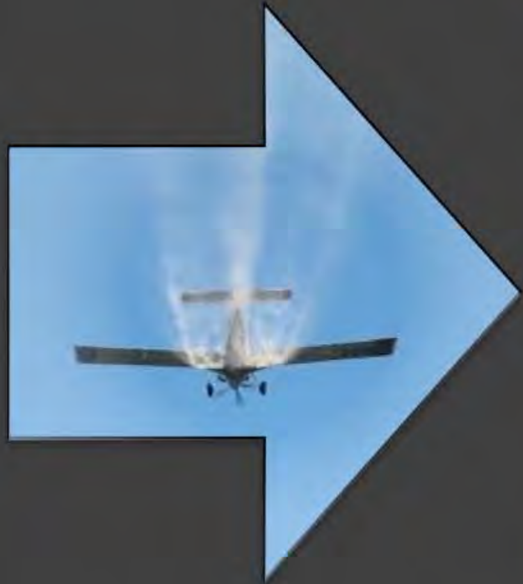
Forest Fertilization:

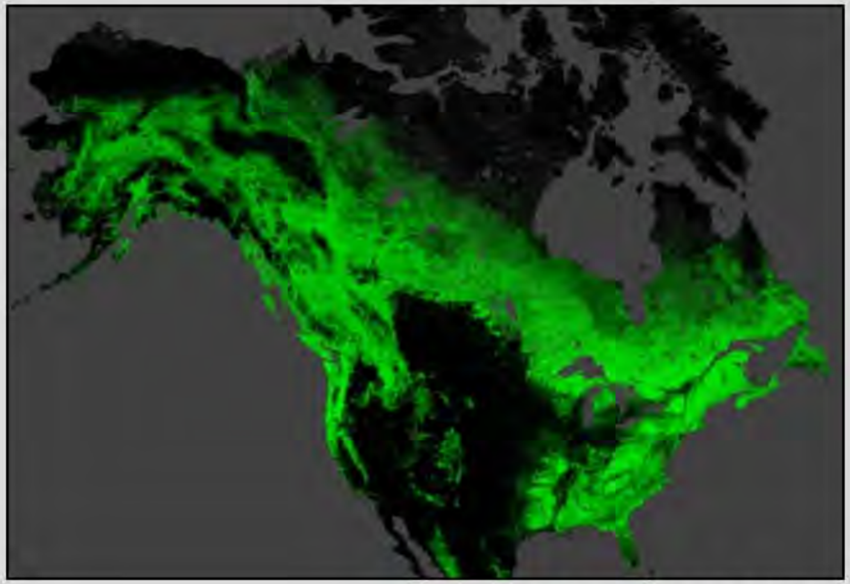
opportunities, efficiencies, and ecosystem responses



Brian D. Strahm

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

US Land Cover and Use



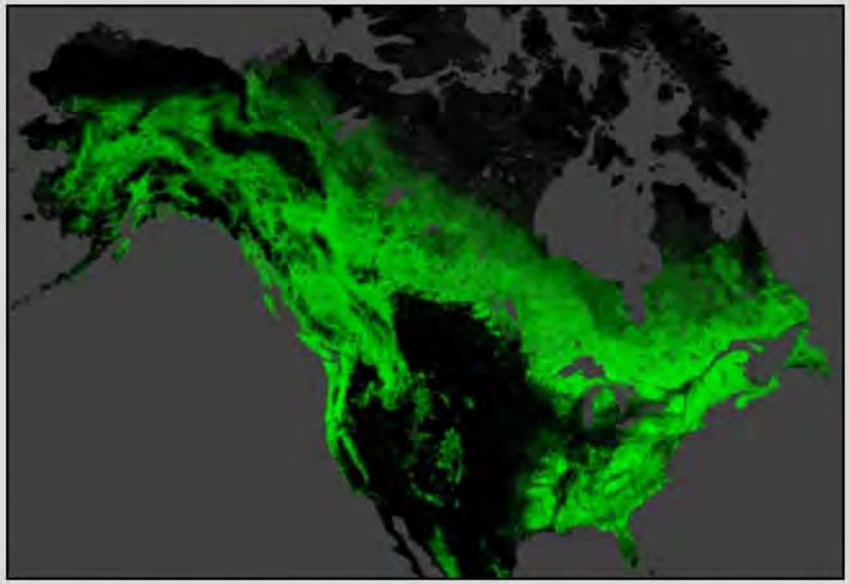
(Hansen et al. 2013)

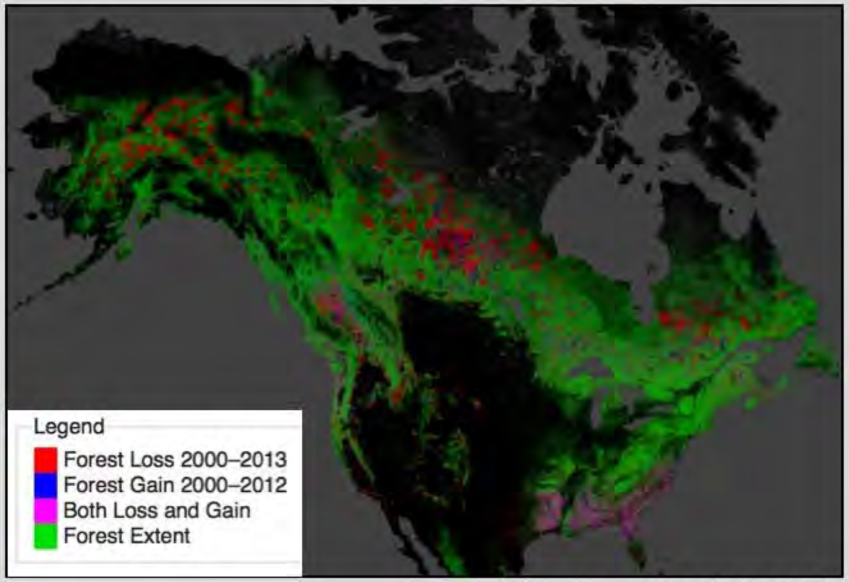
Land-Use Categories	2014
Managed Lands	**890,017**
Forest Land	294,988
Croplands	163,752
Grasslands	321,118
Settlements	42,648
Wetlands	42,113
Other Land	25,399
Unmanaged Lands	**46,213**
Forest Land	9,634
Croplands	0
Grasslands	25,782
Settlements	0
Wetlands	0
Other Land	10,797
Total Land Areas	**936,230**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

(thousands of ha; US EPA 2016)

33% of U.S. is forested

US Land Cover and Use





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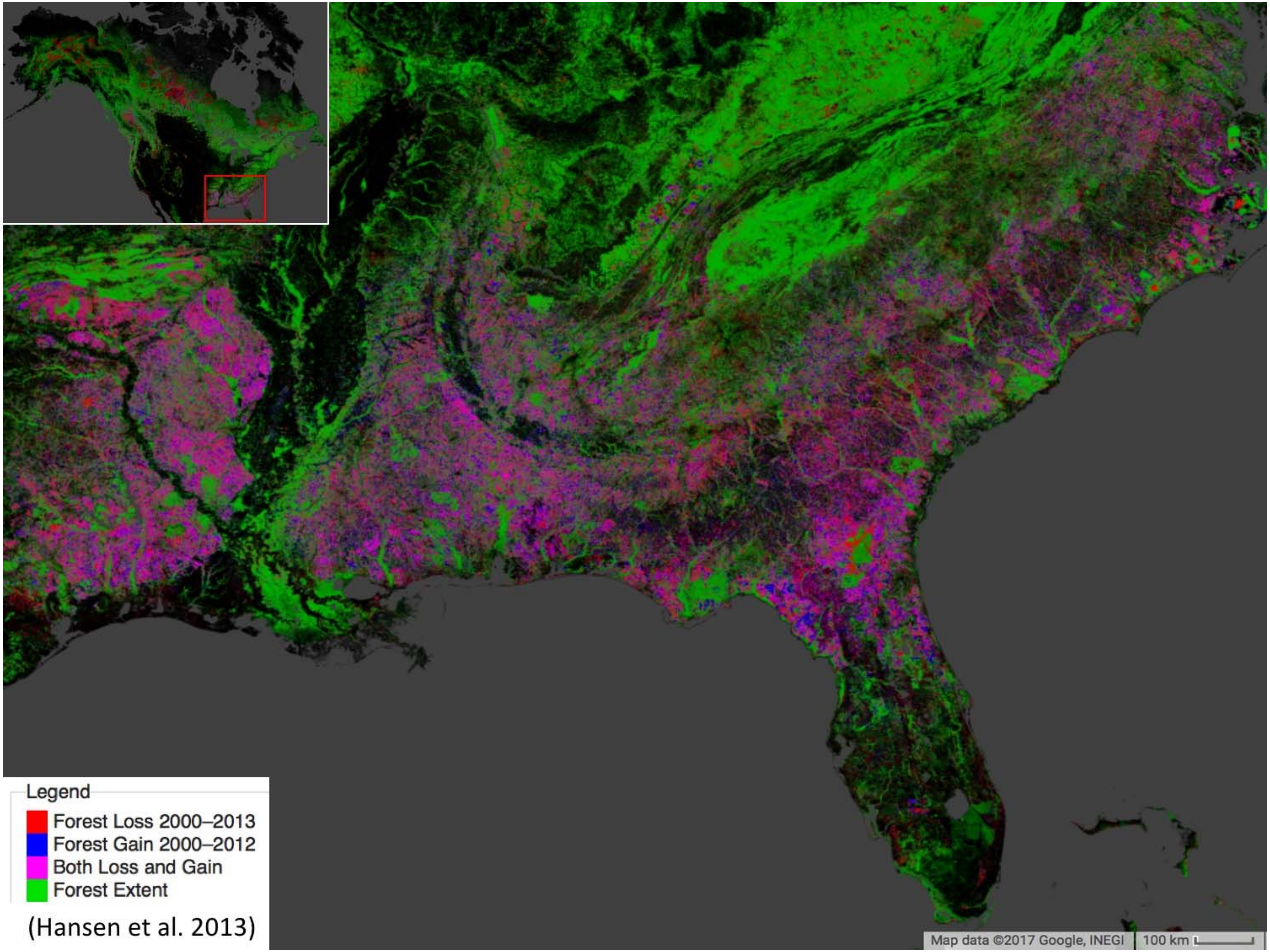
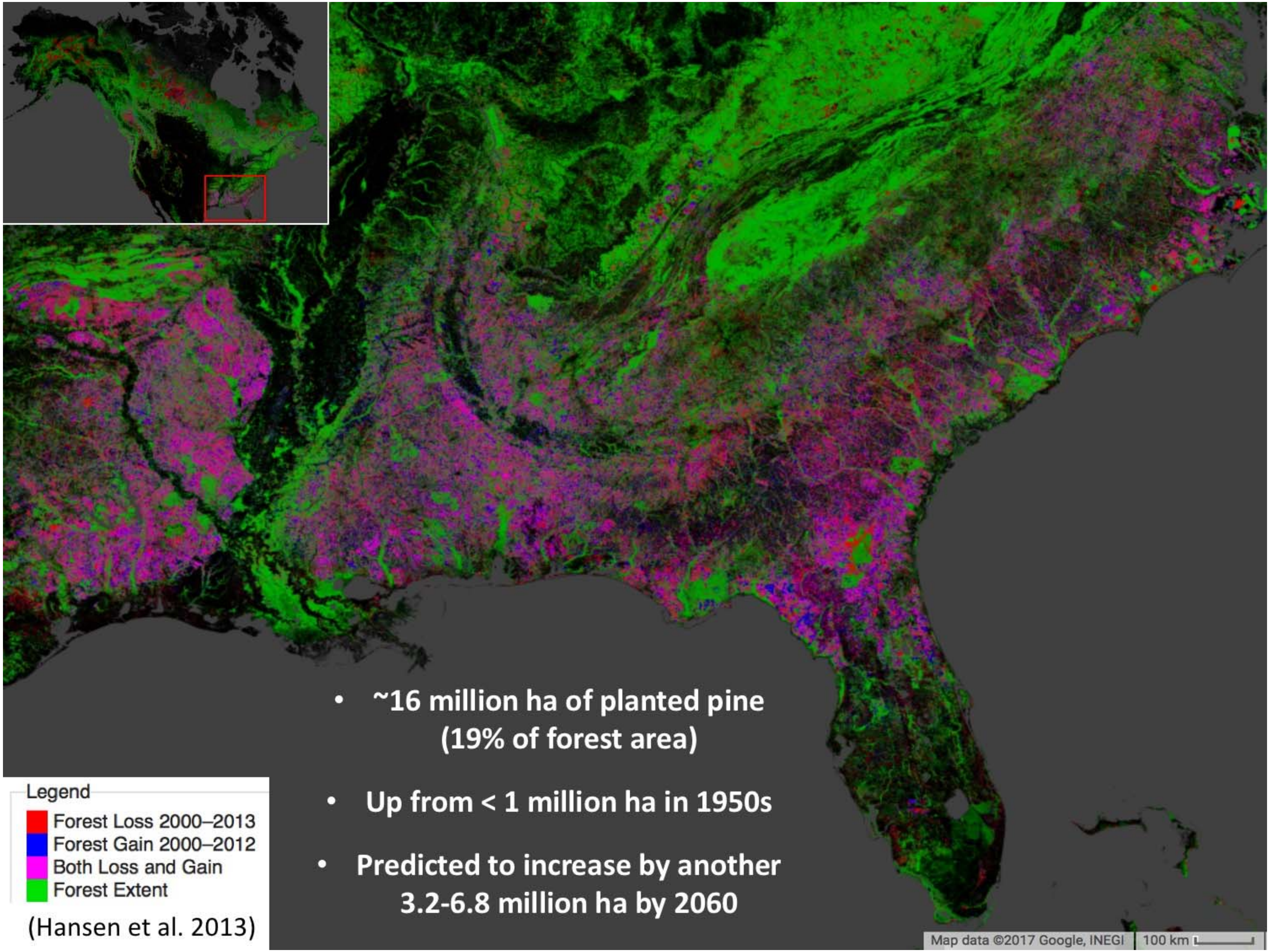
97% of U.S. forests are managed

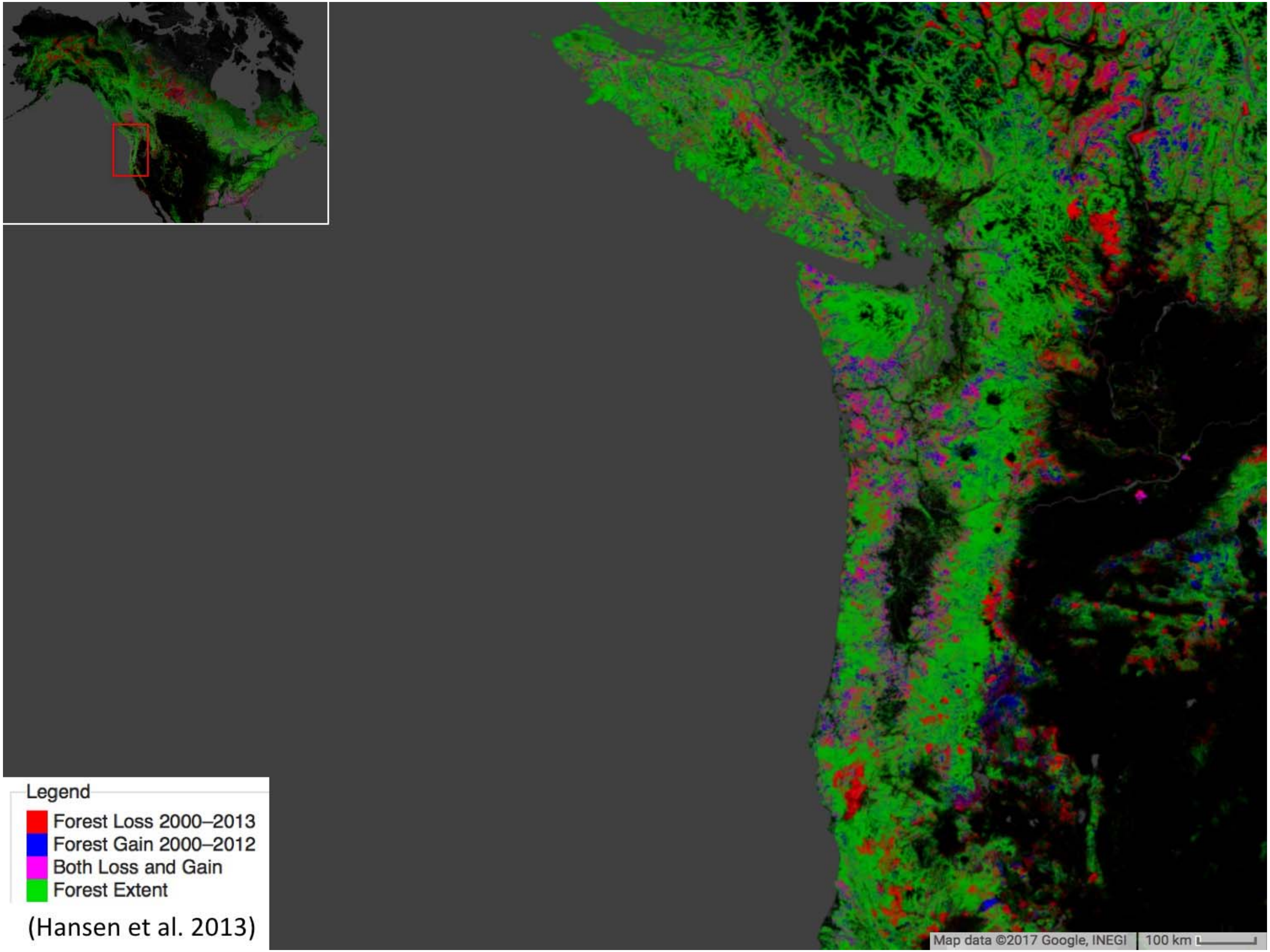


(Hansen et al. 2013)



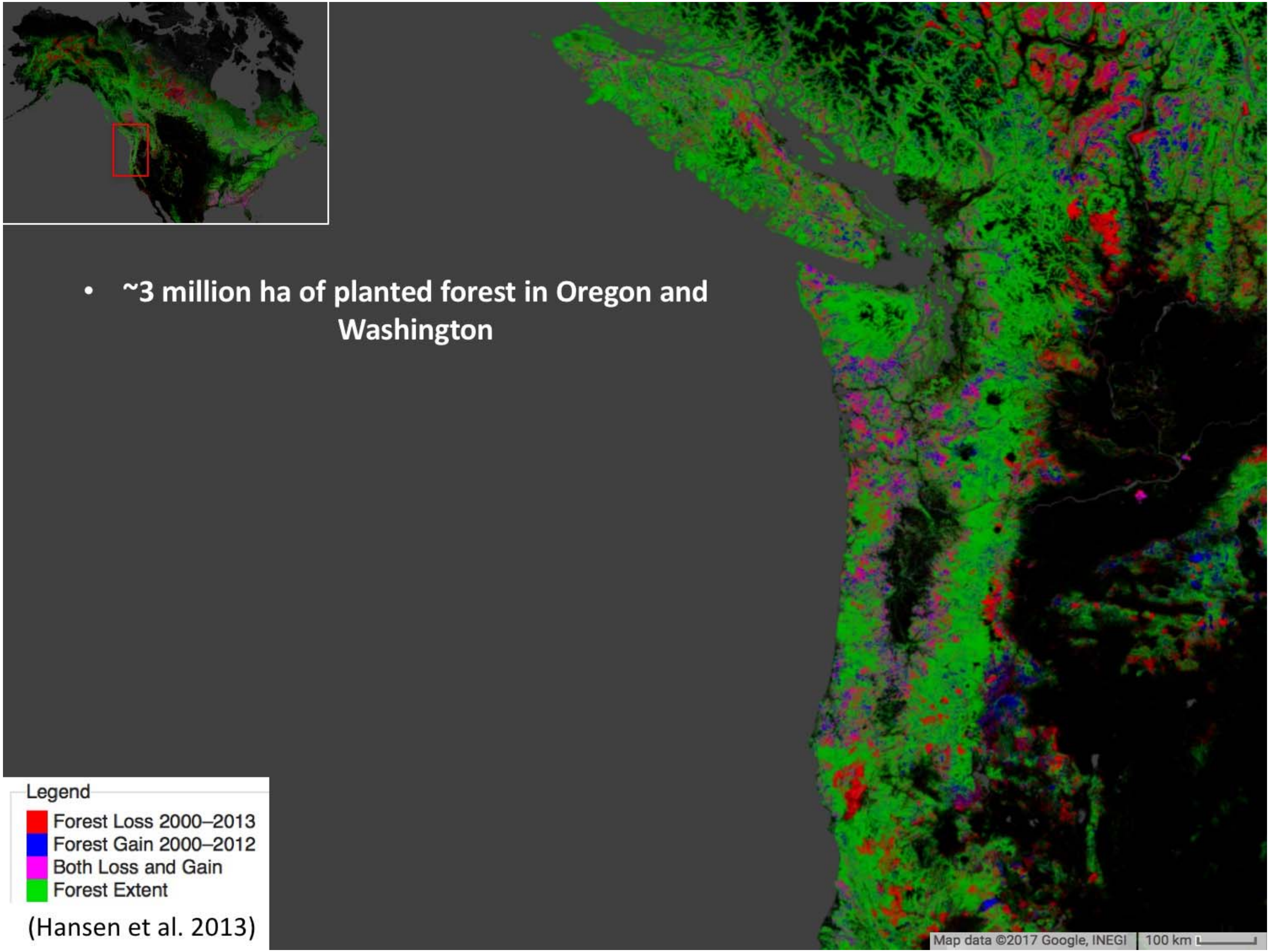
- ~16 million ha of planted pine (19% of forest area)
- Up from < 1 million ha in 1950s
- Predicted to increase by another 3.2-6.8 million ha by 2060

