土壤氮循环的同位素示踪研究

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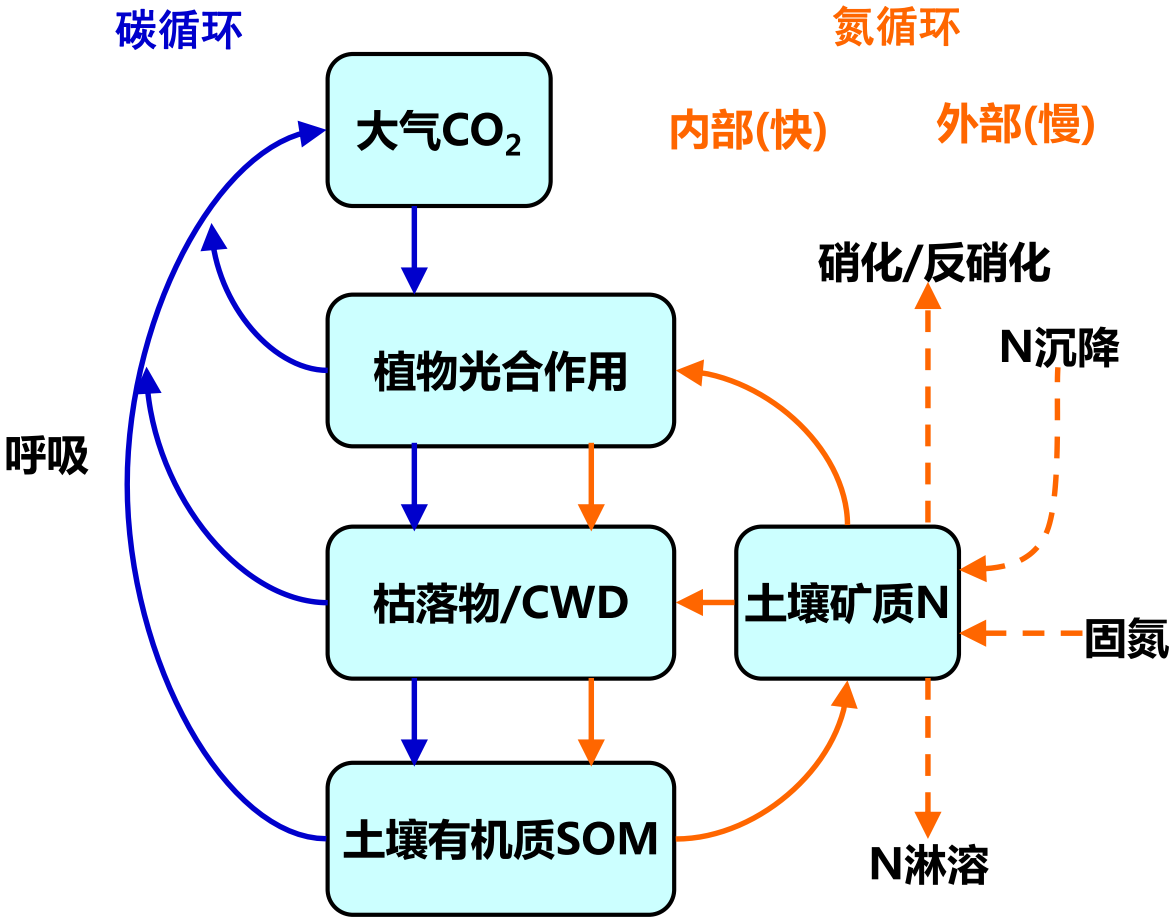
提纲

- 土壤氮过程 (why is it important?)
- 氮同位素示踪 (what are known?)
- 展望 (what are to be addressed?)

土壤氮过程：黑箱vs灰箱

- 前沿性：
  - Final frontier in ecology
- 复杂性 (soil N cycle processes are complex):
  - Multiple transformations, feedbacks, and interactions with other biogeochemical elements [plant-soil-microbe feedbacks].
- 不确定性：
  - To monitor and quantify many specific N cycling processes.
  - Controls on N cycling are uncertain, especially how it responds to global change factors (climate change, elevated atmospheric CO_2, N deposition, etc.).



Coupled C-N cycling in plant-soil system

Soils—The Final Frontier: Wounding Earth's Fragile Skin

SPECIAL SECTION

INTRODUCTION

Ecology in the Underworld

In many ways the ground beneath our feet is as alien as a distant planet. The processes occurring in the top few centimeters of Earth's surface are the basis of all life on dry land, but the opacity of soil has severely limited our understanding of how it functions. As creatures of the aerial world, we have a decidedly distorted view of this nurturing underworld. For ecologists, and flummoxes in equal measure. The techniques and approaches of many oveground ecology don't translate well to the soil environment.

ives are beginning to change, as the articles in this special issue show. Interest in red in part by technical advances of the past decade. Molecular phylogenetics, ing the extent of the diversity of soil microorganisms and how patterns of diver-

standing of the mutual influences of the underground and aboveground compoare reviewed by Wardle *et al.* (p. 1629). Ecologists have traditionally portrayed il as a black box labeled "decomposers"—essentially, a single trophic level veground material, with its multiple trophic levels, is Digging deeper, it turns out that the soil food web is as the aboveground web, with intricate connections to

n world, ecology is writ small. The spatial, chemical, geneity within a few cubic centimeters of soil rivals rest or coral reef. Young and Crawford (p. 1634) dew techniques for documenting and visualizing the mi underfoot. In a News story, Pennisi (p. 1620) provides a stage for one unsung subsurface duet: soil fungi and plant roots.

But Earth's skin is fragile indeed. A map (p. 1614) vividly illustrates the extent of soil degradation and loss across the globe, and in a News story, Proffitt (p. 1617) previews an effort to ascertain the extent to which contaminants have infiltrated soils in North America. Kaiser (News, p. 1616) surveys soil degradation and assesses what it bodes for crop yields, and Lal, in a Viewpoint (p. 1623), outlines the management protocols that are needed to enhance the sustainability of agricultural soils and the ability of soil to sequester carbon. The prospect of massive amounts of carbon being liberated with the melting of frozen soils in the High Arctic is explored in a News story by Stokstad (p. 1618).

Human attitudes toward soil, as toward the rest of the environment, range from reverent to cavalier. The historical development of our varied relationship with soil is charted in a Viewpoint by McNeill and Winiwarter (p. 1627), and a survey of the soil fertility of an ancient agroecosystem is given in a Report by Vitousek *et al.* (p. 1665). Delving deeper into the hidden world of soils will surely reveal new connections to our familiar environs and make subterraneana seem far less of an alien experience.

–ANDREW SUGDEN, RICHARD STONE, AND CAROLINE ASH

CONTENTS

NEWS

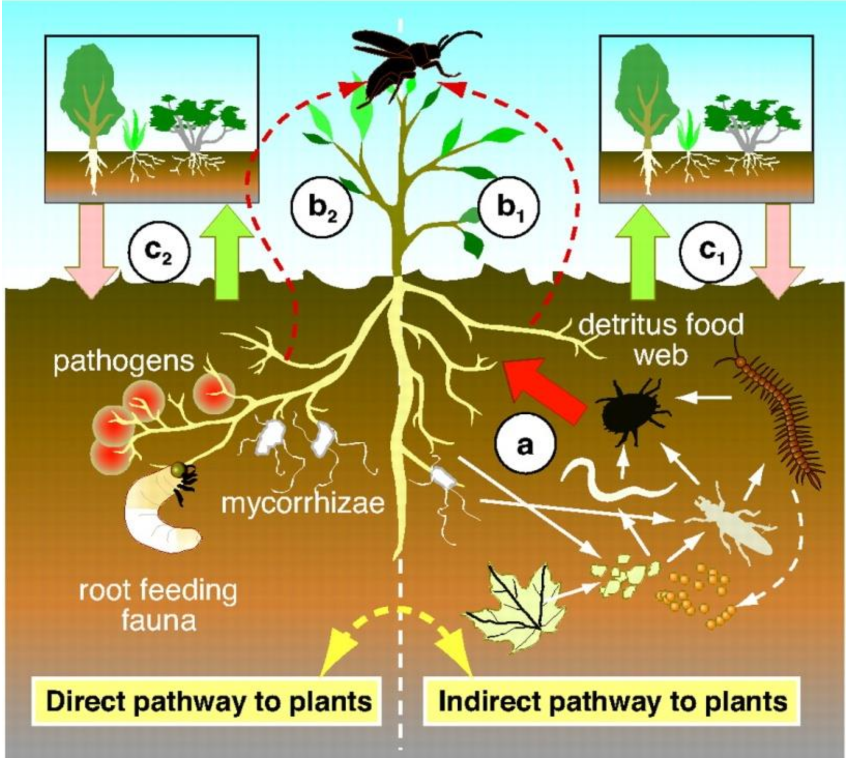
VIEWPOINTS

REVIEWS

See also Report on page 1665.

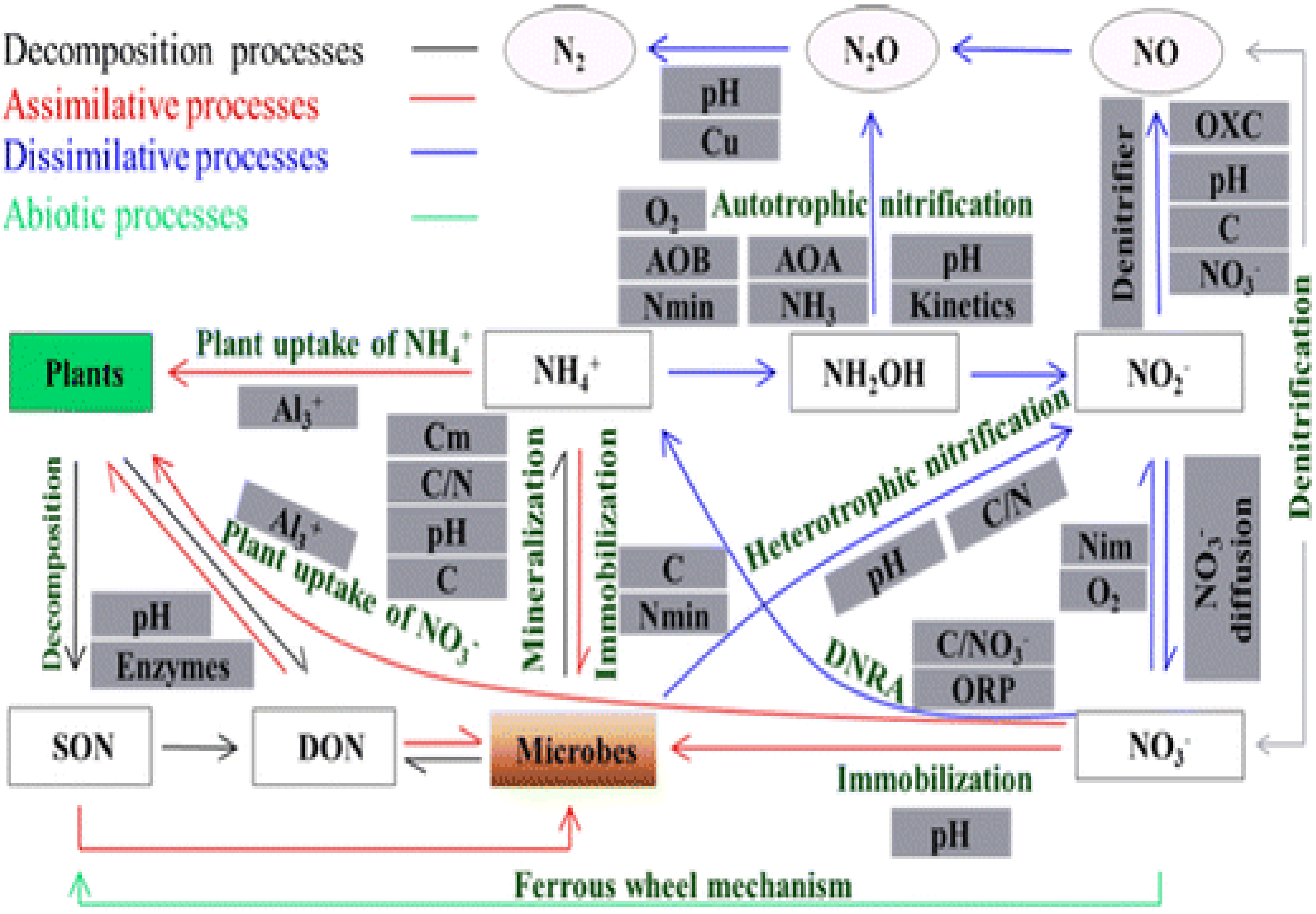
Science

CREDIT: STEFANO PAGIOLA

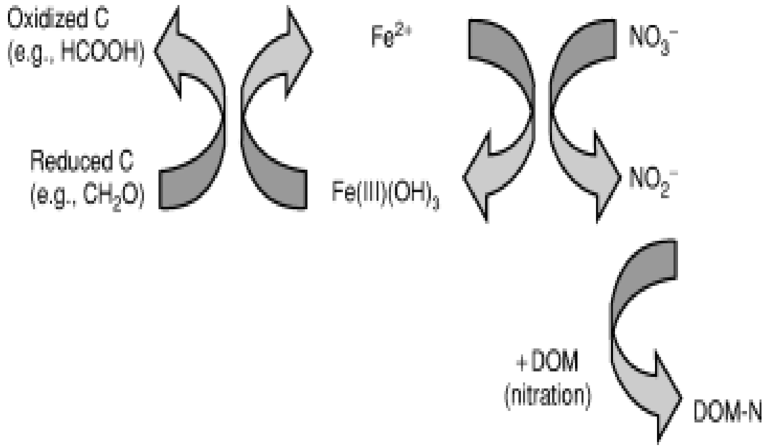


Soil carbon sequestration impacts on global climate change and food security R Lal - science, 2004 - sciencemag.org
被引用次数：3804
Ecological linkages between aboveground and belowground biota. DA Wardle, RD Bardgett, JN Klironomos, H Setälä… - Science, 2004 - sciencemag.org
被引用次数：2466

