

Life-Cycle Assessment of Materials in Residential Construction: How Wood Products Stack Up

Consortium for Research on Renewable Industrial Materials (CORRIM)

Phase I Research Report

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Carbon Dynamics and Forest Performance Index

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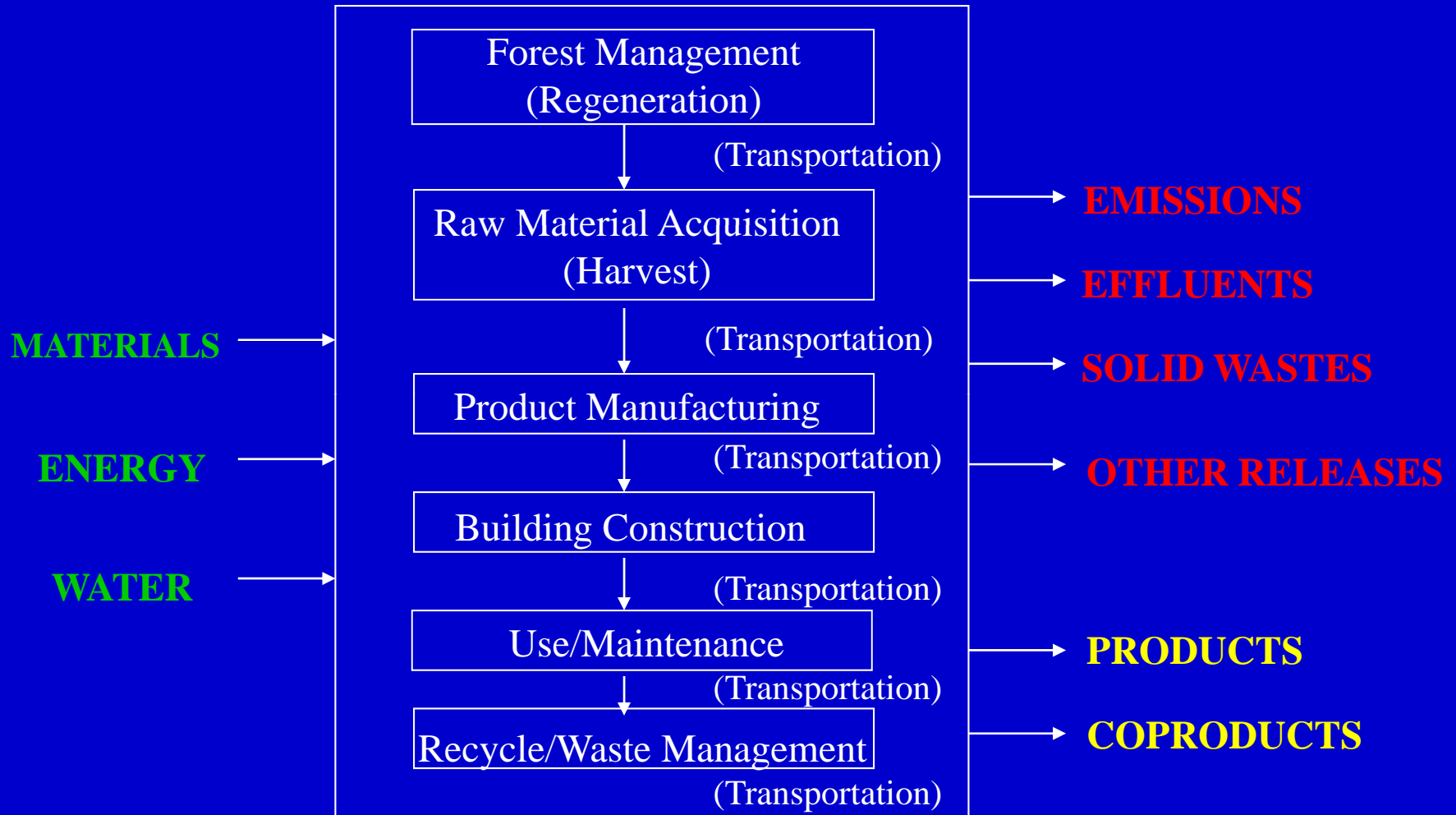
Purpose:

- To develop a database and models of environmental performance measures over the life-cycles of structural building materials:
 - from resource management & extraction, through product-manufacture and transportation,
 - construction of a building structure,
 - use and maintenance of the structure,
 - and ultimate disposal or recycling of the components.
- To examine a range of management, product, and process alternatives to identify strategies that can improve environmental performance.

Methodology

- Life Cycle Inventory (LCI) – environmental database
(collected mostly primary data for wood products)
- Life Cycle Analysis/Assessment (LCA) – risk from environmental burdens
(used existing intermediate risk models)
- Cost Benefit Analysis – analyze cost of making changes
(incorporate time and cost in tradeoff analysis)

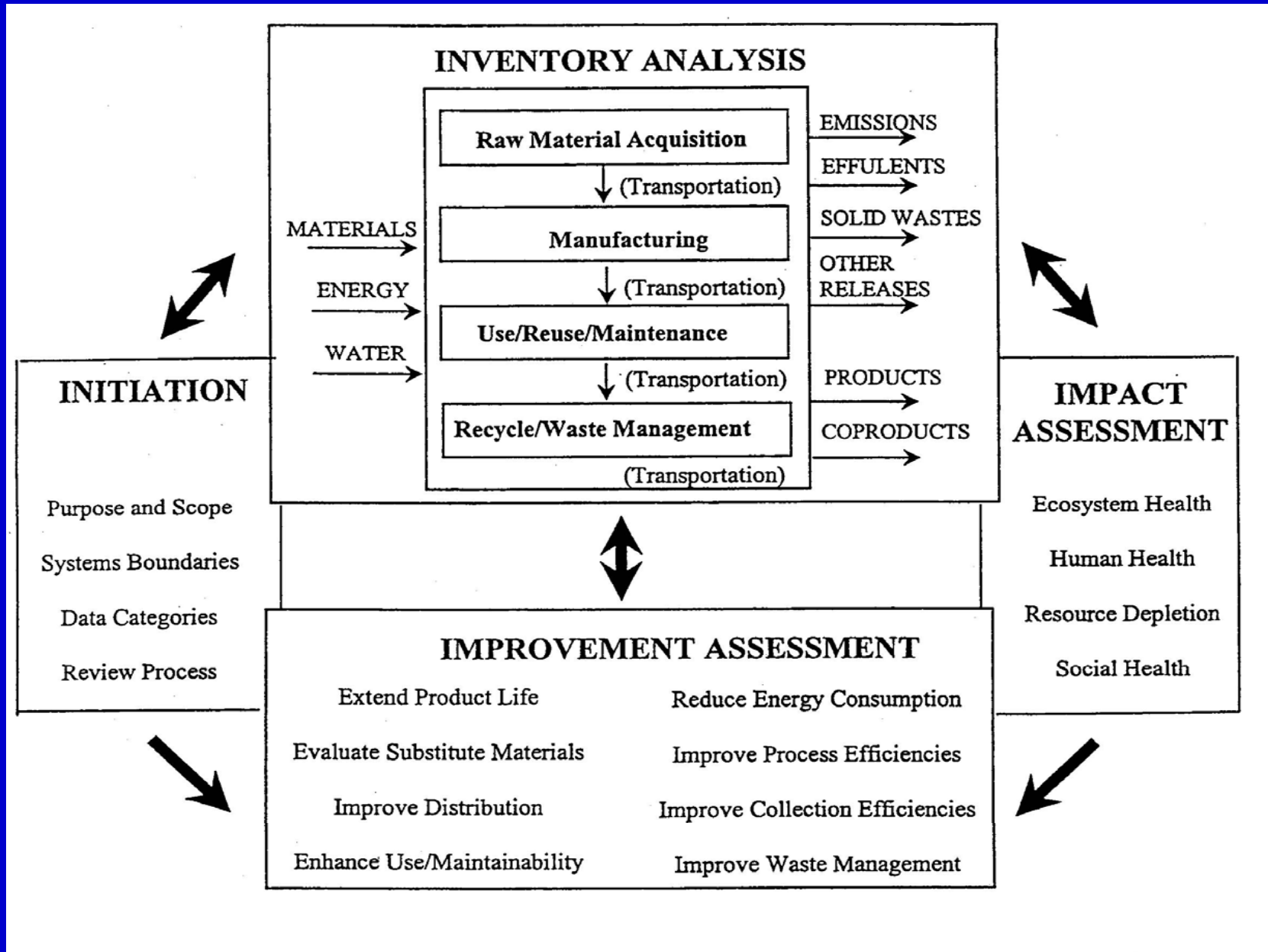
Life Cycle Inventory Analysis



Collected survey data (regional): Regeneration and forest management, Harvesting
Product Manufacturing (lumber, plywood, OSB, other)
Building: designed (to code), construction, occupation and use through final
demolition.

General Flows in a “Cradle-to Grave” LCA System

(Franklin Associates, 1990)



Boundaries:

- Regeneration to waste disposal
- Primary source for wood data
- Secondary source for non wood data (ATHENA)
- Regional product detail,
- Multi-material detail

Environmental
Performance:

- Air, water, toxic substances, energy, carbon, waste,
 - mid-point parameters for human health risk
- Biodiversity/habitat
 - end-point coarse filter indicators for ecosystems

Protocol:

- Strategic Research Plan (1998)
 - Study Guideline (2000) – ISO consistent

Phase I of Research Plan

“Cradle”

Forest Resources: NW and SE (25-100+ years)

Harvesting (< 1 Year)

- **logs** NW and SE

“Gate
to
Gate”

Processing (< 1 Year)

- lumber SE and NW (green and dry)

- plywood NW and SE

- OSB SE

- Glulam, LVL, I-Joists

Construction (< 1 Year)

- wood and steel Minneapolis (cold)

- wood and concrete Atlanta (warm)

“Grave”

Use and Maintenance (40 – 100+ years)

Disposal (< 1 Year)

Final Report

Executive Summary

Introduction, Framework, Integrated Results

Modules: 16 Stand alone reports

LCIs for forest resources (logs) in NW and SE

LCIs for 7 wood products in each of two regions NW, SE

LCA for 2 constructed houses with wood framing and 2 non-wood alternatives plus wall and floor assemblies (and a design module for bill of materials)

LCIs for 3 post construction housing stages (use, maintenance, disposal)

LCI for forest environmental performance

Dynamics of carbon pools for the forest, products & markets

Product LCI'S for lumber, plywood, OSB, LVL, glulam, I-joists, trusses

- Unit process descriptions (saw, dry, plane etc.)
- Mill surveys at unit process level
- Non-wood inputs (energy by source, raw materials)
- Emissions and solid waste outputs
- Yields, flows (co-products) and mass balances
- Unit factor estimates (raw materials, air, water, and solid emissions, energy, carbon) before and after impacts from purchased energy and transportation

Life-Cycle Inventory results for 1.0 MSF 3/8-in. basis plywood production from the PNW region. Results include plywood production only; no emissions are included for the production and use of electricity, fuel, and phenol-formaldehyde resin.

INPUTS			OUTPUTS		
Materials	Units	Per MSF 3/8-in. basis	Materials	Units	Per MSF 3/8-in. basis
Wood resin			Bark		
Roundwood (log)	ft.3	6.56E+01	Bark waste	lb.	1.31E+01
	lb.	1.89E+03	Bark ash	lb.	7.75E+00
Phenol-formaldehyde	lb.	1.59E+01	Total	lb.	2.09E+01
Extender and fillers ^a	lb.	8.90E+00	Products		
Catalyst ^a	lb.	1.11E+00	Plywood	lb.	9.91E+02
Soda ash ^a	lb.	3.30E-01	Co-products		
Bark ^b	lb.	1.98E+02	Wood chips	lb.	4.25E+02
Dry veneer	lb.	6.81E+00	Peeler core	lb.	4.62E+01
Green veneer	lb.	1.51E+01	Green clippings	lb.	3.10E+01
Electrical energy			Veneer downfall	lb.	3.44E+00
Electricity	kWh	1.39E+02	Panel trim	lb.	1.07E+02
Fuel for energy			Sawdust	lb.	9.63E+00
Hog fuel (produced) ^b	lb.	3.83E+02	Solid dry veneer	lb.	6.68E+01
Hog fuel (purchased) ^b	lb.	3.40E+01	Total	lb.	6.89E+02
Wood waste	lb.	5.00E-01	Air emissions		
Liquid propane gas	gal.	3.59E-01	Acetaldehyde	lb.	1.12E-02
Natural gas	ft.3	1.63E+02	Acetone	lb.	4.80E-03
Diesel	gal.	3.95E-01	Acrolein	lb.	4.95E-07
			Benzene	lb.	4.77E-04
			CO	lb.	1.91E+00
			CO 2 fossil	lb.	2.78E+02
			CO 2 non-fossil	lb.	2.78E+02
			Dust (PM10)	lb.	2.08E-01
			Formaldehyde	lb.	1.80E-02
			Methanol	lb.	1.28E-01
			NO x	lb.	2.34E-01
			Organic substances	lb.	2.20E-02
			Particulates	lb.	3.47E-01
			Phenol	lb.	8.27E-03
			SO 2	lb.	7.74E-04
			SO x	lb.	1.01E-01
			VOC	lb.	6.26E-01

