Uneven-aged management, economics, tree diversity, and the supply of carbon storage

Joseph Buongiorno, Espen Halvorsen,
Ole Martin Bollandås, Terje Gobakken,
Ole Hofstad

From even to uneven-aged

=>

Norway spruce

Spruce, pine, birch, etc…

Non-timber values

Willow Tit (Poecile montanus)

Industries

11% of Norway’s exports

Management criteria

Economic:

Net present value (NPV)

Production

Ecological:

Diversity of tree

Species

Size

$$H = -\sum_i p_i \ln(p_i)$$

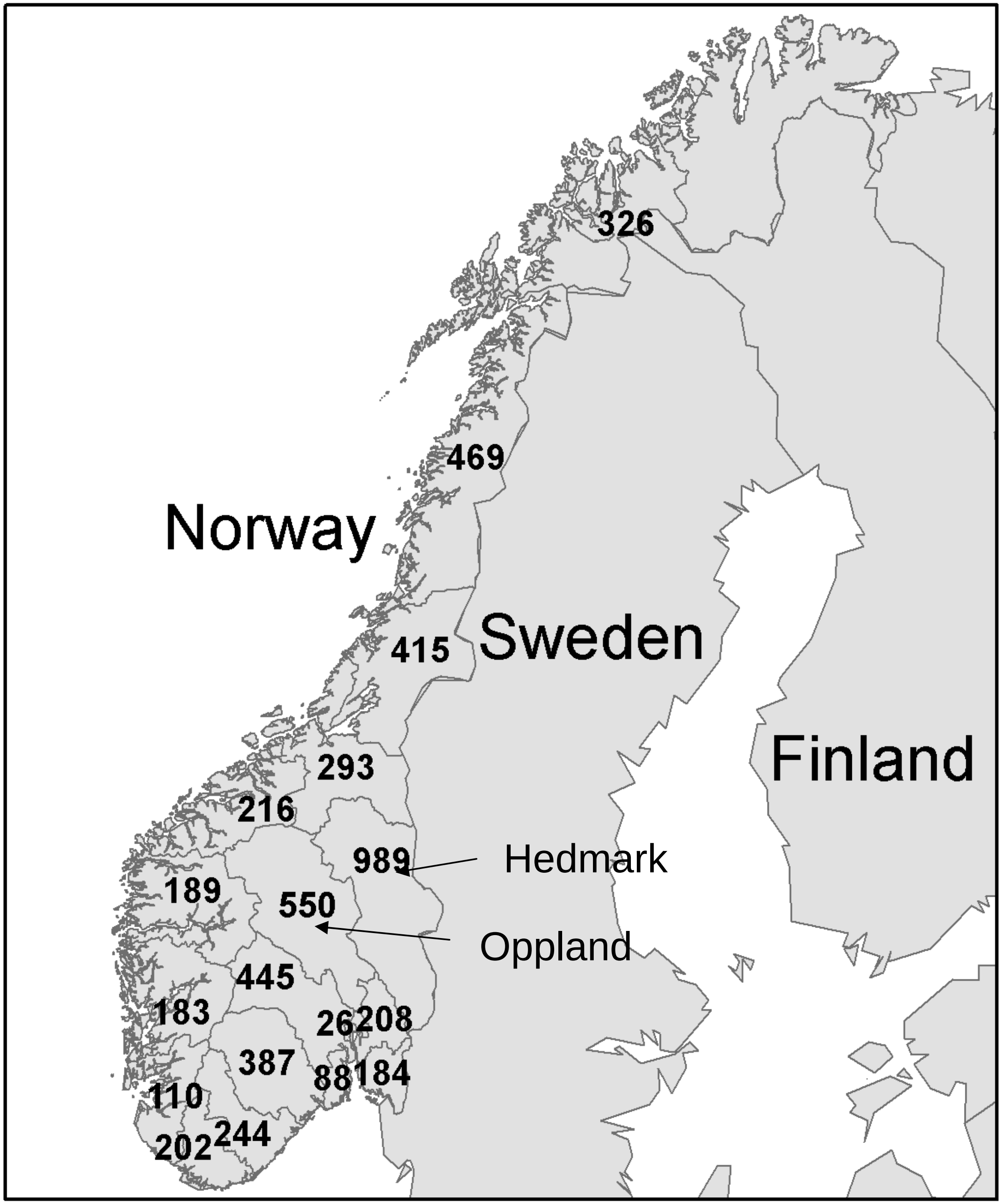
Climatic: CO_2 sequestration

5524 plots

416 for validation

1994 to 2005

Every 5 years



Mixed spruce-pine-birch-hardwoods stands

Norway spruce (38%)
(Picea abies)

Scots pine (16%)
(Pinus sylvestris)

Birch (35%)
(Betula pubescent or pendula)

