Fertilizer Nitrogen & Nitrate Leaching

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Nitrogen Fertilization for Crop Production

- **Nitrogen is the most limiting nutrient for primary production in terrestrial ecosystems.**
- **In crop production, N is added to feed the whole plant, not just the harvestable parts.**
  - In permanent crops (trees & vines, asparagus, etc.), the perennial parts use and store significant amounts of nitrogen (roots, corms, trunk, branches, vines)
- **Supplying crops with nitrogen from external sources (i.e. nitrogen fertilization) is essential for sustainable and profitable crop production.**
- **Nitrogen fertilizer is an expensive input, making luxury applications very unattractive to growers.**

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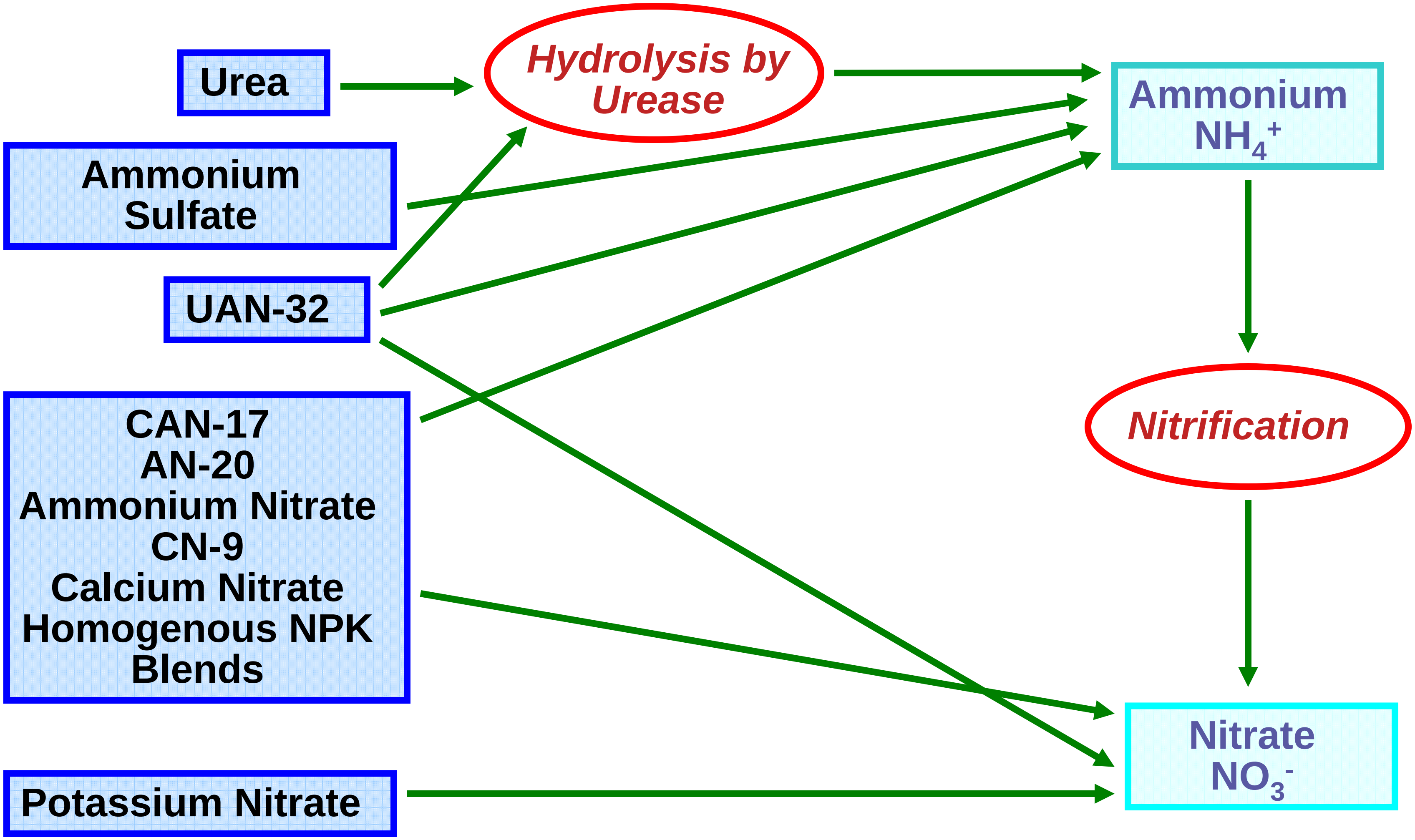
Pathways of Fertilizer Nitrogen Following Application: Synthetic Nitrogen Fertilizers



Hydrolysis of Urea by Urease

$$H_2N-\underset{\underset{O}{\|}}{C}-NH_2 \quad + \quad 3\,H_2O \xrightarrow{\text{Urease}} 2\,NH_4^{+} \quad + \quad OH^{-} \quad + \quad HCO_3^{-}$$

- **Urease is an enzyme that is always present in soils:**
  - Plant residue
  - Soil microbes
  - Clay particles
- **Urease requires very little moisture to hydrolyze urea.**

Nitrification: Oxidation of Ammonium to Nitrate

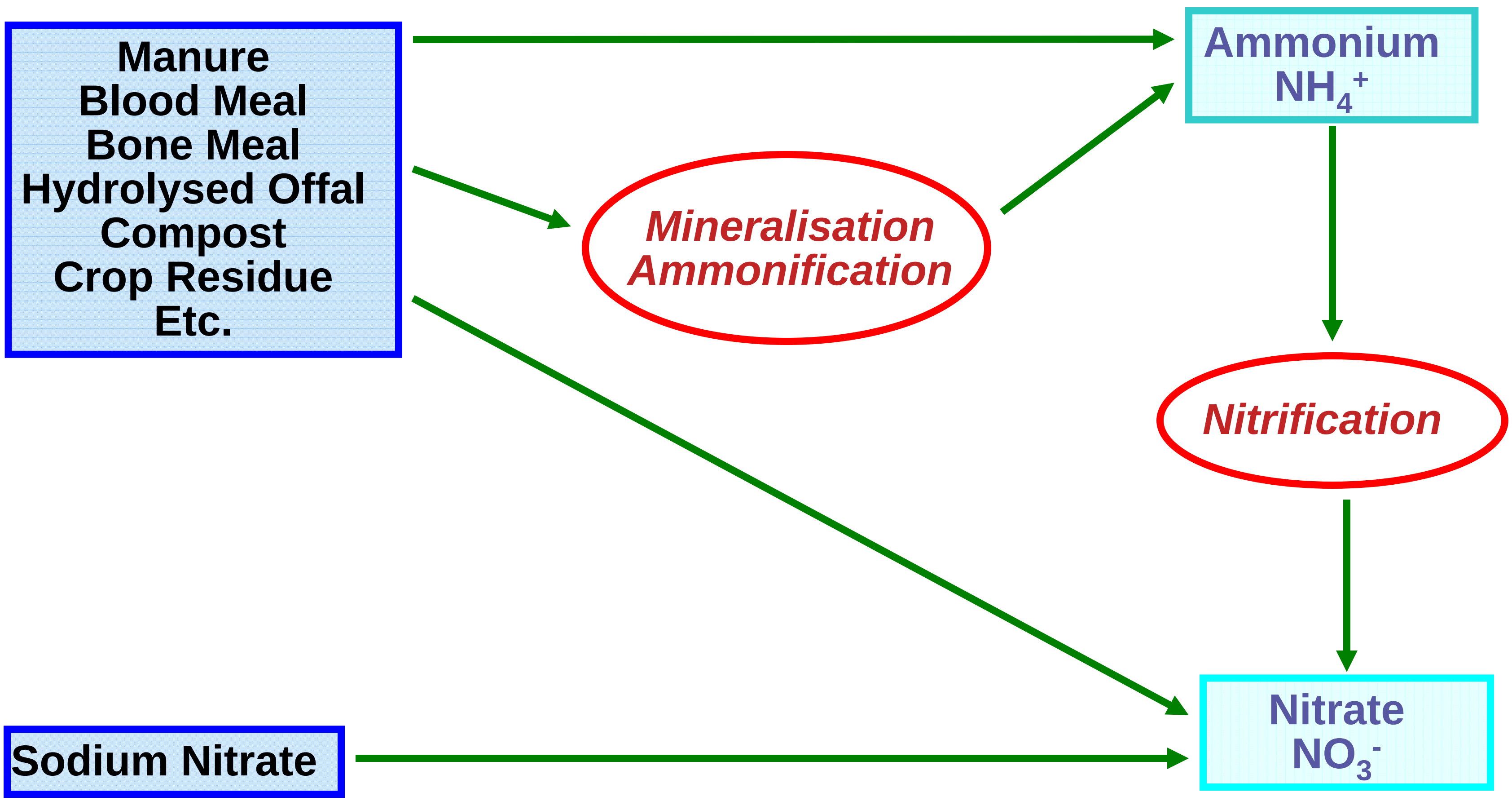
Nitrosomonas (first arrow), *Nitrobacter* (second arrow)

