Lecture 13. Concepts of natural resource management and growth and yield

FOR 4684 Natural Resource Economics and Management

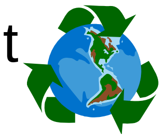
Making College Possible

School of Forest Resources

What is natural resource management?

- Management is the art and science of :
  - Managing the ecological processes of terrestrial ecosystems,
  - Helping landowners or managers understand decisions and results of those decisions,
  - So that the *owners* can make good, informed decisions.
- We manage ecosystems to:
  - Perpetuate ecosystem functions,
  - Preserve components of ecosystems, and
  - Meet the goals and objectives of forest landowners!

Biological basis for ecosystem management



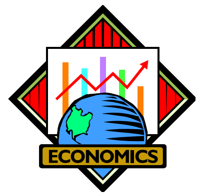
- Mimic natural disturbance patterns
  - Interval, severity, and spatial pattern
  - Historical range of variability (HRV)
- Use native species
- Maintain ecological functions and biological diversity
- Ecology determines good silvicultural regimes from which to choose.

Human dimensions basis for NR management

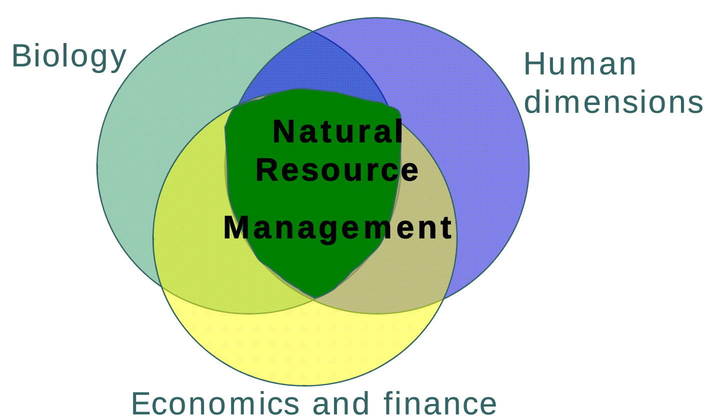
- Humans need healthy terrestrial ecosystems
  - Individuals and communities
- Private rights and societal needs
- Participatory democracy
- Management solutions must be acceptable to landowners and society
- Human dimensions shapes actions to actually work within human cultures, not all of which are dominated by western Europeans.

Economic, financial basis for NR management

- Conflicting needs for resources provided by terrestrial ecosystems
- Need to allocate limited resources to various needs
- Need for efficiency
- Maximizing benefit to humans



What is NR management?



What is natural resource management?

- Sustainability is *integral* to management
- What is it that we "sustain" depends on your view
  - Man dominates nature
  - Man coexists with nature
  - Nature dominates man
- Each of the "philosophies" can be applied within a landscape approach to management

Triad approach to terrestrial ecosystem management

- Extensive forestry
  - Maintain biodiversity and ecosystem functions
  - Extraction of wood attempts to mimic natural disturbance patterns
- Intensive forestry
  - Plantation forestry
  - Maximization of timber yield at lowest cost
  - Protection of long-term productivity of lands
- Protected Areas
  - Natural ecosystem processes only
  - Provide benchmark areas to evaluate changes observed in extenstive and intensive forestry areas

Sustainability…

- Sustained yield of timber
- Sustained yield of timber, water, wildlife and recreation
- Maintaining naturally functioning ecosystems
- Sustaining human-forest systems
  - Vision of American Forestry Congress (pg. 15 in text)

Assessing sustainability

- Specified ecosystem conditions
- Time frame (future, how far?)
- Measures for each condition
- Frame of reference for conditions (HRV – historical range of variability of disturbance)
- Rules for deciding sustainability
- Methods of projecting conditions
- Monitoring and feedback

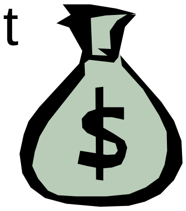
Key elements of NR management

- Adaptive
  - Recognize uncertainty
  - Management policies (decisions) are testable
  - Search for information to test management policies
  - Periodic review of policies
- Recognizes multiple spatial scales
- Considers cumulative effects of multiple ownerships

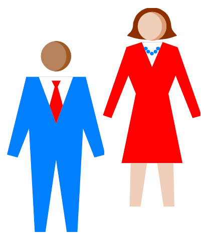
Key elements of NR management

- Quantifies and projects conditions
- Recognizes natural disturbances and their probabilistic nature
- Spatially detailed, at least at watershed level
- Involves temporal element – plans for the future.
- Involves PEOPLE!

Five M's of management



- Money
- Methods
- Machines
- Manpower
- Materials



Political/regulatory concerns in NR management

- Conflict between public interest (what's good for society) and private rights leading to:
  - More management regulations
    - First on public, moving to private lands
  - Forest (ecosystem management)certification
    - Minimum: documentation that good management is taking place
    - Maximum: oversight and corrective (punative) actions.

Ever changing nature of NR management

- Population
  - Baby-boom generation vs. GenX?
- Science and technology
  - Paper, engineered wood materials
  - Computer and spatial tools
- Society
  - Less material-oriented in future?
  - More “eco-centered?”