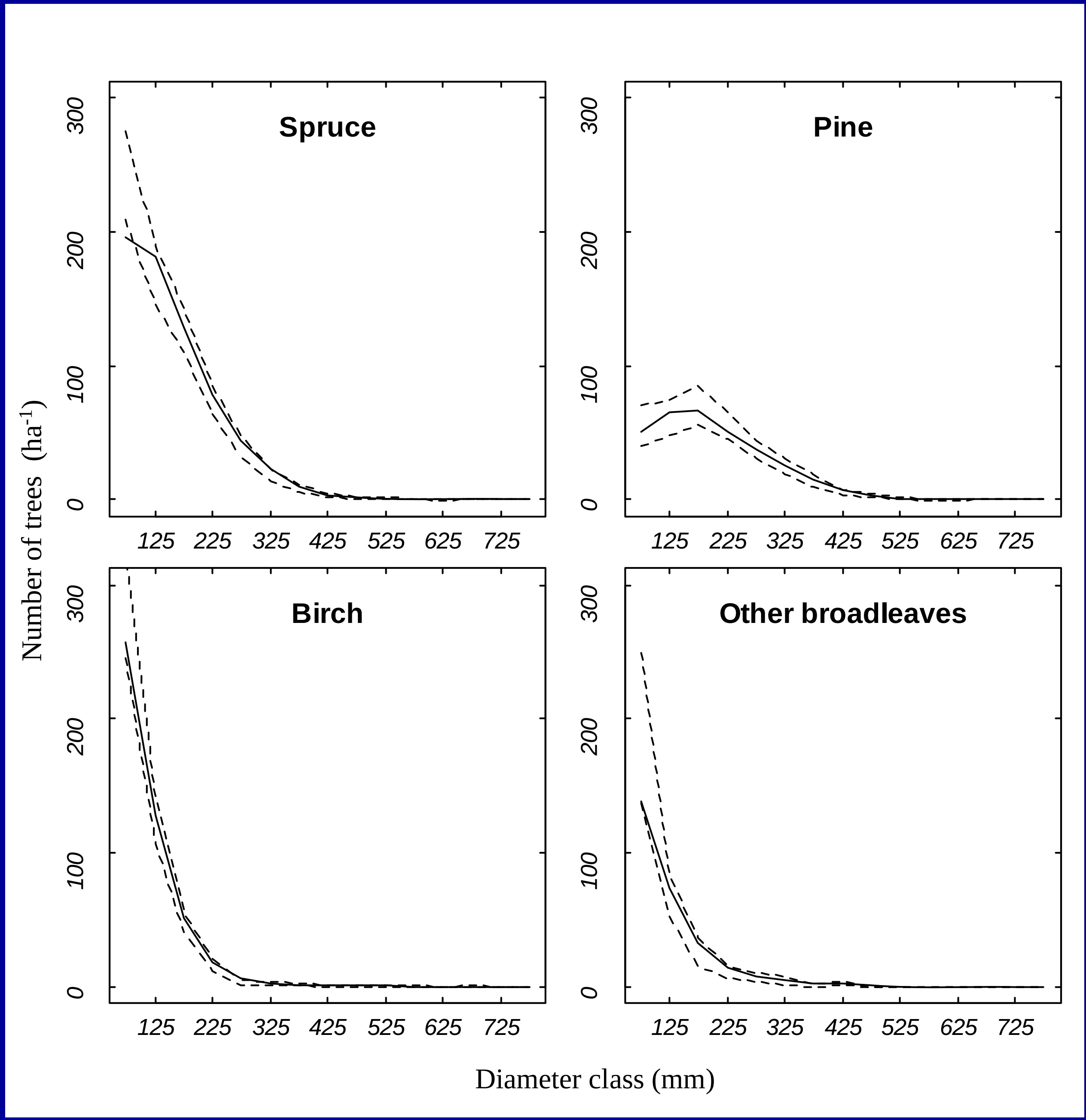
Other broadleaves (11%)
Alder (Alnus spp.)
Ash (Fraxinus excelsior)
Aspen (Populus tremula)
…

Stand growth model

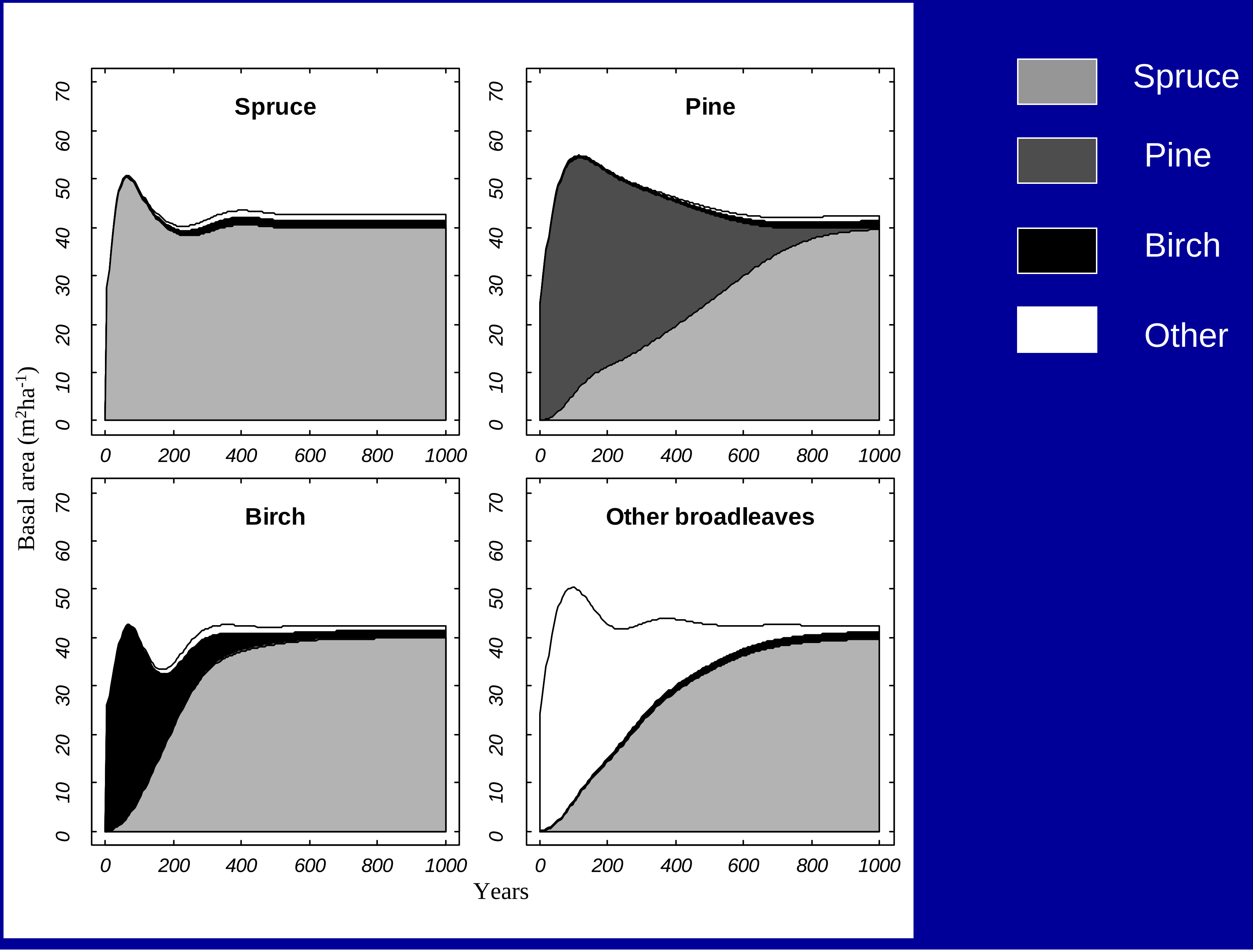
$$\mathbf{y}_{t+5} = \mathbf{G}_t \left(\mathbf{y}_t - \mathbf{h}_t\right) + \mathbf{r}_t$$

