Fire effects on nitrogen dynamics

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Glacier NP
Photo: K. Stephan
Why?

1. N is critical nutrient in forests and streams
   (Vitousek and Howarth 1991, Grimm and Fisher 1986)

2. Fire has profound influence on N dynamics
   Wildfire ↔ Prescribed burns

Why is the study of fire effects on N dynamics important?

2. Fire effects:
   Apparent paradox: net N loss versus increase in ‘available’ N

How do wildfires and prescribed burns compare in their effects on N cycling?
Examples from Stephan et al.

Wildfires: August 2003
(except Danskin Cr. 2002)

Spring Rx: April/May 2004

Elevation range: 1100- 2200 m

Overstory: Pseudotsuga menziesii
Pinus ponderosa

Watershed size: 78 ha (min: 8, max: 512)

Streams: intermittent- small (1st order) perennial

Some of the examples shown are from my own research (together with A. Koyama and K. Kavanagh).
Outline

• Nitrogen cycle
  - Microbes as drivers of the N cycle

• Immediate fire effects: effects of combustion on N in
  - Vegetation
  - Forest floor
  - Mineral soil

• Short term post-fire effects on N concentrations in
  - Soil
  - Vegetation
  - Streams

• Long term post-fire effects on ecosystem N cycling
Nitrogen is the only soil nutrient not generated by rock weathering. Therefore its main source is recycling from decomposing organic matter. Microbes play a key role in the decomposition of organic matter and therefore in N cycling.

Nitrogen cycling within streams is as complex as on the land, but this is often ignored by terrestrial ecologists interested in the leaching of soil ammonium and nitrate.

Generally, very little nitrogen is leached from the land. This changes with disturbance.
Microbes as generators and sinks of inorganic N

Ammonifiers = heterotrophs

**Microbial release of N**

- C source of low quality (lignins, polyphenol-protein)
  - no net microbial population growth
  - low N demand
  - release of inorganic N from substrate being decomposed

  **Accumulation of NH₄⁺ in soil**

**Microbial immobilization of N**

- C source of high quality (glucose, starch, cellulose)
  - fuels microbial growth
  - high N demand
  - N retention & uptake of inorganic N from soil

  **Very low NH₄⁺/NO₃⁻ concentration in soil**

N release or immobilization by heterotrophic microbes (e.g. ammonifiers):
- depends on C:N ratio of substrate and microbial demand of N
- Microbial demand depends on quality of C source, i.e. how much energy microbes gain by breaking C-C bonds
  - spatially and temporally variable in the soil

Nitrification can be autotrophic or heterotrophic.

The conversion of ammonium into nitrate is autotrophic, i.e. C is not used as energy source, but instead ammonium is. Therefore, autotrophic nitrifiers release nitrate whenever substrate (ammonium) is present. Some of the ammonium will be retained for nitrifier population growth.

Heterotrophic nitrification is also possible, that is the direct conversion of organic N to nitrate. This process is not depicted in the diagrams.
Nitrogen pools versus fluxes

Flux:
• N production
• N uptake
rate: mg N / kg dry soil * d

Pool:
N produced – N taken up
soil N concentration: mg N / kg dry soil

▪ Pools are **big** if inorganic N production >> N uptake

▪ Pools are **small** if little N production
  **OR**
  high N production & high N uptake
  (Stark and Hart 1997)

The distinction between N pools and fluxes is important.
Pool sizes are easy to measure but their interpretation is limited because both production and uptake rates determine pool size.
Rates are difficult to measure.
Immediate fire effects
During combustion organic matter is oxidized. Under complete oxidation, organic matter is converted mainly to carbon dioxide, water, and di-nitrogen gas.