Bottom line: every terrestrial ecosystem manager should know how to…

- …estimate future conditions based on management actions
- …determine when and when not to disturb the ecosystem
- …determine sustainable removals of any component of that ecosystem,
- …understand the different public and private forest management settings, and
- …develop simple management plans.

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GROWTH AND YIELD CONCEPTS

Growth and Yield

- Yield can be defined as the amount of any stand attribute (cubic feet of timber, board feet, etc.) that is present per unit area at one point in time.

- Growth is the change in yield over some specified time.

Measuring growth

- Utilization standards important
  - Total biomass accumulation (B)
  - Potentially usable biomass (P)
  - Biomass actually utilized (U)
  - B > P > U
- Important definitions
  - Growth
  - Ingrowth
  - Outgrowth
  - Mortality
  - Cut

Measures of growth

- V_1 = volume at beginning of time period
- V_2 = volume at end of time period
- M = volume of mortality over period
- C = volume of cut (harvest) over period
- I = volume of ingrowth over period

Measures of growth

- Gross increment, including ingrowth
  - $V_2 + M + C – V_1$
- Gross increment of initial volume
  - $V_2 + M + C - I – V_1$
- Net increment including ingrowth
  - $V_2 + C – V_1$
- Net increment of initial volume
  - $V_2 + C - I – V_1$
- Net change in growing stock
  - $V_2 – V_1$

Measures of growth – an example

Plot	Year	Volume	Cut	Mortality	Ingrowth
1	1999	2800	1250	70	250
	2009	4600			
2	1999	3100	850	65	220
	2009	5100			
3	1999	2900	525	1200	90
	2009	3800			
4	1999	3400	645	0	365
	2009	6400			
5	1999	2600	945	105	210
	2009	5200			
6	1999	4100	210	115	140
	2009	5900			
7	1999	3400	460	85	50
	2009	5900			
8	1999	3200	500	45	125
	2009	5300			
9	1999	3800	350	50	190
	2009	6000			
10	1999	3500	400	75	170
	2009	5700			

You have 20 permanent inventory plots on your 200 acre forest property. You have sampled 10 plots and summarized the tree data into per acre volumes (board feet, Doyle log rule) for the 1999 and 2009 inventory years.

Estimate for each plot, and then average for the forest:

(1) Gross increment, including ingrowth

(2) Gross increment of initial volume

(3) Net increment, including ingrowth

(4) Net increment of initial volume

(5) Net change in growing stock

Solutions for plot 1…

- Gross increment, including ingrowth — V2 + M + C – V1
  - =4600+70+1250-2800 =3120
- Gross increment of initial volume — V2 + M + C - I – V1
  - =4600+70+1250-250-2800=2870
- Net increment including ingrowth — V2 + C – V1
  - =4600+1250-2800=3050
- Net increment of initial volume — V2 + C - I – V1
  - =4600+1250-250-2800=2800
- Net change in growing stock — V2 – V1
  - =4600-2800=1800

Results and confidence intervals around estimates

Problem 1

t statistic (alpha = 0.05, df = 9)= 2.262

Plot	V1	V2	Cut	Mortality	Ingrowth	Gross Increment including ingrowth	Gross Increment of initial volume	Net increment including ingrowth	Net increment of initial volume	Net change in growing stock
1	2800	4600	1250	70	250	3120	2870	3050	2800	1800
2	3100	5100	850	65	220	2915	2695	2850	2630	2000
3	2900	3800	525	1200	90	2625	2535	1425	1335	900
4	3400	6400	645	0	365	3645	3280	3645	3280	3000
5	2600	5200	945	105	210	3650	3440	3545	3335	2600
6	4100	5900	210	115	140	2125	1985	2010	1870	1800
7	3400	5900	460	85	50	3045	2995	2960	2910	2500
8	3200	5300	500	45	125	2645	2520	2600	2475	2100
9	3800	6000	350	50	190	2600	2410	2550	2360	2200
10	3500	5700	400	75	170	2675	2505	2600	2430	2200
Mean	3280	5390	614	181	181	2905	2724	2724	2543	2110
SE	145	242	100	114	28	152	137	210	193	179
95% LB	2952	4842	388	-76	117	2562	2414	2249	2107	1706
95% UB	3608	5938	839	438	245	3247	3033	3198	2978	2514

Stocking

- A ratio comparison of some real-world stand's density to some reference or "ideal" stand density
- "Fully stocked" stands often refer to stands with density equivalent to stands used to develop normal yield tables.
- Fully stocked stands have room to grow, but none to waste – full utilization of the site's resources

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YIELD TABLES, STAND-TABLE PROJECTION, AND CONCEPT OF "OPTIMAL" ROTATIONS

Growth and yield models

- Whole stand
  - Density-free $V_A = f(A, S)$
    - Normal yield
    - Empirical yield
  - Variable density $V_A = f(A, S, D)$
- Diameter class
  - Stand table projection
- Individual-tree
  - Distance dependent
  - Distance independent

Density-free whole stand models

- Direct approach
- Estimate growth from other similar forests
- Yield tables can be:
  - Empirical – reflect “average” actual conditions
  - Normal – based on stands that appeared to be “fully stocked”

Example of normal yield table

Shortleaf pine yield in board feet (International ¼-inch rule) per acre. From USDA For. Serv. Misc. Pub. No. 50.

