Aalto University
School of Engineering

Biological treatment processes of water and waste
Lecture 4

WAT - E2180

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Lecture outline

Biological process applications

- Suspended growth
  - *Activated sludge*
  - *Sludge age*
  - *Design of the process*

- DEMO exercise: Activated sludge process design

Removal of organic matter

Nitrogen conversions

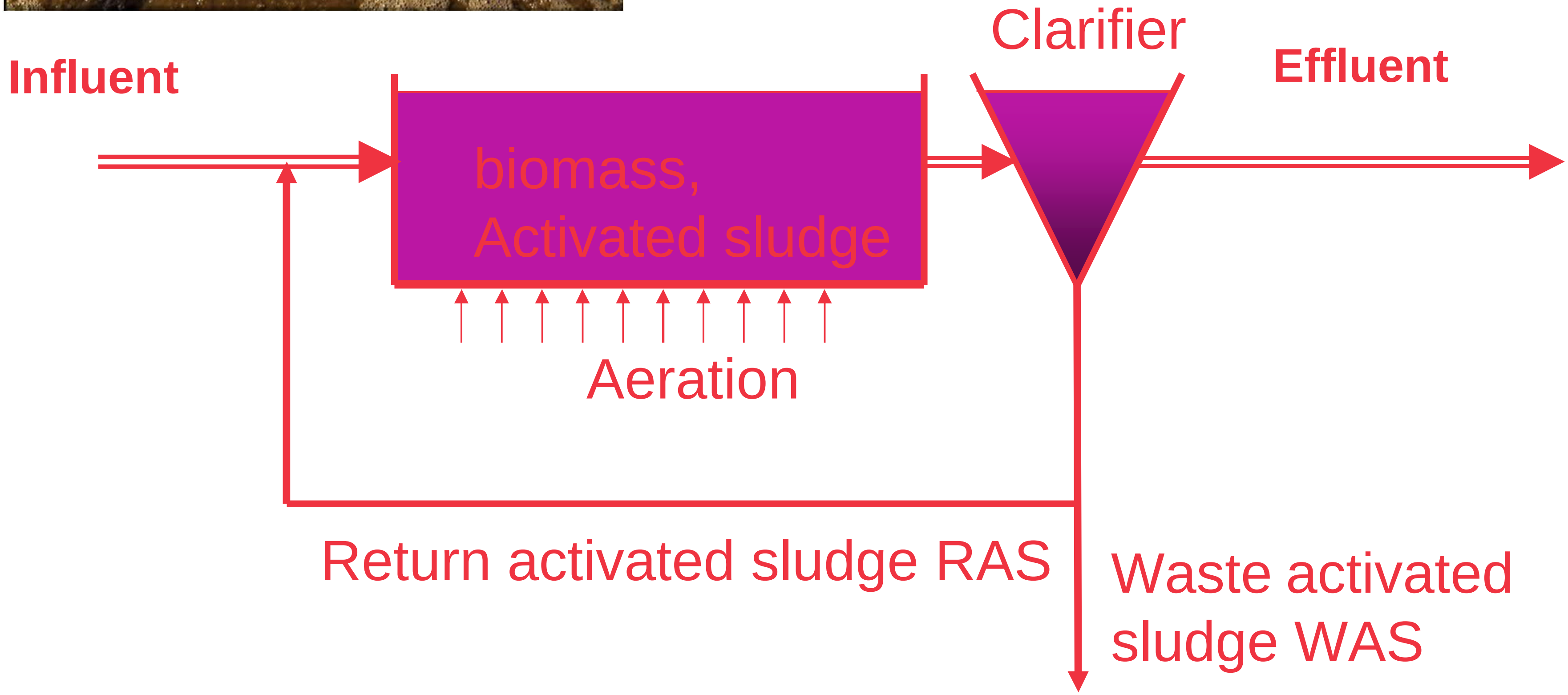
- Nitrification
- Denitrification
- Short-cut processes

Advanced BACTERIA GAME – Nitrogen removal simulation

- N2O

Activated sludge process

Activated sludge process



Activated sludge process

- Aeration basin – oxygen is provided for the microorganisms
- Source of oxygen usually air
- Mixing – with aeration or mixers
- Settling basin – separates the sludge from the water
- Return activated sludge (RAS) recycles most of the sludge back to the aeration basin
- Waste activated sludge (WAS) determines the sludge retention time of the process

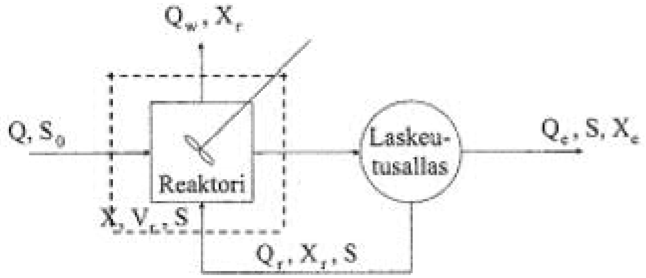
Sludge retention time SRT or sludge age

- The most important parameter in the biological process

$$\boxed{\theta_c = V / Q_w}$$

← When removed from the reactor!

a)



$\theta_c = V X / Q_w X_r$

θ_c = Sludge age d (SRT, MCRT)

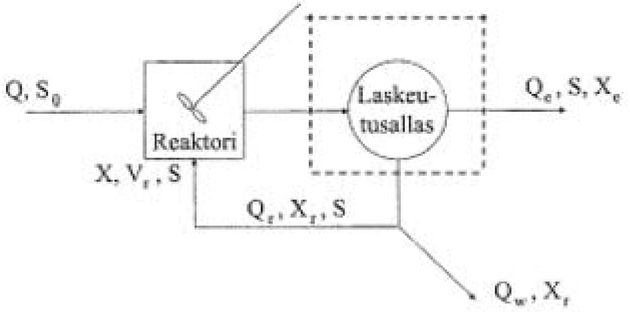
V = Reactor volume m^3

X = MLSS in the reactor kg/m^3

Q_w = WAS flow rate m^3/d

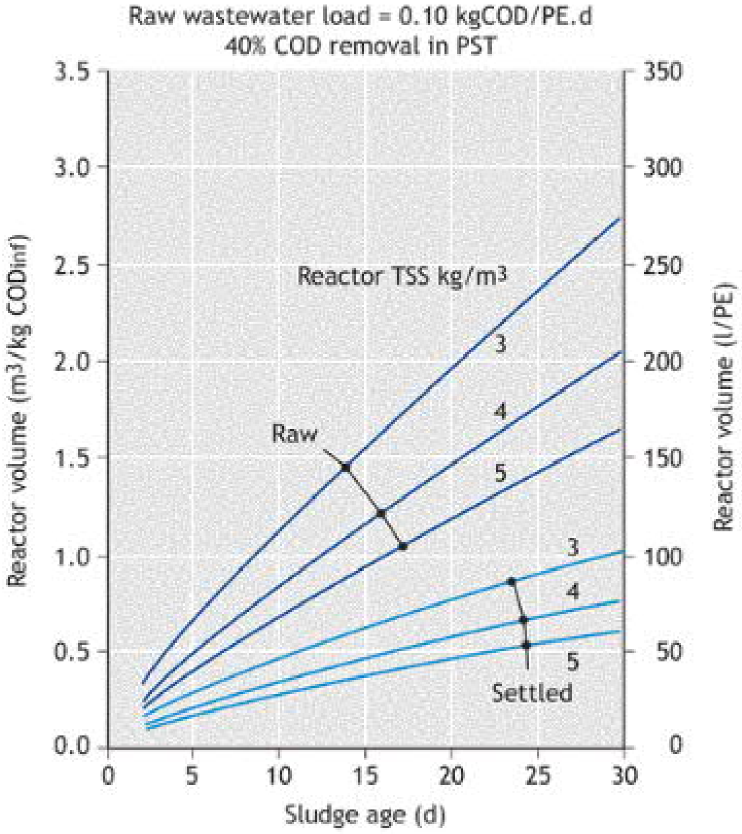
X_r = MLSS in RAS kg/m^3

b)



Sludge age

- **Sludge age determines the reactor volume and sludge concentration**
- **It determines also the biological performance**
    - Short (1-5 days) – only COD removal
    - Intermediate (10-15 days) – COD removal + nutrient removal
    - Long (>20 days) – COD + nutrient removal, enhanced micropollutant removal



Important parameters of activated sludge

- **In bioreactor:**
  - Sludge concentration (MLSS) g/l = X (or MLVSS!!)
  - Sludge age (SRT)
  - Volumetric loading = BOD-load / reactor volume (kgBOD/m^3d)
  - Sludge loading = F/M = BOD-load / V · X (kgBOD/kgMLSSd)
  - Sludge yield (kgSS/kgBOD)
  - Hydraulic retention time
- **In settling**
  - Sludge volume index SVI
  - Surface loading = flow rate / surface area (m/h)
  - Sludge surface loading (SSL) = flow rate · X / surface (kgSS/m^2d)
  - Sludge volumetric loading = SVI/1000 ·SSL (m^3/m^2h)

Dimensioning of activated sludge process

- **First decide which sludge age is needed**
  - Short SRT< 5d → only COD removal
  - Long SRT > 10d → nitrification

Steps:

→ Select the sludge age, take into account the temperature effect

→ The biomass produced is calculated with the following:

→ $Y_{OBS} = Y / 1+b\theta_c$ (or this is known from experience)

→ $XV = \theta_c Q Y_{OBS} (S_0 – S_e)$ → select the MLSS and calculate the volume.

(Y is the yield and b is the decay rate)

- Often used also: dimensioning based on volumetric loading or sludge loading; use of safety factors
- COD removal: 0,5 – 1 kgBOD/kgMLSSd, nitrification 0,04 – 0,1 kgBOD/kgMLSSd (or < 0,3 kgBOD/m3)

DEMO EXERCISE: LOHJA PITKÄNIEMI WWTP

The plant has two bioreactors in two lines, together 3600 m^3. Two thirds are anoxic. Settling surface area is 1150 m^2. Influent flow rate is 8090 m^3/d and the BOD concentration in the influent is 305 mg/l. Sludge concentration MLSS is 7 g/l.

Calculate the hydraulic retention time, volumetric loading and sludge loading in aeration. Do you think nitrification is occuring in the process?

Waste activated sludge WAS is removed directly from the aeration basin. Flow rate is 300 m^3/d. Calculate the sludge age. Based on the sludge are what could you say about nitrification now?

Hydraulic retention time = 3600 / 8090 d = 0,44 d = 10,7 h.

Volumetric loading = 8090 * 305 / 3600 gBOD$_7$ /m^3 d = 685 gBOD$_7$ / m^3 d = 0,69 kg BOD$_7$ / m^3 d

Sludge loading = 8090 * 305 / (3600 * 7) gBOD$_7$ / kg MLSS d = 98 gBOD$_7$ / kg MLSS d = 0,098 kgBOD$_7$ / kg MLSS d.

Based on the volumetric loading, nitrification is not occuring. Based on the sludge loading nitrification might occur.

SRT (when WAS is removed from the reactor) = reactor volume / WAS flow rate (m3/d) = 3600 / 300 = 12 d.