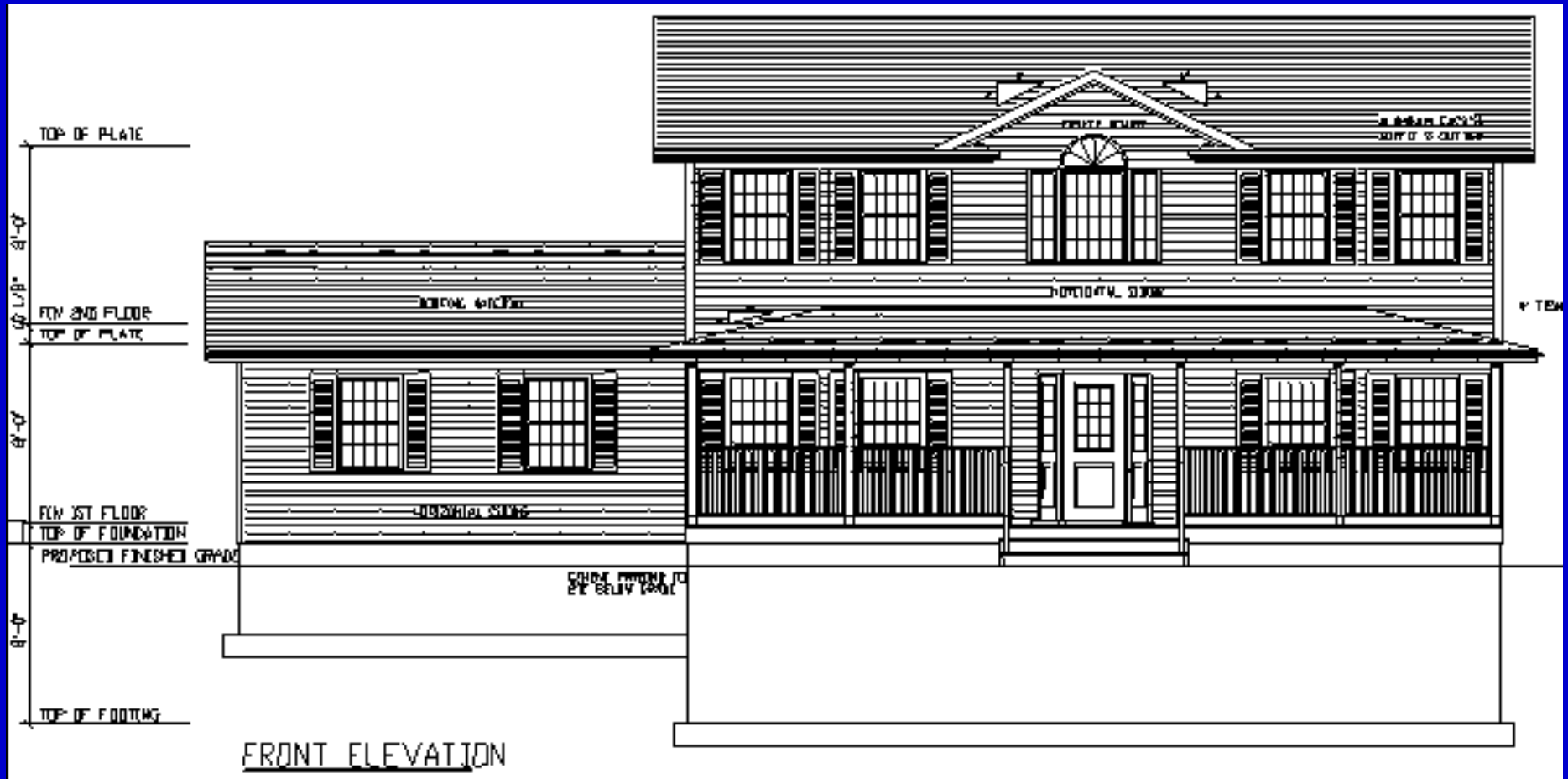
a These materials were excluded based on the 2% rule.
b Bark and hogged fuel are wet weights whereas all other wood materials are oven-dry weights; bark weight is included in the "hog fuel (produced)" weight.

Design representative of
residential shells for:

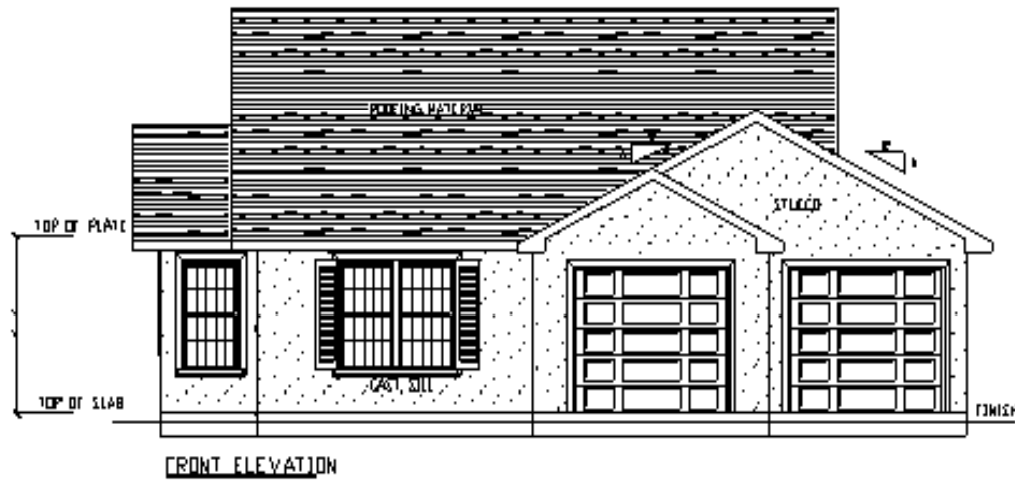
Minneapolis (cold climate) of
wood & steel,

Atlanta (warm climate) of
wood & concrete.

Minneapolis House – Front Elevation



Atlanta House Elevations



Design Differences: Minneapolis

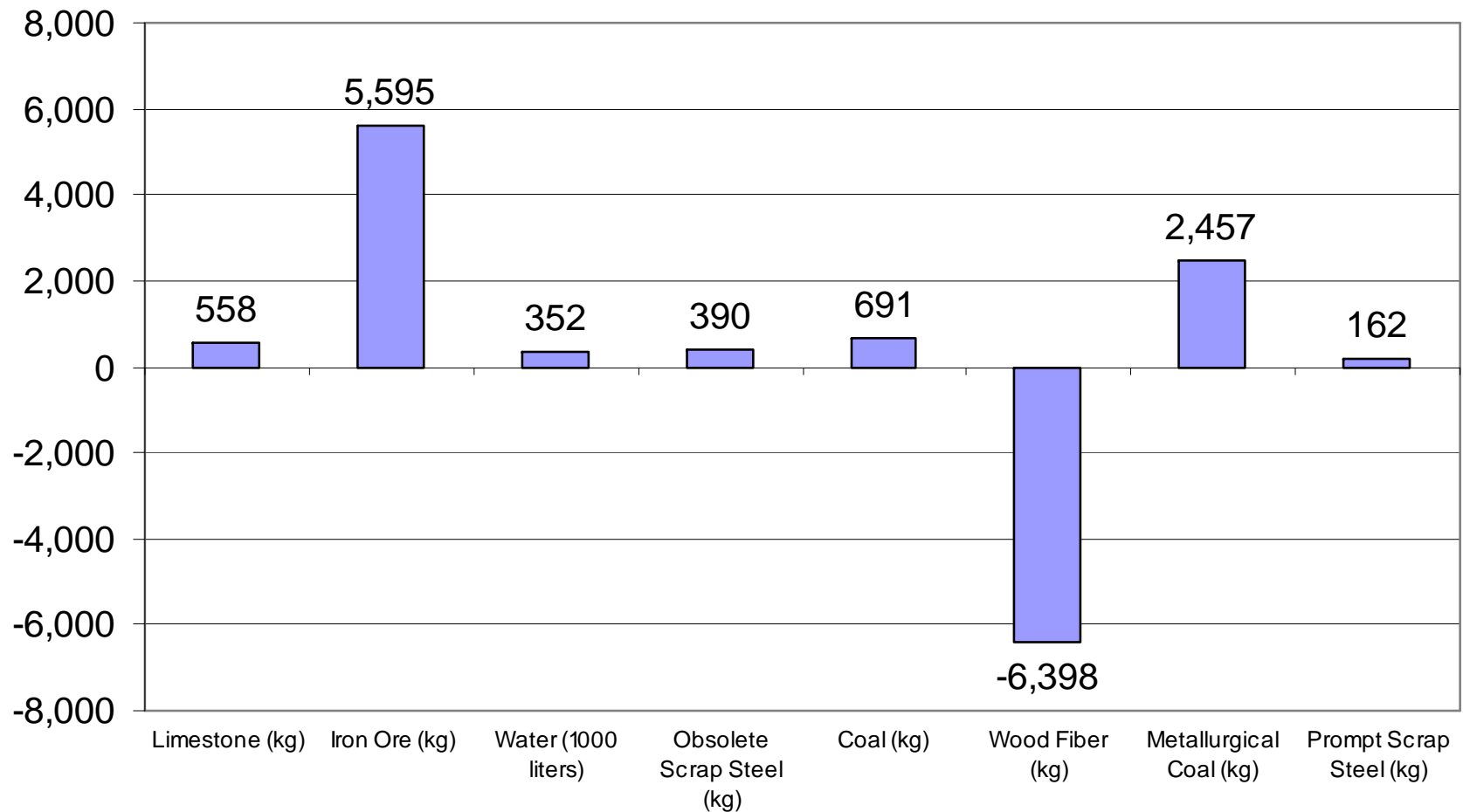
Full Basement 2062 sq.ft. 2 story

Characteristic	Wood Design	Steel Design
1 st and 2 nd Floors	Engineered wood "I" joists @ 16" (400mm) o/c & 19/32" (15mm) plywood decking	Steel 18 ga. "C" joist @ 12" (300mm) o/c & 19/32" (15mm) plywood decking
Above grade exterior walls	2" x 6" wood studs @ 16" (400mm) o/c, #15 organic felt, OSB sheathing, R19 fiberglass batt insulation, 6mil polyethylene vapor barrier, 12mm gypsum board, vinyl siding	1.5" x 3.63" Steel 20 ga. "C" studs @ 16" (400mm) o/c, #15 organic felt, OSB sheathing, R13 fiberglass batt insulation, 1.5" EPS insulation, 6mil polyethylene vapor barrier, 12mm gypsum board, vinyl siding
Below grade exterior walls	2"x4" wood studs @ 24" (600mm) o/c, R13 fiberglass batt insulation, poly vapor barrier, 12mm gypsum board	1.5" x 3.63" Steel 25 ga. "C" studs @ 24" (600mm) o/c, R13 fiberglass batt insulation, poly vapor barrier, 12mm gypsum board
Partition walls	2"x4" wood studs @ 16" (400mm) o/c, 12mm gypsum board two sides	1.5" x 3.63" Steel 25 ga. "C" studs @ 16" (400mm) o/c, 12mm gypsum board two sides

Design Differences: Minneapolis

Steel minus Wood

Extraction (primary materials in kg)



Design Differences: Atlanta

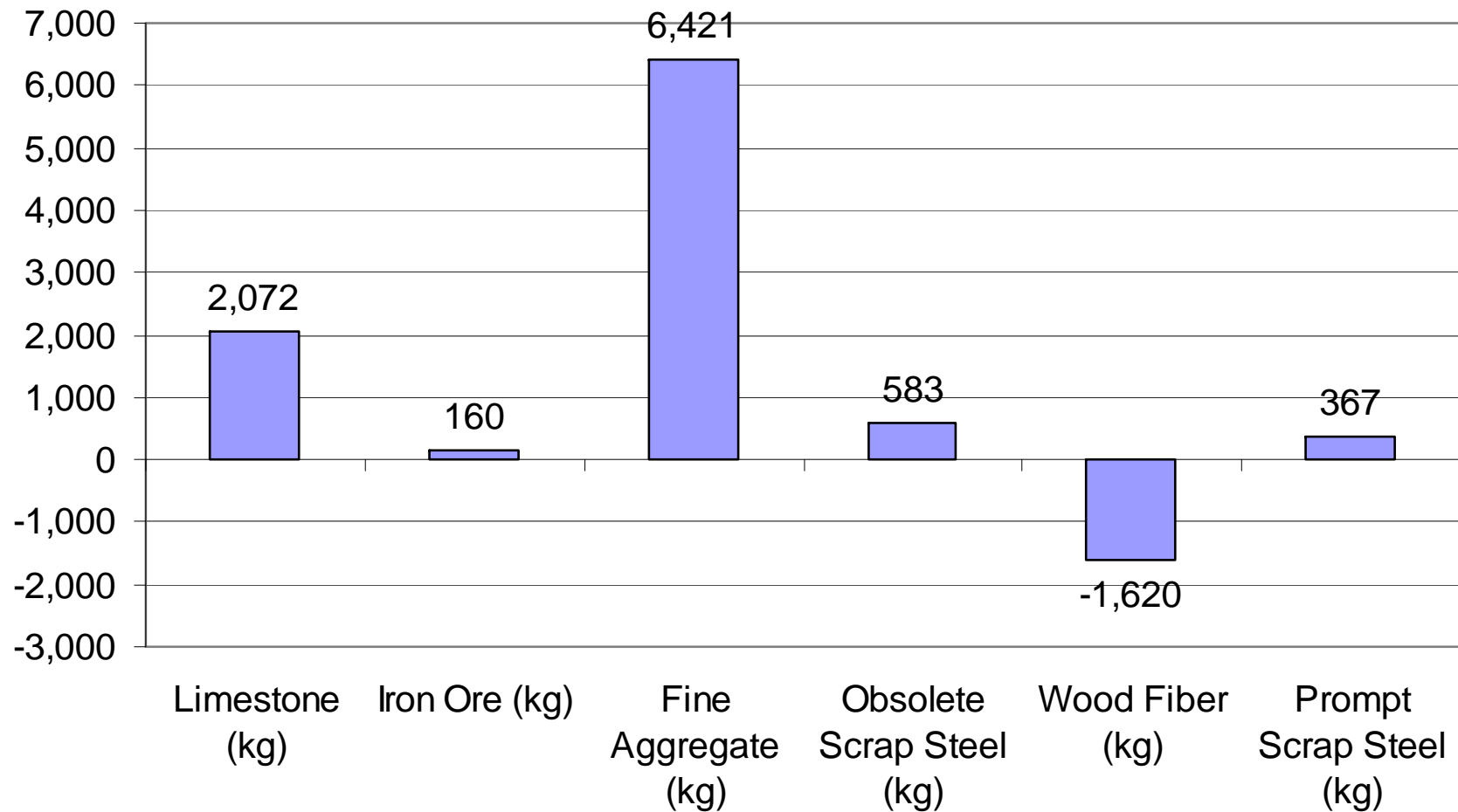
2153 sq.ft. 1 story On-Slab

Characteristic	Wood Design	Concrete Design
Single-family dwelling type	1 story bungalow slab-on-grade	
Floor area	2153 sq. ft. (200 sq.m)	
Structure & Envelope		
Foundation (footing and slab)	3000psi (20 Mpa) concrete	
Foundation walls	None	
Main floor	100mm reinforced Slab-on-grade on footings	
Exterior walls	2"x4" wood studs @ 16" (400mm) o/c, #15 organic felt, OSB sheathing, R13 fiberglass batt insulation, 6mil poly vapor barrier, 12mm gypsum board, vinyl siding	Concrete Block furred out with 2x4 wood studs 24"(600mm) o/c, R13 fiberglass batt insulation, 6mil poly vapor barrier, 12mm gypsum board, two-coat stucco finish
Window system	PVC frame, operable, double glazed Low "E" Argon filled	
Partition walls	2"x4" wood studs @ 16" (400mm) o/c, 12mm gypsum board two-sides	
Roof	Light Frame Wood Trusses with OSB sheathing, R30 blown cellulose insulation, 6mil poly vapor barrier, 16mm gypsum board with 25 yr durability asphalt shingles over #15 organic felt building paper.	

