

Forest Fertilization:

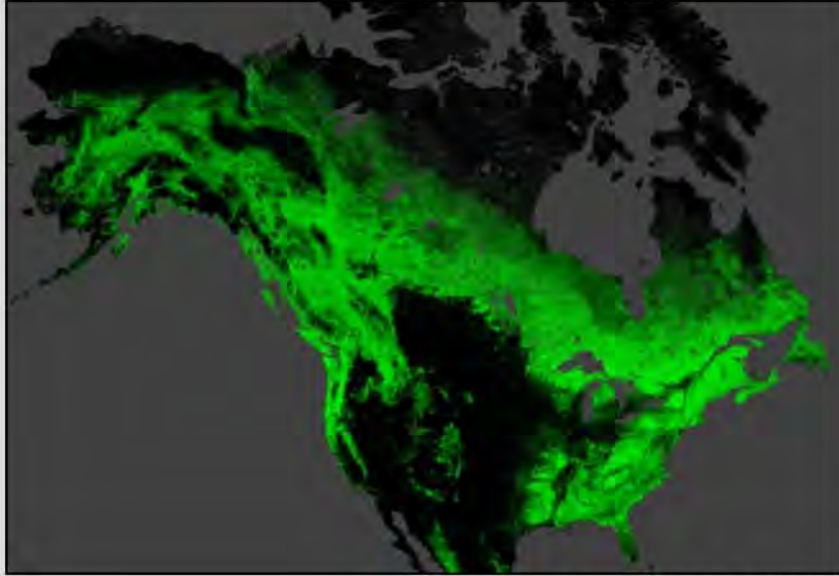
opportunities, efficiencies, and ecosystem responses



Brian D. Strahm

Department of Forest Resources and Environmental Conservation
Virginia Tech, Blacksburg, Virginia, United States

US Land Cover and Use



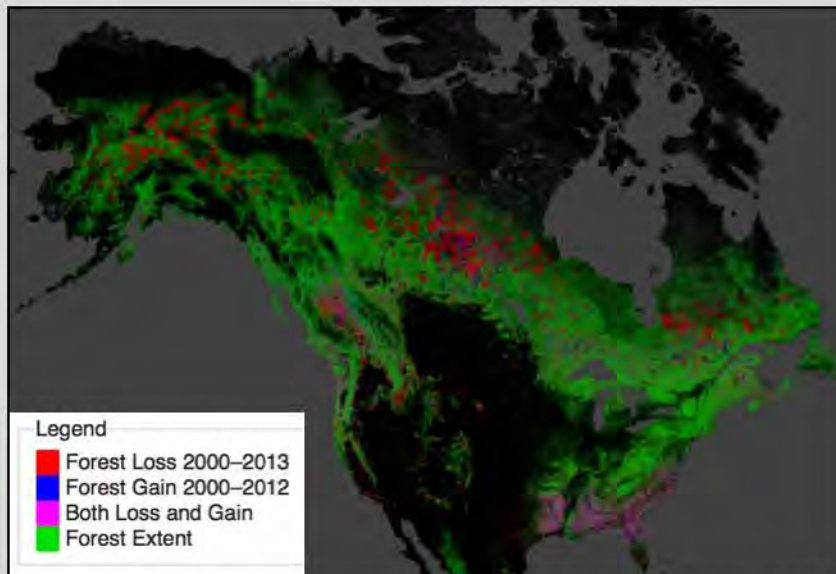
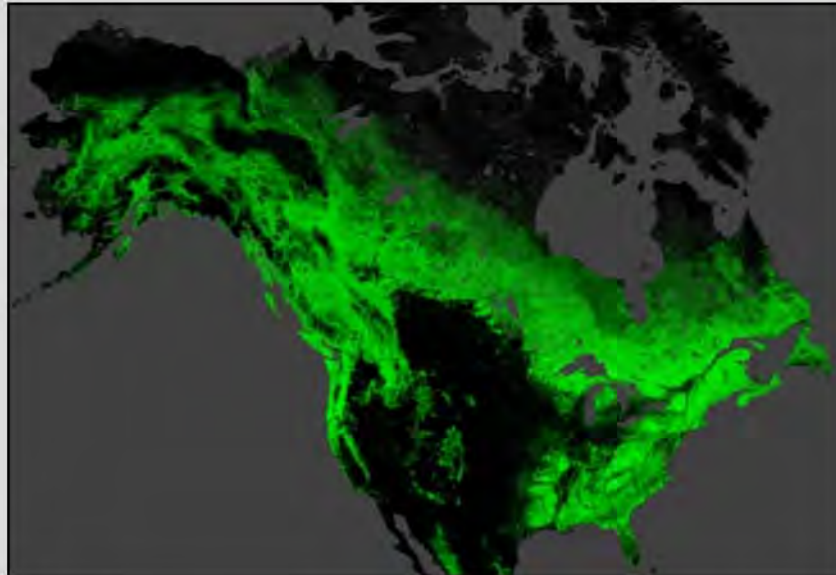
(Hansen et al. 2013)

Land-Use Categories	2014
Managed Lands	890,017
Forest Land	294,988
Croplands	163,752
Grasslands	321,118
Settlements	42,648
Wetlands	42,113
Other Land	25,399
Unmanaged Lands	46,213
Forest Land	9,634
Croplands	0
Grasslands	25,782
Settlements	0
Wetlands	0
Other Land	10,797
Total Land Areas	936,230
Forest Land	304,622
Croplands	163,752
Grasslands	346,900
Settlements	42,648
Wetlands	42,113
Other Land	36,196

**33% of
U.S. is
forested**

(thousands of ha; US EPA 2016)

US Land Cover and Use

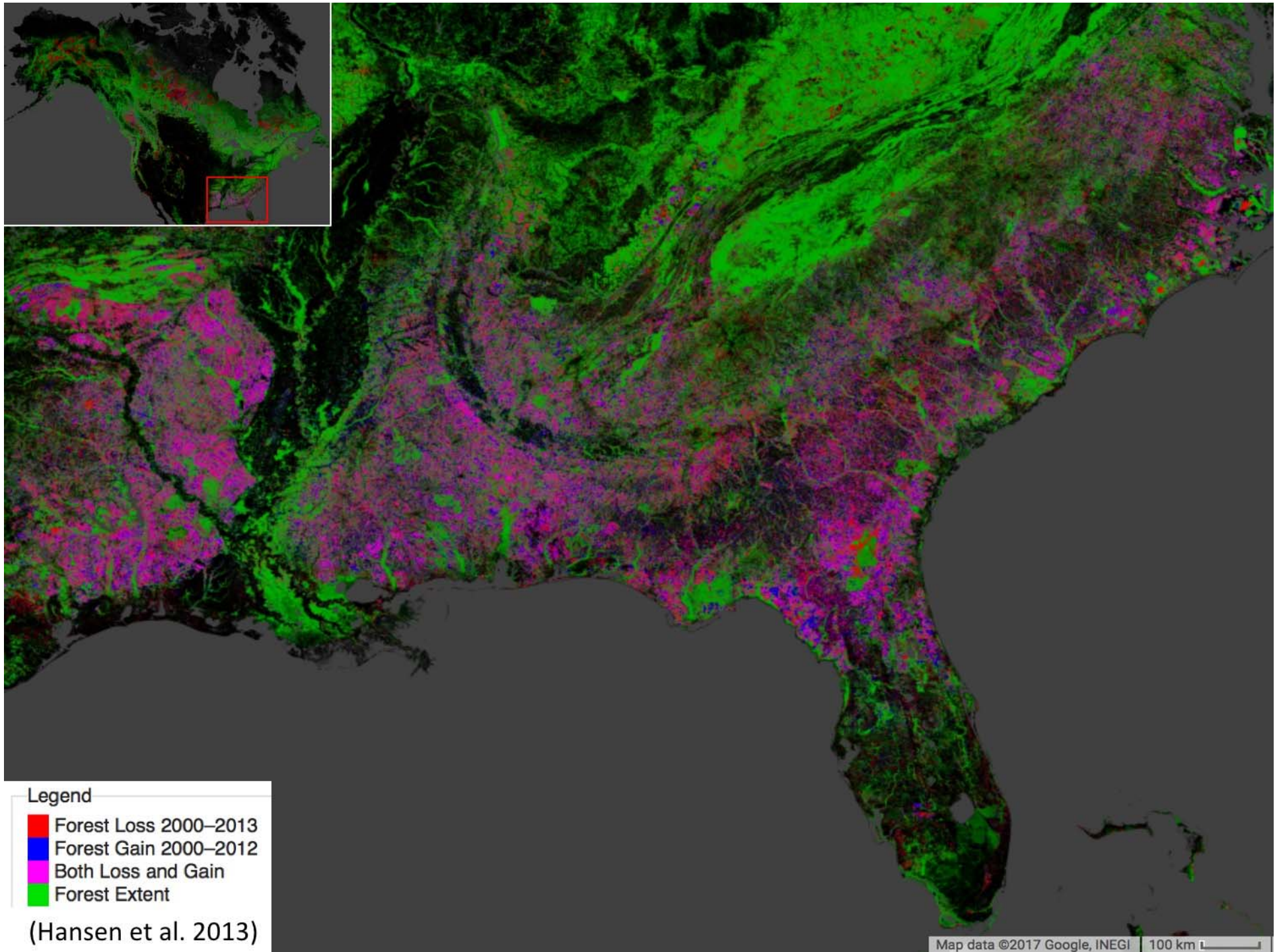


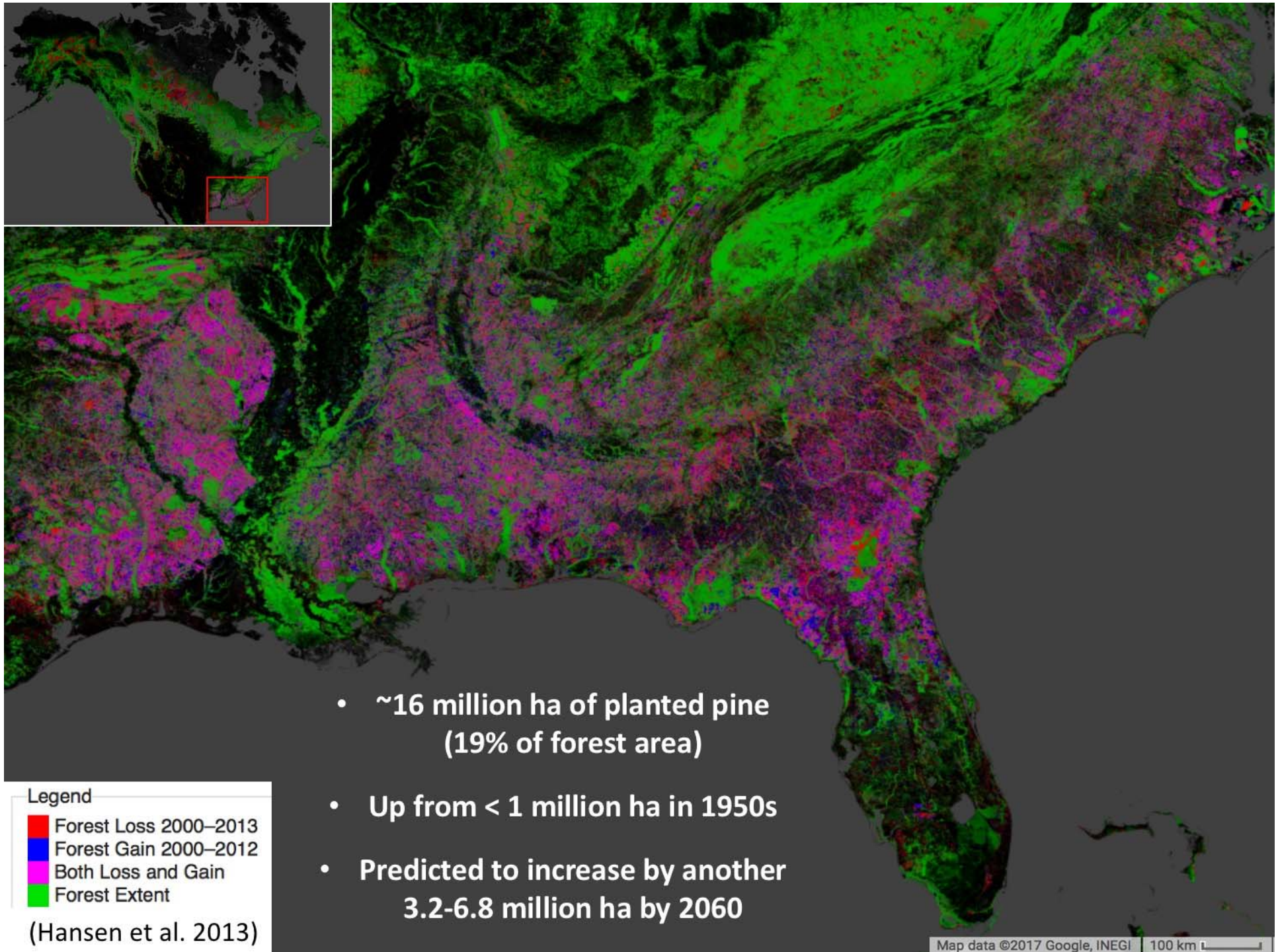
(Hansen et al. 2013)

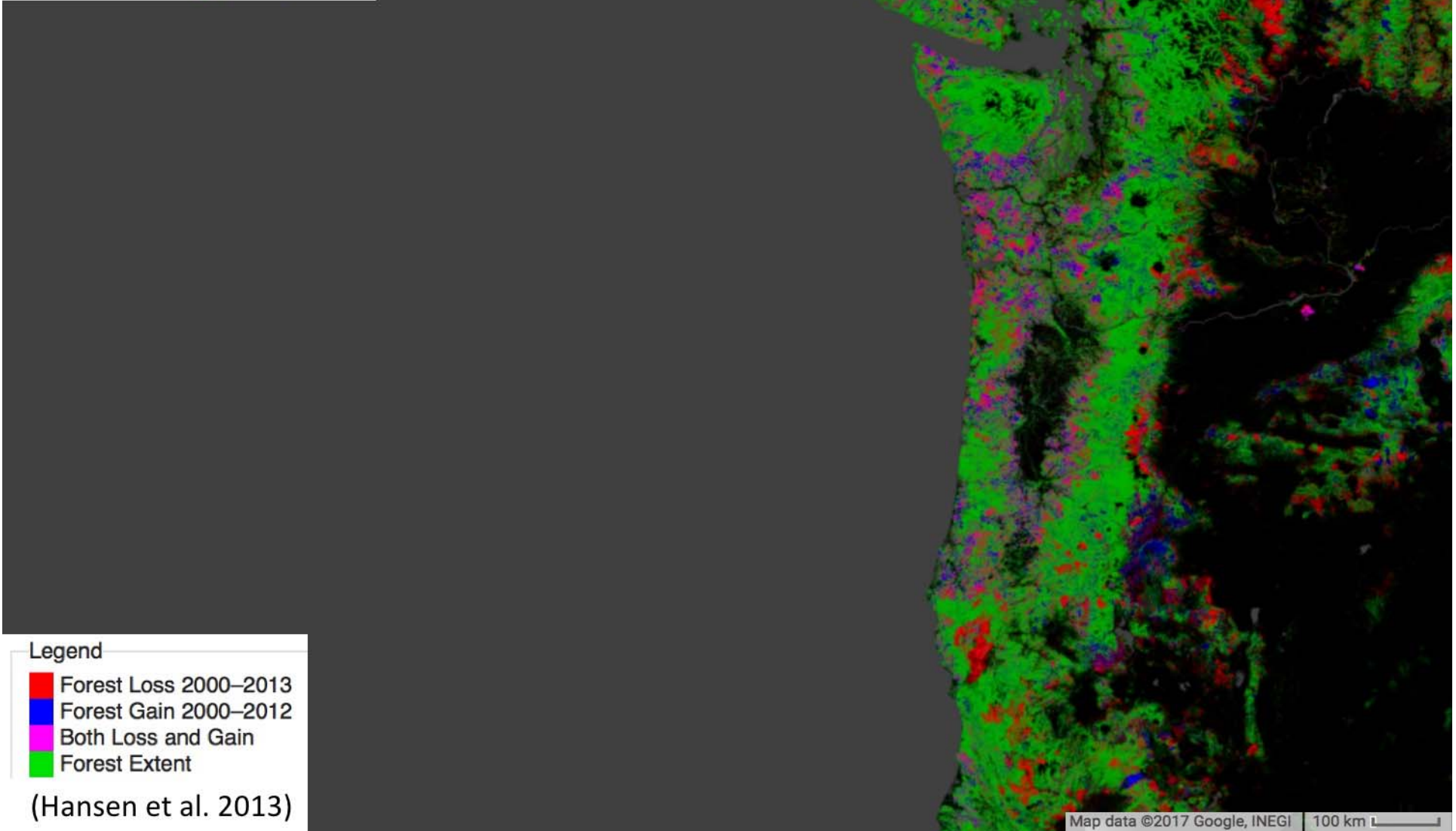
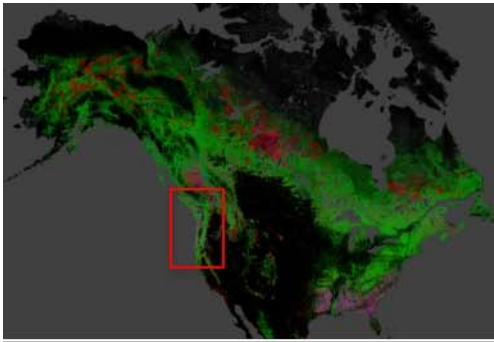
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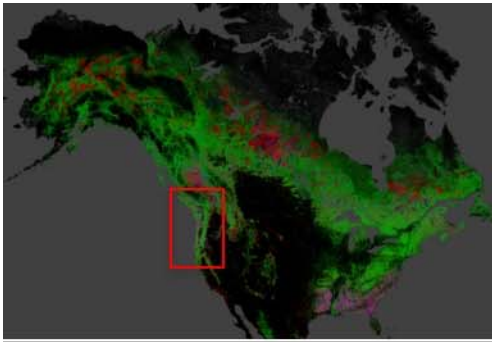




Legend

- Forest Loss 2000–2013
- Forest Gain 2000–2012
- Both Loss and Gain
- Forest Extent

(Hansen et al. 2013)

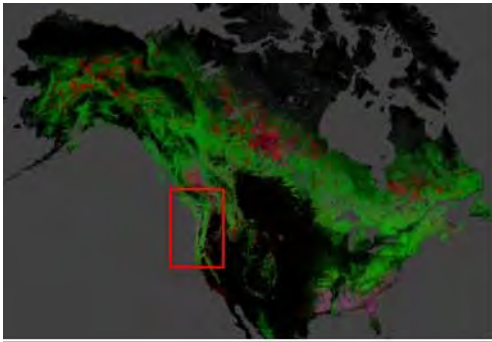


- ~3 million ha of planted forest in Oregon and Washington

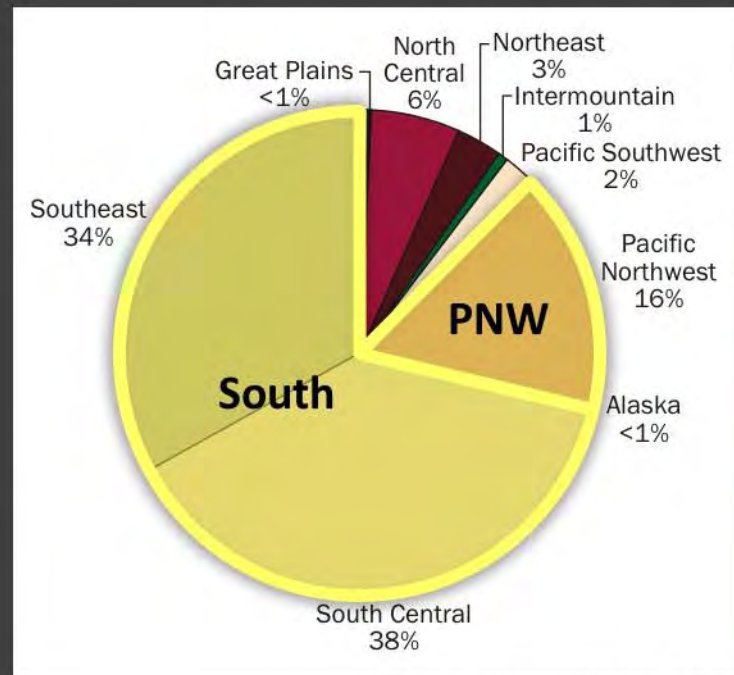
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- ~3 million ha of planted forest in Oregon and Washington
- 88% of planted forests in the US, collectively