Age (years)	Site index in feet at 50 years						
	40	50	60	70	80	90	100
	Yield in board feet (International ¼ inch rule) per acre						
15	--	--	--	--	--	200	1400
20	--	--	--	250	1600	3800	7500
25	--	--	800	2800	5700	10500	14950
30	--	900	3300	6900	11550	17000	23050
35	600	2800	6600	11750	17100	23750	30900
40	1750	5000	10200	16400	22450	29750	37600
45	3000	7500	13600	20250	27200	35300	43850
50	4200	9800	16600	23800	31600	40000	49000
55	5650	11900	19250	27000	35200	44200	53600
60	6900	13800	21500	29700	38200	47500	57300
65	8100	15400	23600	32000	40800	50400	60800
70	9200	16900	25300	34100	43200	53200	63750
75	10150	18200	26900	35900	45300	55500	66250
80	11050	19400	28300	37700	47250	57700	68400
85	11900	20500	29600	39200	49000	59500	70300
90	12600	21400	30750	40700	50700	61000	72000
95	13300	22300	31850	42000	52200	62900	73500
100	14000	23100	32900	43300	53500	63700	74750

Qualifications about normal yield tables..

- A composite of fully stocked stands
- Not “usual” or “regular”
- Growth may approach maximum at less than “normal” stocking
- Are not an upper limit on growth or yield
- Are VALUABLE for long-term estimations
  - Often best available data for long-term maximum growth, height, and tree size for many species

Growth from normal yield tables..

- Can be less than proportional to stocking
- Can be proportional to stocking
- Can be greater than proportional, but less than absolute value in normal yield table
- Can be equal to absolute growth shown in normal yield table
- Can be greater than absolute growth shown in normal yield table

Using a normal yield table

- Inventory data for a 40-acre shortleaf pine stand shows:
  - Date: 2001
  - SI = 70
  - Age: 30 years
  - Volume = 6210 bf / acre
  - What was stocking?
    - 6210 / 6900 = 90%

Shortleaf pine yield in board feet (International c -inch rule) per acre.
From USDA For. Serv. Misc. Pub. No. 50.

Age (years)	60	70	80
15	--	--	--
20	--	250	1600
25	800	2800	5700
30	3300	6900	11550
35	6600	11750	17100
40	10200	16400	22450
45	13600	20250	27200
50	16600	23800	31600

Using a normal yield table

- If growth over last 5 years was proportional to stocking, what would stand volume and stocking be?
  - Normal growth
    - $V_{30,100\%}$ = 6900 bf
    - $V_{35,100\%}$ = 11750 bf
    - Normal Growth = 4850 bf
    - Proportional growth = 4850 x 90% = 4365 bf
  - New stand volume = 6210 bf + 4365 bf = 10575 bf
  - New stocking = 10575 bf / 11750 bf = 90%

Shortleaf pine yield in board feet (International c -inch rule) per acre.
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Age (years)	60	70	80
15	--	--	--
20	--	250	1600
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30	3300	6900	11550
35	6600	11750	17100
40	10200	16400	22450
45	13600	20250	27200
50	16600	23800	31600

Using a normal yield table

- If growth over last 5 years was 100% normal (absolute normal growth), what would stand volume and stocking be?
  - Normal growth
    - $V_{30,100\%}$ = 6900 bf
    - $V_{35,100\%}$ = 11750 bf
    - Normal Growth = 4850 bf
  - New stand volume = 6210 bf + 4850 bf = 11060 bf
  - New stocking = 11060 bf / 11750 bf = 94%

Shortleaf pine yield in board feet (International c -inch rule) per acre.
From USDA For. Serv. Misc. Pub. No. 50.

Age (years)	60	70	80
15	--	--	--
20	--	250	1600
25	800	2800	5700
30	3300	6900	11550
35	6600	11750	17100
40	10200	16400	22450
45	13600	20250	27200
50	16600	23800	31600

Using a normal yield table

- If growth over last 5 years was 100% normal (absolute normal growth), and continued for another 5 years, what would stand volume and stocking be in the year 2011?
  - Normal growth
    - $V_{30,100\%}$ = 6900 bf
    - $V_{,40,100\%}$ = 16400 bf
    - Normal Growth = 9500 bf
  - New stand volume = 6210 bf + 9500 bf = 15710 bf
  - New stocking = 15710 bf / 16400 bf = 96%

Shortleaf pine yield in board feet (International c -inch rule) per acre.
From USDA For. Serv. Misc. Pub. No. 50.

Age (years)	60	70	80
15	--	--	--
20	--	250	1600
25	800	2800	5700
30	3300	6900	11550
35	6600	11750	17100
40	10200	16400	22450
45	13600	20250	27200
50	16600	23800	31600

Using a normal yield table, interpolating site index…

- Find the volume of a 35 year old stand that is 90% stocked and is on site index 76:
  - $V_{SI=70,\ A=35}$ = 11750 bf
  - $V_{SI=80,\ A=35}$ = 17100 bf
  - Interpolate between SI values
  - $V_{SI=76,\ A=35}$ = 11750 bf + 0.6(17100 bf – 11750 bf) = 14960 bf x 90% = 13464 bf / acre

Shortleaf pine yield in board feet (International c -inch rule) per acre.
From USDA For. Serv. Misc. Pub. No. 50.

