Plant-soil models as tools to explain changes in forest productivity and site fertility over successive forest rotations

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Recent experimental studies have observed that soil carbon (C) and nitrogen (N) content often decline following conversion of improved pasture to *Pinus radiata* plantation. This observation has implications for carbon sequestration rates under plantation forestry and potentially for long-term sustainable forest productivity.

We apply a model of C and N cycling in grass and forest ecosystems (G'DAY) to simulate the transition from improved, legume-rich pasture to stands of *P. radiata* at a site near Masterton, New Zealand. Our aim is to quantify biogeochemical mechanisms that can lead to altered soil carbon and nitrogen cycling following afforestation. We run a series of model simulations to investigate the following key questions:

1. Is decomposition of soil organic matter slower under forest because of lower quality of tree litter relative to grass litter? If so, does soil C accumulate under forest relative to pasture? Is soil N availability decreased because of slower decomposition?
2. Is above-ground litter input increased after afforestation because grazing ceases and because the forest has higher net primary production? If so, does soil C accumulate after afforestation? Is soil N availability reduced because of higher soil N immobilisation?
3. Do the answers to questions (2) change if root C allocation or turnover are lower under forest than under pasture?
4. Do soil N mineralisation and inorganic soil N decline after afforestation due to removal of N fixing plants and grazers? Does total soil N decline? If so, is there a commensurate loss of soil carbon? Or, do soil C:N ratios increase while soil C is unchanged? Alternatively, does soil N loss lead to slower soil decomposition and hence accumulation of soil carbon?
5. Is soil N loss after afforestation beneficial to total ecosystem C storage because it leads to a shift of N from soil pools with low C:N ratios to biomass pools with high C:N ratios? If so, should some loss of soil C and N be encouraged?

We run simulations over single and multiple forest rotations to investigate the relative importance of the above 5 mechanisms and consequences for forest sustainability. Simulations over multiple rotations raise issues of C and N losses in harvested wood and from harvest residue. They also raise the question of how to define sustainable productivity in a modelling context.

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THIS TALK

- **Background:** **Pasture ®** ***Pinus radiata***

- **Hypotheses for changes in soil C and N**
    - **Altered litter quality, quantity or N cycling**

- **Simulations of soil C change**
    - **N-rich pasture ®** ***Pinus radiata***
    - **N-poor grassland ®** ***Pinus radiata***

- **Sustainable productivity**
    - **Definition of sustainability**
    - **Simulations of multiple forest rotations**

MODELS =

“framework for understanding forest response, not for predicting response”

Hypotheses for changes in C and N

1 **Low quality tree litter ® Slow decomposition**
® Increased soil C

2 **Increased litter quantity ® Increased soil C**
® Increased N immobilisation

3 Reduced soil N availability ® N loss
® Soil C loss

Supplementary questions:

1 **Consequences of reduced below-ground allocation in forest versus grass ?**

2 Is soil N loss beneficial for total C storage ?

5. Figure with Soil C at 4 *P. radiata* sites: Kaingaroa, Tikitere, Puruki, Ngnaumu

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Glenlean Site

Ngnaumu State Forest, near Masterton, New Zealand

SOIL: texture Clay:silt:sand = 20:70:10

GRASS:

- **Legume-rich pasture**
- **N fixation = 50 – 150 kg ha^{-1} yr^{-1}**
- **fertlised**
- **sheep grazing**

FOREST:

- **30 year-old**
- **1st rotation *Pinus radiata***

Soil Measurements Glenlean

	Pasture	Forest (30 yrs)
Soil inorganic N (g m^{-2})	**4.2**	**0.7**
Soil carbon 0 to 30 cm (t ha^{-1})	**105**	**104**
Soil nitrogen 0 to 30 cm (t ha^{-1})	**6.7**	**4.2**
Soil C:N ratio	**15.7**	**24.8**