N and C contents in organic matter are within fairly constrained range, hence, N and C losses are proportional to fuel consumption.
Immediate fire effects

N loss from forest floor and organic matter of mineral soil

- **Oxidation** of organic compounds during combustion
- **Pyrolysis**: chemical decomposition of organic materials by heating in the absence of oxygen \([R-NH_2 \rightarrow NH_3 \uparrow \text{(ammonia)}]\)
- **Vaporization** (volatilization) during heating: change of phase w/out chemical change \([\text{NO}_3^- \uparrow (80 \, ^\circ C), AA \uparrow (200 \, ^\circ C), NH_3 \uparrow (-33 \, ^\circ C)]\)

Down Wood (1-1000 h fuels):
\(~6300 \, \text{kg/ha} \Rightarrow 6.3 \, \text{kg N/ha}\)

Litter:
\(~500 \, \text{kg/ha} \Rightarrow 5 \, \text{kg N/ha}\)

Duff:
\(~3400 \, \text{kg/ha} \Rightarrow 51 \, \text{kg N/ha}\)

Mineral soil (0-10 cm):
\(~700,000 \, \text{kg/ha} \Rightarrow 1400 \, \text{kg N/ha}\)

Koyama & Stephan unpublished data

There are other forms of N loss even without direct combustion of organic material.

In example: N content in fuel and mineral soil. N loss from forest floor is proportional to combustion.

There is a large N store in mineral soil. N loss from organic matter in mineral soil is rare but has been found (1/3 lost: Grier 1975).
Ammonium concentration in the soil increases immediately after the fire due to physicochemical process.
Immediate fire effects

Soil microbes

- $T > 127 \, ^\circ C$ sterilize the soil
- Temperatures $> 50-70 \, ^\circ C$ kill non-spore forming fungi, protozoa and some bacteria

\[ Nitrifiers: \text{ killed at 53-58 } ^\circ C \text{ (thin walled cells)} \]
\[ Ammonifiers: \text{ some have thick walls or spores, survive at 100 } ^\circ C \]

**Example**

Soil temperatures during fire
- Scrub: on surface $200 \, ^\circ C$; 5 cm: $100 \, ^\circ C$; 10 cm: $60 \, ^\circ C$
- Longleaf pine: 3-6 mm depth: $52 \, ^\circ C$; 2.5 cm: $40 \, ^\circ C$ (Raison 1979)

**Immediate soil ammonium pool increase is not microbially mediated but due to physicochemical breakdown of organic N**

Because microbes are killed or substantially reduced in numbers the immediate increase in NH$_4^+$ is a purely physicochemical process (i.e. lack of microbial N breakdown (mineralization) to contribute to NH$_4^+$ pool but also lack of microbial N uptake (immobilization) to diminish abundant NH$_4^+$ pool).
Short-Term Post-Fire Effects
Short term post-fire effects on soil

Increased ammonium and nitrate concentrations in the soil
1 month - ~5 years

1. Reduced plant N uptake
2. Increase in microbial activity (due to change in moisture, temperature, pH)
3. Reduced microbial N uptake (due to C limitation)

Three processes could explain short term post-fire increase soil N concentrations, proportional contribution of each process is not known yet.
It is quite plausible that soil N pools increase when plants don’t take up any N because they have been killed by the fire.
Short term post-fire increase in soil N
2. Increase in microbial activity: soil temperature and soil moisture

**Soil temperature increases**
- Higher absorption of solar energy by dark surface

**Soil moisture increases**
- Reduced interception and transpiration losses from removed vegetation

**Soil temperature decreases**
- Higher heat loss due to lack of insulation

**Soil moisture decreases**
- Higher soil temperature reduces water viscosity and allows percolation through the soil profile
- Higher evaporation from warm (unshaded, dark) soil surface
- Hydrophobicity reduced infiltration

Microbial activity depends on external factors, such as soil moisture and temperature.
Increase in amplitude of soil temperature and soil moisture variability:
Temperature: higher during the day, colder at night
Moisture: higher in wet season (spring), lower in dry season (summer)
Increased soil temperature & moisture
→ Increases microbial activity and activity of extracellular enzymes

Increased rates of decomposition of residual organic matter (ammonification)
Increased nitrification (NO$_3^-$ production) due to ample (NH$_4^+$) substrate supply

Increased microbial activity and activity of extracellular enzymes due to:
- higher diffusion rates,
- lower cell plasma viscosity,
- presence of water as diffusion medium and reactant as a consequence of higher soil temperature and moisture.