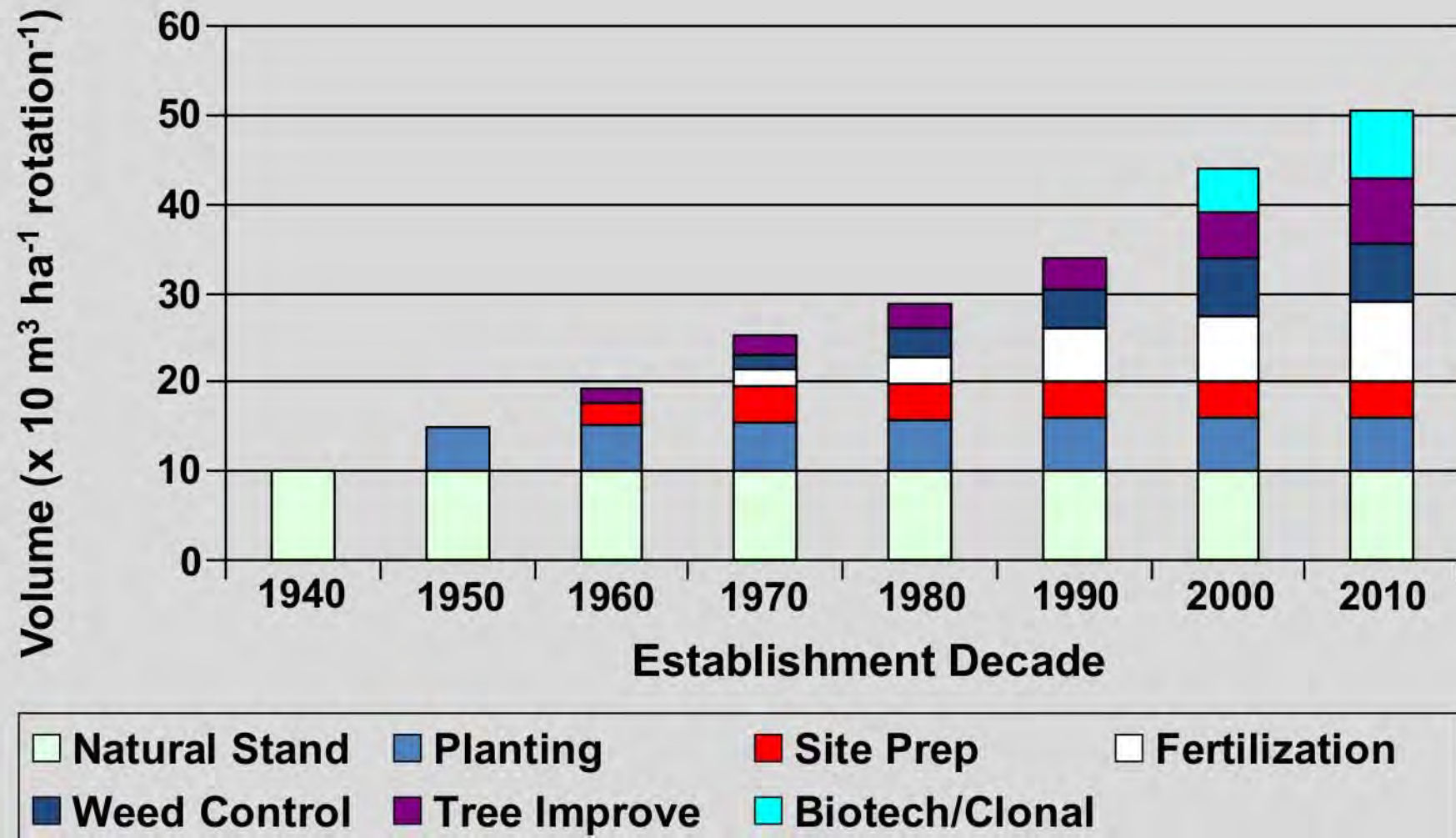
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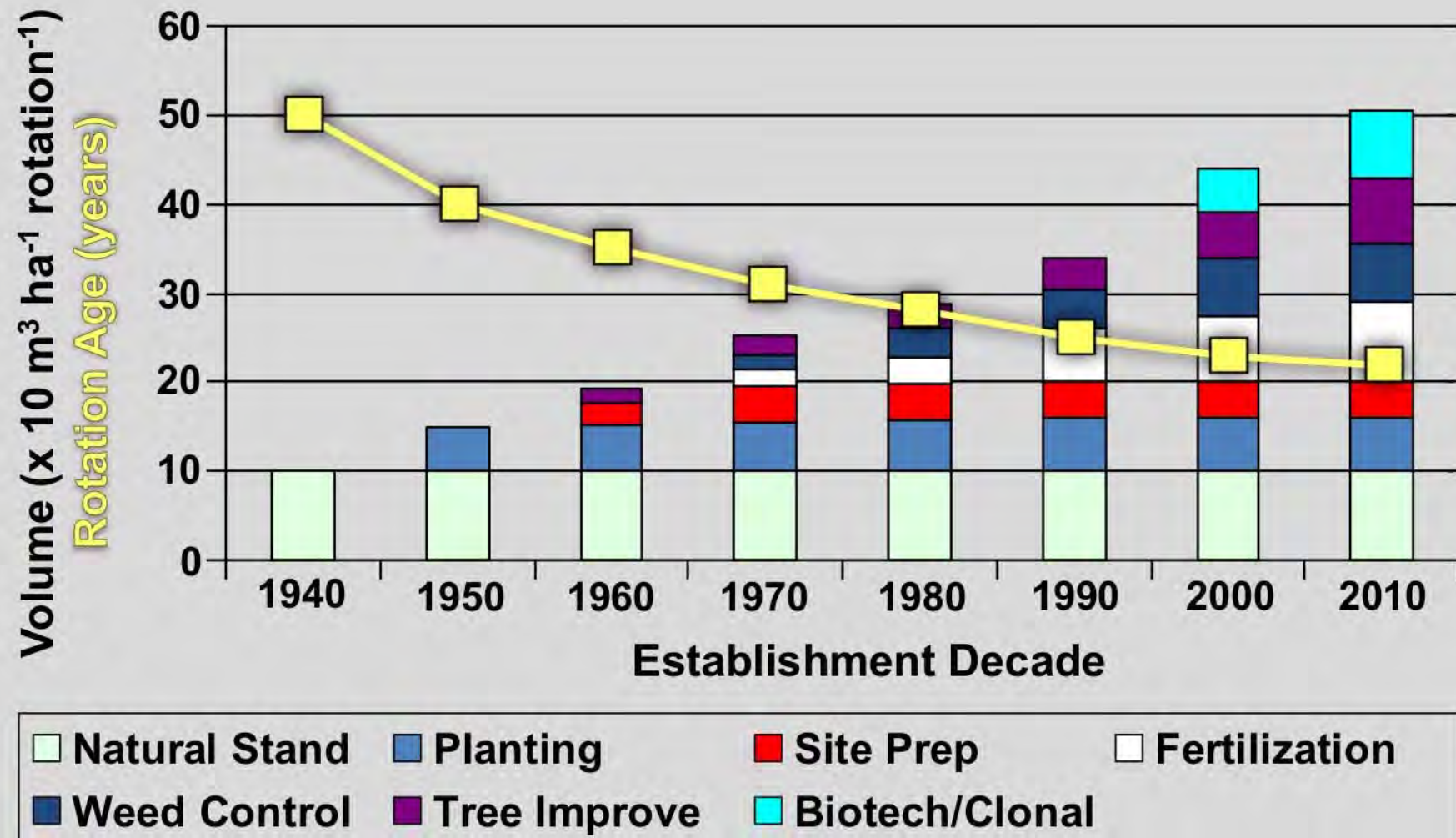
(Oswalt et al. 2014)

Productivity Gains in the Southeastern US



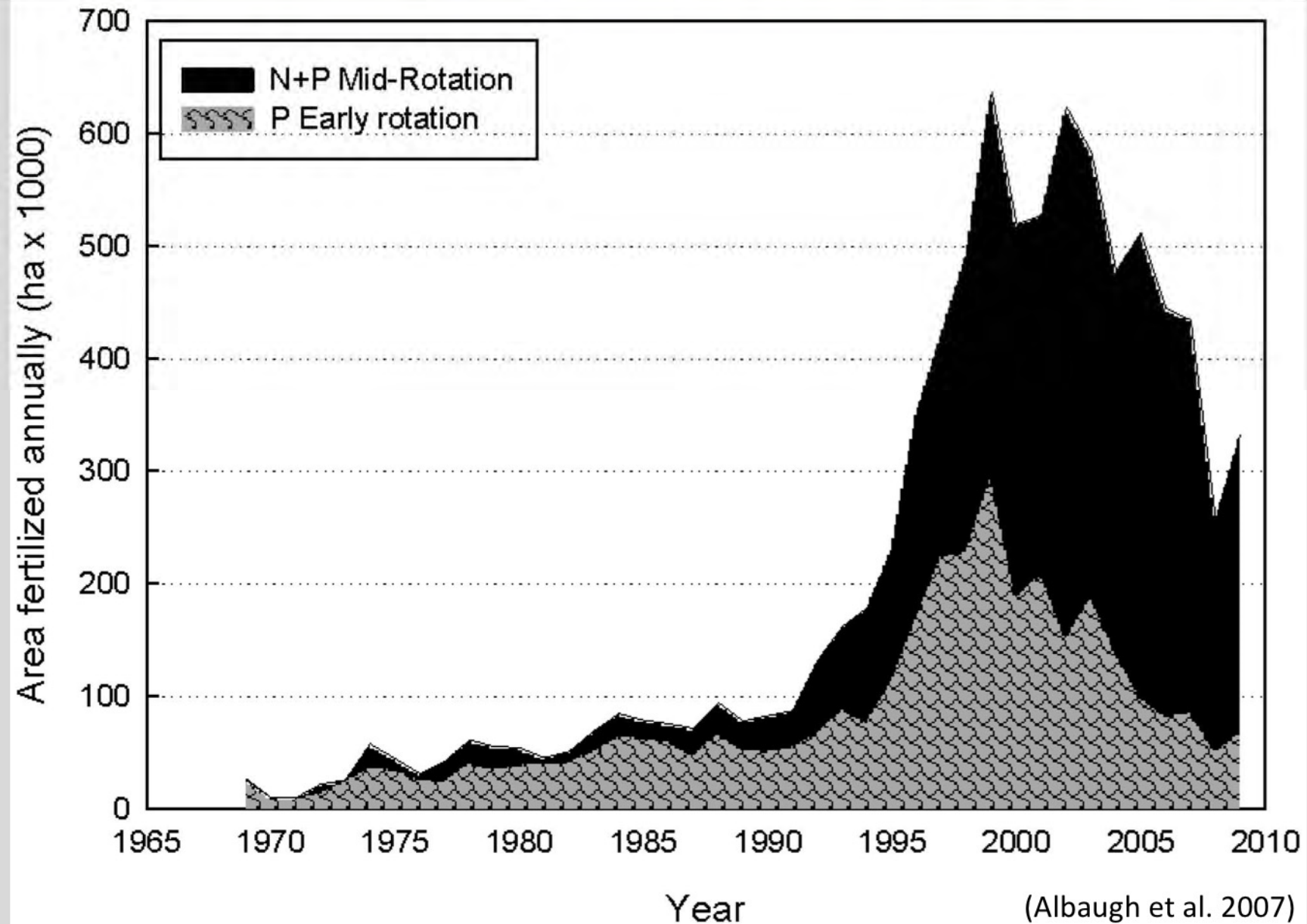
(adapted from Fox et al. 2007)

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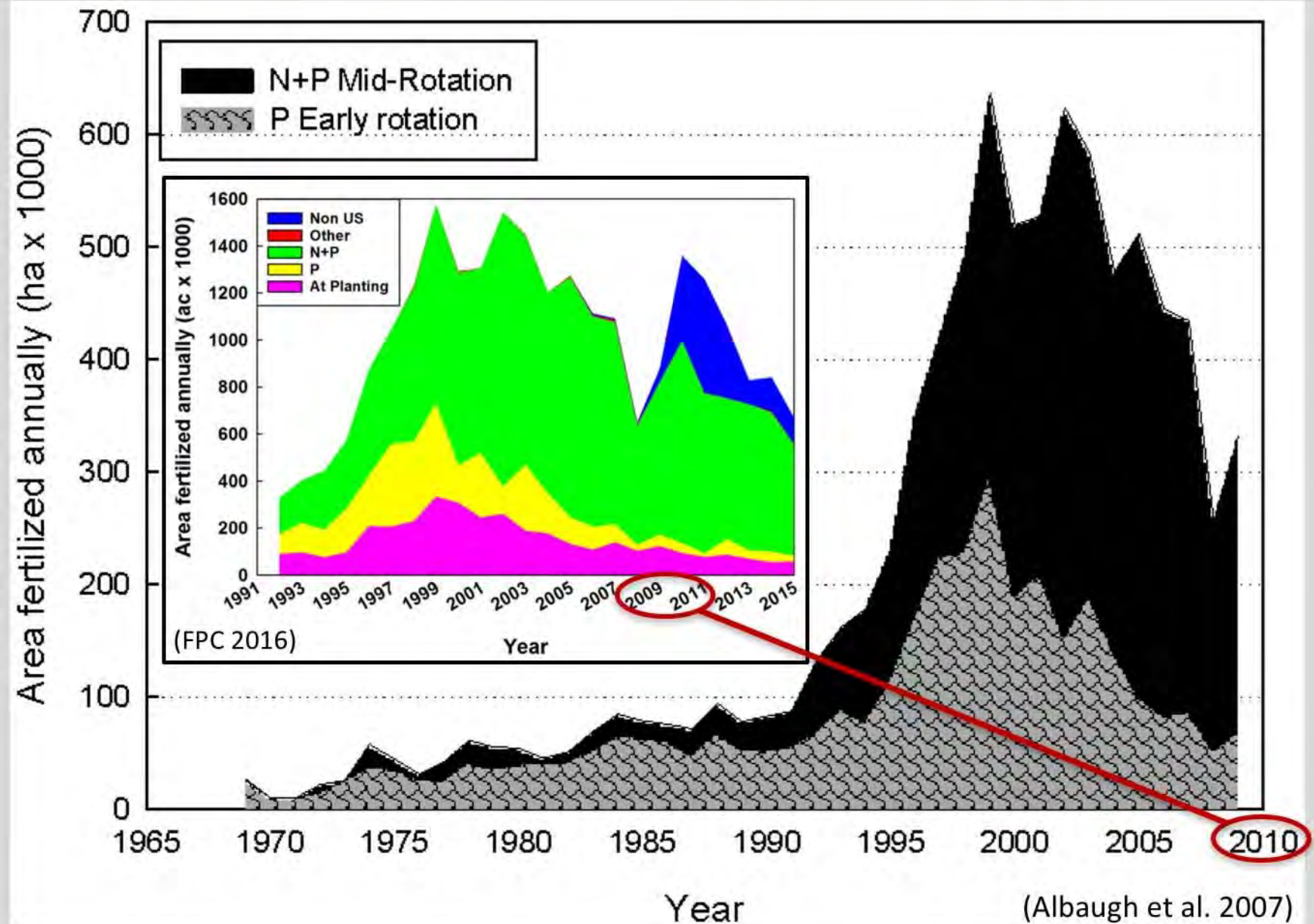


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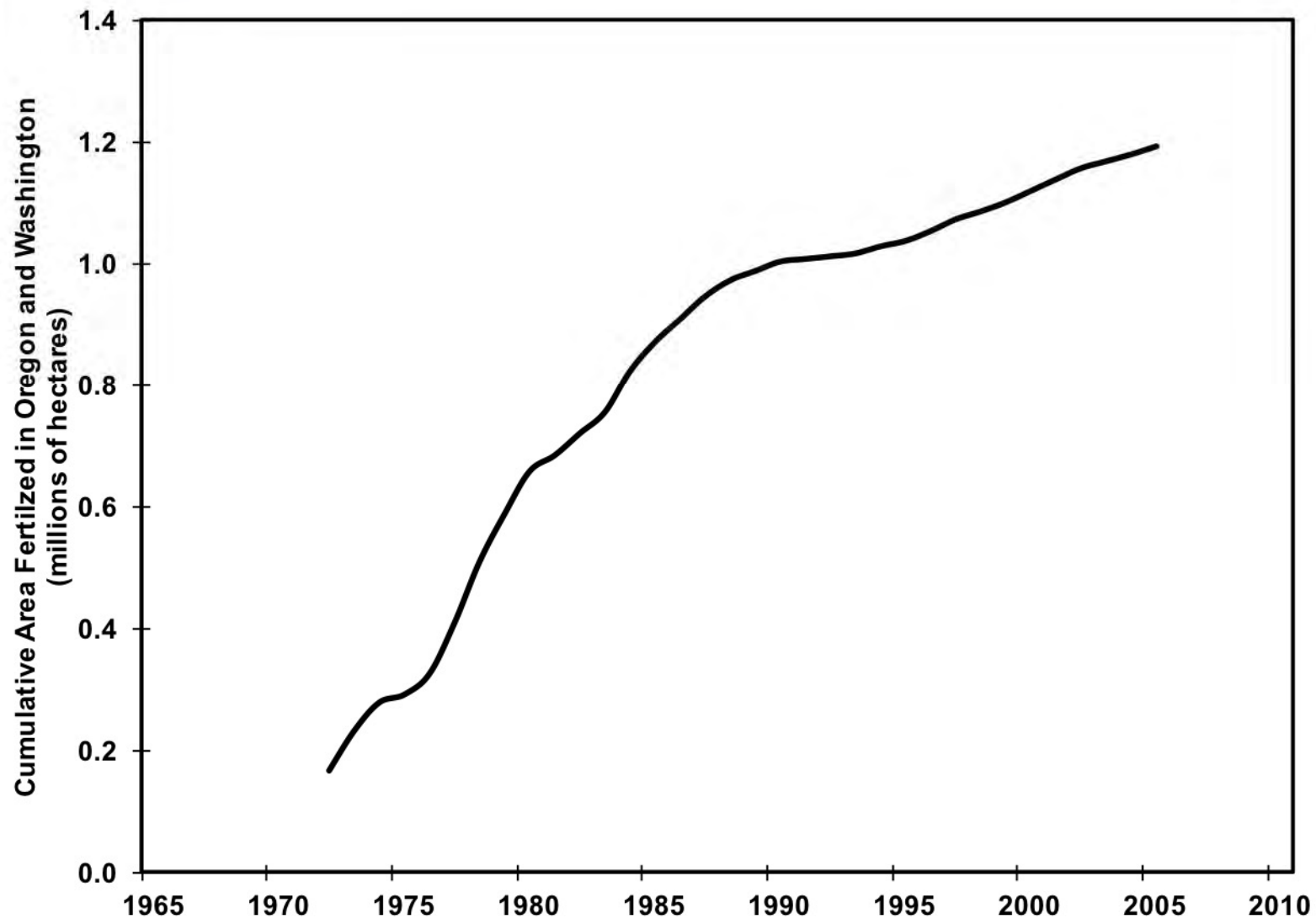
Fertilization in the Southeastern US



Fertilization in the Southeastern US

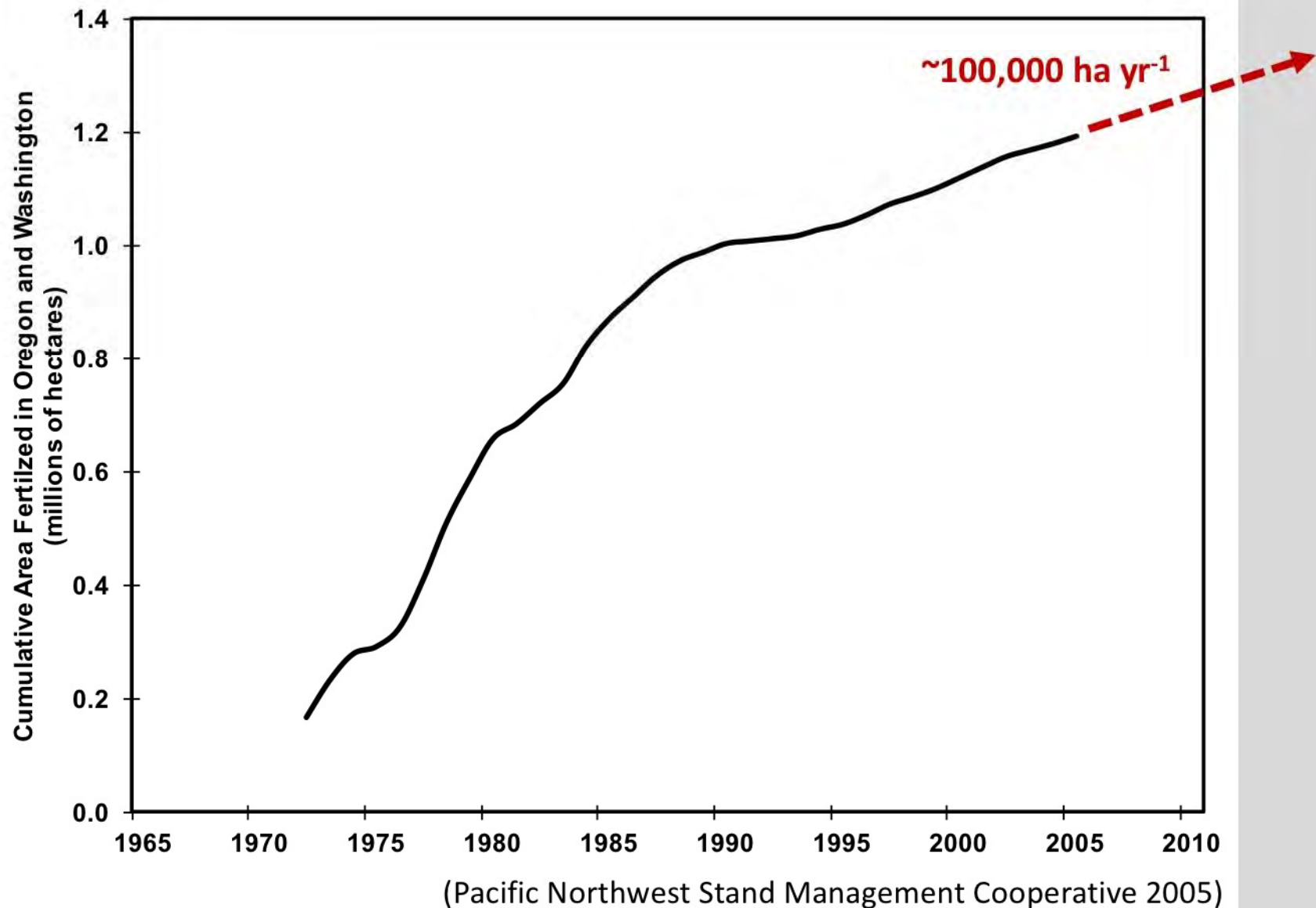


Fertilization in the Pacific Northwest US



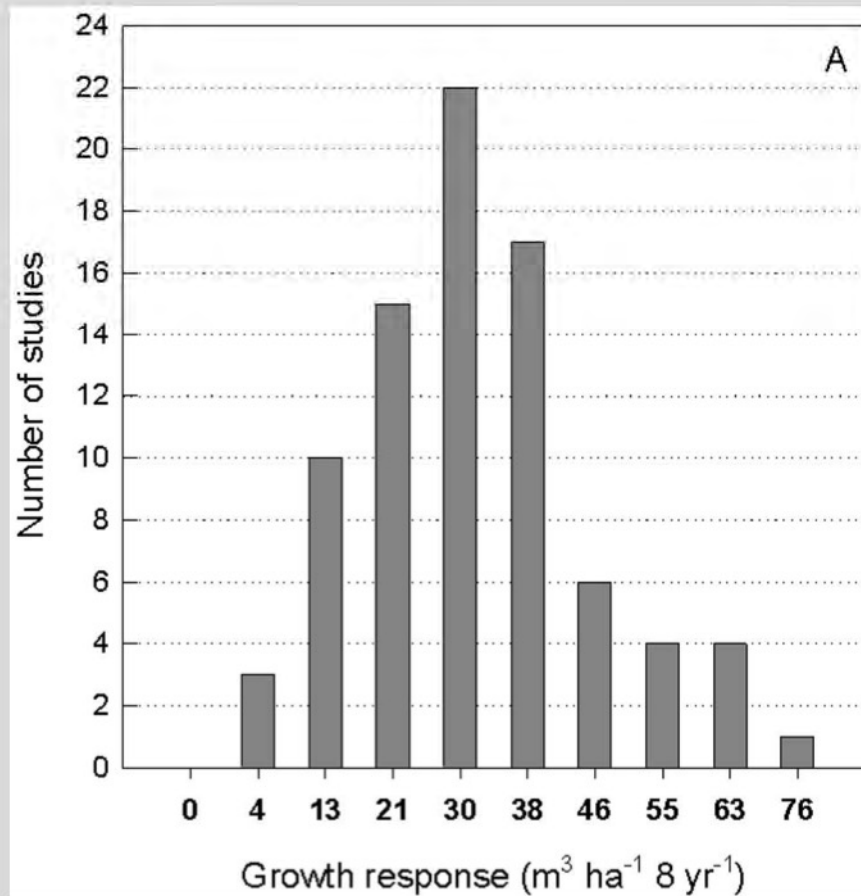
(Pacific Northwest Stand Management Cooperative 2005)