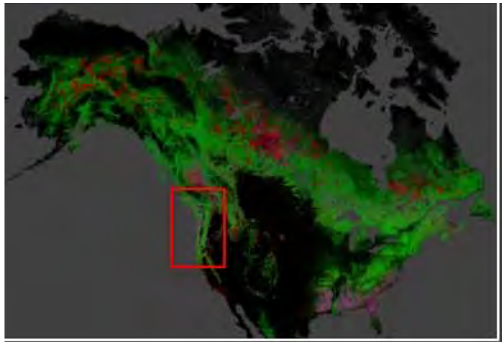
(Hansen et al. 2013)



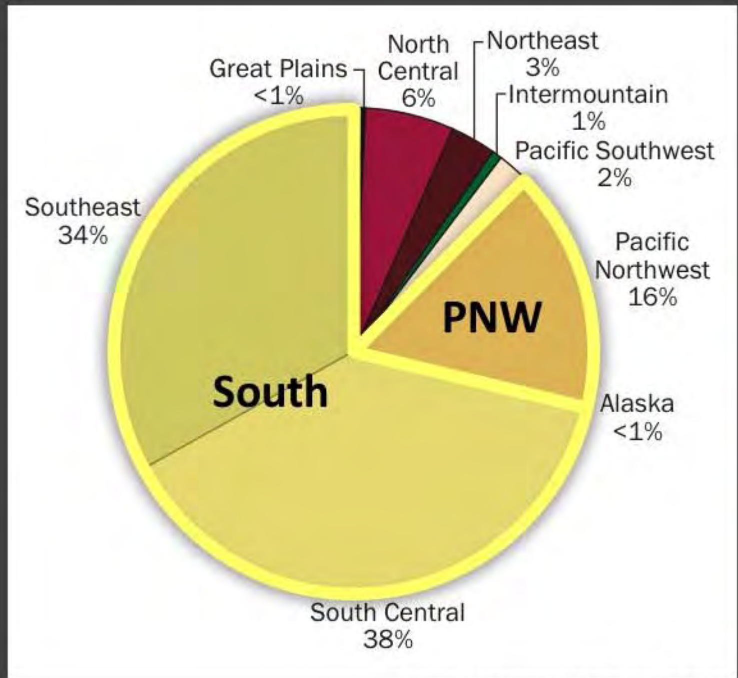
Legend
Forest Loss 2000–2013
Forest Gain 2000–2012
Both Loss and Gain
Forest Extent
(Hansen et al. 2013)
Map data ©2017 Google, INEGI
100 km

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

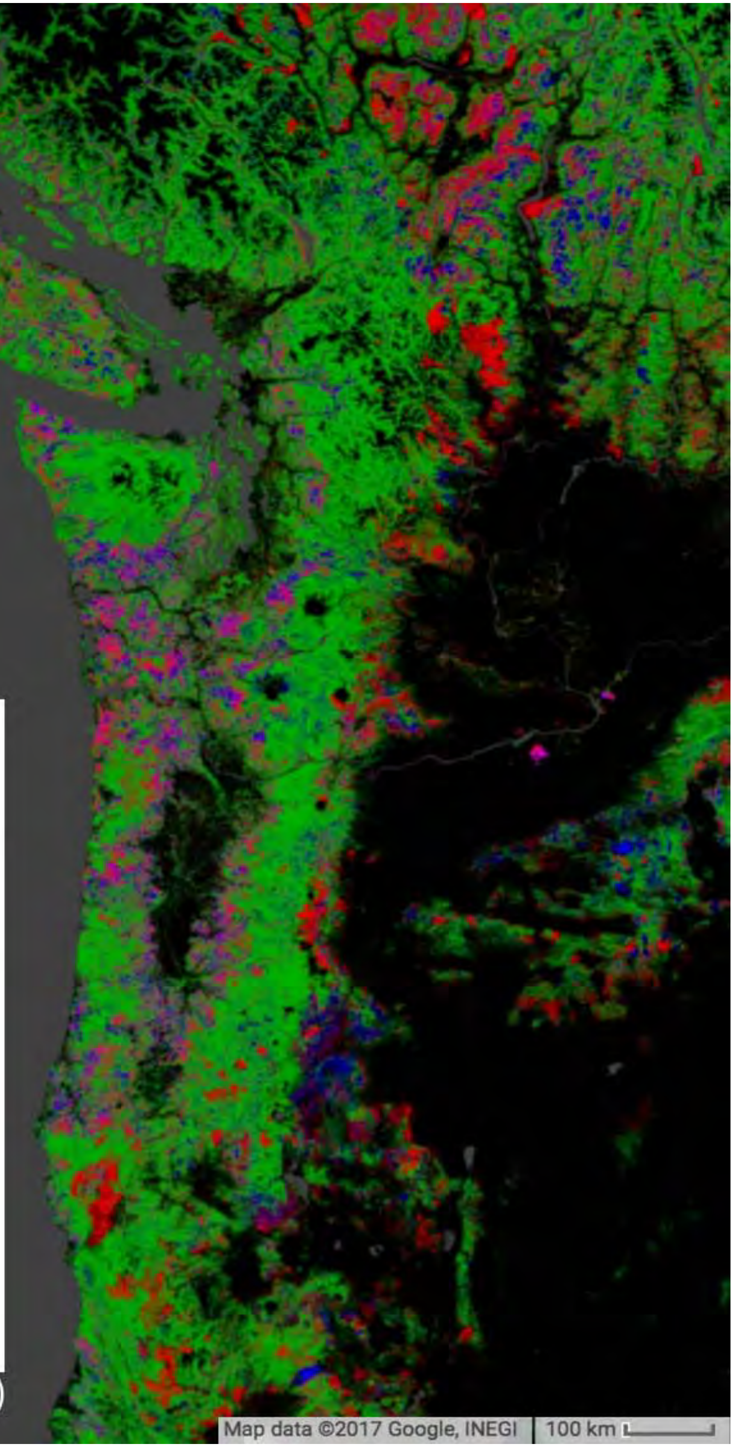




- ~3 million ha of planted forest in Oregon and Washington
- 88% of planted forests in the US, collectively

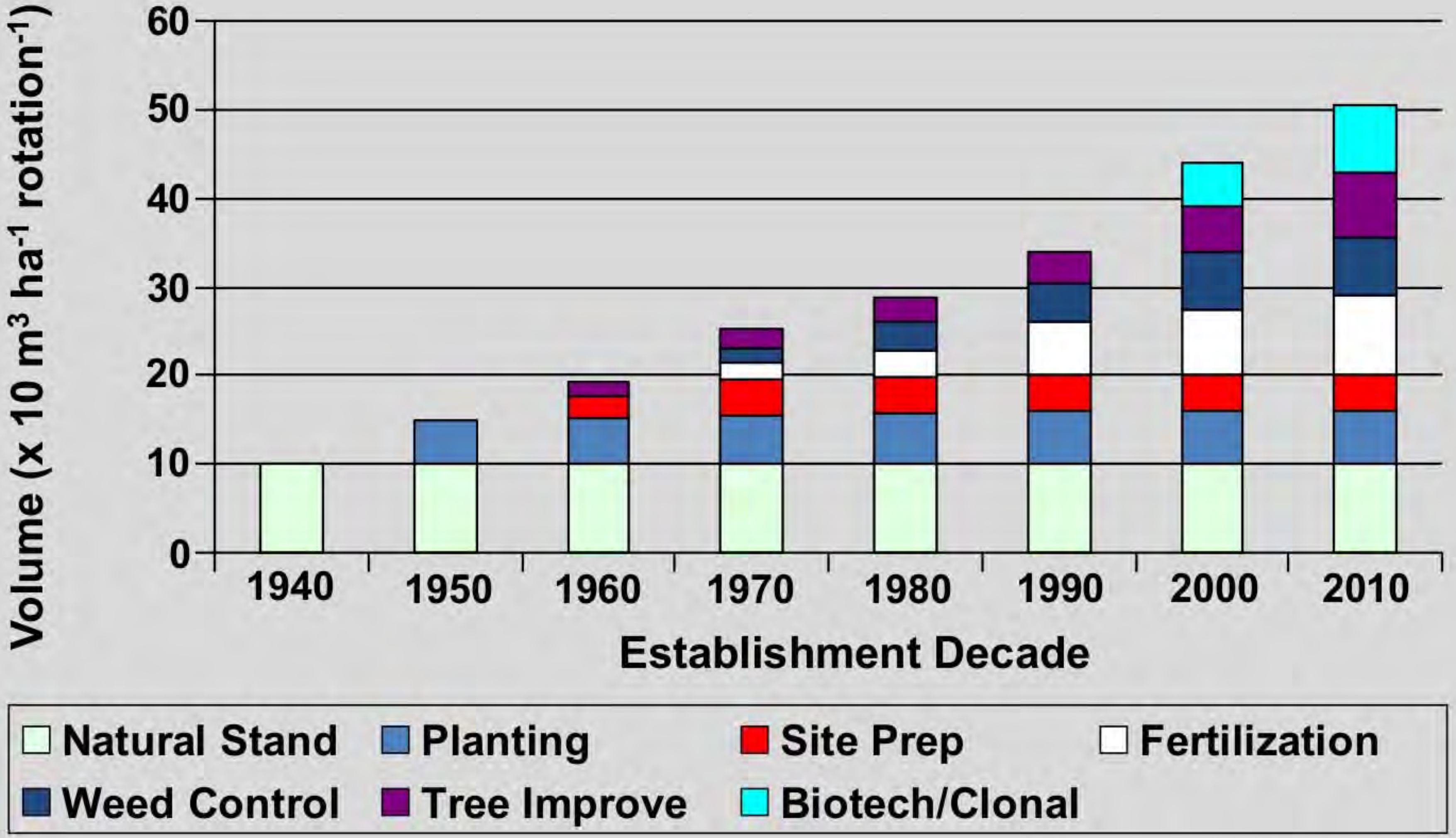


(Oswalt et al. 2014)



(Hansen et al. 2013)

Productivity Gains in the Southeastern US



(adapted from Fox et al. 2007)

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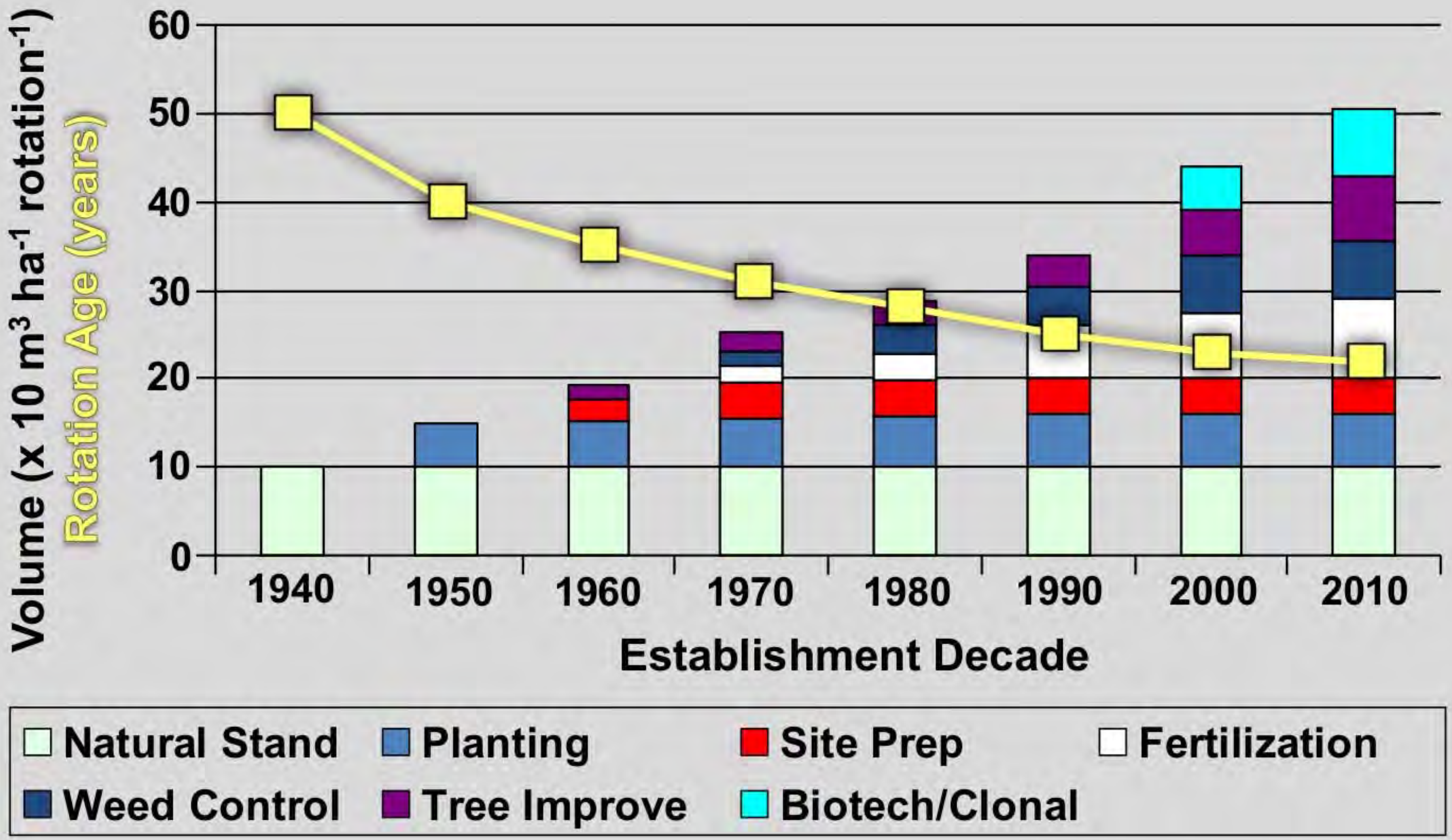

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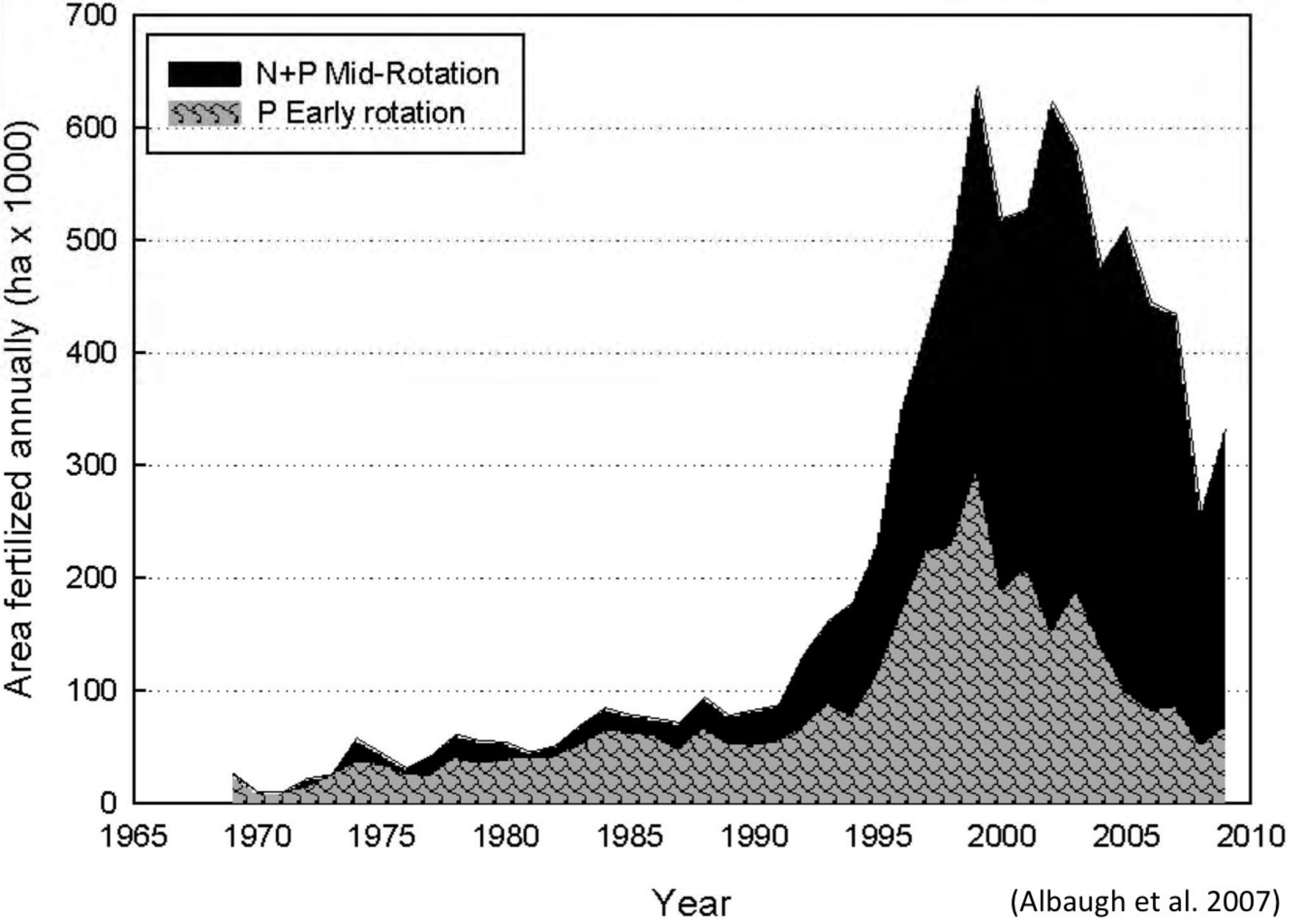
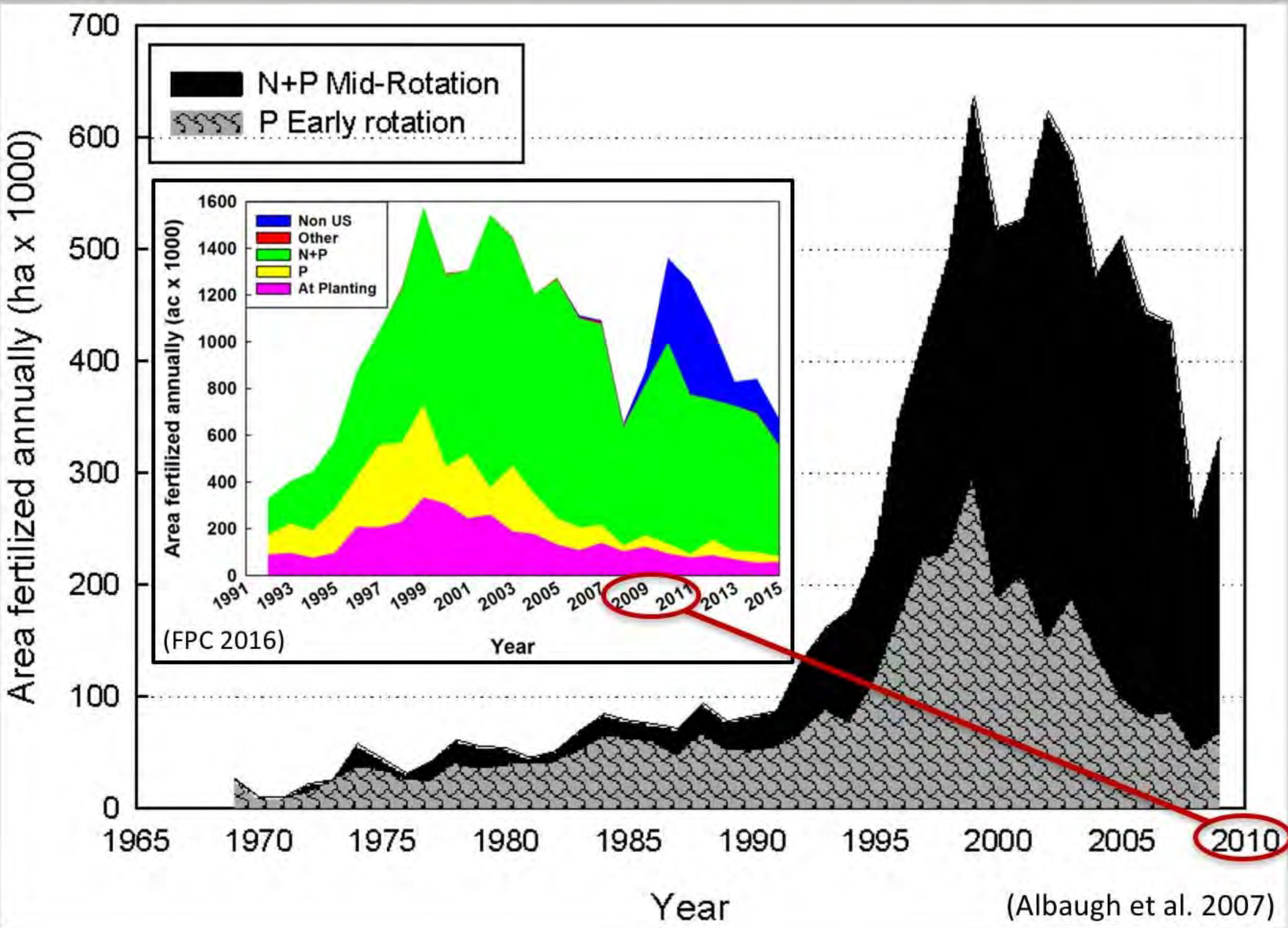
Fertilization in the Southeastern US