8. Model schematic (G'DAY).

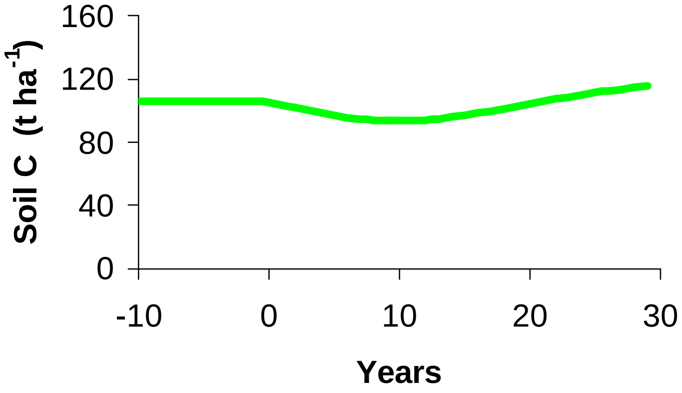
9. Simulated soil C, N, C:N, Inorganic N. Model was run to initial equilibrium for grassland. At time zero grass was killed and trees planted instantaneously! Simulation shows that soil C is maintained in spite of large N loss.

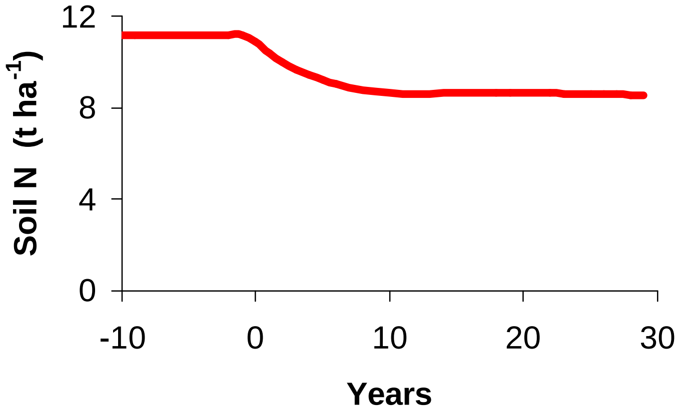
10 Simulated soil C. Figure raises the question: Is soil C change due to altered C input or altered decomposition ?

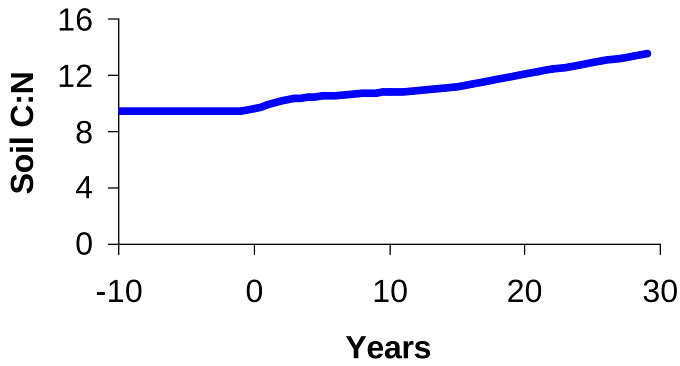
11 Is soil C change due to altered C input or altered SOM decomposition ?
 Show simulation of C input and output. Simulation indicates relatively little change in C output (i.e. decomposition). Hence change in litter quality is relatively unimportant. On the other hand C input to soil does change dramatically over the 30-yr period. That large variation in C input is likely to underlie any change in soil C. Go back to Hypotheses 2 ✓, 1 X .

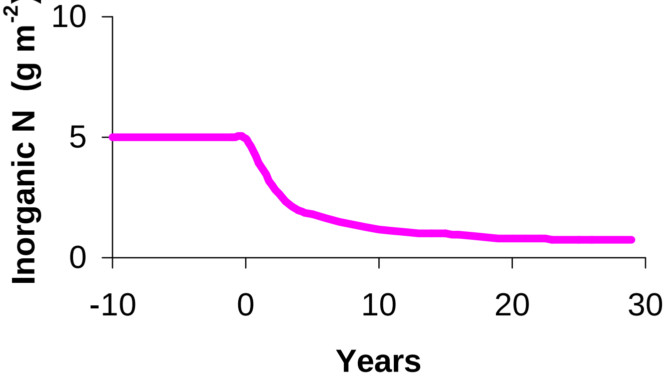
12 Increase in C input is due to increased NPP of forest relative to grass (and to cessation of grazing). Show simulated NPP