Fertilization in the Pacific Northwest US



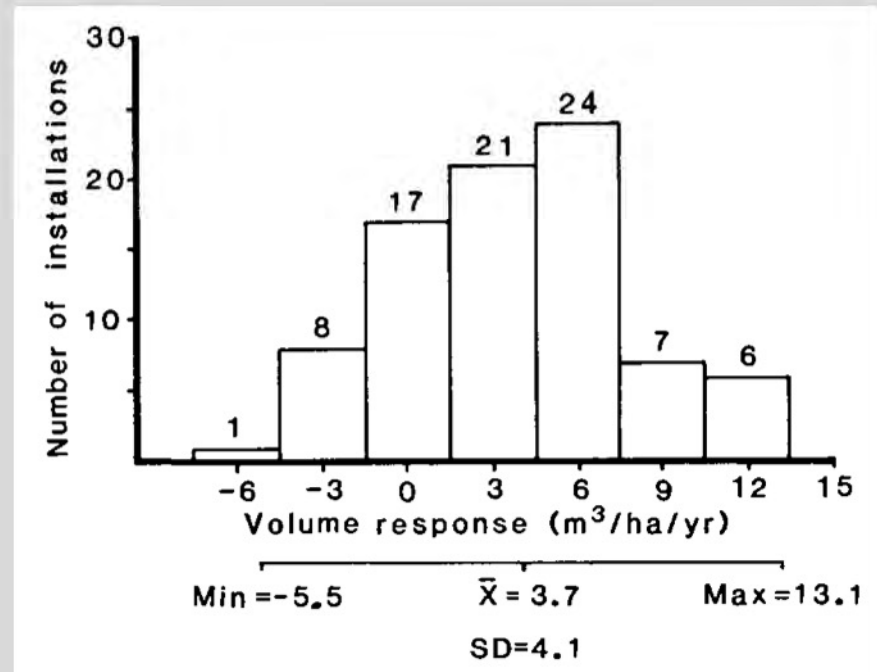
Uncertainty in Fertilization Response

Loblolly pine in the US southeast



(Albaugh et al. 2007)

Douglas-fir in the US Pacific Northwest



(Petersen et al. 1984)

Efficiency



Ecological – Nutrient Use Efficiency

- C fixed per unit N taken up
 - Gerloff (1976)
- C fixed per unit N available
 - Shaver and Melillo (1984)
- C stored per unit N stored
 - Vitousek (1982)
- C fixed per unit N in the plant
 - Ingestad (1979)

Efficiency



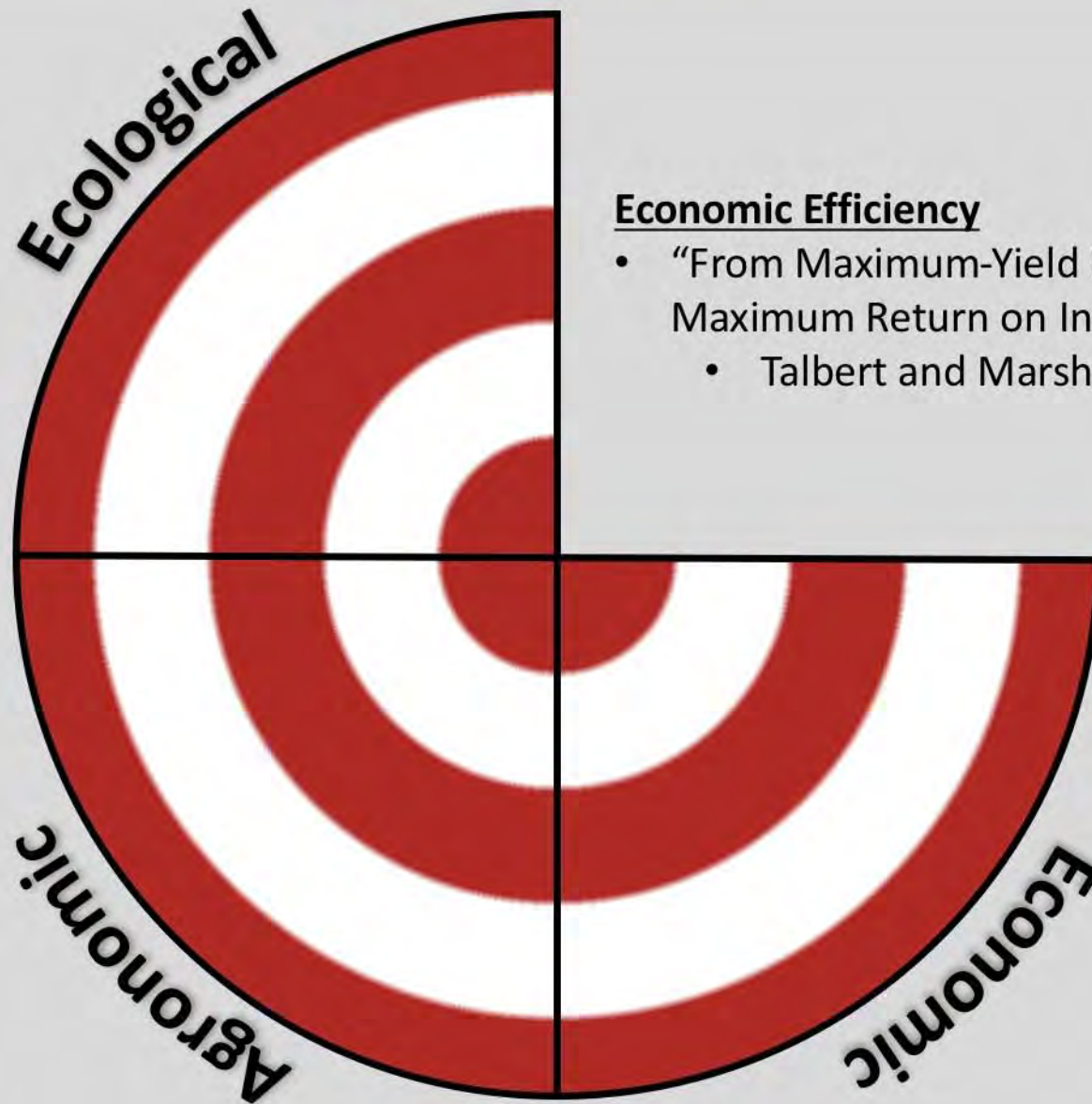
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Agronomic – Fertilizer Efficiency

- increase in yield of the harvested fraction of the crop per unit of fertilizer nutrient applied/supplied
 - Barber (1976)
 - Cooke (1987)

Efficiency



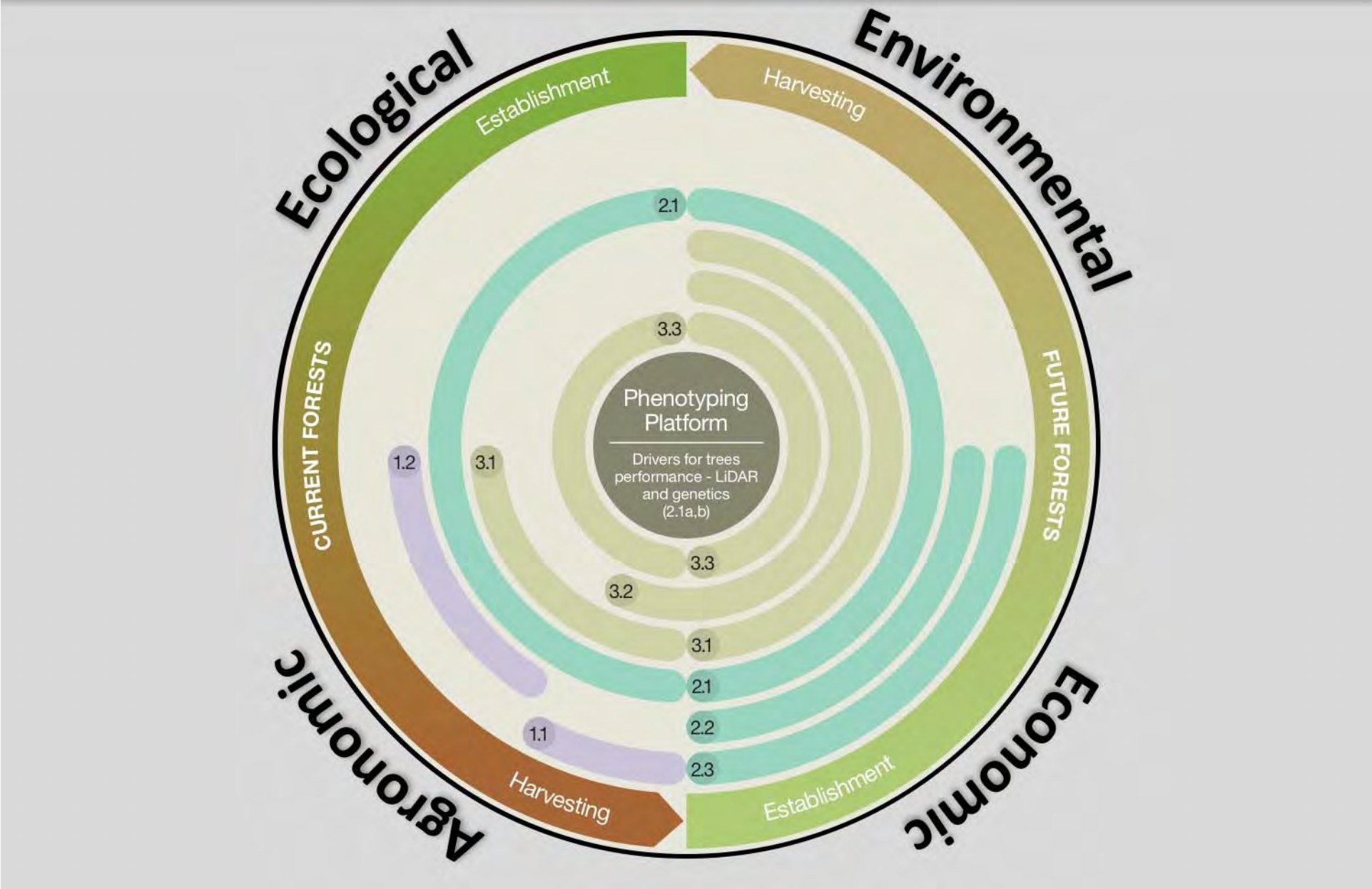
Economic Efficiency

- “From Maximum-Yield Forestry to Maximum Return on Investment”
 - Talbert and Marshall (2005)

Efficiency



Efficiency



Efficient

nature

BIOGEOCHEMISTRY

A plan for efficient use of nitrogen fertilizers

A global analysis finds that nitrogen fertilizers could be used more efficiently if their international distribution across croplands was altered — a measure that would also decrease nitrogen pollution.

XIN ZHANG

Global crop production must double from 2005 levels by 2050 to meet the growing demand for food and bio-fuels. Nitrogen is the main nutrient required for crop growth, and therefore needs to be added to boost crop yield — usually in the form of fertilizers and manure, but in some cases through nitrogen fixation by leguminous crops. However, on average, only about 42–47% of the nitrogen added to croplands globally is harvested as crop product. Most of the rest is lost to the environment, where it poses threats to human and ecosystem health on local to global scales. Writing in *Global Biogeochemical Cycles*, Mueller *et al.* assess regional differences in nitrogen use around the world, and propose that reallocation of

nitrogen resources would help to increase global nitrogen-use efficiency. Crop yields respond to nitrogen addition differently in different regions. In areas where farmers add little nitrogen to croplands — sub-Saharan Africa, for example (Fig. 1) — yield is limited by nitrogen availability, which means that most of the nitrogen products (Fig. 2a) added to the soil are lost to the environment. But in regions that have high nitrogen fertilization rates, such as China, yield is no longer limited by this nutrient. As such, additional input has a limited, or even negative, impact on crop yield (Fig. 2b); most of the added nitrogen is lost as air and water pollution. Other regions, such as Brazil and the United States, have favourable climate and soil conditions, or farms that use advanced technologies and management practices. In these

regions, a high percentage of added nitrogen is converted to crop products, even at relatively high nitrogen-fertilization rates (Fig. 2c) — although the fraction lost to the environment is often still sufficient to have undesirable effects on air and water quality. Using the historical record of nitrogen use for crop production from 1961 to 2009, Mueller *et al.* quantify the yield response to nitrogen input for 12 major world regions, and identify the optimal nitrogen allocation among regions for a given production target. The authors find that the spatial nitrogen-use efficiency became less efficient over the study period, and that nitrogen loss to the environment could be mitigated by 41% if the allocation among regions was optimized. Even greater mitigation is possible if nitrogen resources can be efficiently reallocated on a subregional scale.

But is international coordination of nitrogen resources a realistic proposition? Could, say, Chinese farmers be convinced to apply less nitrogen to croplands, and the amount saved then be used in sub-Saharan Africa or Latin America? No use a realistic proposition? Could, say, Chinese farmers be convinced to apply less nitrogen to croplands, and the amount saved then be used in sub-Saharan Africa or Latin America? No use a realistic proposition? Could, say, Chinese farmers be convinced to apply less nitrogen to croplands, and the amount saved then be used in sub-Saharan Africa or Latin America? No

But although international trade might enable a more efficient allocation of resources across national boundaries, it could have unintended environmental consequences. China's importation of soyabean for instance, has contributed to deforestation in the Brazilian Amazon. Moreover, the main use for soyabean in China is in animal feed, so most of the nitrogen contained in the imported beans ends up in manure, adding to this country's nitrogen pollution. A heavy reliance on foreign crop production can also expose importing countries to other risks. For example, the Middle East relies on wheat imported from Russia, but, in 2010, a heatwave in Russia led to a drop in wheat



Figure 1 | A worker spreads fertilizer on crops at a farm in Meki Bata, Ethiopia.

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Environmental

FUTURE

Agro

Establishment

Economic

Efficient

nature

A plan for efficient use of nitrogen fertilizers

A global analysis finds that nitrogen fertilizers could be used more efficiently if international input distribution across croplands was altered — a measure that would increase nitrogen pollution.

nitrogen resources would help to increase global nitrogen-use efficiency. In areas where crop yields respond to nitrogen addition, the amount of nitrogen to be applied can be reduced (Fig. 1).

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How do we maximize (or optimize) the efficiency of fertilization?



Figure 1 | A worker spreads fertilizer on crops at a farm in Meki Bata, Ethiopia.

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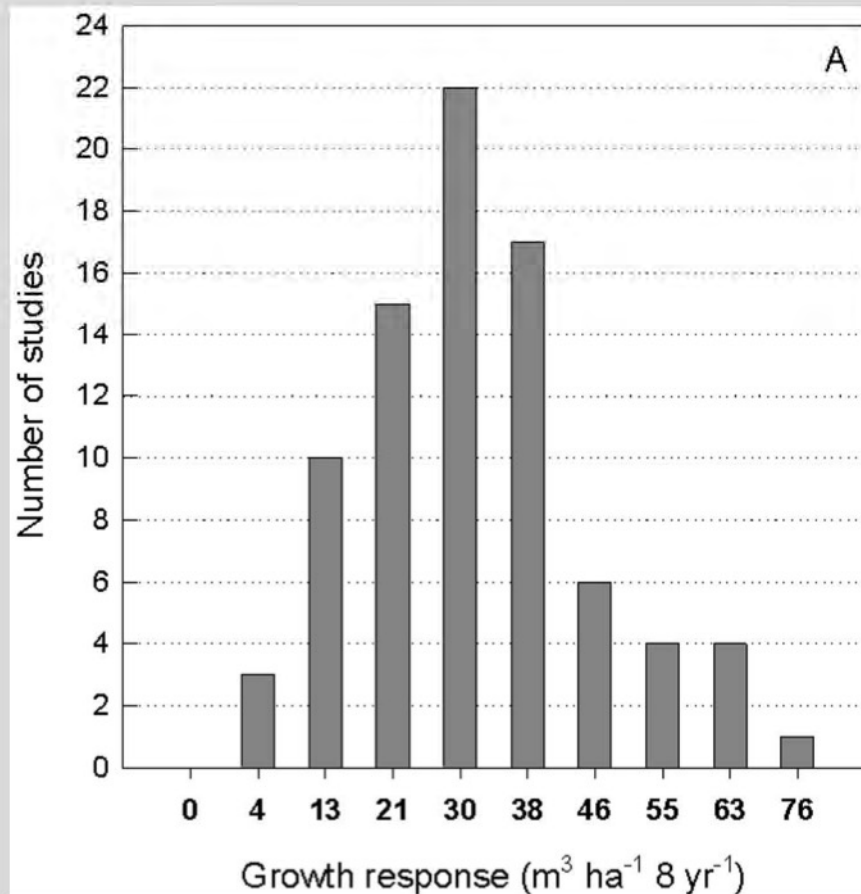
Agro

Economic

Environmental

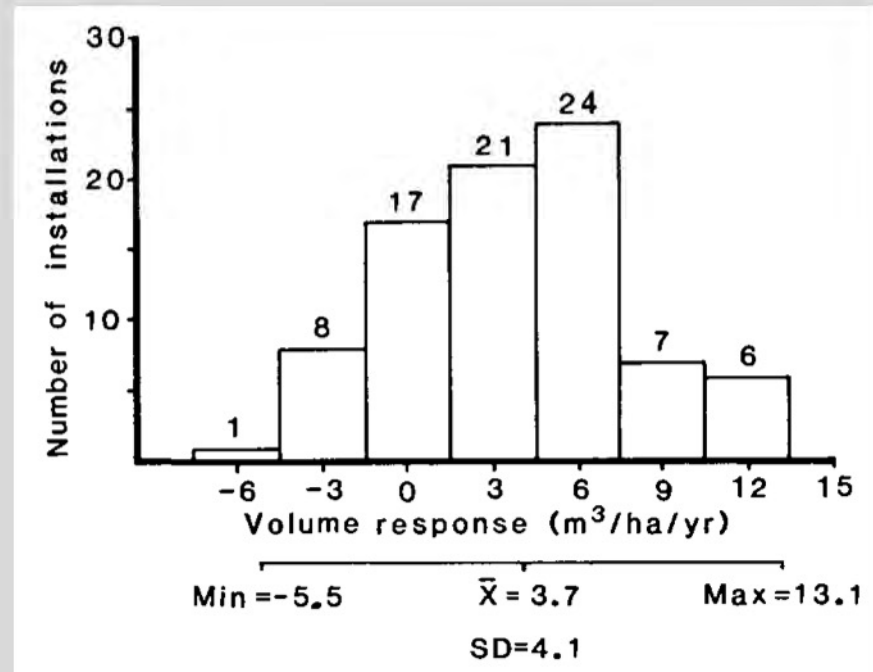
Uncertainty in Fertilization Response

Loblolly pine in the US southeast



(Albaugh et al. 2007)