Looks promising but aerobic SRT is important for nitrification, so in this case nitrification is not working efficiently.

Activated sludge process

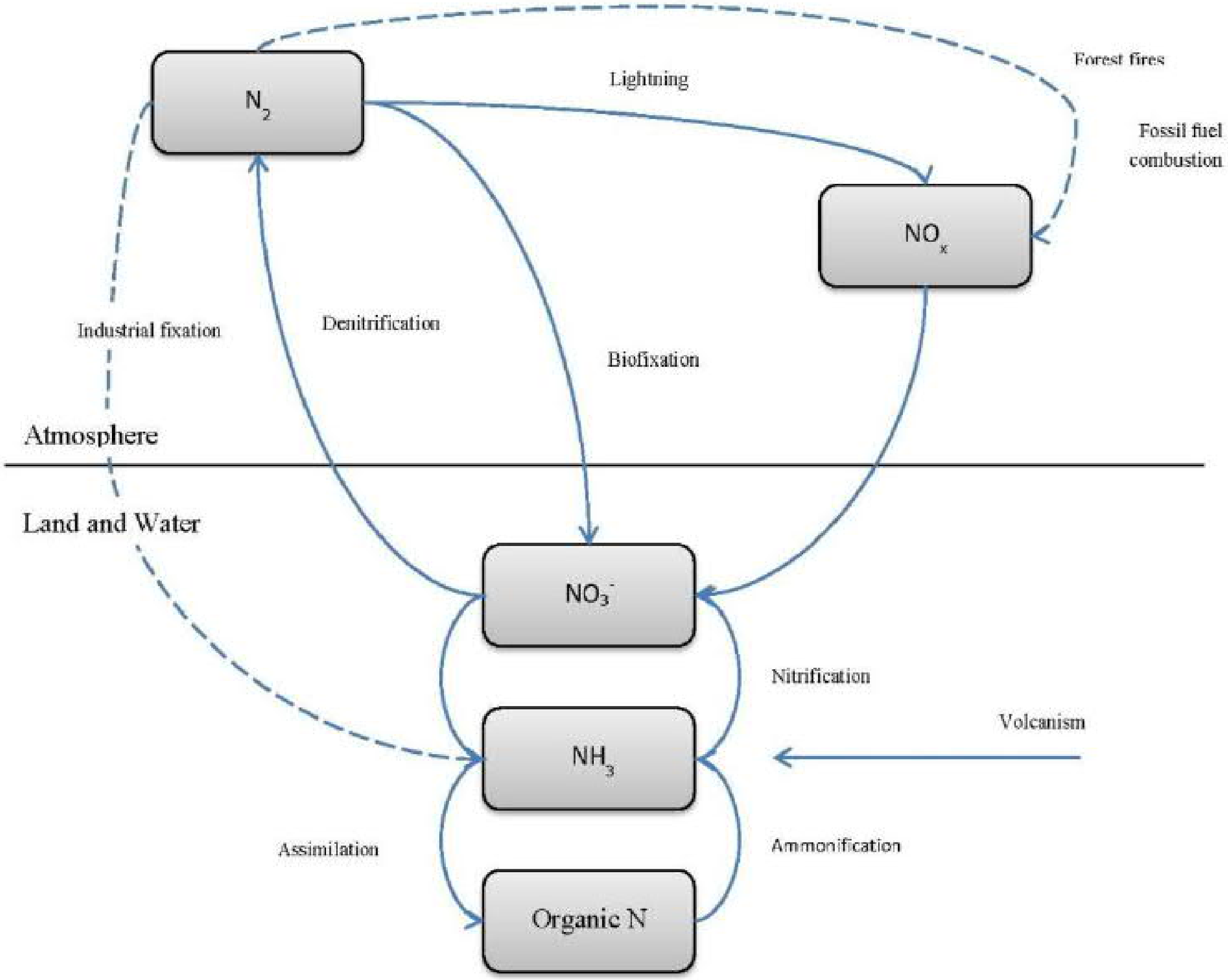
- Based on microbiological activity in aerobic conditions
- Heterotrophic microbes degrade the organic matter to CO_2 and H_2O
- Nutrient are assimilated during the biomass growth
  - $BOD_{7,ATU}$:Nkok:Pkok = 100:5:1
  - => nutrient removal (N,P) ~20-30 %

Basic version

- Autotrophic microbes are oxidazing NH_4
- Nitrogen removal: Denitrifying bacteria + anoxic zone
- BioP: PAOs + anaerobic zone

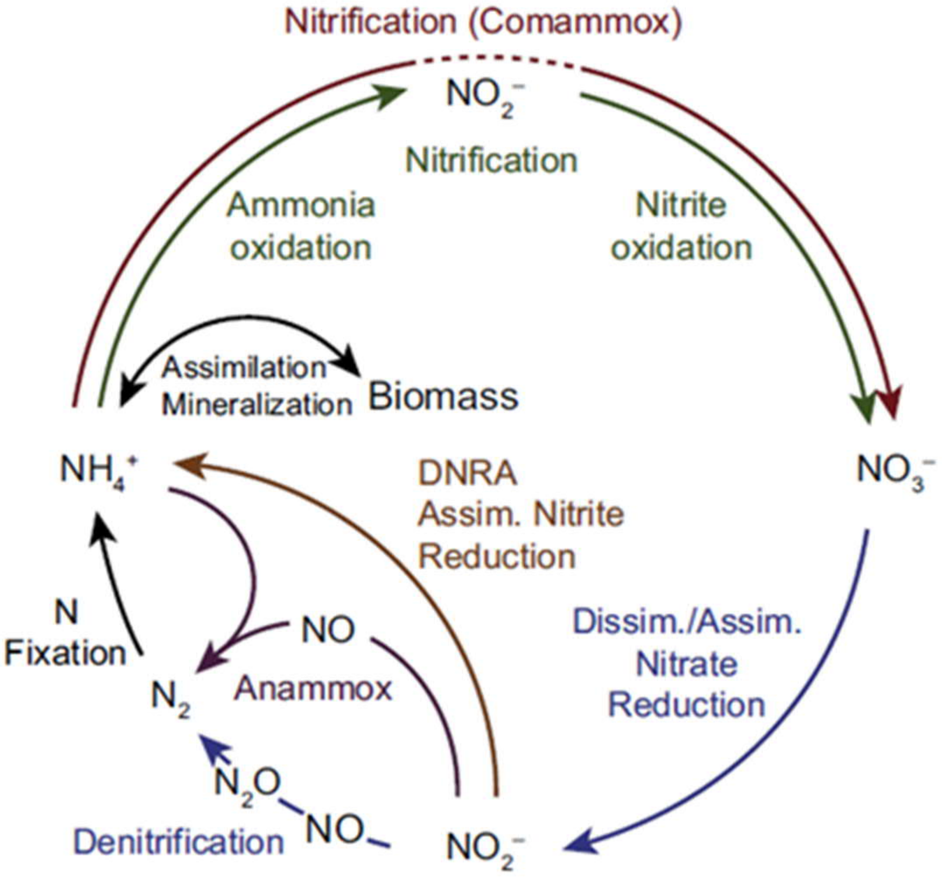
Nitrogen conversions

Global nitrogen cycle



(Vaccari et al. 2006)

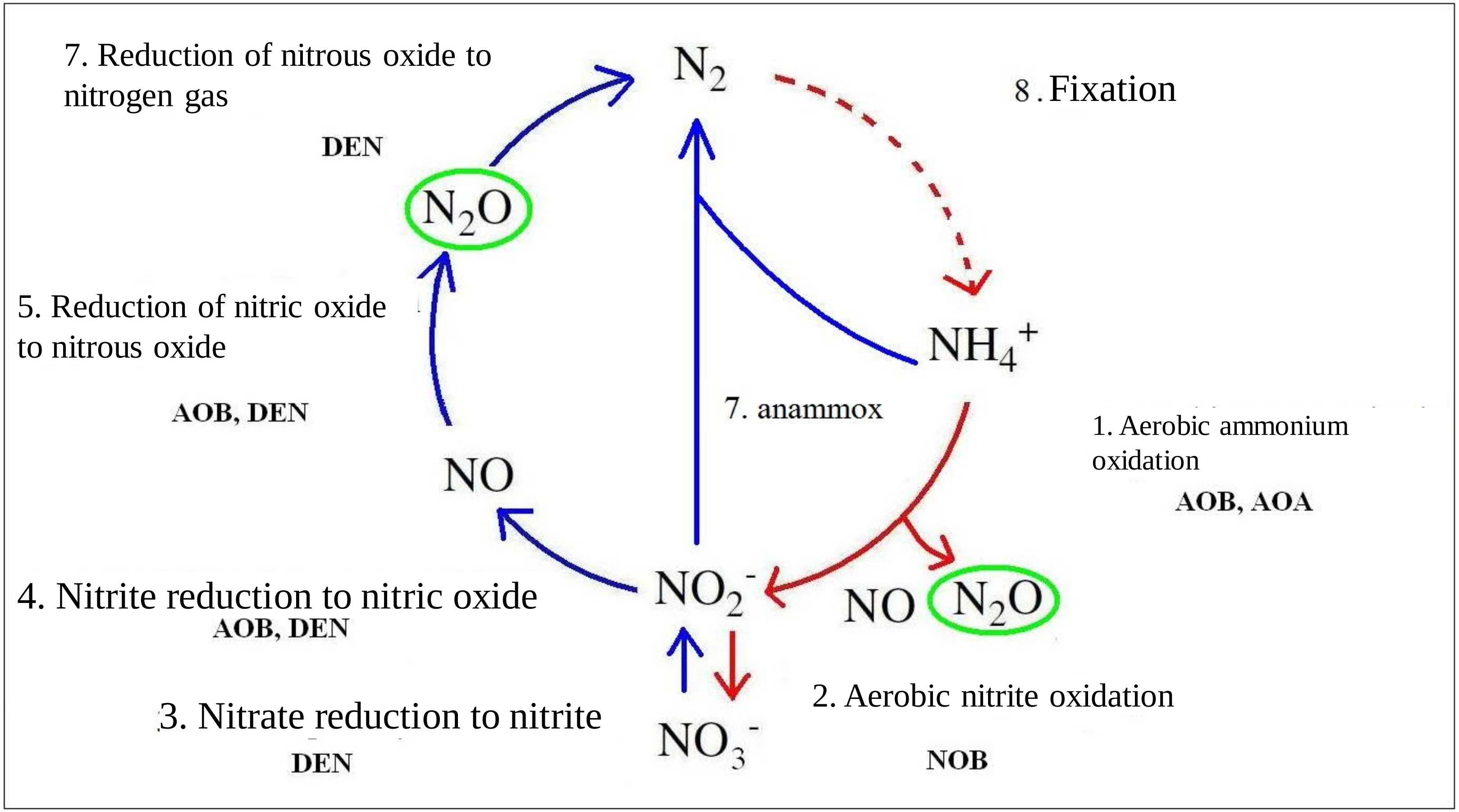
Alternative redox pathways in nitrogen conversions