$$\mathbf{y}_t = \left\{ \begin{array}{ll} \text{Spruce} & 75, 125, \ldots, 675 \text{ mm} \\ \text{Pine} & 75, 125, \ldots, 675 \text{ mm} \\ \text{Birch} & 75, 125, \ldots, 675 \text{ mm} \\ \text{Other} & 75, 125, \ldots, 675 \text{ mm} \end{array} \right\}$$

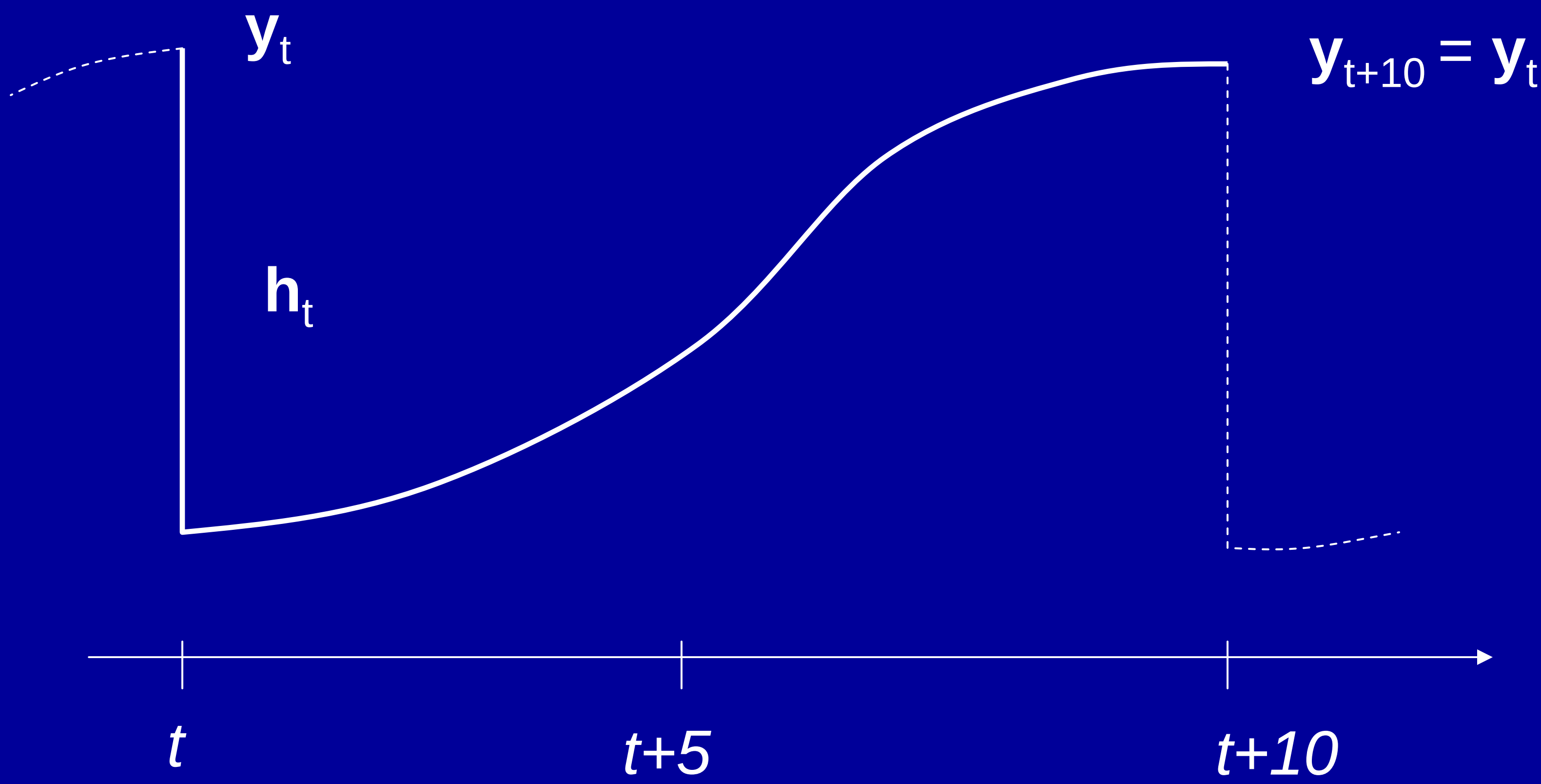
Predicted vs observed, 10 year projections