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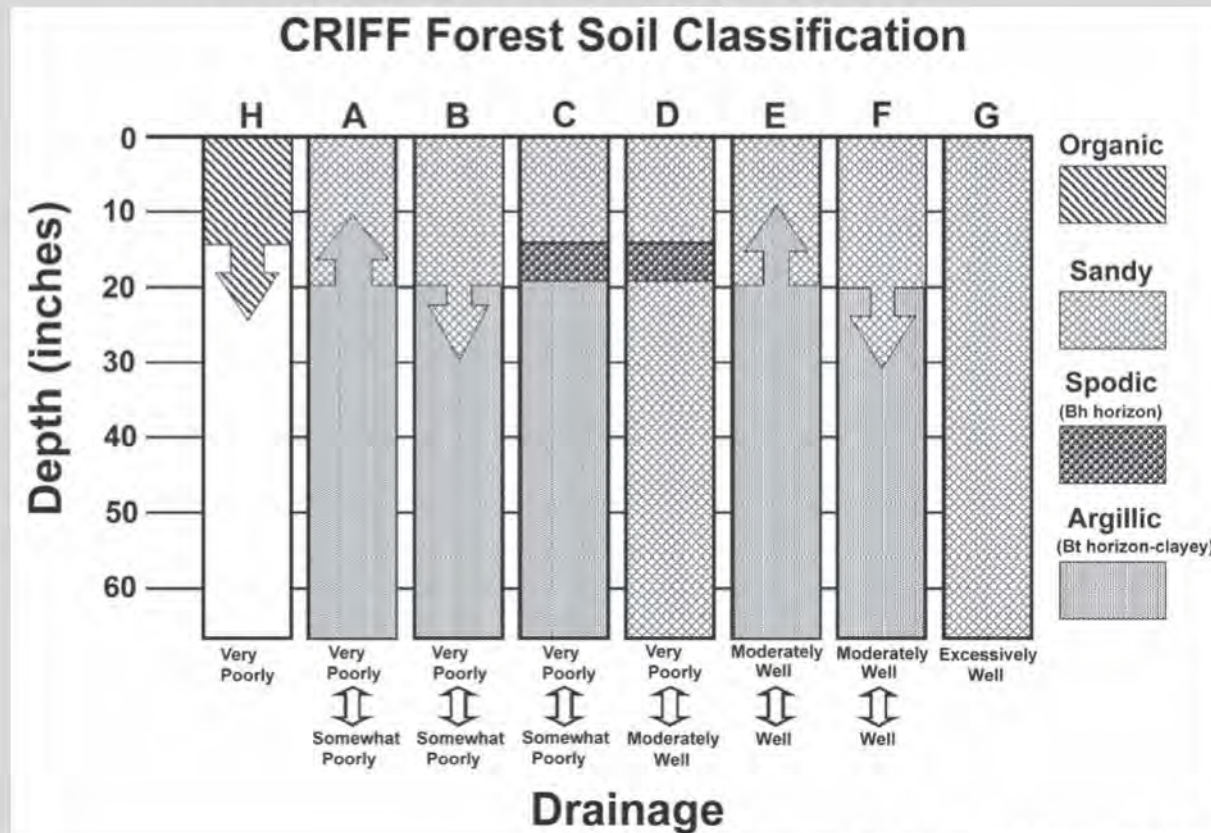


(Petersen et al. 1984)

Stratifying the Landscape

Cooperative Research in Forest Fertilization (CRIFF)

- “Soil groupings, based on easily recognizable features, are used to identify sites where available nutrient supplies are low, or where other site factors (e.g., moisture availability) influence growth.”

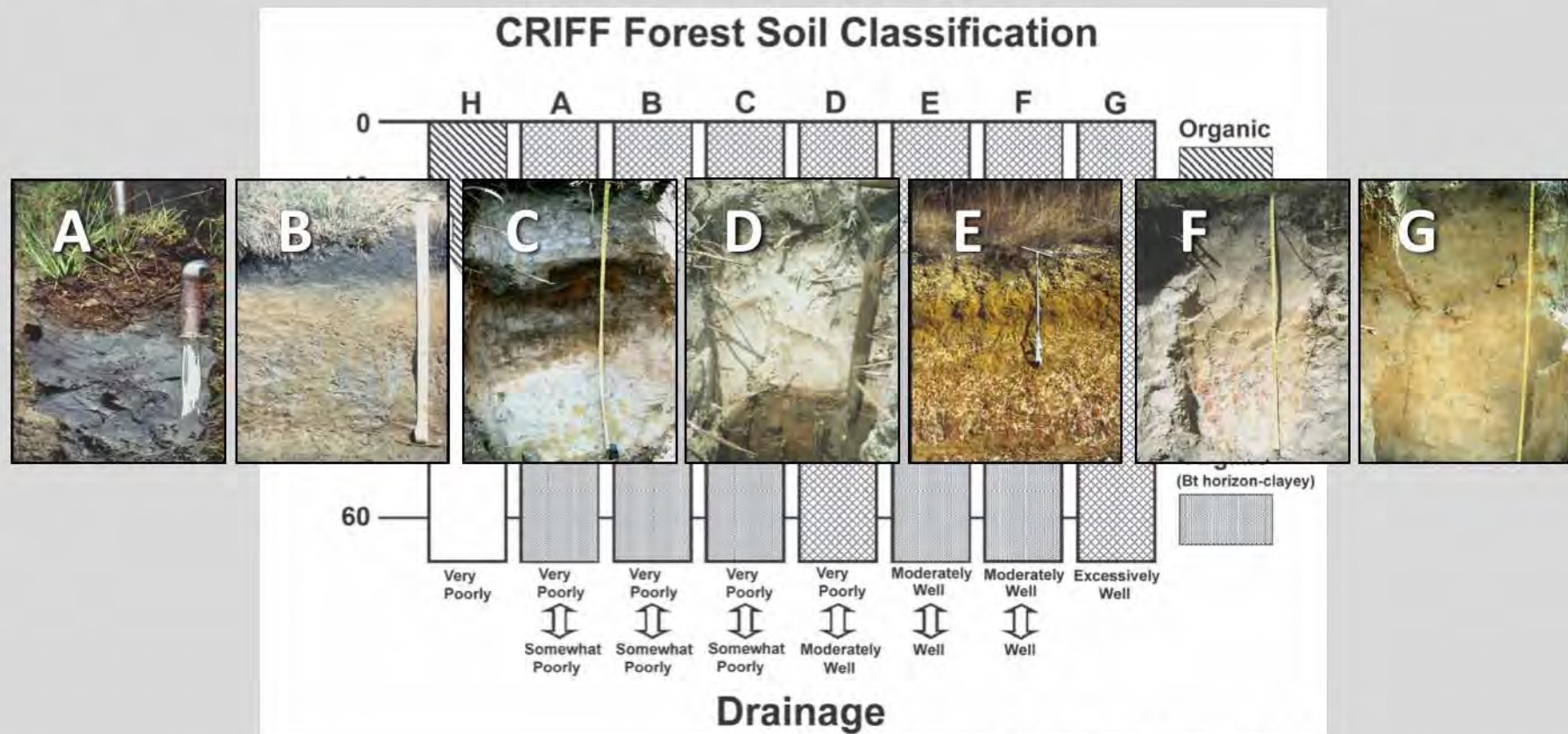


(Jokela and Long 2007)

Stratifying the Landscape

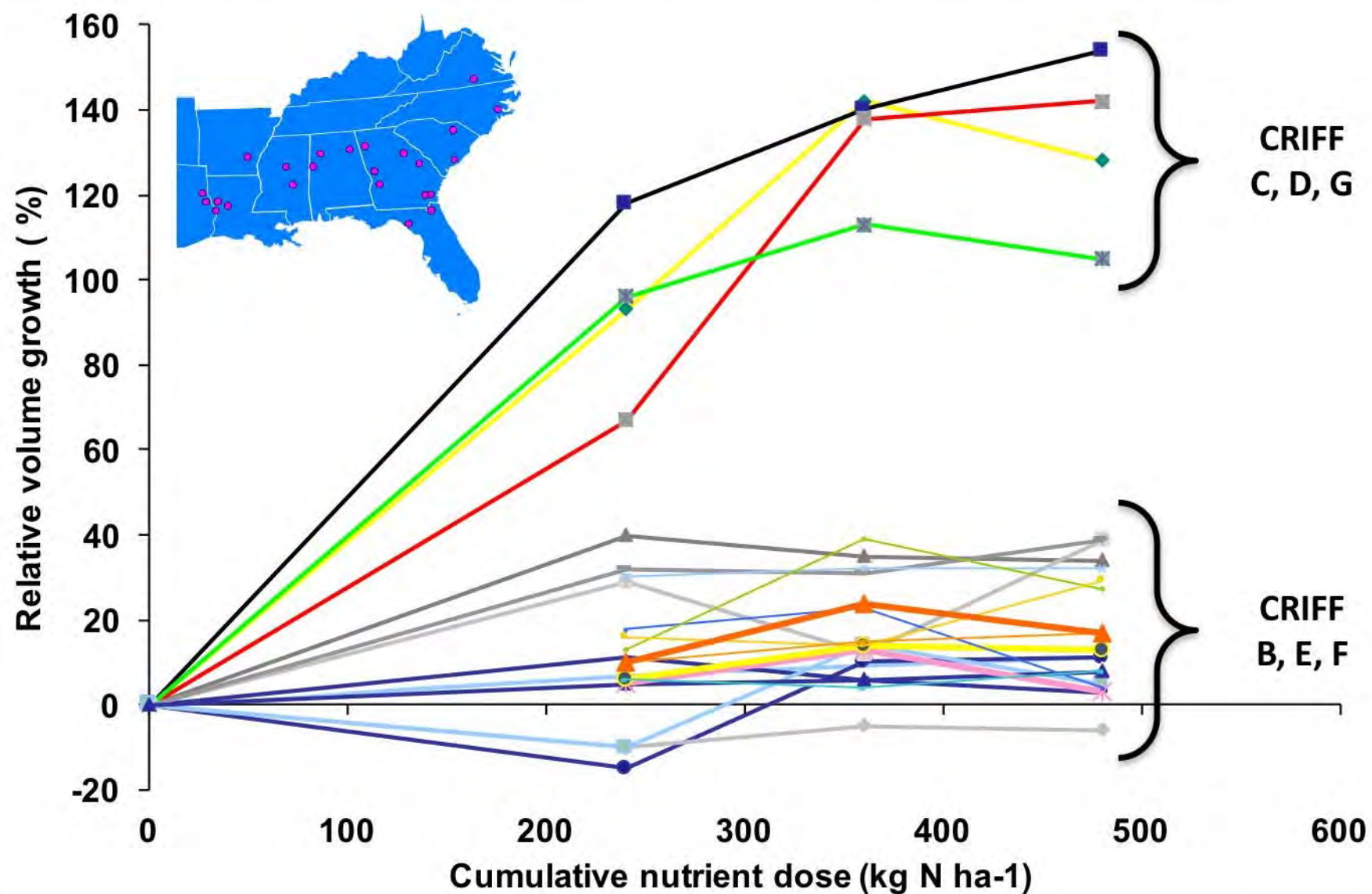
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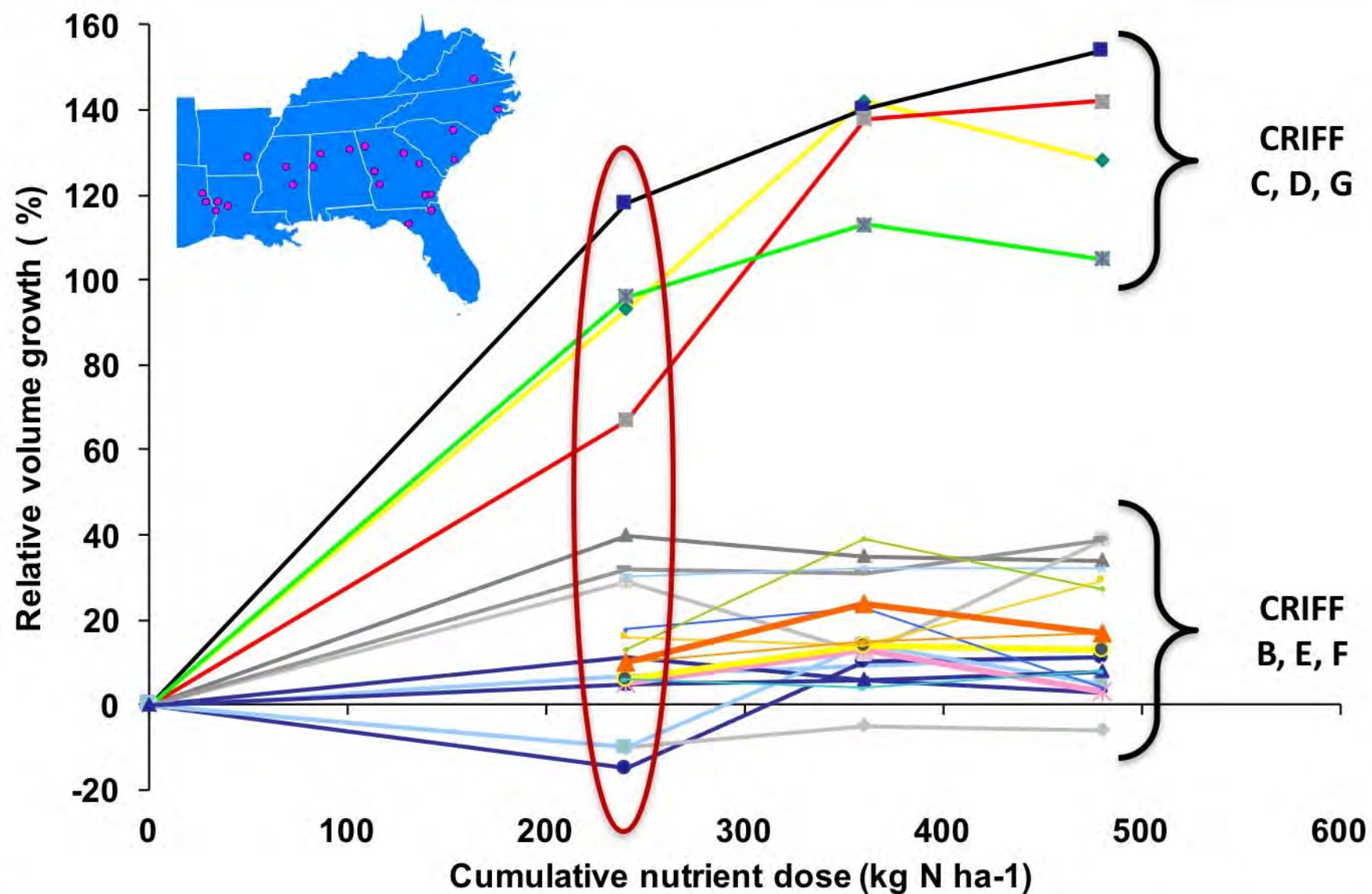
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Stratifying the Landscape with CRIFF



(data from the Forest Productivity Cooperative)

Stratifying the Landscape with CRIFF



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Stratifying the Landscape



ARTICLE

Prediction of Douglas-fir fertilizer response using biogeoclimatic properties in the coastal Pacific Northwest

K.M. Littke, R.B. Harrison, D. Zabowski, M.A. Ciol, and D.G. Briggs

Abstract: Fertilizer response of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) has been related to site and soil properties in the past, but the models have explained only about half of the variation in these investigations. Fertilizer response and percent response after two years were examined, according to mapped and measured biogeoclimatic variables, for 71 Douglas-fir installations in the coastal Pacific Northwest. Paired-tree installations consisted of 12–20 pairs of Douglas-fir trees with one tree fertilized with urea at 224 kg N ha⁻¹. Pearson correlation coefficients and boosted regression tree (BRT) models were used to determine the best predictor variables and models of Douglas-fir fertilizer response. The BRT models, using the combination of mapped and measured variables, performed the best for predicting fertilizer response. Basal area and volume responses were most related to high forest floor and surface soil carbon to nitrogen ratios. Basal area mean annual increment (MAI) and site index were both negatively correlated with fertilizer response. Also, low basal area MAI was the most important tree measurement for predicting fertilizer response in the BRT models. Installations with many of the predictors from the BRT models (>66% of the model criteria) were found to have a significantly greater fertilizer response than installations with only a few predictors (<33% of the model criteria). These findings support the use of these models for predicting fertilizer response of similar Douglas-fir stands in the coastal Pacific Northwest.

Key words: Douglas-fir, fertilizer response, carbon to nitrogen ratio, basal area mean annual increment, Pacific Northwest.

Résumé : Dans les études antérieures la réponse du douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) à la fertilisation a été reliée à la station et aux propriétés du sol mais les modèles ont expliqué seulement environ la moitié de la variation. La réponse à la fertilisation et le pourcentage de réaction après deux ans ont été examinés en fonction de variables biogeoclimatiques mesurées et cartographiées dans 71 dispositifs de douglas de Menzies situés dans la région côtière du Pacifique Northwest. Les dispositifs étaient constitués de 12 à 20 paires de tiges de douglas de Menzies dont une des tiges était fertilisée avec 224 kg N ha⁻¹ sous forme d'urée. Les corrélations de Pearson et des modèles d'arbre de régression augmentée (BRT) ont été utilisés pour déterminer quels étaient les meilleures variables de prédiction et les meilleurs modèles de réponse du douglas de Menzies à la fertilisation. Les modèles BRT utilisant une combinaison de variables mesurées et cartographiées avaient la meilleure performance pour prédire la réponse à la fertilisation. La réponse en surface terrière et en volume était beaucoup reliée à des rapports C : N élevés dans la couverture morte et le sol de surface. L'accroissement annuel moyen (AAM) en surface terrière et l'indice de station étaient négativement corrélés avec la réponse à la fertilisation. Un faible AAM en surface terrière était également la mesure dendrométrique la plus importante pour prédire la réponse à la fertilisation dans les modèles BRT. Les dispositifs où étaient présents plusieurs des prédicteurs des modèles BRT (>66 % des critères des modèles) avaient une réponse à la fertilisation significativement plus forte que les dispositifs où seulement quelques prédicteurs (<33 % des critères des modèles) étaient présents. Ces résultats supportent l'utilisation de ces modèles pour prédire la réponse à la fertilisation de peuplements similaires de douglas de Menzies dans la région côtière du Pacifique Northwest. [Traduit par la Rédaction]

Mots-clés : douglas de Menzies, réponse à la fertilisation, rapport C : N, accroissement annuel moyen en surface terrière, Pacific Northwest.

Introduction

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is the most important commercial tree species in the coastal Pacific Northwest (PNW). Currently, Douglas-fir plantations are being intensively managed to increase growth, shorten rotation age, and improve wood quality. Increasing productivity on plantation forest lands could decrease the amount of land dedicated to plantation forestry throughout the PNW (Sedjo and Botkin 1997).

Nitrogen (N) is the most limiting nutrient in soils of the region, which is supported through the effects of soil N availability on

Douglas-fir growth (Miller et al. 1989; Carter and Klinka 1990). Urea fertilizer has been applied to Douglas-fir plantation forests throughout the coastal PNW to alleviate N deficiencies and increase growth rates (Chappell et al. 1991), although there are difficulties in predicting which sites will respond to fertilization because N fertilization has been found to increase growth only about 70% of the time (Hanley et al. 2006). Forest floor carbon (C) to N ratio (C:N) (Peterson et al. 1984; Edmonds and Hsiang 1987), total soil N content (Turner et al. 1979; Hopmans and Chappell 1994), foliar N concentration (Turner et al. 1988; Hopmans and Chappell 1994), site index (Miller et al. 1989; Carter et al. 1998), and

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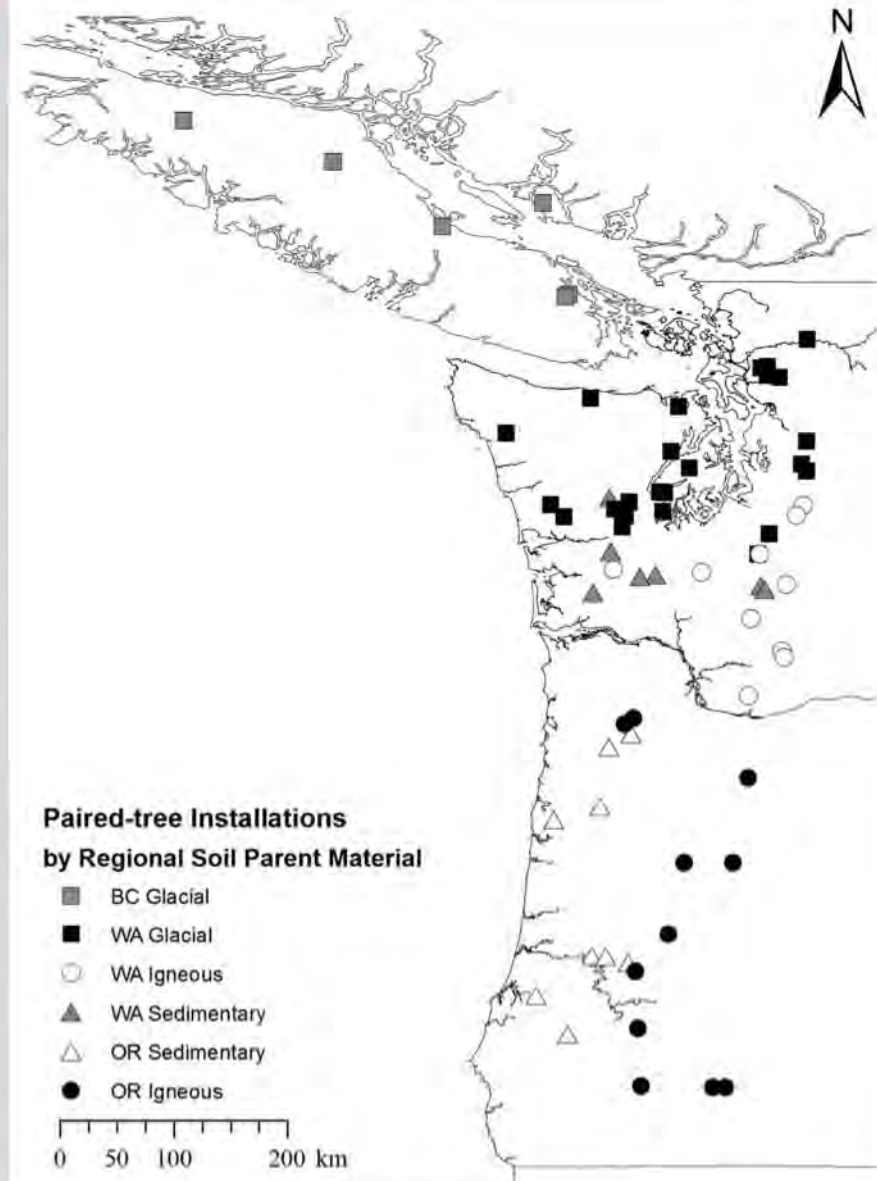
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Corresponding author: K.M. Littke (e-mail: littkek@uw.edu).