土壤N过程的复杂性

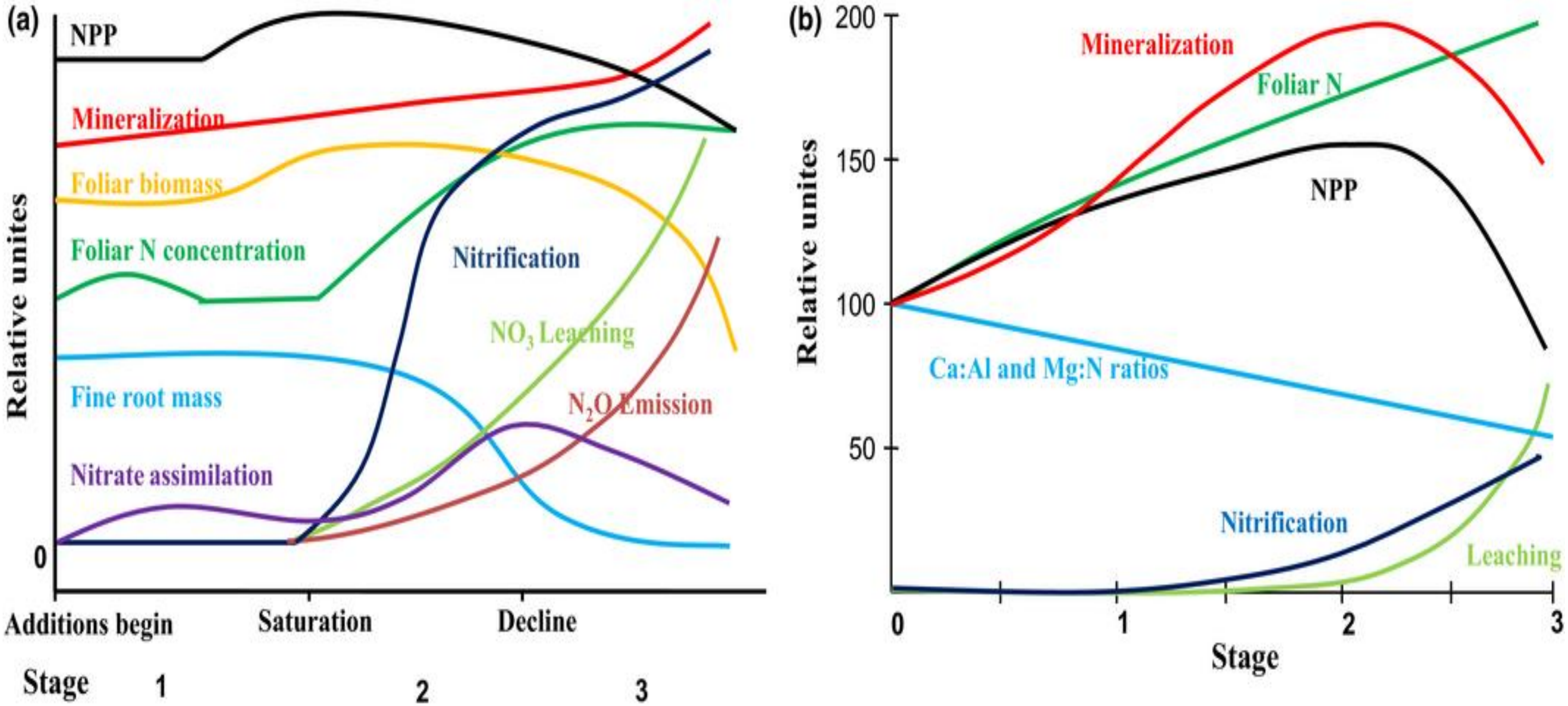


The 'ferrous wheel hypothesis'
for abiotic nitrate immobilization



Gao, Yang , Kou , Li 2015. JSS

氮循环对氮添加的响应



Niu et al. 2016 modified from Aber et al. (1989, 1993) , and Gundersen et al., (1998)

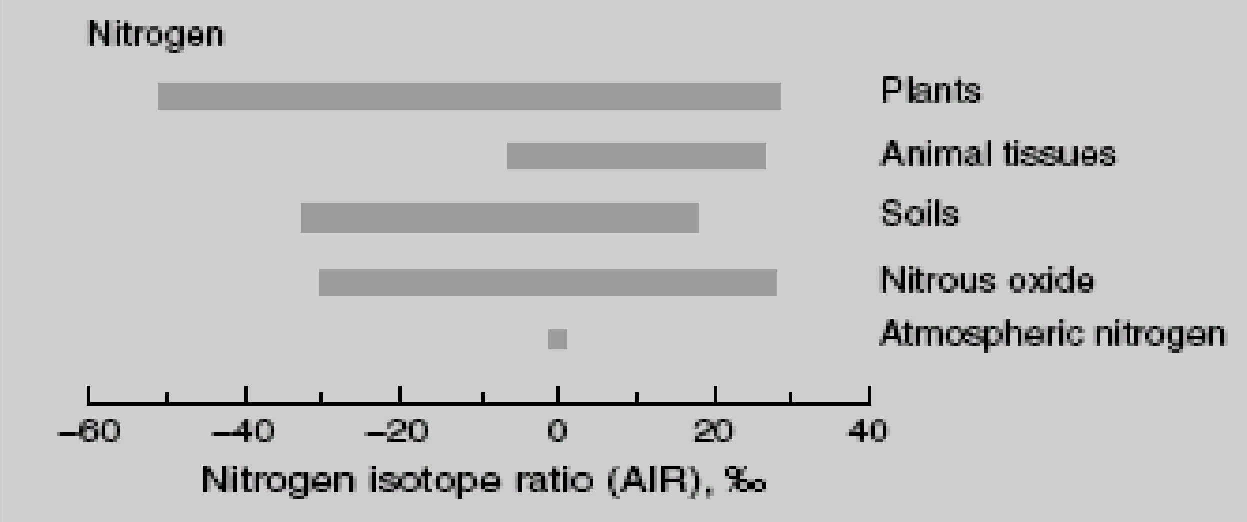
提纲

- **土壤氮过程 (why is it important?)**
- **氮同位素示踪 (what are known?)**
- **展望 (what are to be addressed?)**

氮同位素及其形态

^{14}N	14.003074	99.634%
^{15}N	15.00010896	0.366%

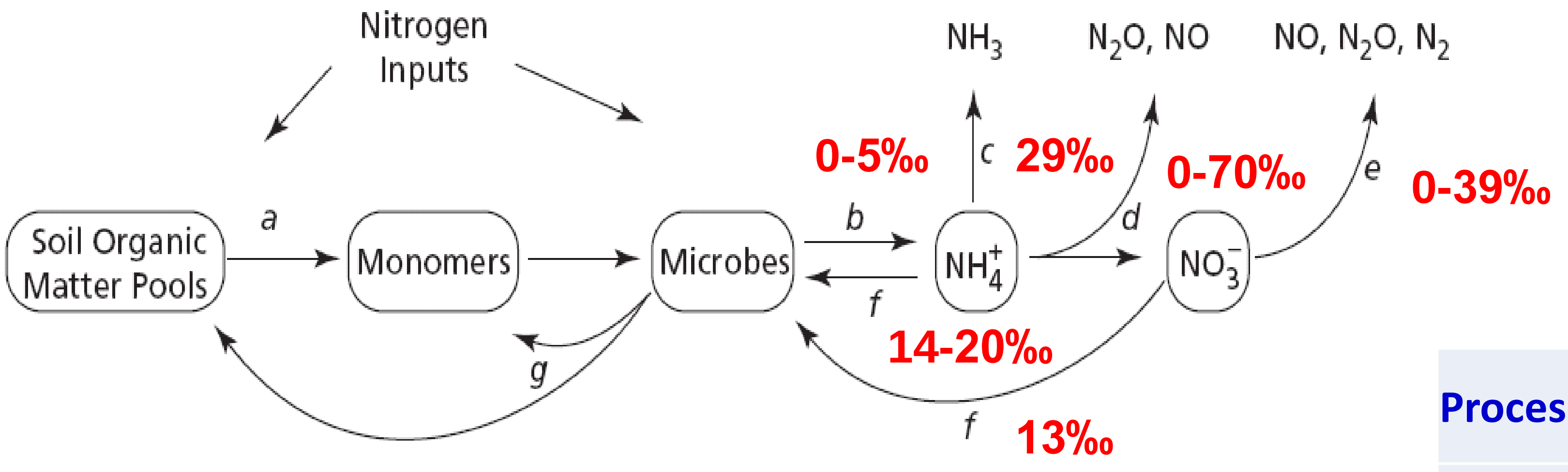
- 惰性（unreactive, inert)
  - 氮气(Nitrogen Gas) (N_2)
- 反应性（reactive）
  - 有机氮(Organic N)
  - 铵根离子(盐)Ammonium N (NH_4^+)
  - 硝酸根离子(盐) Nitrate N (NO_3^-)
  - 亚硝酸根离子(盐) Nitrite N (NO_2^-)
  - 氨Ammonia (NH_3)
  - 二氧化氮（nitrogen dioxide (NO_2)）
  - 一氧化二氮、一氧化氮(Nitrous (N_2O) and Nitric (NO) Oxides)
- 溶解性（ dissolvability ）
  - 颗粒态氮(particulate nitrogen，PN)：PIN、PON
  - 溶解态氮 (dissolved nitrogen，DN)：DIN、DON



Ehleringer & Cerling 2002

Li et al. 2017

氮同位素分馏效应



Evans. 2007

Process	Fractionation (‰)
N_2 fixation	−2 to 2
Assimilation	−1 to 1.6
Nitrification	12 to 35
Denitrification	0 to 33, 26
Ammonia volatilization	20 to 27
Mineralization	−1 to 1
Ion exchange	−1 to −8
Enzymatic hydrolysis	10 to 24
N transfer, ECM fungi to plant host	8 to 10
N transfer, AM fungi to plant host	0 to 3.5

Hobbie & Ouimette 2009

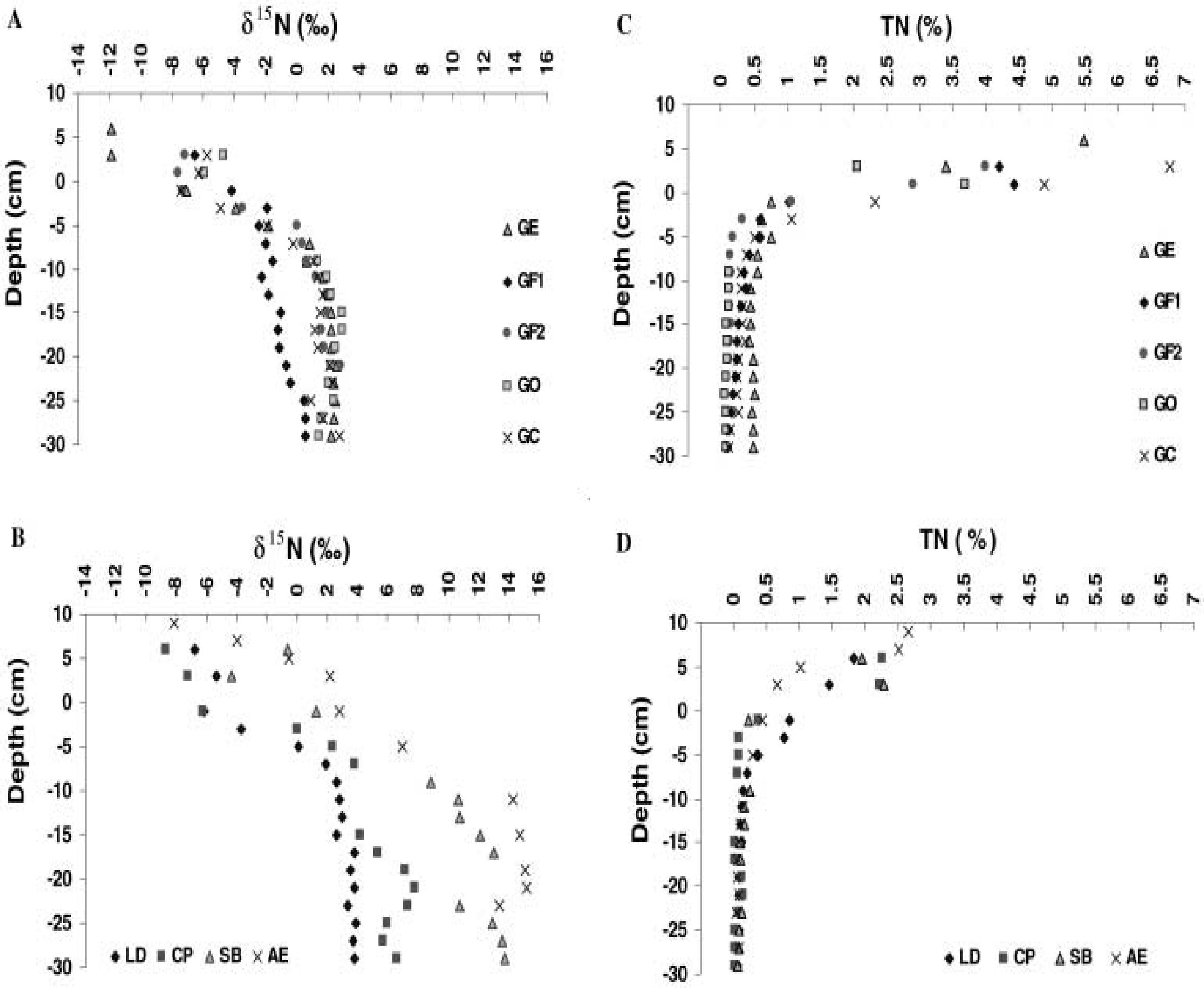
稳定氮同位素技术(Stable N isotope techniques)