Long-term projections



Sustainable management



Policies

EXTREME

- Max Timber $
- Max CO_2 storage

COMPROMISES

- Max Timber $ with CO_2 constraint
- Max CO_2 with NPV constraint

COMBINATION

- Max NPV (Timber AND CO_2)

Timber production

Max timber revenue

$$\max_{\mathbf{h}_t,\mathbf{y}_t} NPV = \mathbf{v}\mathbf{h}_t + \frac{\mathbf{v}\mathbf{h}_t}{(1+r)^{5n}-1} - \mathbf{v}\mathbf{y}_t$$

Stand growth:

$$\mathbf{y}_{t+5} = \mathbf{G}_t(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{r}_t \qquad t = 0,5,\ldots,20$$

Steady state:

$$\mathbf{y}_{t+20} = \mathbf{y}_t$$

Feasibility:

$$\mathbf{0} \le \mathbf{h}_t \le \mathbf{y}_t$$

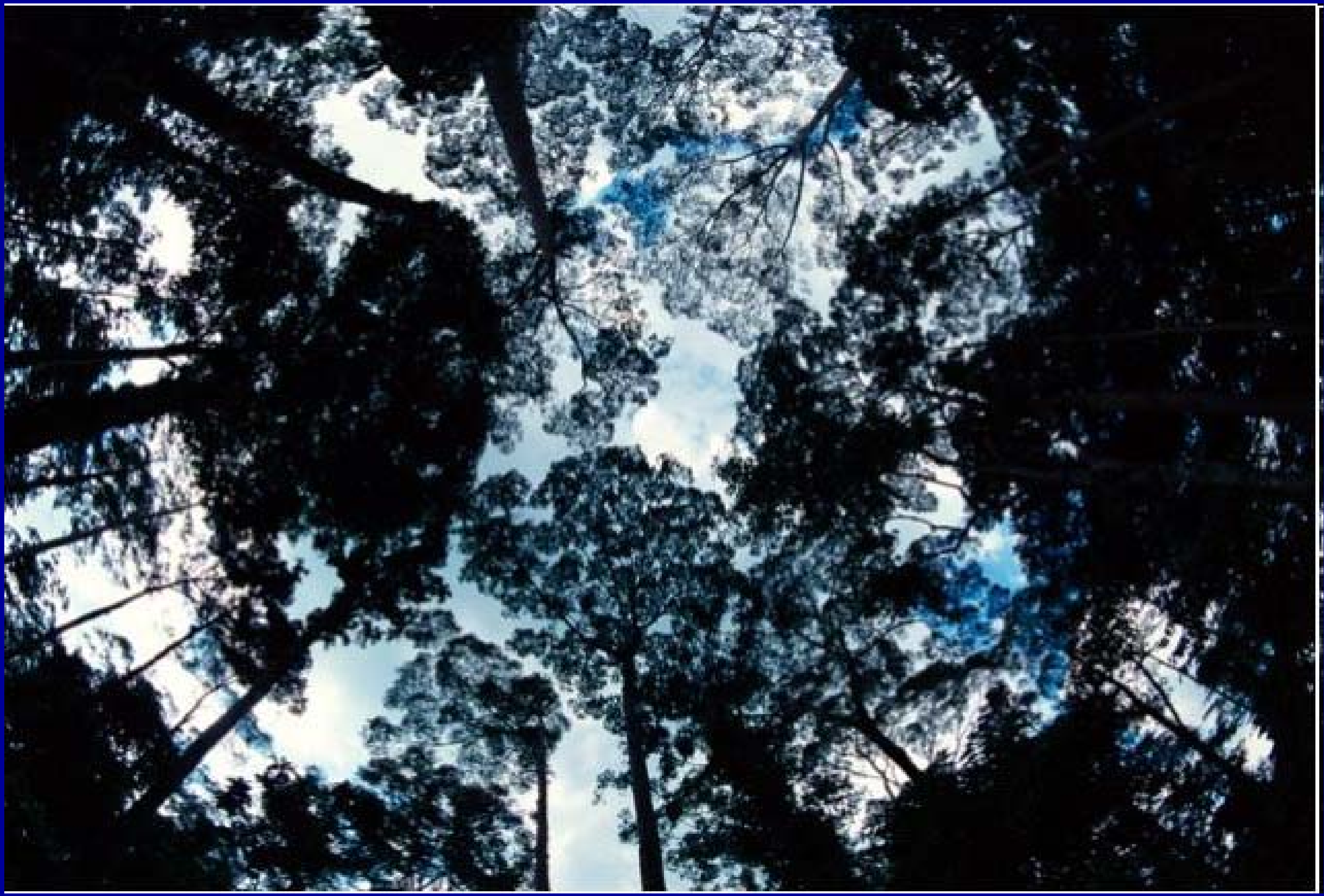
Max Timber NPV, 20 year cycle

		75	125	175	225	275	325	375	425
		------------------------Trees/ha---------------------------							
Spruce	**Stock**	**164**	**138**	**123**	**106**	**77**	**40**	**12**	**1**
	Harvest				52	77	40	12	1
Pine	**Stock**	**2**	**2**	**2**	**1**	**1**			
	Harvest				1	1			
Birch	**Stock**	**61**	**33**	**10**	**2**				
	Harvest		33	10	2				
Other	**Stock**	**84**	**54**	**32**	**14**	**4**			
	Harvest			32	14	4			

