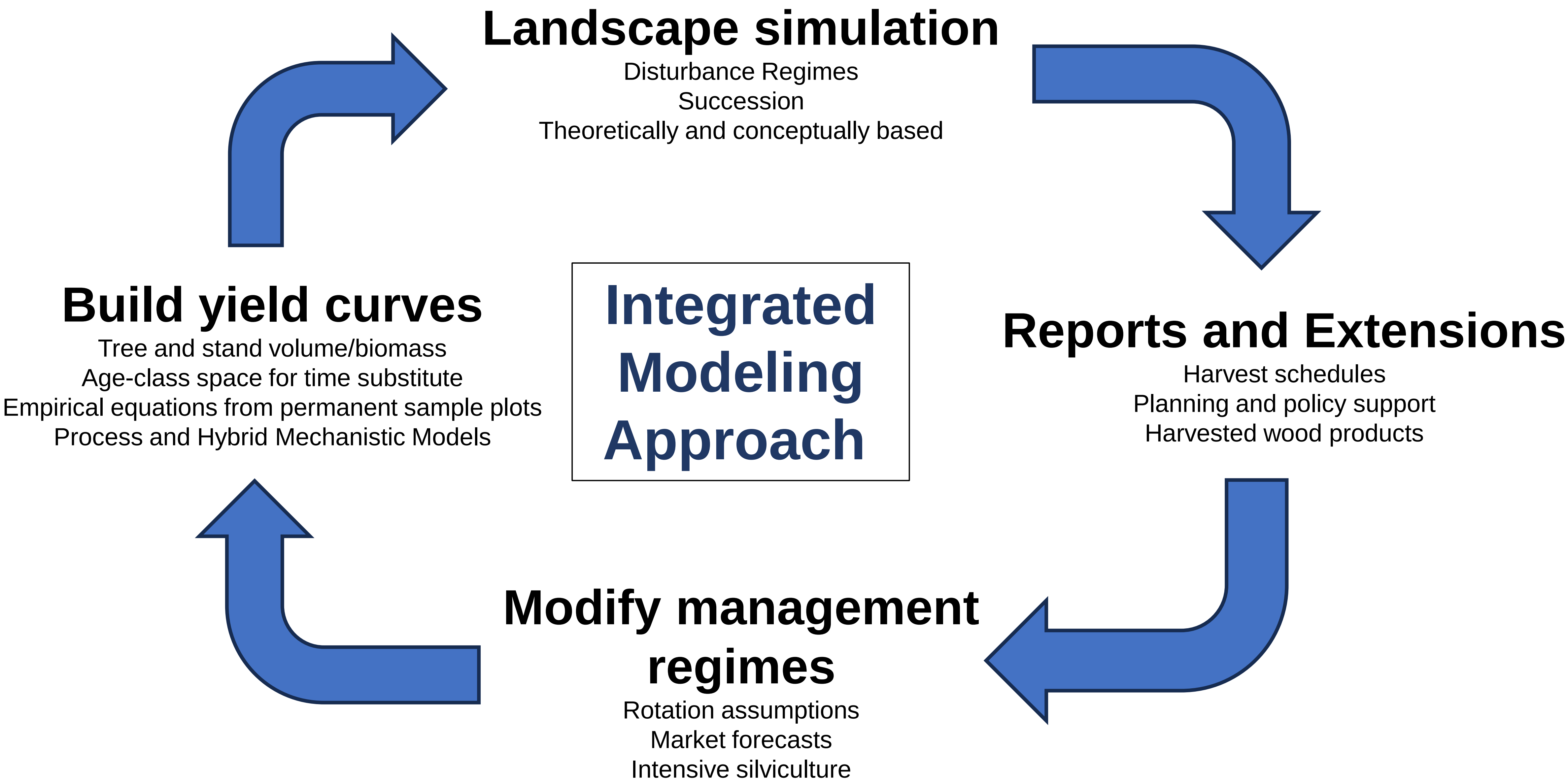
Scoring Example: LANDIS-II & FVS

Criteria	Assessment		Criteria Score	
	LANDIS-II	FVS	LANDIS-II	FVS
Accessibility	High	High	10	10
Learning Curve	Medium	Medium	5	5
Data Requirements	Medium-High	Medium	3	6
Spatial resolution	Pixel, stand, tree	Stand; tree	10	10
Spatial extent	Regions	Regions; variants	10	7
Temporal resolution	Annual	Annual	10	10
Temporal extent	Multi-decadal	Centuries	10	10
Silvicultural systems supported	Any	Any	10	10
Forest Ecosystem Carbon Pools	Above	Multiple	7	10
Timber harvest	Yes	Yes	10	10
Harvested wood products pools	Yes	Yes	10	10
Scenario analysis	Yes	Yes	10	10
Response to disturbance and silviculture	Yes	Yes	10	10
Economic drivers	No	Yes	0	10
Climate sensitivity	Yes	No	10	0
Fire, pest, disease sensitivity	Yes	Yes	10	10
Usability Score			6.0	7.0
Complexity Score			9.6	9.6
Analytical Capability Score			8.1	8.6
Total Score			7.9	8.4

Carbon Model Criteria Scores

Model Name	Usability Score	Complexity Score	Analytical Capability Score	Total Score
FVS	7.0	9.6	8.6	8.4
Open Stand Model	8.3	9.3	6.7	8.1
LANDIS-II	6.0	9.6	8.1	7.9
ForGATE	10.0	7.6	5.7	7.8
GTM	5.0	8.0	10.0	7.7
TEM6	6.7	8.0	8.3	7.7
CBM-CFS3	5.3	9.0	8.6	7.6