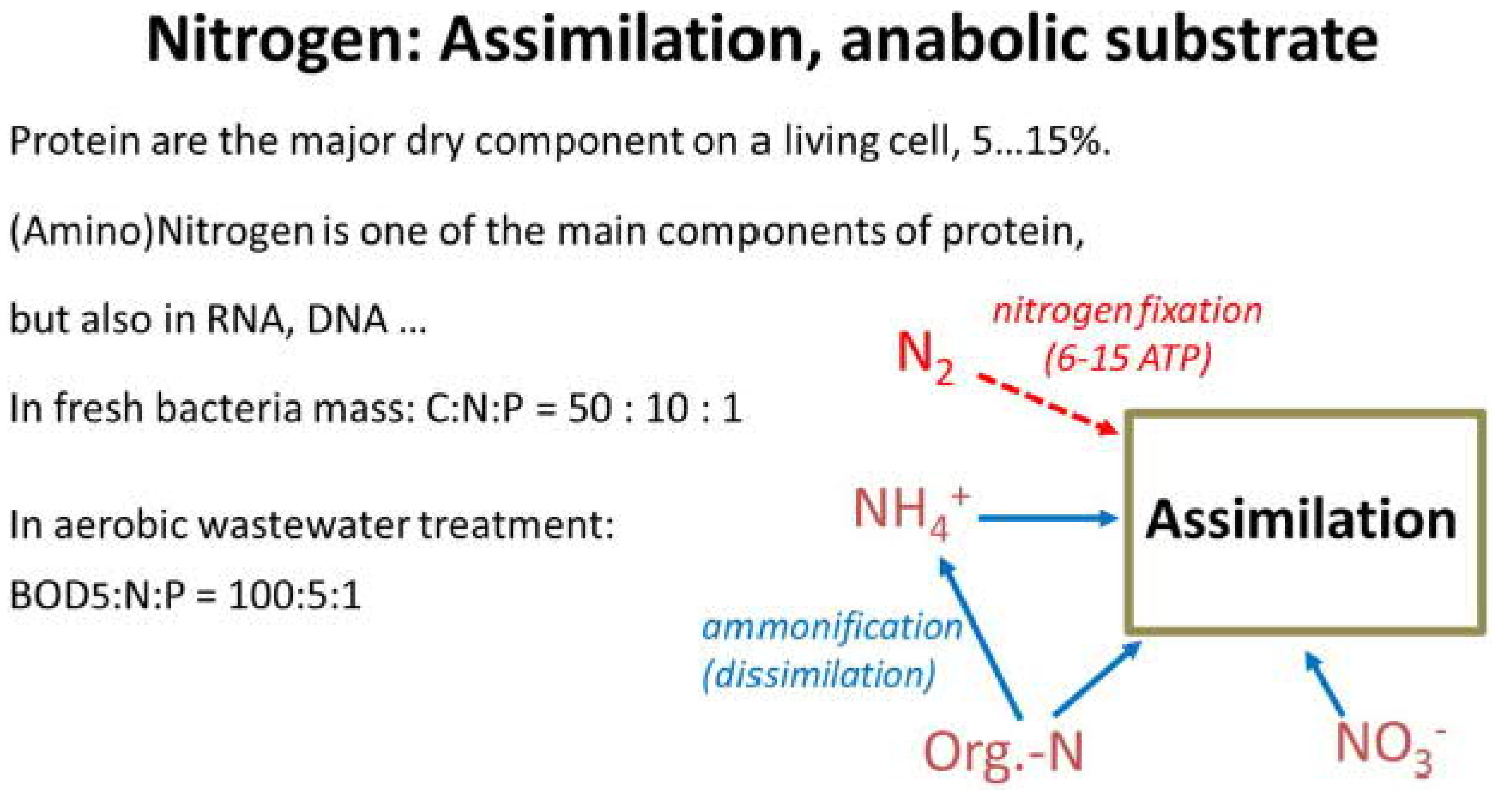
(Daims et al. 2016)

Abbreviations: DNRA, dissimilatory nitrite reduction to ammonia; assim., assimilatory; dissim., dissimilatory.

Nitrogen cycle in wastewater treatment



Assimilation



Nitrogen: Assimilation, anabolic substrate

Protein are the major dry component on a living cell, 5...15%.

(Amino)Nitrogen is one of the main components of protein,

but also in RNA, DNA ...

In fresh bacteria mass: C:N:P = 50 : 10 : 1

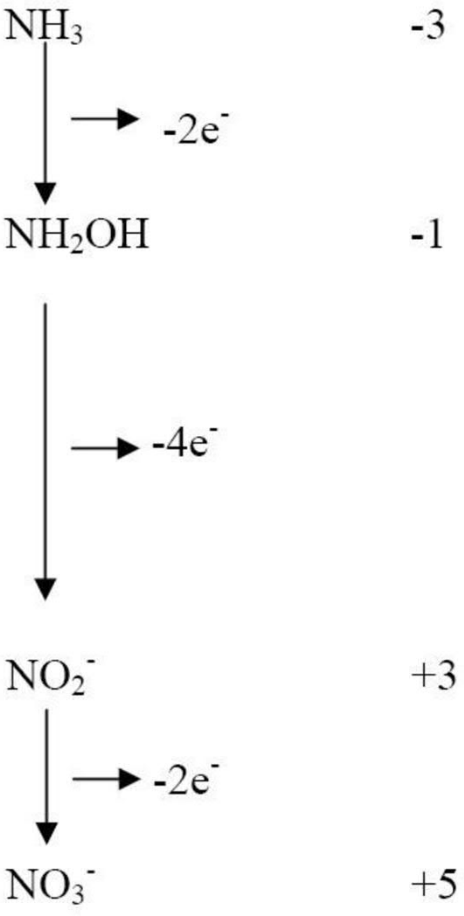
In aerobic wastewater treatment:

BOD5:N:P = 100:5:1

Nitrogen removal

Nitrification (oxidation)

Oxidation state



NH_3 -3

$\downarrow$ $\rightarrow$ $-2e^-$

NH_2OH -1

$\downarrow$ $\rightarrow$ $-4e^-$

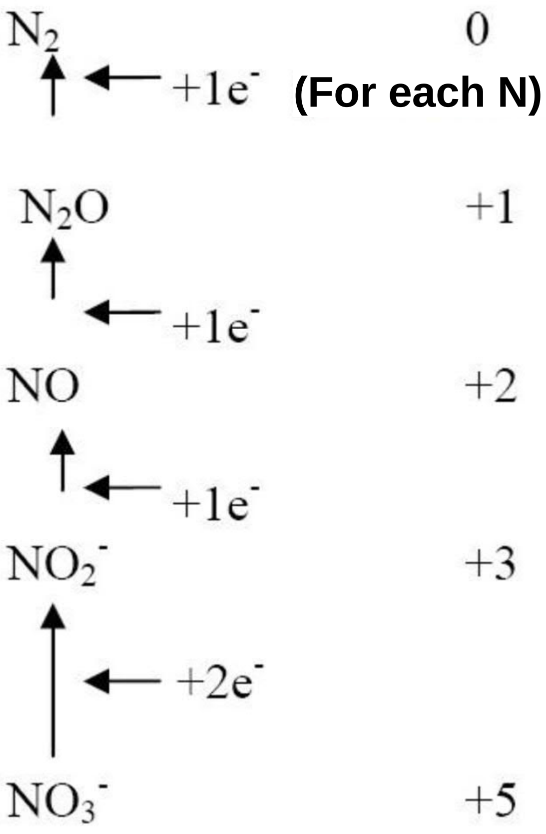
NO_2^- +3

$\downarrow$ $\rightarrow$ $-2e^-$

NO_3^- +5

Denitrification (reduction)

Oxidation state



N_2 0

$\uparrow$ $\leftarrow$ $+1e^-$ **(For each N)**

N_2O +1

$\uparrow$ $\leftarrow$ $+1e^-$

NO +2

$\uparrow$ $\leftarrow$ $+1e^-$

NO_2^- +3

$\uparrow$ $\leftarrow$ $+2e^-$

NO_3^- +5

Nitrification

- Nitrification in two steps

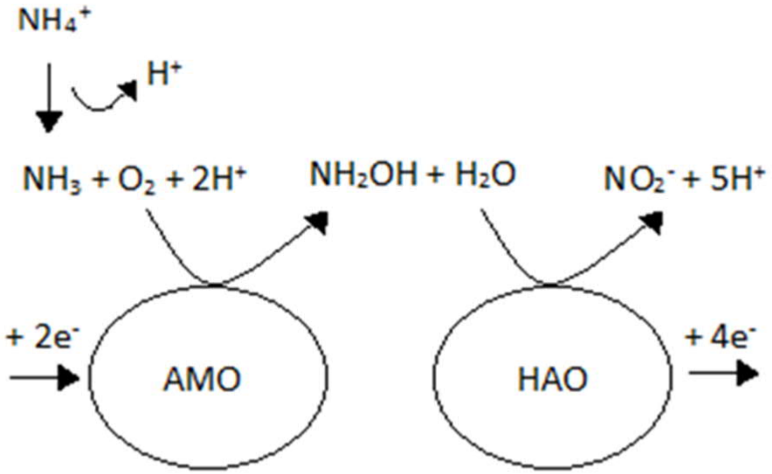
1. $2\ NH_4^+ + 3\ O_2 \rightarrow 2\ NO_2^- + 2\ H_2O + 4\ H^+$ (nitritation)
2. $2\ NO_2^- + O_2 \rightarrow 2\ NO_3^-$ (nitratation)

- Or in more details

$NH_3 + O_2 + 2H^+ + 2e^- \rightarrow NH_2OH + H_2O$

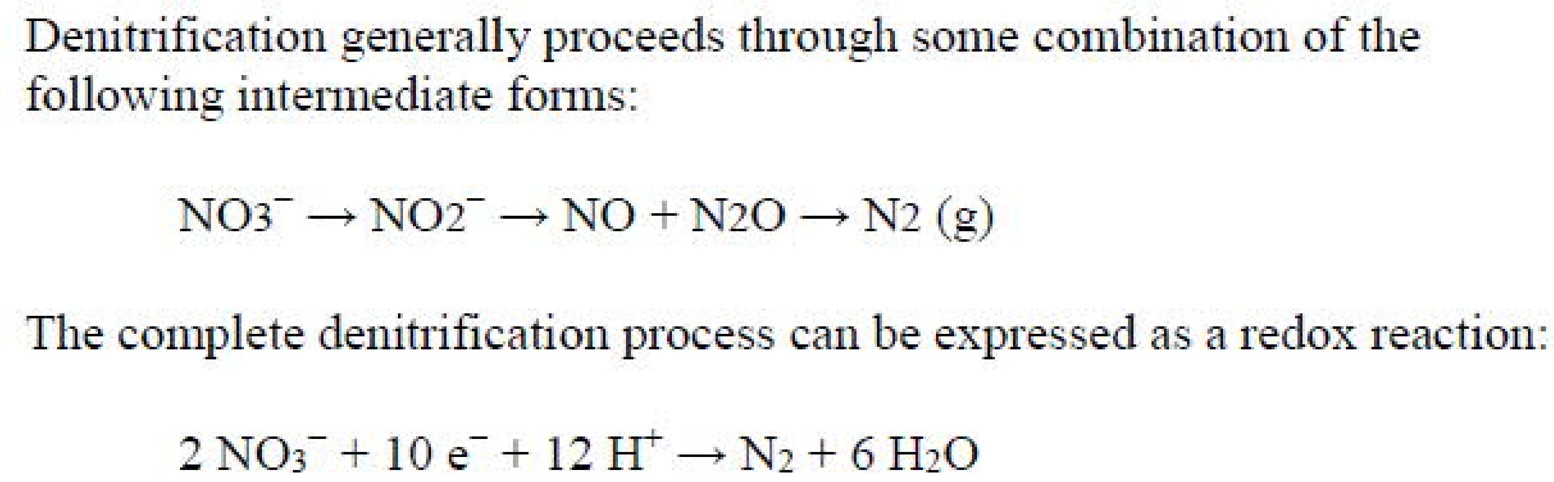
$NH_2OH + H_2O \rightarrow NO_2^- + 5H^+ + 4e^-$