Age (years)	60	70	80
15	--	--	--
20	--	250	1600
25	800	2800	5700
30	3300	6900	11550
35	6600	11750	17100
40	10200	16400	22450
45	13600	20250	27200
50	16600	23800	31600

Using a normal yield table, interpolating age…

- Find the per acre volume of a 80% stocked stand on SI = 80 land that is 24 years old:
  - $V_{SI=80, A=20}$ = 1600 bf
  - $V_{SI=80, A=25}$ = 5700 bf
  - $V_{SI=80, A=24}$ = 1600 bf + 4/5(5700 – 1600) =4880 bf x 80% = 3904 bf / ac

Shortleaf pine yield in board feet (International c -inch rule) per acre.
From USDA For. Serv. Misc. Pub. No. 50.

Age (years)	60	70	80
15	--	--	--
20	--	250	1600
25	800	2800	5700
30	3300	6900	11550
35	6600	11750	17100
40	10200	16400	22450
45	13600	20250	27200
50	16600	23800	31600

Using a normal yield table, extrapolating…

- Based on what you see on this table only, what might be the volume of a 100% stocked stand at age 55 on site index 60 land?
  - If we assume growth between ages 50 to 55 to be the same as growth between ages 45 to 50, then:
    - V = 16600 bf + (16600 - 13600) = 19600 bf
- Extrapolation should be done with extreme caution!

Shortleaf pine yield in board feet (International c -inch rule) per acre.
From USDA For. Serv. Misc. Pub. No. 50.

Age (years)	60	70	80
15	--	--	--
20	--	250	1600
25	800	2800	5700
30	3300	6900	11550
35	6600	11750	17100
40	10200	16400	22450
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50	16600	23800	31600

Example of empirical yield table

- Note that yields don't always increase "normally"
  - Growth between ages 50 and 55 is negative?

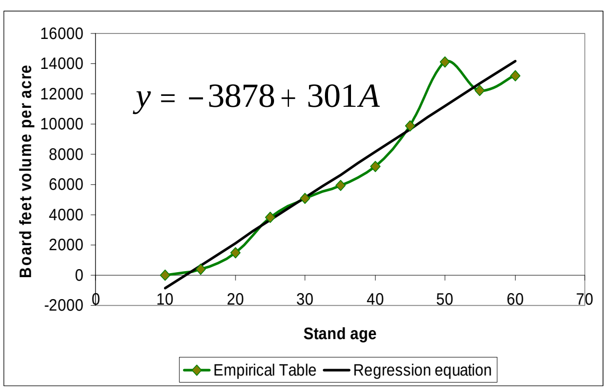
    (- 1874 bf /ac)
  - Can develop regression line to "smooth" the data

Average empirical yields of timber for natural loblolly pine, medium site quality (60-78) in Southeast

USDA For. Serv. Research Paper SE-245 (June 1984)

Stand age	Board feet (Int. ¼" rule)
10	---
15	385
20	1465
25	3822
30	5067
35	5934
40	7225
45	9880
50	14126
55	12252
60	13201

Regression line fit to empirical yield table data…



Age	Table	Equation
10	0	-868
15	385	637
20	1465	2142
25	3822	3647
30	5067	5152
35	5934	6657
40	7225	8162
45	9880	9667
50	14126	11172
55	12252	12677
60	13201	14182

Normal yield equations

- Fit from yield table data
- Advantages
  - No interpolation
  - Smoothed curves
  - Differentiable

Yield (ft^3 /ac) for fully stocked even-aged second-growth upland oak stands

$$y = 37.658S^{1.2479}e^{\frac{-50.412}{A}}$$

$$Growth = \frac{\partial y}{\partial A} = \frac{1898.415S^{1.2479}e^{\frac{-50.412}{A}}}{A^2}$$

Stand Table Projection

DBH	NT	Inc	MR	Percent of trees moving				Number of trees moving				DBH	New NT	Mortality	Cut	Final
				0	1	2	3	0	1	2	3					
4	10	1.4	70	30	70	0	0	3	7	0	0	4	3	1	0	2
6	20	1.6	80	20	80	0	0	4	16	0	0	6	11	2	0	9
8	30	1.9	95	5	95	0	0	1	29	0	0	8	17	3	2	13
10	40	2.1	105	0	95	5	0	0	36	4	0	10	29	1	4	24
12	30	2.2	110	0	90	10	0	0	27	3	0	12	31	1	5	26

Stand table projection

- A good short-term model
- Based on diameter class information
- Assumes that trees of a particular diameter class will grow and die in the near future like trees that an equal amount of time ago where in that diameter class.