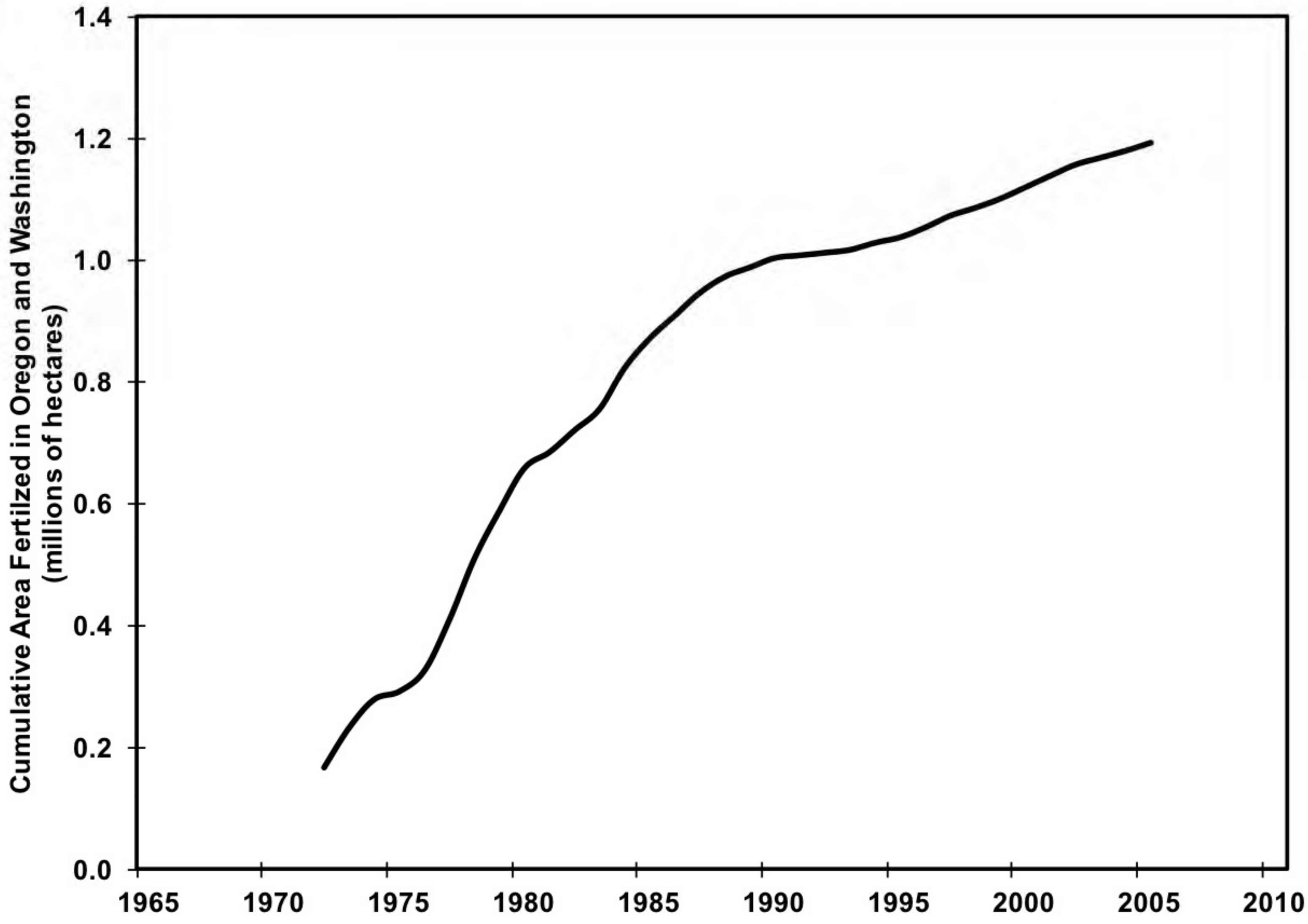


(Albaugh et al. 2007)

Fertilization in the Southeastern US

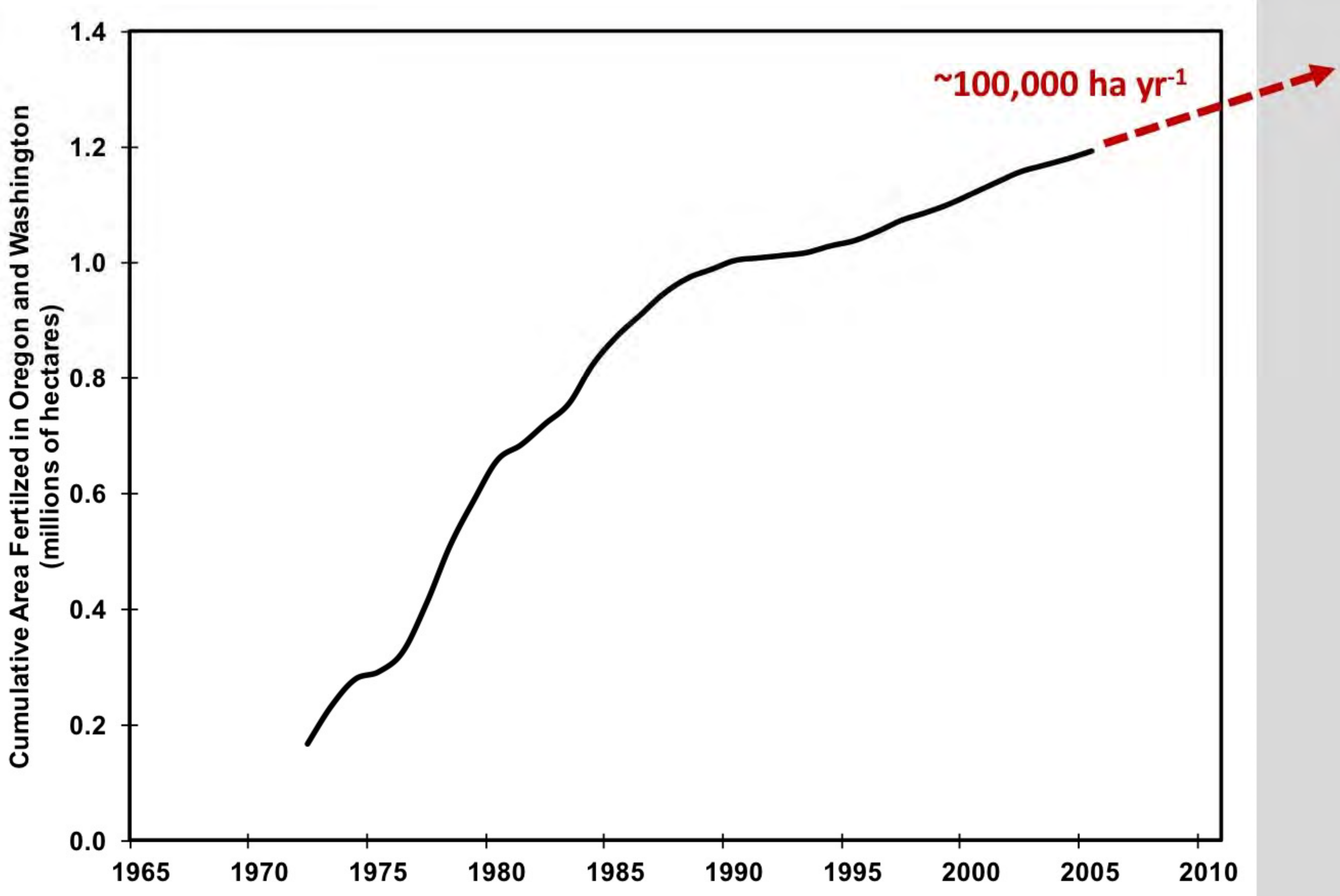


Fertilization in the Pacific Northwest US



(Pacific Northwest Stand Management Cooperative 2005)

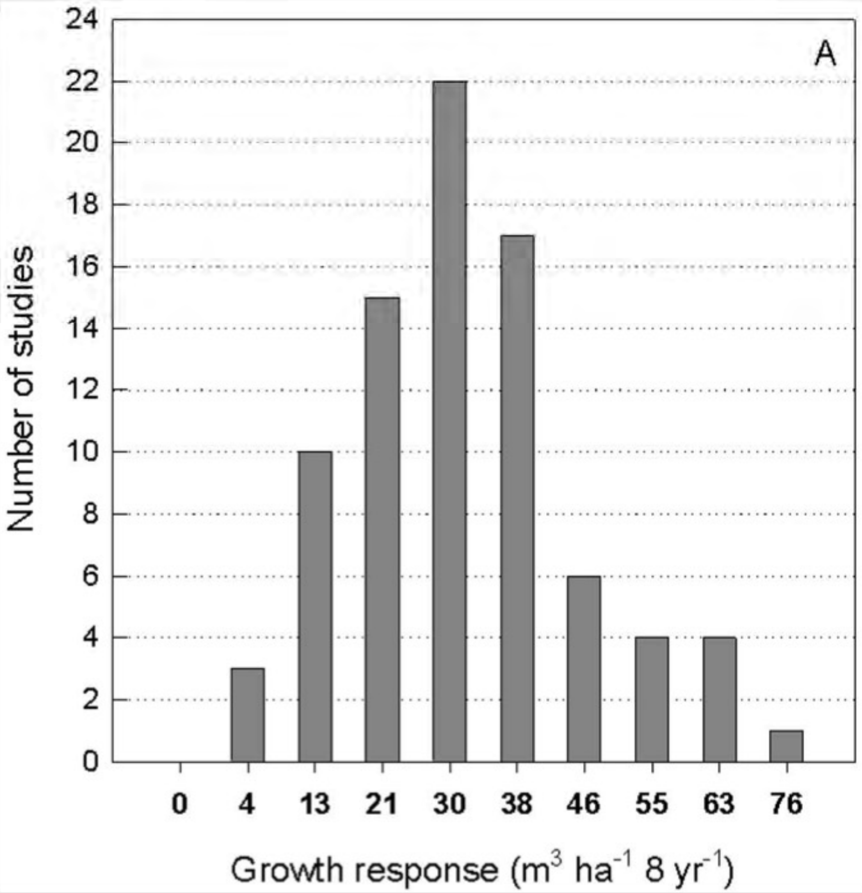
Fertilization in the Pacific Northwest US



(Pacific Northwest Stand Management Cooperative 2005)

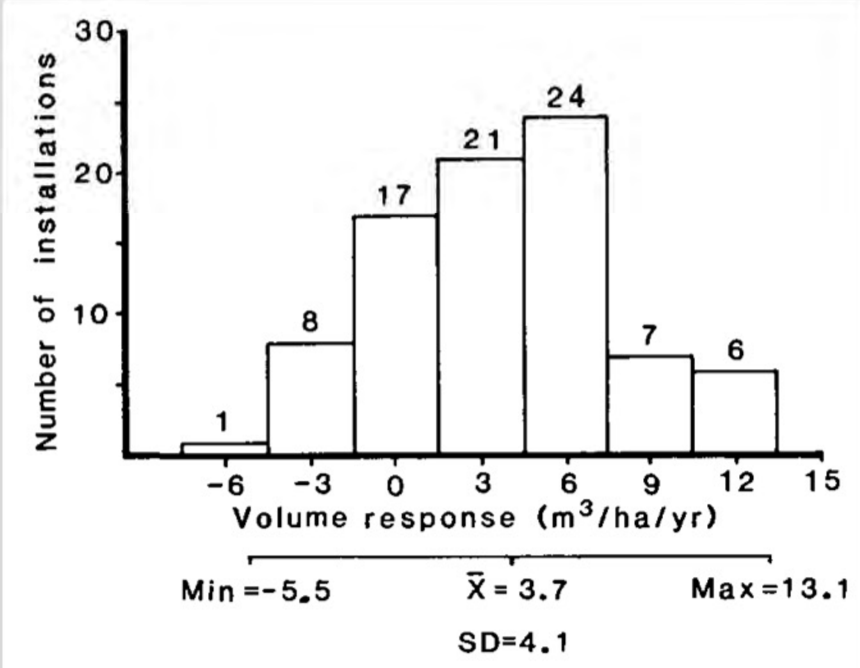
Uncertainty in Fertilization Response

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)

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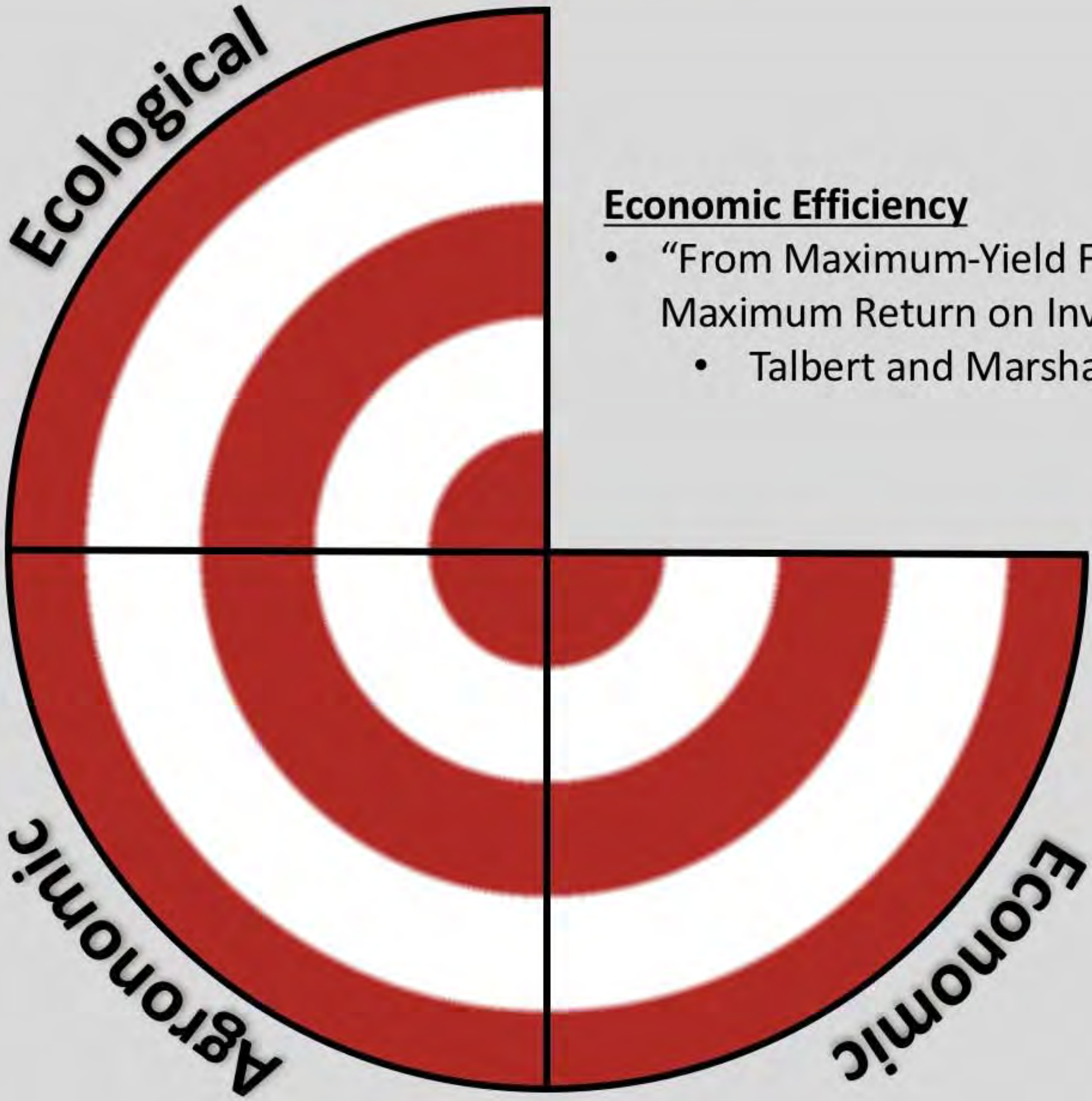
Agronomic – Fertilizer Efficiency

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

Efficiency

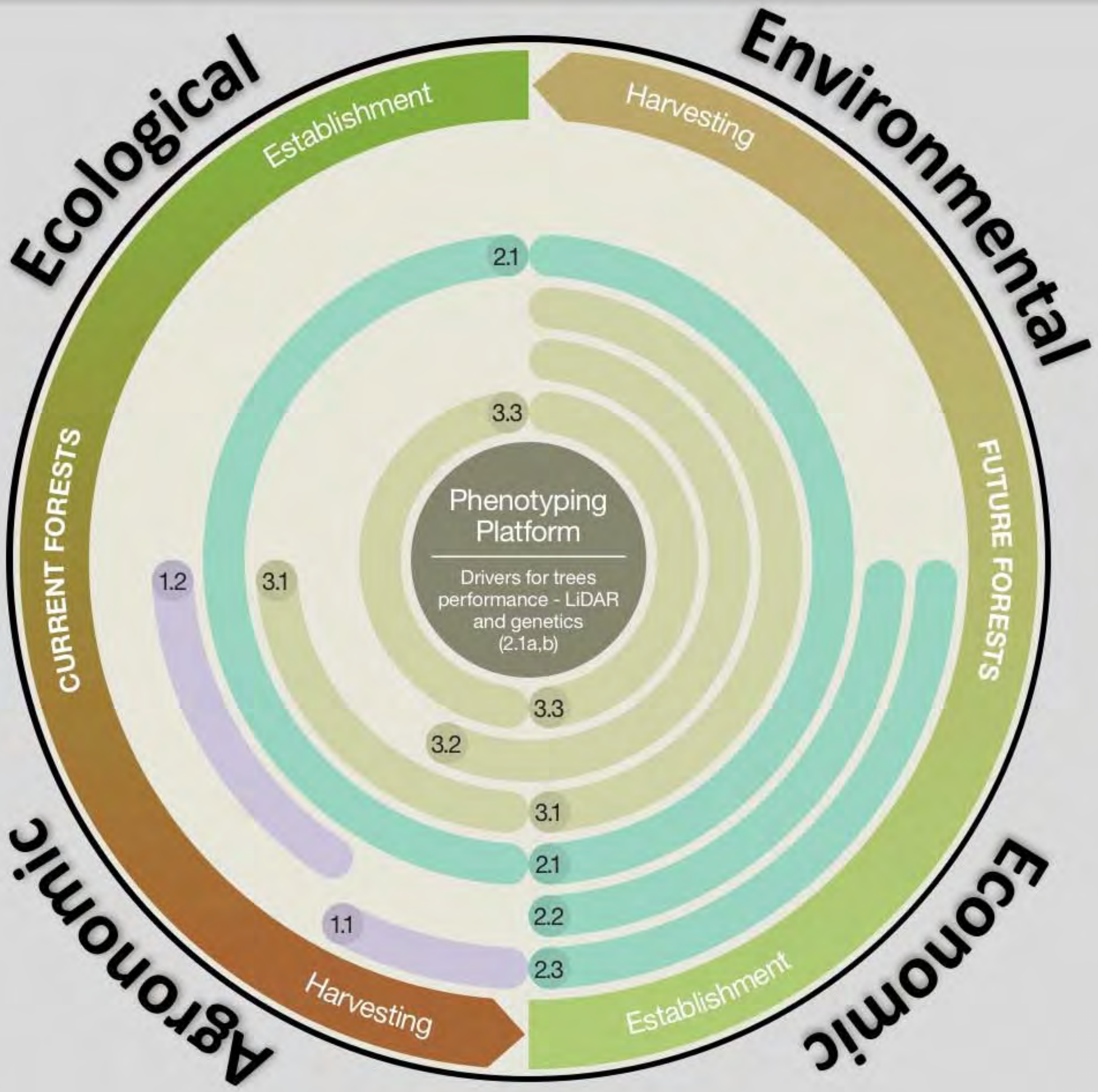


Economic Efficiency

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

Efficiency

Efficiency


Ecological
Environmental
Agronomic
Economic
Establishment
Harvesting
Harvesting
Establishment
CURRENT FORESTS
FUTURE FORESTS
Phenotyping Platform
Drivers for trees performance - LiDAR and genetics (2.1a,b)
1.1
1.2
2.1
2.2
2.3
3.1
3.2
3.3

Effici

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
Figure 1 | A worker spreads fertilizer on crops at a farm in Meki Batu, Ethiopia.
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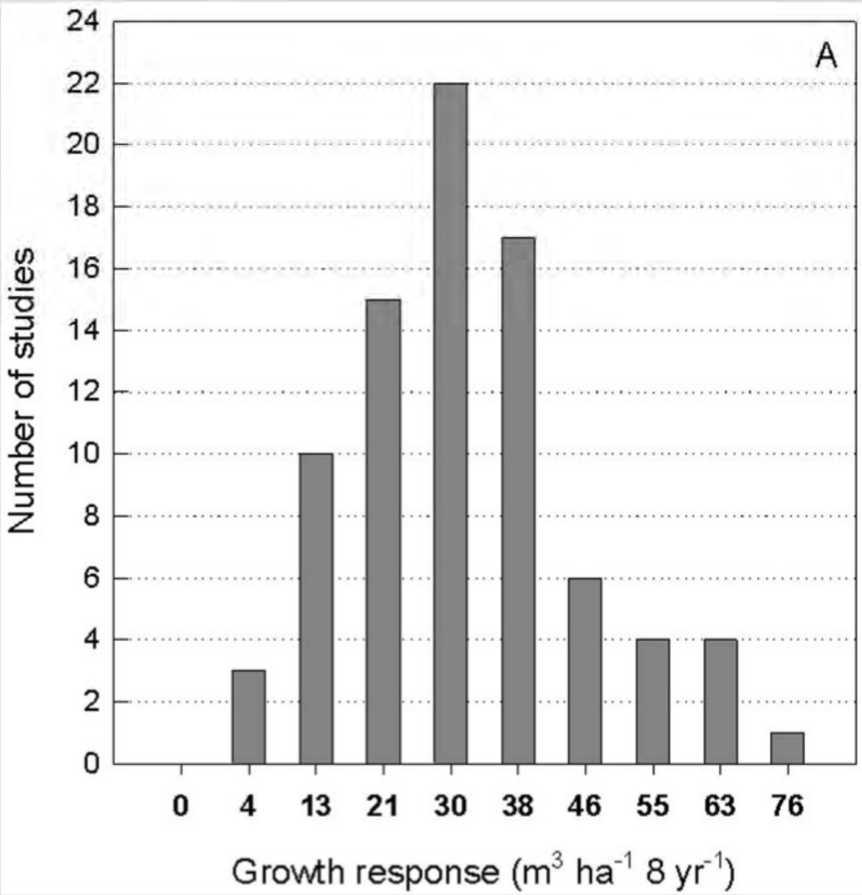
Environmental
Economic
Agronomic
CURRENT FORESTS
Establishment