*Deceased.

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Stratifying the Landscape

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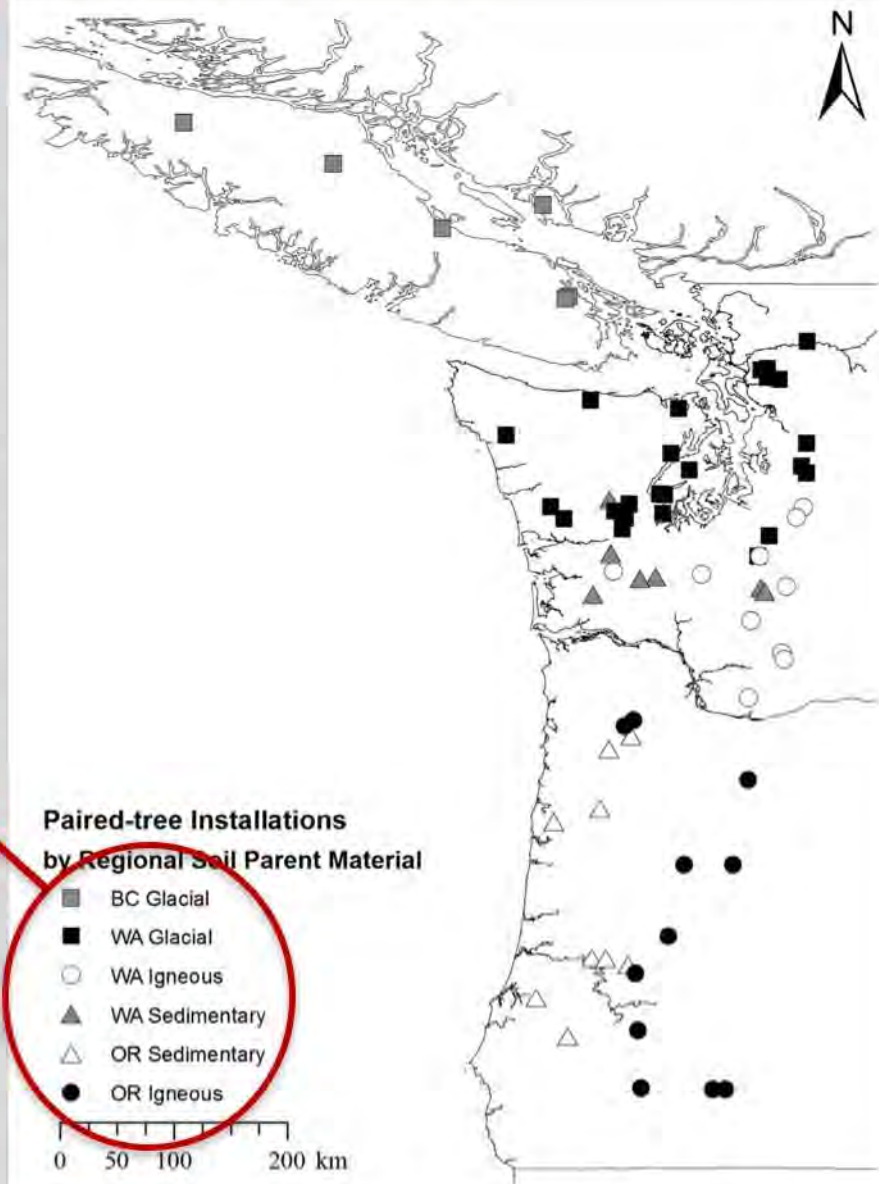
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Industry-University Cooperative Research







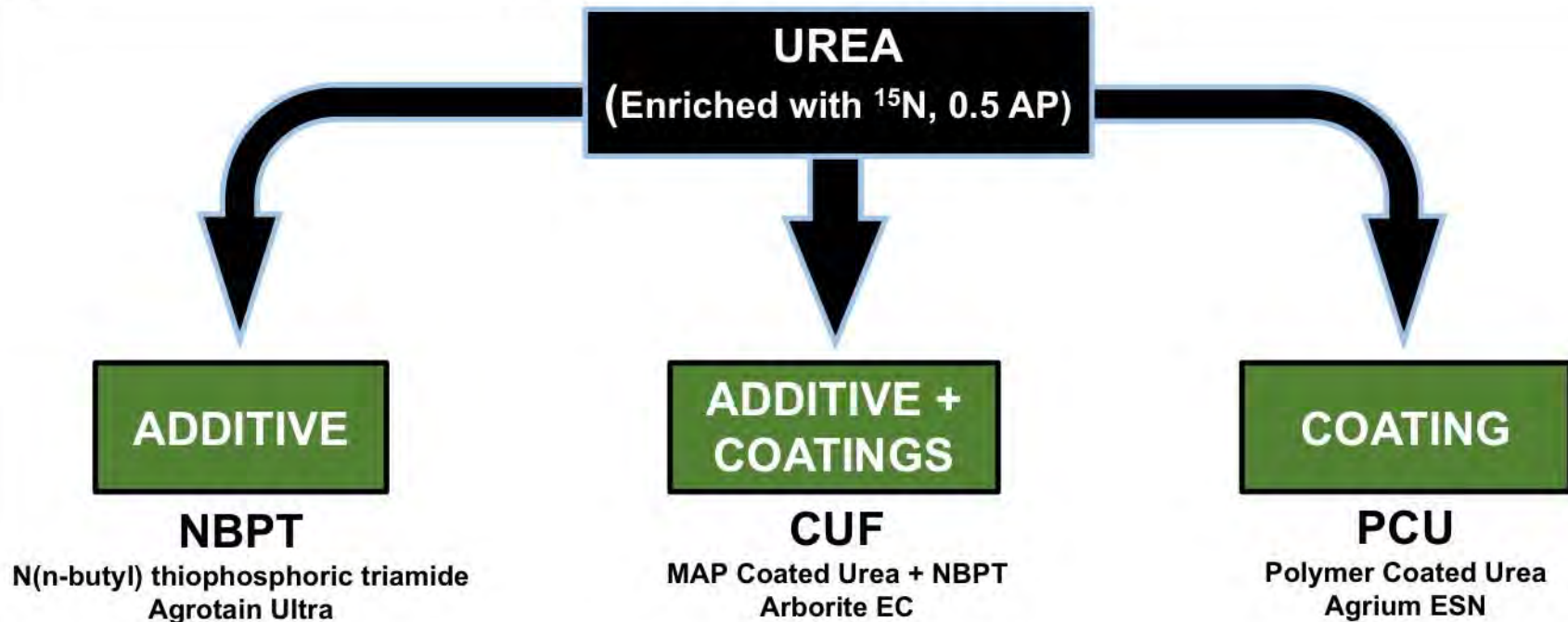






Enhanced Efficiency Fertilizers

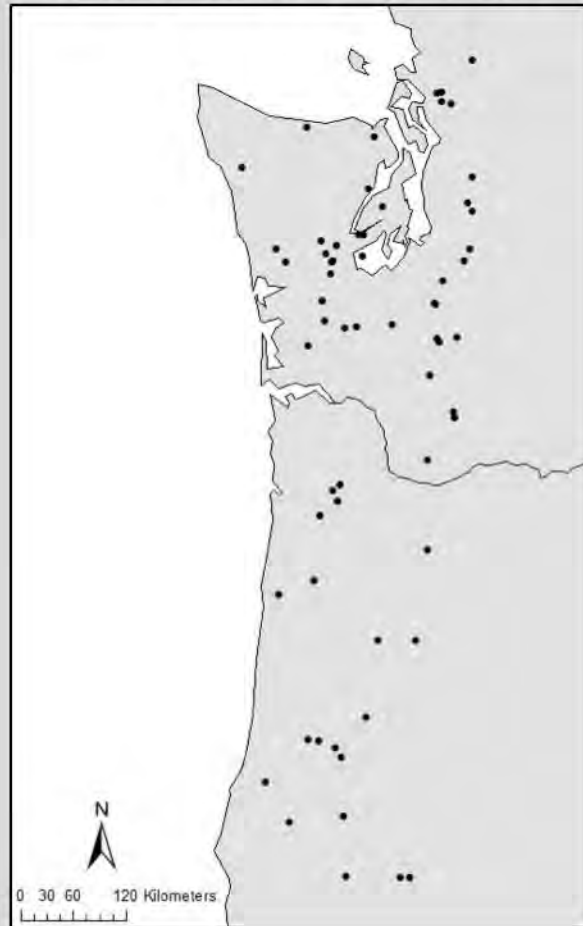
Enhanced Efficiency Fertilizers (EEFs) Reduce Fertilizer N Losses



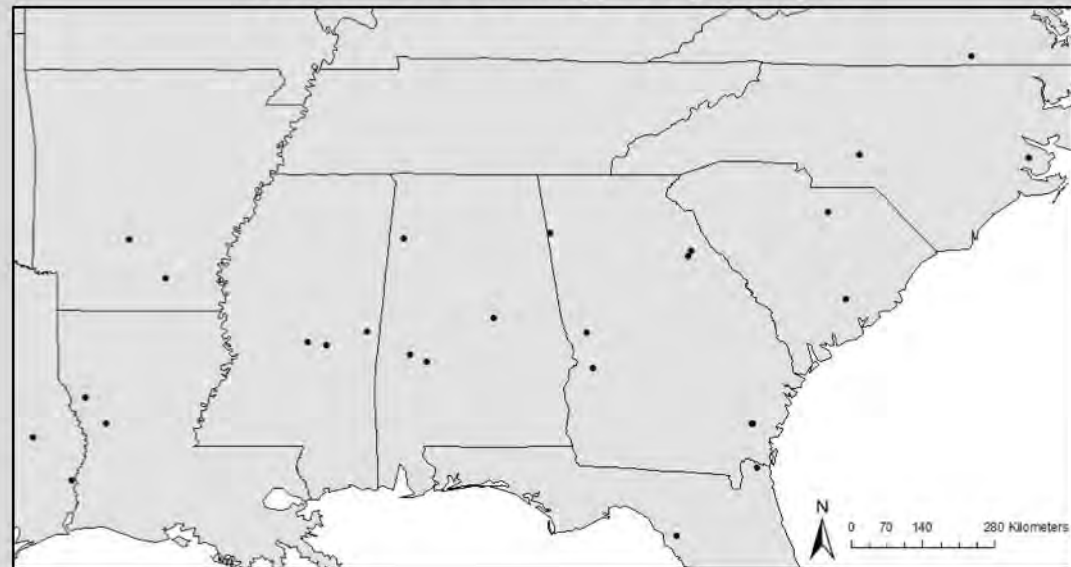
(Raymond et al. 2016)

Regional Fertilization Trials

Pacific Northwest Stand Management Cooperative

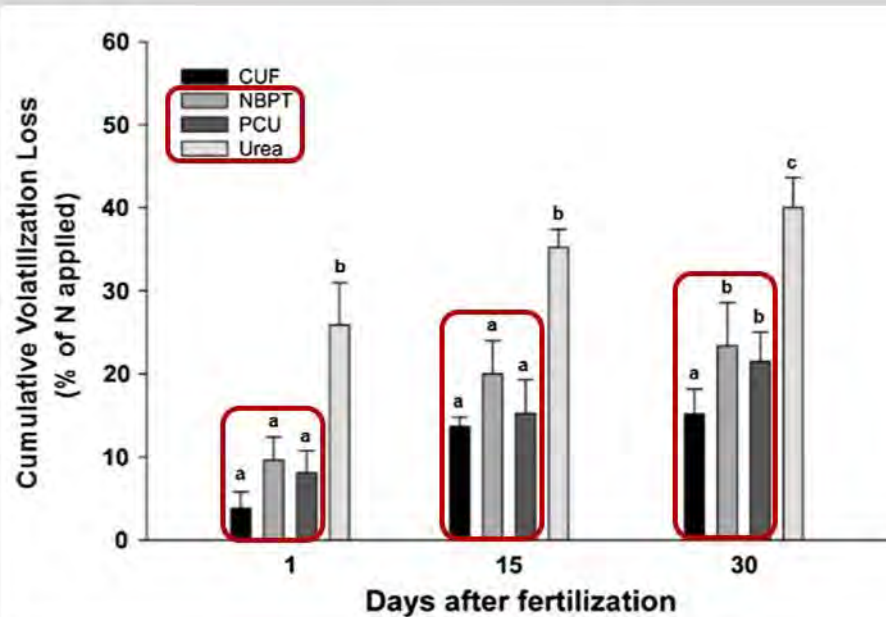


Forest Productivity Cooperative

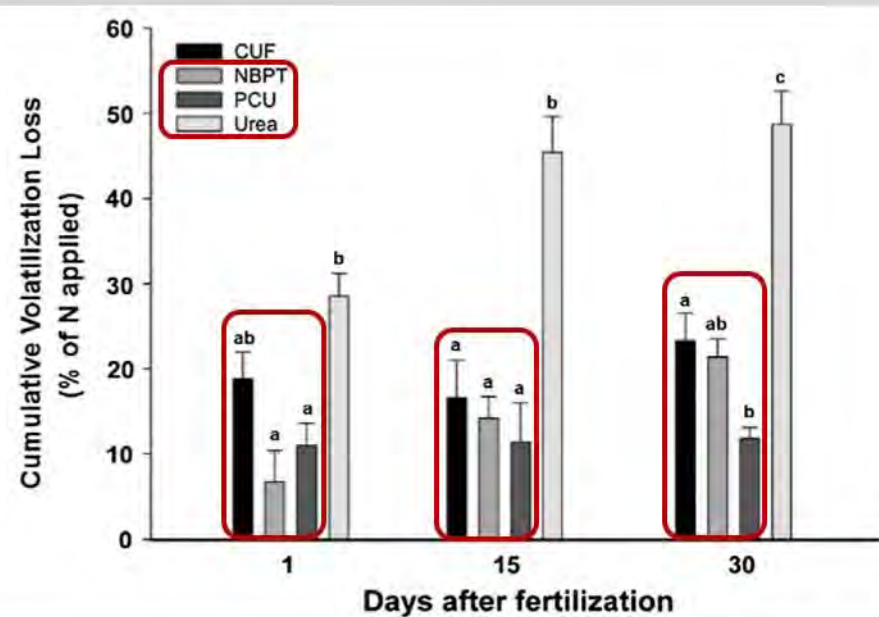


Volatilization Control

Spring Application



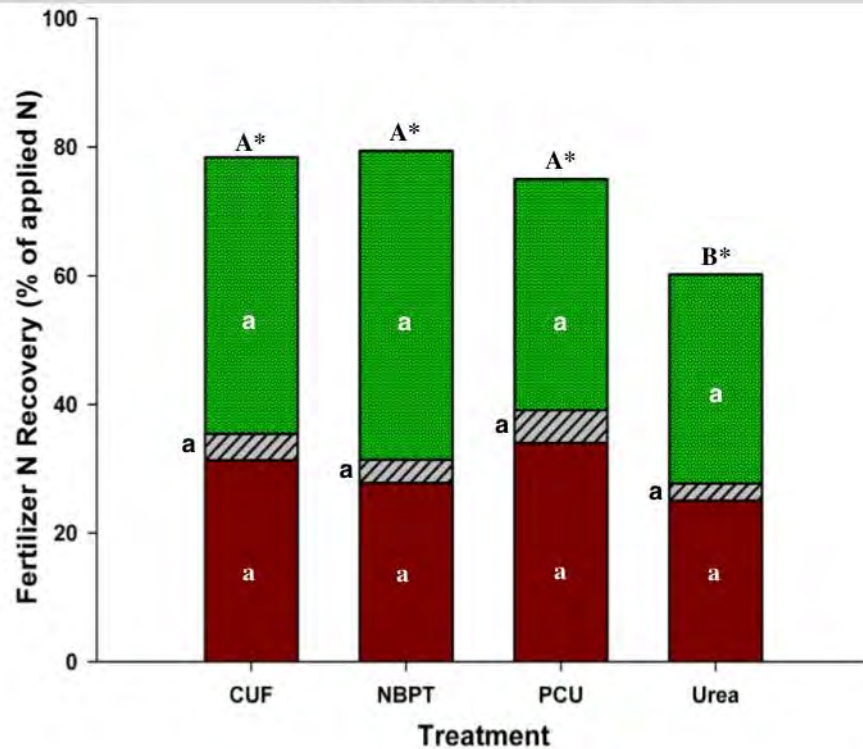
Summer Application



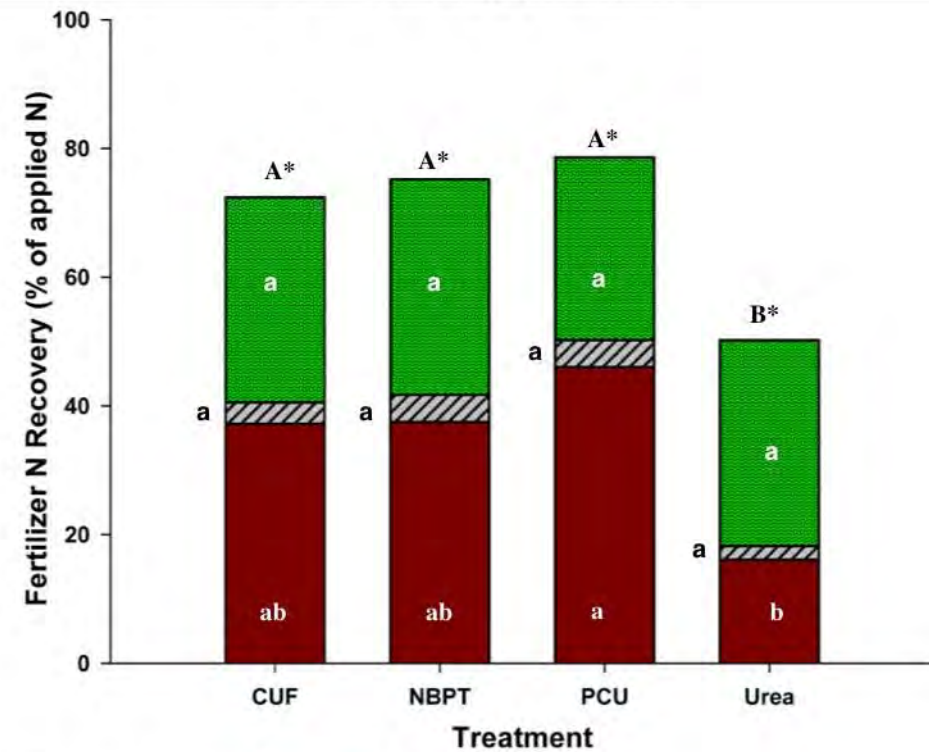
(Raymond et al. 2016)