$$NH_4^{+} \Rightarrow NO_2^{-} \Rightarrow NO_3^{-}$$

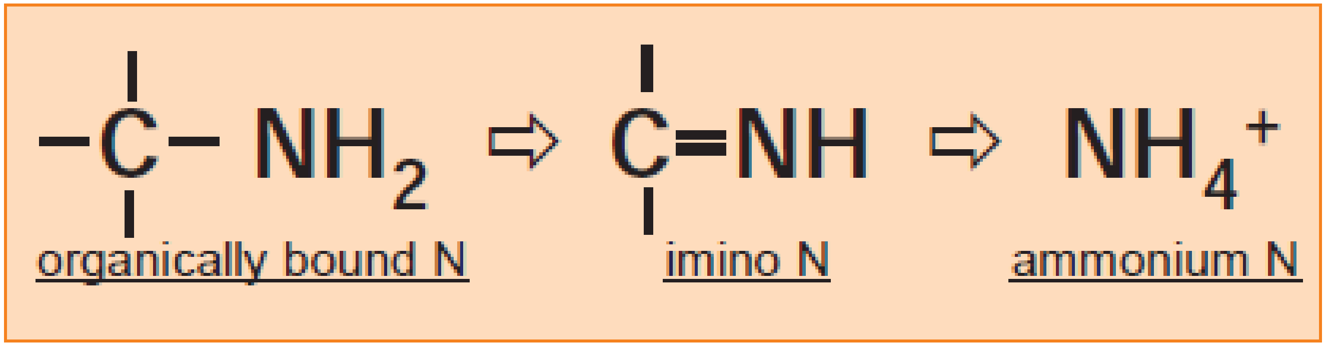
ammonium, nitrite, nitrate

- **Mediated by bacteria to extract the chemical energy from ammonium**
  - Nitrifiers are always present in the soil
  - Nitrification can be suppressed for some time by chemical nitrification inhibitors such as DCD and N-serve
- **Requires aerobic soil conditions (presence of oxygen)**
- **Dependent on moisture and temperature (0 °C < T < 40 °C)**
- **Nitrification acidifies the soil:**
  - for each nitrified ammonium ion, two hydrogen ions are released

Pathways of Fertilizer Nitrogen Following Application: Organic Nitrogen Fertilizers

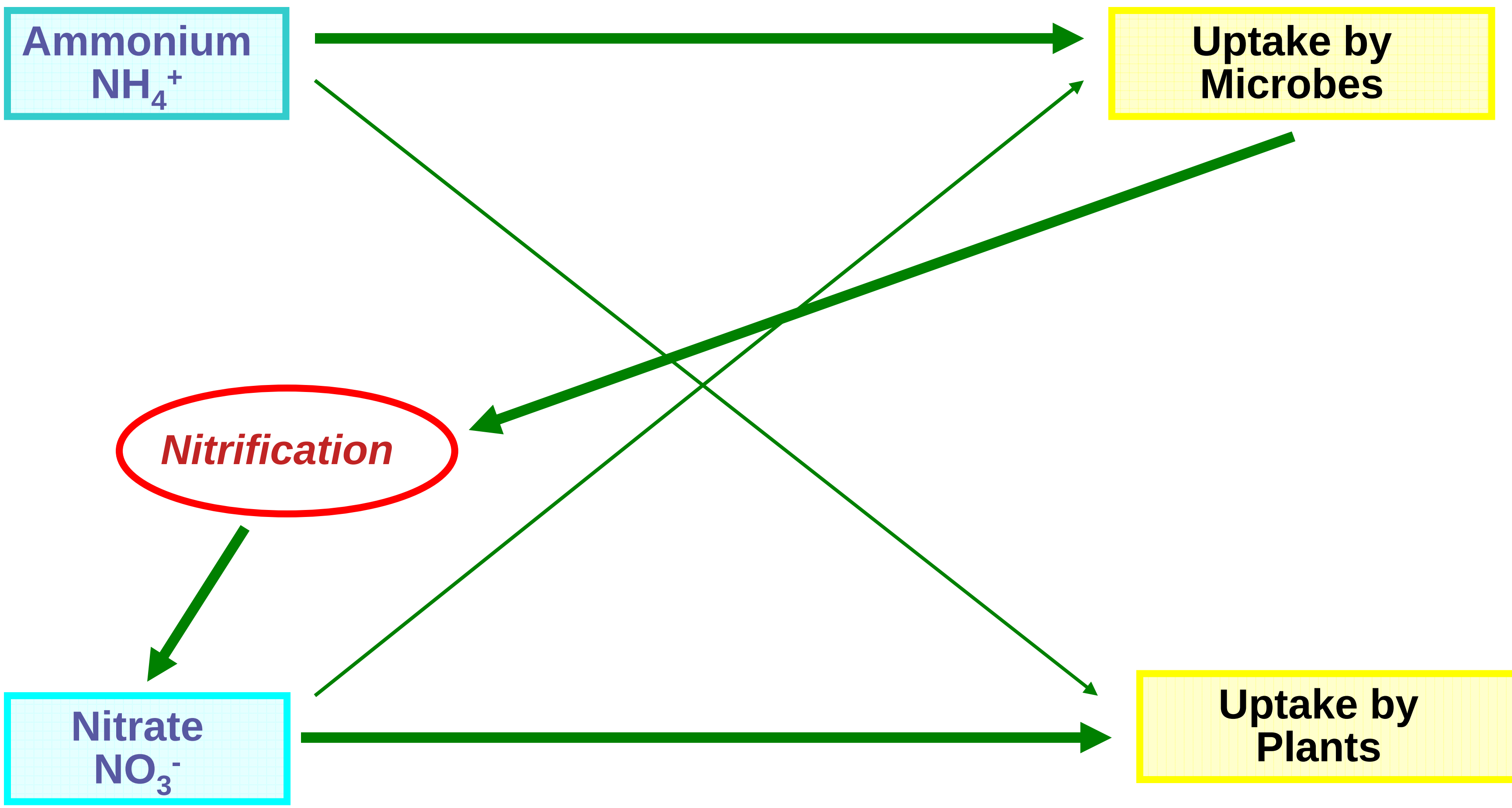


Mineralisation/Ammonification:



- **Soil bacteria (mineralisers) extract the ammonium as a nitrogen source**
- **Soil bacteria also extract the chemical energy of the organic material to power their growth**
- **Mineralisation occurs under aerobic or anaerobic soil conditions**
- **Dependent on moisture and temperature**

Pathways of Fertilizer Nitrogen Following Application: Typical and desirable uptake and removal



Nitrogen Losses: Undesirable pathways

- **Volatilization of ammonia to the atmosphere**
- **Denitrification and loss of N_2O and N_2 to the atmosphere**
- **Incomplete nitrification and loss of NO_x to the atmosphere**
- **Leaching of nitrate beyond the root zone**
- **Leaching of urea beyond the root zone**

Nitrogen Losses: Volatilization

- **Surface-applied urea, urea-containing fertilizers, ammonium fertilizers, and manures are all susceptible to ammonia volatilization.**
- **Topsoil is always rich in urease and/or urease-producing microbes**
  - Urea hydrolysis by urease creates high pH at the hydrolysis site
  - At pH above 7, most ammonium becomes ammonia gas
- **Under unfavorable conditions (high temperature and humidity, wind, high soil pH), ammonia volatilization from surface applied urea can approach 70% of the applied nitrogen, even from soil surfaces with a pH well below 7.0.**

Nitrogen Losses: Denitrification

$$NO_3^- \Rightarrow N_2O\uparrow \Rightarrow N_2\uparrow$$

nitrate — nitrous oxide gas — di-nitrogen gas

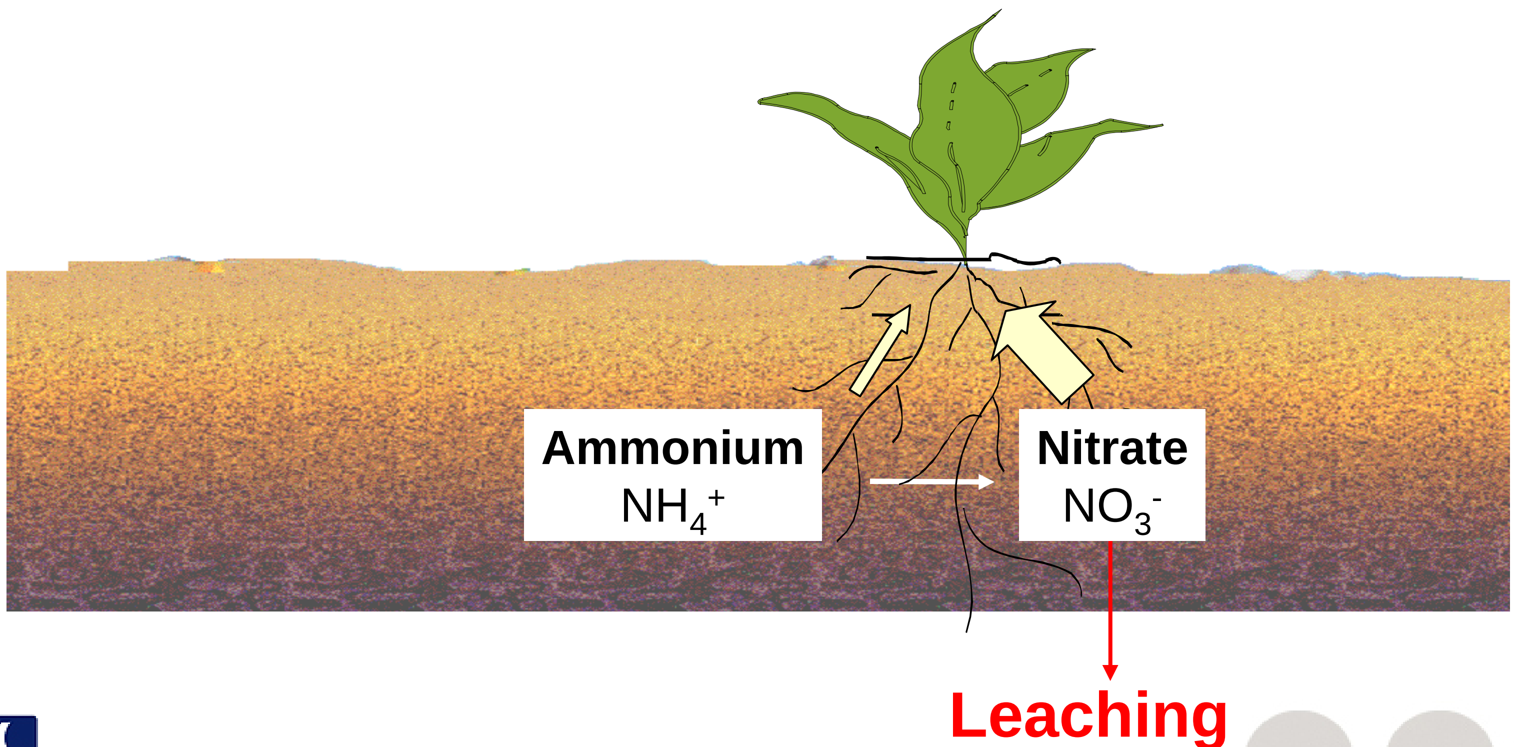
- **Reduction of nitrate to nitrous oxide and N_2 by microbes**
- **Requires anoxic conditions and nitrate**
  - **occurs whenever there is considerable moisture in the soil**
- **Major pathway for attenuation of nitrate leaching to groundwater:**
  - requires soil organic matter or soluble organics leaching along with the nitrate
  - This type of denitrification is desirable since it protects groundwater

Nitrogen Losses: Incomplete Nitrification

- **Nitrite-generating bacteria (e.g.Nitrosomonas) also generate nitrous oxide (N_2O, laughing gas) during the first step of the nitrification process.**
  - The N_2O is subject to loss to the atmosphere
- **The share of N_2O generated is increasing with decreasing soil pH, I.e. under acidic conditions, and with decreasing oxygen levels in the soil.**