Effici

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

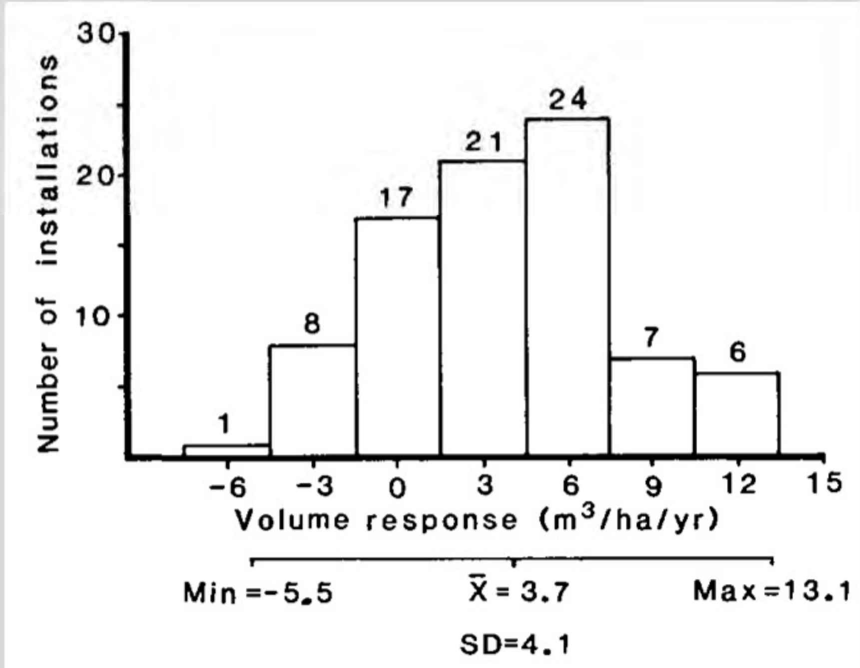
Uncertainty in Fertilization Response

Loblolly pine in the US southeast



(Albaugh et al. 2007)

Douglas-fir in the US Pacific Northwest

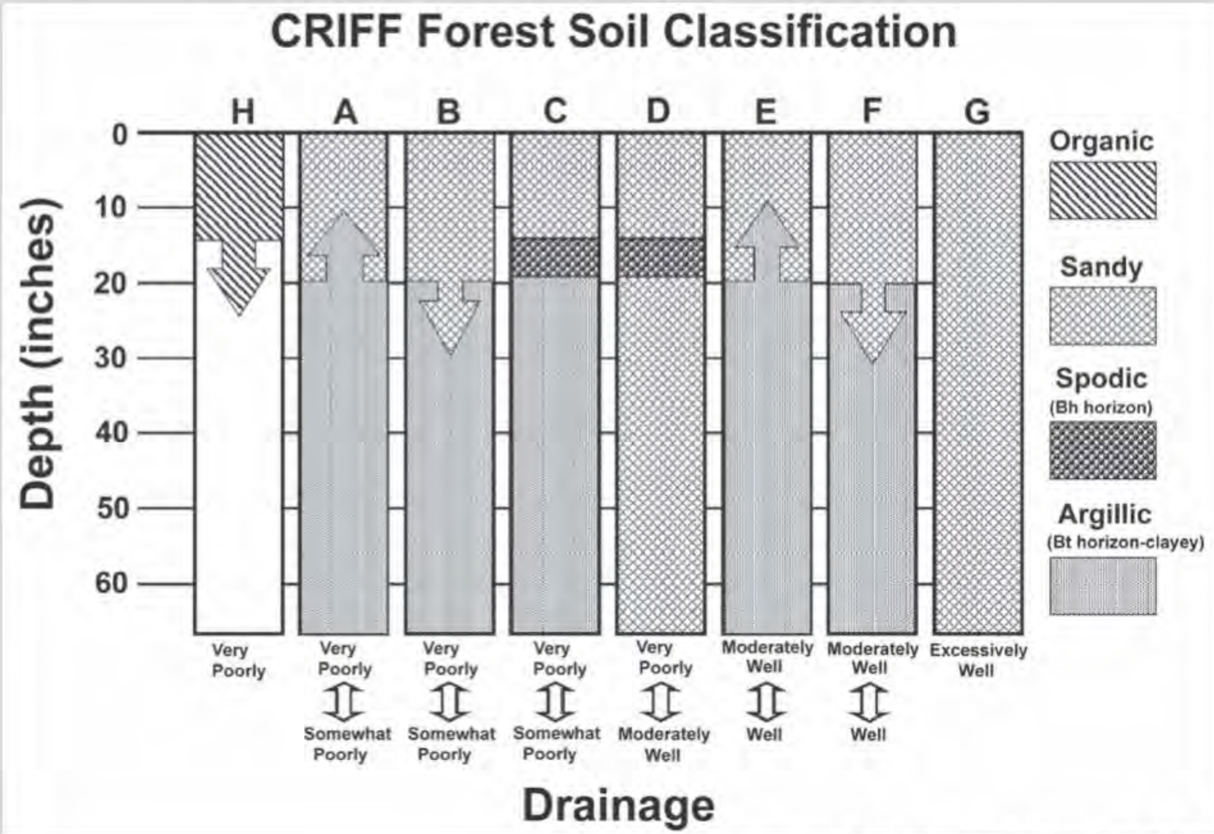


(Petersen et al. 1984)

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)

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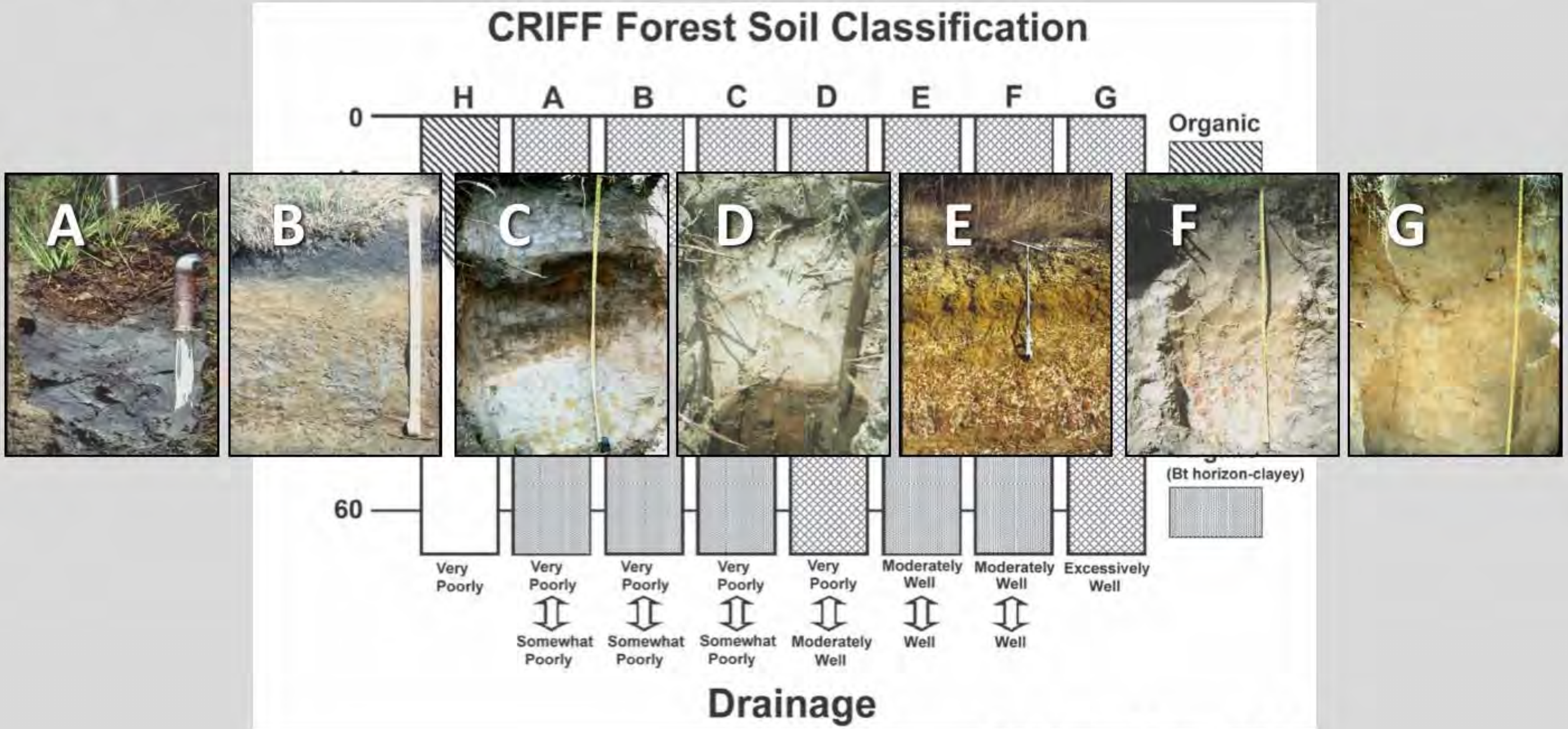
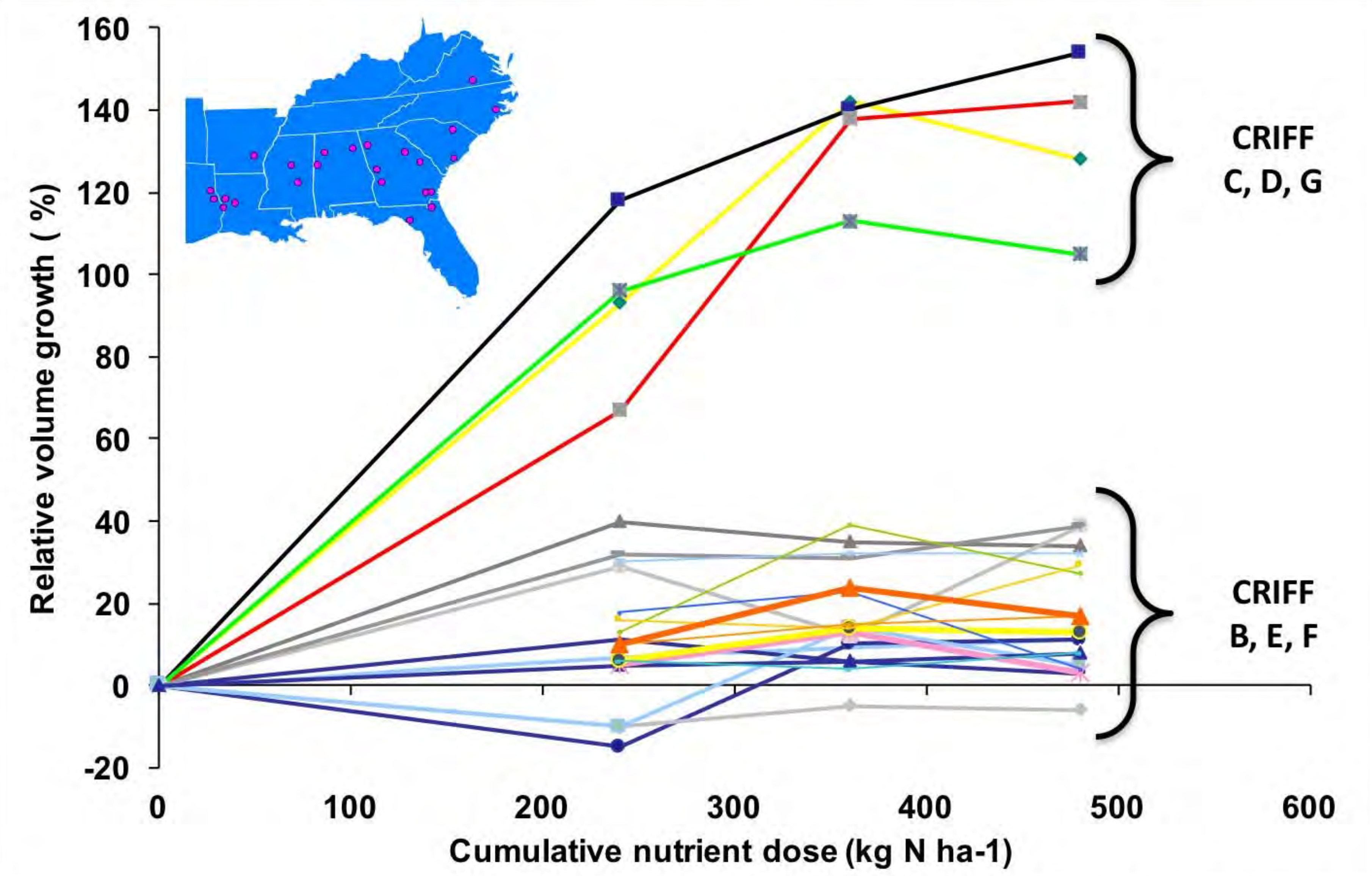


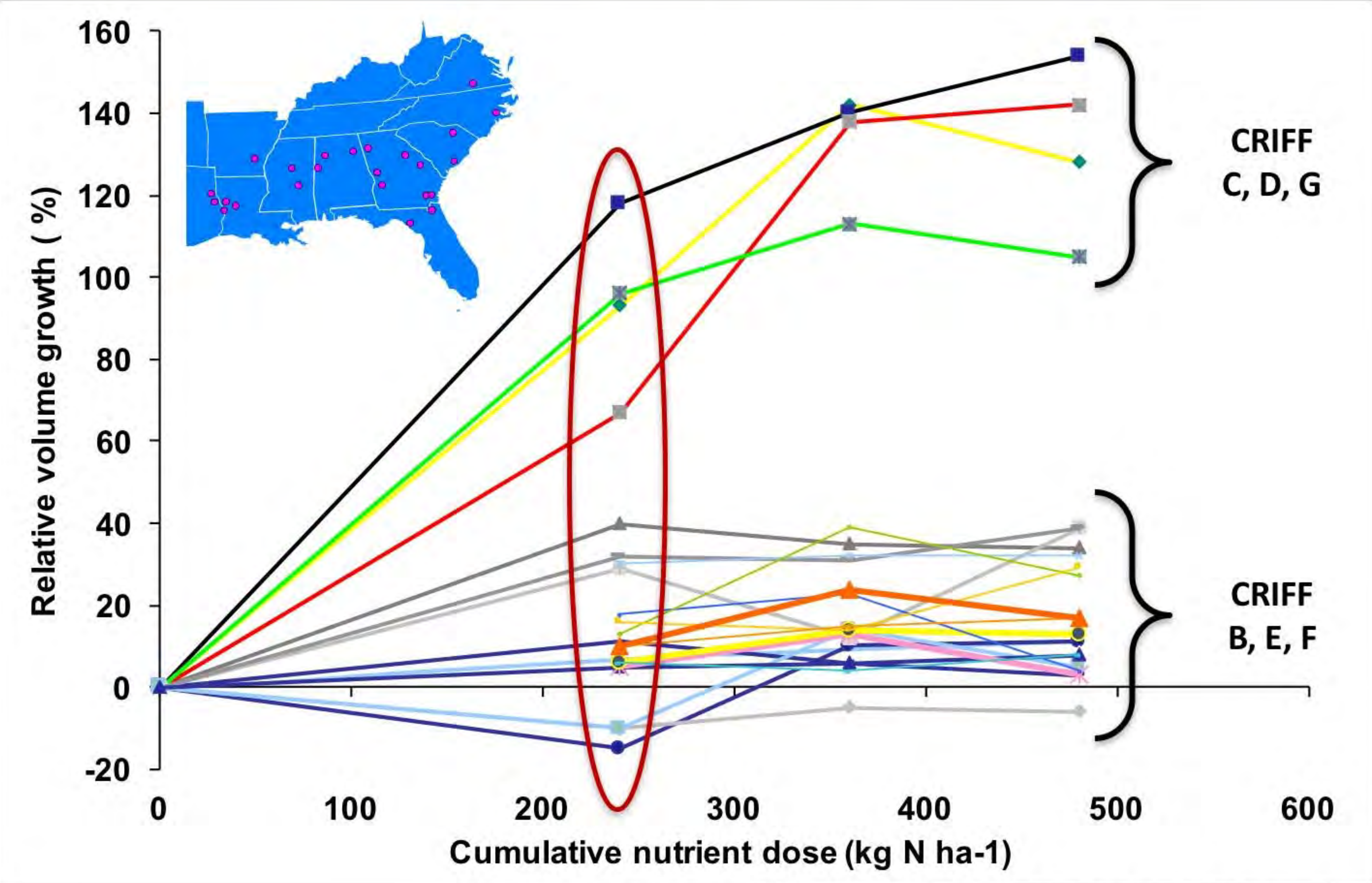
(Jokela and Long 2007)

Stratifying the Landscape with CRIFF



(data from the Forest Productivity Cooperative)

Stratifying the Landscape with CRIFF



(data from the Forest Productivity Cooperative)

Stratifying the Landscape

NRC Research Press

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 $N \cdot ha^{-1}$. 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 biogéoclimatiques mesurées et cartographiées dans 71 dispositifs de douglas de Menzies situés dans la région côtière du Pacific 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 $N \cdot ha^{-1}$ 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 Pacific 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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Corresponding author: K.M. Littke (e-mail: littkek@uw.edu).
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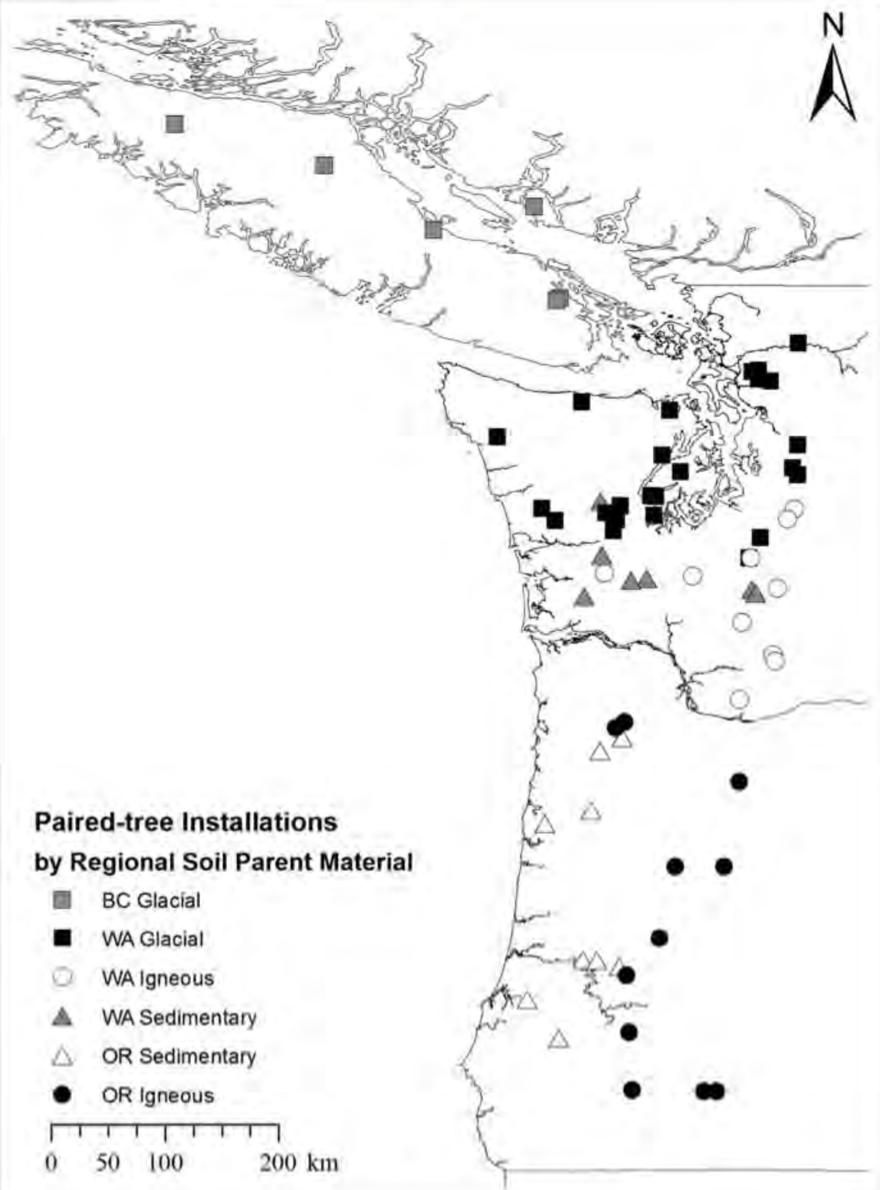