$NO_2- + H_2O \rightarrow NO_3- + 2H+ + 2e-$



Denitrification

- Denitrification in four steps

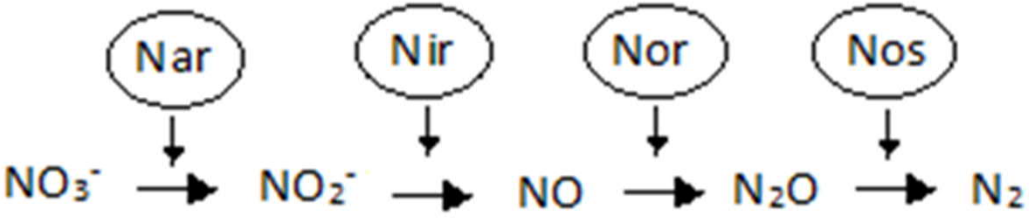


Denitrification generally proceeds through some combination of the following intermediate forms:

$$NO3^- \rightarrow NO2^- \rightarrow NO + N2O \rightarrow N2\ (g)$$

The complete denitrification process can be expressed as a redox reaction:

$$2\ NO_3^- + 10\ e^- + 12\ H^+ \rightarrow N_2 + 6\ H_2O$$



Alkalinity in nitrification and denitrification

- **Nitrification consumes the alkalinity of the wastewater**
- **theoretically 1 g of NH_4^+-N converted requires 7.14 g of alkalinity as $CaCO_3$**

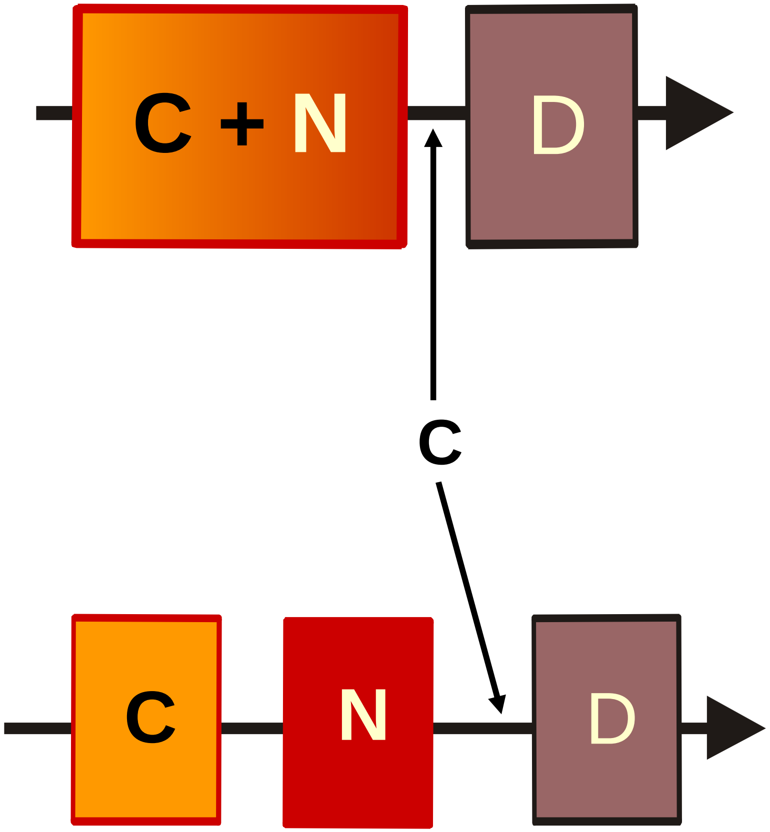
- **Hydrogen ions produced in nitritation are consumed in the denitrification reaction.**
- **3.57 g of alkalinity as $CaCO_3$ is generated per 1 g of reduced NO_3^--N**

Nitrification and denitrification

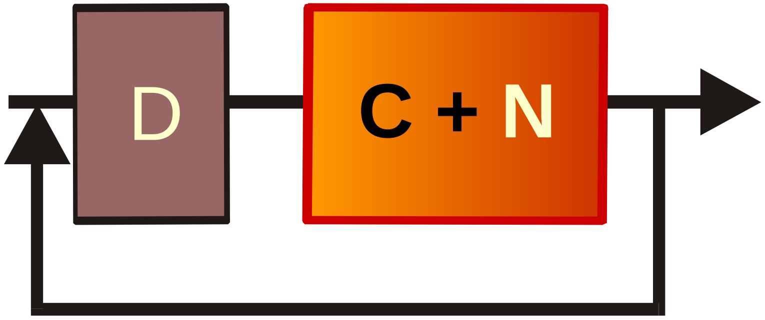
SRT	long SRT	short SRT increases the rate
Oxygen	high, min 2 mg/l	no oxygen or very low
Organic matter	no need (autotrophic)	needs a carbon source
BOD load	low load	high load
Alkalinity	consumes	produces

Process options – N removal

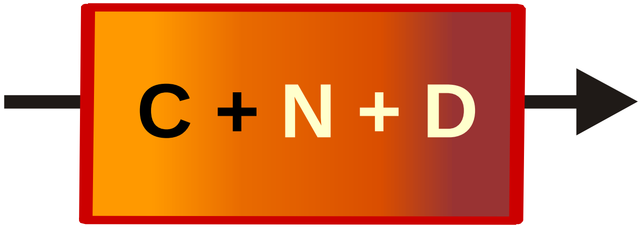
ND processes



DN- processes (recycle)



Sequenced reactors



Comparison of different configurations

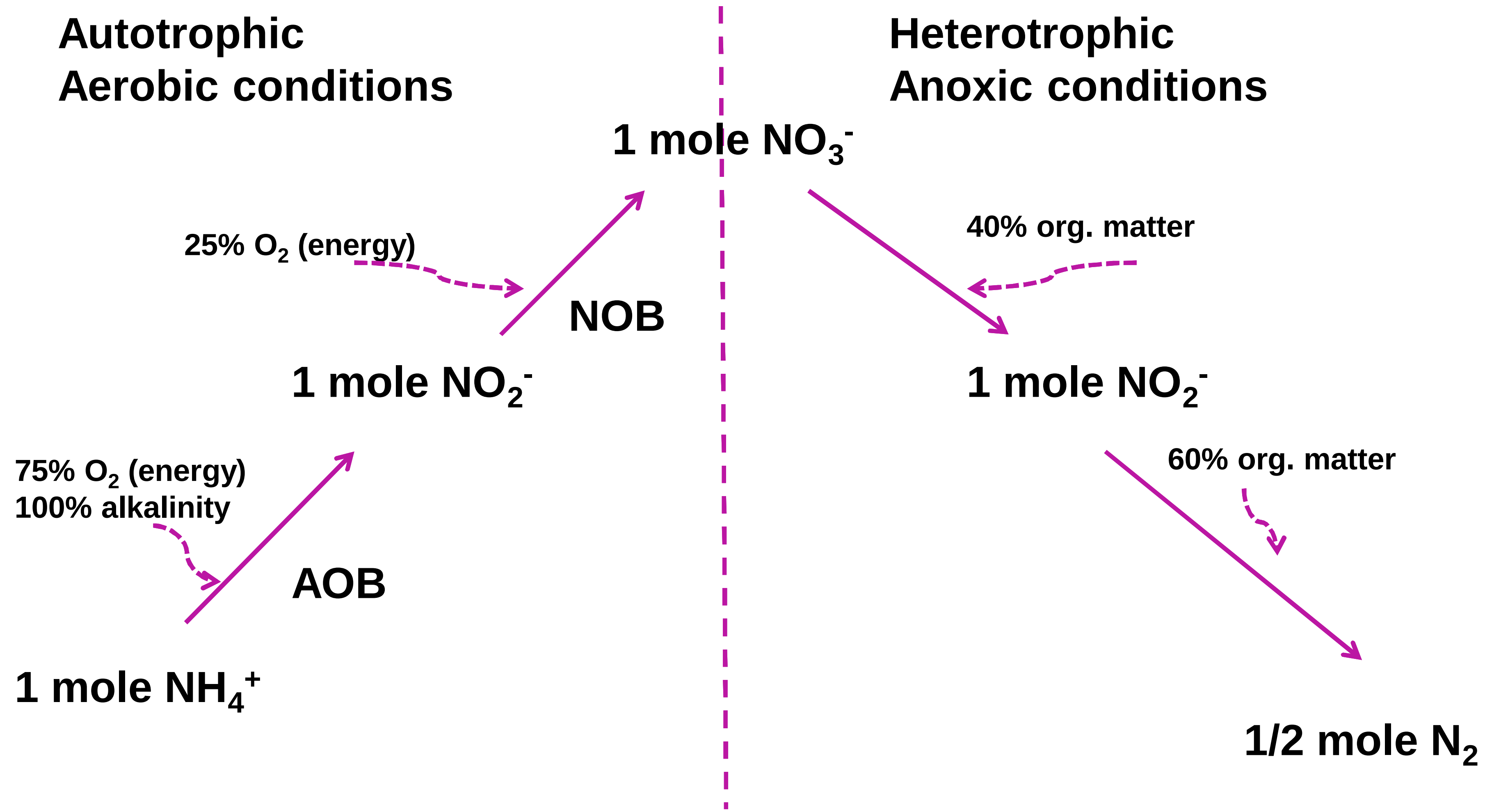
ND processes

- more energy
- carbon source addition
- more lime
- removal up to 95%
- easier to control
- more expensive

DN processes

- some of the aeration compensated
- no carbon addition
- less lime
- removal depends on C/N-ratio and nitrate recycle - max. 70 - 80% (typically 65%) without carbon addition

Conventional (N removal 1.0)



Autotrophic
Aerobic conditions

Heterotrophic
Anoxic conditions

1 mole NO_3^-

25% O_2 (energy)