Data for stand table projection

- Need to collect data on all diameter classes in a stand:
  - 10 year growth
  - 10 year mortality
- Assume a uniform distribution of stems within all diameters in a diameter class

Collecting data for stand table projection…

Let's say we measure 100 trees…

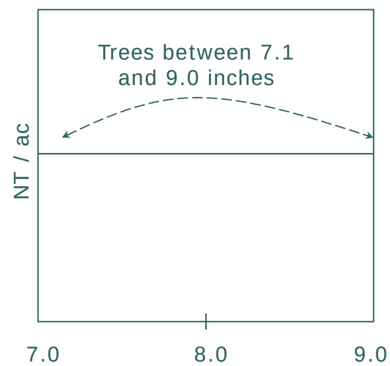
Tree #	1= Live 0 = Dead	Diam. Today	Diam. Class today	10 year growth	Diam class 10 yrs ago
1	1	8.6	8	1.7	6
2	1	11.8	12	2.3	10
3	1	4.8	4	0.9	4
4	1	6.1	7	1.2	4
5	1	9.8	10	1.3	8
6	1	10.3	10	1.4	8
7	1	3.2	4	0.8	Ingrowth
8	0	6.8	6	---	6
9	1	14.7	14	2.8	12

Calculating averages

- Determine, for each diameter class:
  - Number of current trees
  - Average DBH increment based on diameter class for trees at previous time period
  - Ingrowth (NT / acre) over time period
  - Mortality (NT / acre) over time period

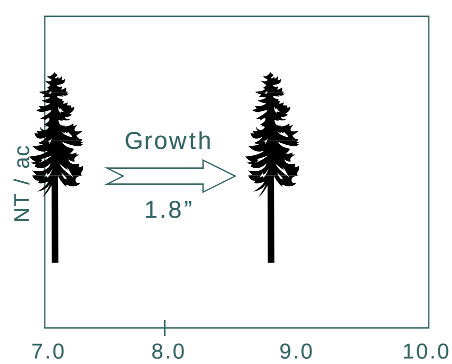
Using diameter class data

- Let's say that all the 8 inch class trees 10 years ago:
  - There were 32
  - 2 of them died
  - The average 10 year diameter growth was 1.80 inches
- The 30 live trees are uniformly distributed between 7.1 and 9.0 inches (in the 8 inch class)



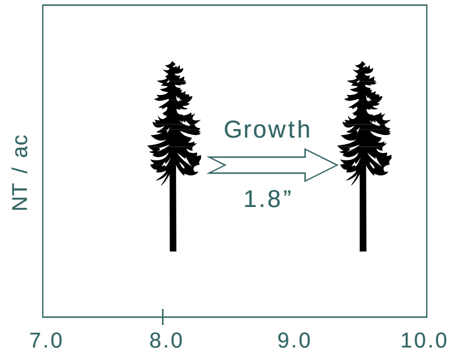
Visualizing a "movement ratio"

- The 30 live 8" trees all grow 1.8 inches
  - A tree that started at 7.1 inches grows to 8.9 inches, and doesn't leave the 8" class



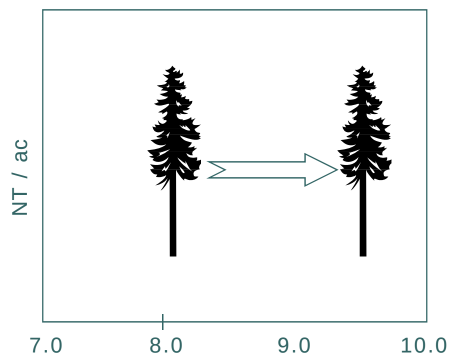
Visualizing a "movement ratio"

- The 30 live 8" trees all grow 1.8 inches
  - A tree that started at 7.1 inches grows to 8.9 inches, and doesn't leave the 8" class
  - A tree that starts at 8.0 inches grows to 9.8 inches, and moves to the 10" dbh class



Visualizing a "movement ratio"

- The 30 live 8" trees all grow 1.8 inches
  - A tree that started at 7.1 inches grows to 8.9 inches, and doesn't leave the 8" class
  - A tree that starts at 8.0 inches grows to 9.8 inches, and moves to the 10" dbh class
- A movement ratio can be calculated based on the "uniform" distribution of trees…



Movement ratio

- Relates width of DBH class to growth within a DBH class and predicts the percent of stems that move
- M=G/W where,
  - G = growth in a dbh class
  - W = width of DBH class
- Interpreting the movement ratio
  - M = X.Y
    - .Y = fraction of stems that move X+1 DBH classes
    - 1 - .Y = fraction of stems that move X DBH classes
  - If M = 1.2 then
    - .2 or 20% of stems move 1+1 = 2 DBH classes
    - 1 - .2 =0.8 or 80% of stems move 1 DBH class

Ingrowth, mortality and harvest in stand table proj.