Design Differences: Atlanta

Concrete minus Wood

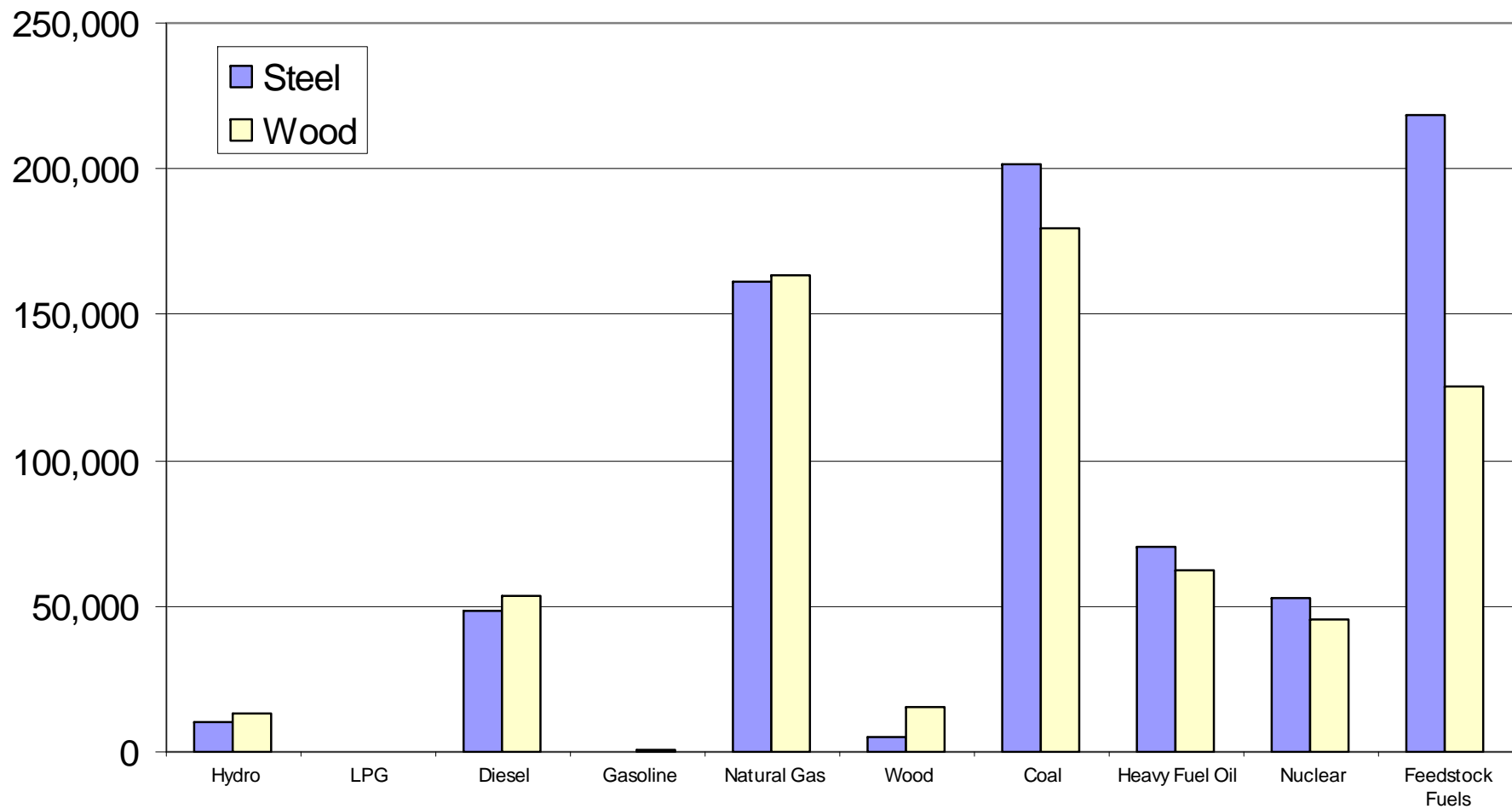
Extraction (primary materials in kg)



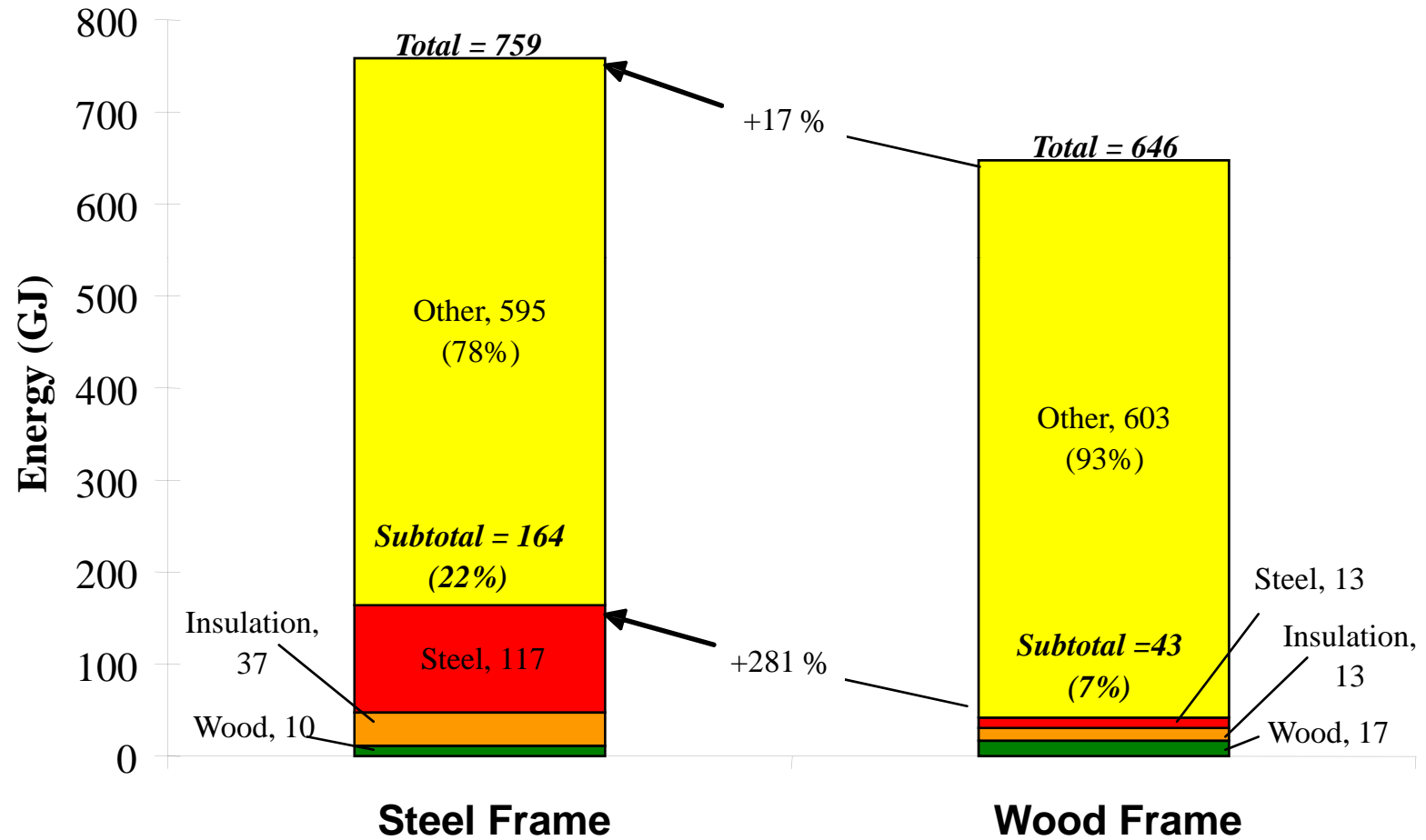
Energy Consumption: Minneapolis

(ten different energy sources)

Total Energy (MJ)



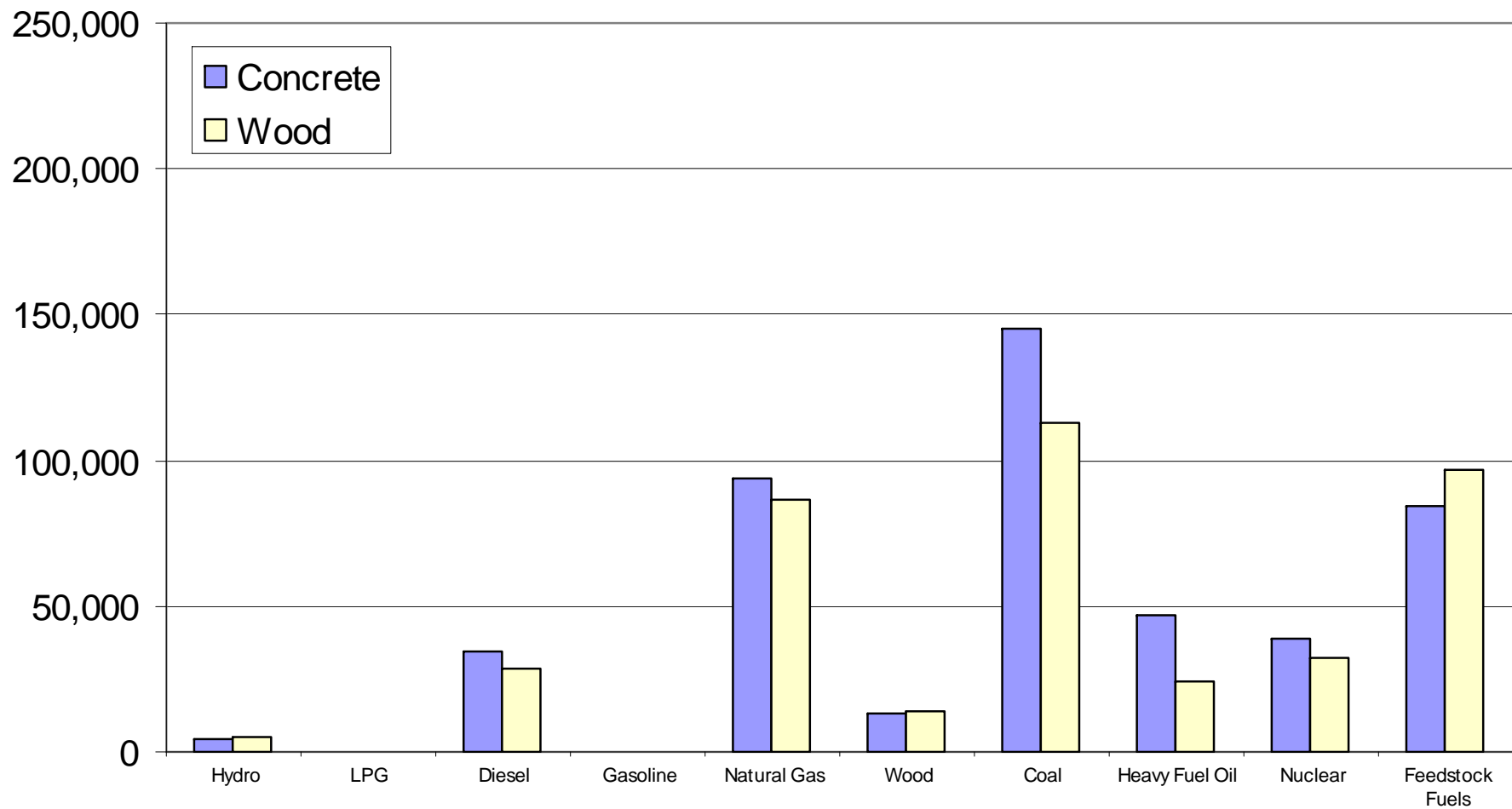
Energy in Products Being Substituted - Minneapolis



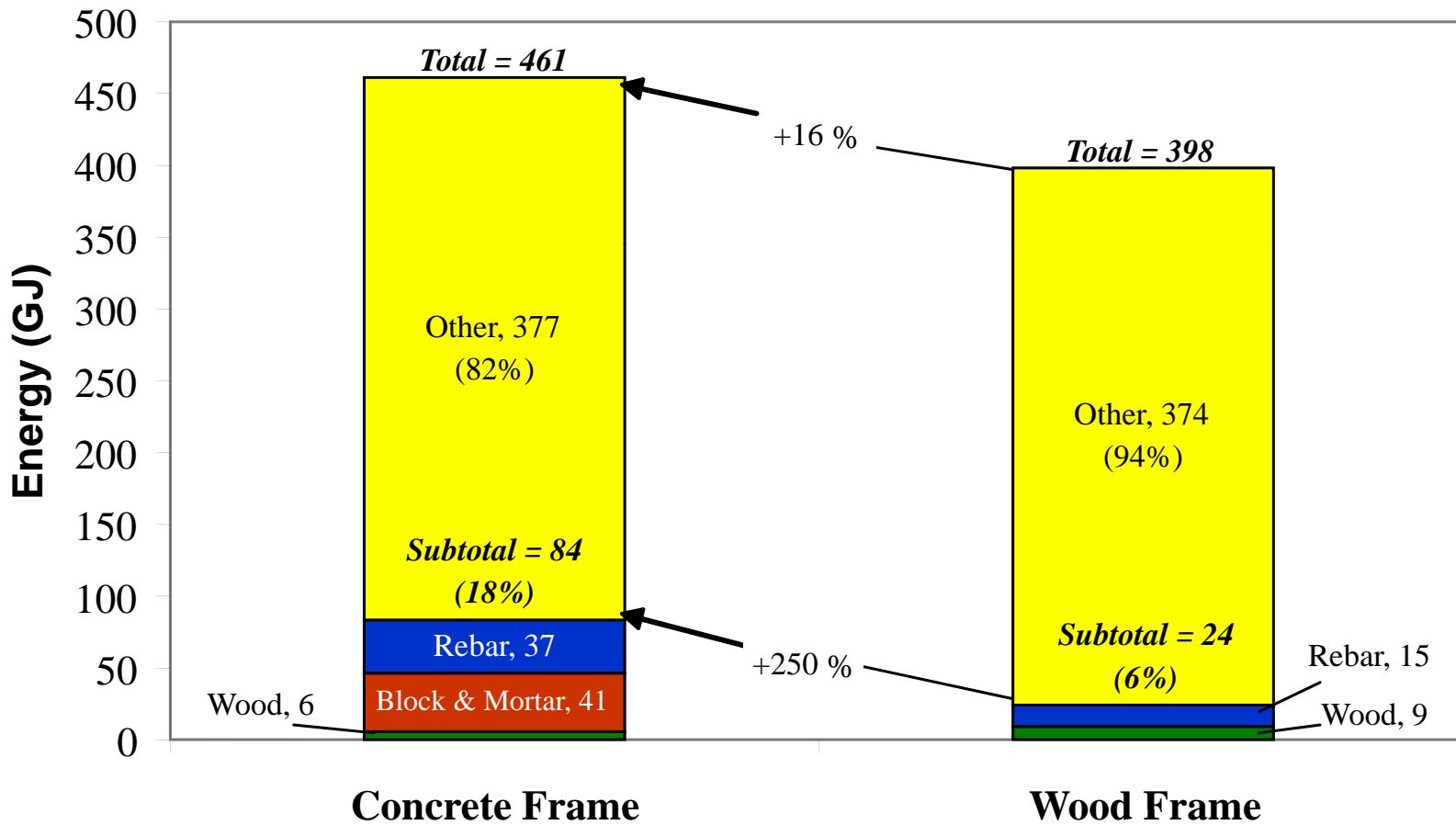
Energy Consumption: Atlanta

(ten different energy sources)