Maximum timber NPV

		Cutting cycle	
		5 year	20 year
NPV	($/ha)	6800	6300
CO_2 stored	(t/ha)	162	196
Stock value	($/ha)	3300	4500
Harvest	(m^3/ha/yr)	6.2	6.3
Species diversity		0.3	0.4
Size diversity		0.6	0.7

CO_2 storage



Max CO_2 sequestration

$$\max_{\mathbf{h}_t, \mathbf{y}_t} C = \mathbf{c}(\mathbf{y}_t - \mathbf{h}_t)$$

Stand growth:

$$\mathbf{y}_{t+5} = \mathbf{G}_t(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{r}_t \qquad t = 0,5,\ldots,20$$

Steady state:

$$\mathbf{y}_{t+20} = \mathbf{y}_t$$

Feasibility:

$$\mathbf{0} \leq \mathbf{h}_t \leq \mathbf{y}_t$$

Max CO_2 sequestration

		Diameter class (mm)											
		75	125	175	225	275	325	375	425	475	525	575	625
		----------------------------------Trees/ha----------------------------------											
Spruce	**Stock**	**264**	**127**	**85**	**67**	**57**	**51**	**47**	**43**	**38**	**30**	**18**	**5**
	Harvest												
Pine	**Stock**												
	Harvest												
Birch	**Stock**	**4**											
	Harvest	4											
Other	**Stock**	**4**											
	Harvest	4											

Maximum CO_2 sequestration

		Cutting cycle	
		5 year	20 year
NPV	($/ha)	-23000	id.
CO_2 stored	(t/ha)	630	id.
Stock value	($/ha)	-23000	id.
Harvest	(m^3/ha/yr)	0.06	id.
Species diversity		0.00	id.
Size diversity		0.92	id.

Carbon storage with production

Max CO_2 with r^*

$$\max_{\mathbf{h}_t,\mathbf{y}_t} C = \mathbf{c}(\mathbf{y}_t - \mathbf{h}_t)$$

Stand growth:

$$\mathbf{y}_{t+5} = \mathbf{G}_t(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{r}_t \qquad t = 0,5,\ldots,20$$

Steady state:

$$\mathbf{y}_{t+20} = \mathbf{y}_t$$

Feasibility:

$$\mathbf{0} \leq \mathbf{h}_t \leq \mathbf{y}_t$$

AND:

$$\mathbf{vh}_t + \frac{\mathbf{vh}_t}{(1+r^*)^{5n} - 1} - \mathbf{vy}_t = O$$

Max CO_2 with r^*=3%, 20 year cycle

		75	125	175	225	275	325	375	425	475	525
		-----------------------------------Trees/ha---------------------------------									
Spruce	**Stock**	**205**	**147**	**121**	**105**	**94**	**85**	**67**	**38**	**12**	**2**
	Harvest							56	38	12	2
Pine	**Stock**	**1**	**1**								
	Harvest										
Birch	**Stock**	**32**	**21**	**9**	**3**						
	Harvest			9	3						
Other	**Stock**	**28**	**14**	**5**	**2**						
	Harvest			5	2						

Maximum CO_2 with *r**=3%

		Cutting cycle	
		5 year	20 year
NPV	(\$/ha)	0	0
CO_2 stored	(t/ha)	427	434
Stock value	(\$/ha)	9500	14000
Harvest	(m^3/ha/yr)	6.3	7.5
Species diversity		0.5	0.1
Size diversity		0.8	0.8

Production with CO_2 storage

Max timber revenue with CO_2

$$\max_{\mathbf{h}_t,\mathbf{y}_t} NPV = \mathbf{vh}_t + \frac{\mathbf{vh}_t}{(1+r)^{5n}-1} - \mathbf{vy}_t$$

Subject to:

$$\mathbf{y}_{t+5} = \mathbf{G}_t(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{r}_t \qquad t = 0,5,\ldots,20$$