Short term increase in post-fire soil N due to microbial activity only possible if microbial numbers recover post-fire:
Recovery of ammonifiers is quick (1 wk), often surpassing pre-burn numbers (for limited time)
Recovery of nitrifiers is more gradual (weeks-months), depending on heat intensity, soil moisture and inoculation opportunity

Change in microbial community composition?
Short term increase in post-fire soil N

2. Increases in microbial activity: pH

**pH increases after fire**
- due to consumption of \( H^+ \) and
- concurrent release of base cations (\( K^+, Mg^+, \) etc.)
  during combustion of organic compounds

**Example:**
\( pH \) in central Idaho Rocky Mountain soils:
Unburned soils: \( \sim 6 \leftrightarrow \) Burned soils: \( \sim 6.7 \)
(Koyama & Stephan unpublished data)

- Higher \( pH \) raises solubility of organic N
- Nitrification occurs at \( pH > 5 \)

Low \( pH \) response to fire: strongly buffered soils at \( pH > 6.5 \) or \(< 4.5 \)
Strongest \( pH \) response to fire: soils with \( pH \) between 4.5 and 6.5
Short term increase in post-fire soil N
Role of ash as organic N source

- Contains between 0.15-1.88 % N depending on
  - fuel type (wood vs. foliage)
  - ash type (grey: more mineral, black: more OM remains due to inhibited combustion)
    [e.g. grey wood ash : 0.15 % N, 3.5 % P, 1.2 % K, 24 % Ca, 2.5 % Mg]
    (Raison et al. 1985)

- N form in ash: 0.1 % NO₃⁻, 2.2 % NH₄⁺, 97.7 % organic N (Grogan et al. 2000)

Examples: N input by ash cited in Grogan et al. 2000
- 89 kg N/ha California bishop pine forest
- 66 kg N/ha South African coastal shrub fynbos
- 21 kg N/ha California chaparral
- 23 kg N/ha Washington conifer stand

Ash does not only alter microbial activity via increased pH but it also contains significant amounts of N itself.

Which aspect of ash is most important?: influence on pH (which affects nitrifier activity and solubility of soil organic N) or direct source of decomposable organic N?

Presence of ash had substantial influence on aboveground biomass of regenerating vegetation: aboveground biomass after the first growing season post-fire in a bishop pine forest in CA was 3 time higher in plots with ash than in plots with ash removed.
Ash contributes to landscape scale heterogeneity

Ash redistribution post-fire by wind and water
⇒ major factor in heterogeneity of soil N availability
and hence to vegetation patchiness in fire-prone ecosystems

Grogan et al. 2000

Danskin Cr., Boise NF
Photos A. Koyama

Surface ash is rapidly displaced by wind and rain and tends to accumulate in local hollows, on leeward side of stumps/fallen trees, and downslope in ravines.

The photo shows how ash is blown around about a month after the fire (and before the onset of rain).
Microbial activity also depends on the availability of quality decomposable substrate.

Low substrate quality results in low N demand for microbial population growth and thus a net release of NH4+ from decomposing substrate. This will be measurable as increased N pool sizes.
Example: Short term effect on \( \text{NH}_4^+ \) concentration in soil

**Wildfires**

**Spring Burns**

Stephan et al. unpubl. data

Arrow: denotes time of fire
Asterisk (*) denoted statistically significant difference between burned and unburned fire sites

Ammonium concentrations:
- **Wildfire**: increased for 1st post-fire season
- **Prescribed burn (spring)**: increased for 1 month post-fire
Example: Short term effect on NO$_3^-$ concentration in soil