NOB

1 mole NO_2^-

75% O_2 (energy)
100% alkalinity

AOB

1 mole NH_4^+

40% org. matter

1 mole NO_2^-

60% org. matter

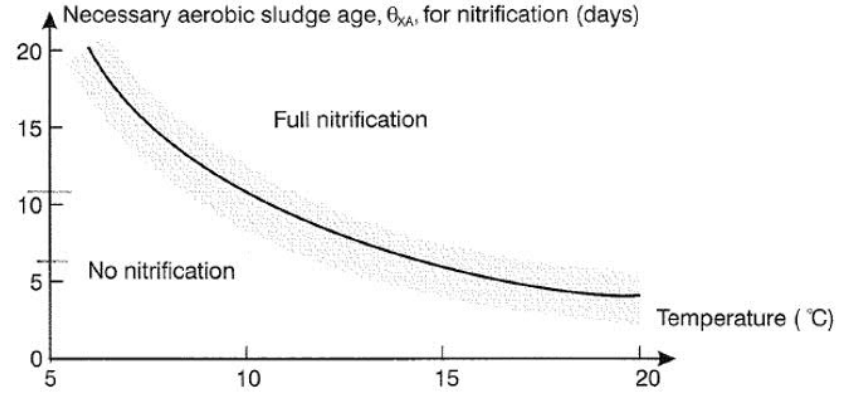
1/2 mole N_2

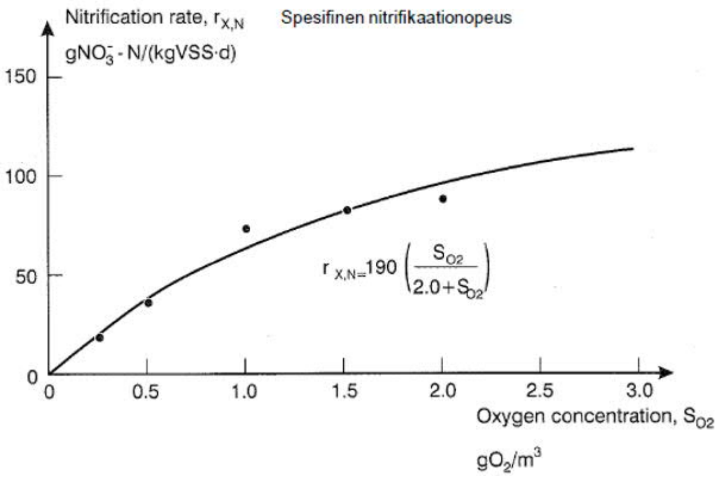
Nitrification

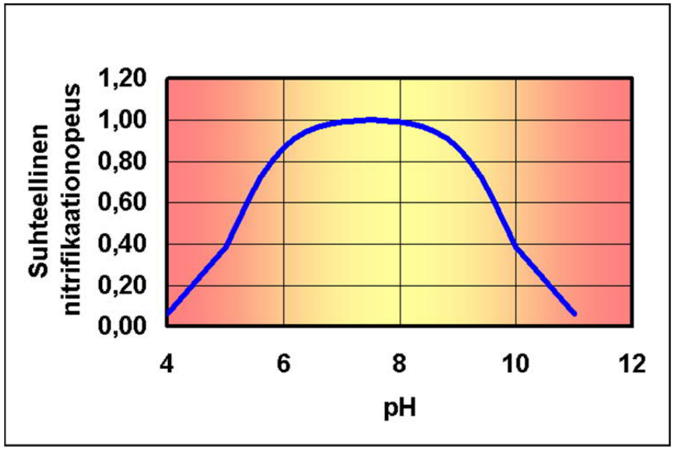
Denitrification

Dimensioning of the process for nitrification

- The limiting process
- Temperature
- DO
- pH
- Toxic substances







Dimensioning of the anoxic volume (denitrification)

- Wastewater quality

- Carbon to nitrogen ratio
- Toxic substances
- Readily biodegradable organic matter

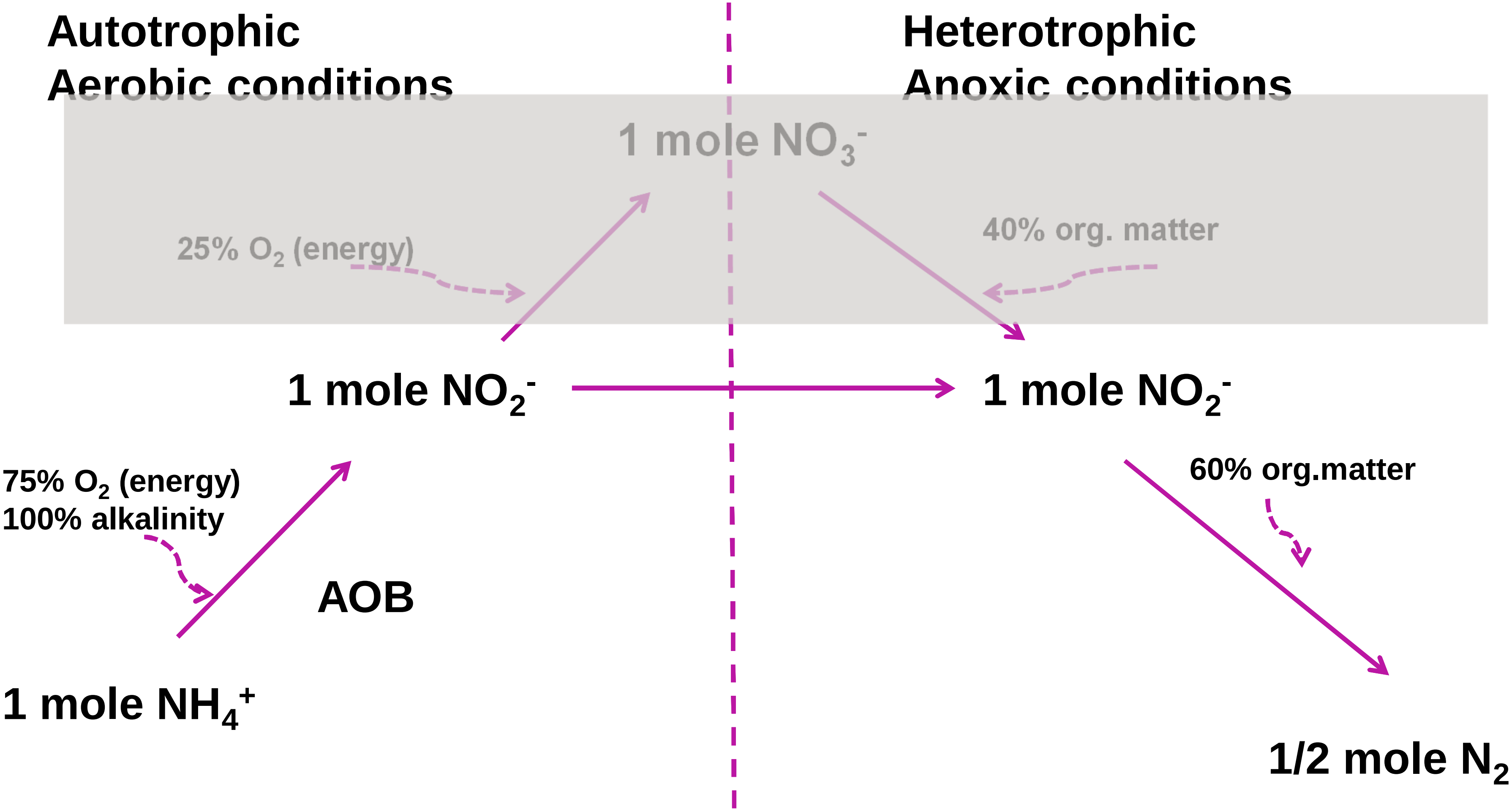
- **Retention time minimum 0,5 – 2 h**
- **To be checked based on the carbon source**

Carbon source	Denitrification rate g N / kgVSSh		
	7 °C	14 °C	20 °C
Raw WW	0,6	1,5	3
Primary settled WW	0,6	1,5	3
Pre-fermented WW	1-2	2-5	5-10
Acetic acid	2	5	10
Methanol	2	5	10

BREAK

Short-cut nitrogen removal

Nitritation-denitritation (SND)
N removal 2.0



Autotrophic
Aerobic conditions

Heterotrophic
Anoxic conditions

1 mole NO_3^-

25% O_2 (energy)

40% org. matter

1 mole NO_2^-

1 mole NO_2^-

75% O_2 (energy)
100% alkalinity

AOB

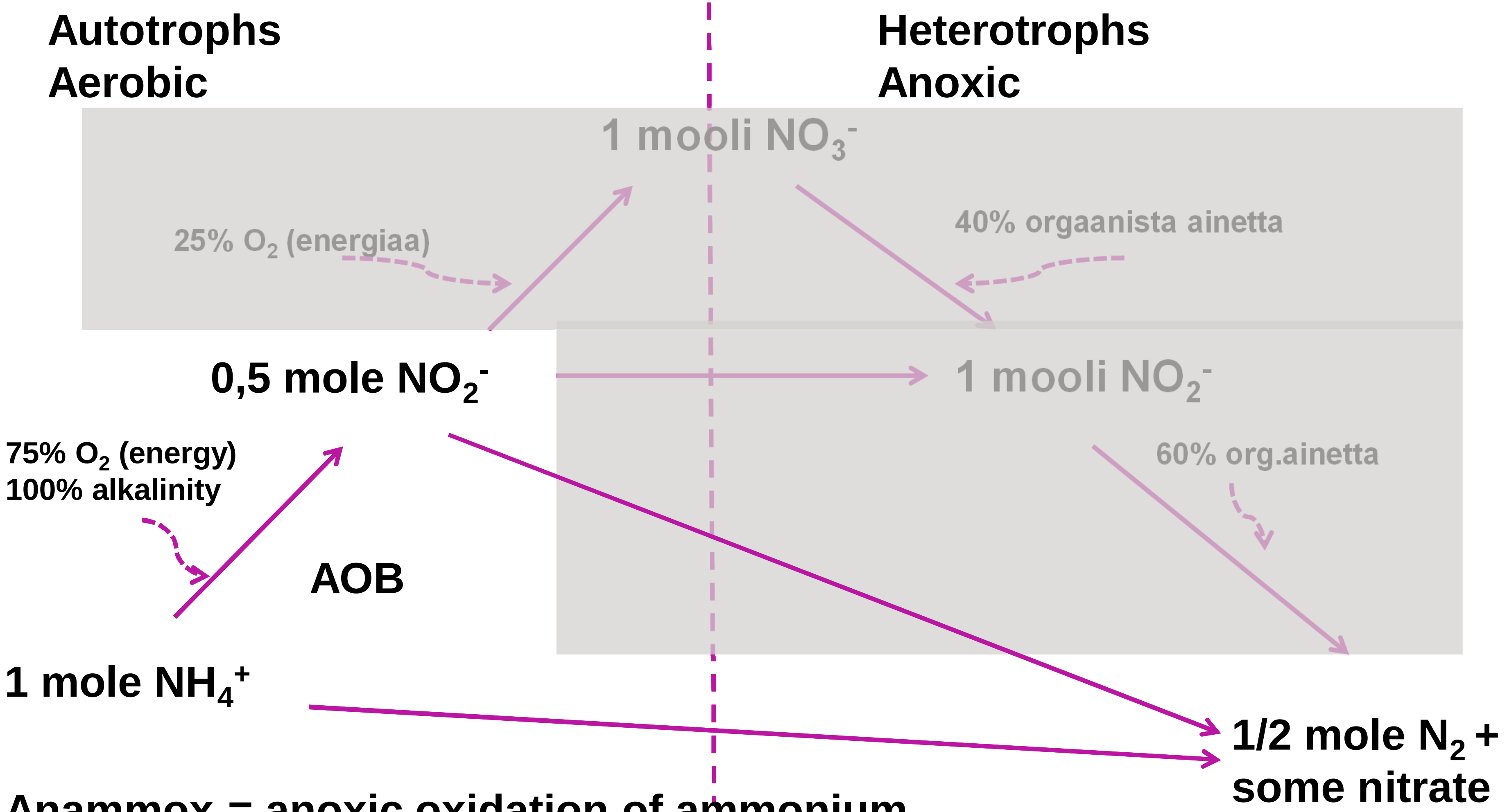
60% org.matter

1 mole NH_4^+

1/2 mole N_2

Less oxygen, less organic matter, less sludge

Nitritation – Anammox or Deammonification



Autotrophs
Aerobic

Heterotrophs
Anoxic

1 mooli NO_3^-

25% O_2 (energiaa)