- 主要示踪方法：
  - 自然丰度法 (**Natural abundance methods**)
  - ^{15}N示踪法 (**^{15}N tracer methods**)
  - ^{15}N稀释法 (**^{15}N pool dilution methods**)
  - ^{15}N模型 (**^{15}N isotope models**)

- 氮稳定同位素(自然丰度或示踪物)是记录、追溯、综合反映N循环过程与机制的强有力工具。

- 发展历史
  - 1940s：Pioneering 15N tracer experiments: N2 fixer (固氮菌)
  - 1950s：The 15N pool dilution technique
  - 1960s：Isotopic methods for soil N determination, BNF
  - 1970s：The SIN δ15N altered by transformations
  - 1980s：reconstruction of the diet and ecology of human and animal species
  - 1990s：ON uptake，Injection techniques
  - 2000s：N deposition, global change responses
  - 2010s：isocape, SP, bioassay

土壤δ^{15}N剖面



Soil δ^{15}N is usually positive and increases with depth

Mechanisms：

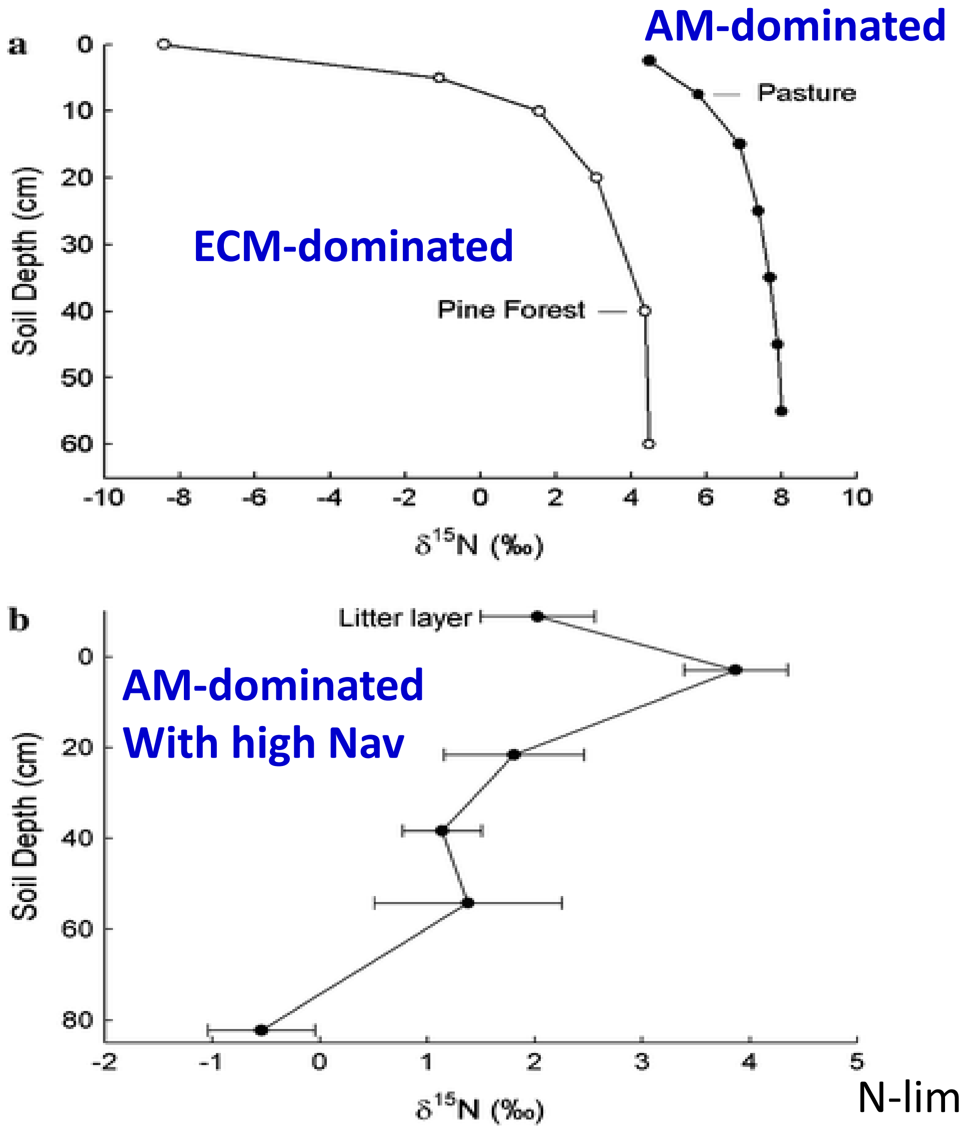
1) δ^{15}N of N inputs into soil

2) Fractionation during internal transformations

3) Fractionation during N loss

Vervaet et al. 2002

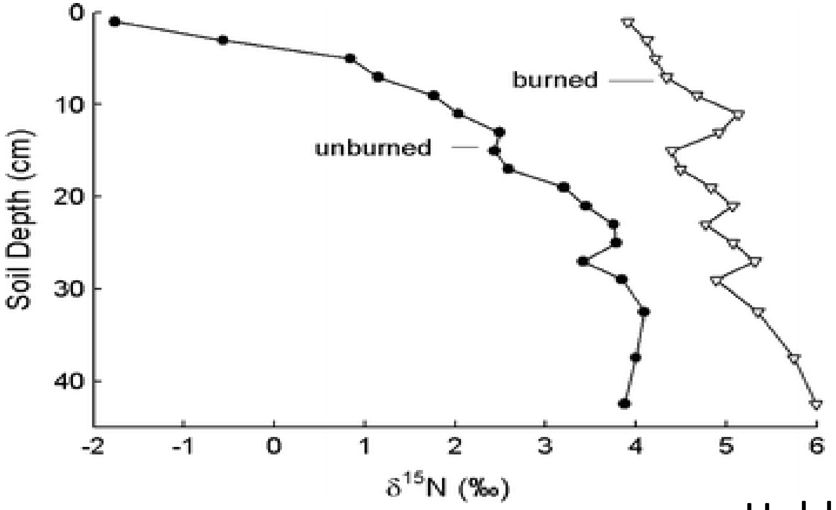
土壤δ^{15}N剖面：LUCC



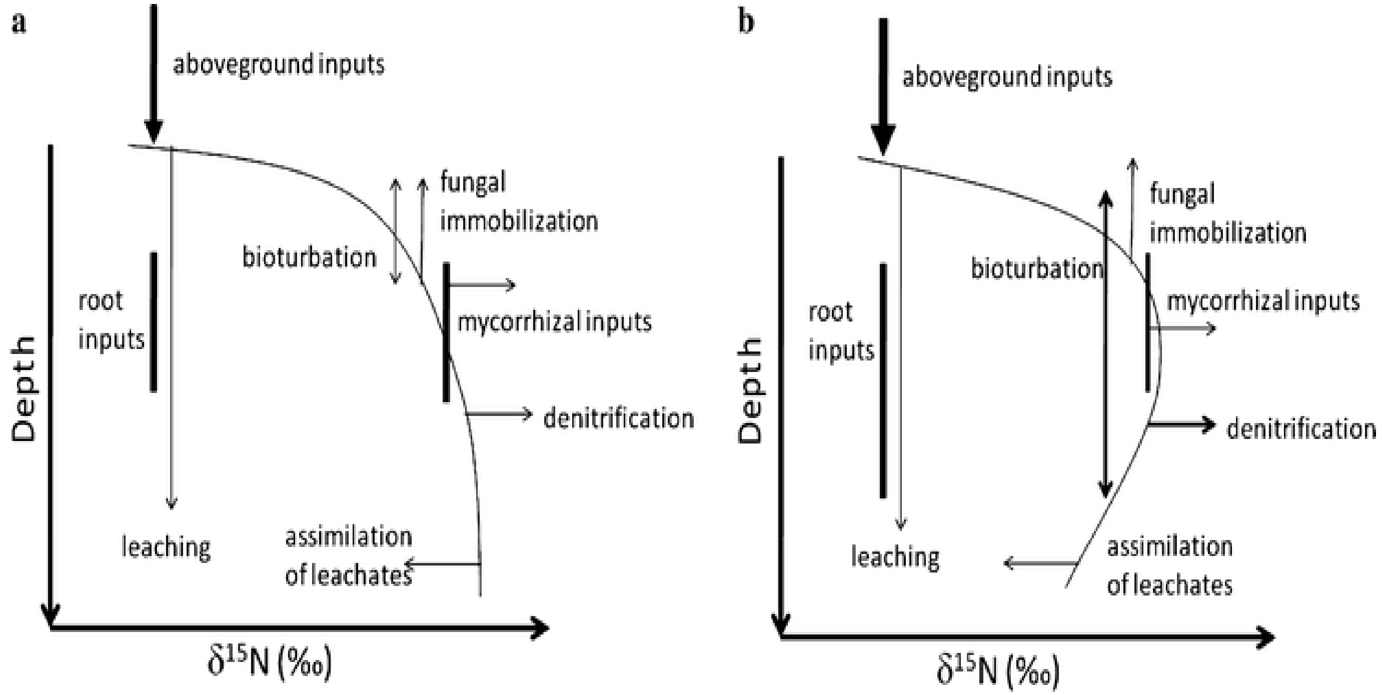
AM-dominated

ECM-dominated

AM-dominated
With high Nav



Hobbie & Ouimette 2009



N-limited system dominated by mycorrhizal transfer and organic N cycling

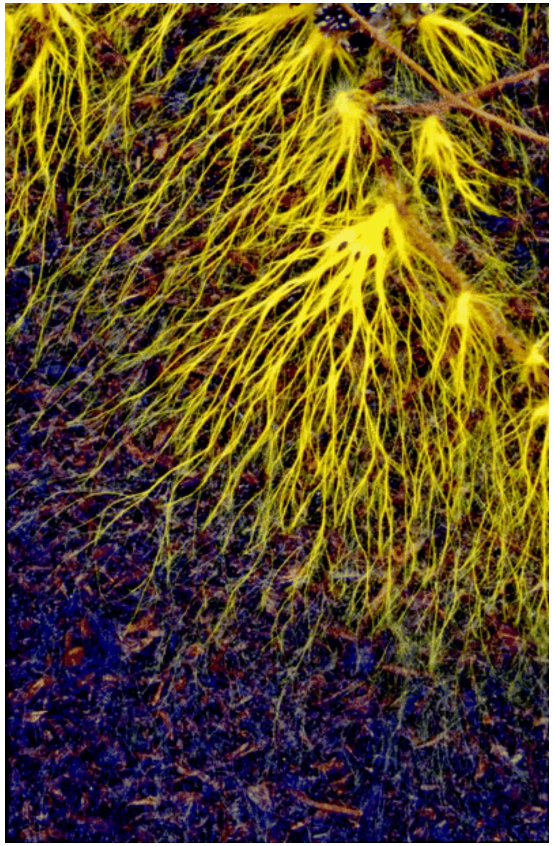
System with less N limitation and more inorganic N cycling