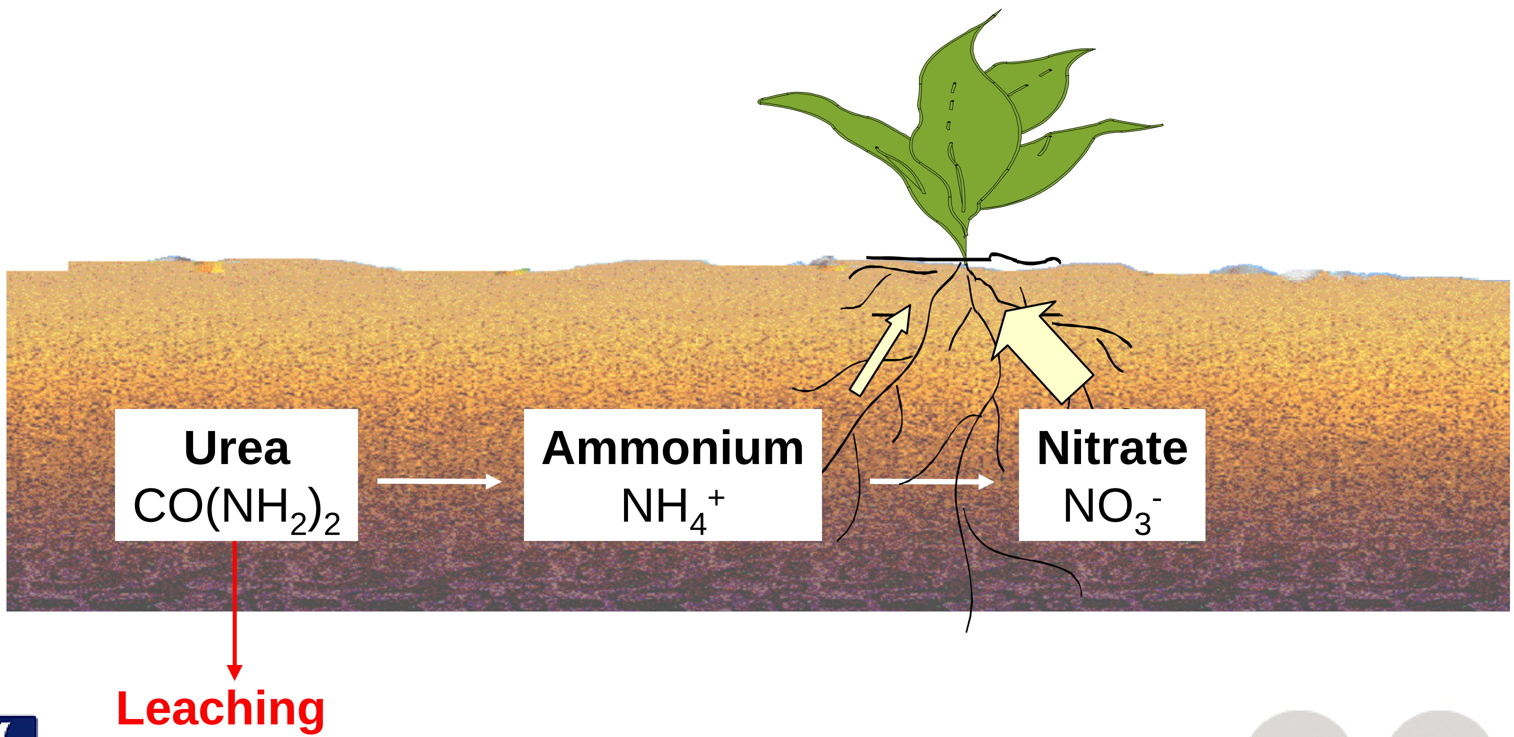
Nitrogen Losses: Leaching of Nitrate

- **Nitrate (NO_3^-) is mobile in soil and immediately plant available.**
- **In case of over-fertilization or over-irrigation, nitrate can be leached below the root zone**
- **The risk of leaching is minimized by good fertilizer management.**



Nitrogen Losses: Leaching of Urea

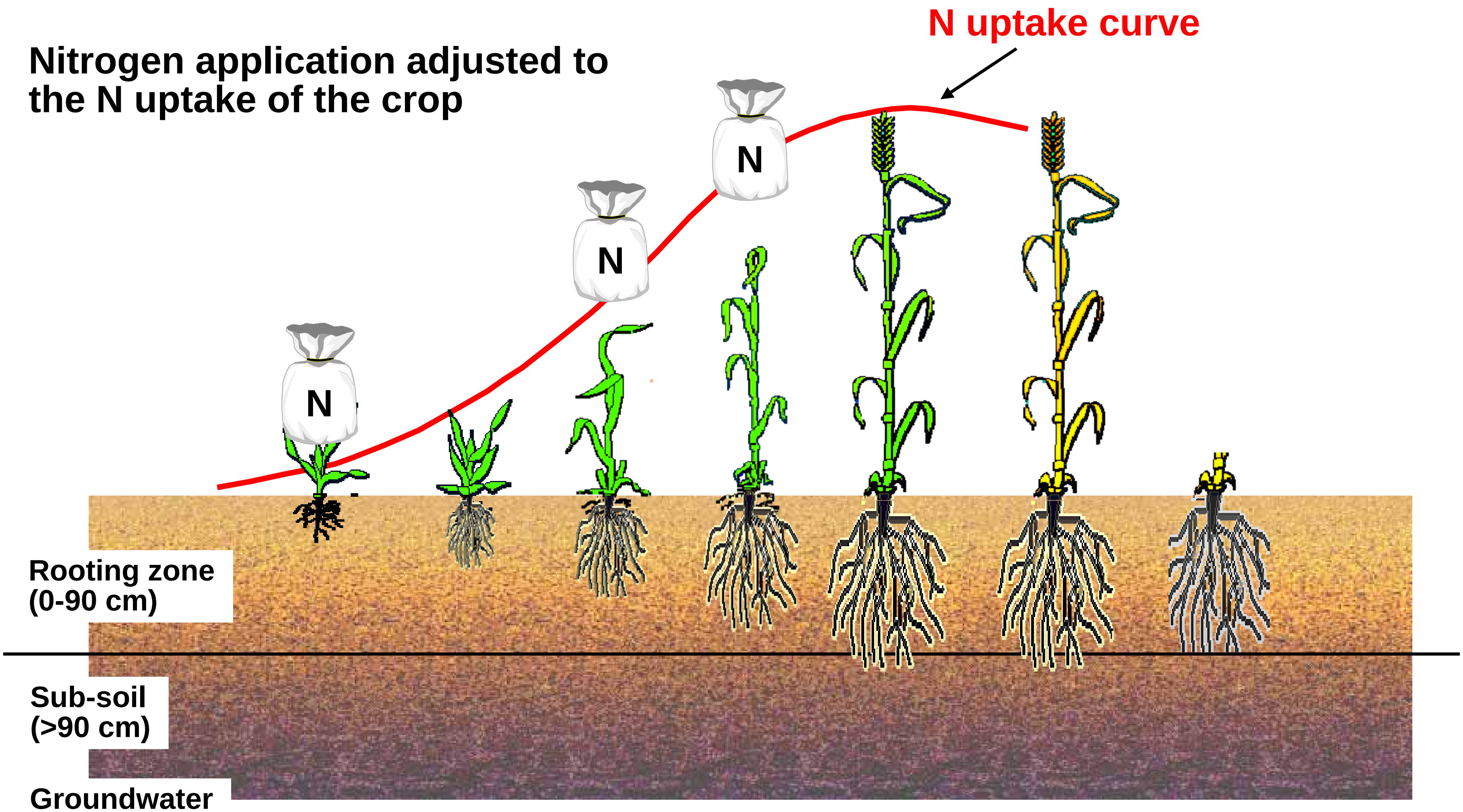
- Urea is and uncharged solute (like sugar) and moves with the soil water.
- Over-irrigation immediately after application or excessive fertigation can leach urea below the root zone.
- The risk of leaching is minimized by proper irrigation/fertigation.