FASOM	3.3	8.0	10.0	7.1
ED2	8.3	7.0	3.9	6.4
PnET	8.3	6.5	4.0	6.3
Biome-BGC	8.3	6.3	4.0	6.2
3PG	6.7	6.0	5.4	6.0
CLM5 / CLM-FATES	6.7	5.6	5.4	5.9
LURA	3.3	7.3	6.7	5.8
Woodstock / REMSOFT	0.3	7.9	6.7	5.0

- No perfect model
- Growth & Yield models and carbon 'calculators' typically scored higher
- Tradeoff between analytical capability and usability
- User-data requirements & licenses decrease usability


Landscape simulation
Disturbance Regimes
Succession
Theoretically and conceptually based
Build yield curves
Tree and stand volume/biomass
Age-class space for time substitute
Empirical equations from permanent sample plots
Process and Hybrid Mechanistic Models
Integrated Modeling Approach
Reports and Extensions
Harvest schedules
Planning and policy support
Harvested wood products
Modify management regimes
Rotation assumptions
Market forecasts
Intensive silviculture

LANDIS-II

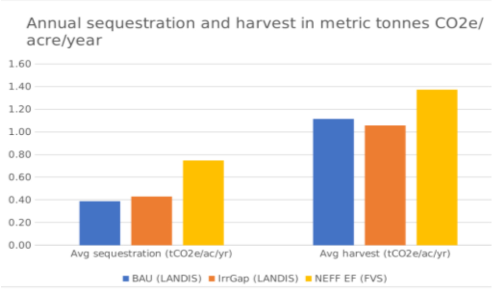
REMSOFT CBM CFS3

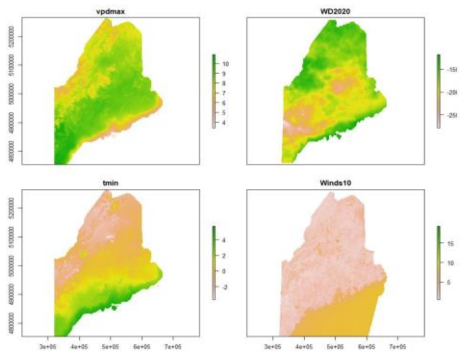
COMMUNITY LAND MODEL

CBM CFS3

Forest Vegetation Simulator FVS Forest Management Service Center

Compare trends in volume, terrestrial C sequestration, storage, harvested wood products, market impacts, etc.