Total Energy (MJ)



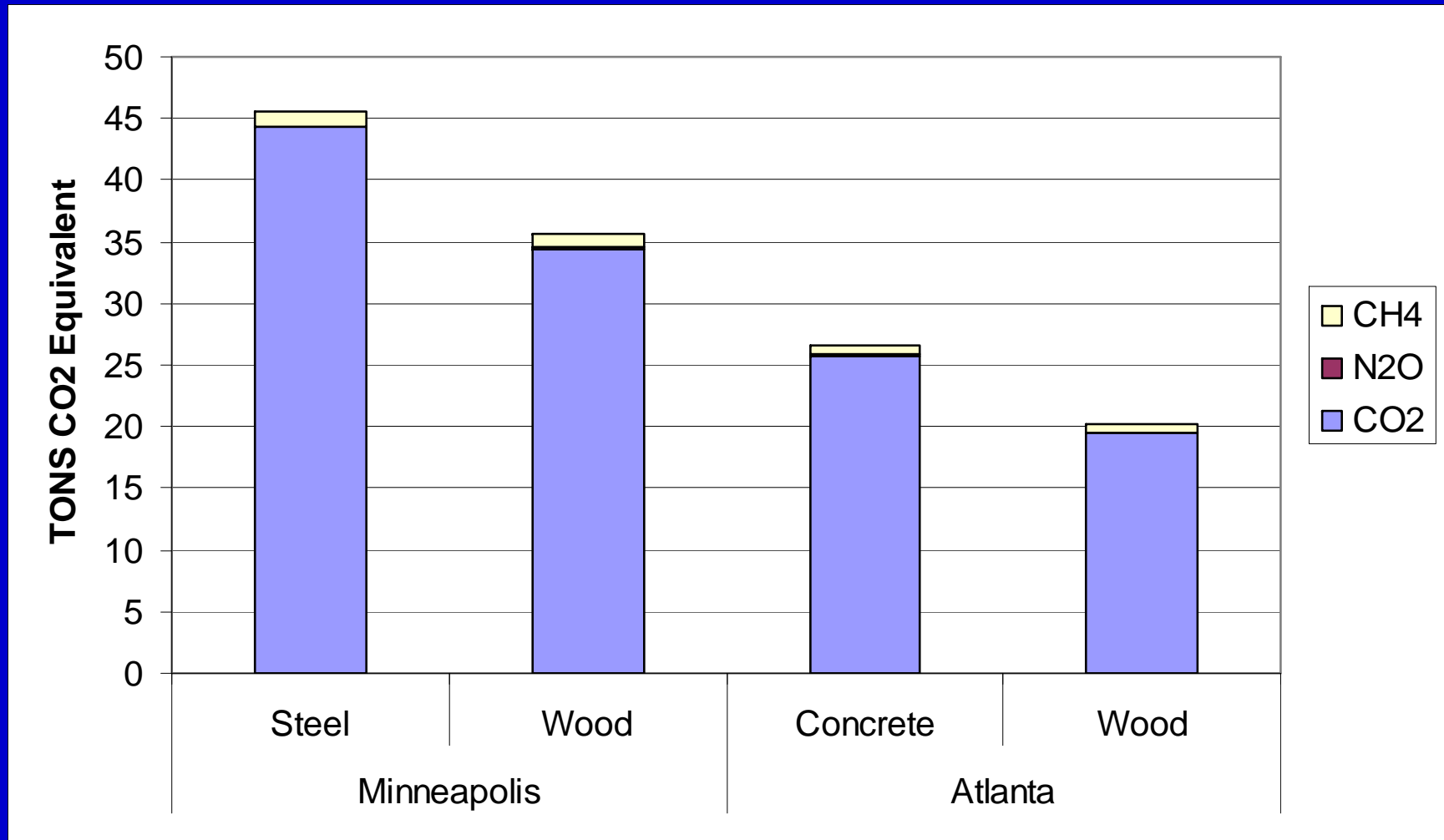
Energy in Products Being Substituted - Atlanta



Global Warming Potential Index

CO₂ Equivalence Effects:
(CO₂, N₂O, CH₄)

GWP: Minneapolis and Atlanta



Solid Waste (kg) by Stage of Processing

	Minneapolis			Atlanta		
	Wood	Steel		Wood	Concrete	
Manufacturing (5)	6,605	7,763		5,317	5,865	
Construction (6)	7,162	5,879		2,127	5,403	
<hr/>						
TOTAL	13,767	13,642	-1%	7,444	11,268	+51%

Volume may be as good if not a better indicator of the problem

Air and Water Pollution Indices

*Better Intermediate Risk Measures Than
Aggregate Mass.*

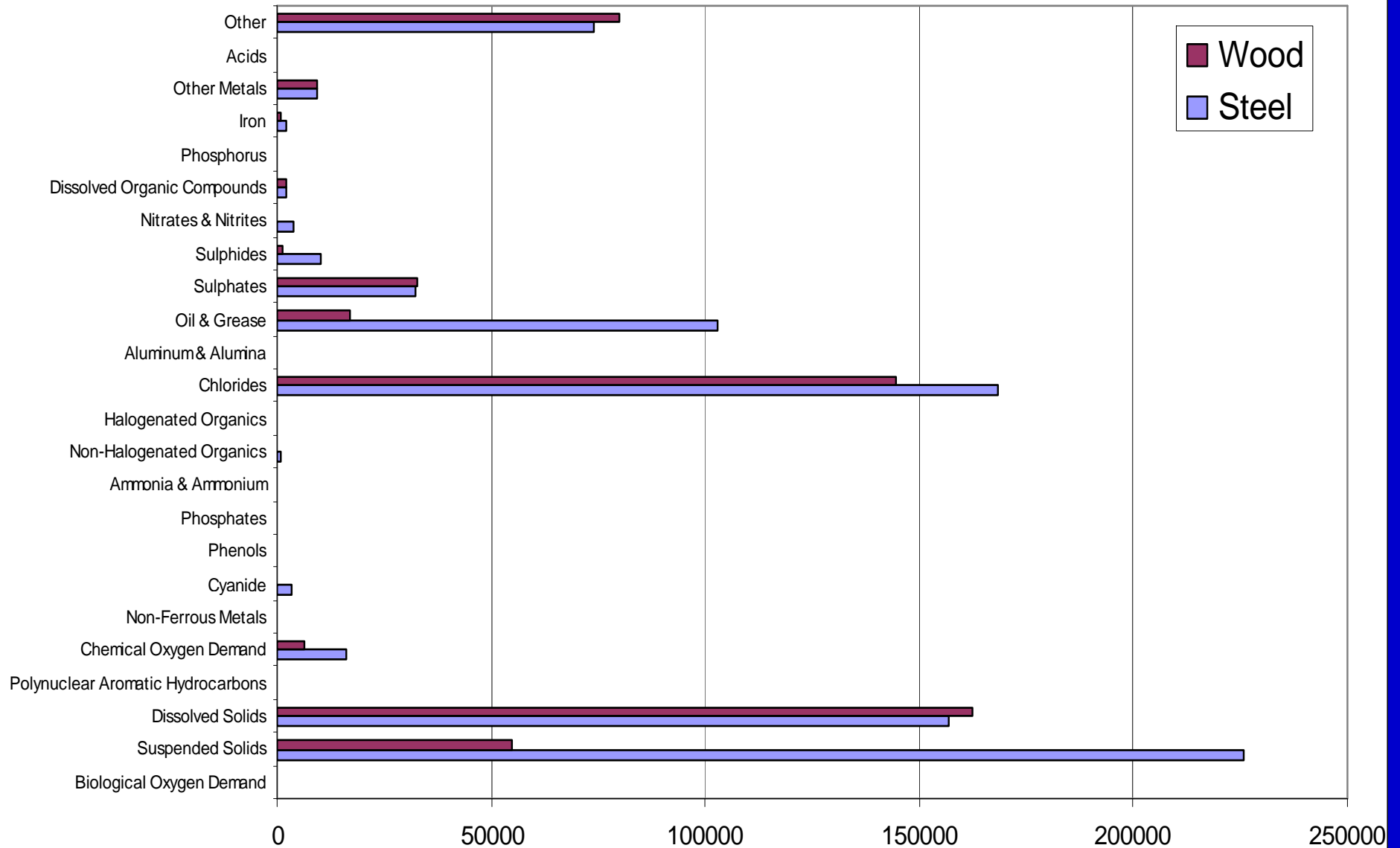
Emissions to Water (kg) by Stage of Processing

MANUFACTURING *(23 substances)*

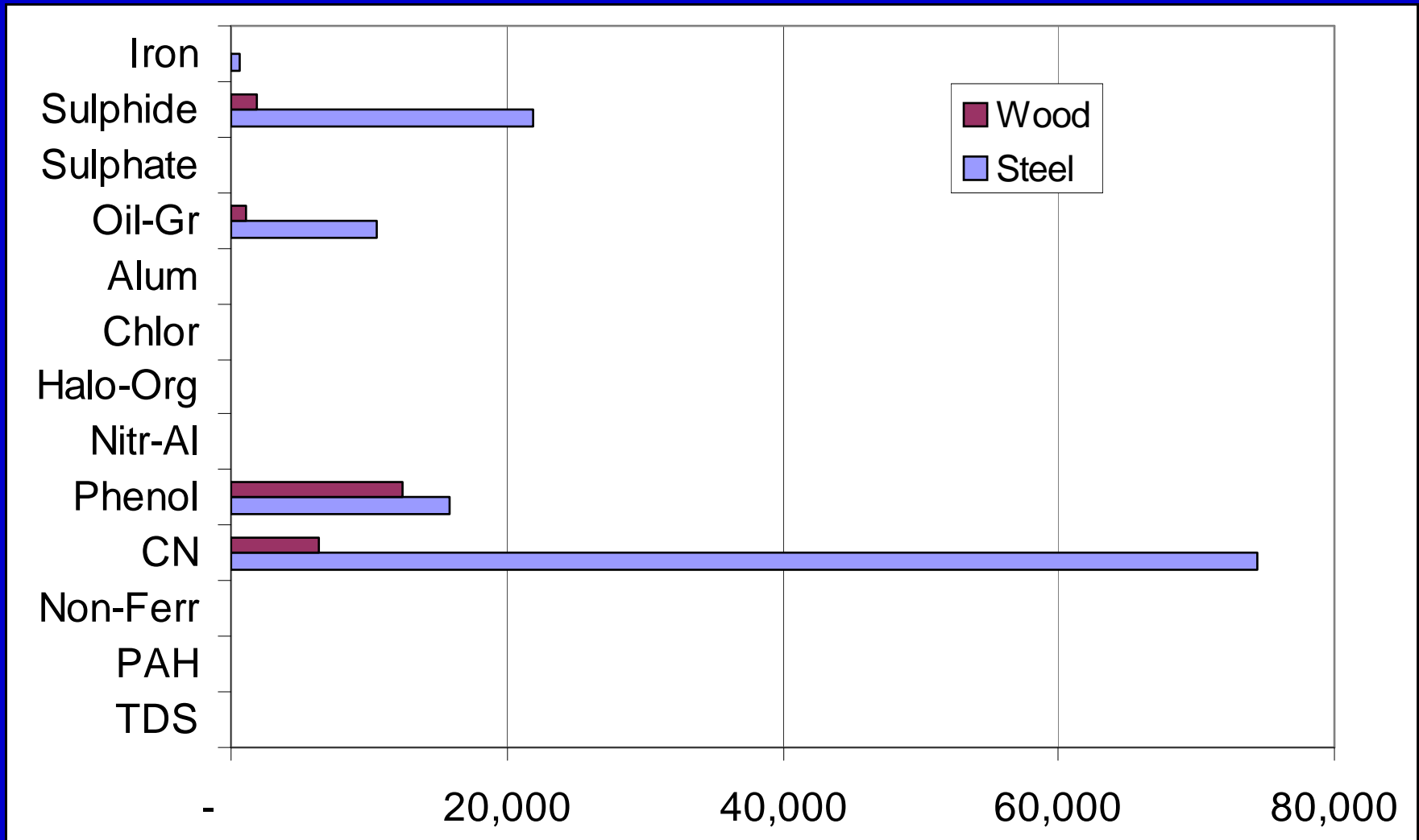
	Minneapolis		Atlanta	
	Steel	Wood	Concrete	Wood
TOTAL	809	514	299	288

Totals are not a sufficient indicator of risk

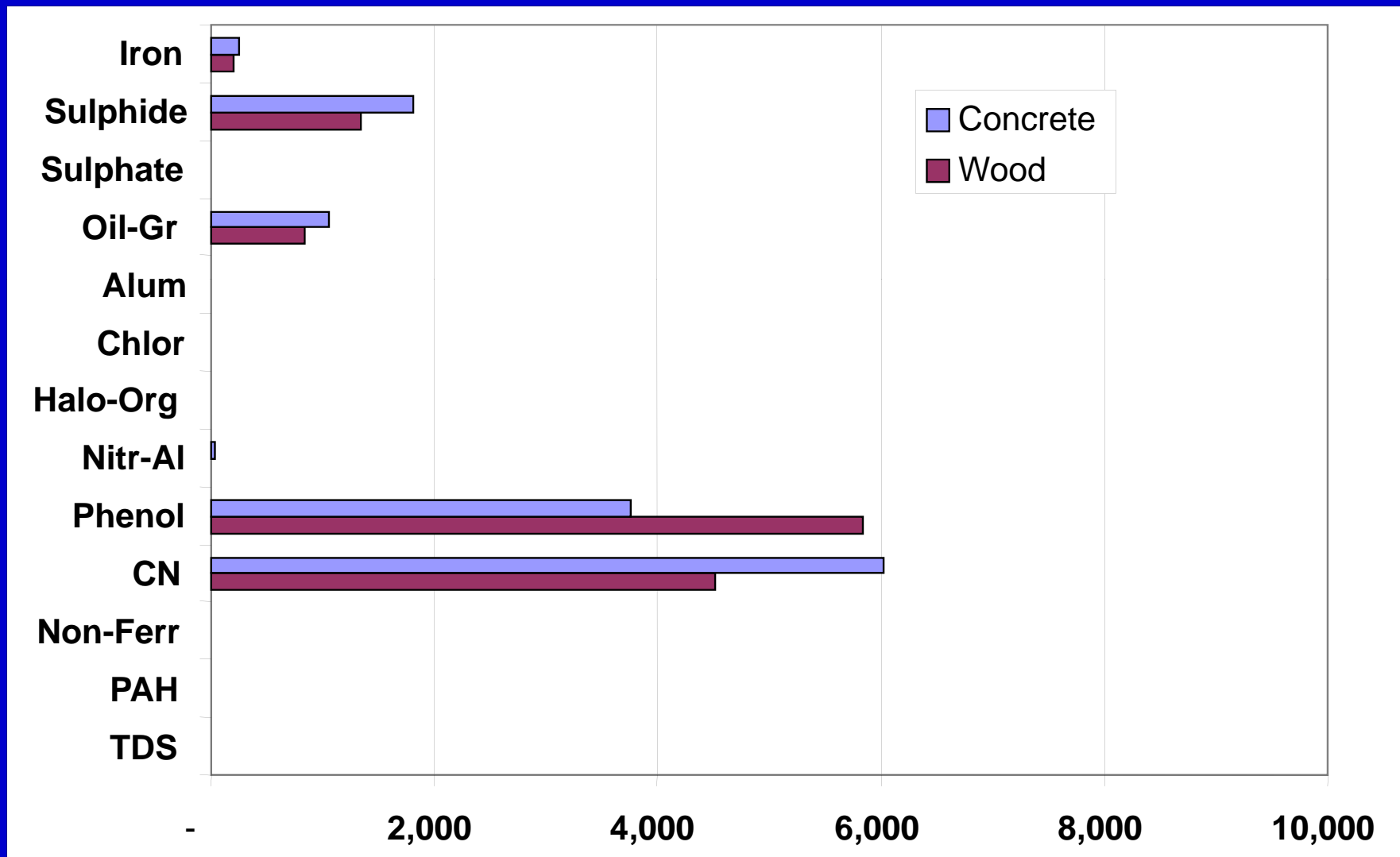
Emissions to Water: Minneapolis



Emissions to Water: Minneapolis On Equal Health Risk Basis



Emissions to Water: Atlanta On Equal Health Risk Basis



Emissions to Air (kg) by Stage of Processing (excluding CO₂)