Stratifying the Landscape

1253

NRC Research Press

ARTICLE

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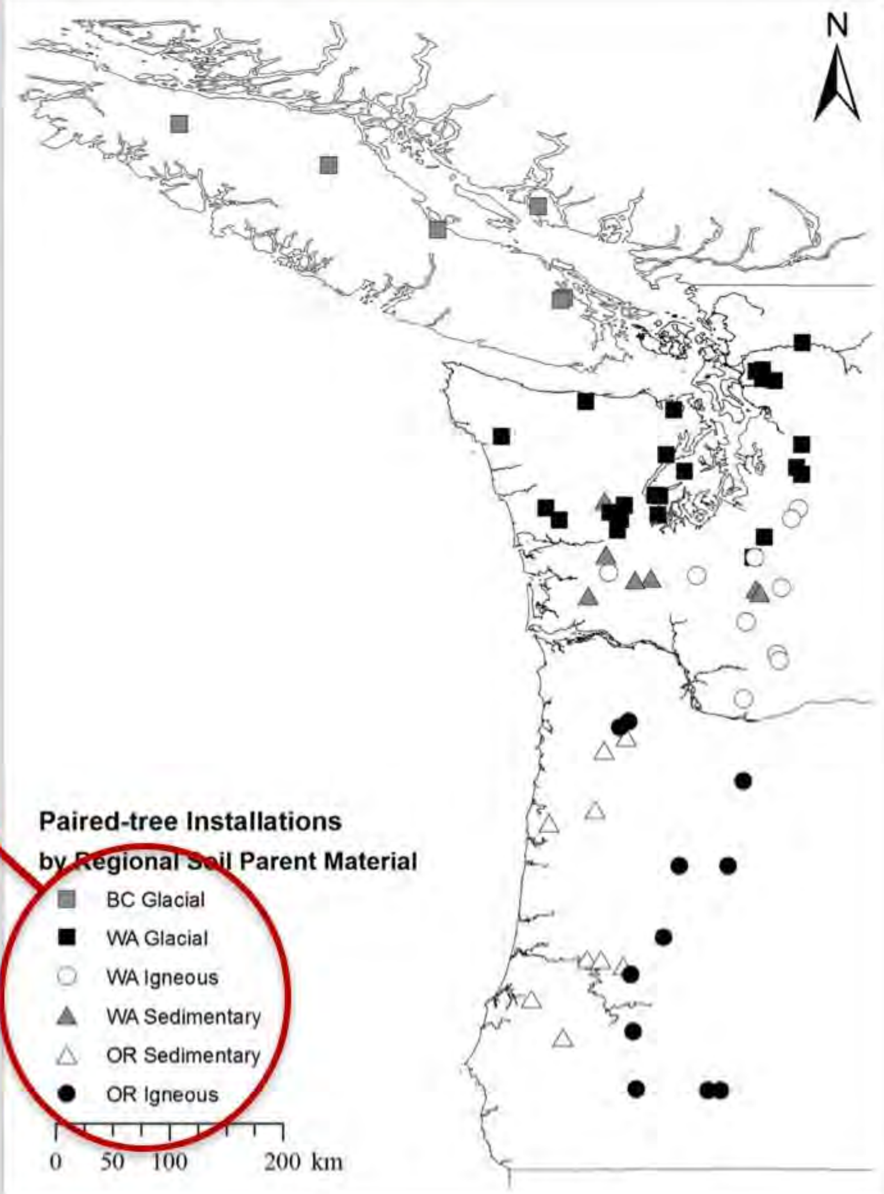


Industry-University Cooperative Research

CAFS Center for Advanced Forestry Systems

NSF

FOREST PRODUCTIVITY COOPERATIVE

North Carolina State University · Virginia Polytechnic Institute and State University · Universidad de Concepción

HTIRC

HARDWOOD TREE Improvement & Regeneration CENTER

Stand Management Cooperative

SILVICULTURE ▪ NUTRITION
WOOD QUALITY ▪ MODELING

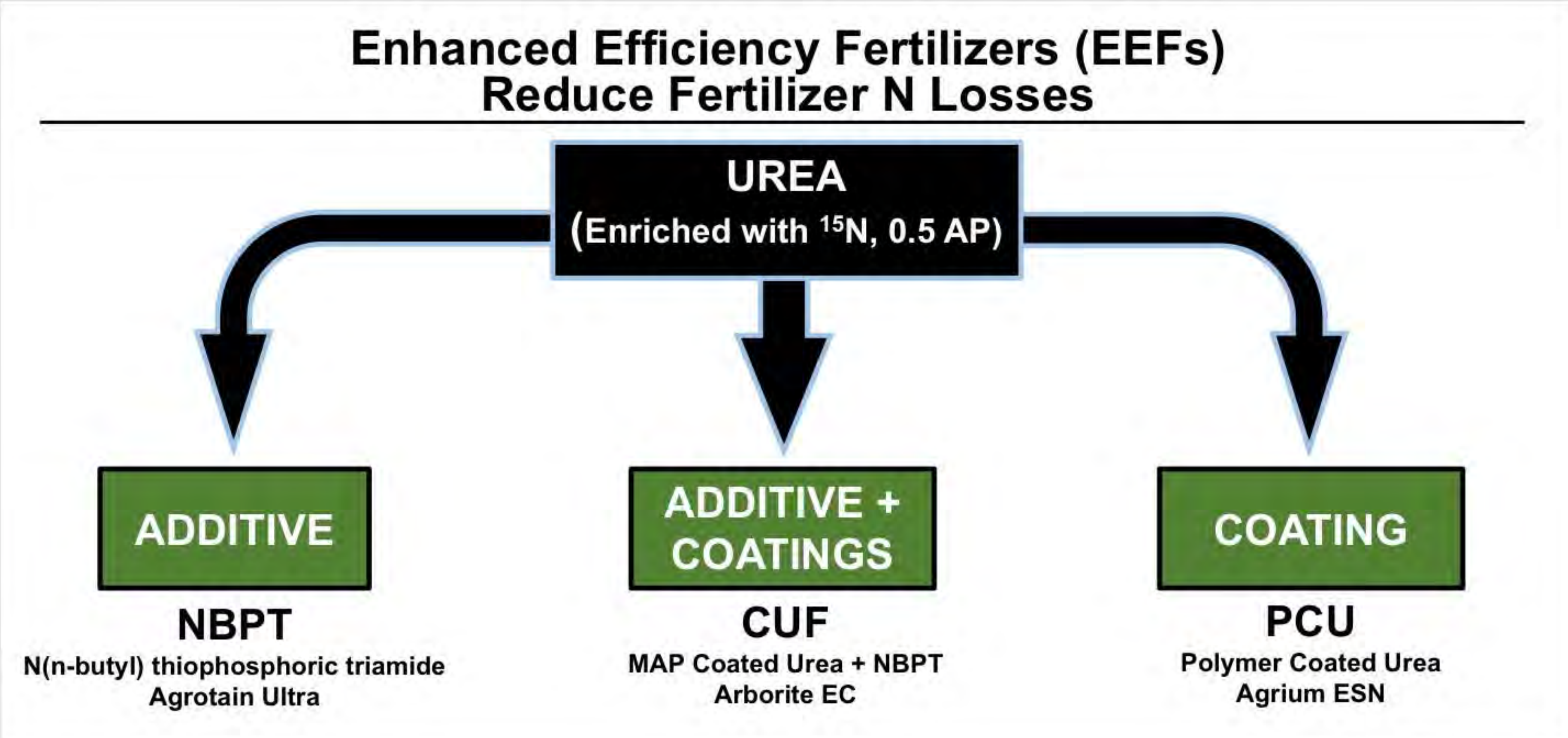

Scotts
ISOTEC


0% N15 Urea
Soln.
MASTERFLEX L/S
4.3
Cole-Parmer Instrument Company
AVERY DENNISON


500W
UREA FEED
UREA FEED
UREA FEED
UREA FEED


1 MM 2 3 4 5 6 7 8
METRIC

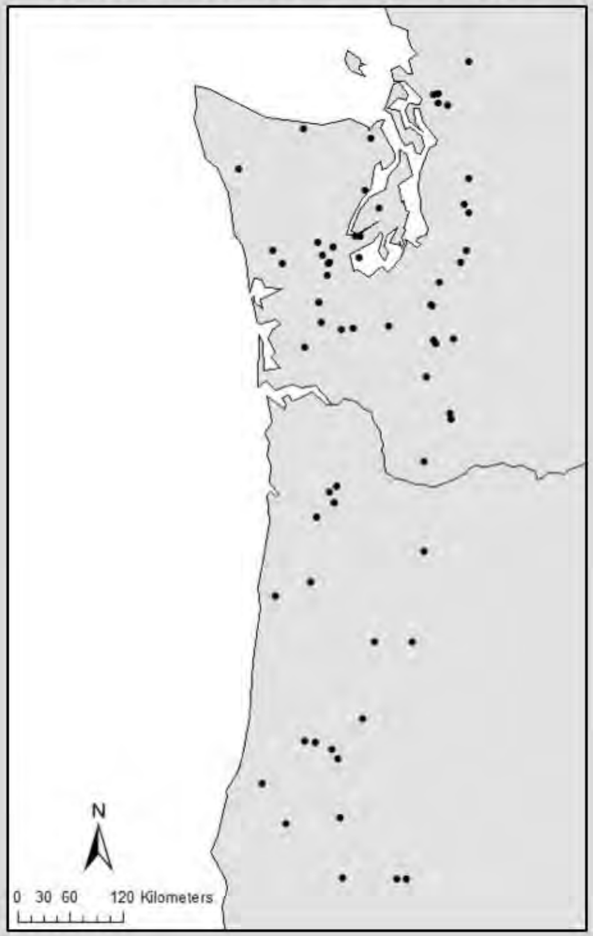
Enhanced Efficiency Fertilizers



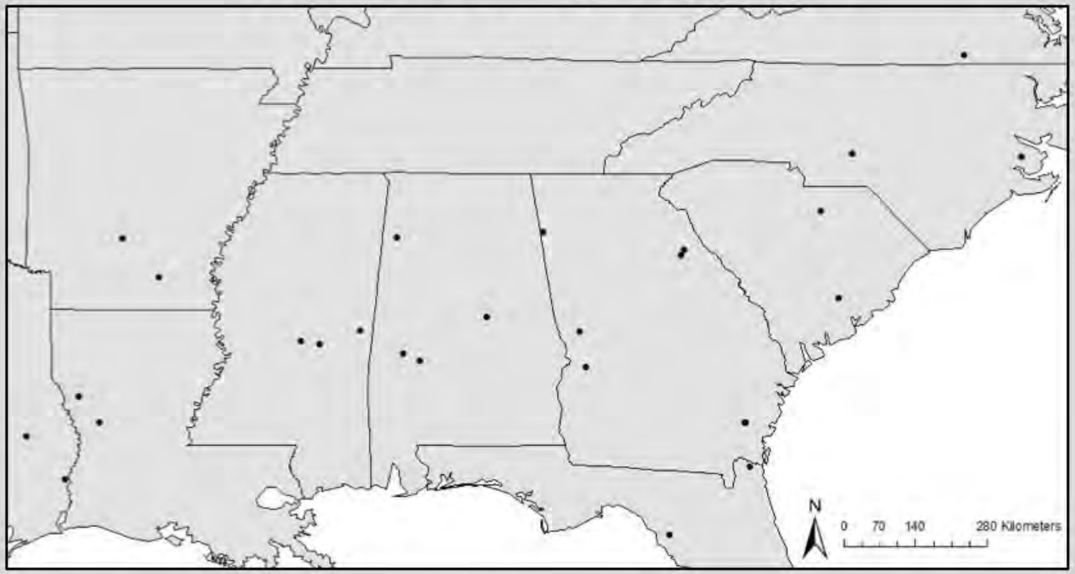
(Raymond et al. 2016)

Regional Fertilization Trials

Pacific Northwest Stand Management Cooperative

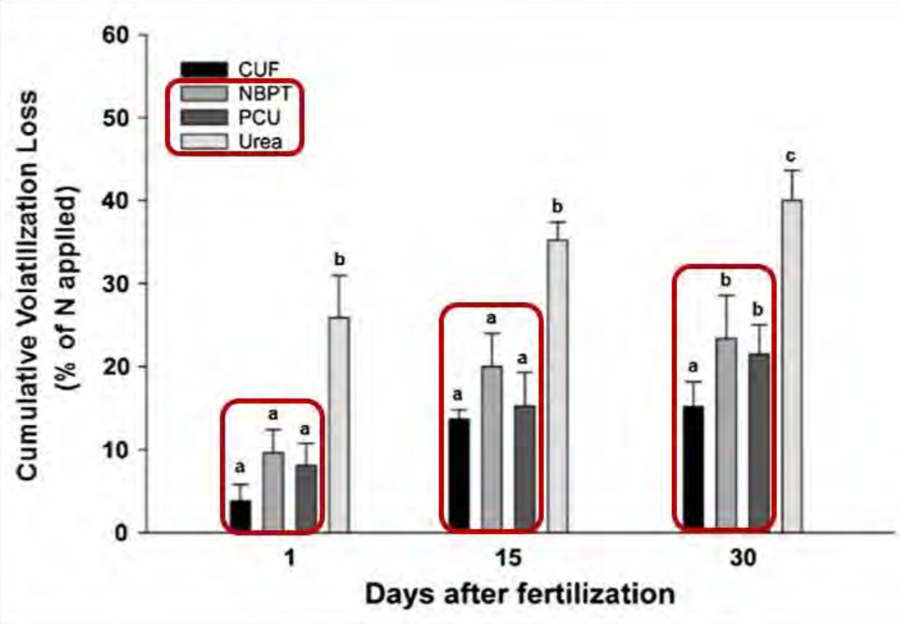


Forest Productivity Cooperative

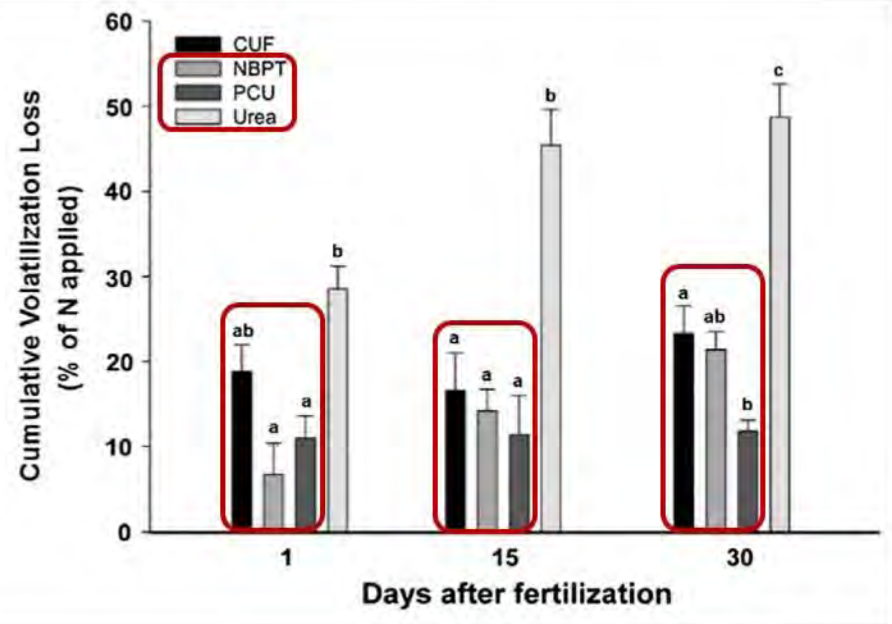


Volatilization Control

Spring Application

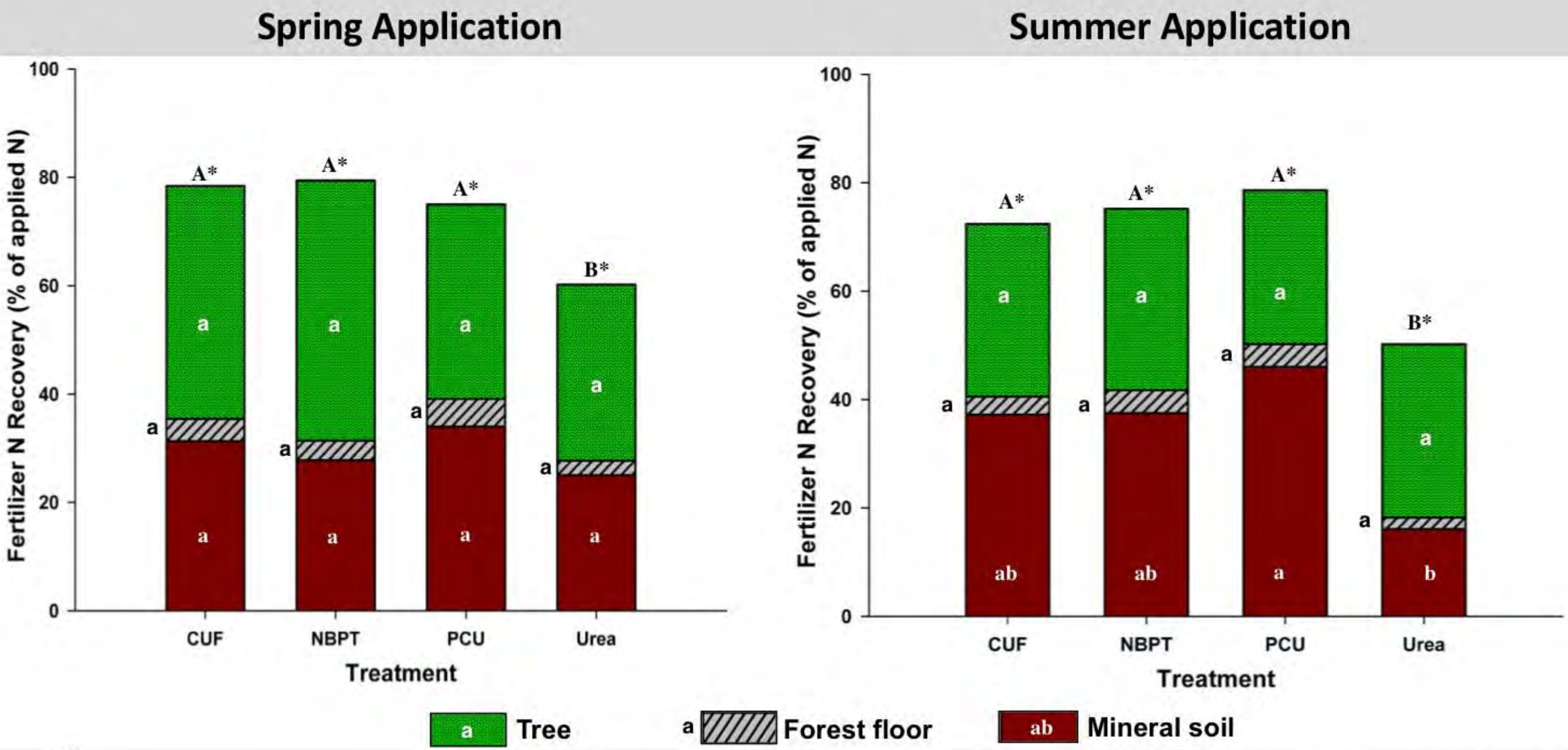


Summer Application



(Raymond et al. 2016)

Fertilizer N Partitioning and Retention



(Raymond et al. 2016)

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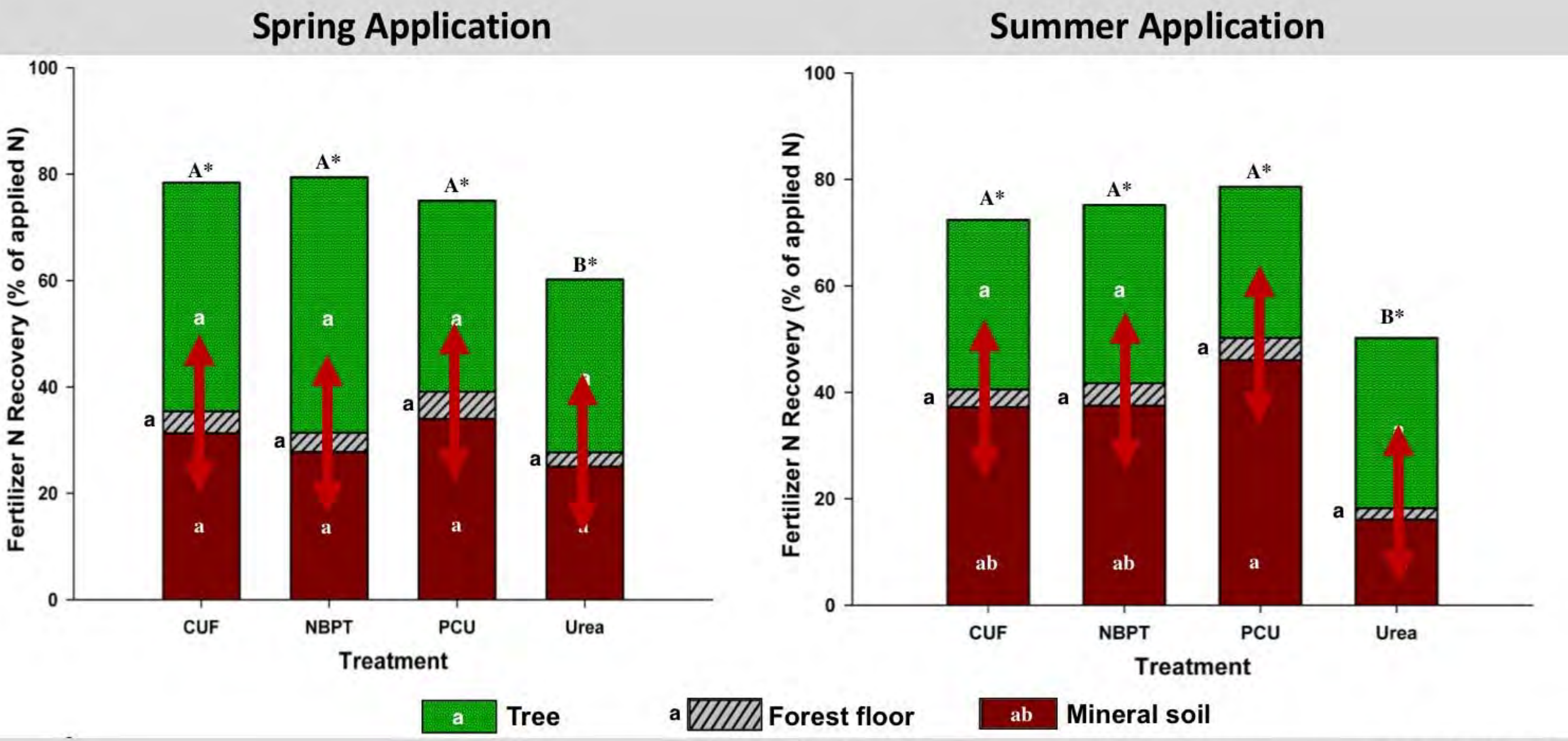

(Raymond et al. 2016)