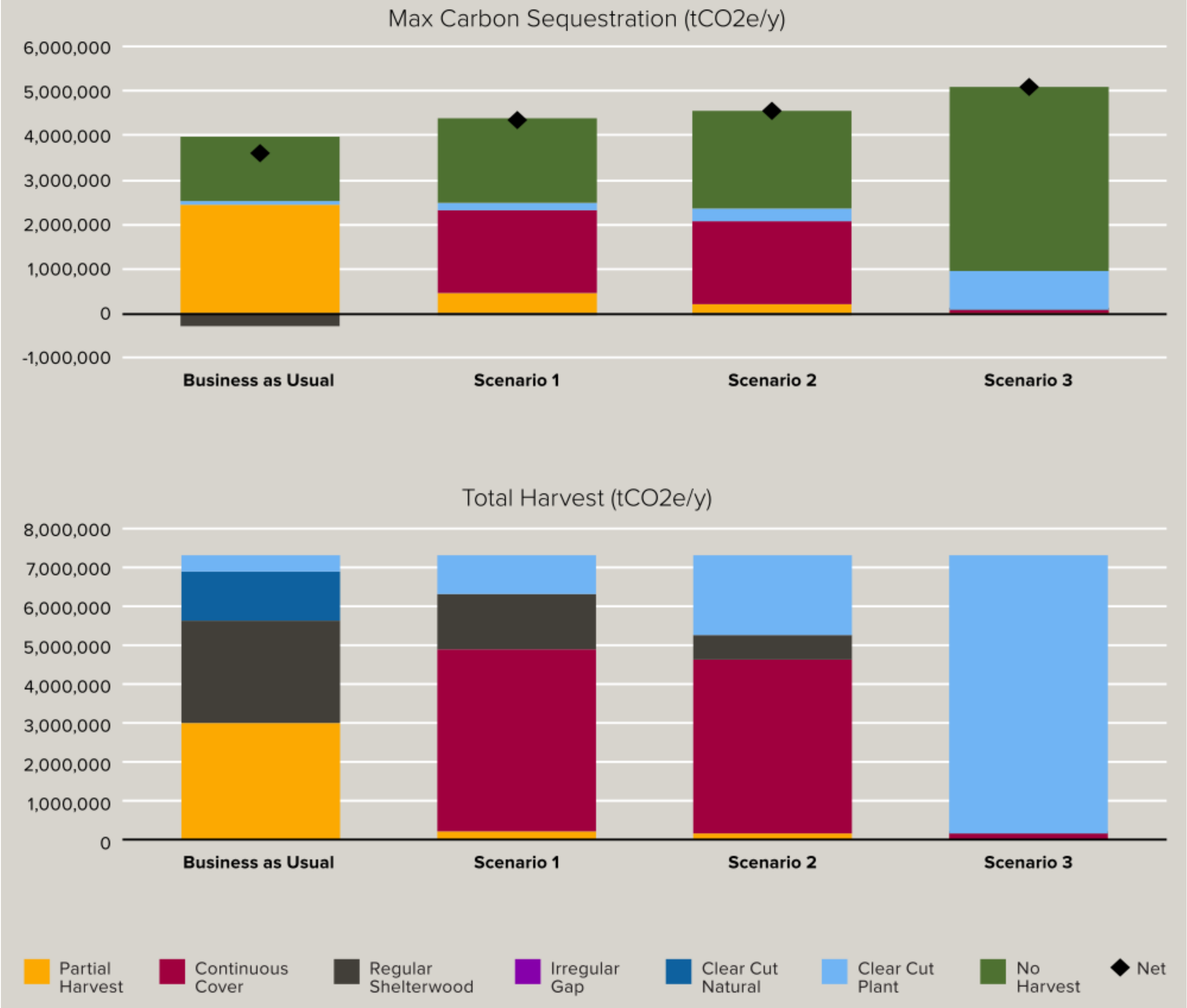




Example Application: Forest Carbon in Maine

Integrated LANDIS-II with economic optimization model to evaluate C and market impacts of 9 silvicultural practices

Can increase carbon sequestration up to 20% without reducing total harvest by changing management