	Minneapolis		Atlanta	
	Steel	Wood	Concrete	Wood
Manufacturing (<i>15</i>)	841.5	683.3	449.7	398.3
<small>(# in italic = # of substances in tables)</small>				
Construction (<i>15</i>)	21.9	23.2	24.2	17.9
TOTAL*	864.6	707.7	474.8	417.0

* Includes transportation

Totals are not a sufficient indicator of risk

Summary Performance Indices Minneapolis Building

Minneapolis design	Wood	Steel	Difference	Other Design vs. Wood (% Change)
Embodied Energy (GJ)	651	764	113	17%
Global Warming Potential (CO ₂ kg)	37,047	46,826	9,779	26%
Air Emission Index (index scale)	8,566	9,729	1,163	14%
Water Emission Index (index scale)	17	70	53	312%
Solid Waste (total kg)	13,766	13,641	-125	-1%

Summary Performance Indices Atlanta Building

Atlanta design	Wood	Concrete	Difference	Other Design vs. Wood (% Change)
Embodied Energy (GJ)	398	461	63	16%
Global Warming Potential (CO ₂ kg)	21,367	28,004	6,637	31%
Air Emission Index (index scale)	4,893	6,007	1,114	23%
Water Emission Index (index scale)	7	7	0	0%
Solid Waste (total kg)	7,442	11,269	3,827	51%

Environmental Performance Indices for Above Grade Wall Designs

Minneapolis Design	Wood	Steel	Difference	Other Design vs. Wood (% Change)
Embodied Energy (GJ)	250	296	46	18%
Global Warming Potential (CO ₂ , kg)	13,009	17,262	4,253	33%
Air Emission Index (index scale)	3,820	4,222	402	11%
Water Emission Index (index scale)	3	29	26	867%
Solid Waste (total kg)	3,496	3,181	-315	-9%

Environmental Performance Indices for Above Grade Wall Designs

Atlanta Design	Wood	Concrete	Difference	Other Design vs. Wood (% Change)
Embodied Energy (GJ)	168	231	63	38%
Global Warming Potential (CO ₂ kg)	8,345	14,982	6,637	80%
Air Emission Index (index scale)	2,313	3,373	1,060	46%
Water Emission Index (index scale)	2	2	0	0%
Solid Waste (total kg)	2,325	6,152	3,827	164%

Environmental Performance Indices for Floor & Roof Assemblies

Minneapolis design	Wood	Steel	Difference	Other Design vs. Wood (% Change)
Embodied Energy (GJ)	109	182	73	67%
Global Warming Potential (CO ₂ kg)	3,763	9,650	5,914	157%
Air Emission Index (index scale)	981	1,813	832	85%
Water Emission Index (index scale)	17	70	53	312%
Solid Waste (total kg)	13,766	13,641	-125	-1%

Energy Used in Representative Building Life Cycle Stages

	Minneapolis House		Atlanta House	
	Wood	Steel	Wood	Concrete
Energy in the Structure (GJ)	646	759	395	456
Energy from Maintenance (GJ)	73	73	110	110
Energy for Demolition (GJ)	7	7	7	9
Energy Subtotal (GJ)	727	840	512	573
<i>House Cost</i>	<i>\$168,000</i>	<i>\$168,000</i>	<i>\$135,000</i>	<i>\$135,000</i>
<i>Construction Cost</i>	<i>\$92,000</i>	<i>\$92,000</i>	<i>\$74,000</i>	<i>\$74,000</i>
Energy Use				
Heat & Cool (GJ) (75 yrs)	7800	7800	4575	4575
<i>Cost/yr heat & cool</i>	<i>\$692</i>	<i>\$692</i>	<i>\$491</i>	<i>\$491</i>
<i>Present Value Cost (75 years @ 5%)</i>	<i>\$13,490</i>	<i>\$13,490</i>	<i>\$9565</i>	<i>\$9565</i>
% of Construction \$	14.7	14.7	12.9	12.9

Carbon Emissions in Representative Building Life Cycle Stages

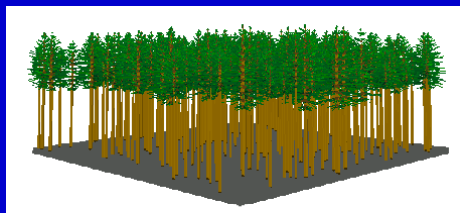
CO ₂ Metric Tons	Minneapolis House		Atlanta House	
	Wood	Steel	Wood	Concrete
Emissions in Mfg Construction & Demo	37.1	46.8	21.4	28.0
Emissions from Biofuel	3.6	2.6	3.4	2.7
Emissions from Maintenance	3.4	3.4	4.1	4.1
Emissions from Heating & Cooling	390	390	232	232
<i>Subtotal of Sources</i>	<i>434</i>	<i>443</i>	<i>261</i>	<i>267</i>
Forest Sequestration	(467)	(246)	(103)	(85)
Wood product Storage	(22.4)	(11.8)	(17.1)	(14.1)
<i>Subtotal of Sinks and Stores</i>	<i>(489)</i>	<i>(258)</i>	<i>(121)</i>	<i>(100)</i>
Net emissions	(55)	185	140	167

Carbon Dynamics vs Steady State

- LCI provides a cross sectional profile of all processes -- a steady state analysis
- Tracking carbon pools over time offers a dynamic alternative for a more financial cost/benefit perspective

Silvicultural Pathways are Designed and Simulated

1999



NO ACTION

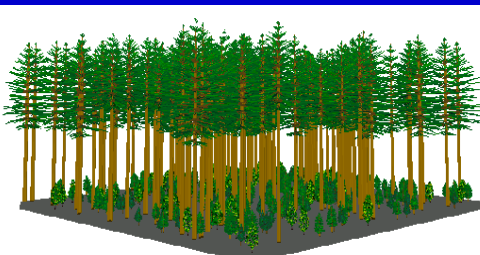
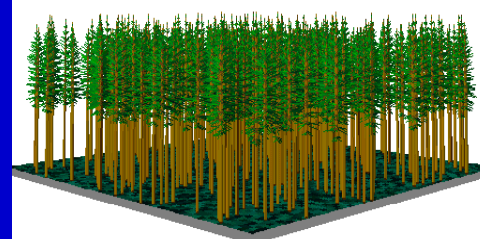
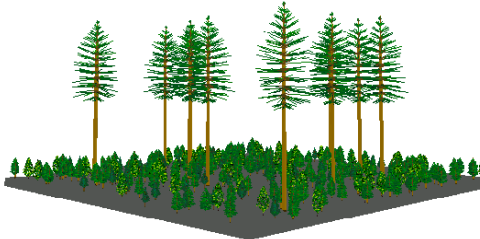
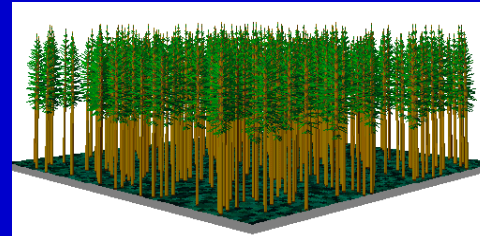
RETENTION

DELAY

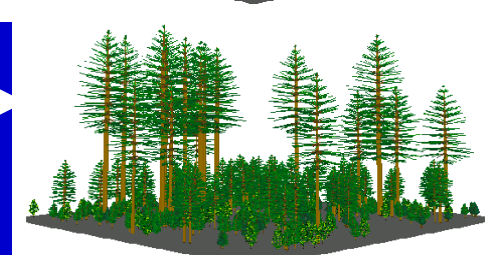
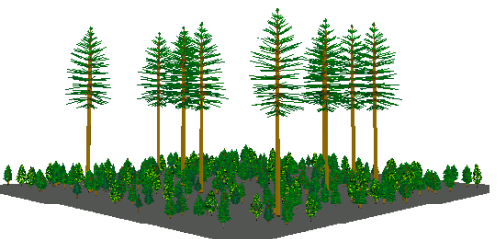
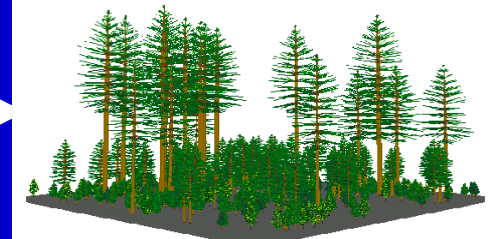
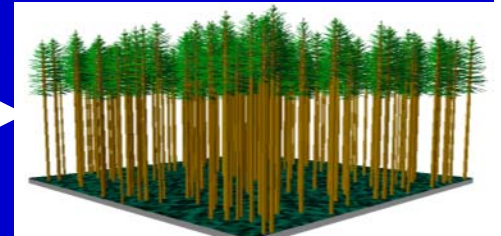
THIN

THIN,
LATER
RETENTION

2009



2049



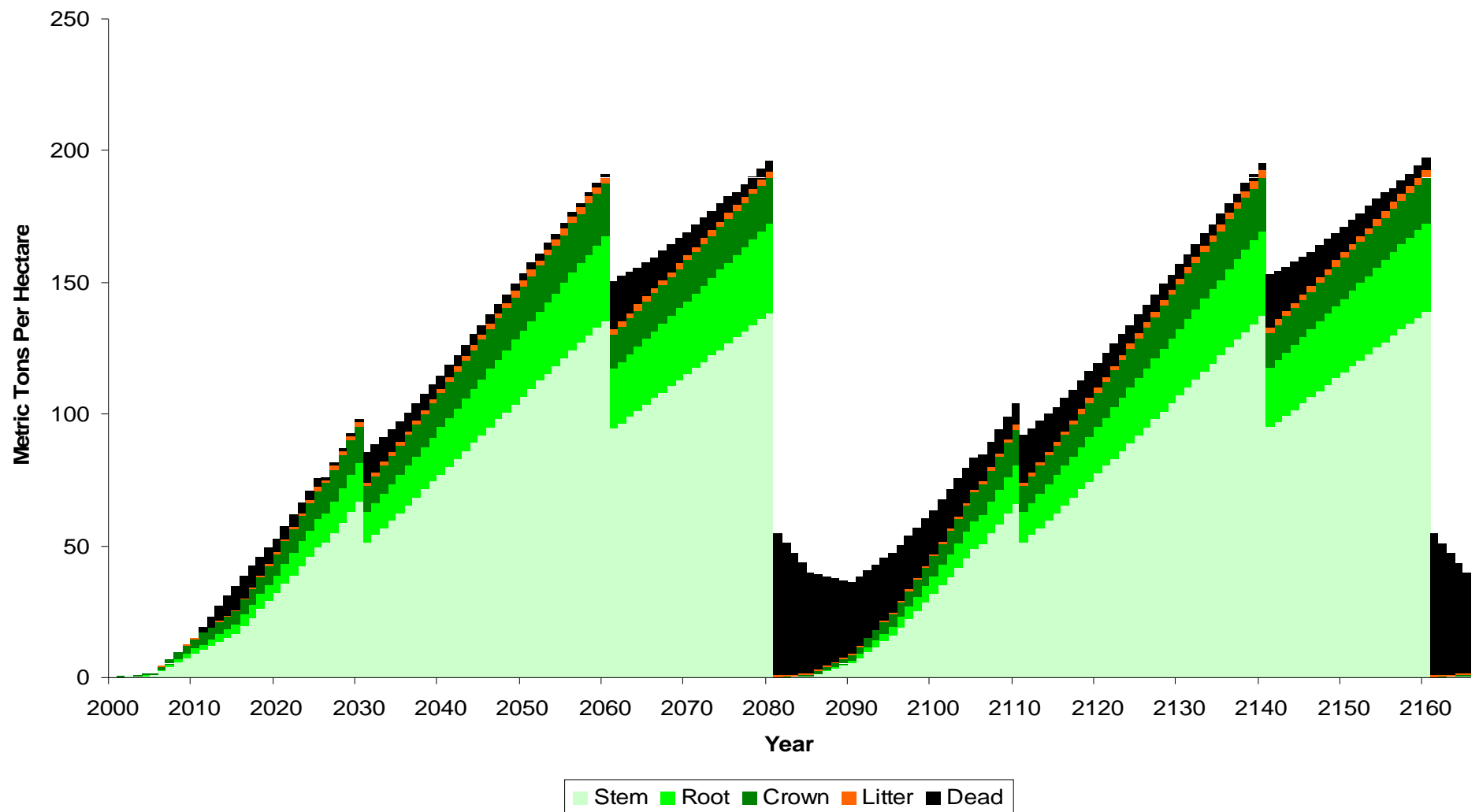
Testing - Photorealistic Visualization



Visual comparison of photograph and visualization for Pack Forest.
Visualization image is from (Wilson and McGaughey 2000)