- Best to estimate from inventory
  - Assumes mortality over next period of time same as last
- May be modeled from secondary source
- Ingrowth data exogenous
  - From inventory, or other data model
- Harvest is determined by simply deducted planned harvest in each diameter class over next time period

Stand table projection

		Mean 10 yr	Movement	Percent of trees moving				Number of trees moving				Future	Future
DBH Class	NT / ac	Increment	Ratio	0	1	2	3	0	1	2	3	DBH Class	NT / ac
4	11.3	1.2	0.6										
6	15.4	1.9	0.95										
8	31.7	2.5	1.25										
10	21.4	3.1											
12	14.2	3.9											
14	8.9	4.6											
16	3.1	5.1											
18	0												
20	0												
22	0												
24	0												

- Initial diameter distribution and growth increment
- Step 1: Calculate movement ratio for each dbh class

Stand table projection

		Mean 10 yr	Movement	Percent of trees moving				Number of trees moving				Future	Future
DBH Class	NT / ac	Increment	Ratio	0	1	2	3	0	1	2	3	DBH Class	NT / ac
4	11.3	1.2	0.6										
6	15.4	1.9	0.95										
8	31.7	2.5	1.25	0	0.75	0.25	0	0	23.8	7.9	0		
10	21.4	3.1	1.55										
12	14.2	3.9	1.95										
14	8.9	4.6	2.3										
16	3.1	5.1	2.55										
18	0												
20	0												
22	0												
24	0												

- Remember movement ratio format = X.Y
  - .Y fraction of stems move X+1 classes
  - 1 - .Y fraction of stems move X classes
- Step 2: Calculate percent of trees and number of trees moving into larger classes
  - For example, the 8” DBH class…

Stand table projection

		Mean 10 yr	Movement	Percentage of trees moving				Number of trees moving				Future	Future
DBH Class	NT / ac	Increment	Ratio	0	1	2	3	0	1	2	3	DBH Class	NT / ac
4	11.3	1.2	0.6	40	60	0	0	4.5	6.8	0.0	0.0	4.0	
6	15.4	1.9	0.95	5	95	0	0	0.8	14.6	0.0	0.0	6.0	
8	31.7	2.5	1.25	0	75	25	0	0.0	23.8	7.9	0.0	8.0	
10	21.4	3.1	1.55	0	45	55	0	0.0	9.6	11.8	0.0	10.0	
12	14.2	3.9	1.95	0	5	95	0	0.0	0.7	13.5	0.0	12.0	17.5
14	8.9	4.6	2.3	0	0	70	30	0.0	0.0	6.2	2.7	14.0	
16	3.1	5.1	2.55	0	0	45	55	0.0	0.0	1.4	1.7	16.0	
18	0											18.0	
20	0											20.0	
22	0											22.0	
24	0											24.0	

- Step 3, determine future number of trees in each dbh class in future…
  - Example, future NT / ac in 12” class
  - 0.0 + 9.6 + 7.9 + 0.0 = 17.5 (actually, 17.6)
  - Adding diagonally, top right to bottom left

Stand table projection

		Mean 10 yr	Movement	Percentage of trees moving				Number of trees moving				Future	Future
DBH Class	NT / ac	Increment	Ratio	0	1	2	3	0	1	2	3	DBH Class	NT / ac
4	11.3	1.2	0.6	40	60	0	0	4.5	6.8	0.0	0.0	4.0	4.5
6	15.4	1.9	0.95	5	95	0	0	0.8	14.6	0.0	0.0	6.0	7.6
8	31.7	2.5	1.25	0	75	25	0	0.0	23.8	7.9	0.0	8.0	14.6
10	21.4	3.1	1.55	0	45	55	0	0.0	9.6	11.8	0.0	10.0	23.8
12	14.2	3.9	1.95	0	5	95	0	0.0	0.7	13.5	0.0	12.0	17.6
14	8.9	4.6	2.3	0	0	70	30	0.0	0.0	6.2	2.7	14.0	12.5
16	3.1	5.1	2.55	0	0	45	55	0.0	0.0	1.4	1.7	16.0	13.5
18	0											18.0	6.2
20	0											20.0	4.1
22	0											22.0	1.7
24	0											24.0	0.0

- Now, we must apply mortality and harvest data, and calculate volumes…

Stand table projection

DBH Class	Initial NT /ac	Future NT / ac	Number Mortality	Number Harvested	Residual Stand	Volume Per tree	Initial Volume	Mortality Volume	Harvest Volume	Residual Volume
4	11.3	4.5				0				
6	15.4	7.6				0				
8	31.7	14.6				0				
10	21.4	23.8				36				
12	14.2	17.6				75				
14	8.9	12.5				114				
16	3.1	13.5				185				
18	0.0	6.2				280				
20	0.0	4.1				364				
22	0.0	1.7				458				
24	0.0	0.0				558				

- Step 4: add number of stems in each diameter class that are expected to die…

Stand table projection

DBH Class	Initial NT /ac	Future NT / ac	Number Mortality	Number Harvested	Residual Stand	Volume Per tree	Initial Volume	Mortality Volume	Harvest Volume	Residual Volume
4	11.3	4.5	2.4			0				
6	15.4	7.6	1.9			0				
8	31.7	14.6	1.2			0				
10	21.4	23.8	0.9			36				
12	14.2	17.6	0.7			75				
14	8.9	12.5	0.4			114				
16	3.1	13.5	0.2			185				
18	0.0	6.2	0.1			280				
20	0.0	4.1	0.1			364				
22	0.0	1.7	0			458				
24	0.0	0.0	0			558				