40% orgaanista ainetta

0,5 mole NO_2^-

1 mooli NO_2^-

75% O_2 (energy)
100% alkalinity

60% org.ainetta

AOB

1 mole NH_4^+

1/2 mole N_2 +
some nitrate

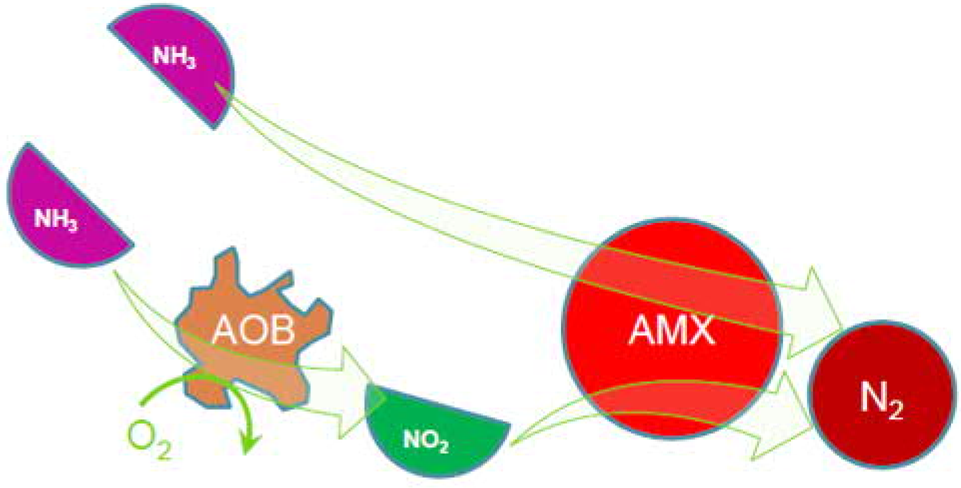
Anammox = anoxic oxidation of ammonium
Anammox belong to Planctomycetes

Deammonification reaction

Catabolic reaction: $NH_4^+ + NO_2^- \rightarrow N_2 + 2\,H_2O$ ($\Delta G° = -357$ **kJ/mol**)

Anabolic reaction: $0.26\,NO_2^- + 0.066\,HCO_3^- \rightarrow 0.26\,NO_3^- + 0.066\,CH_2O_{0.5}N_{0.15}$

- **The combination of partial nitritation and anammox is referred to as deammonification.**
- **Due to the anabolic reaction, AMX growth is always associated with NO_3^- production, which is stoichiometrically 11 % of ammonium converted.**



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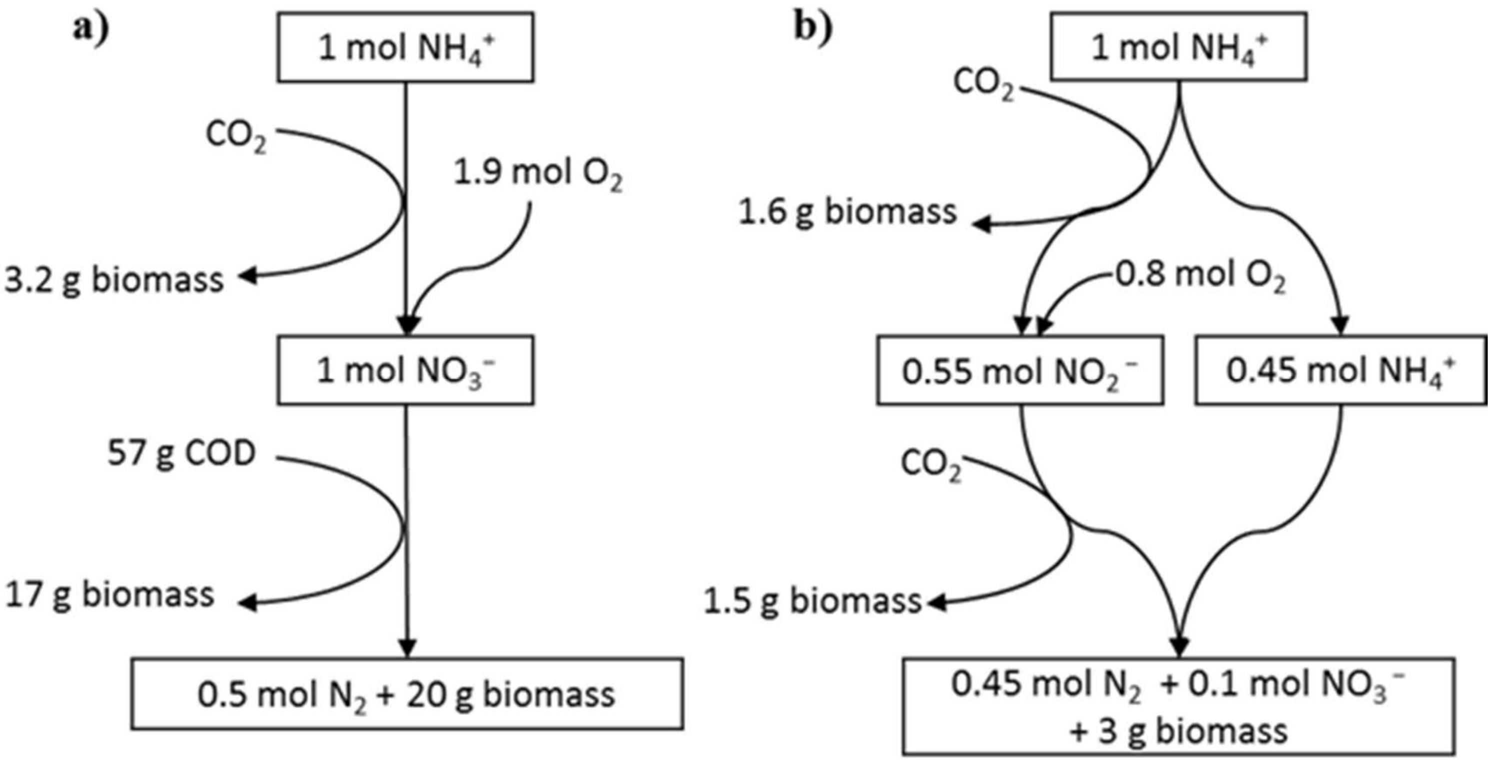
Vilpanen, 2017

Conventional nitrification + denitrification versus deammonification

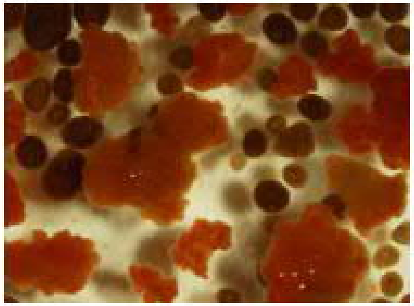


Nitrification + denitrification **Deammonification**

Anammox bacteria

- Low Growth Rate
  - approx. 10 day doubling time at 30°C
  - <10 day has been reported (Park et. al - 5.3 - 8.9 days)
  - SRT (>30 days)

- Sensitive to;
  - Nitrite
    - Toxic- irreversible loss of activity based on concentration & exposure time
    - $NH_4^+ : NO_2^-$ ratio 1 : 1.32
  - DO - reversible inhibition
  - Free ammonia (<10 -15 mg/l)
  - Temperature >30°C preferred
  - pH (neutral range)



Source: AECOM 2012

Deammonication processes

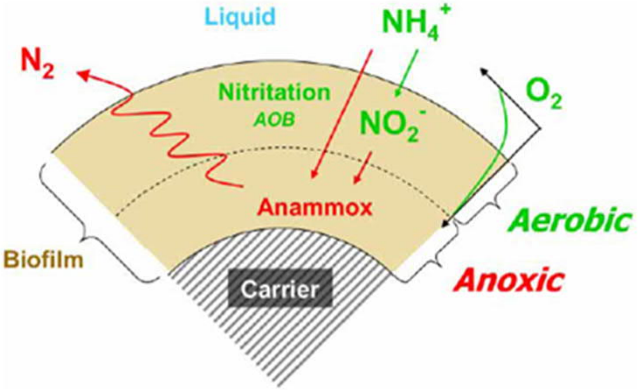
OLAND (Oxygen Limited Autotrophic Nitrification Denitrification)

CANON Completely Autotrophoic Nitrogen removal Over Nitrite

DEMON® Suspended growth SBR

AnitaMOX® Attached growth MBBR

ANAMMOX® (Paques) Upflow granulation process



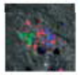
(Christensson et al. 2013).

BACTERIA GAME – Nitrogen removal ☺

- Groups of 2 – 3 in breakout rooms
- Go to your group's platform in Miro
- Move the carbon sources and electron donors and acceptors in the game in order to create beneficial conditions for each bacteria
- You can use the table in the previous slide

Match microorganisms and their beneficial conditions by moving the elements.