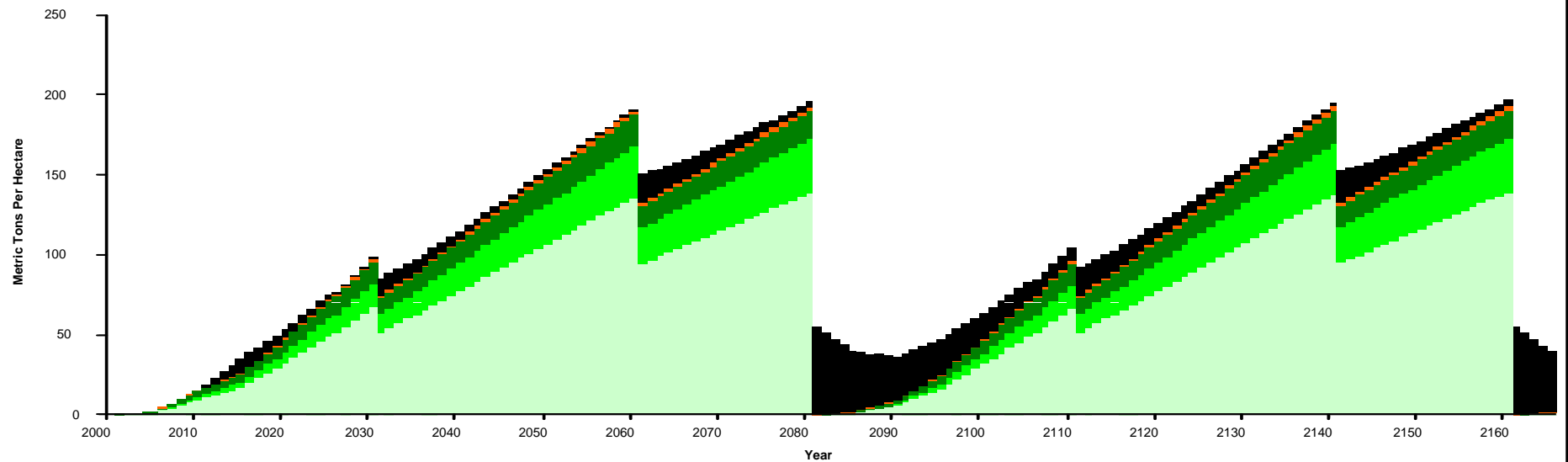
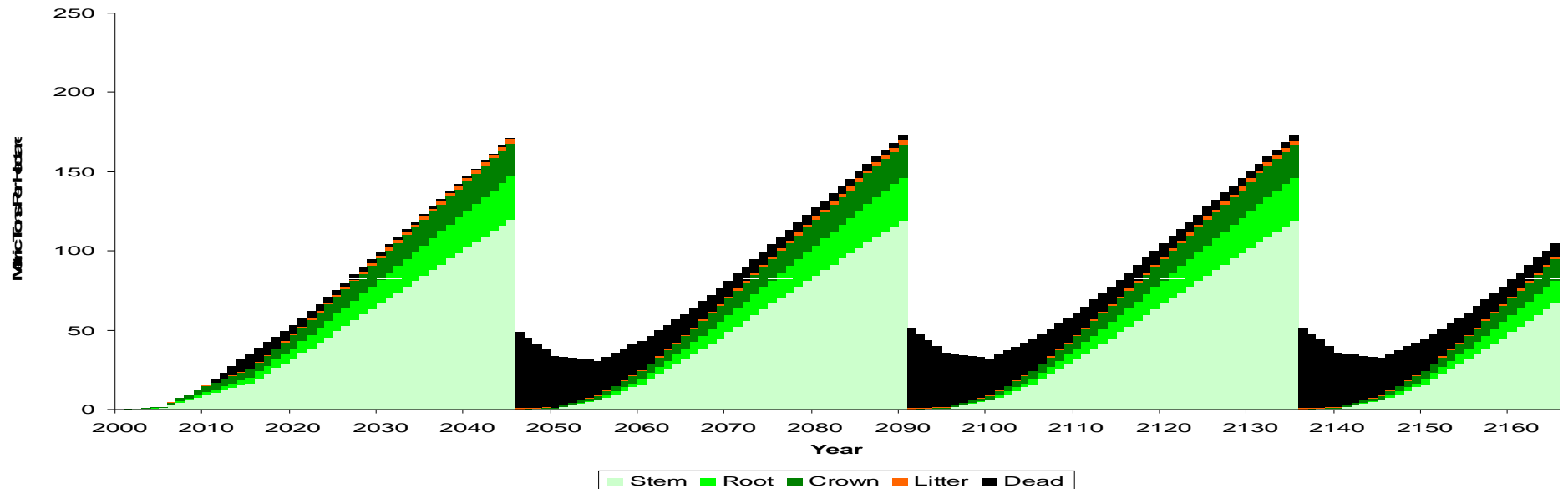
CARBON IN FOREST POOLS