- Step 5: add number of stems in each diameter class that are expected to be harvested

Stand table projection

DBH Class	Initial NT /ac	Future NT / ac	Number Mortality	Number Harvested	Residual Stand	Volume Per tree	Initial Volume	Mortality Volume	Harvest Volume	Residual Volume
4	11.3	4.5	2.4	0		0				
6	15.4	7.6	1.9	2		0				
8	31.7	14.6	1.2	4		0				
10	21.4	23.8	0.9	6		36				
12	14.2	17.6	0.7	4		75				
14	8.9	12.5	0.4	3		114				
16	3.1	13.5	0.2	2		185				
18	0.0	6.2	0.1	2		280				
20	0.0	4.1	0.1	1		364				
22	0.0	1.7	0	0		458				
24	0.0	0.0	0	0		558				

- Step 6: Subtract mortality and harvest from each dbh class to obtain residual stand…

Stand table projection

DBH Class	Initial NT /ac	Future NT / ac	Number Mortality	Number Harvested	Residual Stand	Volume Per tree	Initial Volume	Mortality Volume	Harvest Volume	Residual Volume
4	11.3	4.5	2.4	0	2.1	0				
6	15.4	7.6	1.9	2	3.7	0				
8	31.7	14.6	1.2	4	9.4	0				
10	21.4	23.8	0.9	6	16.9	36				
12	14.2	17.6	0.7	4	12.9	75				
14	8.9	12.5	0.4	3	9.1	114				
16	3.1	13.5	0.2	2	11.3	185				
18	0.0	6.2	0.1	2	4.1	280				
20	0.0	4.1	0.1	1	3.0	364				
22	0.0	1.7	0	0	1.7	458				
24	0.0	0.0	0	0	0.0	558				

- Step 7: Use volume per tree to determine initial volume, mortality volume, harvest volume, and residual volume

Stand table projection

DBH Class	Initial NT /ac	Future NT / ac	Number Mortality	Number Harvested	Residual Stand	Volume Per tree	Initial Volume	Mortality Volume	Harvest Volume	Residual Volume
4	11.3	4.5	2.4	0	2.1	0	0	0	0	0
6	15.4	7.6	1.9	2	3.7	0	0	0	0	0
8	31.7	14.6	1.2	4	9.4	0	0	0	0	0
10	21.4	23.8	0.9	6	16.9	36	770	32	216	608
12	14.2	17.6	0.7	4	12.9	75	1065	53	300	964
14	8.9	12.5	0.4	3	9.1	114	1015	46	342	1035
16	3.1	13.5	0.2	2	11.3	185	574	37	370	2089
18	0.0	6.2	0.1	2	4.1	280	0	28	560	1156
20	0.0	4.1	0.1	1	3.0	364	0	36	364	1079
22	0.0	1.7	0	0	1.7	458	0	0	0	781
24	0.0	0.0	0	0	0.0	558	0	0	0	0
							3424	232	2152	7712

- You are finished!
  - Note that
    - Initial basal area 52 sq. ft. per acre
    - Residual basal area 67 sq. ft. per acre
  - Stand table projection ideally suited for spreadsheet!

"Biologically optimal" rotation length

Determining rotation length

- When do we conduct a "regeneration harvest" and start the next generation of trees?
- We'll start with a simple stand-level concept of optimizing long-term volume production
  - Then include financial considerations for single trees, groups of trees, stands, and whole forests.

Look at yield table

- If we look at SI = 60:
  - What's better?
    - 50 year rotation that produces 2275 cubic feet?
    - 100 year rotation that produces 3766 cubic feet?
    - 200 year rotation that produces 4846 cubic feet?
- Let's assume we want to maximize long-term cubic foot production…

Age	SI 40	SI 60	SI 80
10	24	40	58
20	302	501	718
30	700	1162	1663
40	1066	1768	2532
50	1371	2275	3257
60	1622	2691	3853
70	1829	3034	4345
80	2002	3320	4754
90	2147	3561	5099
100	2271	3766	5392
110	2377	3943	5645
120	2470	4096	5865
130	2551	4231	6058
140	2622	4349	6228
150	2686	4455	6379
160	2743	4550	6515
170	2794	4635	6636
180	2841	4712	6747
190	2883	4782	6847
200	2921	4846	6938

Normal yield table and normal yield equation

$$Y = 37.658 S^{1.2479} e^{\left[\frac{-50.412}{A}\right]}$$

This equation is differentiable! First derivative of yield with respect to age is growth or current annual increment?