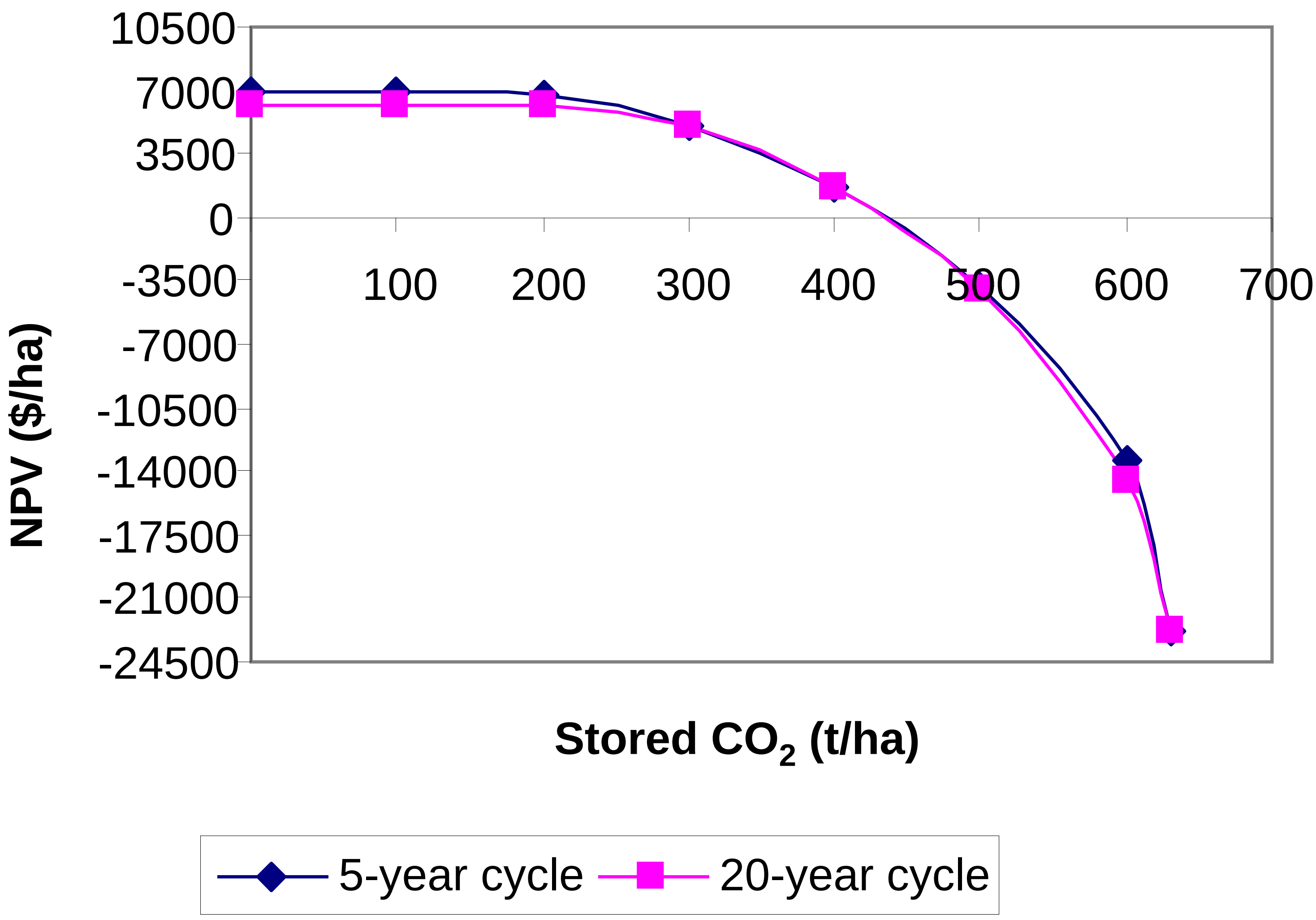
$$\mathbf{y}_{t+20} = \mathbf{y}_t$$

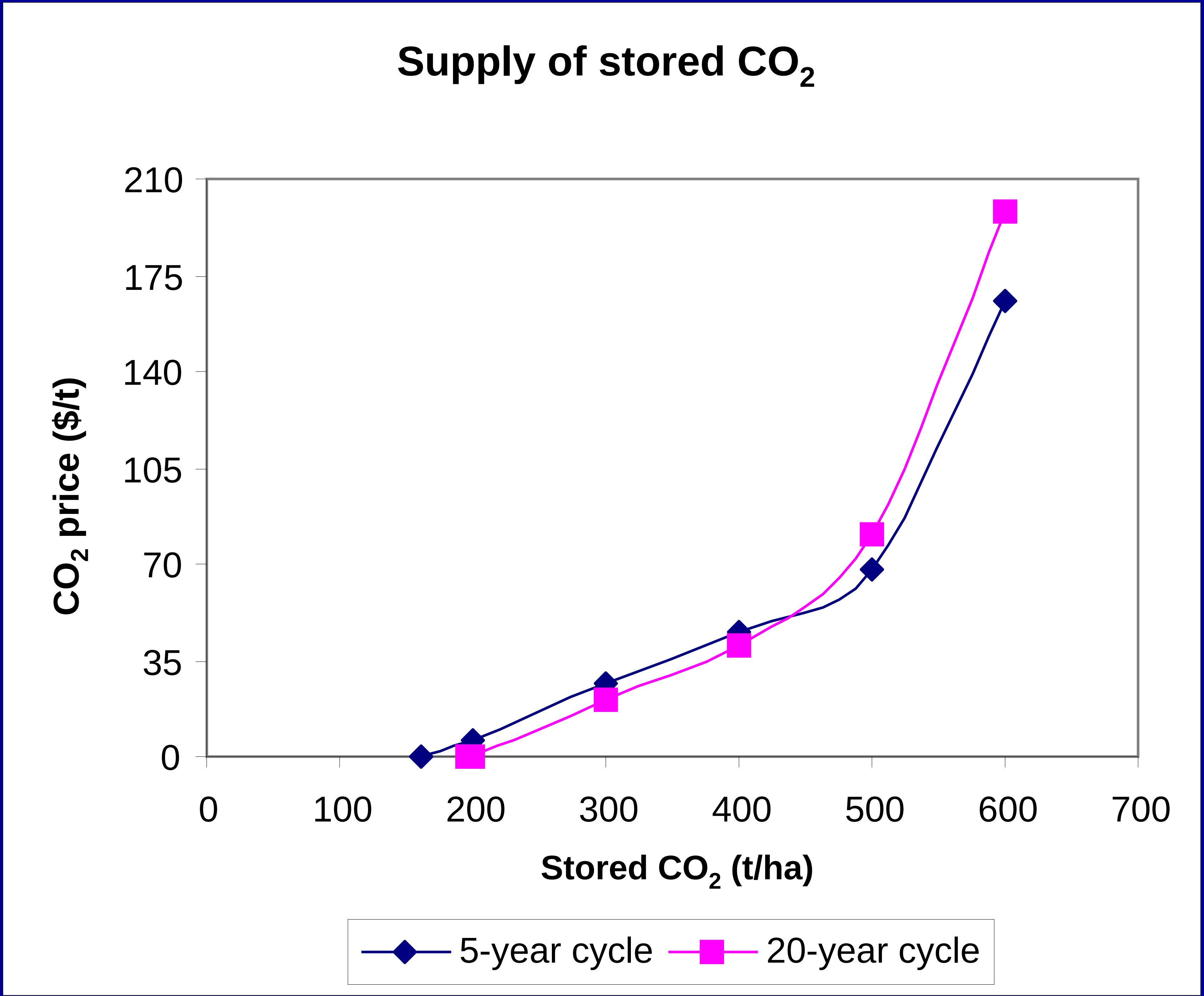
$$\mathbf{0} \le \mathbf{h}_t \le \mathbf{y}_t$$