80 year rotation with two thinnings



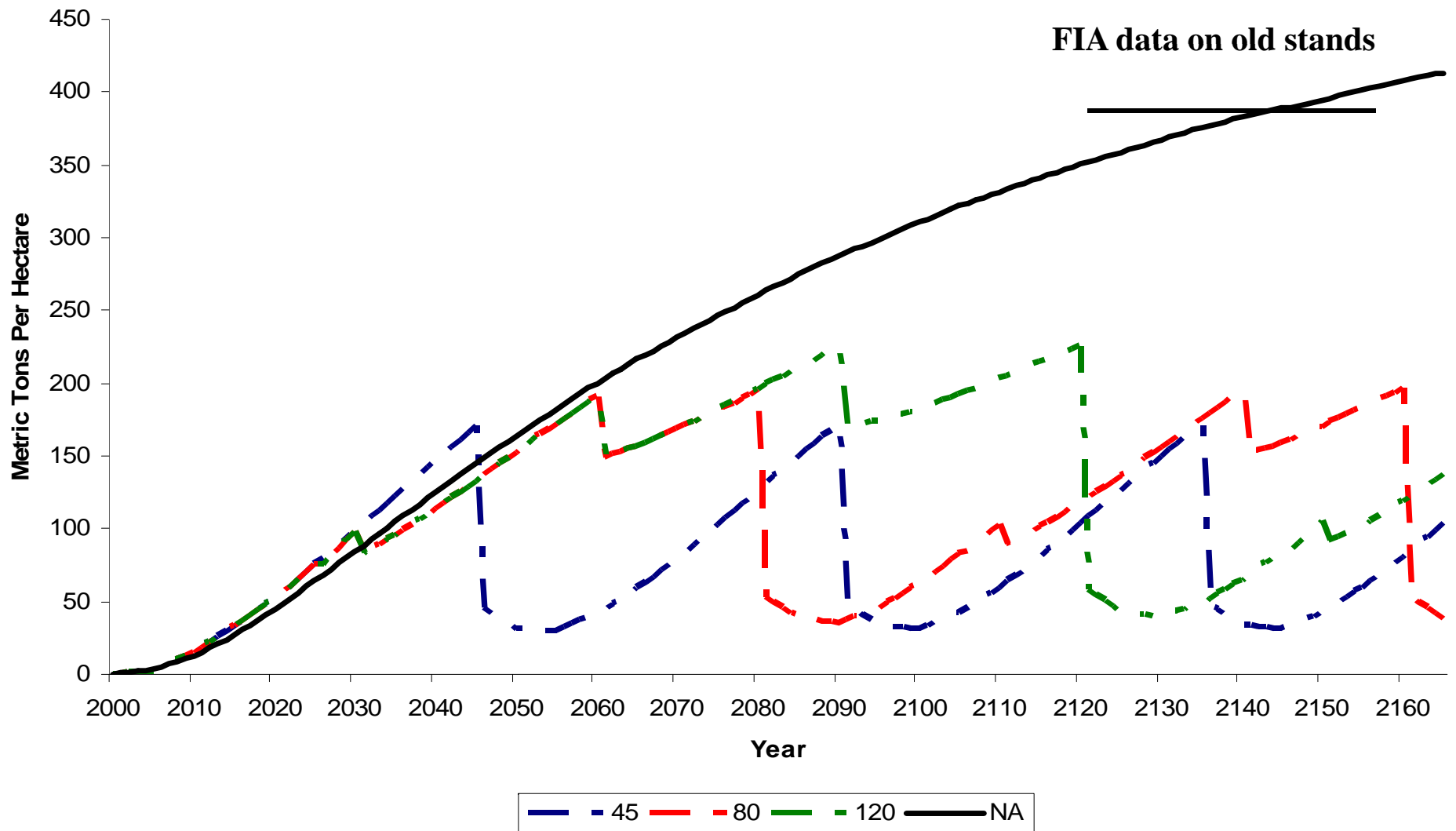
CARBON IN FOREST POOLS

45 yr & 80 yr rotation with two thinnings

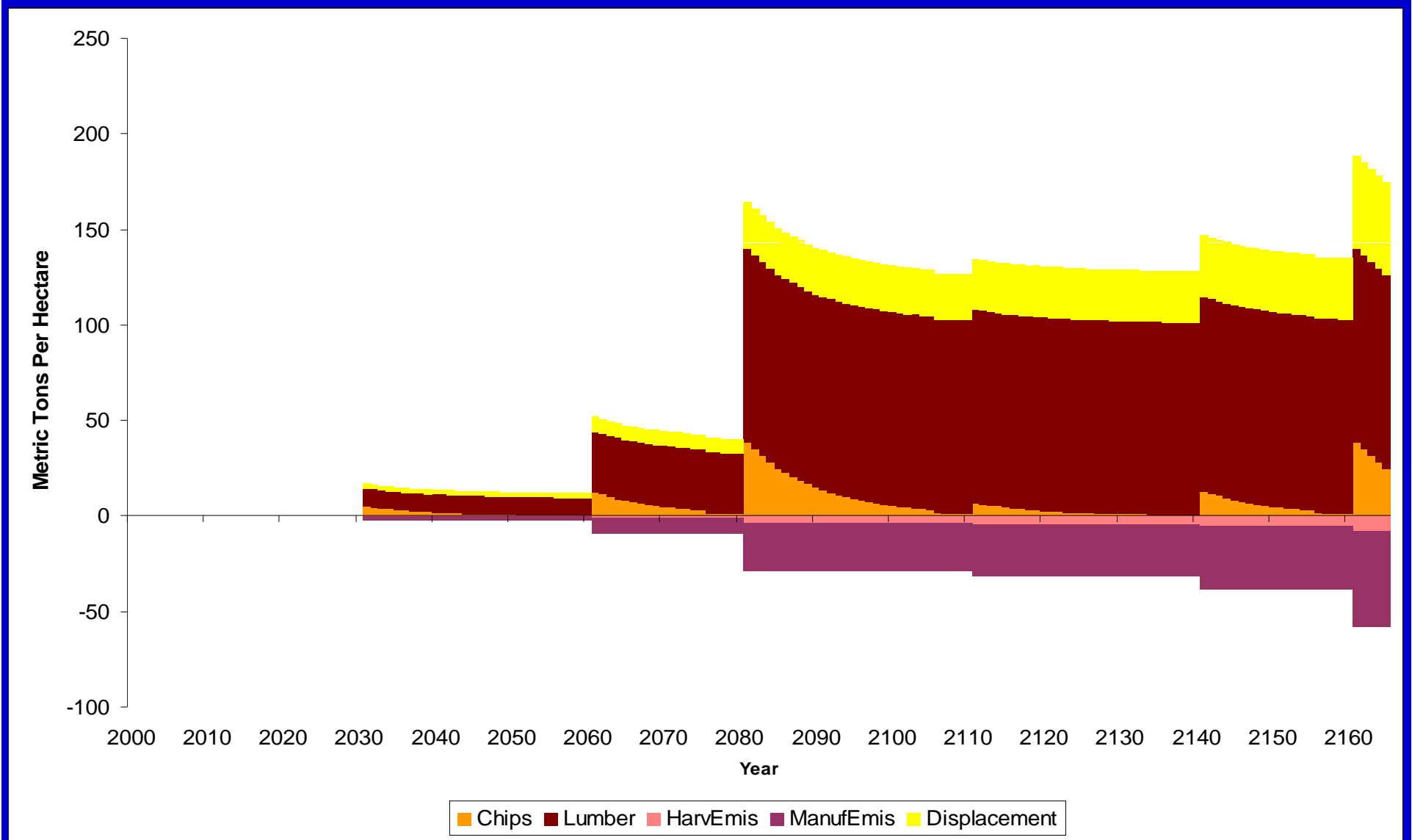


CARBON IN FOREST POOLS

44, 80, 120 yr rotations, no action, & empirical old stands



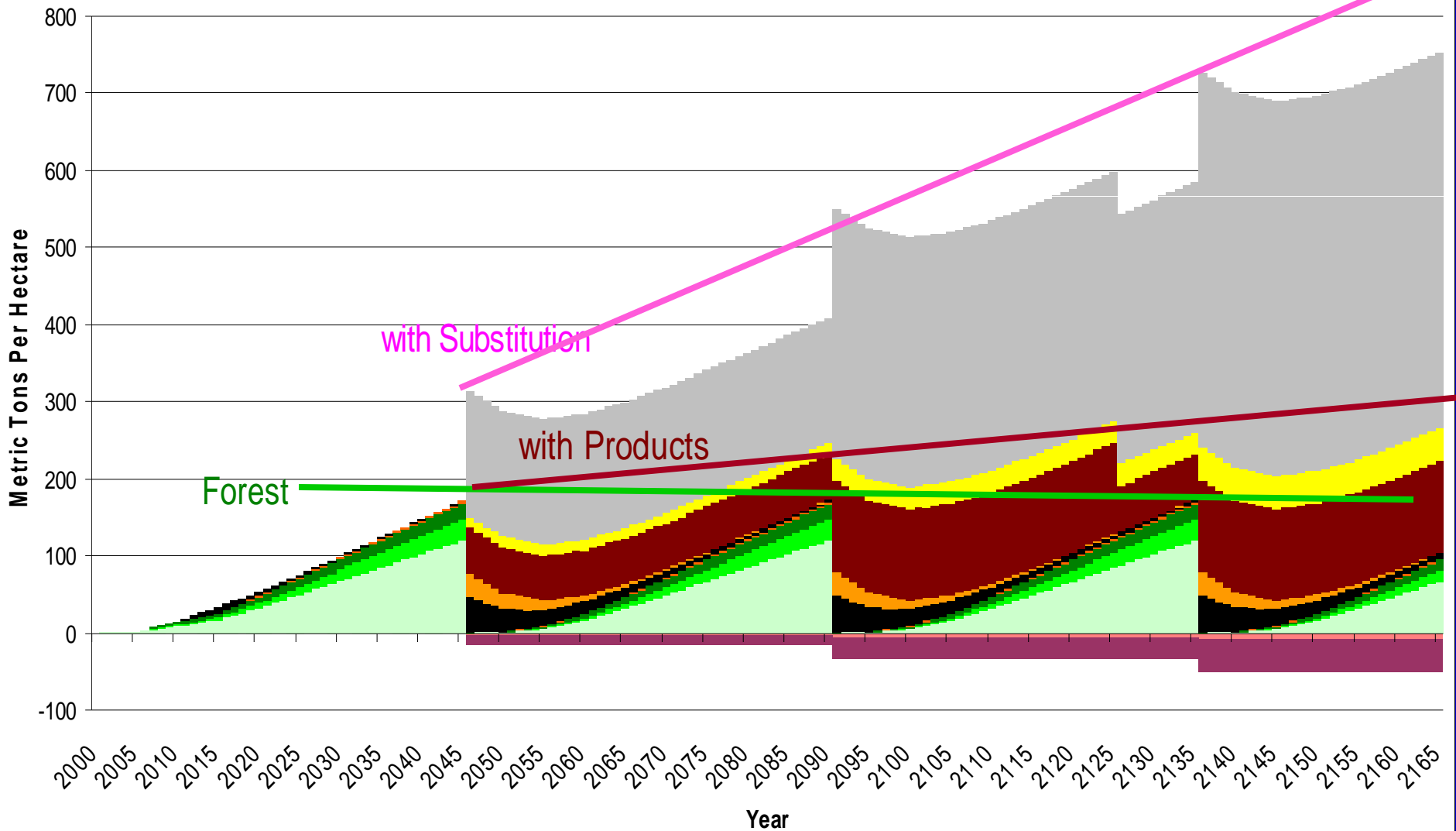
CARBON IN PRODUCT POOLS AND PROCESSING ENERGY + DISPLACEMENT



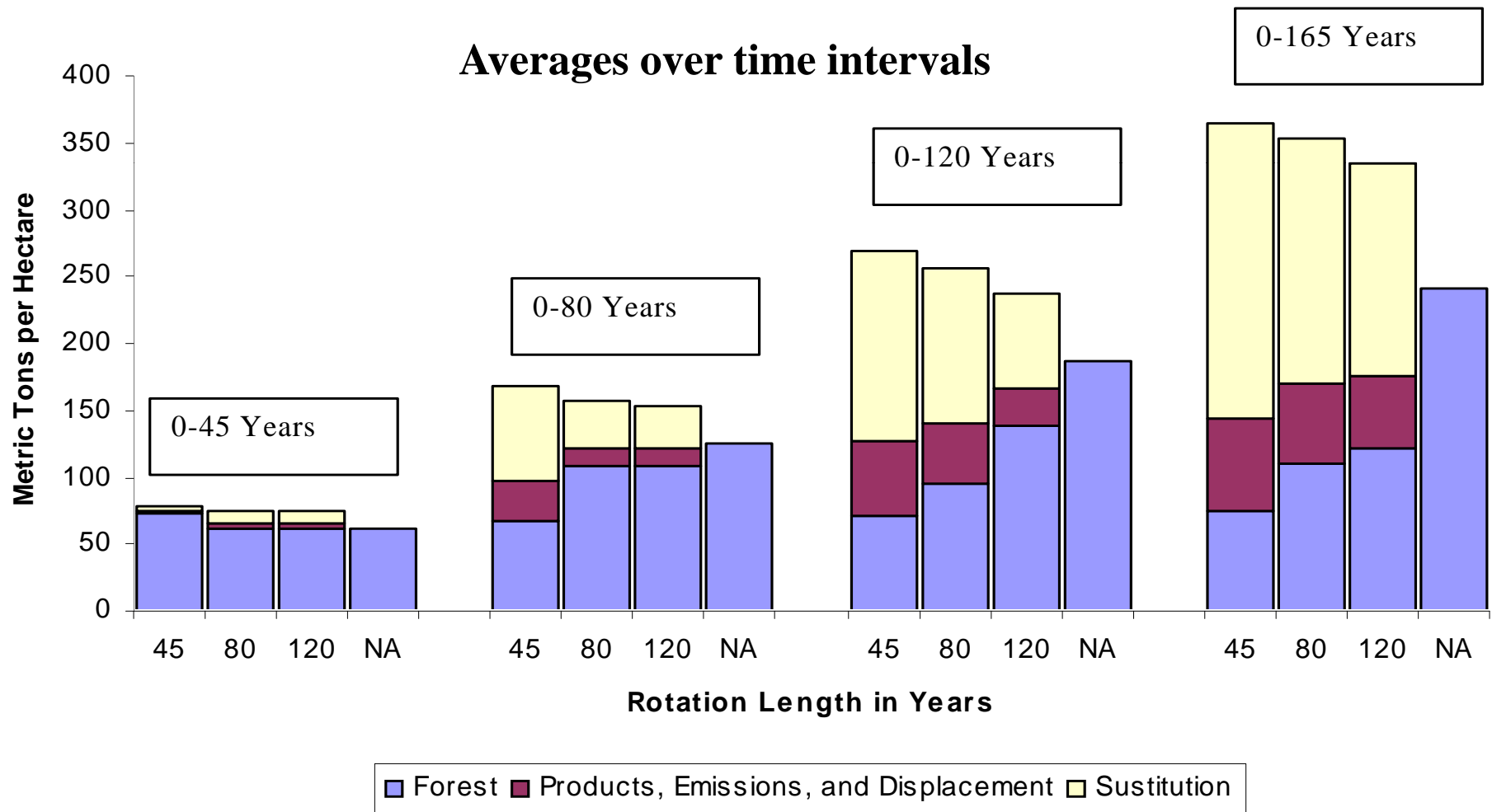
FOREST, PRODUCT & SUBSTITUTION POOLS

Forest, Product, Emissions, Displacement & Substitution Carbon by Component

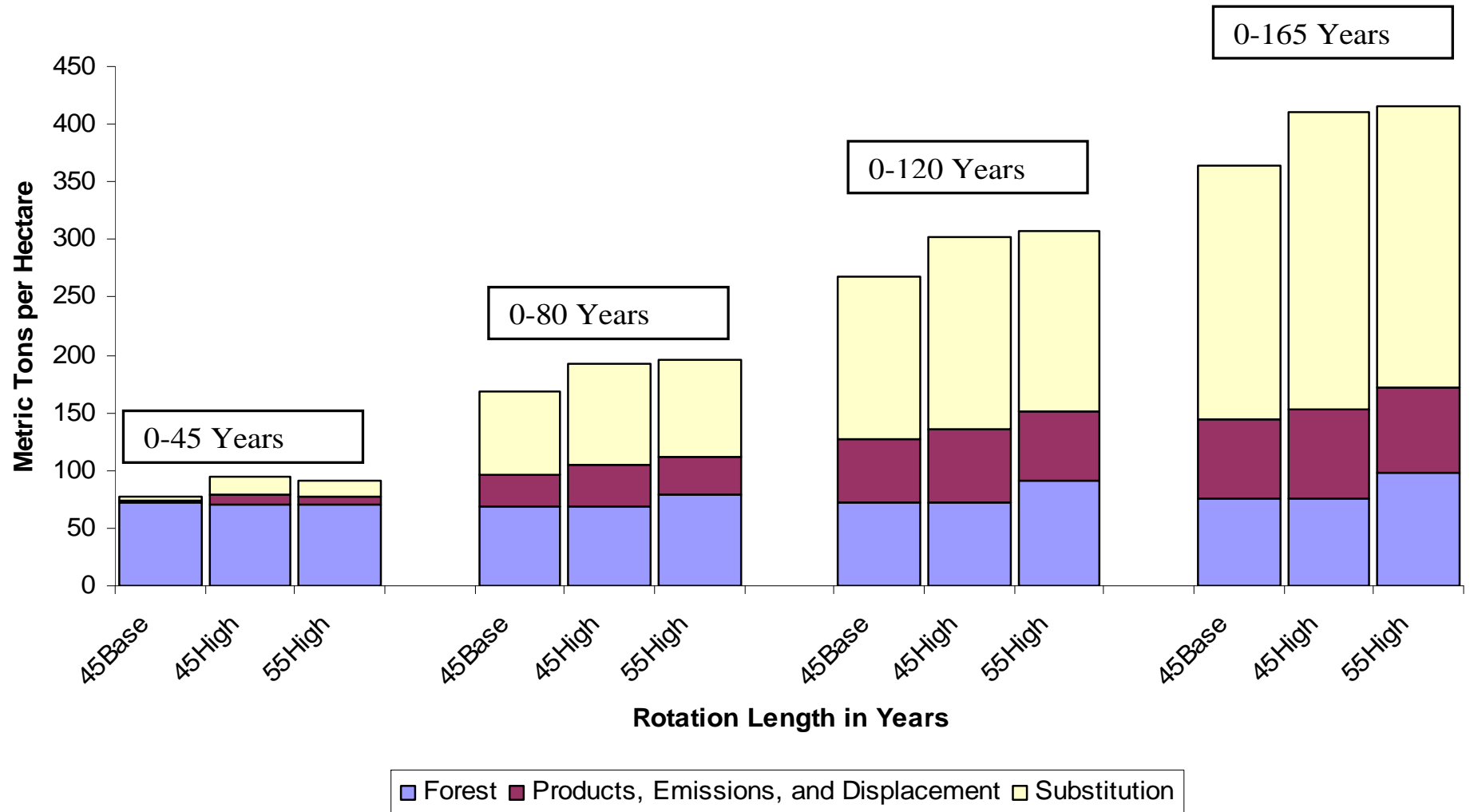
■ Stem ■ Root ■ Crown ■ Litter ■ Dead ■ Chips ■ Lumber ■ HarvEmis ■ ManufEmis ■ Displacement ■ Substitution



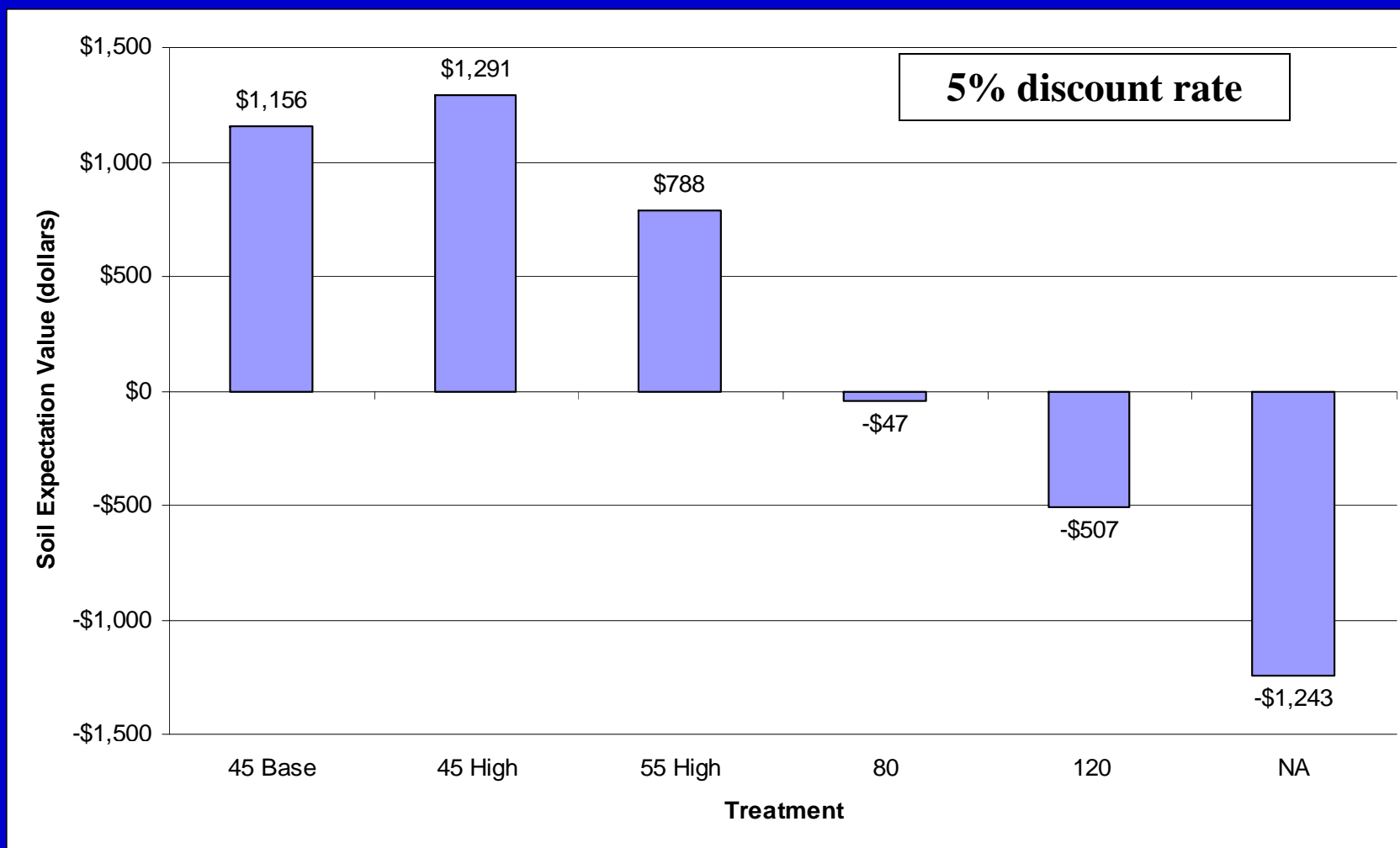
CARBON IN FORESTS, PRODUCTS AND CONCRETE FRAME SUBSTITUTES



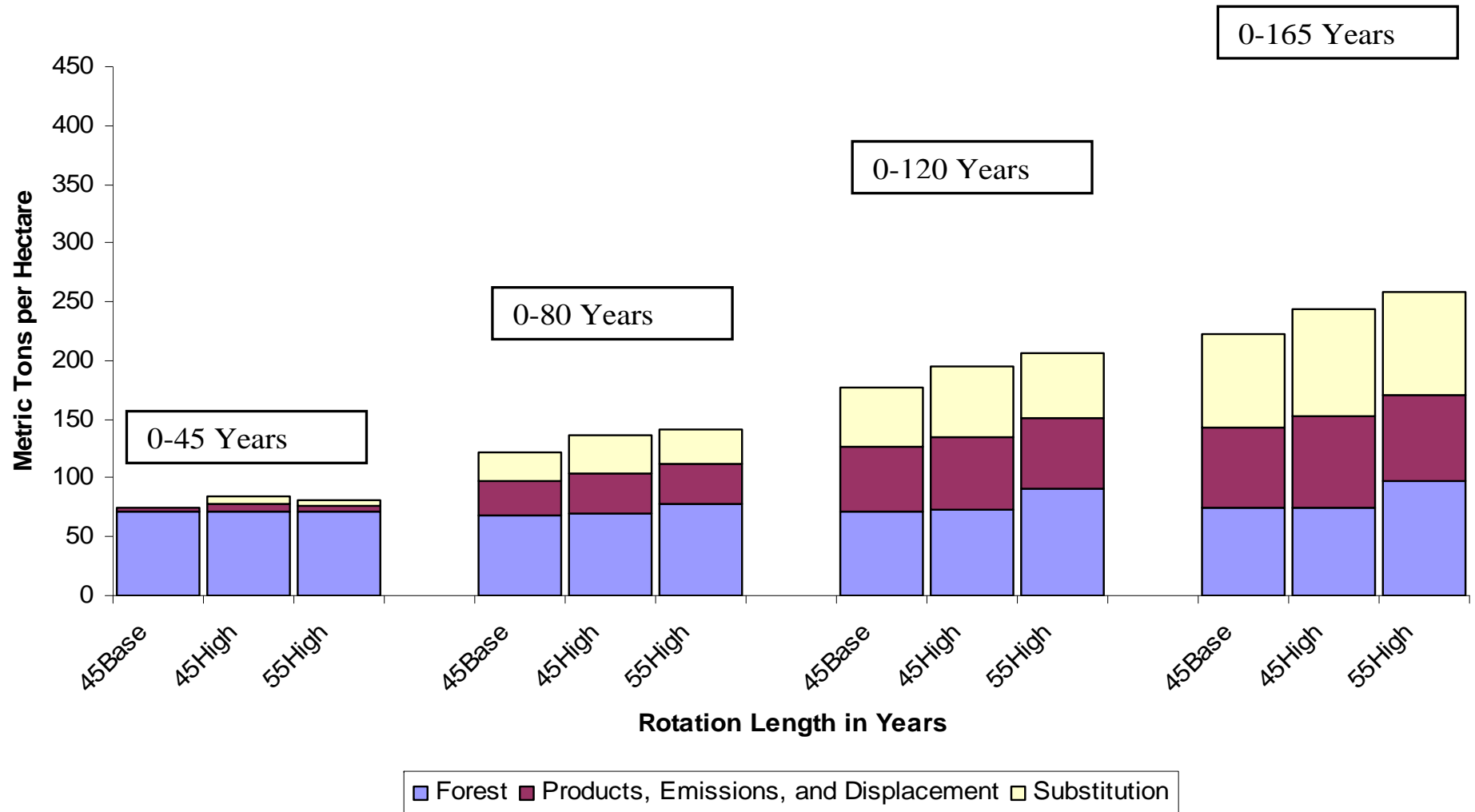
CARBON IN INTENSIVELY MANAGED FORESTS, PRODUCTS & CONCRETE FRAME SUBSTITUTES



Soil Expectation Value for each rotation length and management intensity.