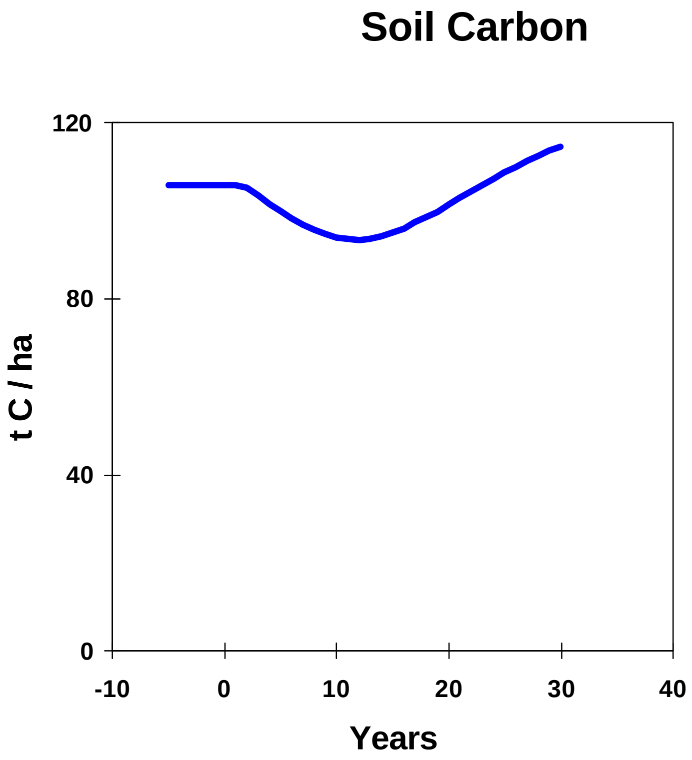
13 Simulated NPP, NUE & N uptake shows that NPP increases in spite of reduced N uptake - because of enhanced NUE.