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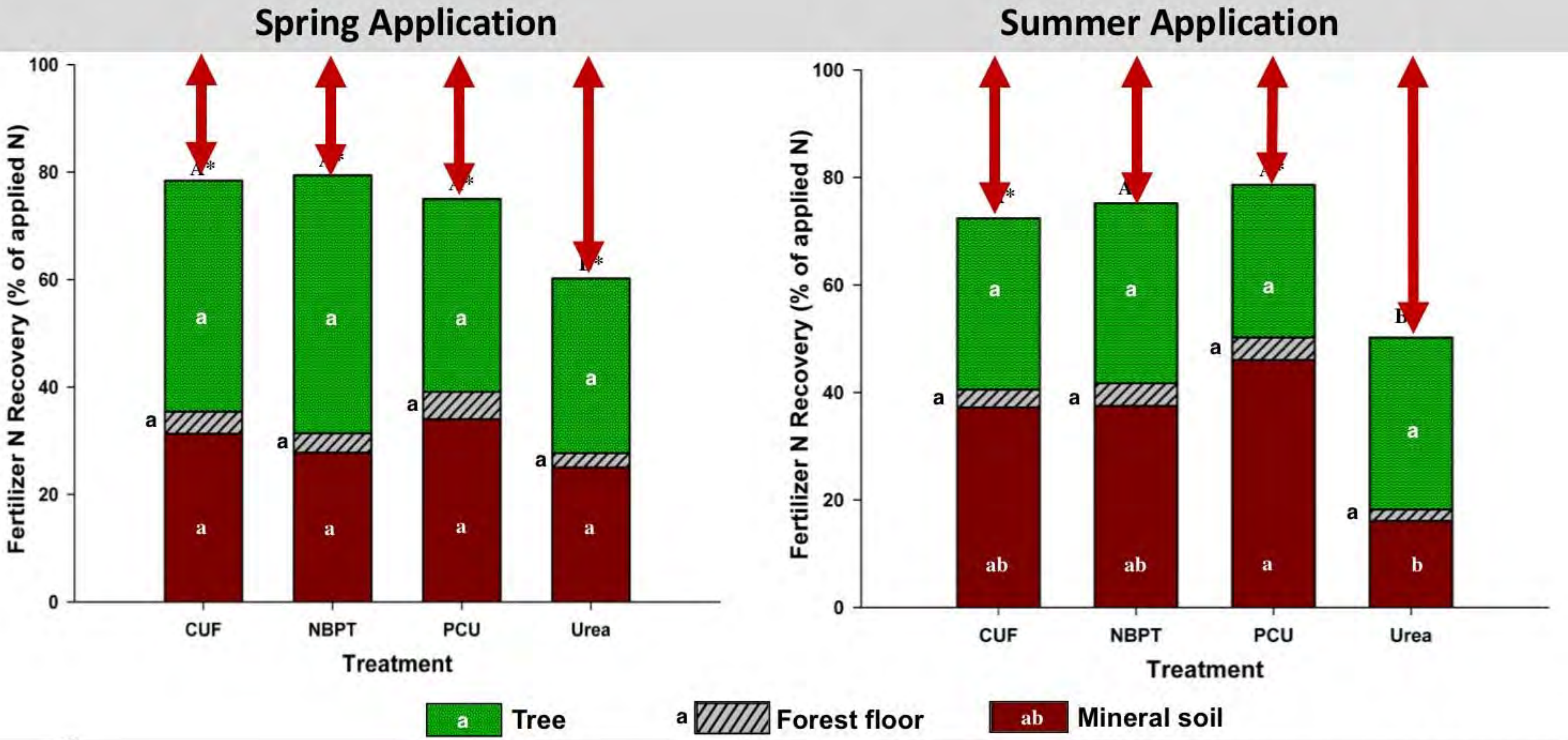

(Raymond et al. 2016)

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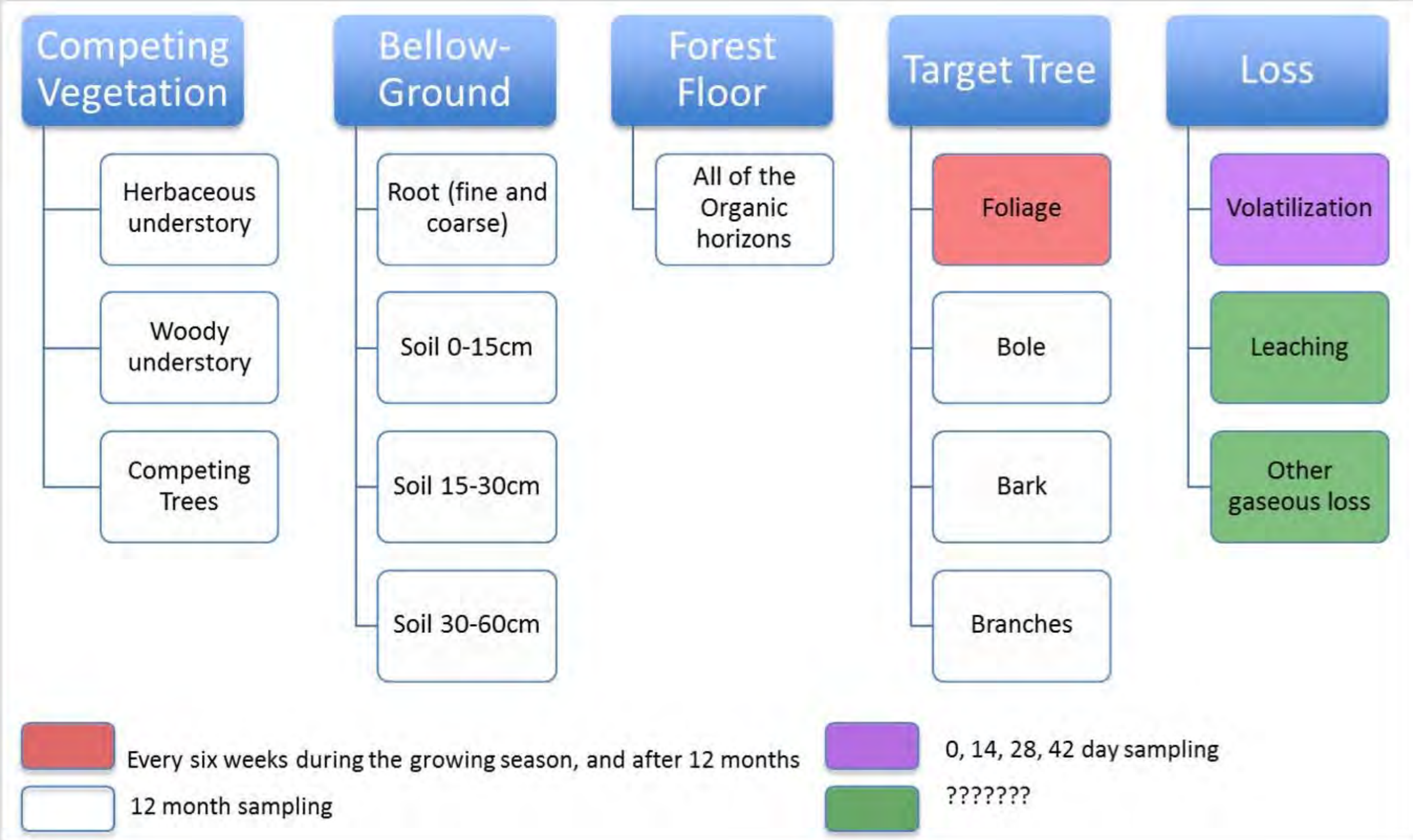
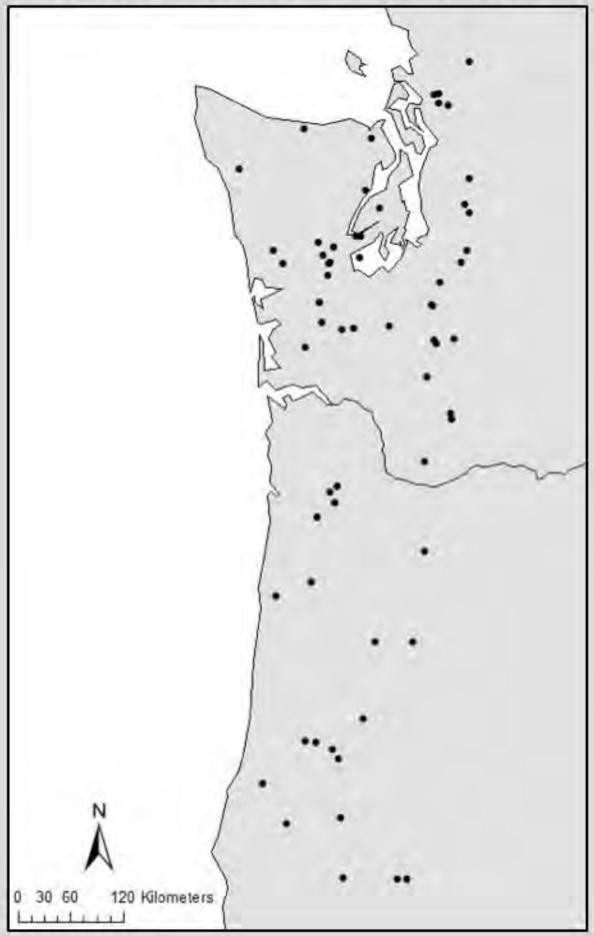
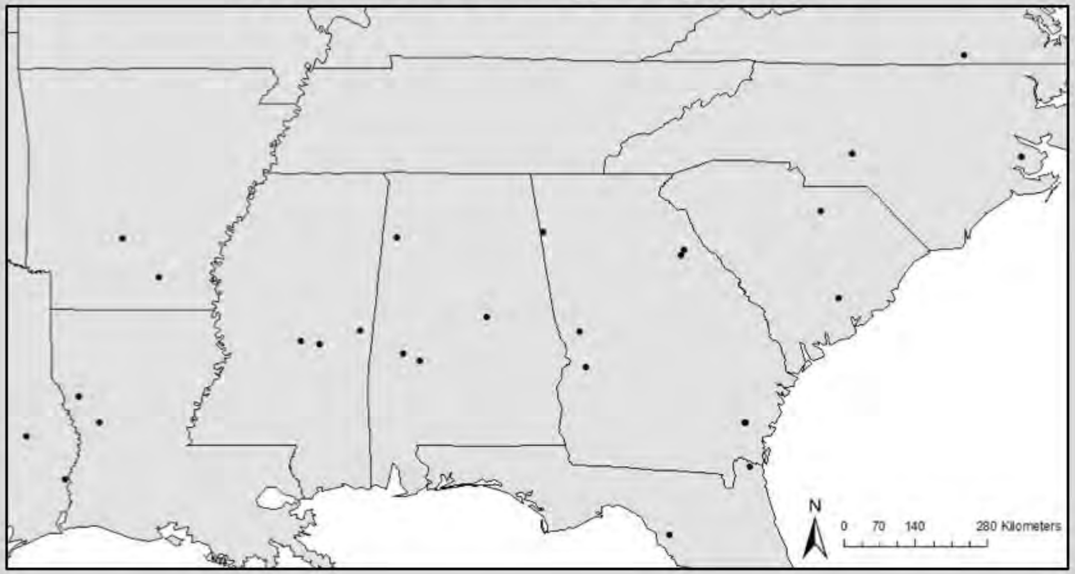


Fertilizer N Partitioning and Retention

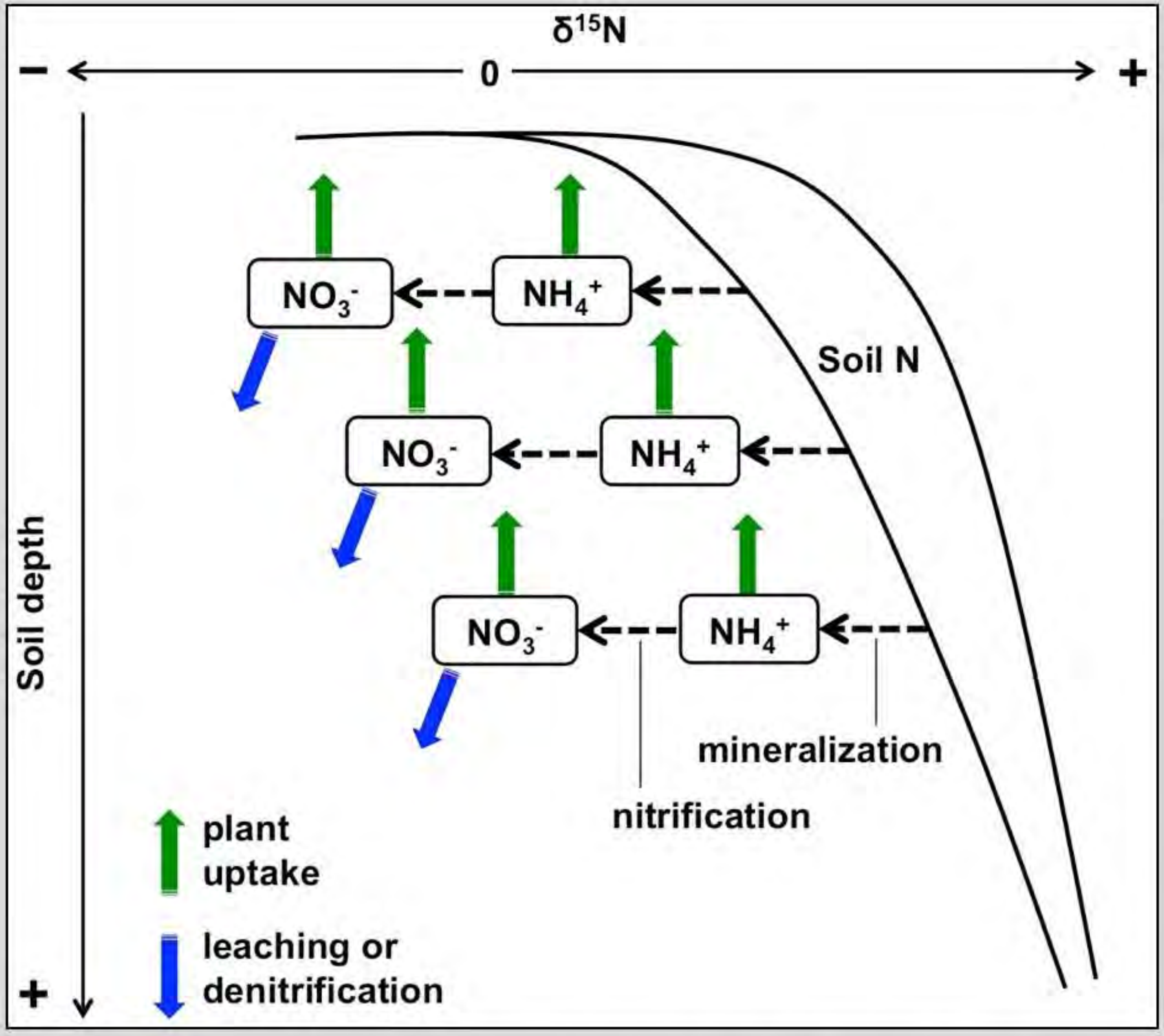
Pacific Northwest Stand Management Cooperative



Forest Productivity Cooperative

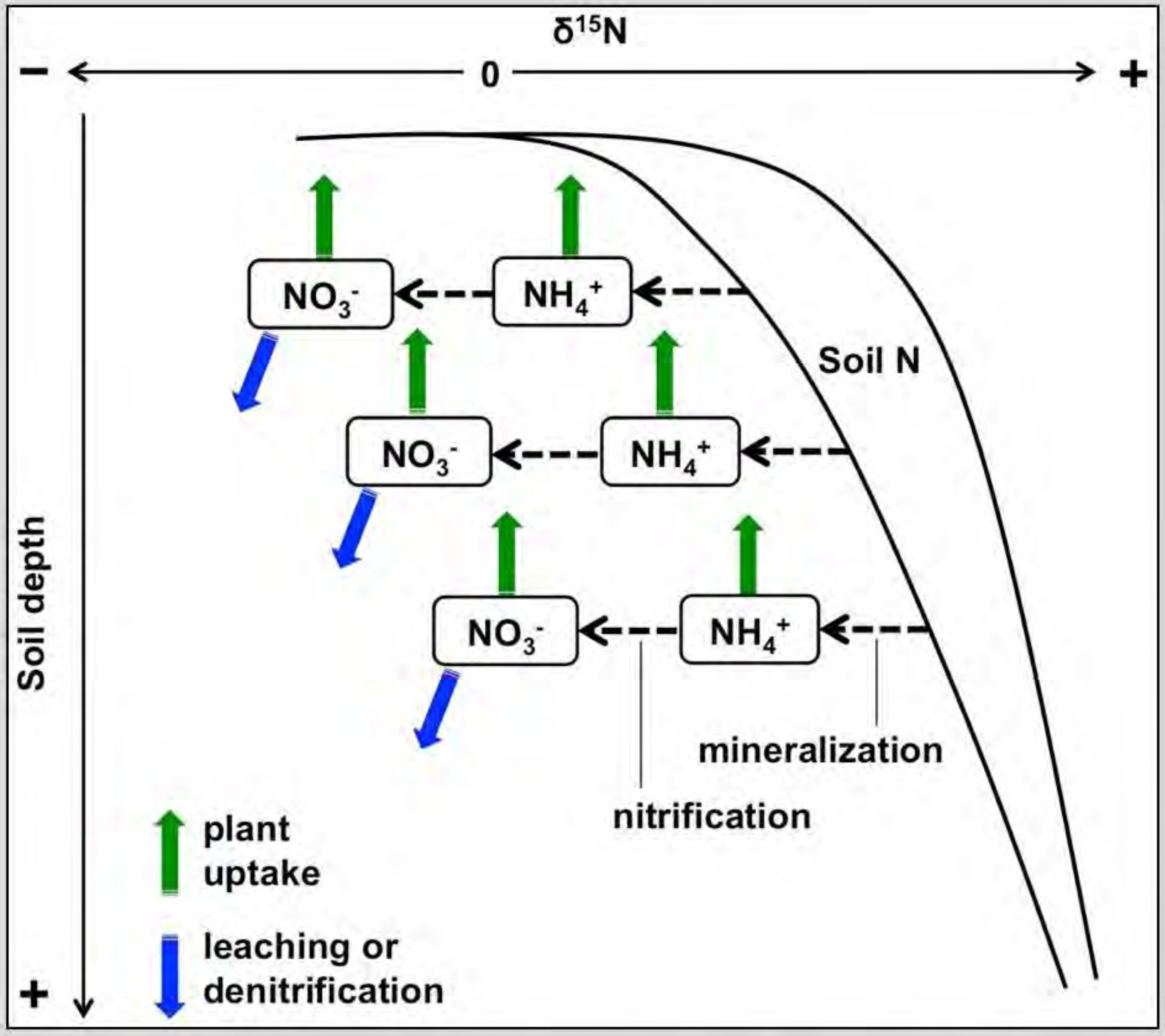


Patterns in Natural Abundance $\delta^{15}N$

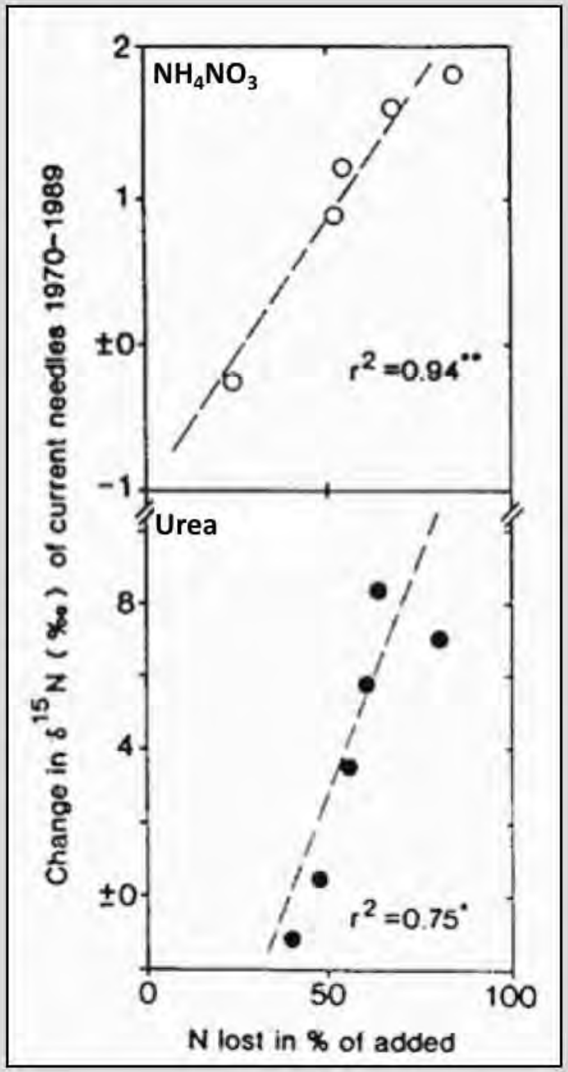


(recreated from Nadelhoffer and Fry, 1994)