Nitrogen Losses: Surface Runoff

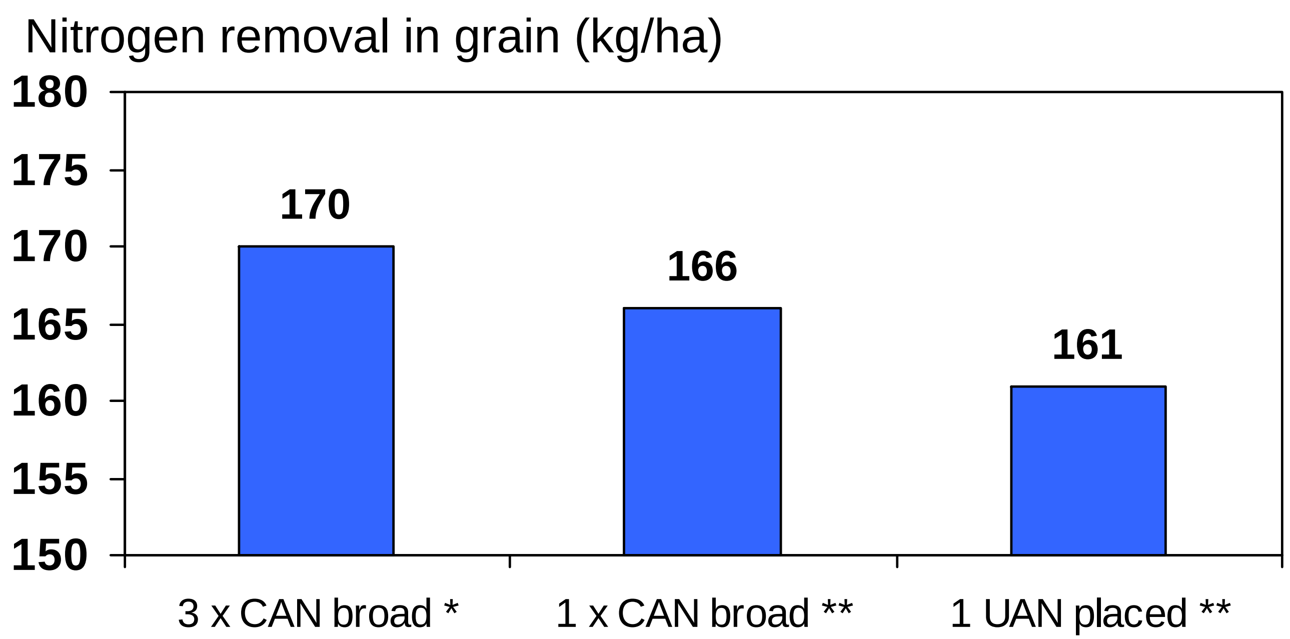
- **Surface runoff can contain significant amounts of nitrogen in all forms**
  - Nitrate
  - Ammonium
  - Organically bound N
- **Runoff that causes erosion and carries topsoil off the field is especially undesirable, since it removes the most nutrient-rich topsoil**

The risk of nitrate leaching during the growing season is low



Highest N removal with split application

- **Hanninghof**
  - Average of 43 field trials (38 x wheat, 3 x barley, 2 x rye)
- **Average N fertilizer level of 186 kg N/ha**

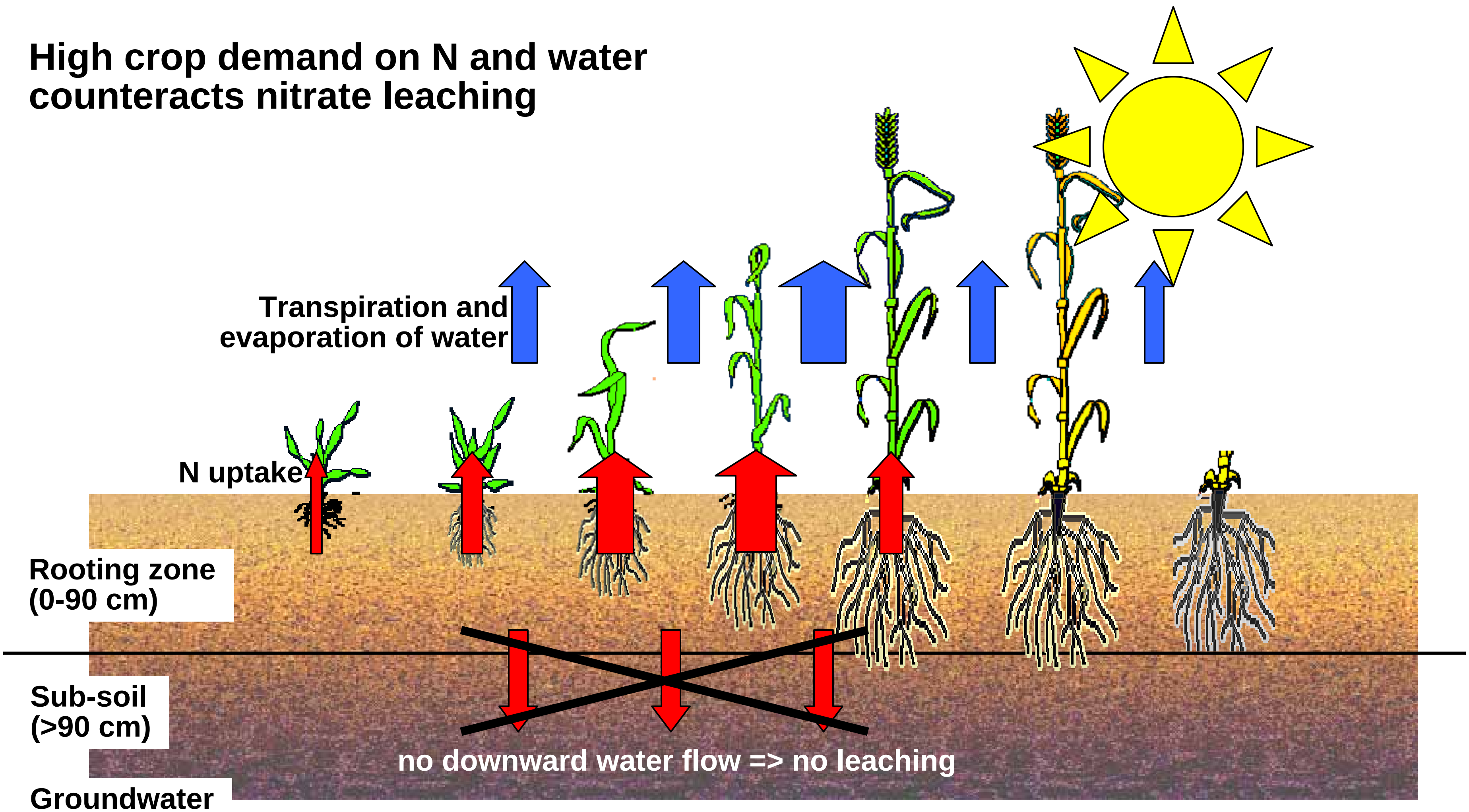


*Split N application: Tillering, stem elongation, ear emergence
**One application at stem elongation

Source: RC Hanninghof (1996 – 1998)