氮固定（Nitrogen fixation）

- 化学固氮（工业化肥生产）
  - Haber-Bosch 反应
  - 闪电

- 生物固氮 (Biological N fixation)
  - 豆科植物- Legumes
    - 根瘤菌 （Rhizobia）– N fixing bacteria
    - 豆科植物与根瘤菌共生关系（Symbiotic relationship）
    - 除豆科植物自身利用外尚有大量氮留存土壤
  - 其他生物
    - 独立生活或非共生土壤生物（Free living or non-symbiotic soil organisms）
    - 固氮菌,固氮细菌（Azotobacter）
    - 固氮螺菌（Azospirillum）
    - 蓝绿藻（Blue-green algae）
    - 苔藓和地衣（mosses and lichens）

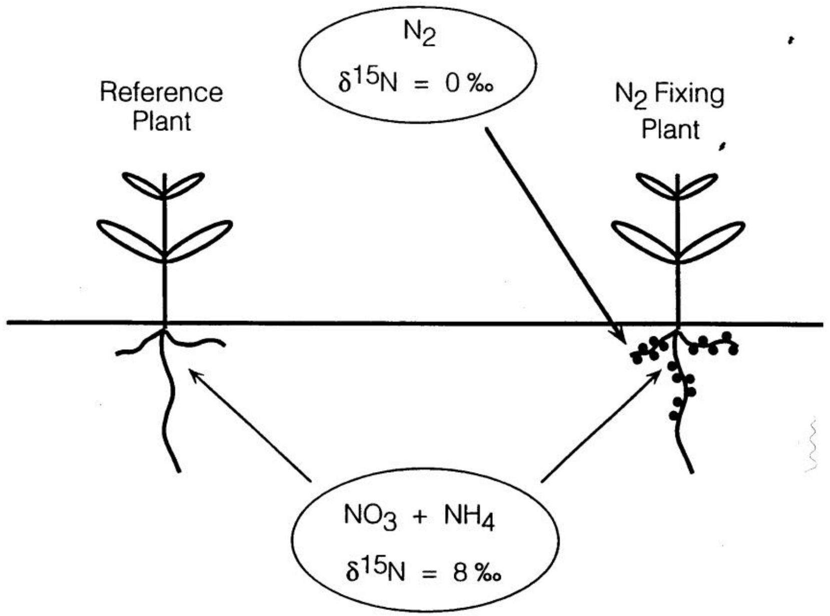
common mycelial networks (CMNs)

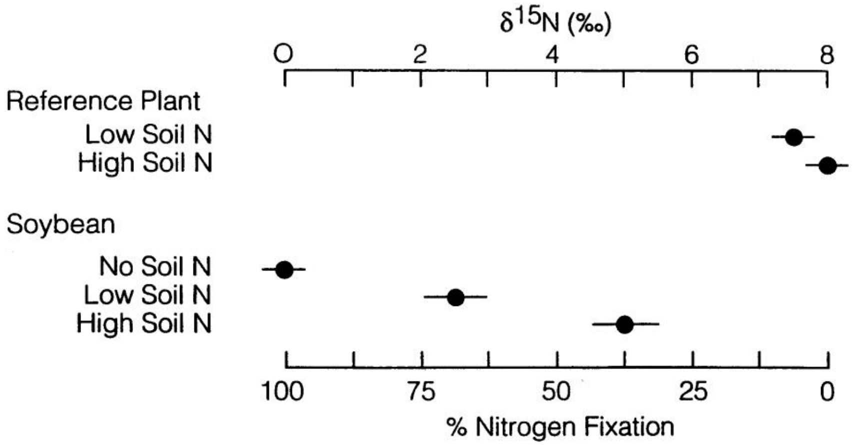


Taylor 2006

Li et al. 2017

豆科植物固氮比例的确定





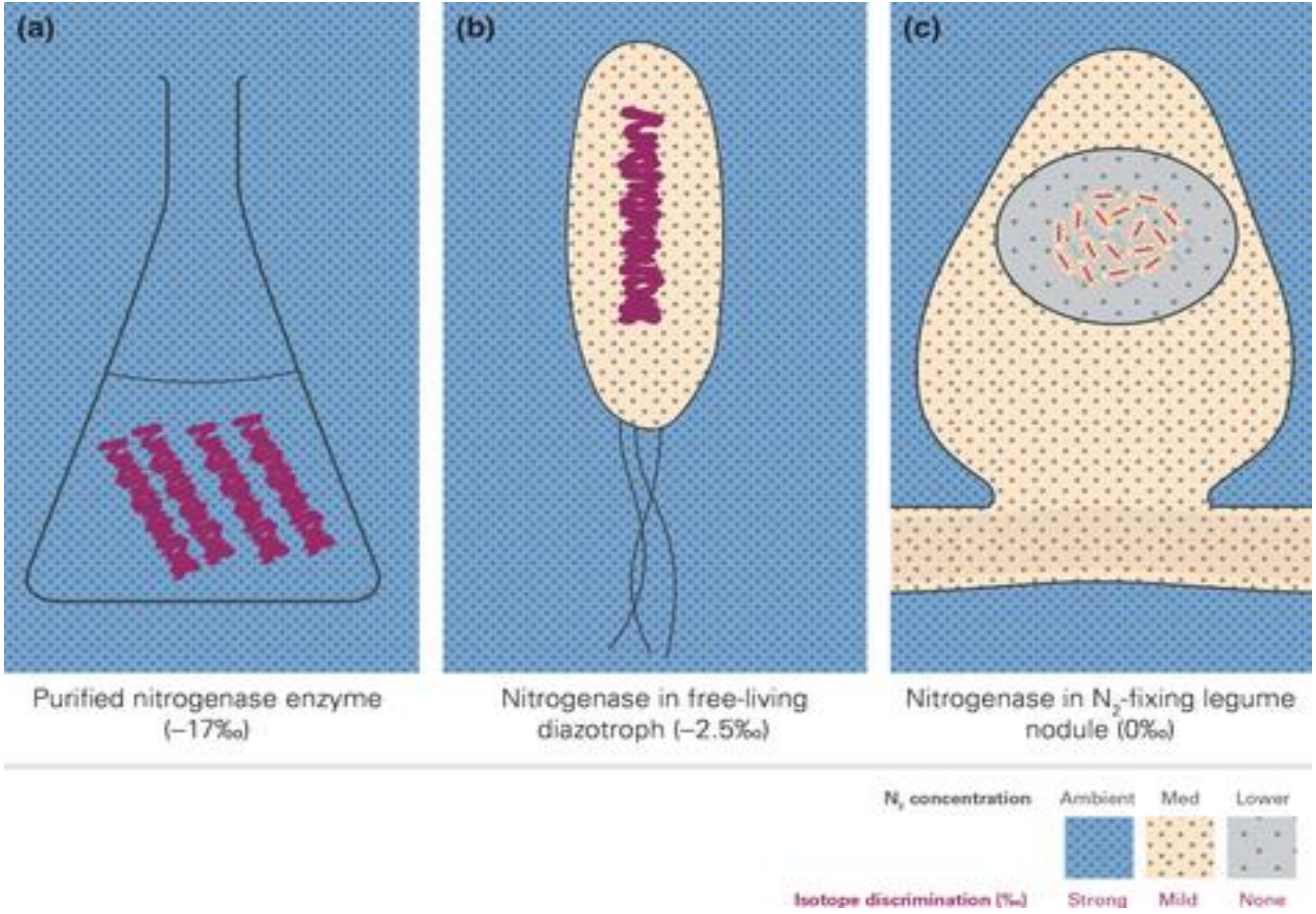
Nitrogen-Fixing Bacteria in Root Nodules

Assumptions and limitations:

1) The soil N source is isotopically consistent spatially and through time;
2) Selection of suitable reference species (fixing and non-fixing species are co-existing and do not in their $\delta^{15}N$ values);
3) Isotopic fractionation during plant uptake, assimilation and turnover is either small or comparable between unrelated species;
4) The temporal resolution is limited; $\delta^{15}N_{foliage}$ represents an integrated isotopic signature of N during leaf lifetime (formation, turnover and resorption).

氮同位素判别为生物固氮提供新认知

New Phytologist



Purified nitrogenase enzyme (−17‰)

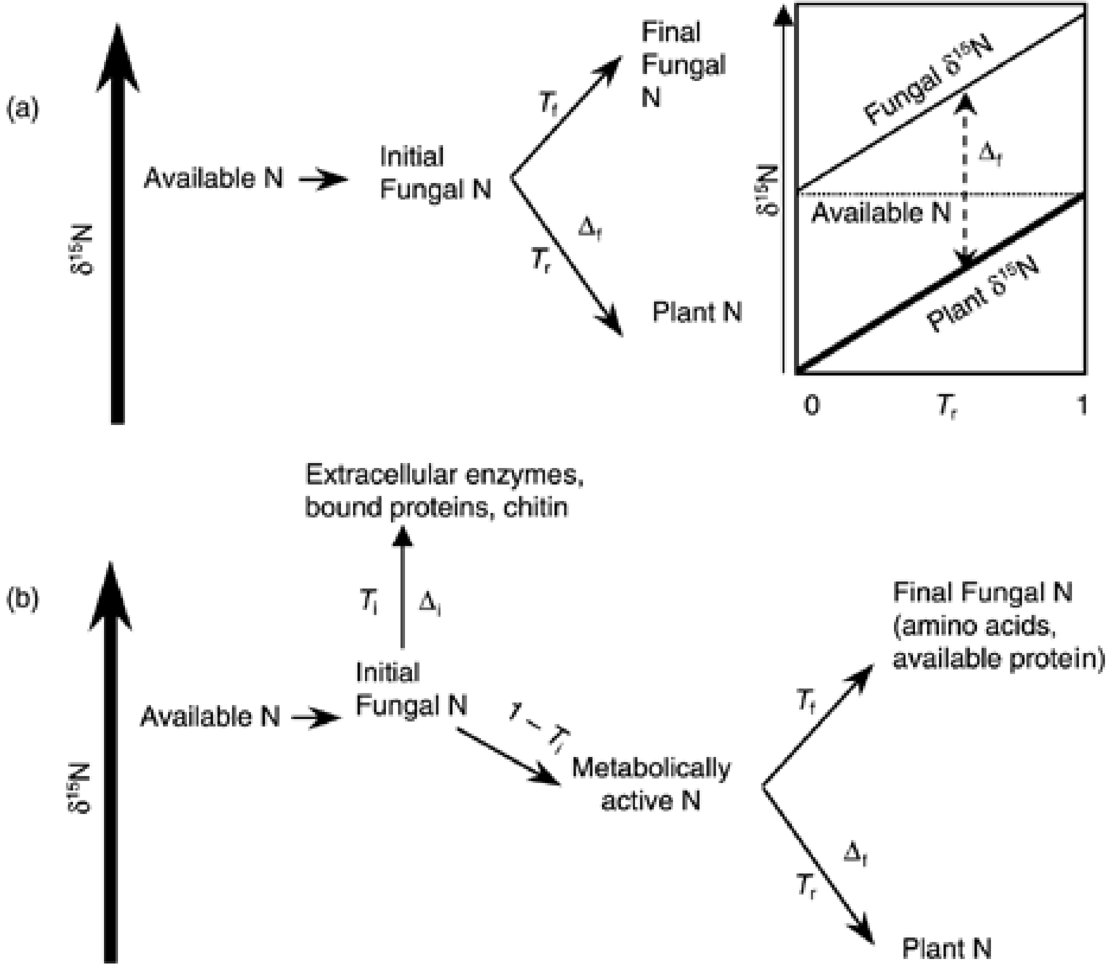
Nitrogenase in free-living diazotroph (−2.5‰)

Nitrogenase in N_2-fixing legume nodule (0‰)