Soil C (t ha-1)
160
120
80
40
0
-10
0
10
20
30
Years

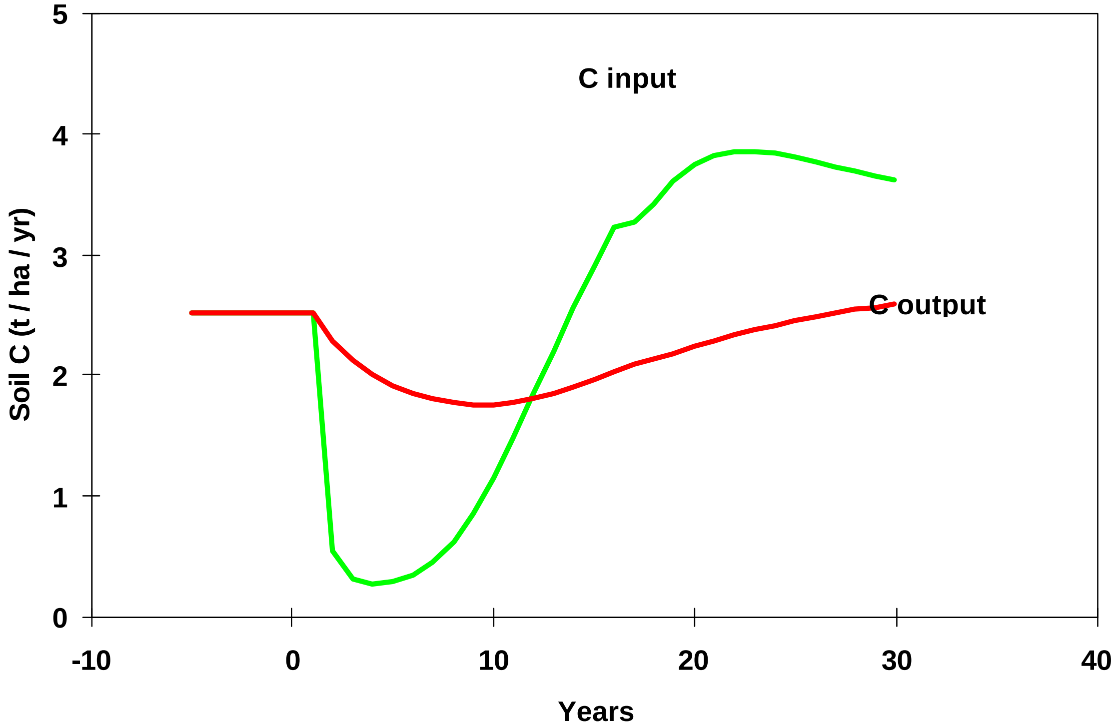

Soil N (t ha-1)
12
8
4
0
-10
0
10
20
30
Years


Soil C:N
16
12
8
4
0
-10
0
10
20
30
Years

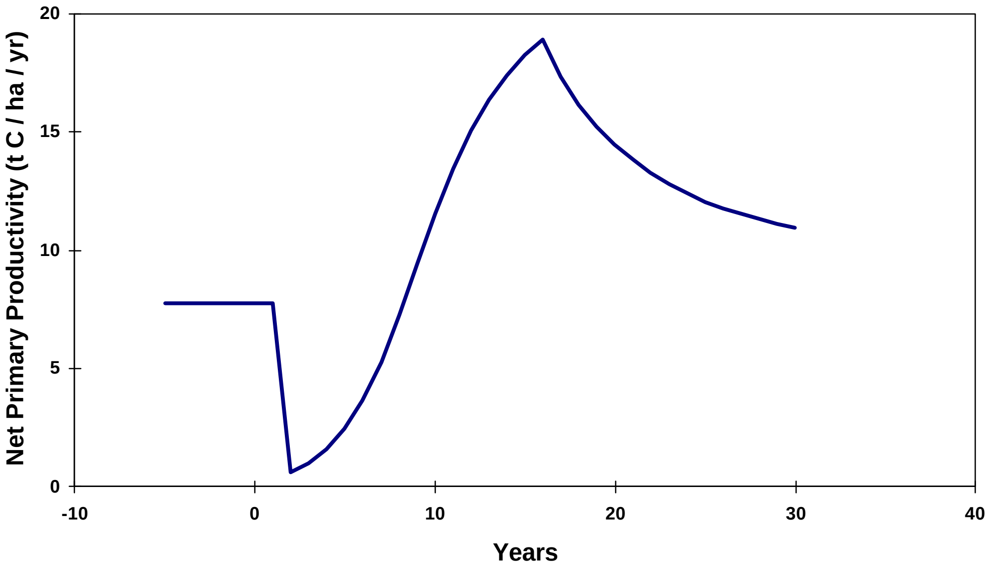

Inorganic N (g m-2)
10
5
0
-10
0
10
20
30
Years


Soil Carbon
120
80
40
0
t C / ha
-10
0
10
20
30
40
Years

Is soil C change due to altered C input or altered decomposition?



Why does litter quantity change?



Why does forest have higher NPP ?

Trick:

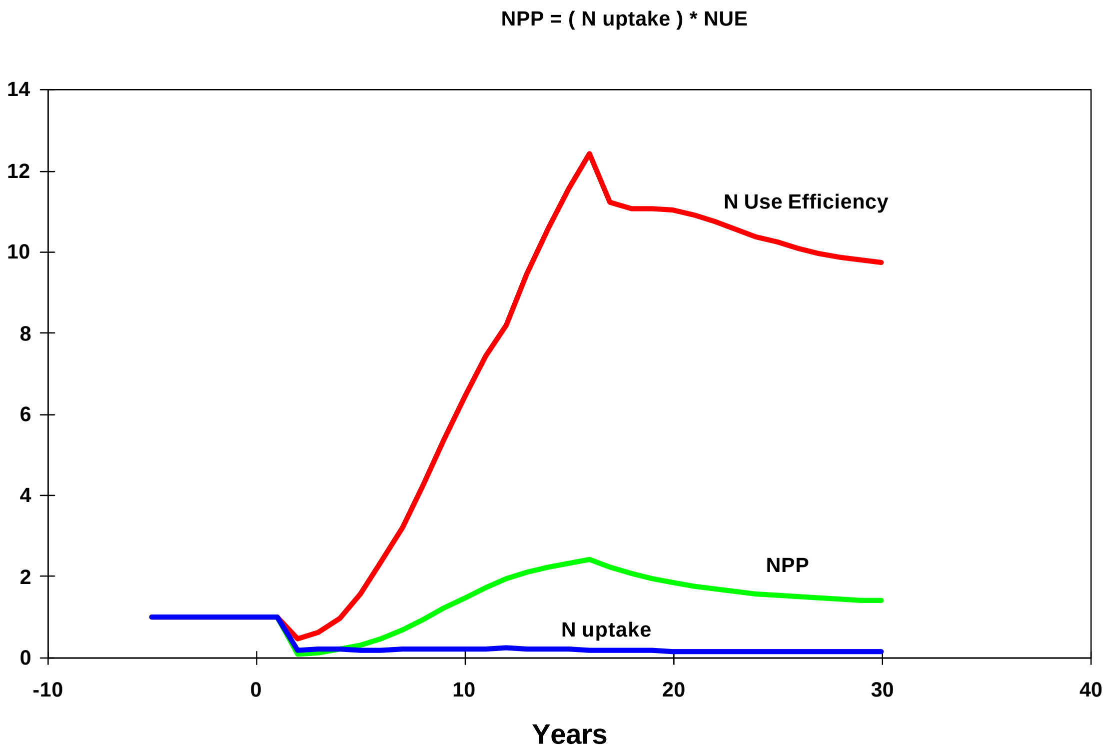
NPP = f(NPP,N uptake) * N uptake

NPP = NUE * N uptake

Is NPP increase due to:

- **Increased N use efficiency (i.e. higher plant C:N ratios) ?**

- **Increased N uptake ?**


NPP = (N uptake) * NUE
14
12
10
8
6
4
2
0
-10
0
10
20
30
40
Years
N Use Efficiency
NPP
N uptake

Effect of N loss on soil C:

If N loss were reduced, would soil C increase more ?

	30-year old forest versus	
	N-rich pasture	**N-poor grass**
Soil N	**- 24 %**	**- 4 %**
N uptake	**- 86 %**	**- 40 %**
NPP	**+ 39 %**	**+ 97 %**
NUE	**+ 970 %**	**+ 330 %**
Soil C	**+ 10 %**	**+ 19 %**
C:N	**+ 43 %**	**+ 25 %**