Fertilizer N Partitioning and Retention

Spring Application



Summer Application



a Tree

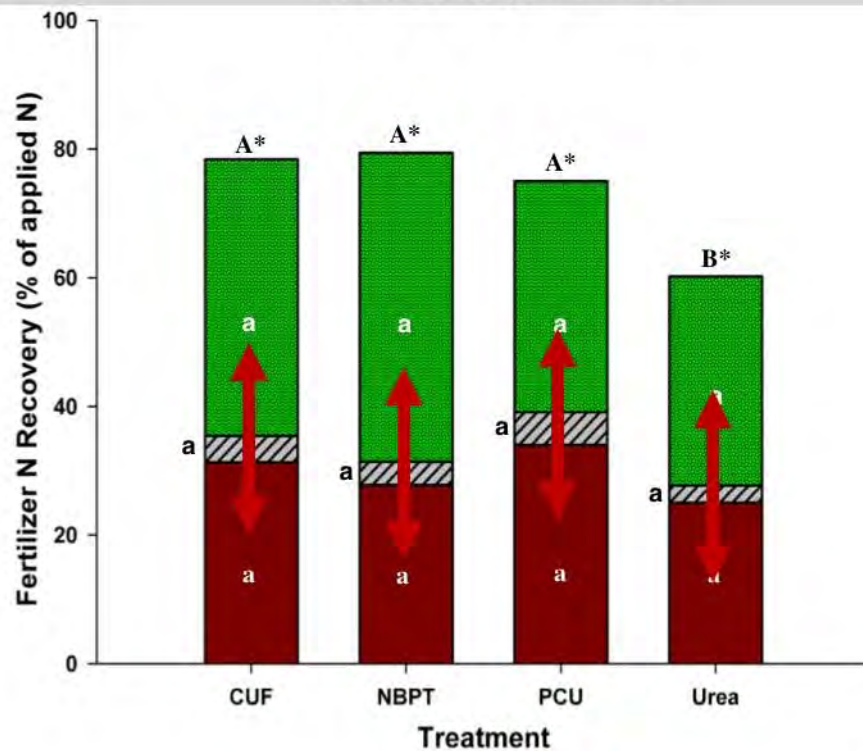
a Forest floor

ab Mineral soil

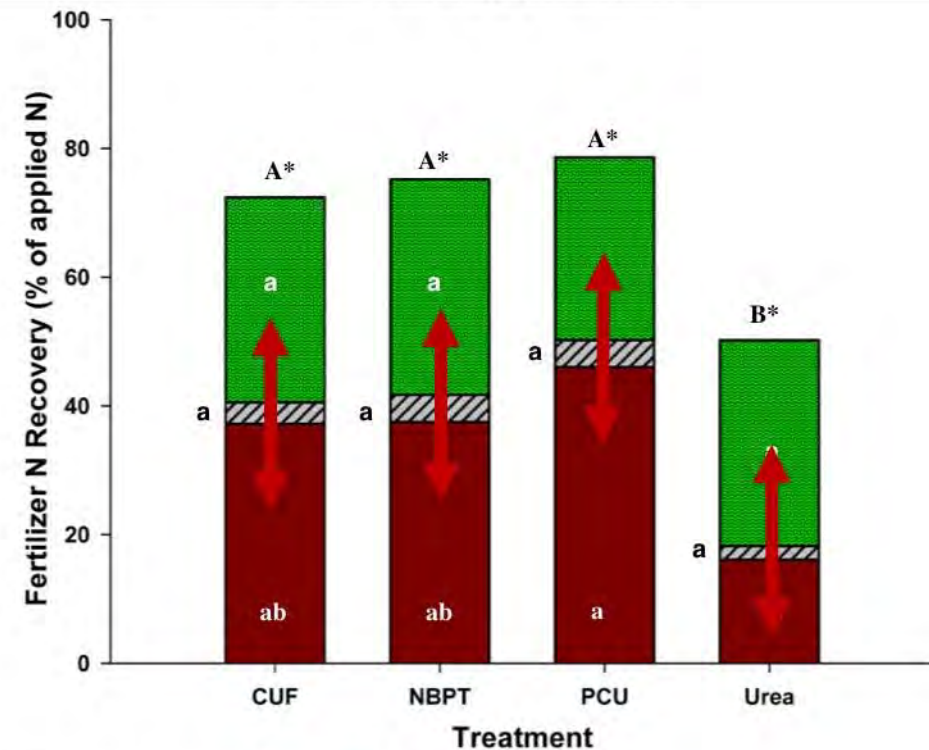
(Raymond et al. 2016)

Fertilizer N Partitioning and Retention

Spring Application



Summer Application



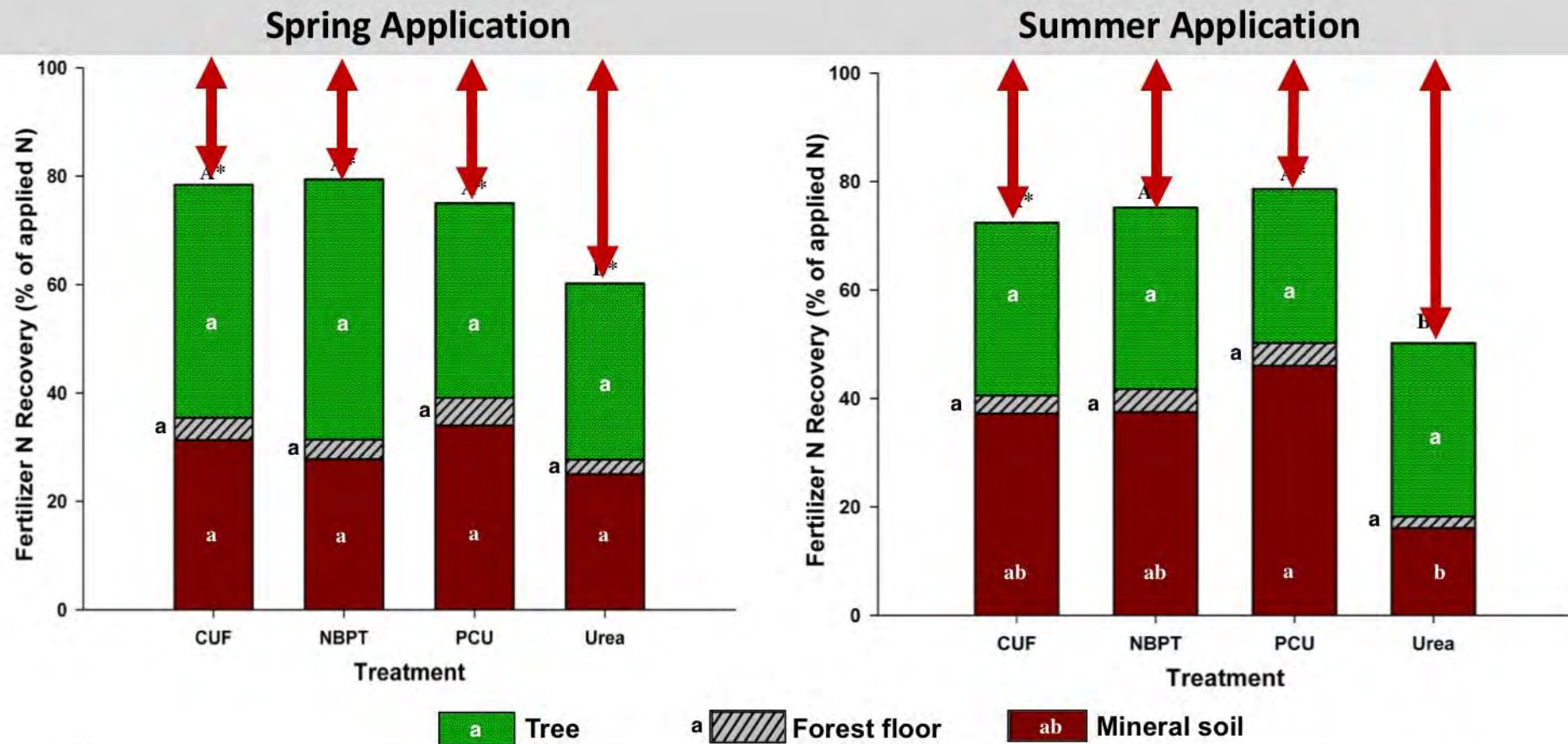
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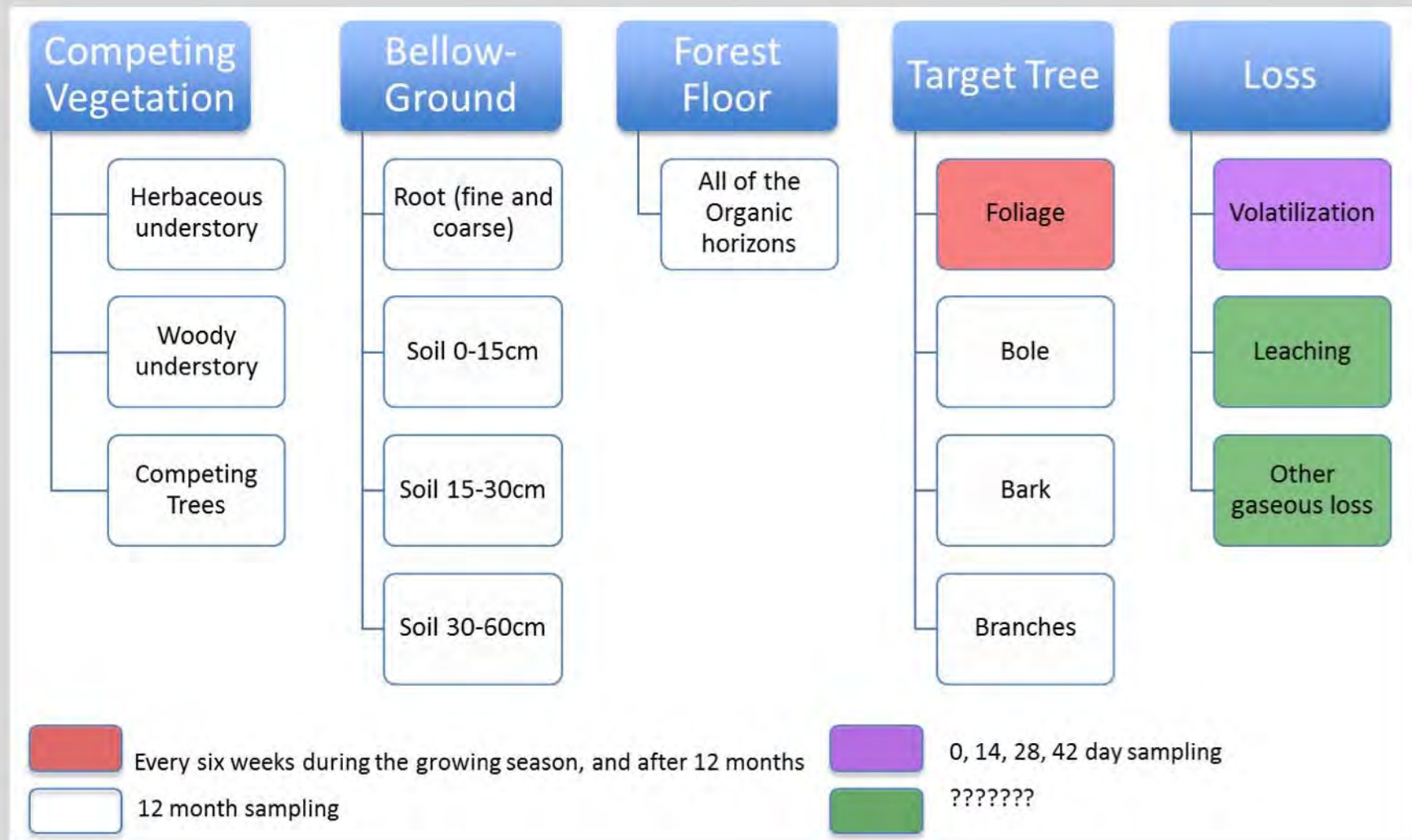
(Raymond et al. 2016)

Fertilizer N Partitioning and Retention



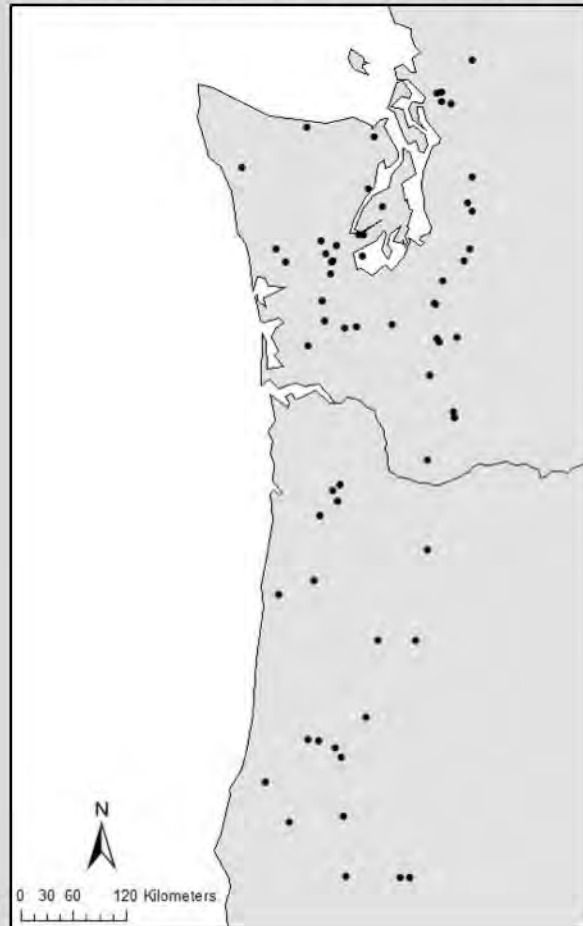
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Fertilizer N Partitioning and Retention

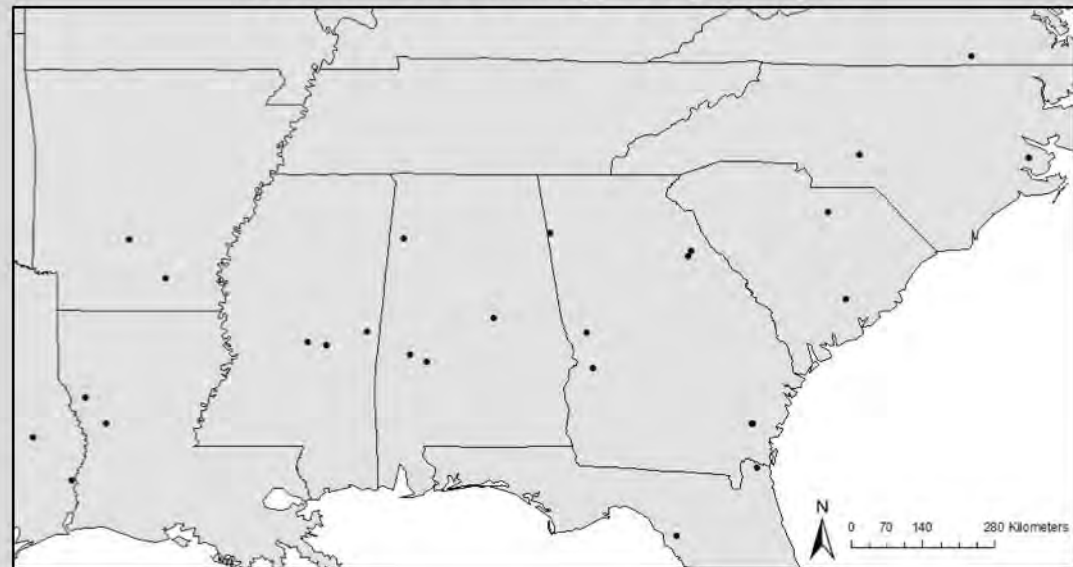


Fertilizer N Partitioning and Retention

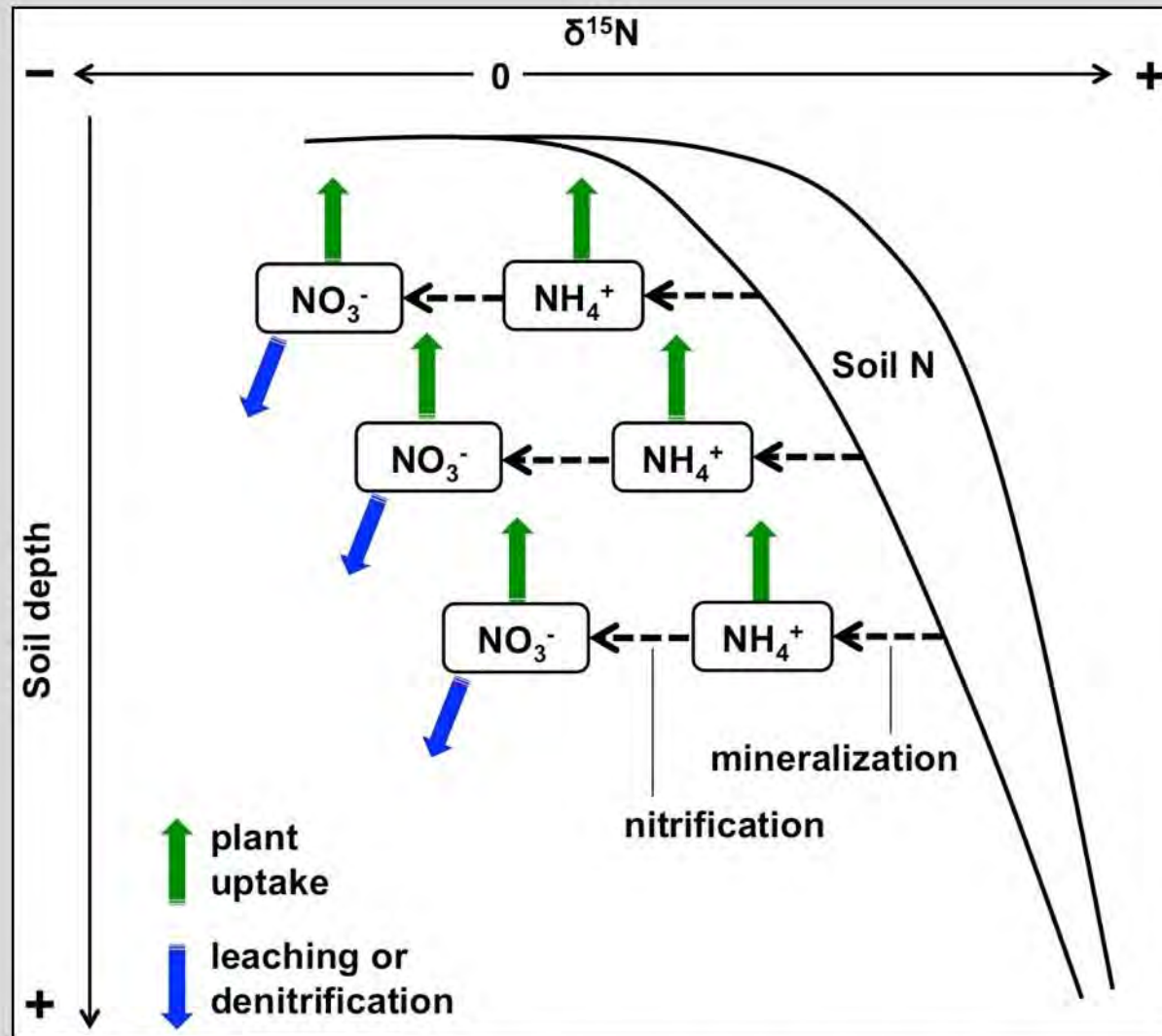
Pacific Northwest Stand Management Cooperative



Forest Productivity Cooperative

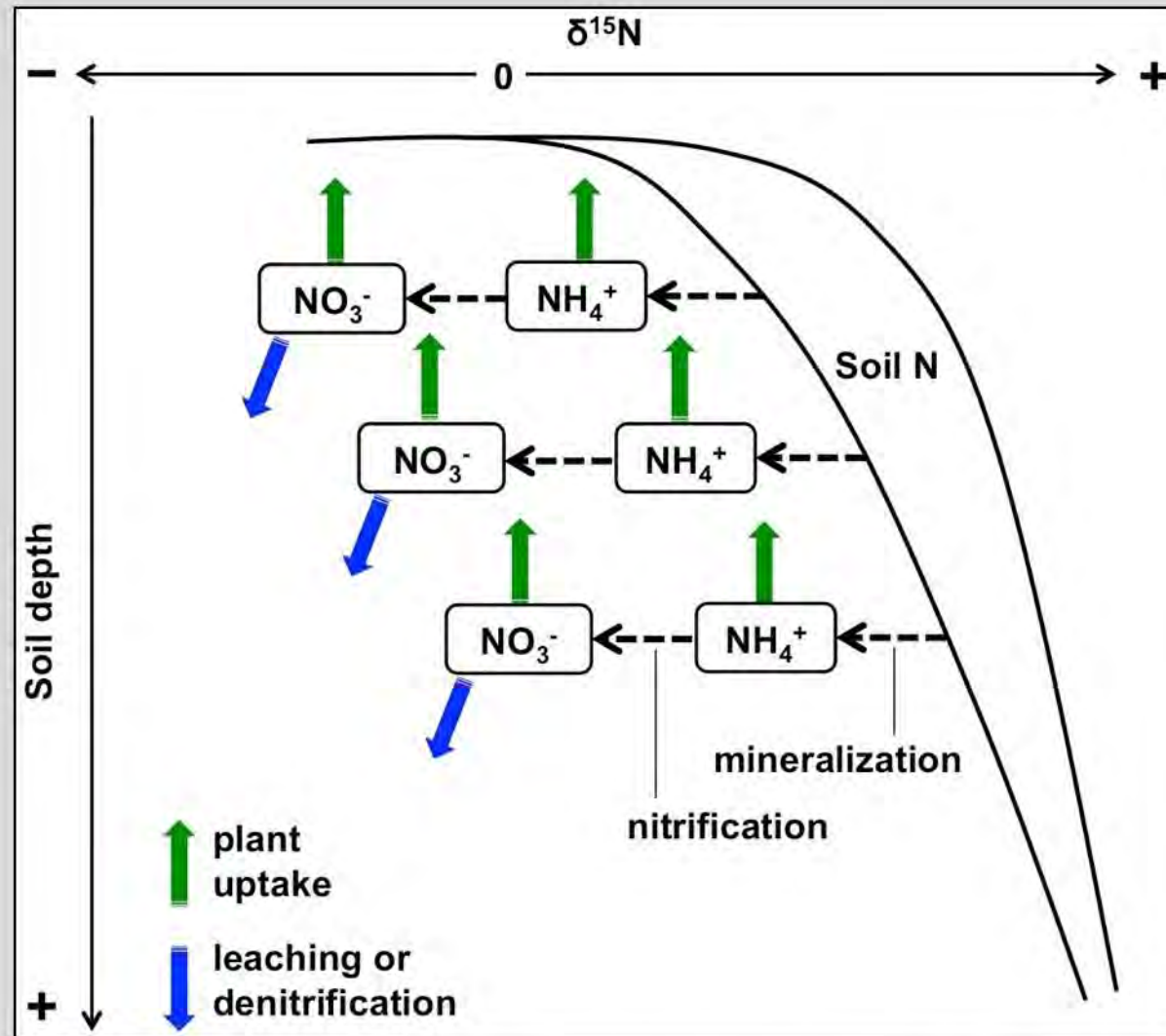


Patterns in Natural Abundance $\delta^{15}\text{N}$

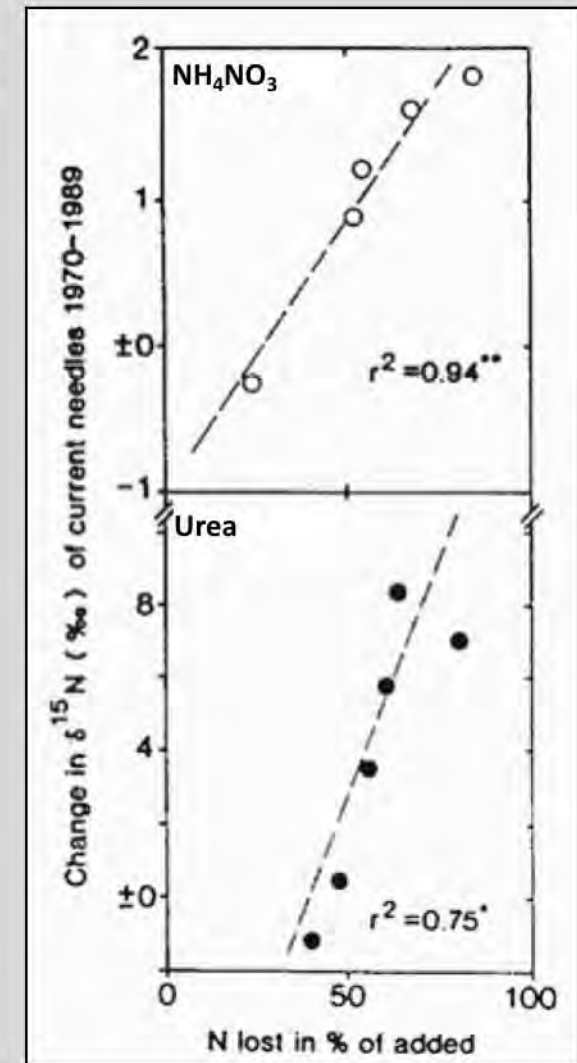


(recreated from Nadelhoffer and Fry, 1994)