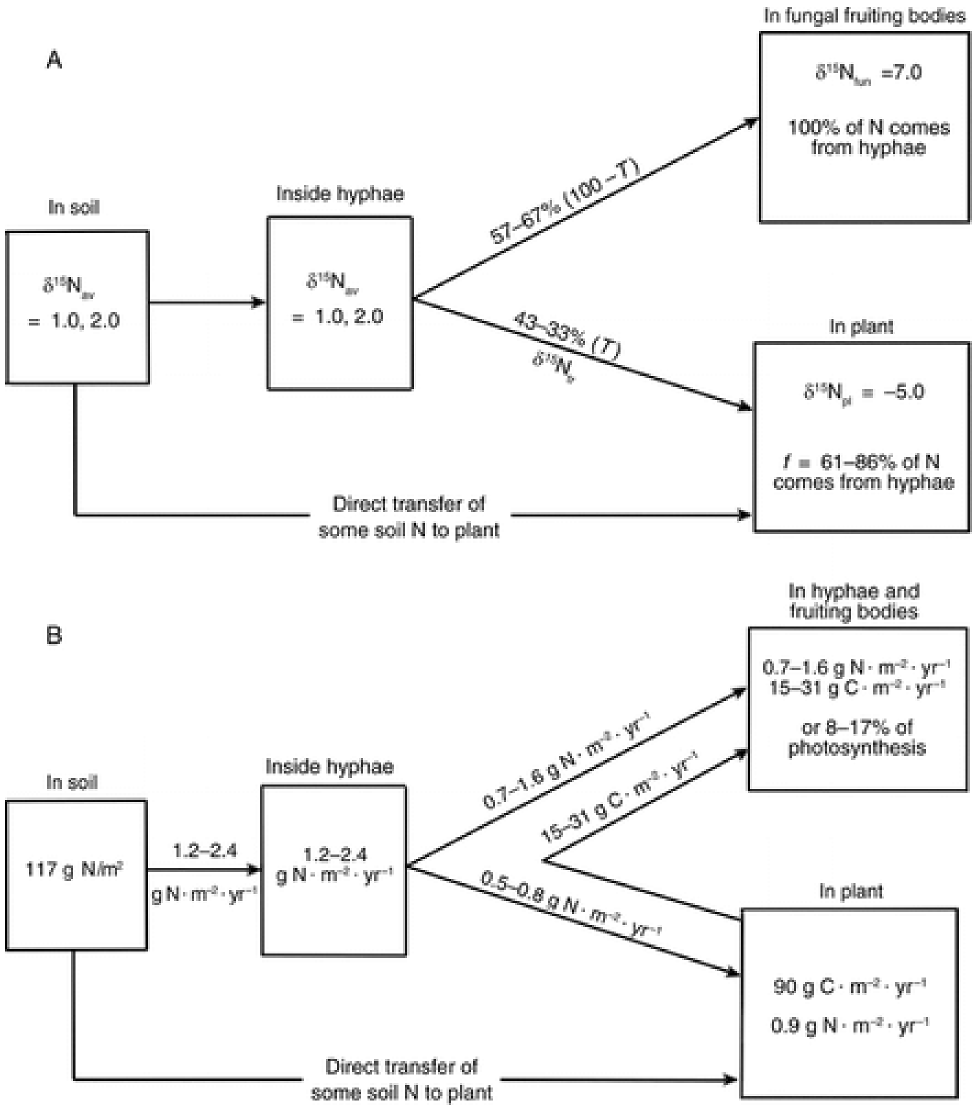
Unkovich 2013

共生菌根与植物氮吸收

New Phytologist



Hobbie & Colpaert 2003



Hobbie & Hobbie 2006

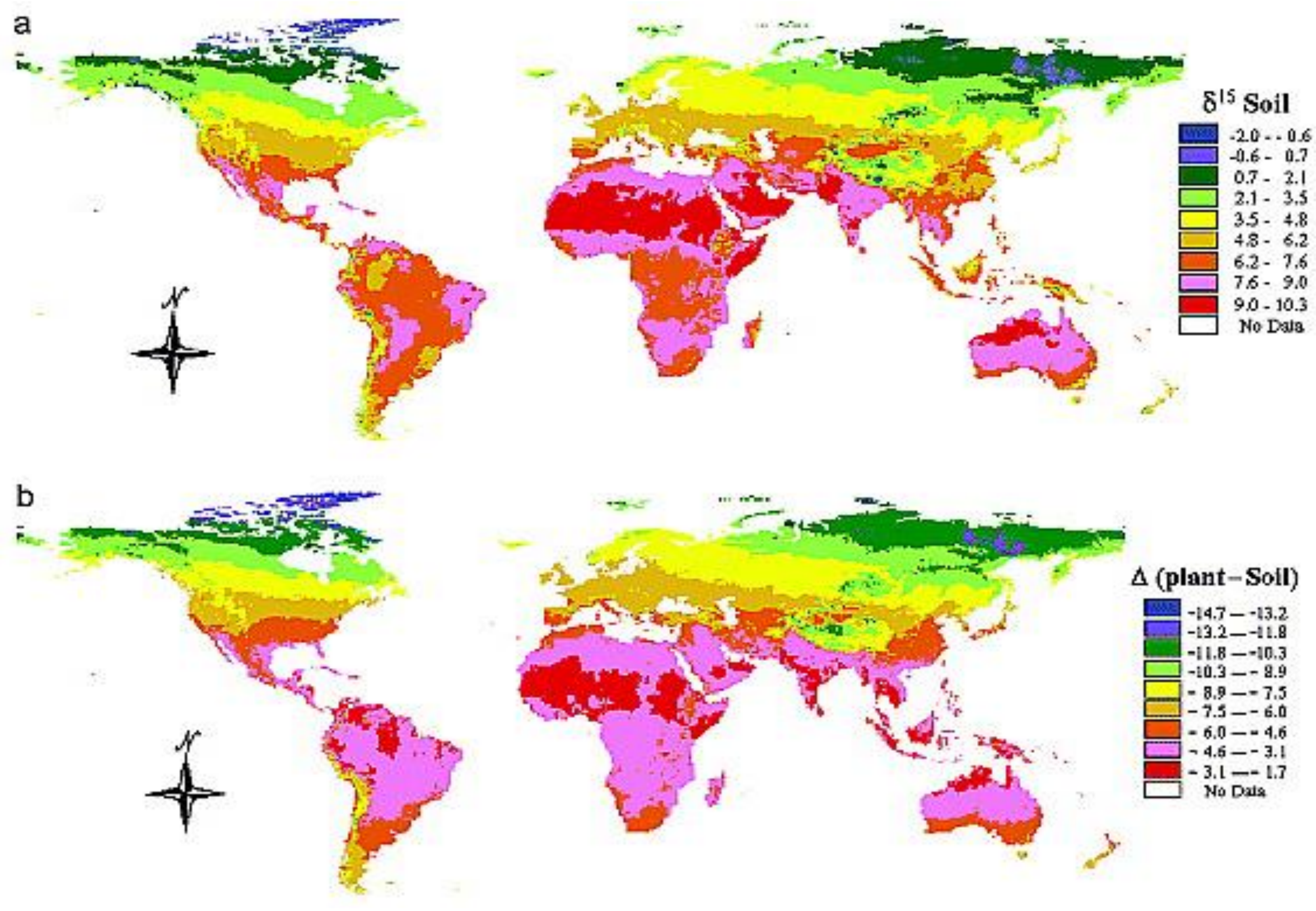
土壤氮δ^{15}N的空间格局（Spatial pattern of soil δ^{15}N）

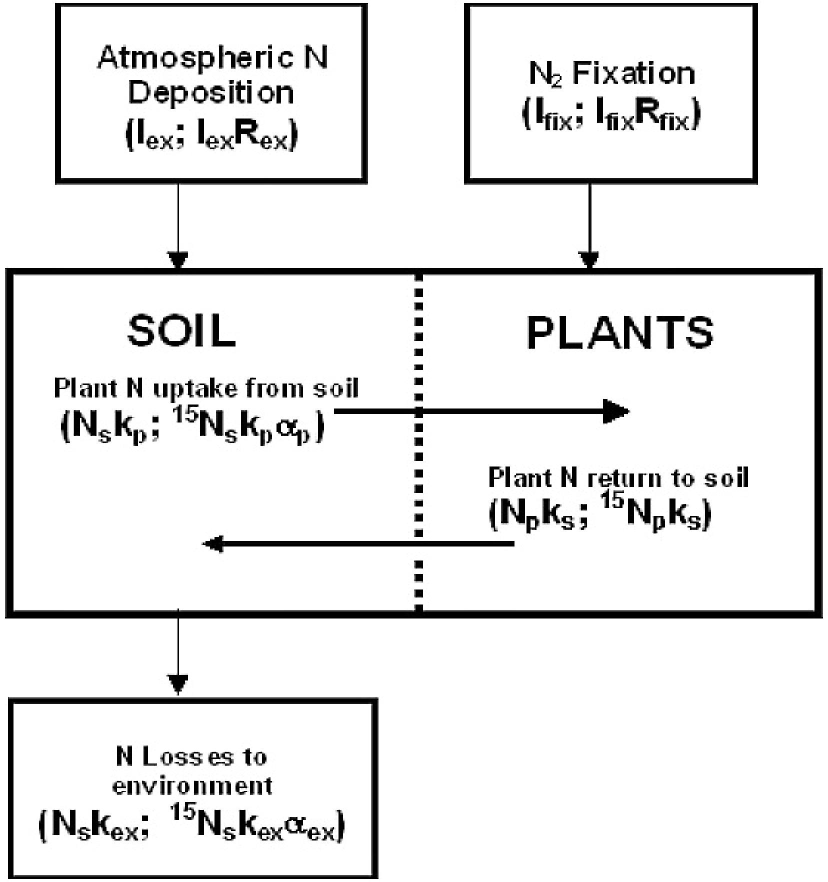
- 区域格局 (along a precipitation gradient or a transect)：
  - Mariotti et al. 1980. *Catena*
  - Austin & Vitousek 1998. *Oecologia*
  - Aranibar et al. 2004. *Glob. Change Biol.*
  - Menge et al. 2011. *New Phytol.*
  - Peri et al. 2012. *Glob. Change Biol.*
  - Díaz et al. 2016. *Scientific Reports*
  - Wang et al. 2015. *Nat. Commun.*
  - Liu et al. 2017. *Biogeosciences*
- 全球格局（with precipitation and temperature or latitude）
  - Handley et al. 1999. *Aust. J. Plant Physiol.*
  - Amundson et al. 2003. *Global Biogeochem. Cy.*
  - Craine et al. 2009. *New Phytol.*
  - Pardo & Nadelhoffer 2010. *Isoscapes.*
  - Craine et al. 2015. *Scientific Reports.*

Global soil and plant δ^{15}N patterns

Global Biogeochemical Cycles

AN AGU JOURNAL





Atmospheric N Deposition
$(I_{ex}; I_{ex}R_{ex})$

N_2 Fixation
$(I_{fix}; I_{fix}R_{fix})$

SOIL

PLANTS

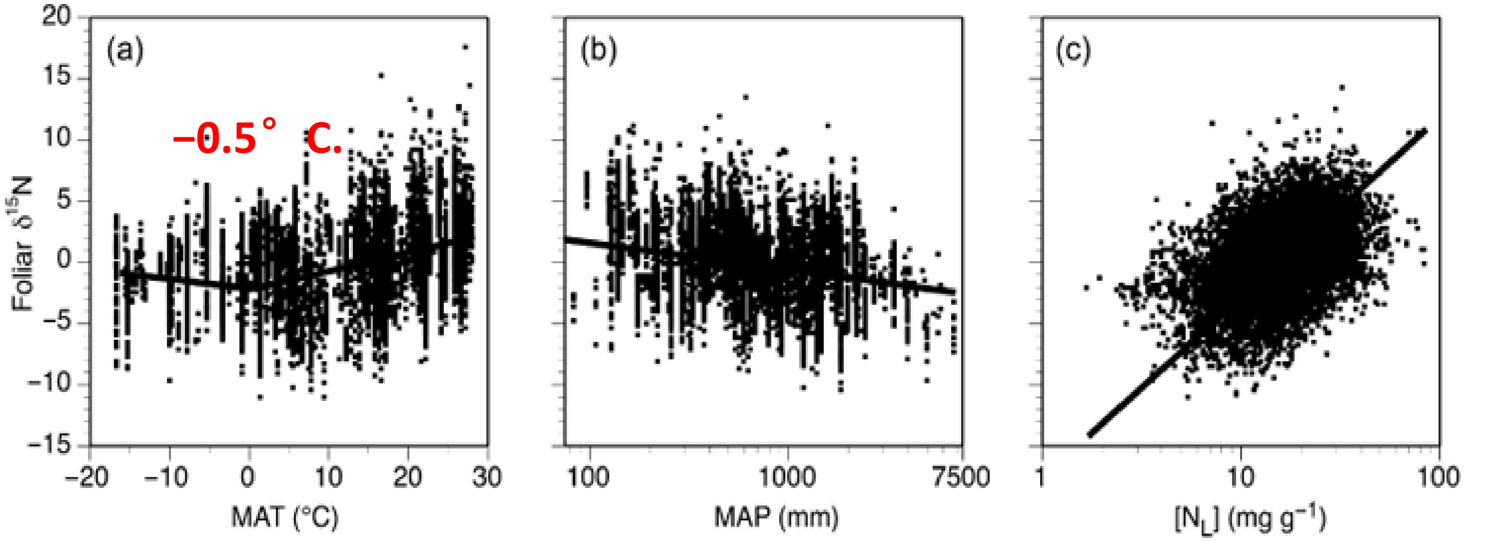
Plant N uptake from soil
$(N_sk_p; {}^{15}N_sk_p\alpha_p)$