Patterns in $\delta^{15}N$

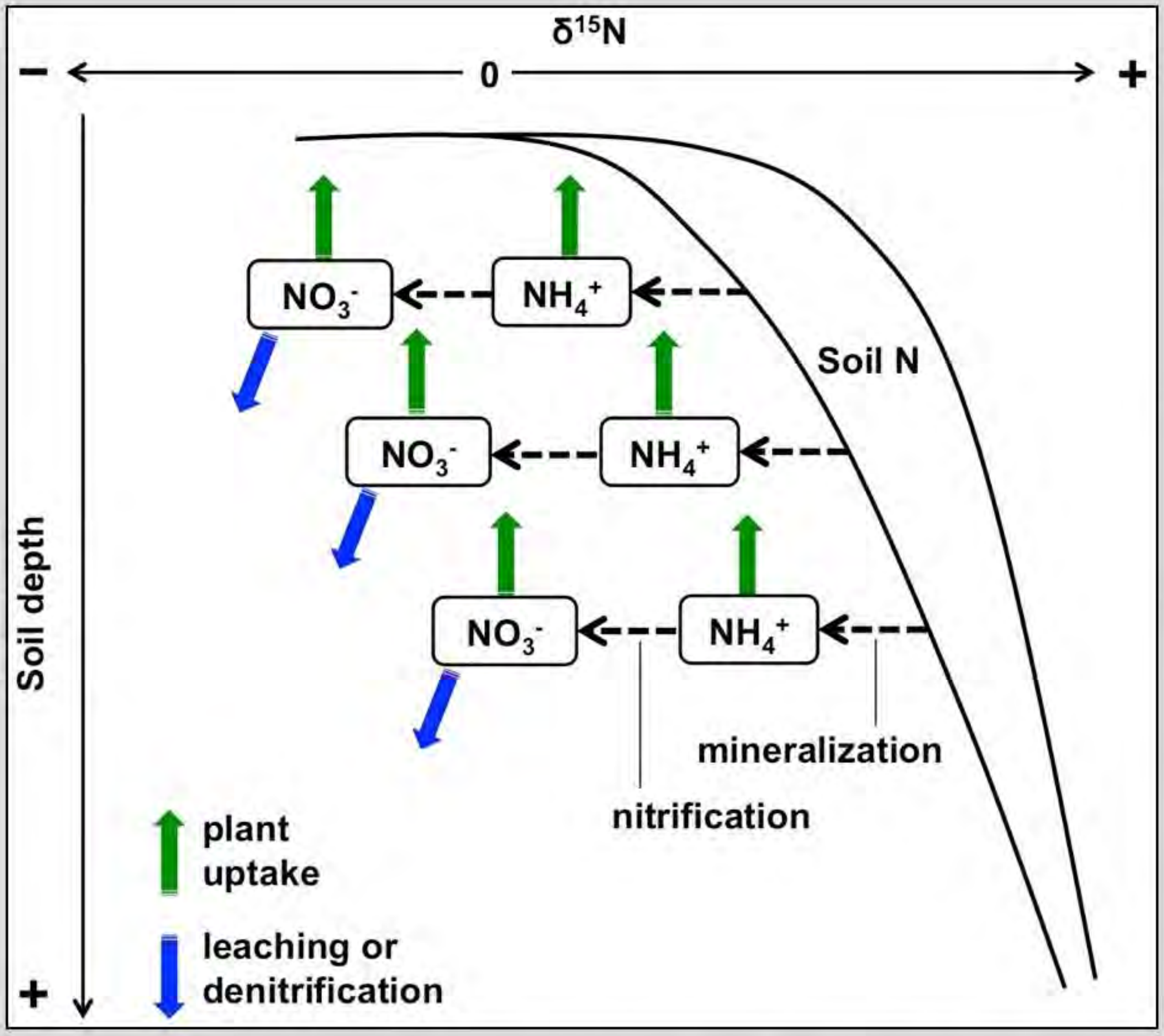


(recreated from Nadelhoffer and Fry, 1994)



(adapted from Högberg, 1993)

Patterns in $\delta^{15}N$



(recreated from Nadelhoffer and Fry, 1994)

- Foliar = $\delta^{15}N_{Fol}$
- Soil = $\delta^{15}N_{Soil}$
- Enrichment Factor (EF) =

  $\delta^{15}N_{Fol} - \delta^{15}N_{Soil}$

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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Good responders

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(Lorentz et al. *In Prep*)

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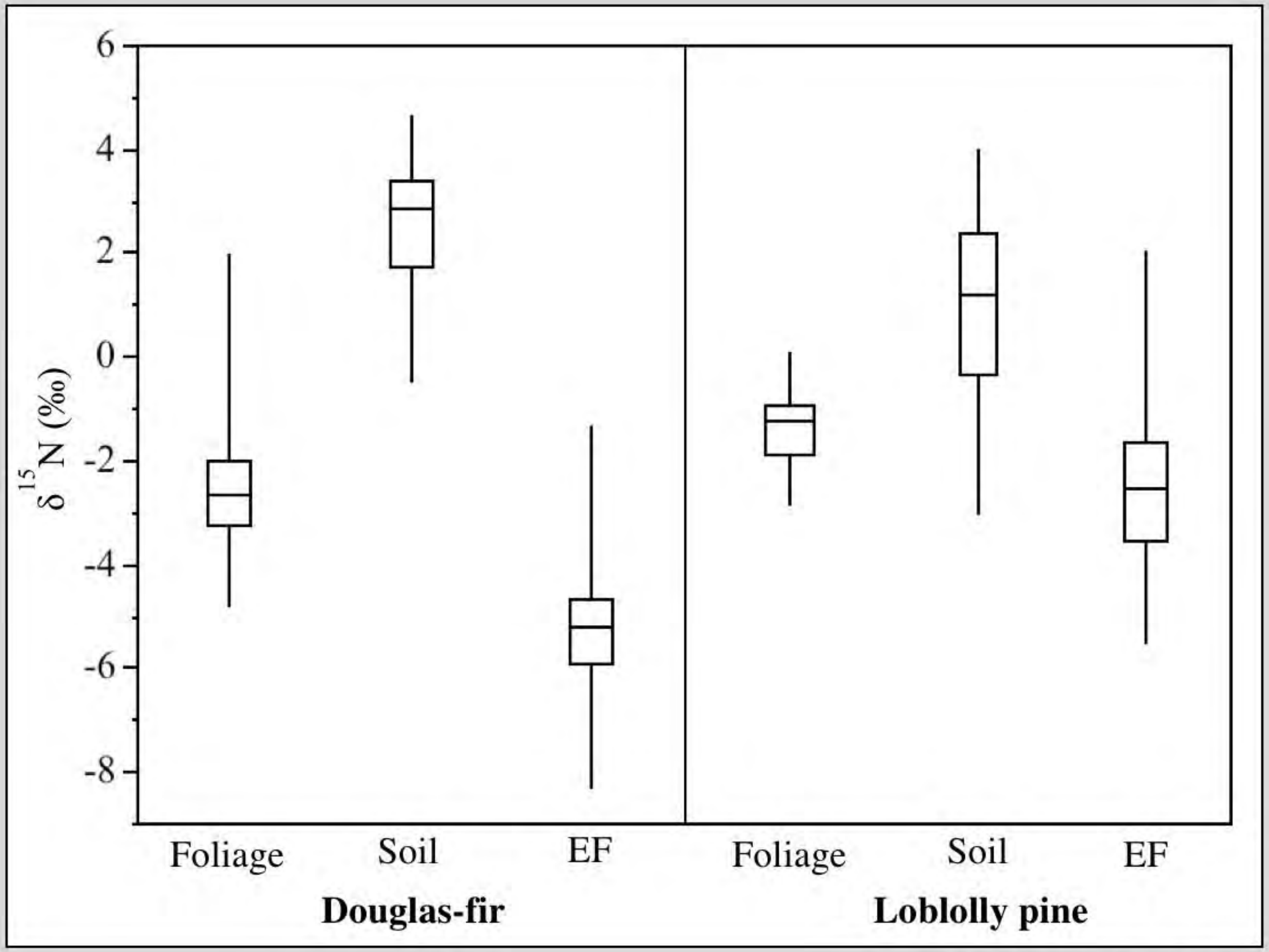
Range of responses

(Lorentz et al. *In Prep*)

Variability in δ¹⁵N



(Lorentz et al. *In Prep*)

Douglas-fir Fertilization Response

	$\delta^{15}N_{Fol}$	$\delta^{15}N_{Soil}$	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	Shaprio-Wilk W	Shaprio-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

(Lorentz et al. *In Prep*)

Douglas-fir Fertilization Response

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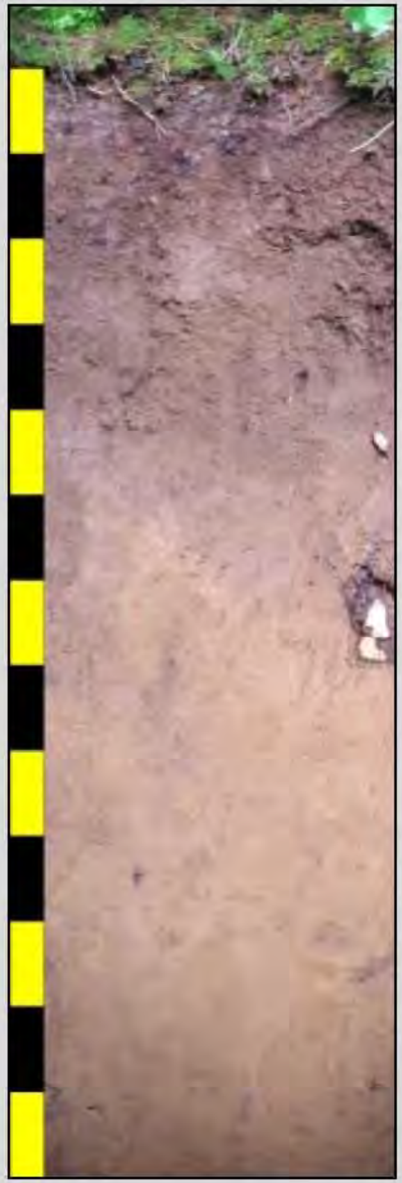
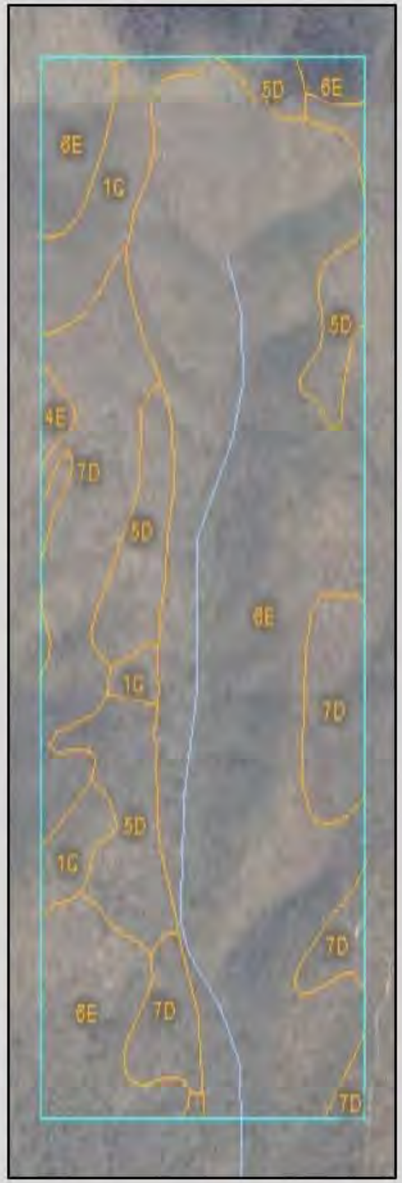
Mineralogical Controls on Nutrient Mobility



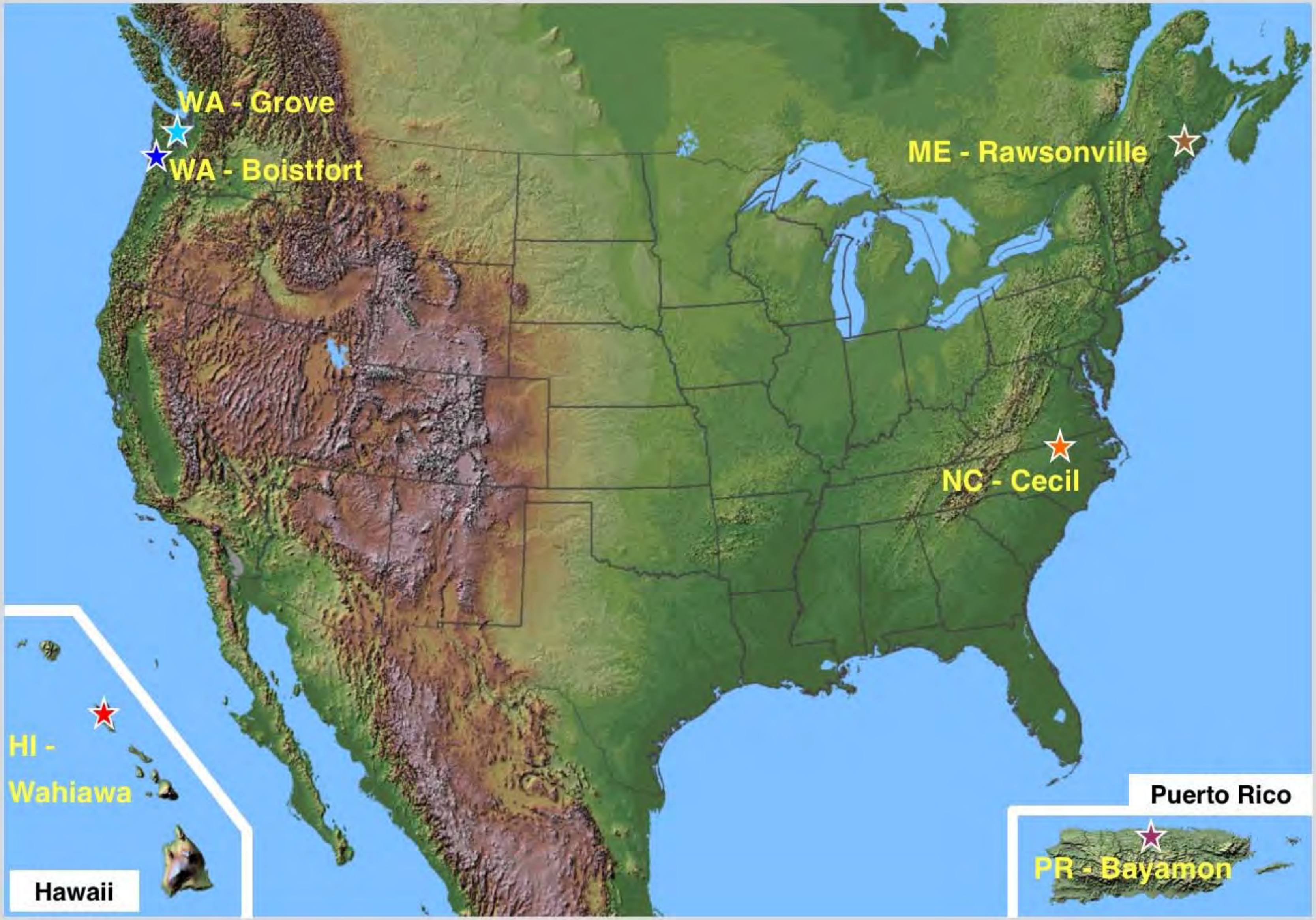
Variable	Description	Estimation[a]
Fe_{PED}	Pedogenically active Fe fraction	$= Fe_d$
Al_{PED}	Pedogenically active Al fraction	$= Al_o$
Fe_{SRO}	Short-range-order Fe fraction	$= Fe_o$
Al_{SRO}	Short-range-order Al fraction	$= Al_o - Al_p$
Al_{ORG}	Organically bound Al	$= Al_p$
Al_{SUB}	Al substituted 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)

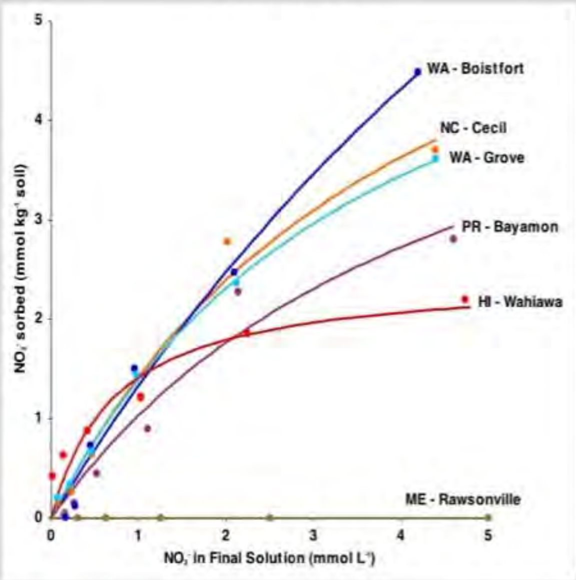


Mineralogical Controls on Nutrient Mobility

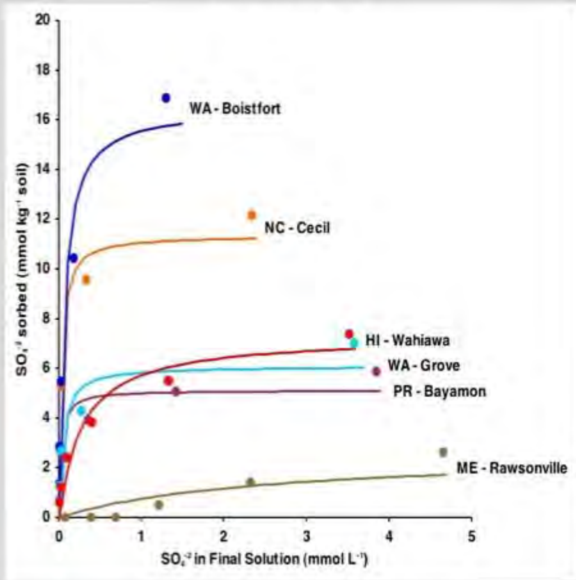


Mineralogical Controls on Nutrient Mobility

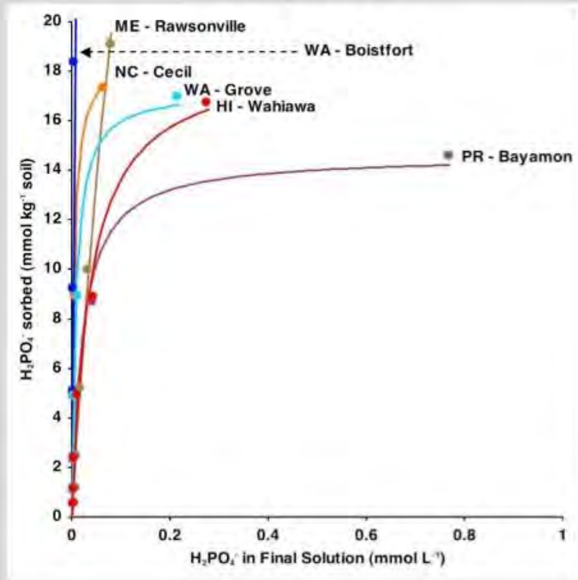
Nitrate



Sulfate



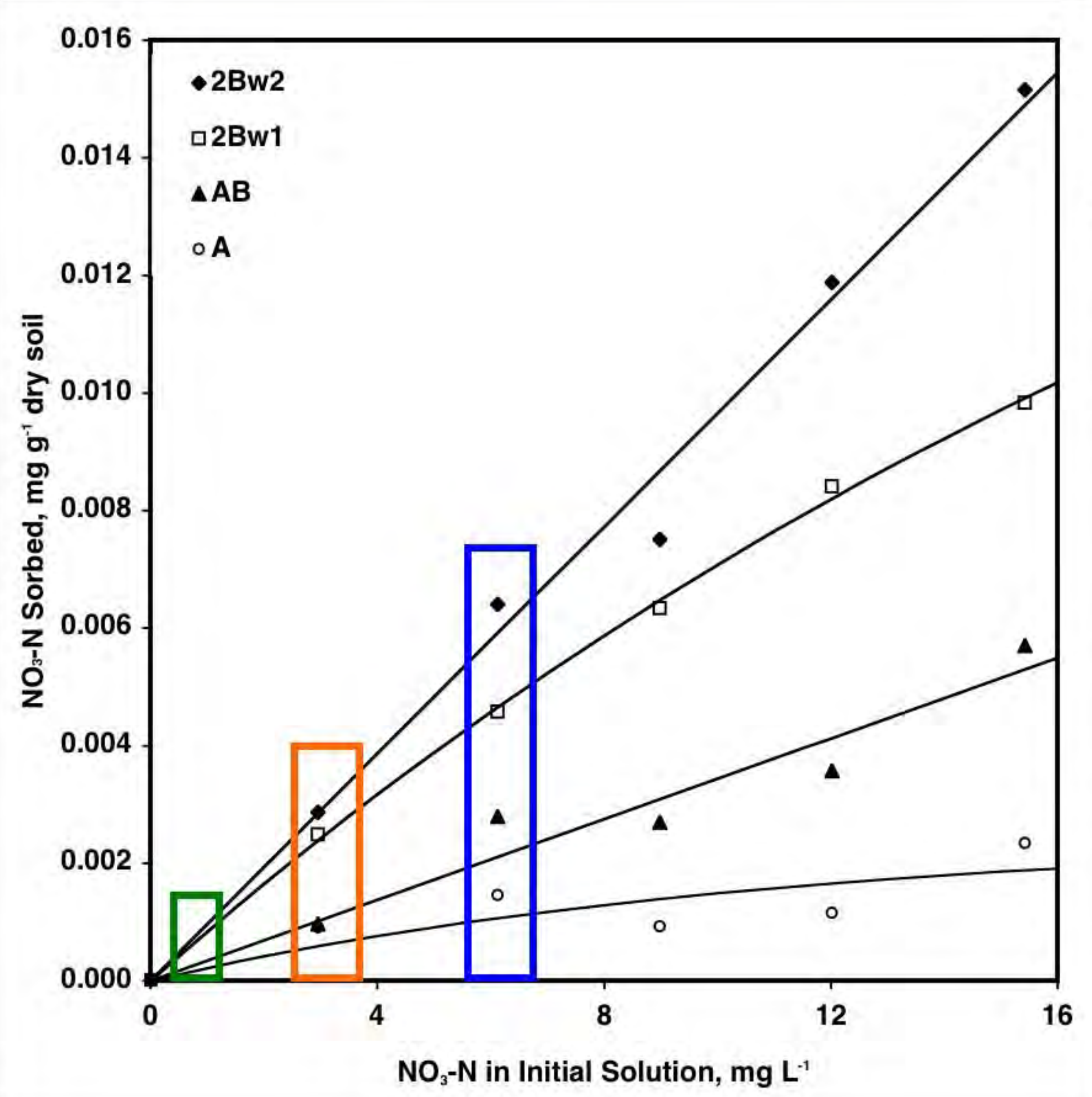
Phosphate



Anion	Parameter	Equation	Adjusted R^2	P
NO_3^-	N_{max}	6.06 – 3.27(organic C) + 33.28(organically bound Al)	0.88	0.020
	b	–0.049 + 0.125(short-range-order Al/Si ratio)	0.89	0.003
SO_4^{2-}	N_{max}	–1.643 – 2.00(organic C) + 33.9(Al substituted in Fe oxides)	0.77	0.053
	b	52.5 – 76.4(Al substituted in Fe oxides)	0.48	0.077
$H_2PO_4^-$	N_{max}	15.8 + 11.9(short-range-order Fe)	0.98	<0.001
	b	–117 – 103(organic C) + 1160(organically bound Al)	0.67	0.087