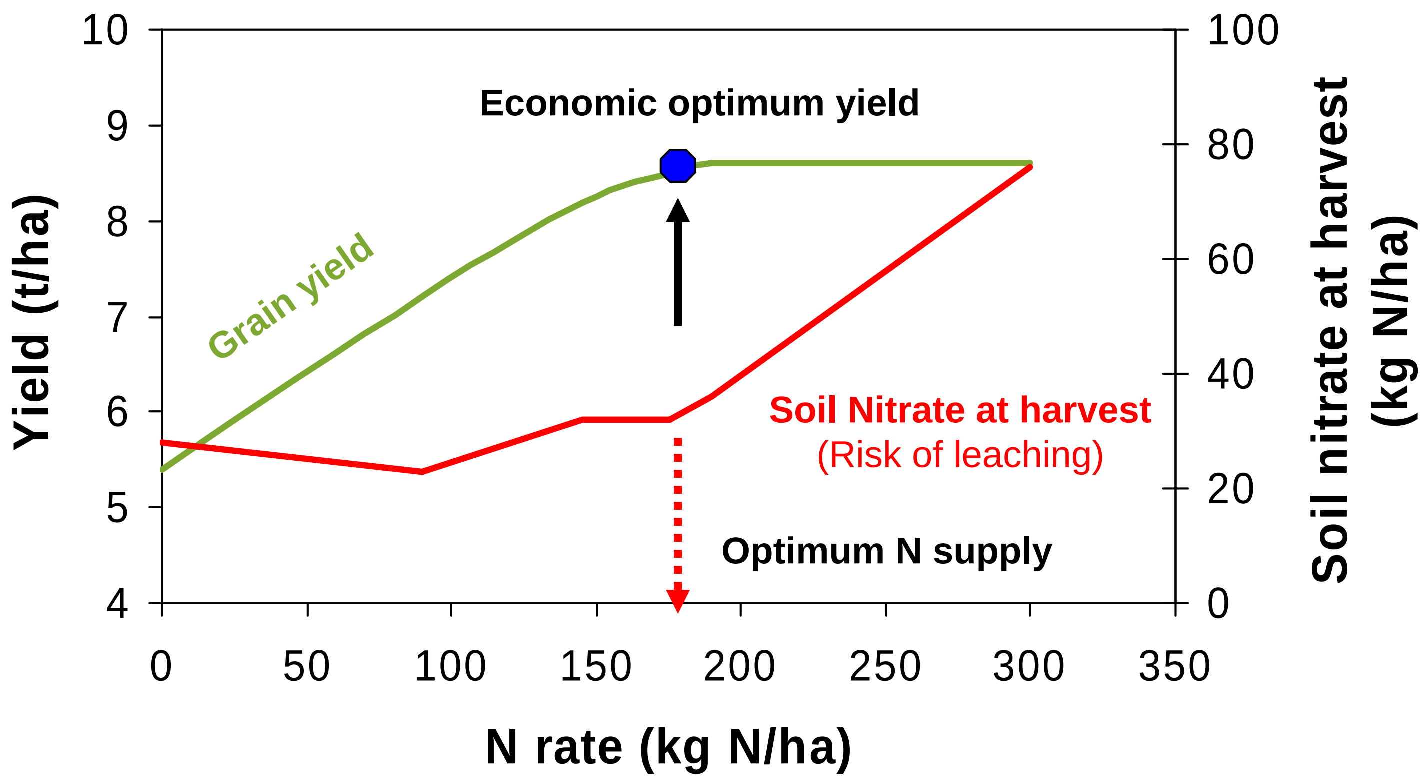
The risk of nitrate leaching during the growing season is low

High crop demand on N and water counteracts nitrate leaching



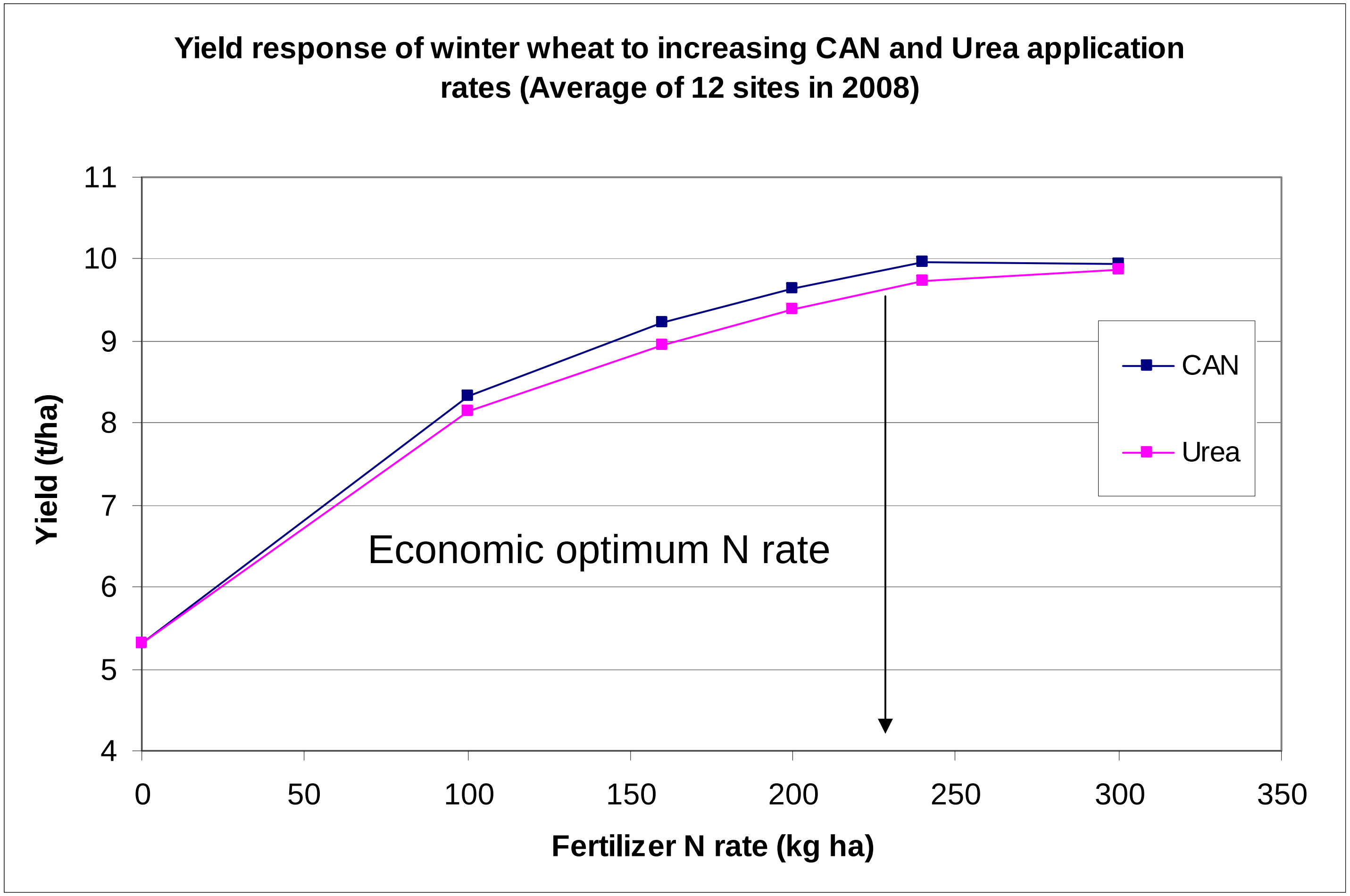
Low N leaching risk at optimum N supply

- **No increase of soil nitrogen from zero to optimum N application rate**
- **Trials with winter cereals (Germany, N applied in 3 dressings)**