Biological rotation

- Maximization of volume production is typically called “biologically optimal rotation.”
  - *Yes, it is a “timber focused” term that ignores all other aspects of the terrestrial ecosystem*
- Optimization of volume production over multiple rotations, rather than a single rotation
- The criteria that maximizes long term sustained volume production is mean annual increment
  - Assumes productivity of land is sustained

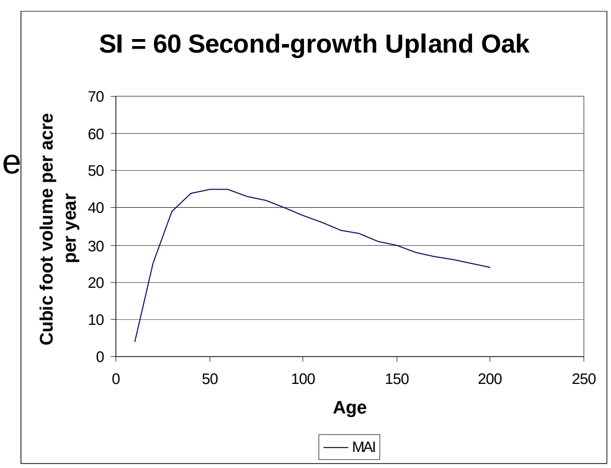
Mean annual increment

$$MAI = \frac{V_A}{A}$$

Where V_A = volume at age A
A = stand age

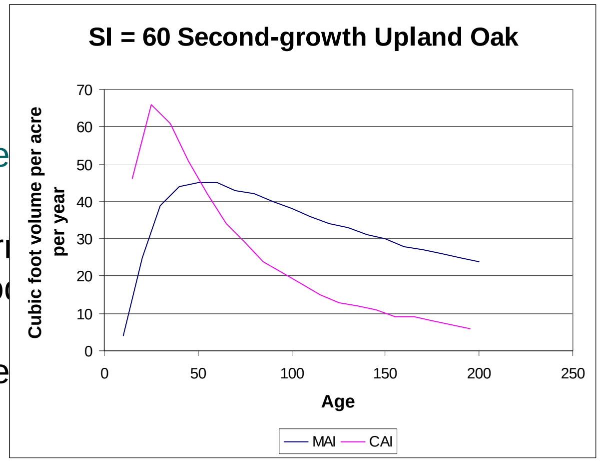
Finding maximum MAI

- Mean annual increme plotted



Finding maximum MAI

- Mean annual increme plotted
- Plot curr or period annual increme



Maximum mean annual increment

- MAI is maximized at age where:
  - MAI = CAI
  - MAI = PAI (remember PAI ~ CAI)
- Remember, PAI is a periodic estimation of current annual increment

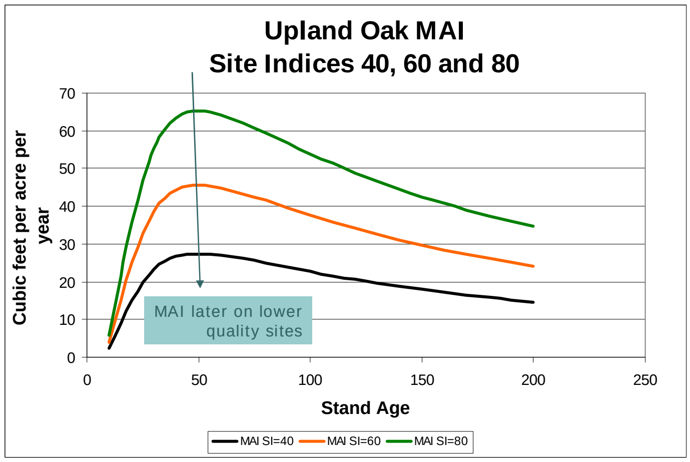
MAI maximized

- In our example:
  - MAI maximized at 50 years
  - MAI maximum is 45 cubic feet per acre per year
- What does this mean?
  - That a rotation of 50 years will maximize cubic foot volume production of oak over any number of rotations and that production rate will be 45 cubic feet per acre per year.

MAI dependent on site

- The higher the site quality, the faster MAI will culminate
- Generally:
  - $MAI_{SI = 40} > MAI_{SI = 60} > MAI_{SI = 80}$

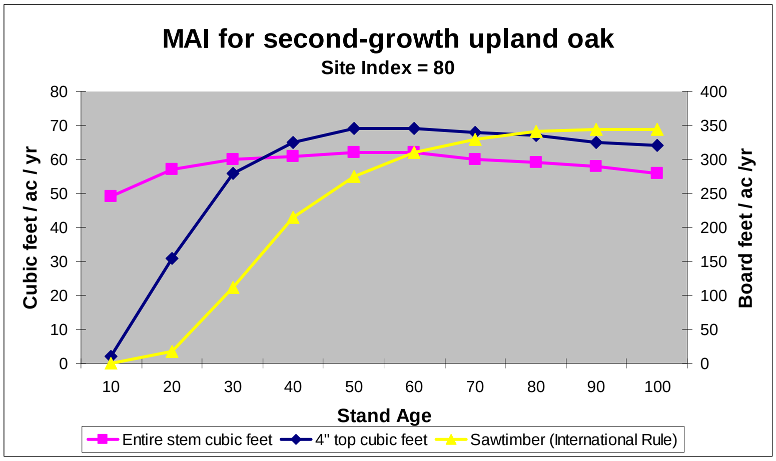
Optimal MAI culminates faster on better sites…



MAI dependent on product

- The larger the diameter requirements for a product, the longer MAI will take to maximize
- Generally:
  - $MAI_{\text{cubic feet}} < MAI_{\text{cords}} < MAI_{\text{sawtimber}}$

MAI culminates later for sawtimber…



Next lecture: more on "optimal" rotation length for trees and forests…