Anammox bacteria


Nitrite oxidizing bacteria (NOB)


Organotrophic denitrifying bacteria


Ammonia oxidizing bacteria (AOB)


Aerobic heterotrophs

Carbon sources

Organic matter

Organic matter

CO2

CO2

CO2

Electron donors

Organic matter

Organic matter

Ammonium NH4+

Ammonium NH4+

Nitrite NO2-

Electron acceptors

Oxygen O2

Oxygen O2

Nitrate NO3-

Oxygen O2

Nitrite NO2-

Nitrite NO2-

Microorganismsin water and wastewater treatment

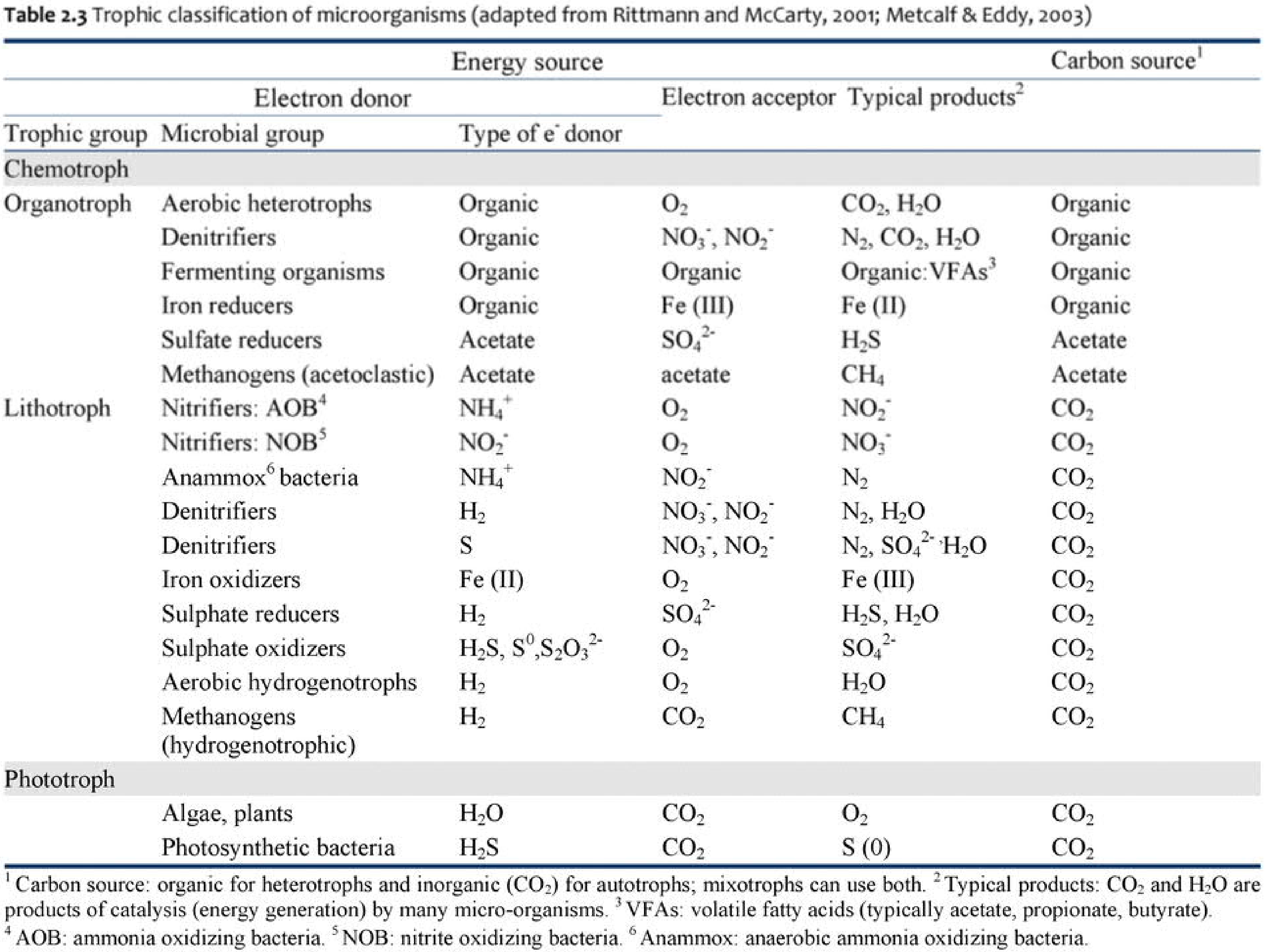


Table 2.3 Trophic classification of microorganisms (adapted from Rittmann and McCarty, 2001; Metcalf & Eddy, 2003)

Energy source					Carbon source[1]
Electron donor			Electron acceptor	Typical products[2]	
Trophic group	Microbial group	Type of e^- donor			
Chemotroph					
Organotroph	Aerobic heterotrophs	Organic	O_2	CO_2, H_2O	Organic
	Denitrifiers	Organic	NO_3^-, NO_2^-	N_2, CO_2, H_2O	Organic
	Fermenting organisms	Organic	Organic	Organic:VFAs[3]	Organic
	Iron reducers	Organic	Fe (III)	Fe (II)	Organic
	Sulfate reducers	Acetate	SO_4^{2-}	H_2S	Acetate
	Methanogens (acetoclastic)	Acetate	acetate	CH_4	Acetate
Lithotroph	Nitrifiers: AOB[4]	NH_4^+	O_2	NO_2^-	CO_2
	Nitrifiers: NOB[5]	NO_2^-	O_2	NO_3^-	CO_2
	Anammox[6] bacteria	NH_4^+	NO_2^-	N_2	CO_2
	Denitrifiers	H_2	NO_3^-, NO_2^-	N_2, H_2O	CO_2
	Denitrifiers	S	NO_3^-, NO_2^-	N_2, $SO_4^{2-}\cdot H_2O$	CO_2
	Iron oxidizers	Fe (II)	O_2	Fe (III)	CO_2
	Sulphate reducers	H_2	SO_4^{2-}	H_2S, H_2O	CO_2
	Sulphate oxidizers	H_2S, S^0,$S_2O_3^{2-}$	O_2	SO_4^{2-}	CO_2
	Aerobic hydrogenotrophs	H_2	O_2	H_2O	CO_2
	Methanogens (hydrogenotrophic)	H_2	CO_2	CH_4	CO_2
Phototroph					
	Algae, plants	H_2O	CO_2	O_2	CO_2
	Photosynthetic bacteria	H_2S	CO_2	S (0)	CO_2

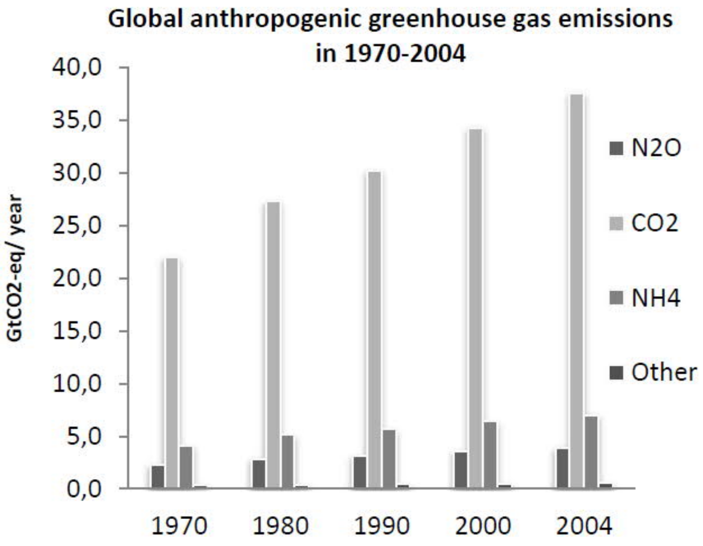
[1] Carbon source: organic for heterotrophs and inorganic (CO_2) for autotrophs; mixotrophs can use both. [2] Typical products: CO_2 and H_2O are products of catalysis (energy generation) by many micro-organisms. [3] VFAs: volatile fatty acids (typically acetate, propionate, butyrate). [4] AOB: ammonia oxidizing bacteria. [5] NOB: nitrite oxidizing bacteria. [6] Anammox: anaerobic ammonia oxidizing bacteria.

BREAK

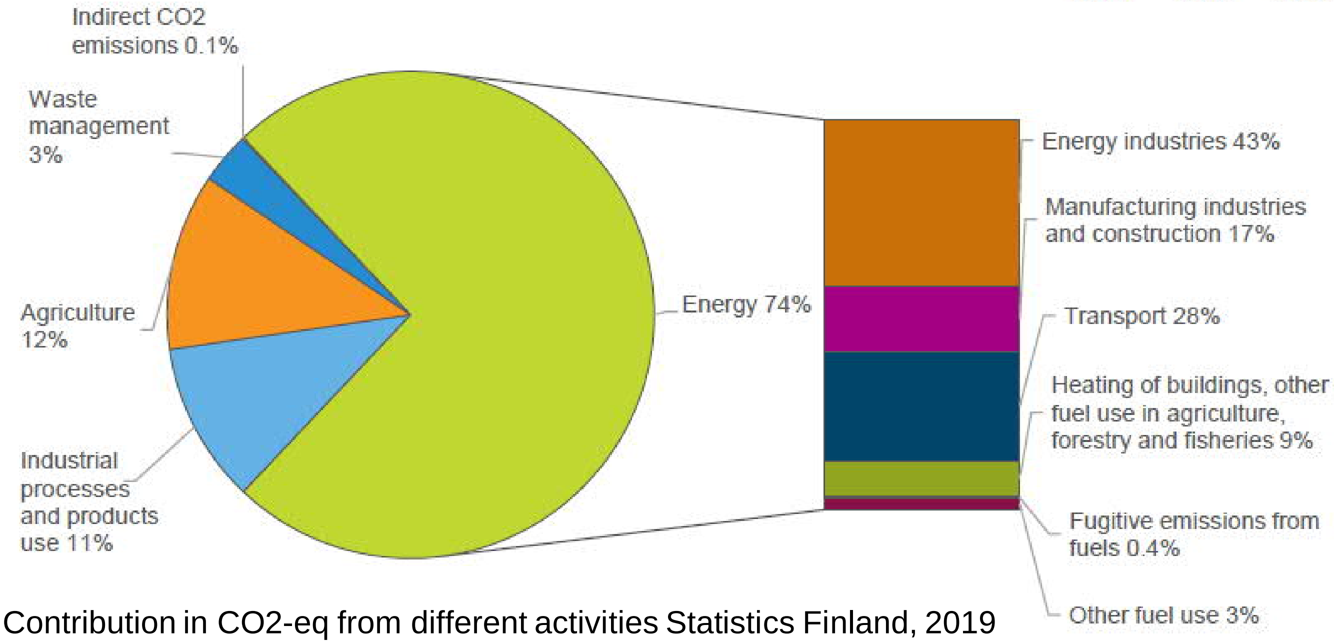
Gaseous emissions during nitrogen conversions

N_2O emissions globally and in Finland

300 times stronger greenhouse gas compared to CO_2



IPCC, 2007



Contribution in CO2-eq from different activities Statistics Finland, 2019

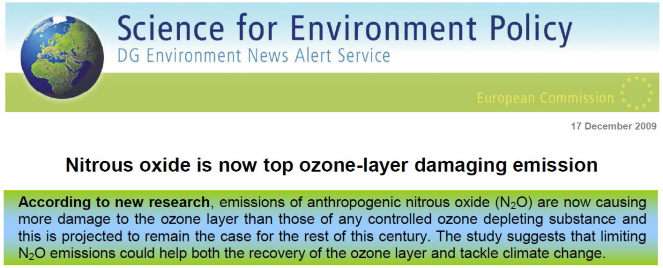
Role in ozone depletion

Laughing gas is biggest threat to ozone layer

24

EARTH 27 August 2009

By **Lisa Grossman**

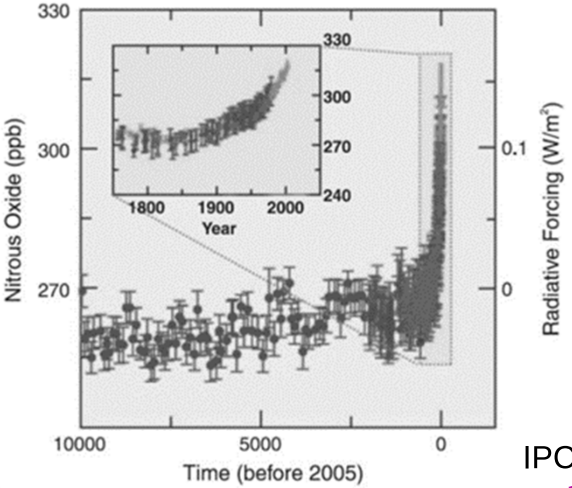


Science for Environment Policy
DG Environment News Alert Service
European Commission

17 December 2009

Nitrous oxide is now top ozone-layer damaging emission

According to new research, emissions of anthropogenic nitrous oxide (N_2O) are now causing more damage to the ozone layer than those of any controlled ozone depleting substance and this is projected to remain the case for the rest of this century. The study suggests that limiting N_2O emissions could help both the recovery of the ozone layer and tackle climate change.