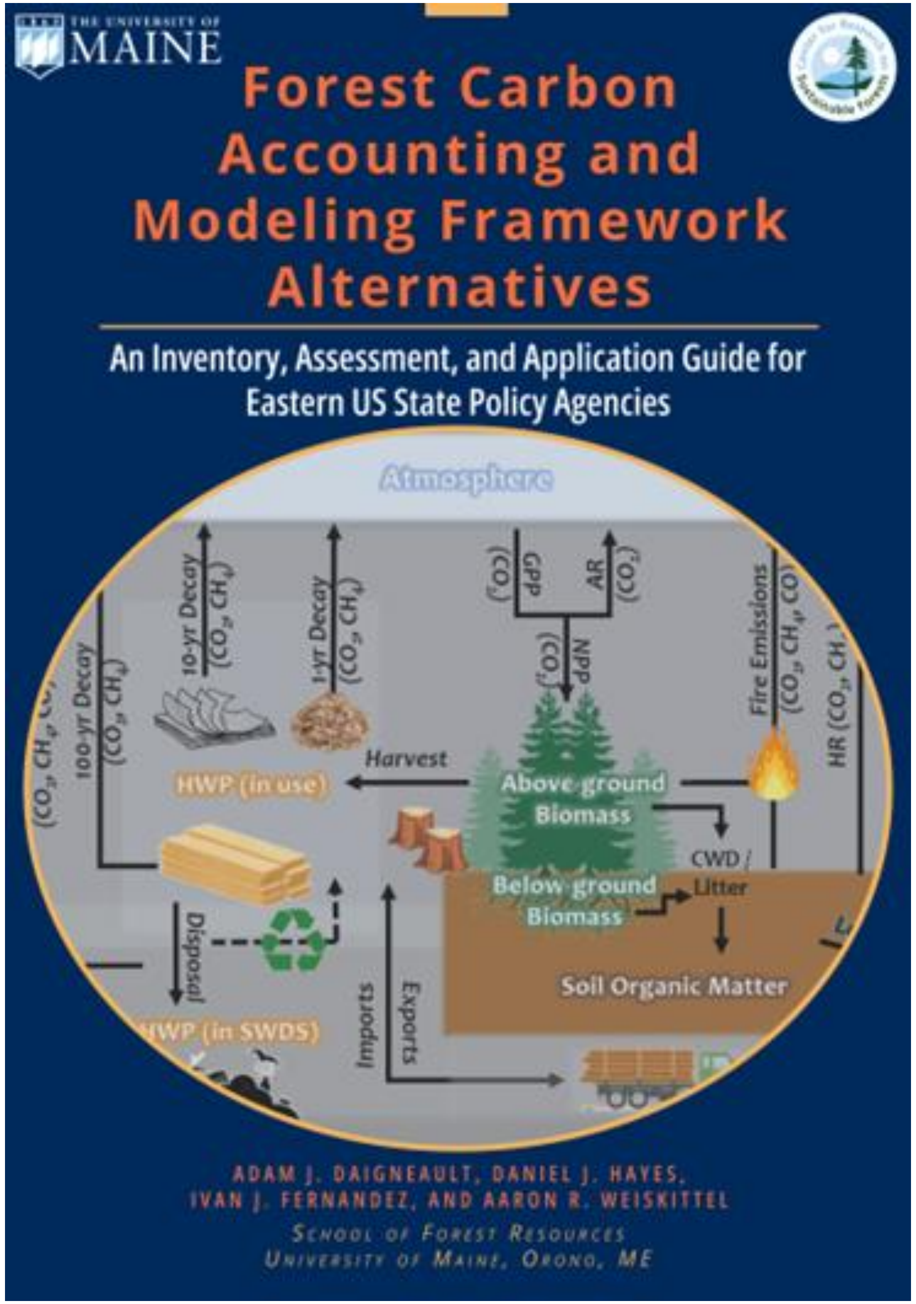
Want to know more about integrated applications of forest C models?