(Strahm and Harrison 2007)

Mineralogical Controls on Nutrient Mobility

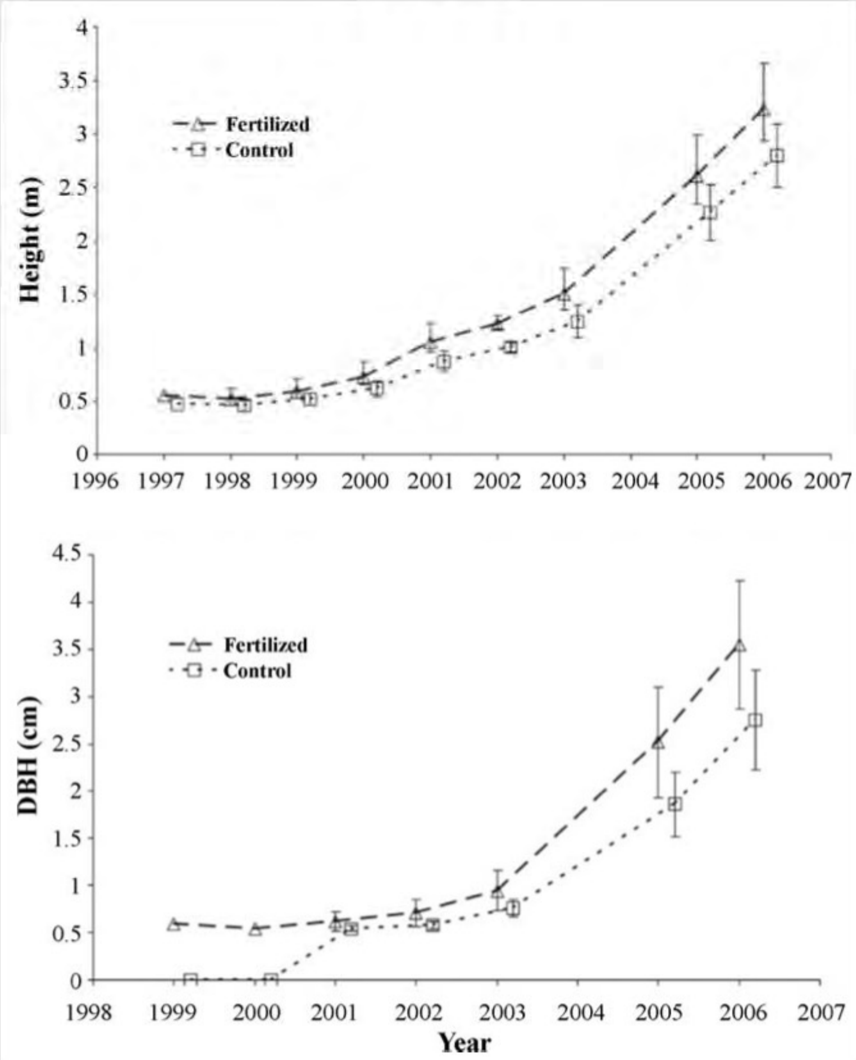


Treatment	BOLE-ONLY	TOTAL TREE PLUS	FOREST
Mean NO_3^--N Conc (mg L^{-1})	6	2.5	0.5
NO_3^--N Sorbed (kg ha^{-1})	49	19	3.4
Mean NO_3^--N Leached (kg ha^{-1} yr^{-1})	73	26	2.0
% of NO_3^--N Leached	67	73	170

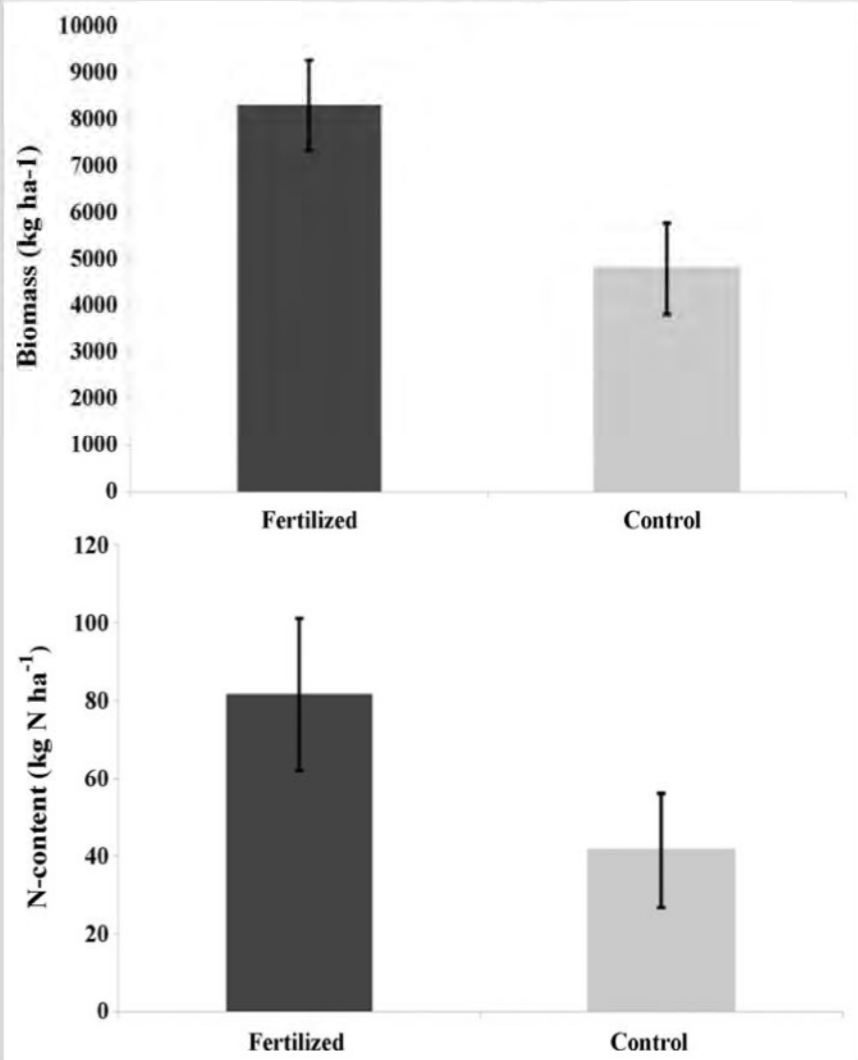
(Strahm and Harrison 2006)

Nitrogen Retention and "Carryover"

Overstory

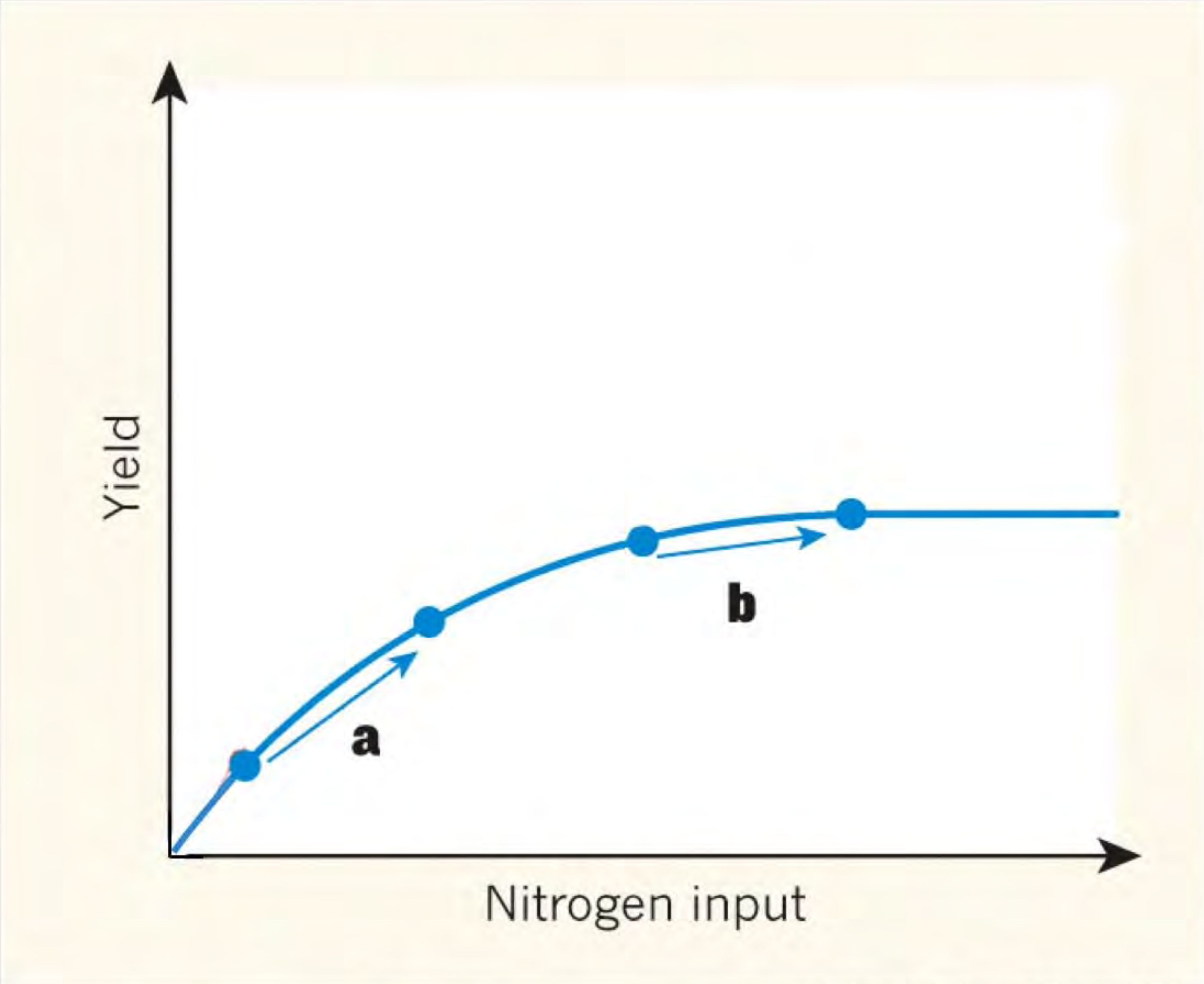


Understory



(Footen et al. 2009)

Fertilizer Efficiency in a Changing World



(adapted from Zhang 2017)

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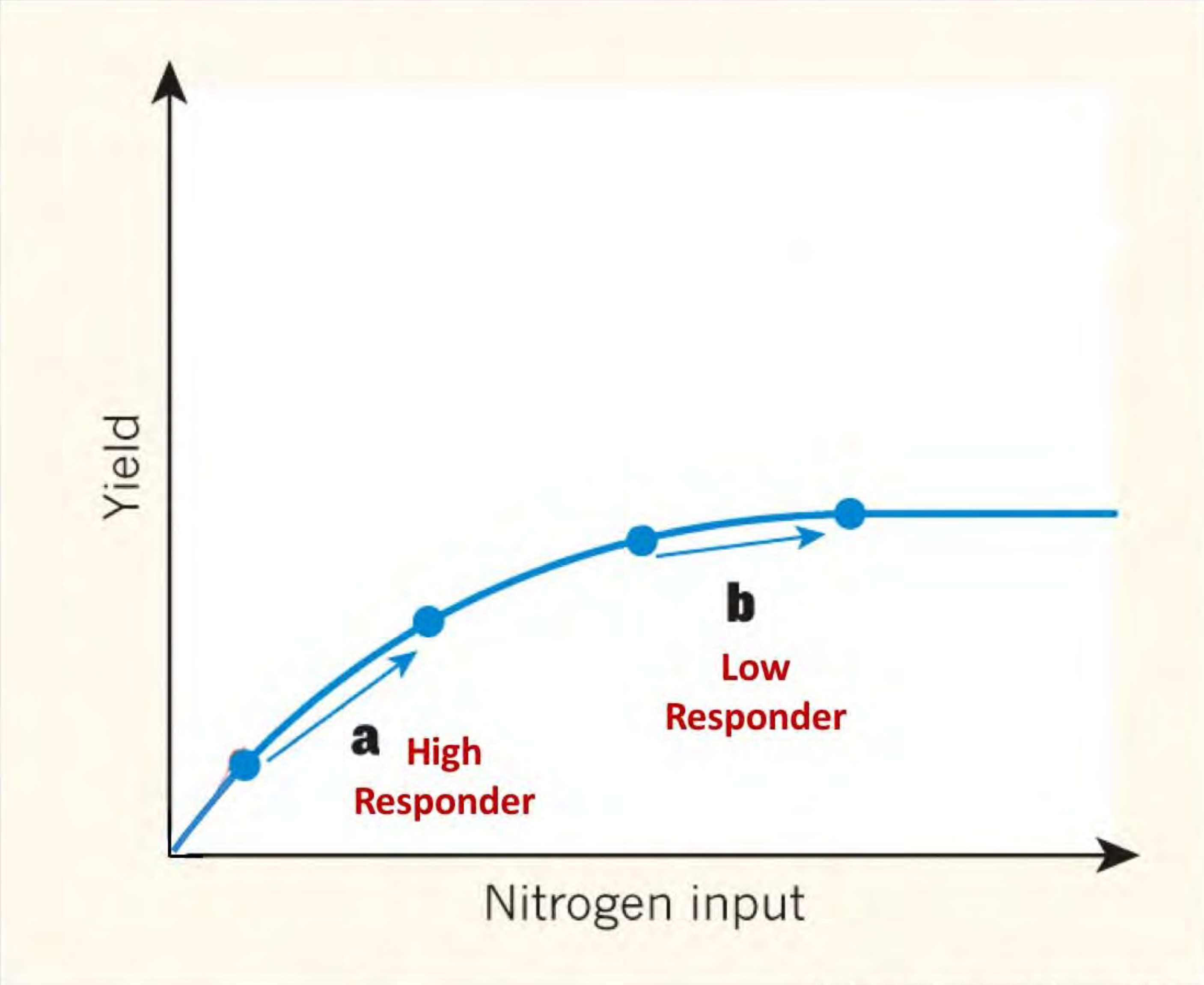

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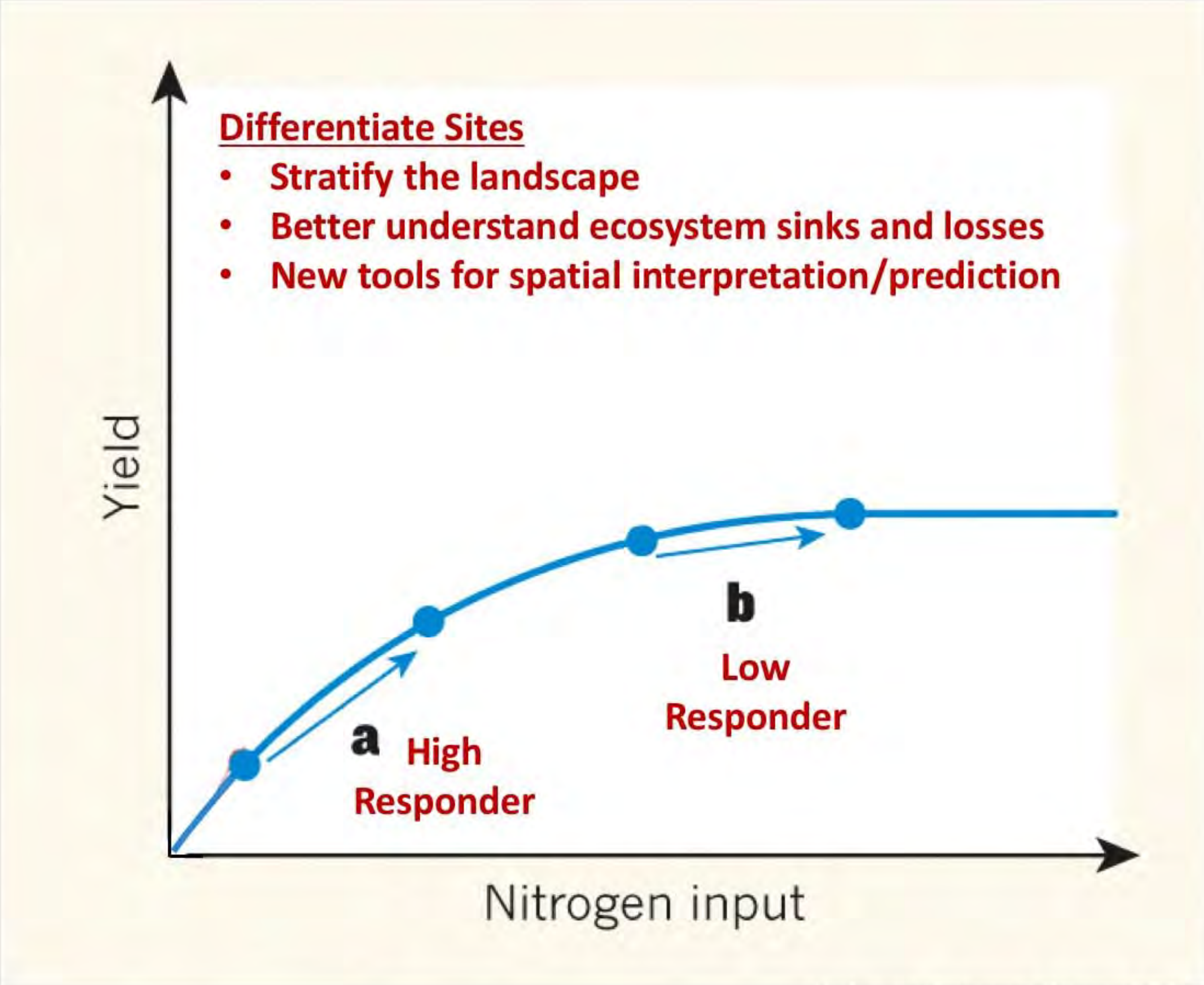

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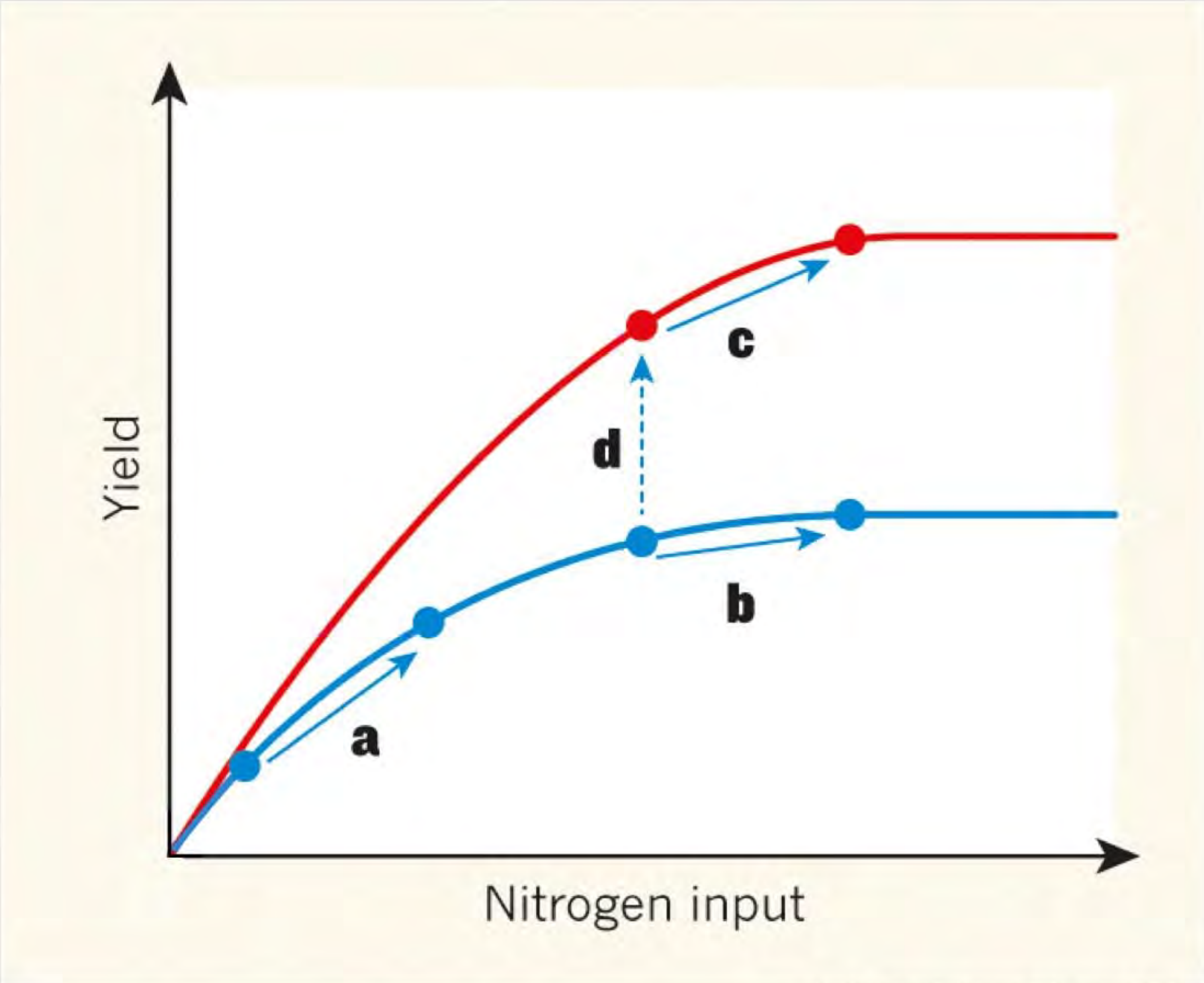

(adapted from Zhang 2017)

Fertilizer Efficiency in a Changing World

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

Multiscale and Multifactor Approaches