Plant N return to soil
$(N_pk_s; {}^{15}N_pk_s)$

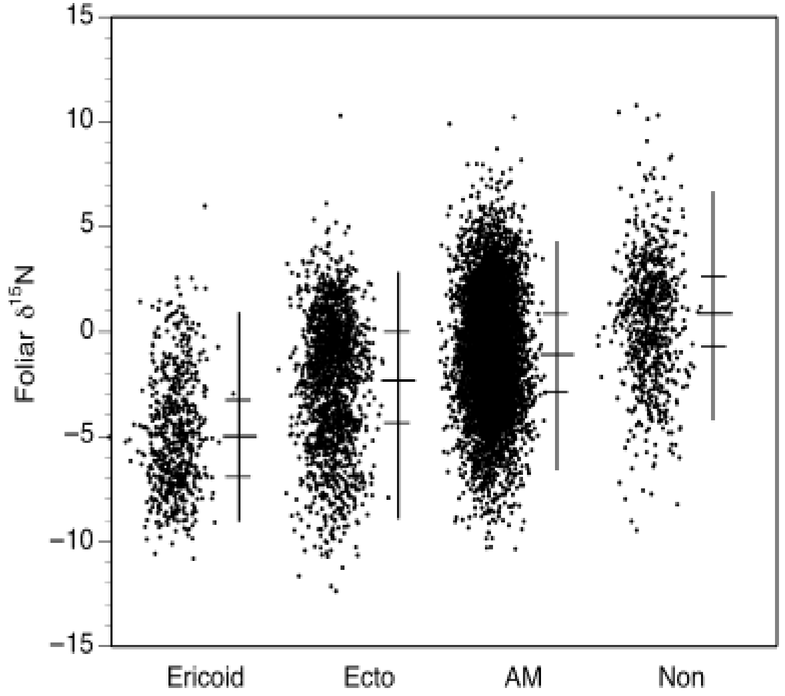
N Losses to environment
$(N_sk_{ex}; {}^{15}N_sk_{ex}\alpha_{ex})$

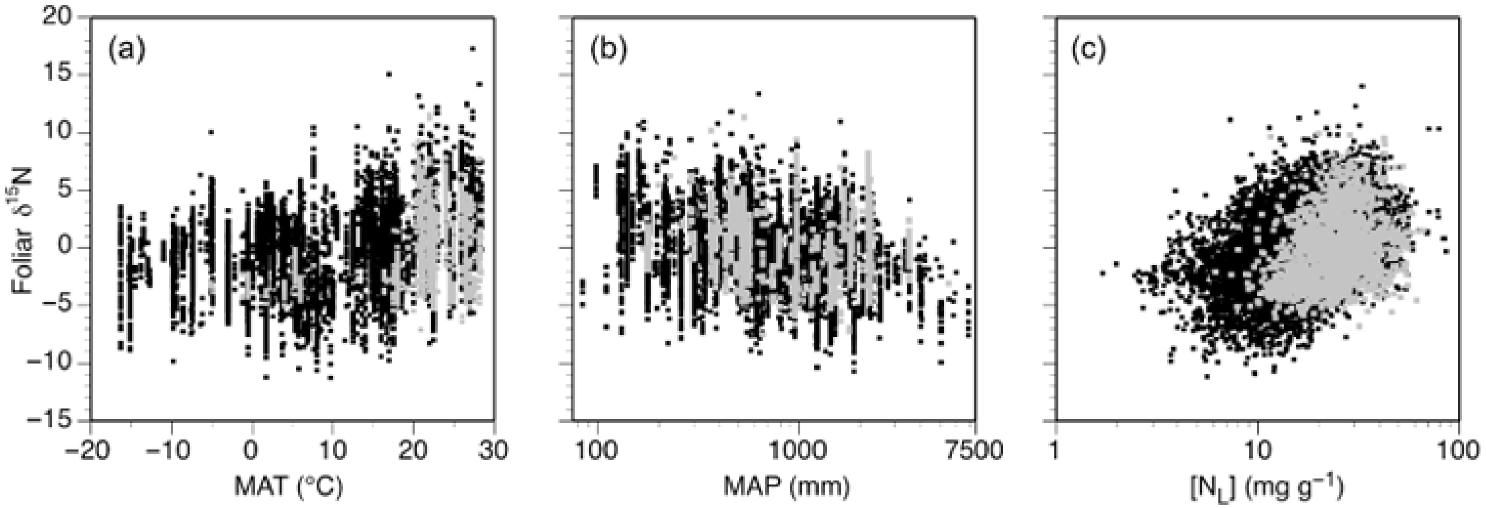
Amundson et al. 2003

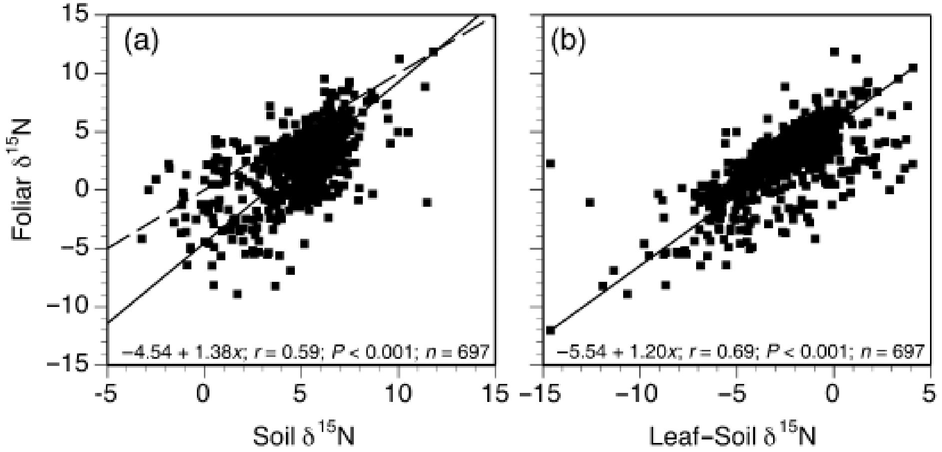
Global soil and plant $\delta^{15}N$ patterns



(non-N_2-fixing plants)



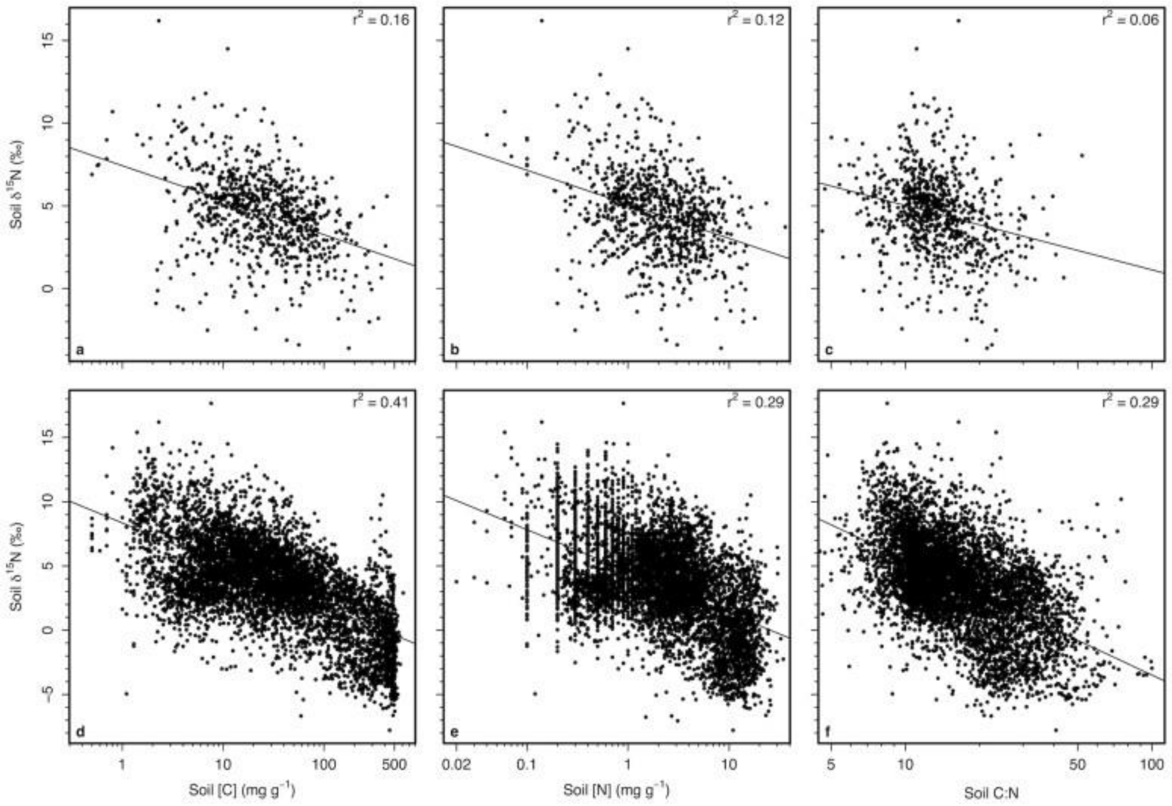


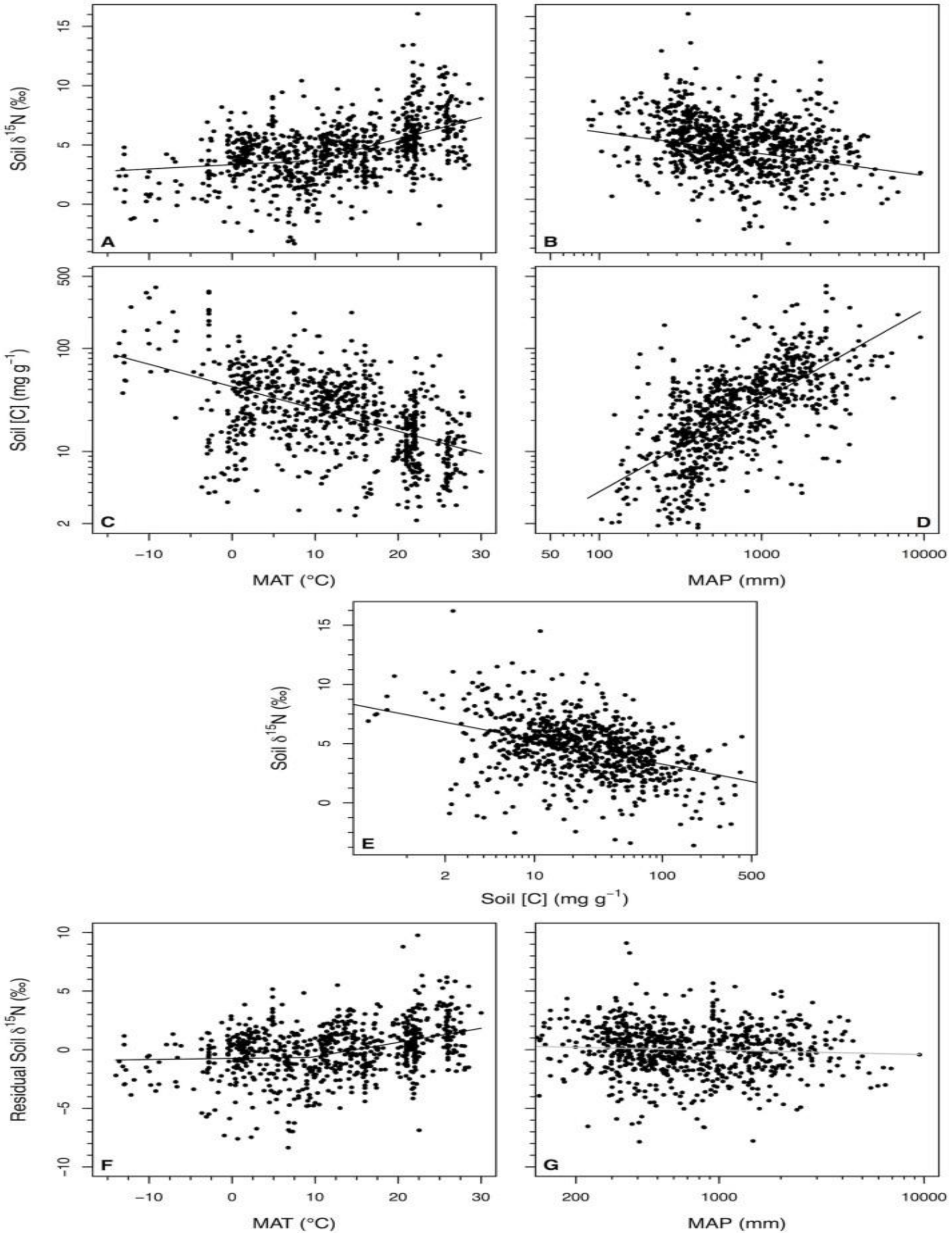


(potentially N_2-fixing plants)

Craine et al. 2009

Global soil and plant δ^{15}N patterns





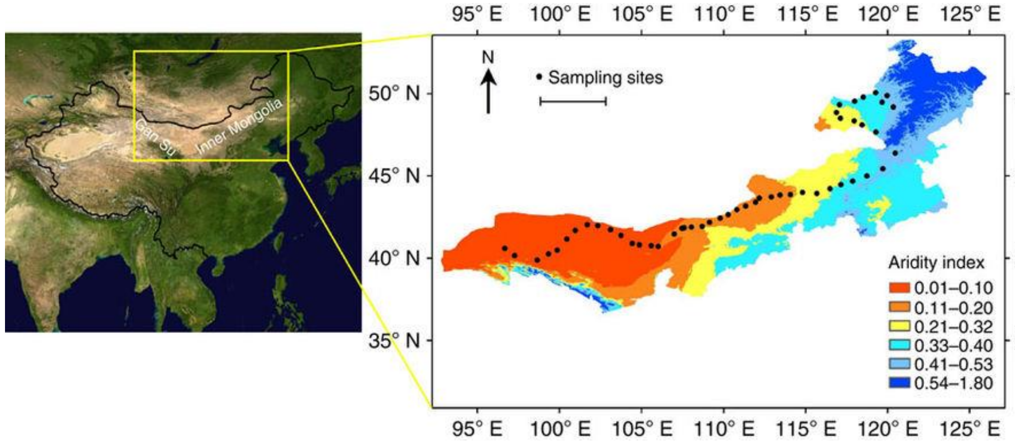
Strong global relationships among soil N isotopes, mean annual temperature (MAT), mean annual precipitation (MAP), and the concentrations of organic carbon and clay in soil.