11/2/22 Webinar

2/7/24 Webinar

Summary

- Several model framework and methods to choose from
- Dozens of forest C models 'available'
- Models vary in usability, complexity, and analytical capability
- Ultimate choice of what model(s) to use will depend on:
  - Time and resources
  - Question(s) that are being asked
- May be advantageous to engage experts on development and application
- Our criteria based largely on expert input
- Scores and recommendations subject to revision with more info and experience

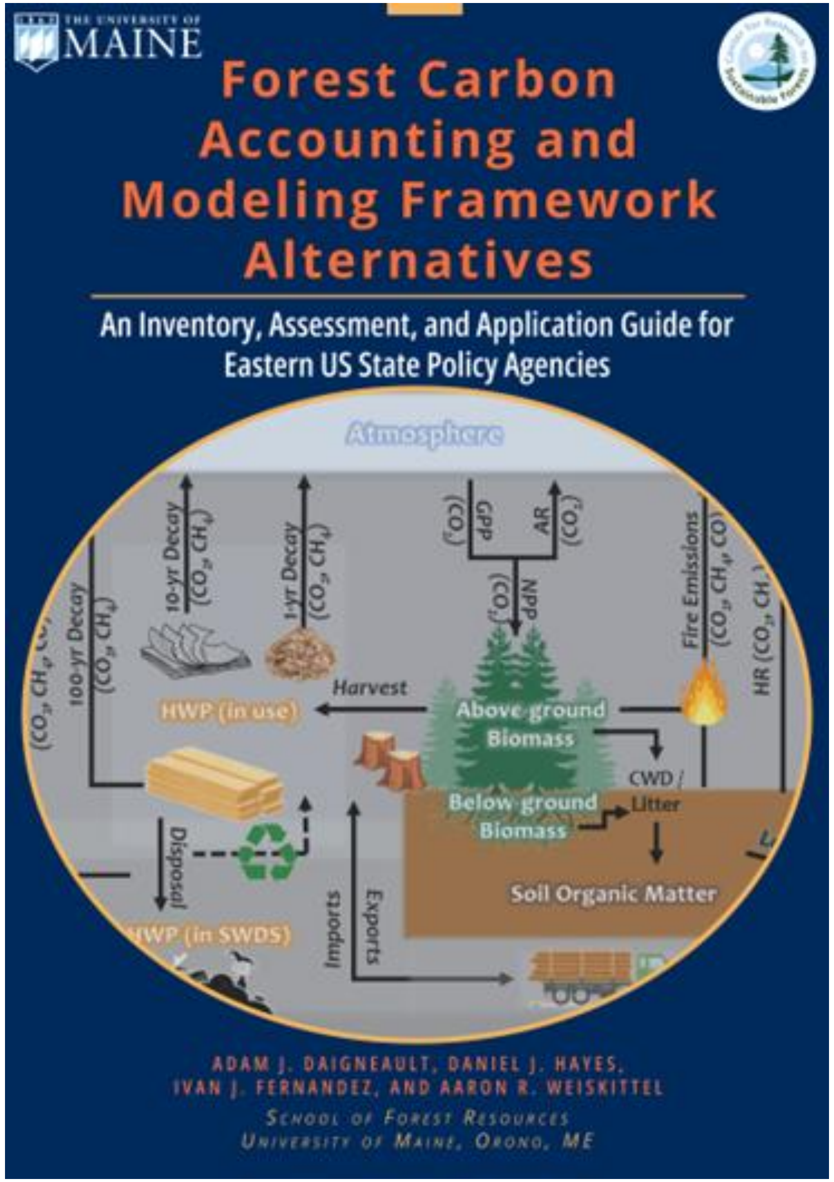


Want to learn more?

Daigneault, A., Hayes, D.J., Fernandez, I.J., & Weiskittel, A.R. 2022. "Forest Carbon Accounting and Modeling Framework Alternatives: An Inventory, Assessment, and Application Guide for Eastern US State Policy Agencies." Report prepared for USDA Forest Service

https://crsf.umaine.edu/wp-content/uploads/sites/214/2023/01/Daigneault-et-al-Eastern-Forest-C_Final.pdf

Report includes links to detailed model assessment tables.



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Contact Details

Dr. Daniel Hayes
Assoc Prof of Geospatial Analysis & Remote Sensing
Director, Barbara Wheatland Geospatial Analysis Laboratory
University of Maine
daniel.j.hayes@maine.edu

Dr. Adam Daigneault
E.L. Giddings Assoc Prof of Forest Policy and Economics
Assoc Director, Center for Research on Sustainable Forests
University of Maine
adam.daigneault@maine.edu