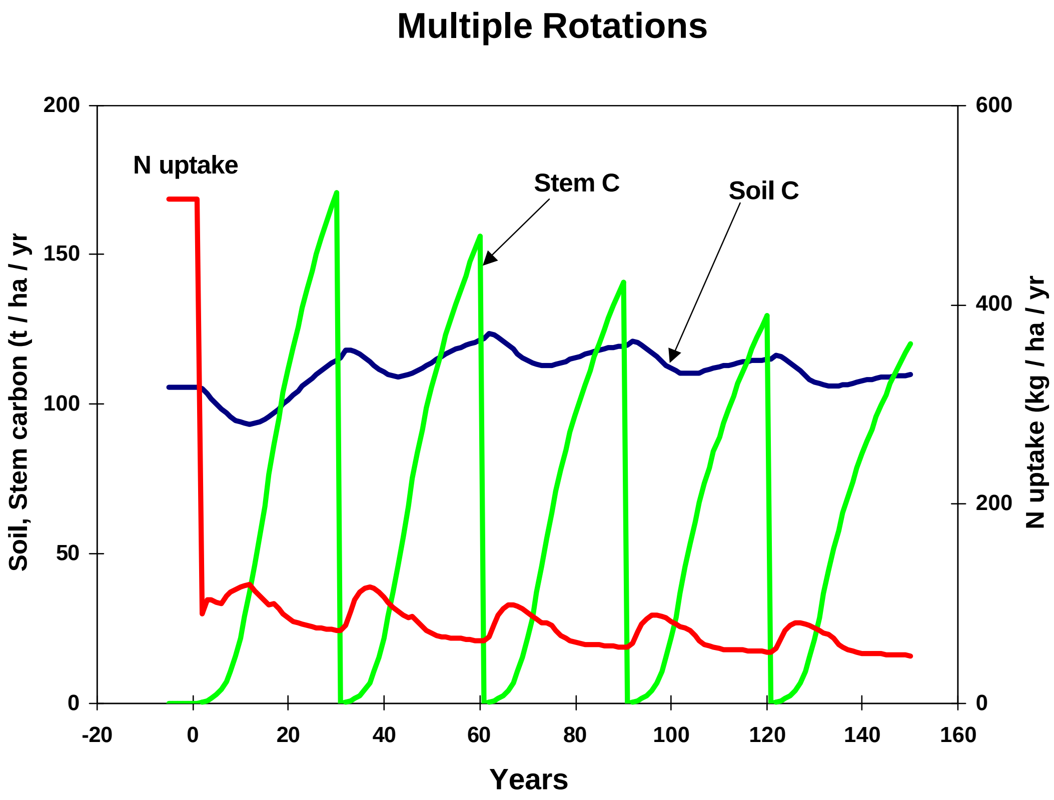
Forest Sustainability

- **How do N removals in harvesting, residue management and leaching affect long-term forest productivity ?**

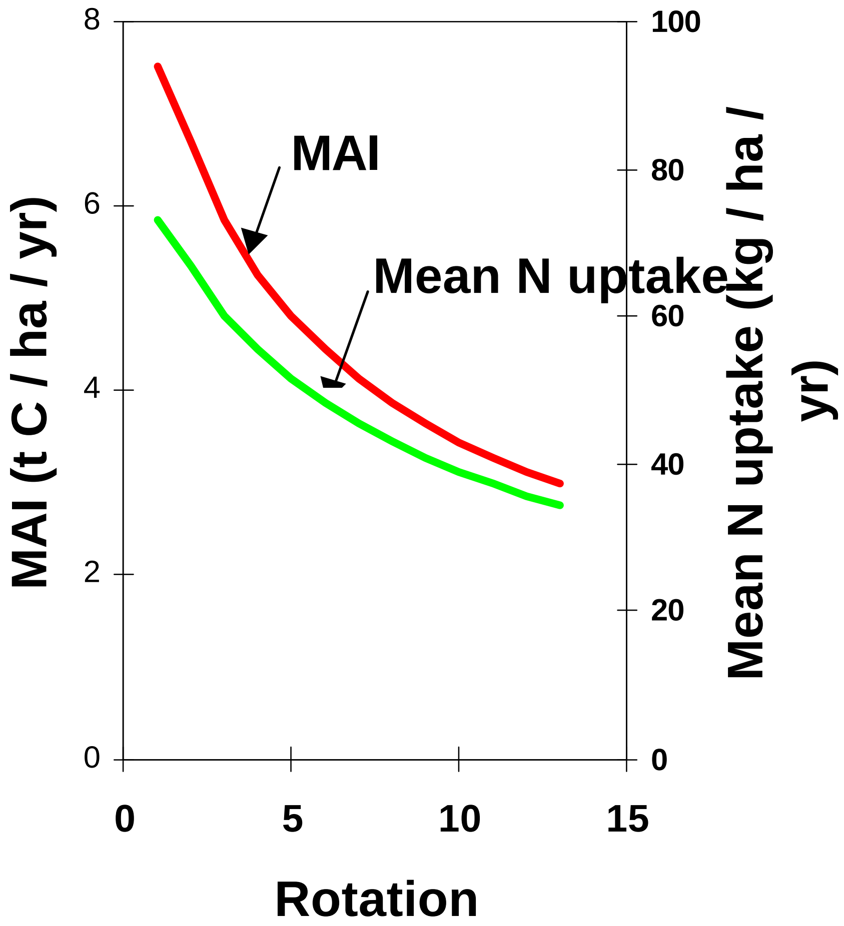
- **What do we mean by sustainable productivity ?**