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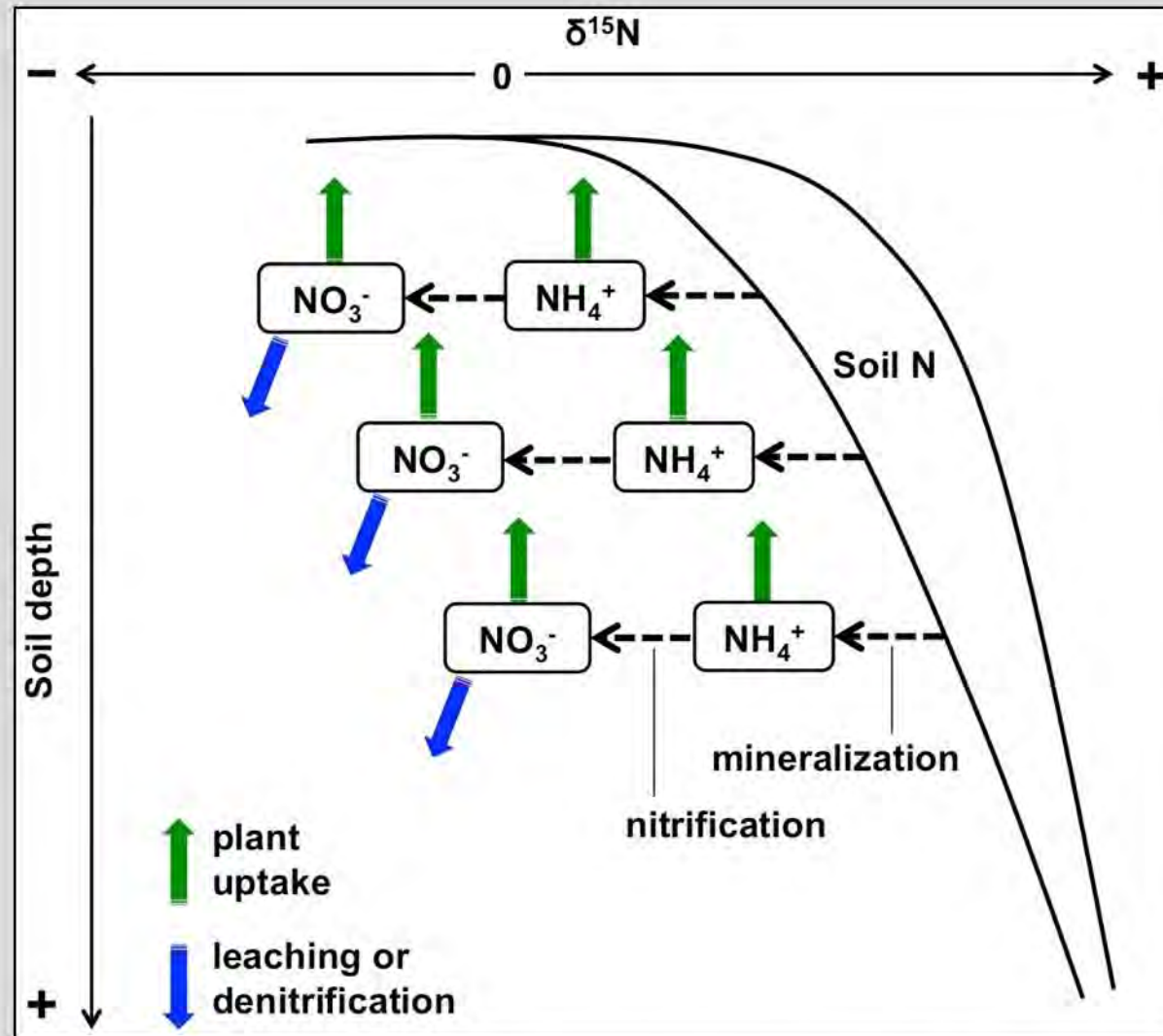


(recreated from Nadelhoffer and Fry, 1994)



(adapted from Högberg, 1993)

Patterns in $\delta^{15}\text{N}$



(recreated from Nadelhoffer and Fry, 1994)

- Foliar = $\delta^{15}\text{N}_{\text{Fol}}$

- Soil = $\delta^{15}\text{N}_{\text{Soil}}$

- Enrichment Factor (EF) =

$$\delta^{15}\text{N}_{\text{Fol}} - \delta^{15}\text{N}_{\text{Soil}}$$

Variability in Fertilization Response



	Douglas-fir		
	BA	Ht.	Vol.
Min	-23.5	-12.6	-12.7
Max	41.5	61.1	34.1
Mean	9.2	6.2	7.3
Range	65.0	73.7	46.8
Std. Dev.	15.2	12.3	10.1



	Loblolly pine		
	BA	Ht.	Vol.
Min	-34.3	-12.5	-30.4
Max	118.8	49.7	179.7
Mean	30.1	8.4	36.9
Range	153.1	62.2	210.1
Std. Dev.	26.5	12.9	40.4

(Lorentz et al. *In Prep*)

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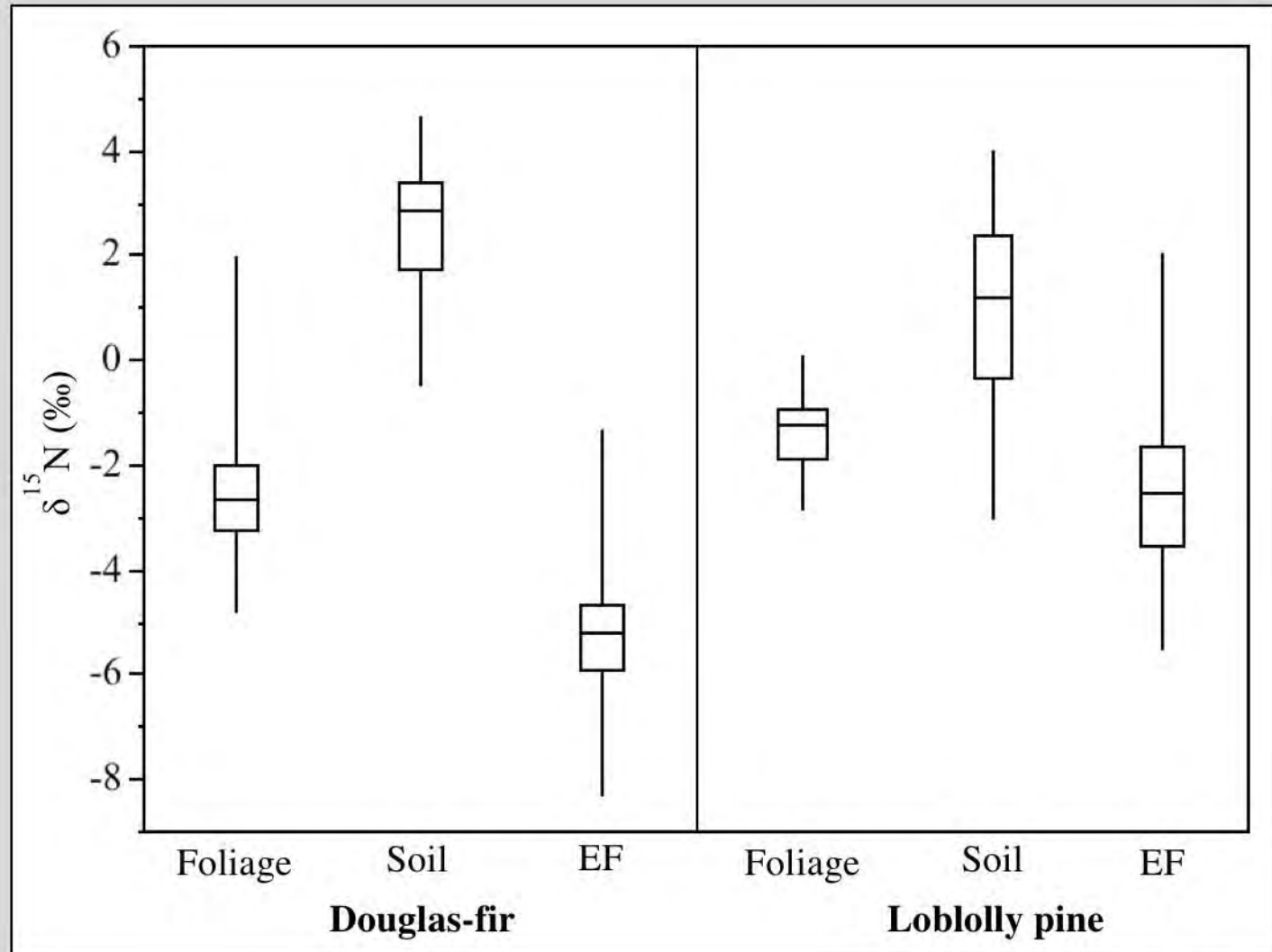
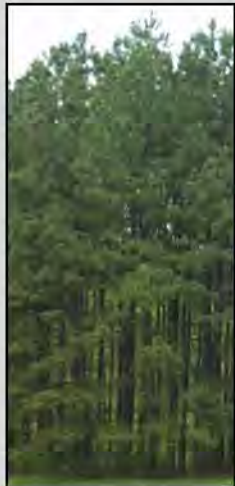


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Range of
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(Lorentz et al. *In Prep*)

Variability in $\delta^{15}\text{N}$



(Lorentz et al. *In Prep*)

Douglas-fir Fertilization Response

	$\delta^{15}\text{N}_{\text{Fol}}$	$\delta^{15}\text{N}_{\text{Soil}}$	EF
Basal area	-0.14 (0.30)	0.29 (0.03)*	-0.34 (0.01)*
Height	-0.17 (0.20)	-0.04 (0.76)	-0.04 (0.75)
Volume	-0.17 (0.21)	0.19 (0.16)	-0.27 (0.05)*

Variables	R^2	Adj. R^2	RMSE (%)	Press RMSE (%)	p-value	Shapiro-Wilk	p-value
Forest Floor C:N Ratio	0.24	0.23	13.4	13.5	<0.01	0.97	0.16
Forest Floor C:N Ratio EF	0.39	0.36	12.4	12.6	<0.01	0.98	0.33
Forest Floor C:N Ratio EF Effective Depth (cm)	0.44	0.41	11.9	12.1	<0.01	0.99	0.76

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Mineralogical Controls on Nutrient Mobility



Variable	Description	Estimation ^a
Fe_{PED}	Pedogenically active Fe fraction	= Fe _d
Al_{PED}	Pedogenically active Al fraction	= Al _o
Fe_{SRO}	Short-range-order Fe fraction	= Fe _o
Al_{SRO}	Short-range-order Al fraction	= Al _o - Al _p
Al_{ORG}	Organically bound Al	= Al _p
Al_{SUB}	Al substituted in Fe-oxides	= Al _d
Al:Si	Short-range order Al:Si ratio	= (Al _o - Al _p) / Si _o
Fe_{G+H}	Fe in goethite and hematite	= Fe _d - Fe _o
CLAY	Clay particle size fraction	
Org. C	Percent organic C	

^a Values represent pyrophosphate (Al_p), acid oxalate (Fe_o, Al_o, Si_o) and dithionite-citrate (Fe_d, Al_d) extractable fractions.

(Strahm and Harrison 2007)

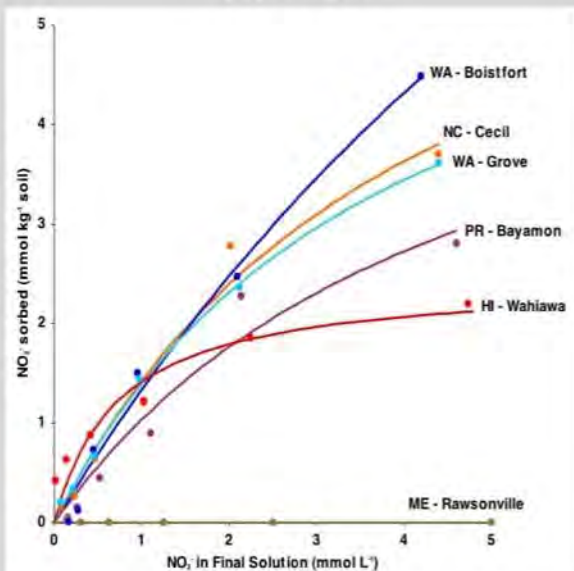


Mineralogical Controls on Nutrient Mobility

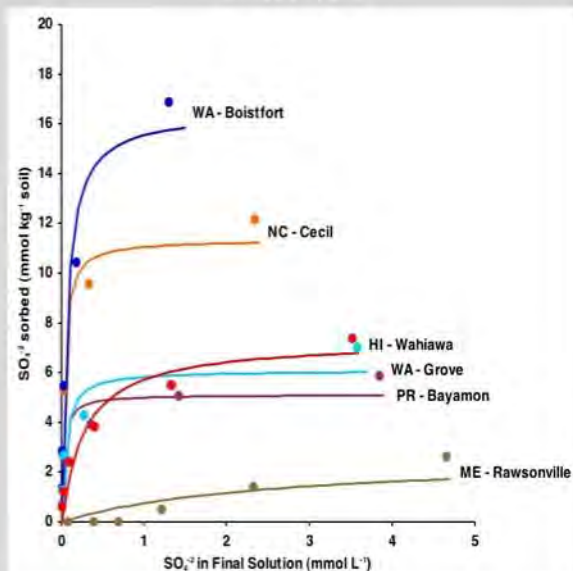


Mineralogical Controls on Nutrient Mobility

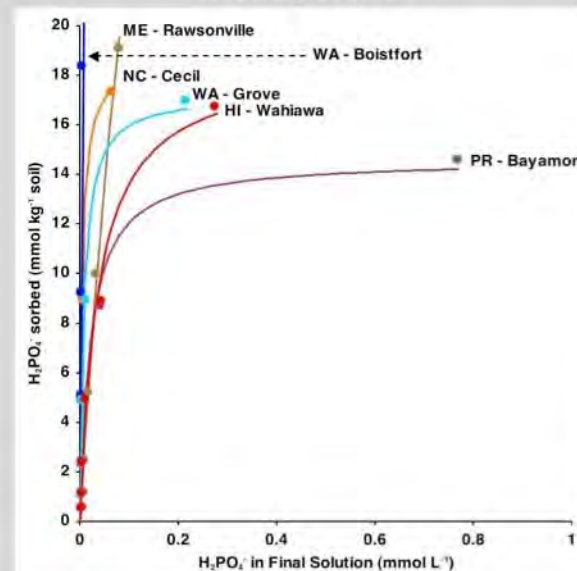
Nitrate



Sulfate



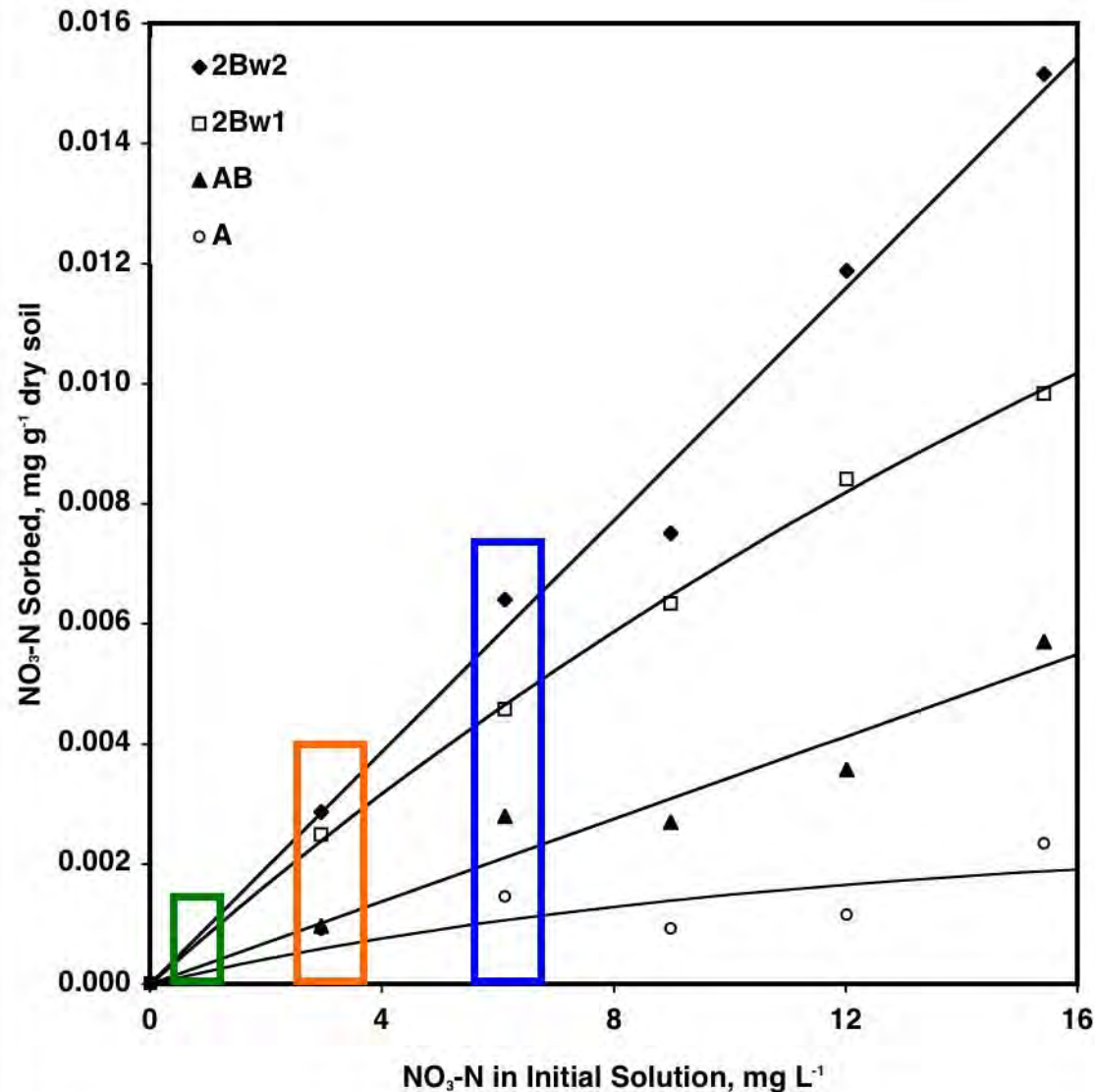
Phosphate



Anion	Parameter	Equation	Adjusted R ²	P
NO ₃ ⁻	N _{max}	6.06 – 3.27(organic C) + 33.28(<u>organically bound Al</u>)	0.88	0.020
	b	–0.049 + 0.125(<u>short-range-order Al/Si ratio</u>)	0.89	0.003
SO ₄ ²⁻	N _{max}	–1.643 – 2.00(organic C) + 33.9(<u>Al substituted in Fe oxides</u>)	0.77	0.053
	b	52.5 – 76.4(<u>Al substituted in Fe oxides</u>)	0.48	0.077
H ₂ PO ₄ ⁻	N _{max}	15.8 + 11.9(<u>short-range-order Fe</u>)	0.98	<0.001
	b	–117 – 103(organic C) + 1160(<u>organically bound Al</u>)	0.67	0.087

(Strahm and Harrison 2007)