AND:

$$\mathbf{c}(\mathbf{y}_t - \mathbf{h}_t) \ge C_{\min}$$

max NPV with CO_2 storage constraint

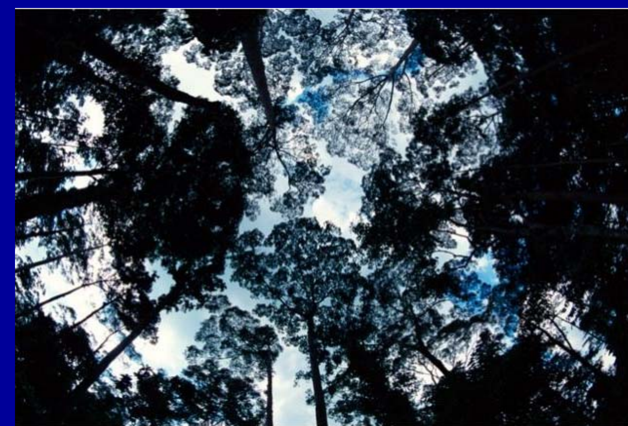


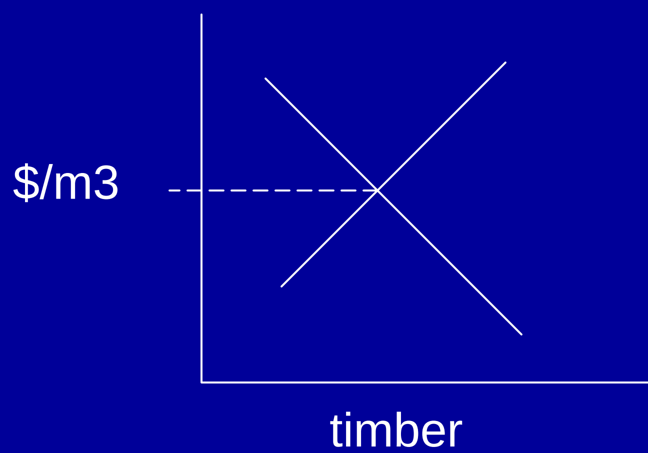


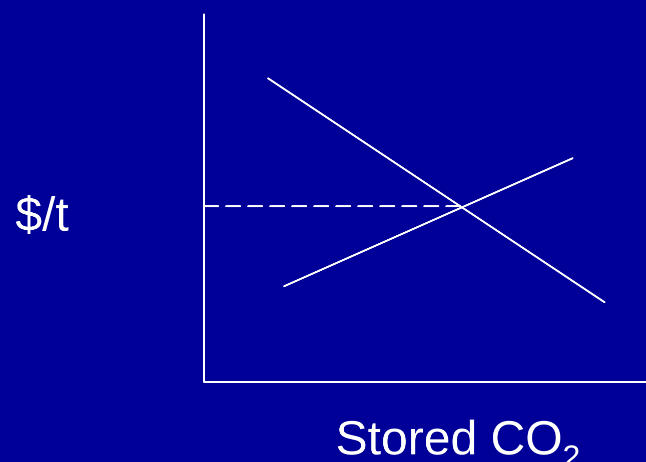
Supply of stored CO_2
210
175
140
105
70
35
0
0
100
200
300
400
500
600
700
CO_2 price ($/t)
Stored CO_2 (t/ha)
5-year cycle
20-year cycle

Production AND CO_2 storage

=







Max NPV (timber & CO_2)

$$\max_{\mathbf{h}_t,\mathbf{y}_t} NPV = \mathbf{v}\mathbf{h}_t + \frac{\mathbf{v}\mathbf{h}_t}{(1+r)^{5n}-1} - \mathbf{v}\mathbf{y}_t + q\mathbf{c}(\mathbf{y}_t - \mathbf{h}_t)$$

Stand growth:

$$\mathbf{y}_{t+5} = \mathbf{G}_t(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{r}_t \qquad t = 0,5,\ldots,20$$