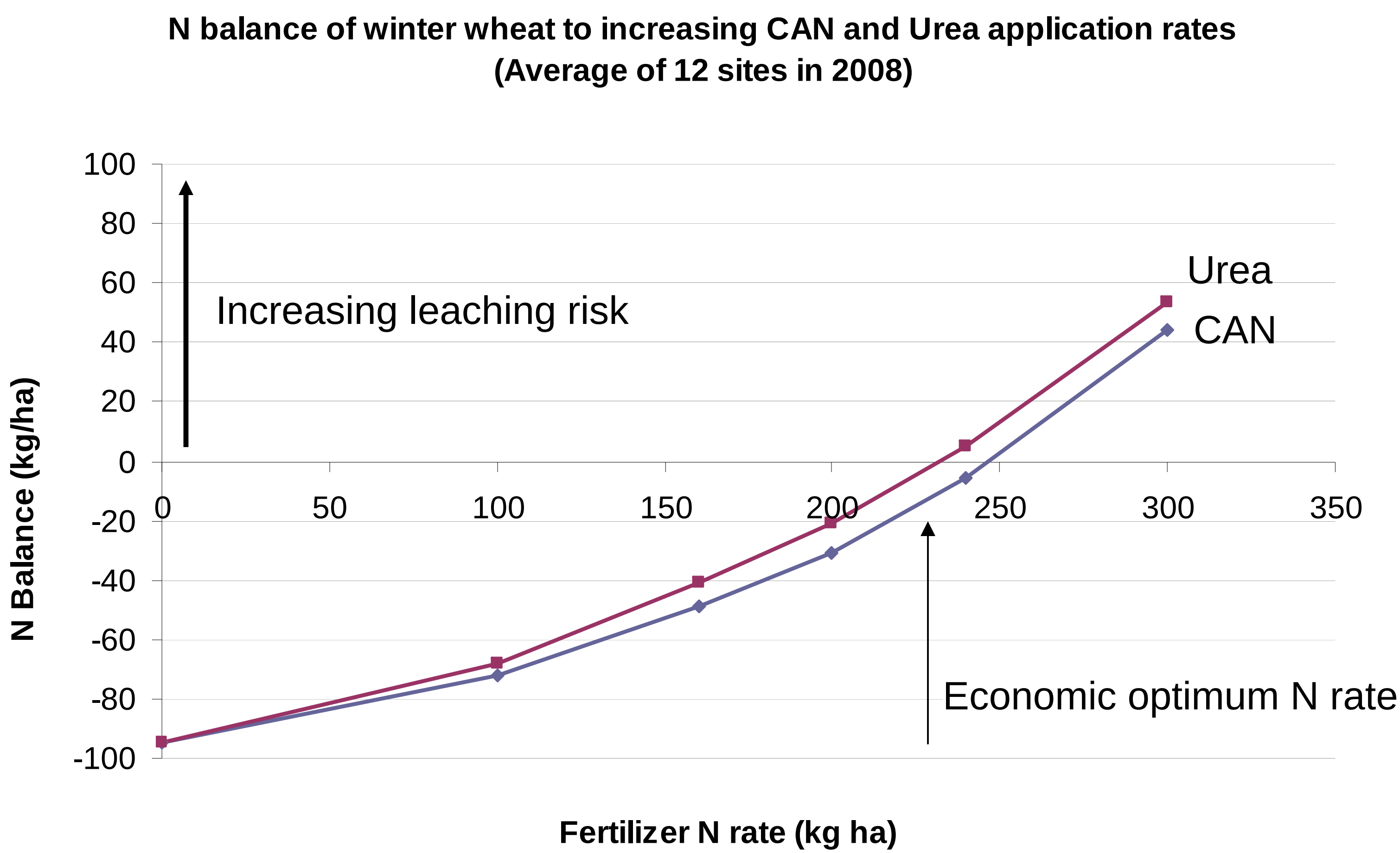


Source: Baumgärtel et al. (1989)

Yield response to increasing N application rates



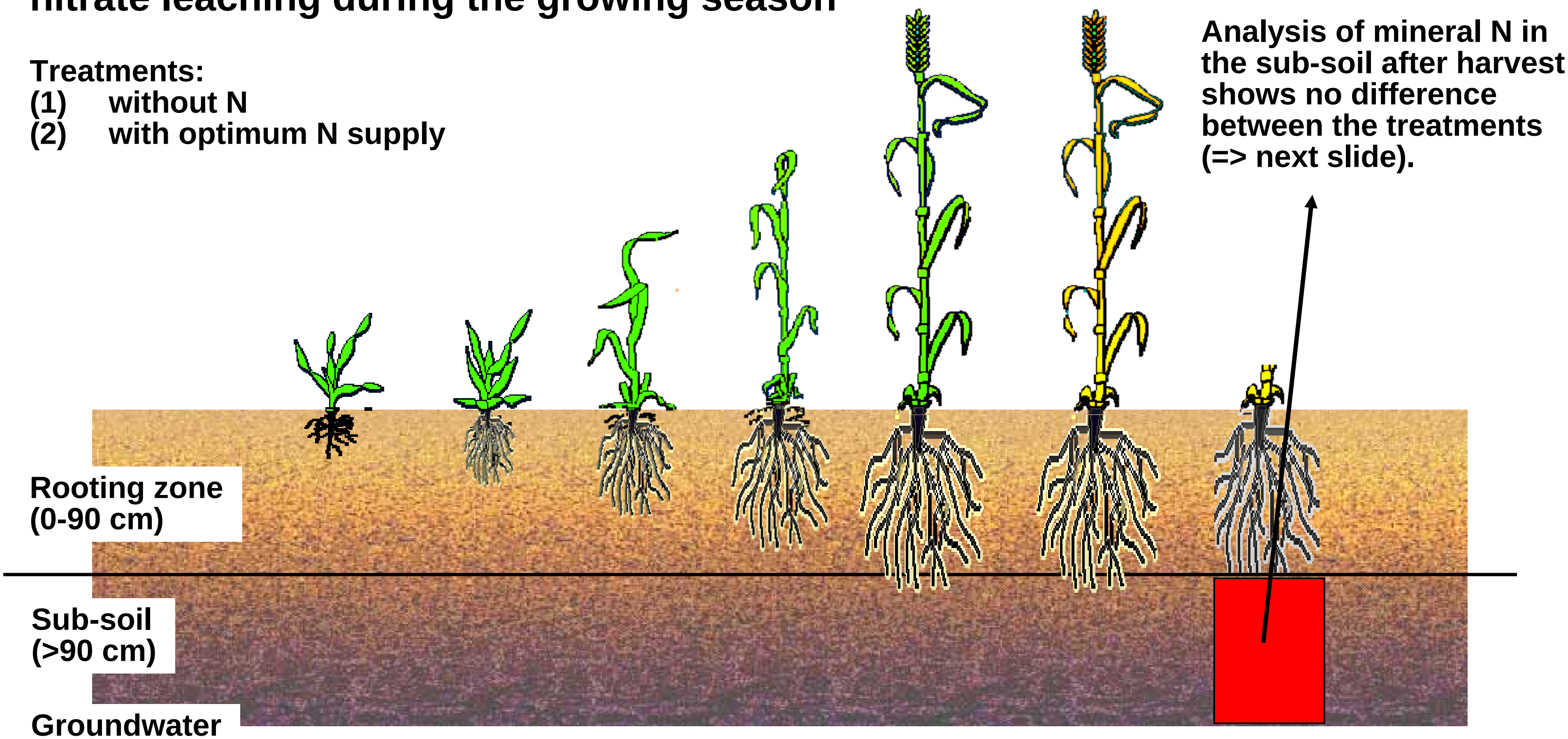
N balance of winter wheat at increasing N rates