CARBON IN INTENSIVELY MANAGED FORESTS, PRODUCTS & STEEL FRAME SUBSTITUTES



PNW Carbon Response

(metric tons/hectare)

»	0-45yrs	0-120 yrs
• Ignore products vs. Base (the Kyoto accounting error)	0	-63
• Intensive-Mgt vs. Base	17	35
• Intensive vs. No-mgt (i.e. no-harvest)	27	116

Environmental Performance Index for Western Washington Forests

- Model in LMS by owner group and strategy
- Use Carey Stand Structure Classes (initiation, exclusion, understory reinitiation, late-seral)
- Initiate Structure Class by FIA age
- Simulate impact of treatment strategies
- Regulatory objectives are seeking increased late-seral and decreased stem exclusion

Western WA 9.2 mil acres

- Base Case

Fed: no harvest

State: no change

Priv: 15% RMZ & NA

85% 40 yr base rot

- Long Rotation

Priv: 30% 80yr rot

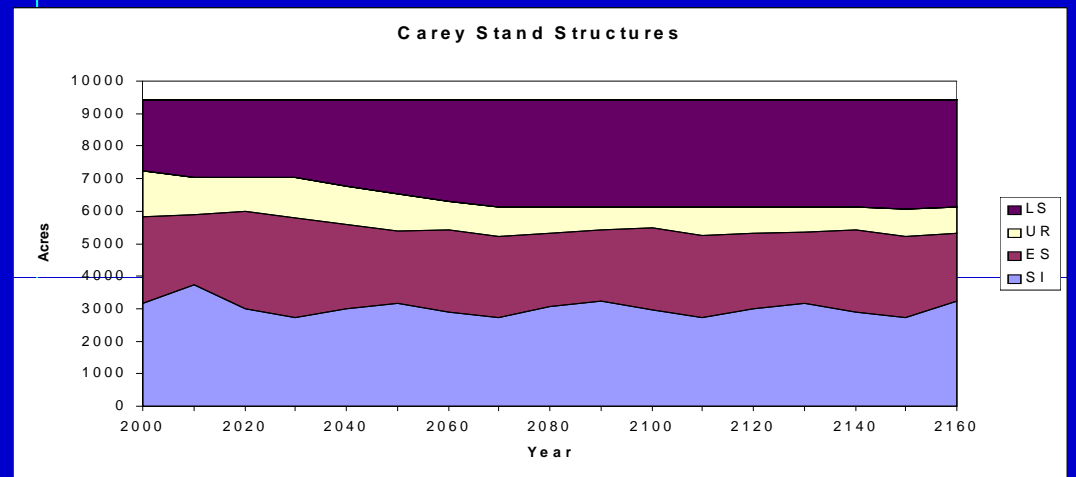
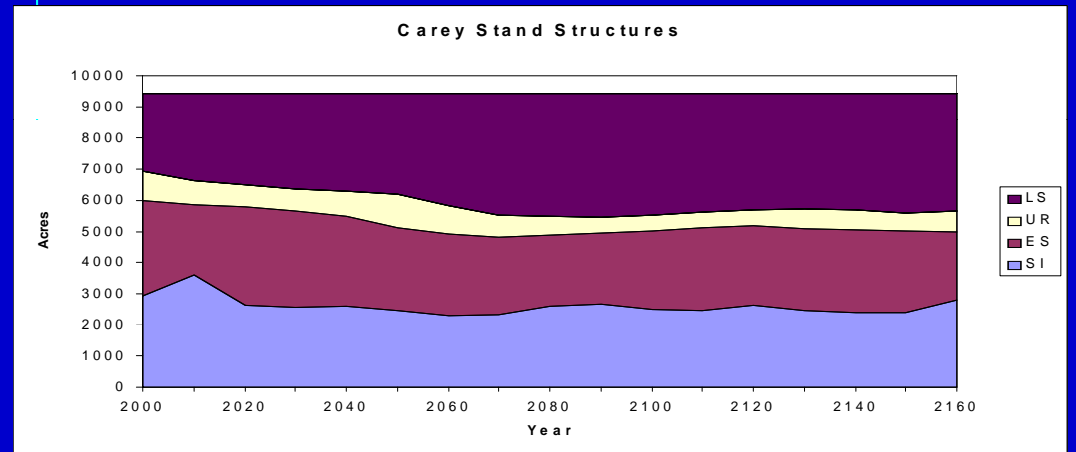
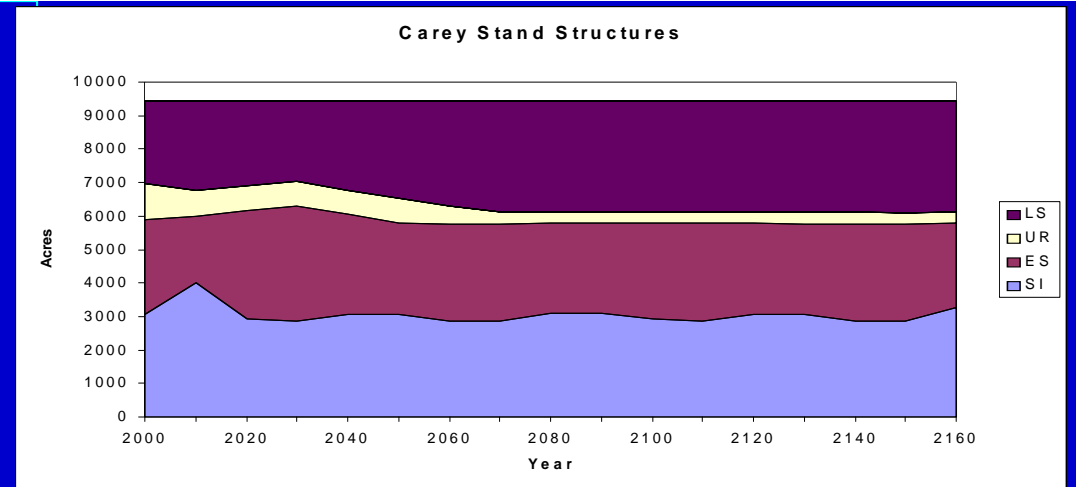
4% 120 yr rot

51% 40 yr base rot

- Intensive Mgt

Priv: 56% 40yr base rot

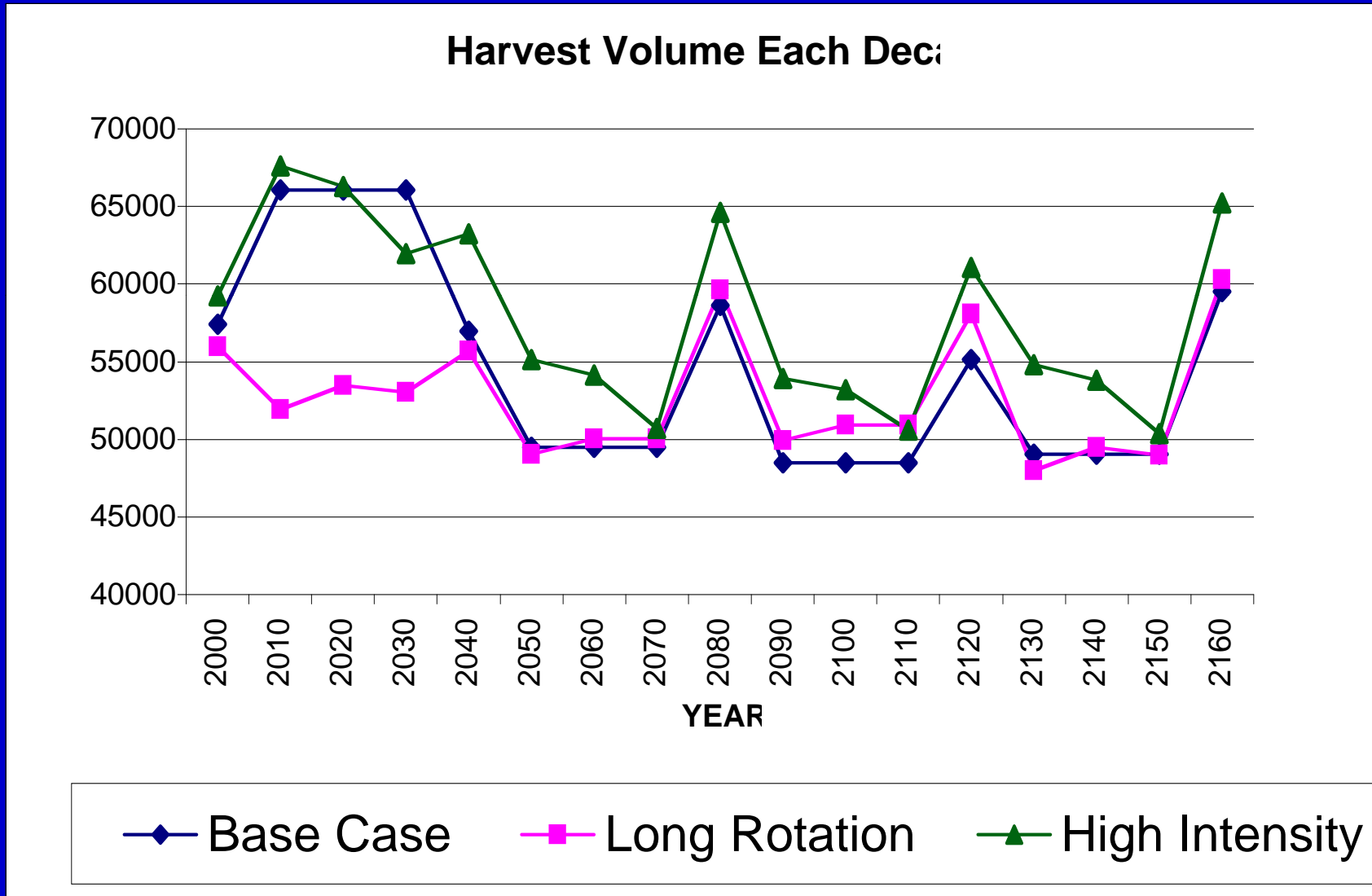
30% CT & Fertilize



Average Bio-index Shares & Harvest Levels under Mgt Alts.

	Base	Long Rotation	Intensive Mgt.
Late Seral average	32%	37%	32%
Stand Initiation average	32%	28%	32%
Stem Exclusion average	30%	28%	26%
Reinitiation average	5%	7%	10%
Harvest billion bdft/yr	5.4	5.2 (-4%)	5.8 (+6%)

Impact of Management Alternatives on Harvest Volume over Time



ENVIRONMENTAL IMPROVEMENT OPPORTUNITIES

- Redesign of the house to use less fossil intensive products
- Redesign of the house to reduce energy use (both active and passive)
- Redesign of the codes that result in excessive use of wood and concrete
- Greater use of low valued wood fiber for biofuel
- Greater use of engineered products producing higher valued products from less desirable species.
- Improved process efficiencies such as the boiler or dryer (including air drying)
- Environmental pollution control improvements
- Recycling demolition wastes
- Increased product durability (given the already long expected life of a house, from 75-100years, this applies primarily to moisture/weather exposed areas).

ENVIRONMENTAL IMPROVEMENT OPPORTUNITIES - Forest Management -

- More intensive forest management
- More solid wood production
 - But not longer rotations
- Even small carbon incentives for additionality
- Longer rotations produce better biodiversity but less stored carbon and at a high cost

The details:

Corrim: WWW.CORRIM.ORG

Athena: WWW.athenaSMI.ca

LMS: <http://LMS.cfr.washington.edu>

USLCI database: www.nrel.gov/lci

CORRIM Phase II vs. I

Phase I

- **Forest Resources LCIs – PNW and SE Softwoods**
- **Product LCIs – Lumber, Plywood, Glulam, LVL, and I-joists (NW & SE); OSB SE**
- **Residential Construction (typical to code) LCA – Minneapolis (cold), Atlanta (warm)**
 - **Construction**
 - **Building use**
 - **Maintenance (and life expectancy)**
 - **Demolition**
- **Pilot test procedures to develop LCI data from primary surveys of mills and LCA for residential structures using ATHENA EIE**

Phase II

- **Forest Resources LCIs – Inland West (IW) Softwoods, NE/NC Soft and Hardwoods**
- **Product LCIs – Lumber IW and NE/NC, OSB NE/NC, MDF, Particleboard, Resins**
- **Building Component LCIs – wall and floor component by component**
- **Product LCI/LCA for easier use**
- **Residential Construction (alternatives) LCA**
 - **West Coast residential**
 - **Demo building NCSU**
 - **Townhouse**
 - **Alternative materials and designs**
- **Full geographic coverage for high volume products and more end uses**

CORRIM Funding: Phase II vs. I

Phase I Funding (Initial Budget \$740,000 - Institution match \$320,000)	
Working capital carry over from Research Plan development of USFS JV 3 years	\$35,000
Company contributions (pledged for 3 yrs \$410,000 less 3 rd yr receivables of \$62,500)	\$237,000
Total Cash Sources:	\$347,500
Institutional match (estimate)	\$604,500
Total (revised) Budget:	\$200,000
Cash Expense (to date):	\$804,500
Completion Expenses (Final publications and audit):	\$574,863
Estimated Phase I cash cost	\$20,000
Net project contingency and addition to working capital	\$594,863
Phase II Funding (over 2 years):	
USFS JV FY03 and 04	\$9,637
Company fund raising campaign for match (25%)	\$479,000
Total Cash Sources:	\$220,000
Institutional match:	\$699,000
Total Budget (direct and institutional match):	\$170,000
	\$869,000