Mineralogical Controls on Nutrient Mobility

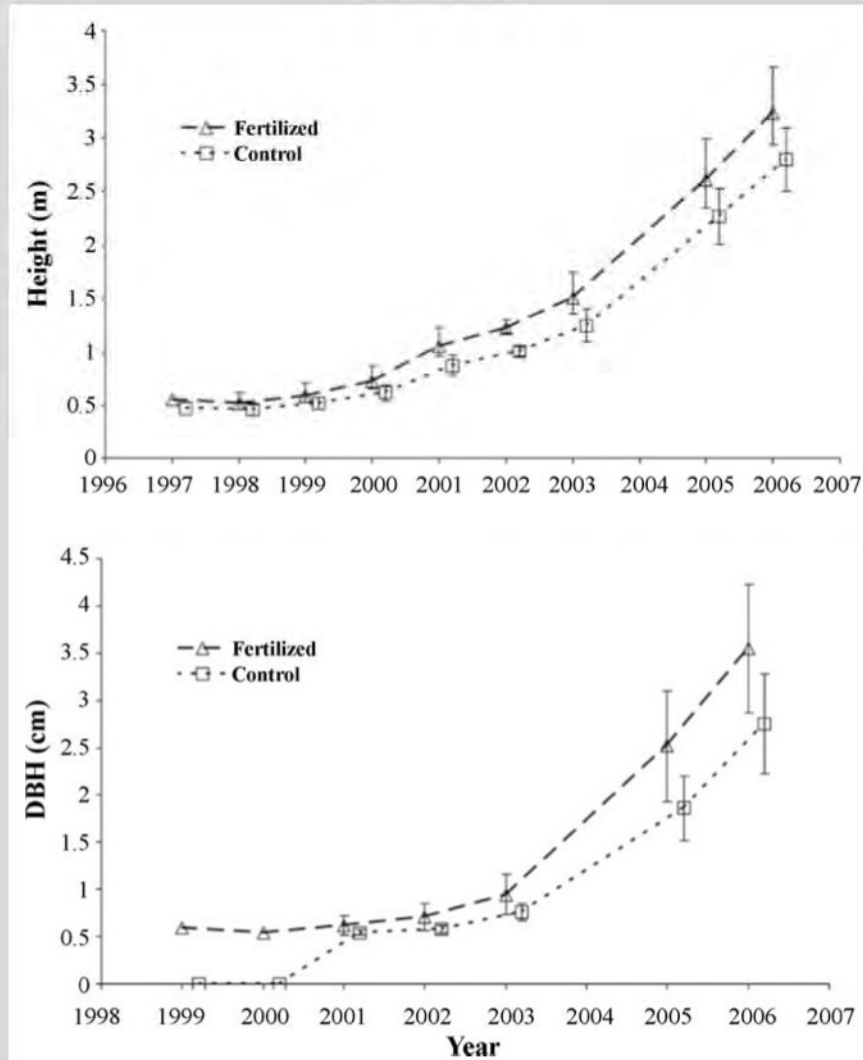


Treatment	BOLE-ONLY	TOTAL TREE PLUS	FOREST
Mean $\text{NO}_3\text{-N Conc (mg L}^{-1}\text{)}$	6	2.5	0.5
$\text{NO}_3\text{-N Sorbed (kg ha}^{-1}\text{)}$	49	19	3.4
Mean $\text{NO}_3\text{-N Leached (kg ha}^{-1} \text{ yr}^{-1}\text{)}$	73	26	2.0
% of $\text{NO}_3\text{-N Leached}$	67	73	170

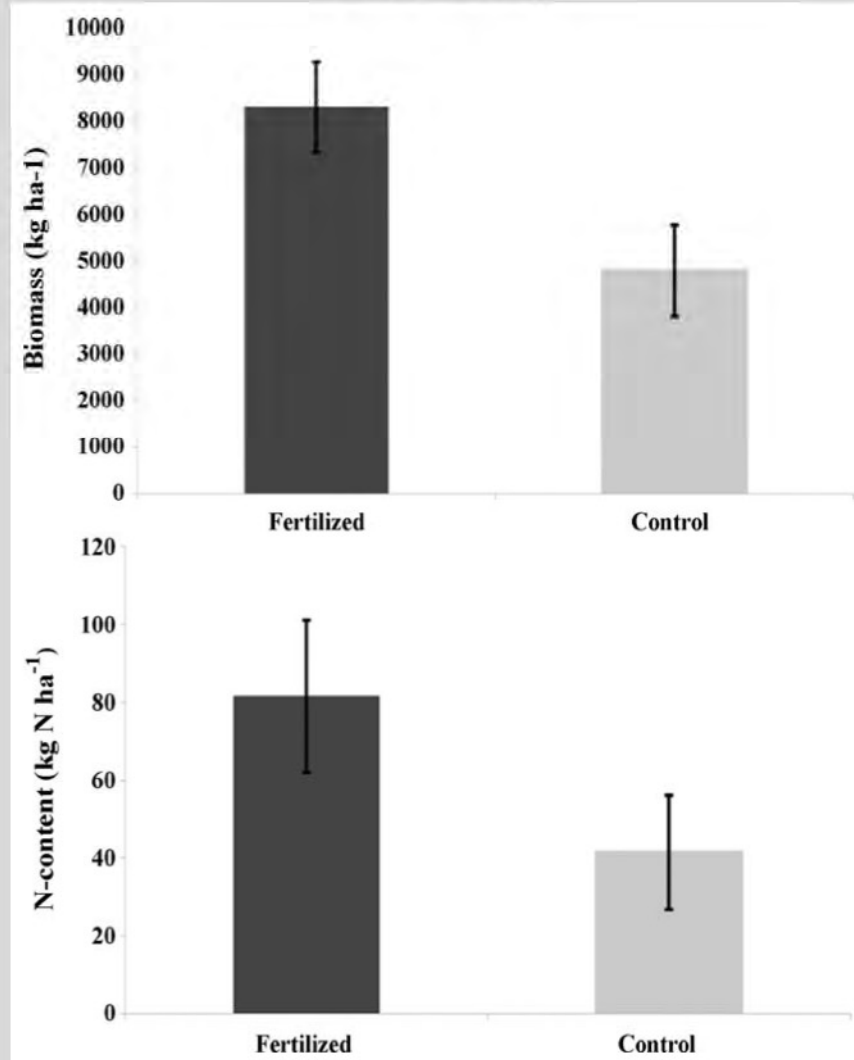
(Strahm and Harrison 2006)

Nitrogen Retention and “Carryover”

Overstory

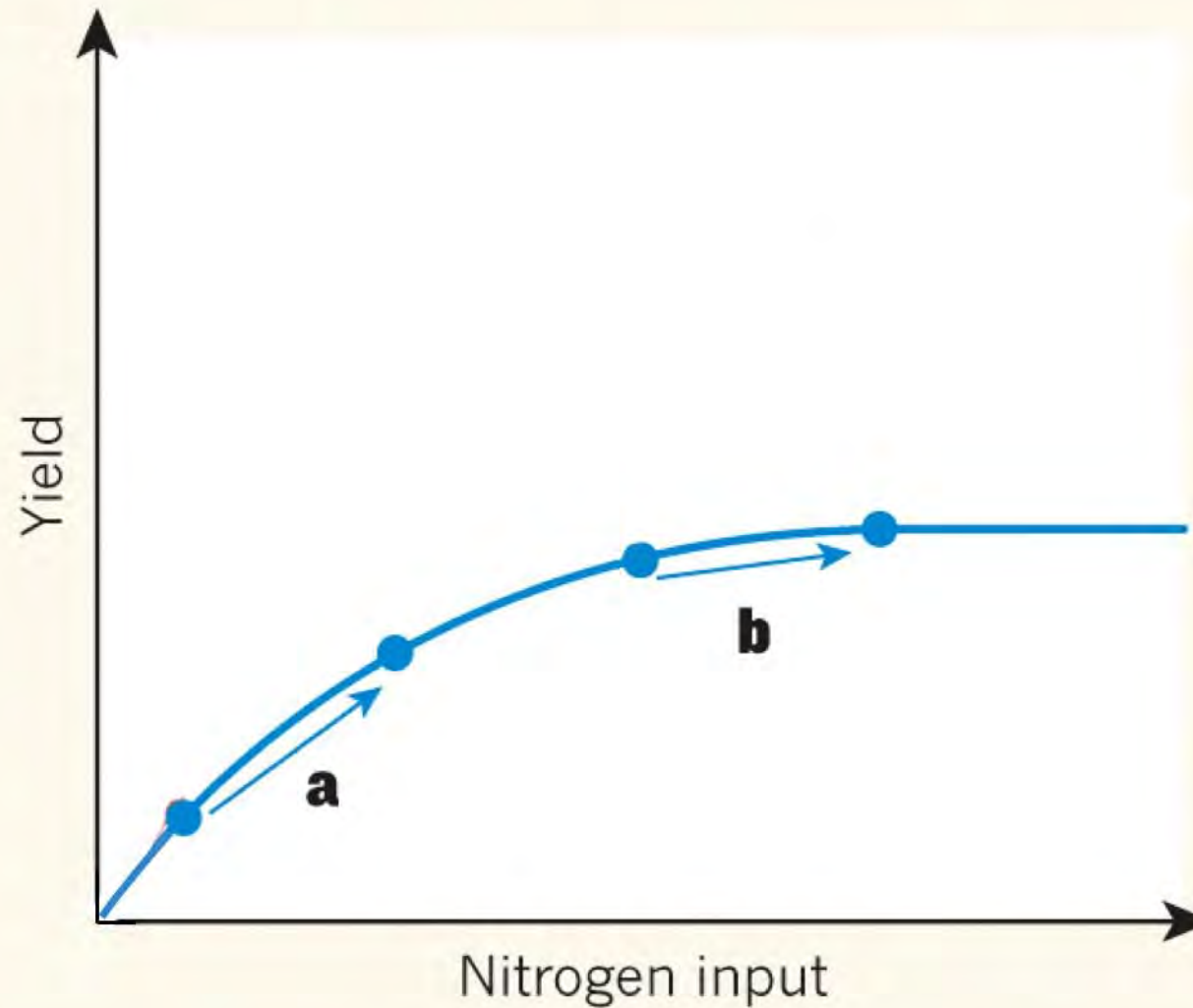


Understory



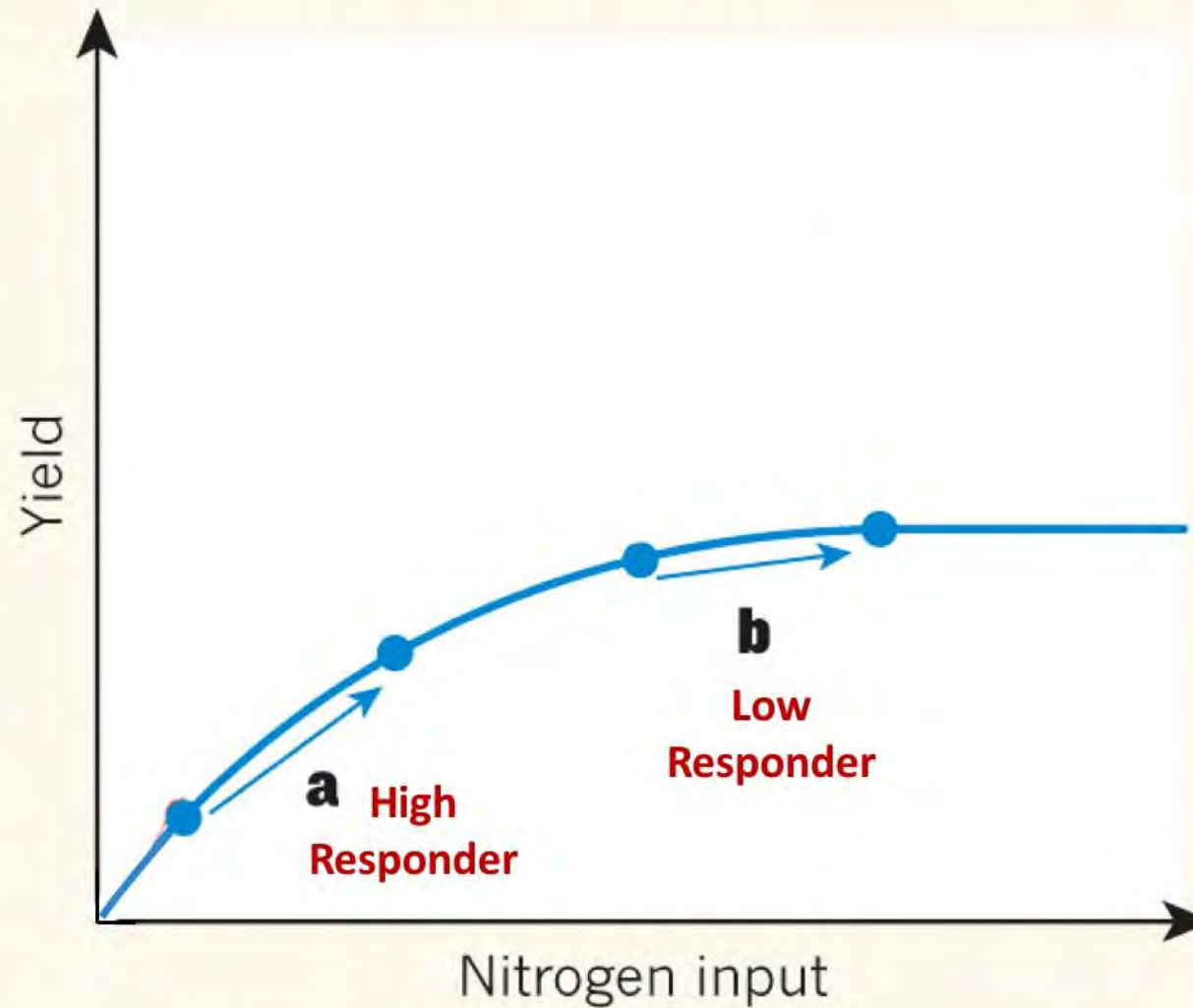
(Footen et al. 2009)

Fertilizer Efficiency in a Changing World



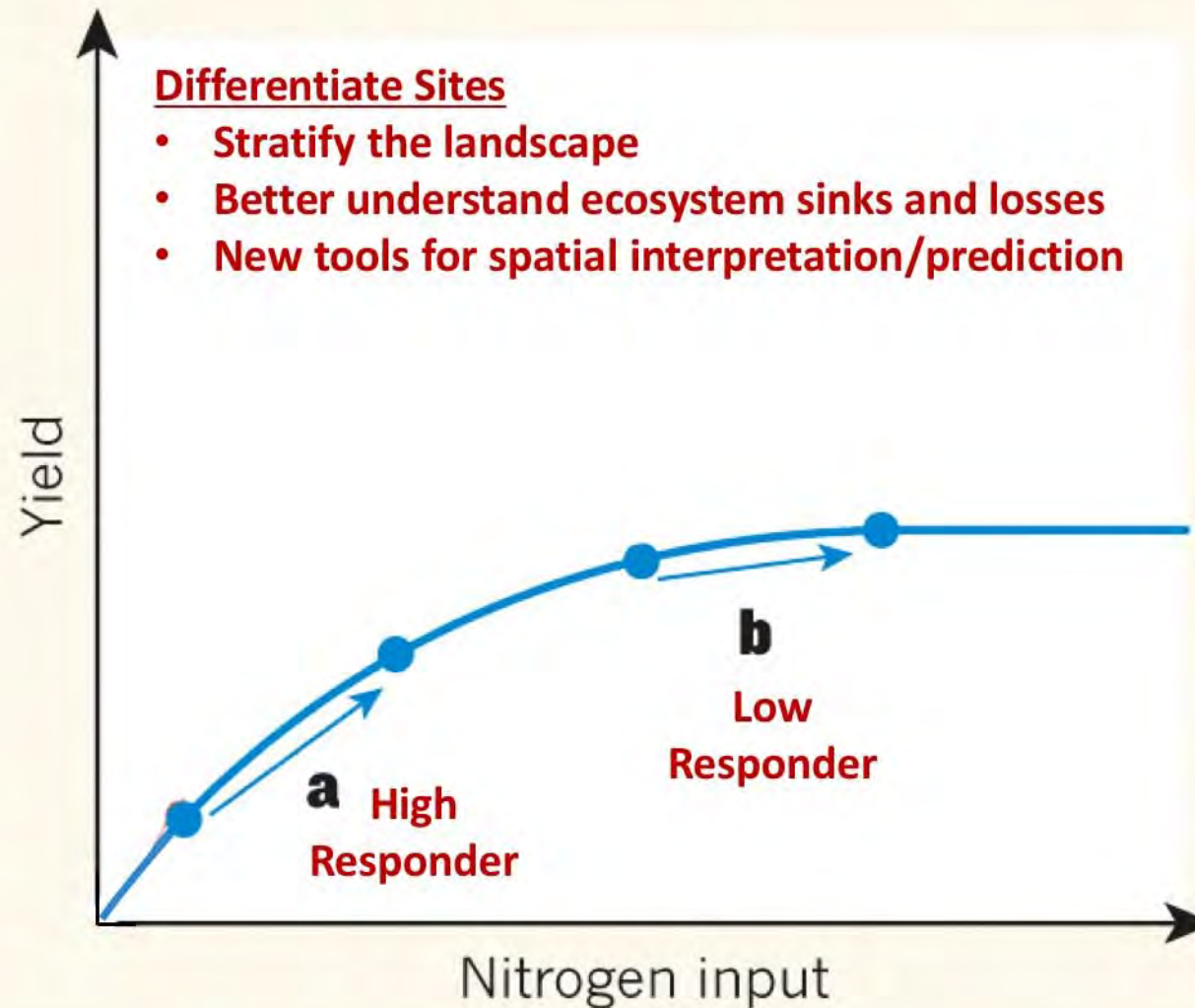
(adapted from Zhang 2017)

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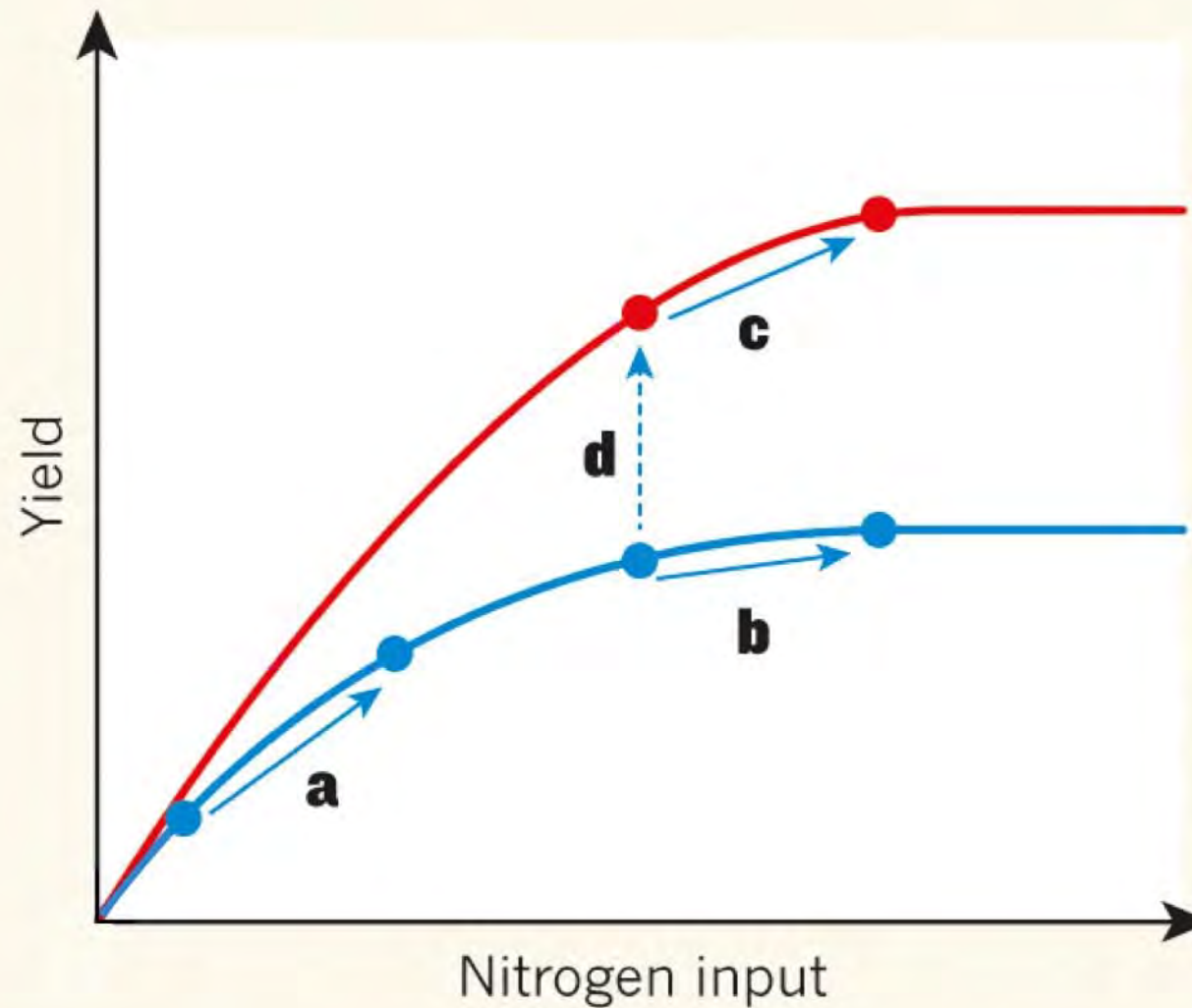
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Fertilizer Efficiency in a Changing World



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Fertilizer Efficiency in a Changing World



Multiscale and Multifactor Approaches