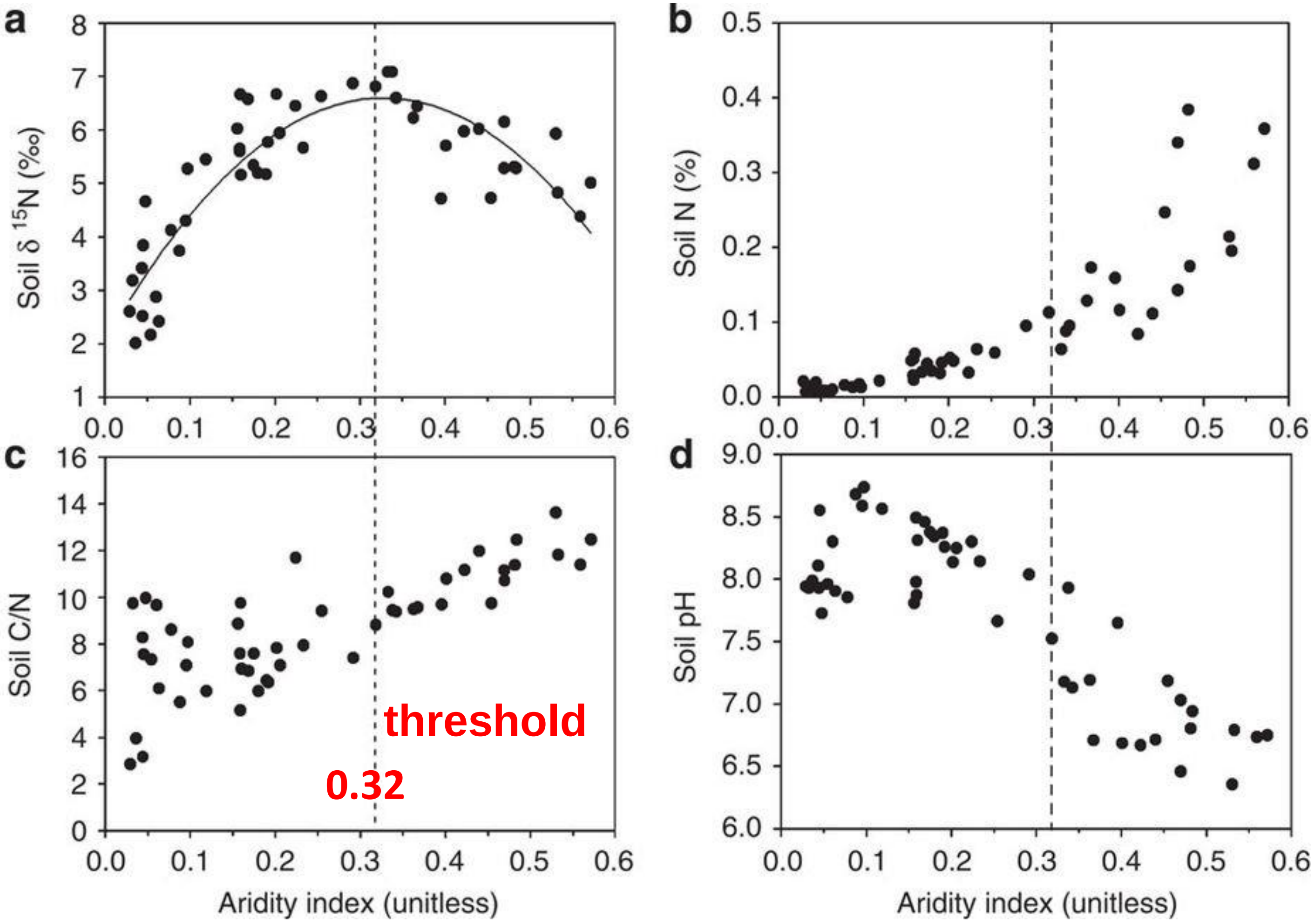
In both hot ecosystems and dry ecosystems, soil organic matter was more enriched in ^{15}N than in corresponding cold ecosystems or wet ecosystems.

Below a MAT of 9.8° C, soil δ^{15}N was invariant with MAT.

Craine et al. 2015

Soil δ^{15}N varies with aridity a 3200 km transect in grasslands of northern China





threshold

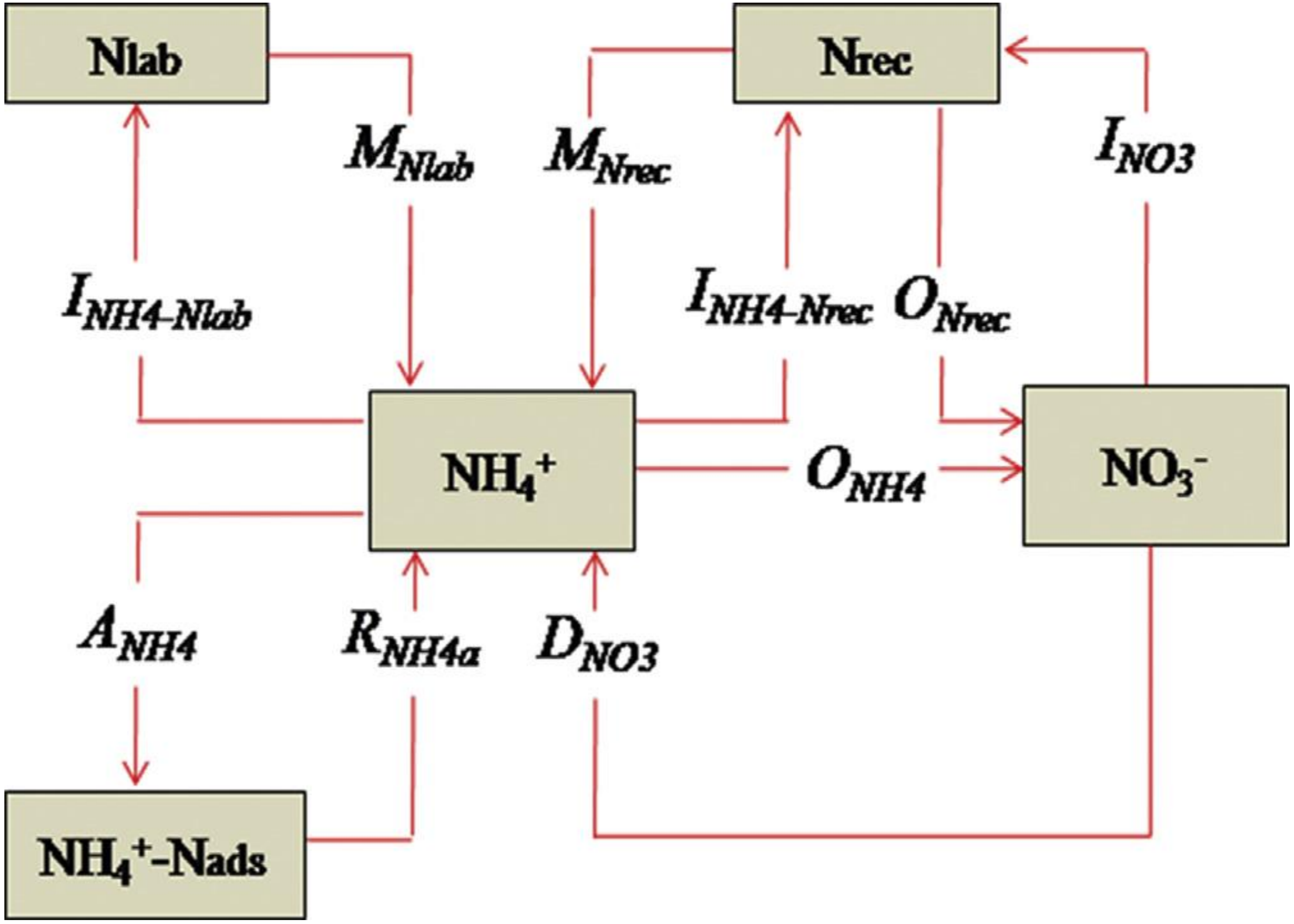
0.32

Wang et al. 2014. *Nature Communications*

土壤氮循环的δ^{15}N模型模拟

- Kirkham & Bartholomew. 1954
- Focht. 1973
- Shearer et al. 1974
- Myrold & Tiedje. 1986
- Mary et al. 1998
- Li et al. 2000
- **Müller et al. 2004, 2007, 2014**
- Currie. 2008
- Dijkstra 2009
- Denk et al. 2017

^{15}N示踪模型



Müller et al, (2007) *SBB*

模型特点:

- N库拆分: 活/惰性N库
- N库动态: 周转时间
- 过程拆分: 自/异养硝化
- 量化参数: 多且可靠

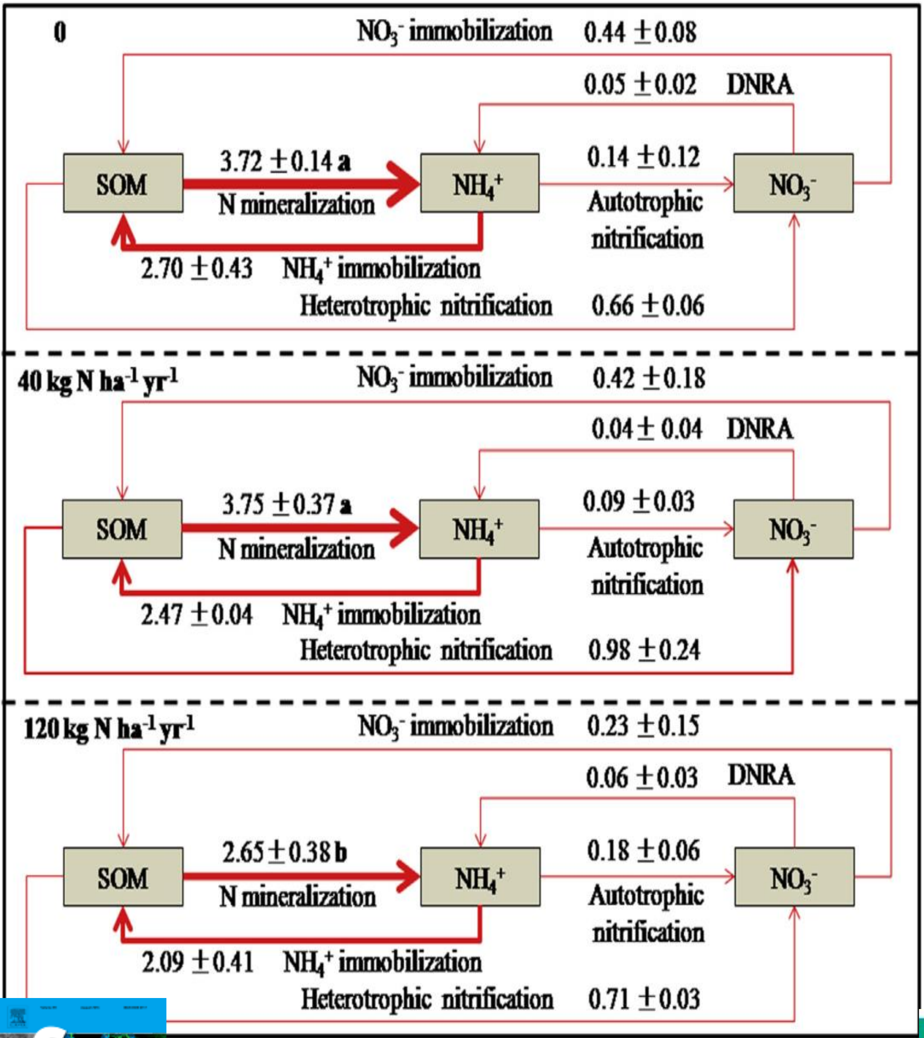
应用优势:

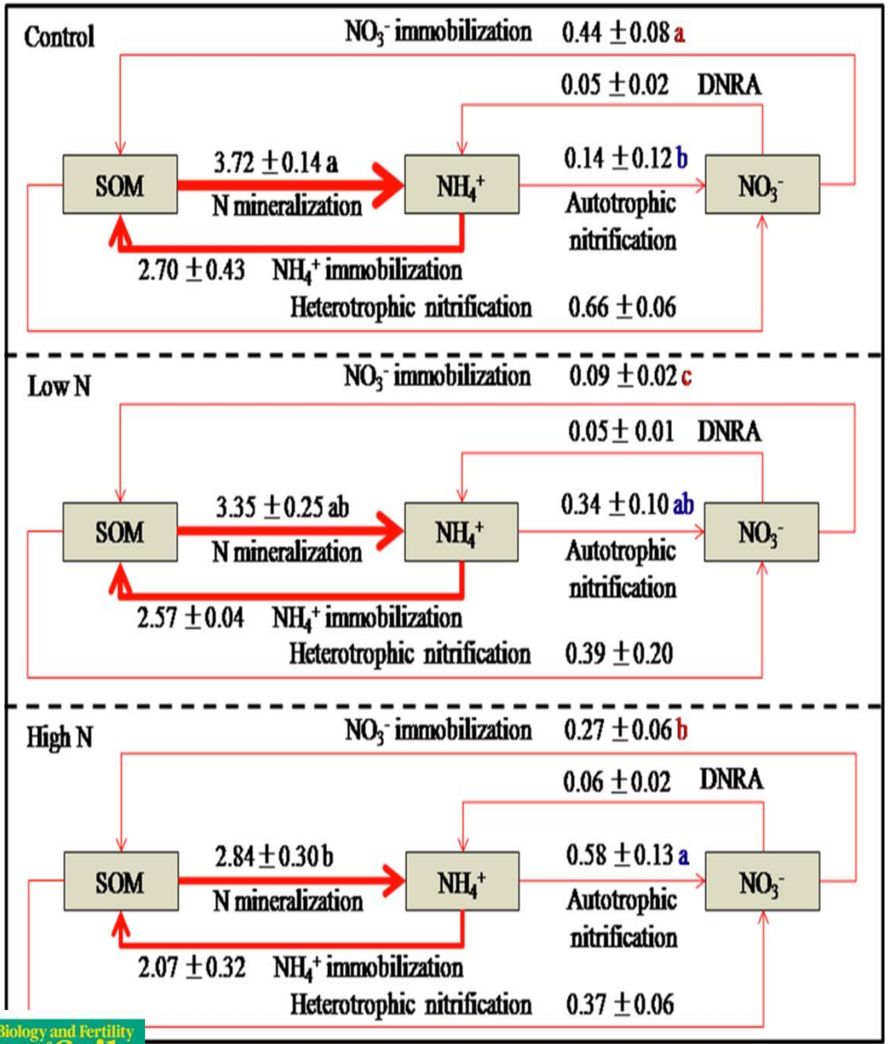
- 清晰地揭示响应机制
- 长期响应趋势的评估

亚热带湿地松林土壤N循环对N添加的响应:

NH_4^+ 添加

NO_3^- 添加





	高NH_4^+添加	高NO_3^-添加
M	↓ 29%	↓ 24%
I(NH_4^+)	↓ 23%	↓ 23%
I(NO_3^-)	↓ 48%	↓ 39%
AN	↑ 29%	↑ 314% ***
HN	↑ 8%	↓ 44%
N	↑ 11%	↑ 19%
DNRA	→	→
	低NH_4^+添加	低NO_3^-添加
I(NO_3^-)	↓ 5%	↓ 80%

- **NH_4^+添加并未刺激土壤NO_3^-生产和削弱NO_3^-固持；**
- **NO_3^-添加刺激土壤自养硝化和抑制NO_3^-固持，加剧N损失风险。**

Gao et al. 2016 SBB.

Gao et al. 2016 BFS.

Mechanisms for the retention of inorganic N in acidic forest soils of southern China

- **南方酸性森林土壤总N矿化速率、N周转速率和无机氮保持能力高于高纬度北方森林土壤；**
- **因为pH低，南方土壤的自养硝化和氨挥发显著低于北方土壤；**
- **南方土壤相对较高的将NO^{3-}固持（ immobilization ）为有机氮，从而一定程度上避免了淋溶、径流和反硝化的N损失；**
- **这些过程决定了南方森林土壤N富集（ enrichment ）或留存（ retention ）的机制。**

SCIENTIFIC REPORTS
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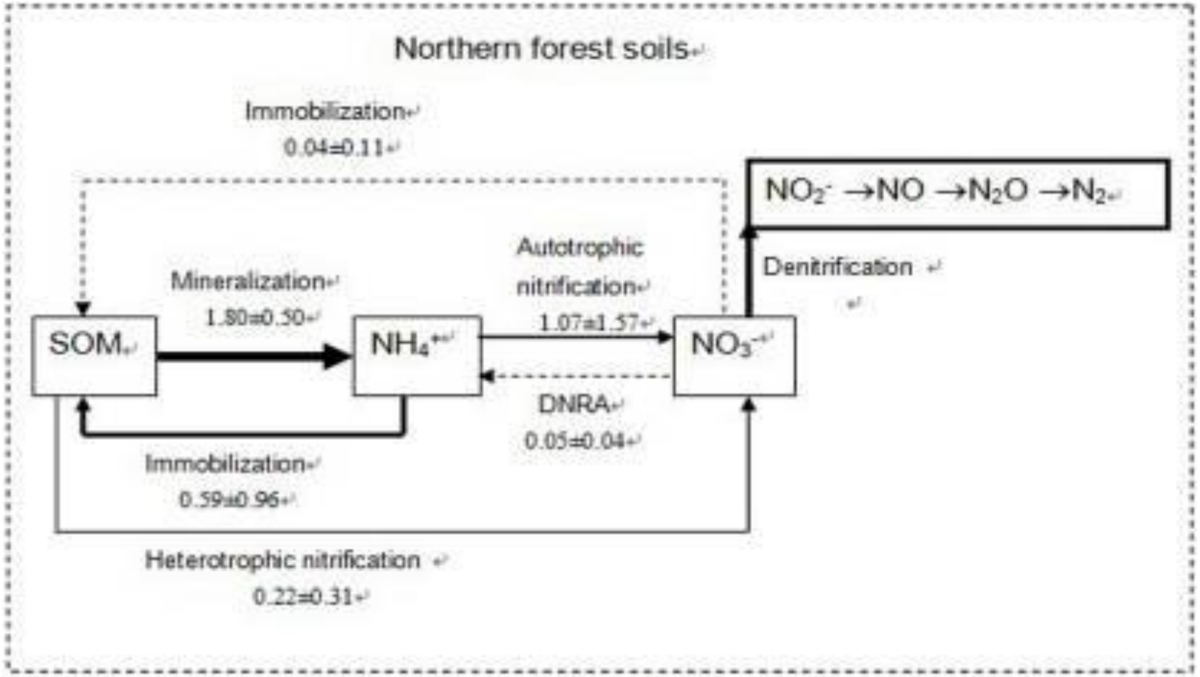
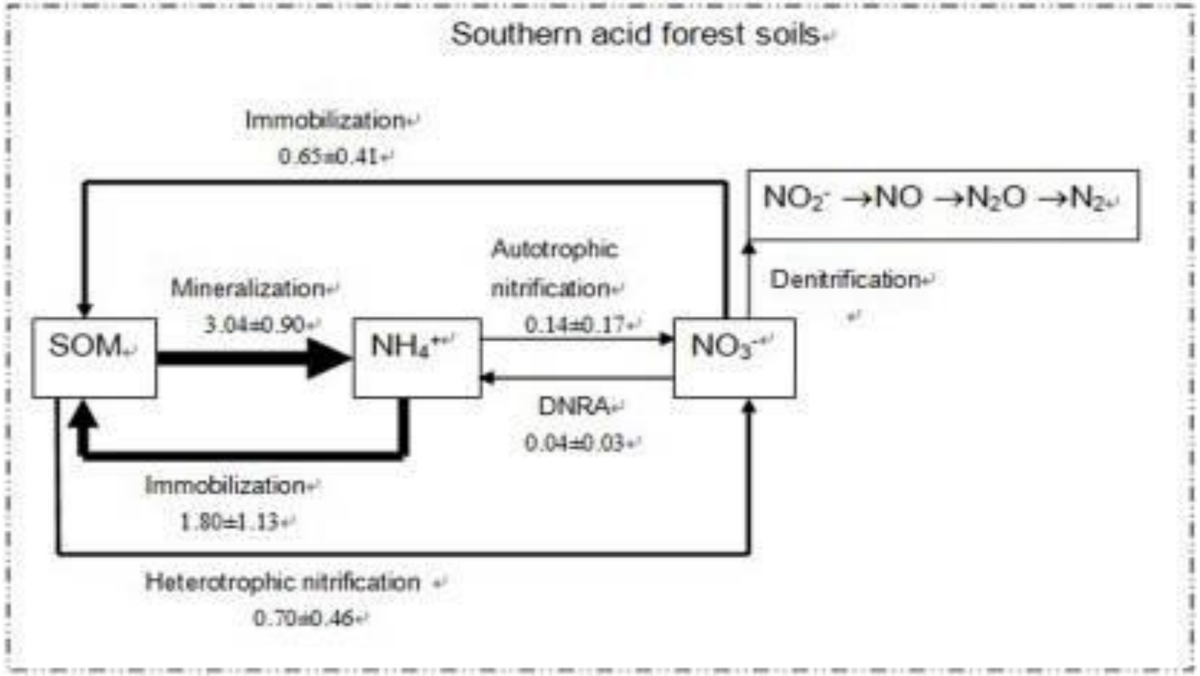
Zhang et al. 2013

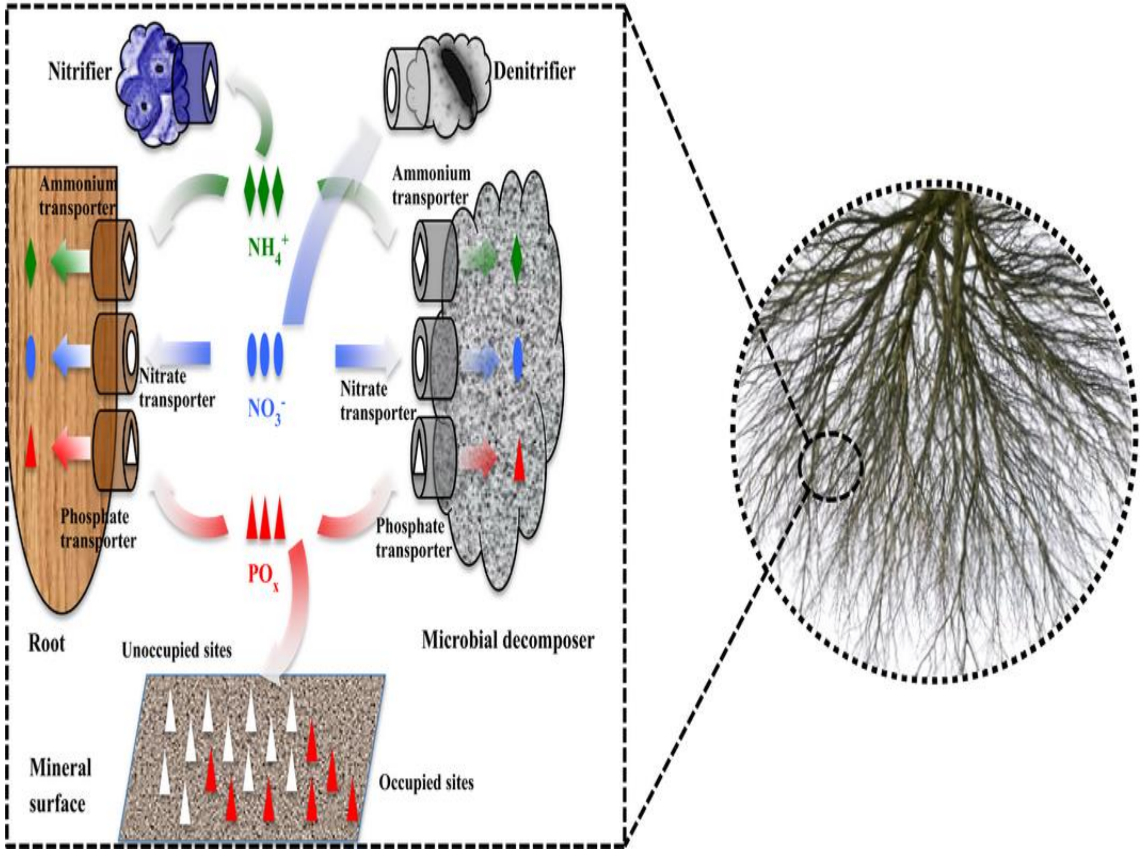




提纲

- **土壤氮过程 (why is it important?)**
- **氮同位素示踪 (what are known?)**
- **展望 (what are to be addressed?)**

- **开放系统/封闭系统**
- **短期响应/长期响应**
- **直接影响/间接影响**
- **Plant-soil feedbacks/plant-microbial feedbacks**
    - **plant N acquisition, transformation, translocation , retranslocation**
    - **菌根**
    - **PE**
- **C-N-（P）interaction**
    - **速率、周转与稳定性**
- **不同微生物功能群的作用**
- **尺度效应**
- **新机制：anammox, codenitrification, DNRA, hetero-nitrif., etc.**
- **新技术：SIP、SP，高通量, proteomics, bioassay**



Zhu et al. 2017

谢谢！欢迎批评指正！