Steady state:

$$\mathbf{y}_{t+20} = \mathbf{y}_t$$

Feasibility:

$$\mathbf{0} \le \mathbf{h}_t \le \mathbf{y}_t$$

Max NPV (timber &CO_2), $110/t, 20 year cycle

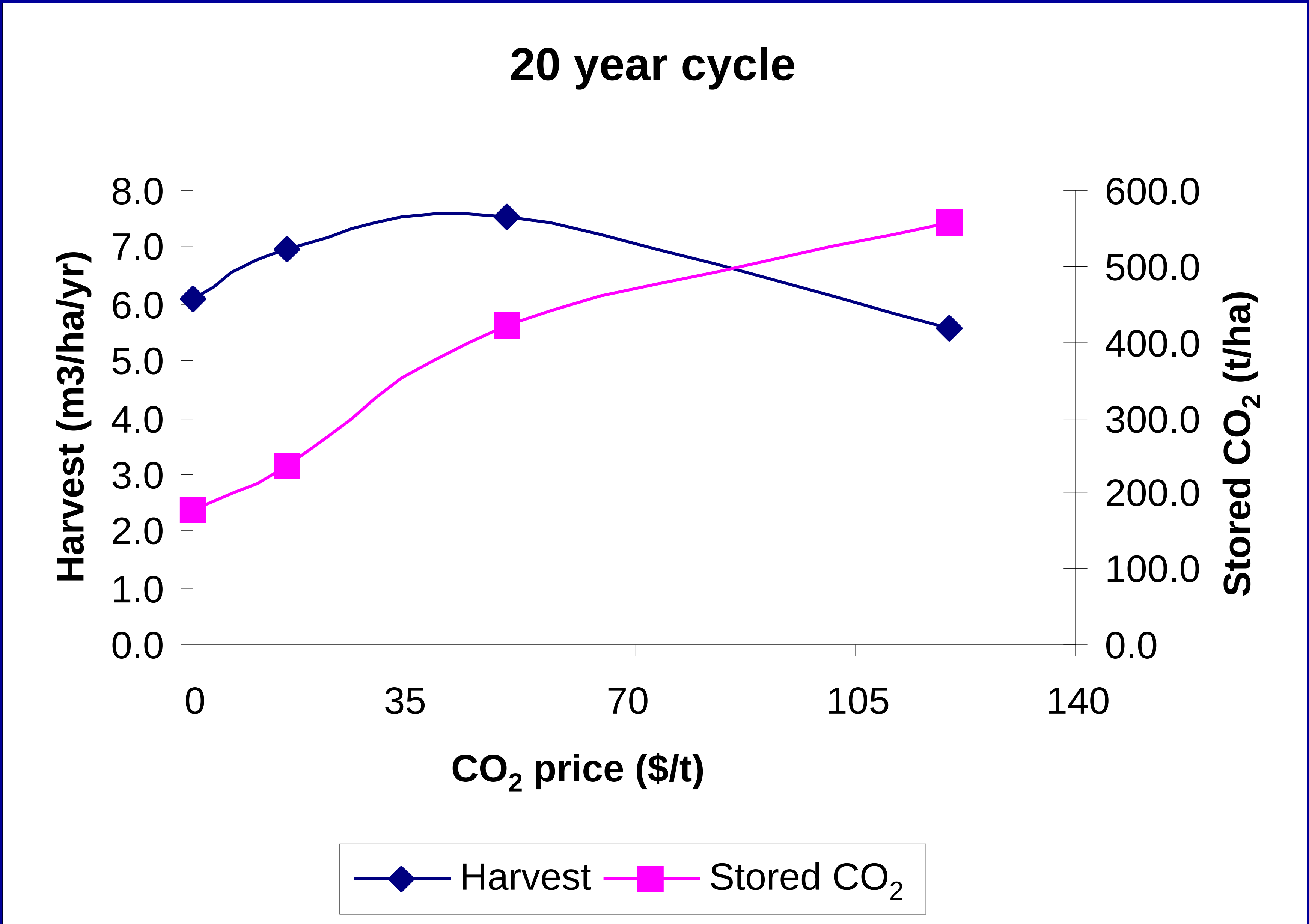
		Diameter class (mm)										
		75	125	175	225	275	325	375	425	475	525	575
		-----------------------------------Trees/ha---------------------------------										
Spruce	**Stock**	**232**	**140**	**106**	**88**	**76**	**69**	**62**	**57**	**38**	**14**	**2**
	Harvest									38	14	2
Pine	**Stock**											
	Harvest											
Birch	**Stock**	**22**	**12**	**5**	1							
	Harvest			5	1							
Other	**Stock**	**22**	**9**	**5**	**4**	**3**	**2**	**1**				
	Harvest						2	1				

IEA (2010) scenario 450 =>110 $US/t in 2030

Max NPV (timber & CO_2)

CO_2 price ($/t)	CO_2 (t/ha)	Species	Size	NPV ($/ha)	From timber
		20 year cycle			
0	177	0.30	0.72	6300	6300
15	237	0.29	0.73	9600	6100
50	421	0.16	0.80	22000	700
110	556	0.10	0.85	52000	-9000

Max NPV(timber & CO_2)



Conclusion

- Uneven-aged management is profitable
  - Short cutting cycle => Highest NPV
  - Longer cutting cycle => Higher CO_2 and diversity
- Max CO_2 storage=> pure spruce, high cost
- First 200 t/ha CO_2 are free
- Timber production and stored CO_2 both increase up to 50 $/t CO_2
- Current: $15/t CO_2e, IEA: $50/t 2020, $110/t 2030


Thank you!