Wildfires

Spring Burns

Stephan et al. unpubl. data

Arrow: denotes time of fire
Asterisk (*) denoted statistically significant difference between burned and unburned fire sites

Nitrate concentrations:
• Wildfire: increased at 2-3(?) years
• Prescribed burn: increased 1 season (low intensity spring burns), 2(?) y (when including one intense spring burn)
  Literature: Choromanska & DeLuca 2001: increase 1 y with spring prescribed burn in MT (1 site only, i.e. pseudoreplication)
Example: Short term post-fire effects on N in vegetation

Increase of N concentrations in foliage of surviving or resprouting plants

Wildfire: 2 (+?) y ↔ Rx: 1 y

Graph: N concentrations in understory foliage 1 y post fire (wildfire only)
Species on x-axis: Carex geyeri (elk sedge), Physocarpus malvaceus (ninebark), Symphoricarpus albus (snowberry), Spiraea betulifolia (spiraea)
Generally, streamwater inorganic N concentrations increase short term post-fire -mainly assumed to be a result of leaching from hillside -studies of fire effects on aquatic N cycling lacking
### Fire effects on streamwater inorganic N concentrations

<table>
<thead>
<tr>
<th>Effect</th>
<th>Immediate</th>
<th>Short term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium NH$_4^+$</td>
<td>60-fold increase (dissolved NH$_3$ of smoke)</td>
<td>3-20 fold increase 1$^{st}$ spring run off</td>
</tr>
<tr>
<td>Nitrate NO$_3^-$</td>
<td>no change</td>
<td>increase 1- 3 spring run offs</td>
</tr>
</tbody>
</table>

#### Long term

? decrease in N concentrations below pre-burn level due to sequestration into growing forest  
(Hauer and Spencer 1998, Flathead NF & Glacier NP)

Increase in streamwater N concentrations is most noticeable in small streams because of the tight linkage to the uplands in small watersheds.
Short term post-fire streamwater ammonium (NH$_4^+$) concentrations were not altered by fire: ~ 15 microgram N/ l

Strong effect of wildfire on streamwater nitrate concentrations but none with spring prescribed burns.
Dashed line in wildfire graph: spring run-off missed in 2004, peak concentrations therefore unknown.

Maximum allowed nitrate concentration in drinking water is 1000 microgram N/ l.
Example: Short term post-fire effects on N in moss

Graph in slide is for 4 wildfires only
With wildfires moss N concentrations are increased. Rx had no influence on N concentration in moss (no effect on streamwater in the first place).

Moss is not “aquatic” in the strict sense, it grows on rocks that are submerged in the spring.

Moss as bioindicators? Studies in France and Germany that moss are used as monitors for heavy metal mobilization in acidified streams.
Summary short term:
Increased N pools in soil and water
and increased N concentrations in terrestrial vegetation and in-stream moss
-> increased uptake by autotrophs is an important N retention mechanism

Long term post-fire fire effects are little studied.
Long term post-fire effects on ecosystem

Example (Grier 1975)
907 kg N/ ha lost (forest floor + mineral soil) during severe wildfire in WA

Ecosystem N inputs/ outputs

+ Atmospheric N deposition rate of 1.5 kg/ha/y

+ N\textsubscript{2}-fixation
  - N-fixing soil bacteria: <0.1-1.4 kg/ha/y
  - Symbiotic N fixation of legumes: 1 kg/ha/y (low legume density)
    5-10 kg/ha/y (high legume density)
    alder: 50-150 kg/ha/y
    ceanothus: 0-110 kg/ha/y
    lichens: 3.5 kg/ha/y

- N leaching losses 0.6 kg/ha/y (Vanderbilt et al. 2003)

Example (Giessen et al. in prep.)
Douglas-fir forest of western Cascades: 200 y till combusted N is replaced

Eventually the N lost through combustion will be restored, through N fixation and deposition- if fire interval is long enough.