The risk of nitrate leaching during the growing season is low

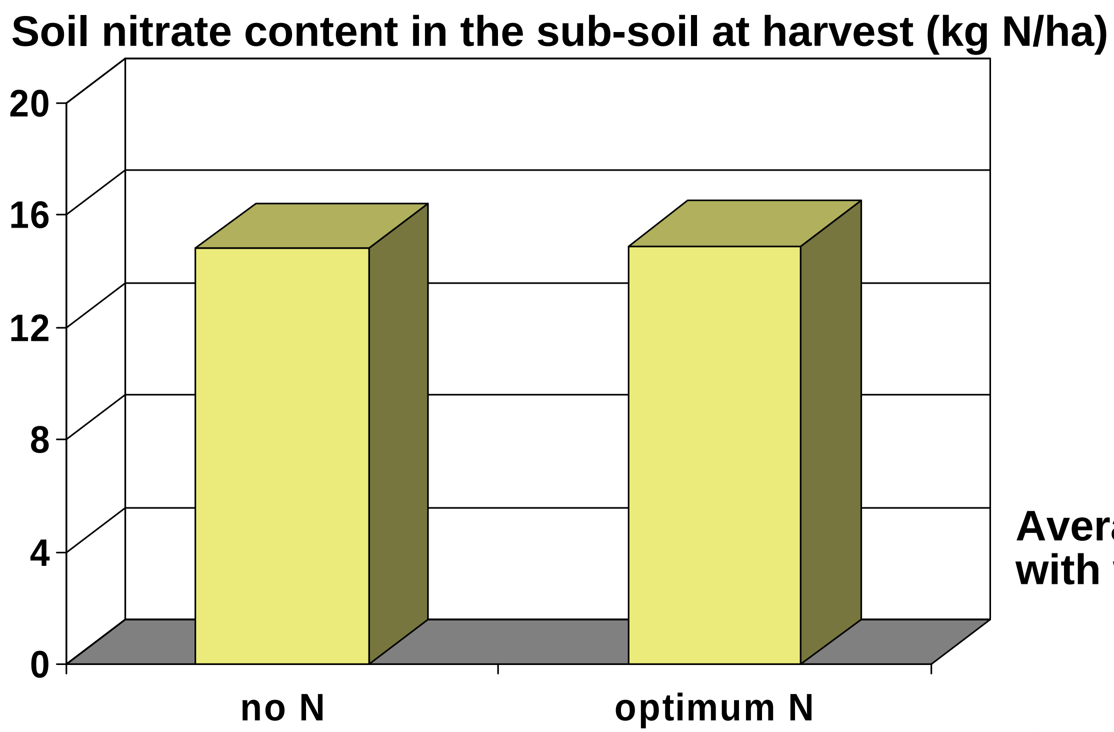
Example: field trials with winter wheat to measure nitrate leaching during the growing season

Treatments:
(1) without N
(2) with optimum N supply



No increased mineral soil N in the sub-soil at optimum N fertilizer supply = no leaching

- **After N application in spring, there's usually no downward water movement, because of high evapotranspiration rates of soils and crops.**
- **The crops need to absorb high amounts of mineral N for optimum growth.**

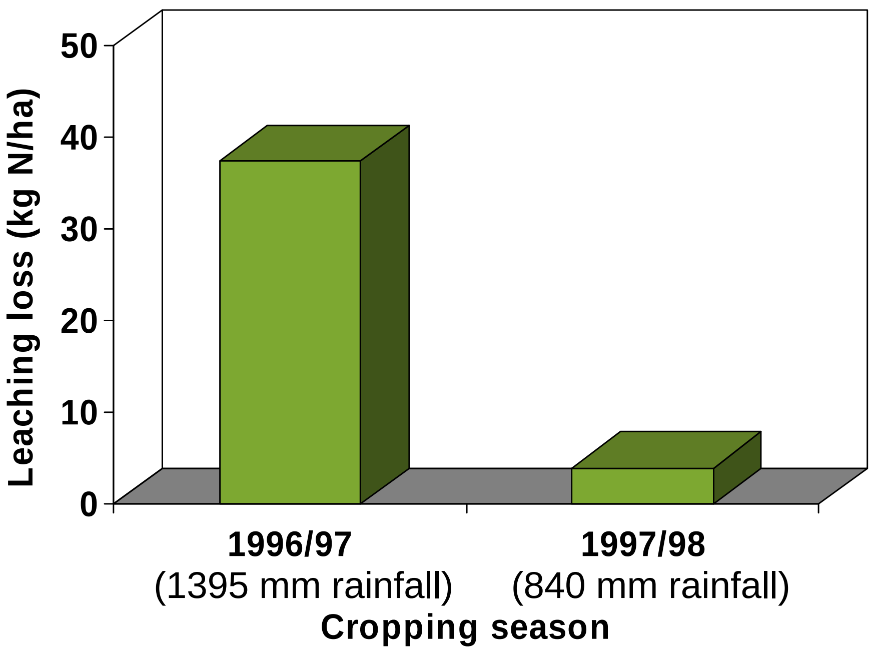


Average of 7 field trials with winter wheat

Source: Blankenau (2000)

Nitrate leaching during growth period at high rainfall or irrigation

- **In the season 1996/97 high rainfall leads to leaching of N on a sandy soil.**
- **Only little leaching at 840mm rainfall during the following season.**



- Field trials with maize on a tropical sandy soil in Zimbabwe
- N rate = 120 kg N/ha applied in one dressing at planting
- Note: Split application could have reduced the risk of nitrate leaching

Source: Nyamangara et al. (J. Environ. Qual., 2003)

Strategies to Reduce Nitrate Leaching

- **Any increase of N fertilizer use efficiency reduces leaching potential**
  - Application rate according to crop demand
  - Timing of application to crop uptake
  - Split applications
  - Preferred N-form by crops is nitrate – fast N uptake
  - Balanced fertilization with other nutrients
  - Good irrigation management
  - Crop rotation
  - Cover crops
- **No excessive use of fertilizers containing organically-bound N:**
  - Potential for "leftover" organic N that mineralizes and nitrifies when no crop is growing
- **=> Taken in aggregate, the above actions have been researched and combined for crops to create Best Management Practices (BMPs)**

Summary

- **Uptake by the crop is the intended fate for nitrogen from fertilizer.**
- **Only nitrate that has been leached below the root zone can potentially continue to leach to the groundwater**
  - Capillary rise can bring nitrates back into the root zone
  - Attenuation by denitrification is still possible if leaching continues
- **Irrigated cropping under arid or semiarid conditions affords a high level of control over potential N-losses, including nitrate leaching**
  - Leaching depth can be controlled with the amount of water applied per irrigation and irrigation frequency

Conclusions

- **There are many pathways for fertilizer nitrogen to be lost to the environment**
  - These pathways are the reasons why more fertilizer N is added than can later be found in the grown crop
- **Nitrate leaching is not the dominant loss pathway for fertilizer nitrogen in developed cropping systems**
- **The amount of nitrate at risk of leaching can be minimized in agricultural fields with good agronomic practices**
  - Existing BMPs should be followed
  - => further development and ongoing refinement of BMPs specific for California's crops and regions is highly desirable.

References and Information Sources

- **Mosier, A. R., Syers, J. K., and Freney, J. R. (eds): Agriculture and the Nitrogen Cycle: Assessing the impacts of fertilizer use on food production and the environment. 2004. Island Press, Washington DC, USA**
- **Marschner, P., and Rengel, Z. (eds): Nutrient Cycling in Terrestrial Ecosystems. 2007. Springer-Verlag, Heidelberg & Berlin, Germany**