17 Figure with simulation over 5 30-yr rotations

18 Figure with simulated rotation-mean MAI (t stem C/ha/yr) and N uptake over 13 30-yr rotations


Multiple Rotations
N uptake
Stem C
Soil C
200
150
100
50
0
600
400
200
0
-20
0
20
40
60
80
100
120
140
160
Years
Soil, Stem carbon (t / ha / yr
N uptake (kg / ha / yr

Multiple Rotations



Sustainable forest productivity

Definition:

The mean annual increment in wood C obtained in the long term when forest management regimes (harvesting, thinning, burning, fertilising...) are continued indefinitely.

i.e. **the steady-state MAI when net N depletion over a rotation is zero**

Units of MAI:

t C ha^{-1} yr^{-1}

(Dewar & McMurtrie, 1996, Tree Physiol. 16:173-182)

20 Schematic from Dewar & McM (96) showing Nitrogen balance of a managed forest

Two constraints between MAI and N supply that determine sustainable yield

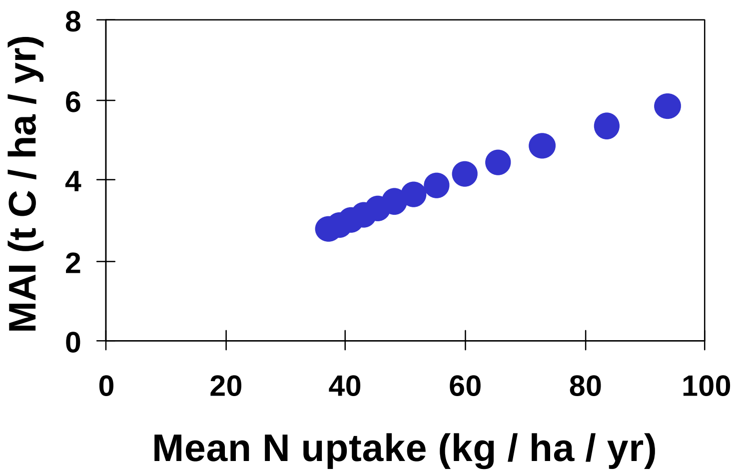
1st constraint: **Growth response to N supply**

2nd constraint: **Steady-state N capital**

N input over rotation	=	N removals in harvested timber + from slash + fire + leaching

(Dewar & McMurtrie, 1996, Tree Physiol. 16:173-182)

Multiple rotations - slash retained



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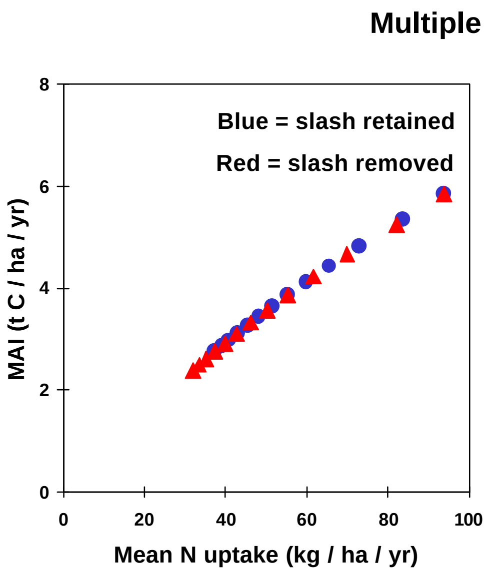

Multiple rotations
Blue = slash retained
Red = slash removed
MAI (t C / ha / yr)
Mean N uptake (kg / ha / yr)
0
2
4
6
8
0
20
40
60
80
100

CONCLUSIONS

1 Soil C is maintained in spite of large soil N loss. Soil C:N is higher in forest than grass.

2 Soil C is sensitive to variation in litter quantity. (but is relatively insensitive to altered litter quality.)

3 NPP is higher for forest than grass due to increased N use efficiency.

4 Sustainable wood yield is much less than in first rotation.

5 Gradual N loss over successive rotations has large effect on sustainable yield