“Fire exclusion has been shown to reduce the number of N-fixers (Newland and DeLuca, 2000) and it is likely that historic timber harvest further reduced total soil N reserves.” from MacKenzie et al. 2006
Long term post-fire effects on ecosystem

Immediate & short term effects

Fires occur at natural fire interval  Fire suppressed

But what happens to the N cycling processes within the soil/plant system during the long term post-fire recovery of forest?
Two scenarios: fires occur at natural fire return interval or fires suppressed
Long term post-fire effects on soil

MacKenzie et al. 2006: Chronosequence in western Montana

**Decrease in N production rate and pool size**

Microbial numbers constant but decrease in microbial activity

**Phenolic compounds**
- secondary metabolites of plants
- byproduct of microbial decomposition of lignin

- Allelopathic interference with microbes
- N uptake by microbes for breakdown of phenols as C source
- phenolic sorption of N

Y- axis: N adsorbed to ion exchange resins placed in the soil; this represents a mix of N production rate and pool size

Decrease in microbial activity has been inferred from slower decomposition of experimentally placed cotton strips (cellulose) and tongue depressors (lignin+cellulose)

Lower microbial activity due to phenols?
It is possible that N availability is modified by soil organic matter quality which is mediated by plant community composition: low soil N availability leads to plants with low quality litter (higher contents of secondary plant metabolites, low N content) which in turn leads to slow decomposition and low soil N

Decrease in N production rate/pool size not linear and differs for ammonium and nitrate. Why?
Ammonium decrease: plant uptake & initially sustained high nitrate production
Nitrate decrease: sigmoidal curve with inflection point at 40-70 y. Role of Charcoal !??
Long term post-fire effects on soil

Charcoal increases soil nitrate concentration

Role of charcoal in soil nitrate concentrations
- Adding charcoal to soil (89 y since last fire) almost doubled nitrate concentration in a 14 d incubation experiment
- Adding a phenol-rich extract of kinnikinnick (Arctostaphylos uva-ursi) resulted in low nitrate concentrations
- Adding extract and charcoal could offset the effect of the extract.
Charcoal loses its absorptive capabilities after ca 100 y (Zackrisson et al., Oikos 1996)
Long term post-fire effects on ecosystem

Immediate & short term effects

Fires occur at natural fire interval

Fire suppressed

N availability mediated by fire

N availability mediated by plant community/succession

MacKenzie et al. (2006):
Steep decline in soil nitrate concentrations coincides with fire return interval of 50 y at the study site.
Disturbance maintains high nitrate availability during the historic fire return interval; potentially mediated by charcoal.
Fire suppression: charcoal loses ‘activity’, processes associated with late successional stage (e.g. accumulation of phenols in soil) determine (slow) N cycling rates and (low) productivity.
Summary

• N dynamics are very complex

• Fire alters many aspects of N dynamics
  - Immediate, short term, long term
  - Local, watershed ecosystem
  - Consequences vs. mechanisms

• Ultimate goal: understand mechanisms at all temporal and spatial scales
  - Predictions of fire effects on ecosystem N cycling
  - Informed management decisions

Fire alters many aspects of N dynamics: not all equally well studied
- Short term & local post-fire effects fairly well studied for terrestrial part of the ecosystem:
  - Net ecosystem N loss but immediate / short term increase in inorganic (plant-available) N in soil
  - Post-fire soil N is retained in regenerating vegetation and leaches to streams
  - Despite in-stream retention of N still export from watershed
- Mechanisms that lead to observed effects are less well studied
  - e.g. microbial processes no well studied, because methods are time intensive and involved, large spatial heterogeneity in soil in general); instead, net effects are studied (e.g. soil and streamwater N concentrations) that have limited
- Long term effects little studied so far
- Lack of integrating land and water

Management decisions: evaluate ecological trade-offs between:
suppression, rehabilitation, wildland fire use, prescribed burning
“The focus of the Healthy Forest Initiative in the US has been on fuel loading and not on N cycling and microbial activity, both of which are equally important components of secondary succession and healthy forests.”

MacKenzie et al. 2006
References