IPCC, 2007

- N_2O rises up into the stratosphere where most of it breaks down to nitrogen and oxygen.
- Remaining N_2O destroys ozone and makes the ozone layer thinner everywhere.
- N_2O is now the dominant ozone-depleting substance
- N_2O emissions increase by 0,25% every year

Group discussion

Search for information about the CO_2 goals of your home town / town of your origin.

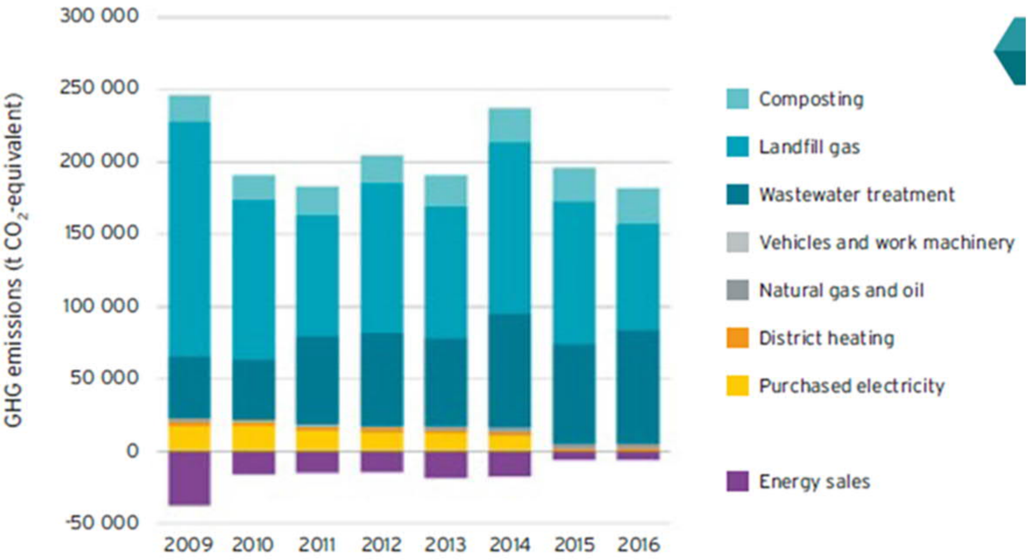
Discuss and compare the goals in groups.

(10 minutes)

Why is N_2O relevant for cities?

Wastewater treatment emissions are becoming more dominant

Can’t be solved by switching into renewables



HSY’s greenhouse gas emissions in 2010-2016 and that of similar operations in 2009.

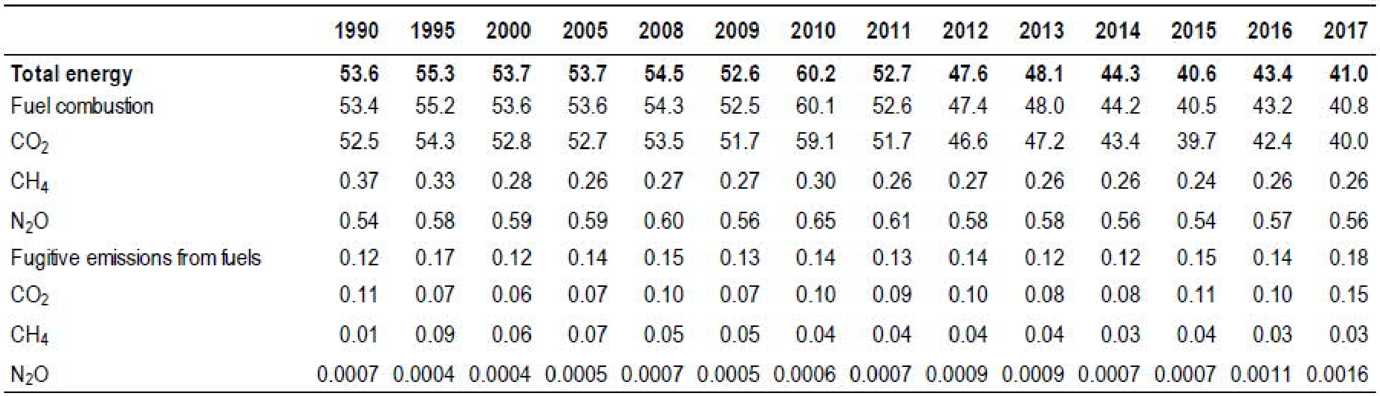


Table 3.1-2 Emissions from the energy sector by subcategory and gas (Mt CO_2 eq.)

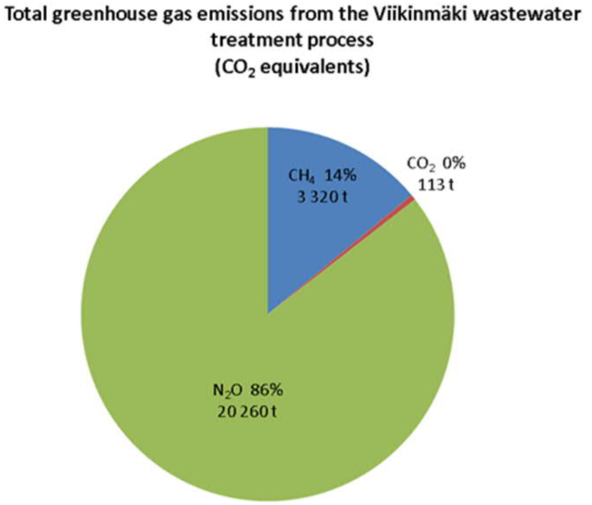
	1990	1995	2000	2005	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Total energy	**53.6**	**55.3**	**53.7**	**53.7**	**54.5**	**52.6**	**60.2**	**52.7**	**47.6**	**48.1**	**44.3**	**40.6**	**43.4**	**41.0**
Fuel combustion	53.4	55.2	53.6	53.6	54.3	52.5	60.1	52.6	47.4	48.0	44.2	40.5	43.2	40.8
CO_2	52.5	54.3	52.8	52.7	53.5	51.7	59.1	51.7	46.6	47.2	43.4	39.7	42.4	40.0
CH_4	0.37	0.33	0.28	0.26	0.27	0.27	0.30	0.26	0.27	0.26	0.26	0.24	0.26	0.26
N_2O	0.54	0.58	0.59	0.59	0.60	0.56	0.65	0.61	0.58	0.58	0.56	0.54	0.57	0.56
Fugitive emissions from fuels	0.12	0.17	0.12	0.14	0.15	0.13	0.14	0.13	0.14	0.12	0.12	0.15	0.14	0.18
CO_2	0.11	0.07	0.06	0.07	0.10	0.07	0.10	0.09	0.10	0.08	0.08	0.11	0.10	0.15
CH_4	0.01	0.09	0.06	0.07	0.05	0.05	0.04	0.04	0.04	0.04	0.03	0.04	0.03	0.03
N_2O	0.0007	0.0004	0.0004	0.0005	0.0007	0.0005	0.0006	0.0007	0.0009	0.0009	0.0007	0.0007	0.0011	0.0016

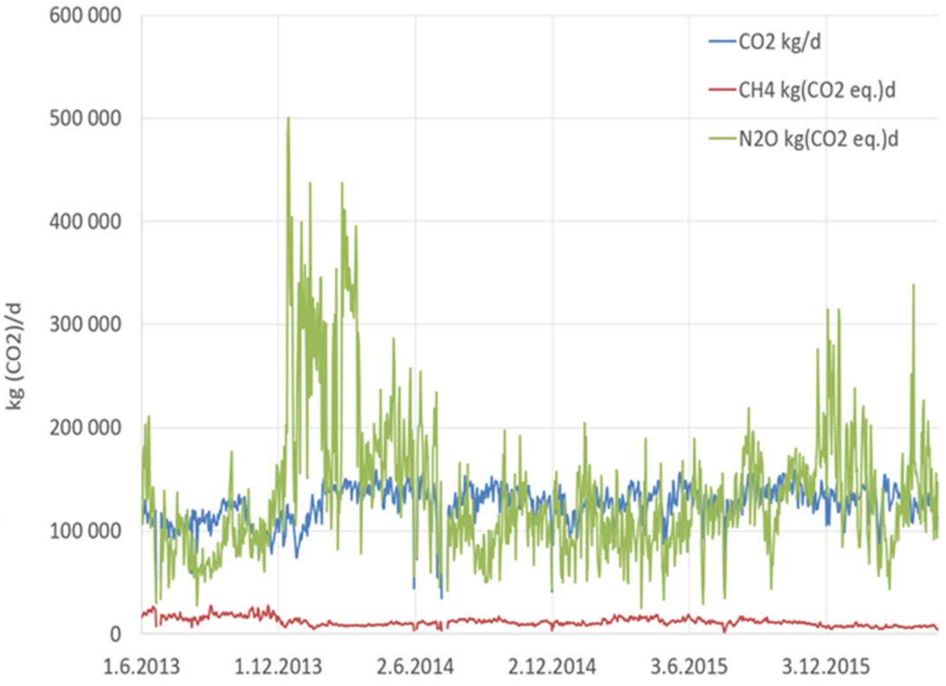
Statistics Finland, 2019

Why is N_2O relevant for wastewater treatment?

Produced in the biological nitrogen removal

Often the most significant greenhouse gas emitted in wastewater treatment


Total greenhouse gas emissions from the Viikinmäki wastewater treatment process (CO_2 equivalents)



Pathways of N_2O production

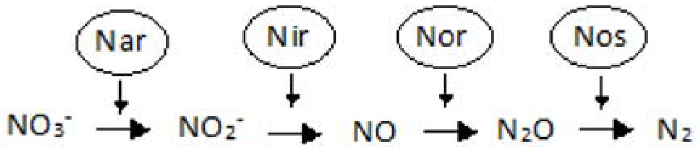
Nitrification

$NH_3 + O_2 + 2H^+ + 2e^- \rightarrow NH_2OH + H_2O$

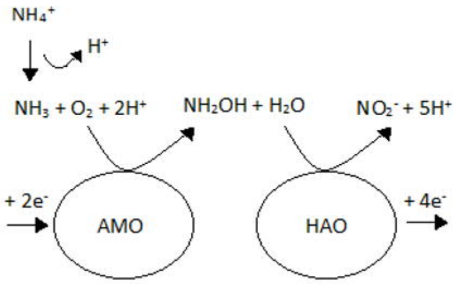
$NH_2OH + H_2O \rightarrow NO_2^- + 5H^+ + 4e^-$

$NO_2- + H_2O \rightarrow NO_3- + 2H+ + 2e-$

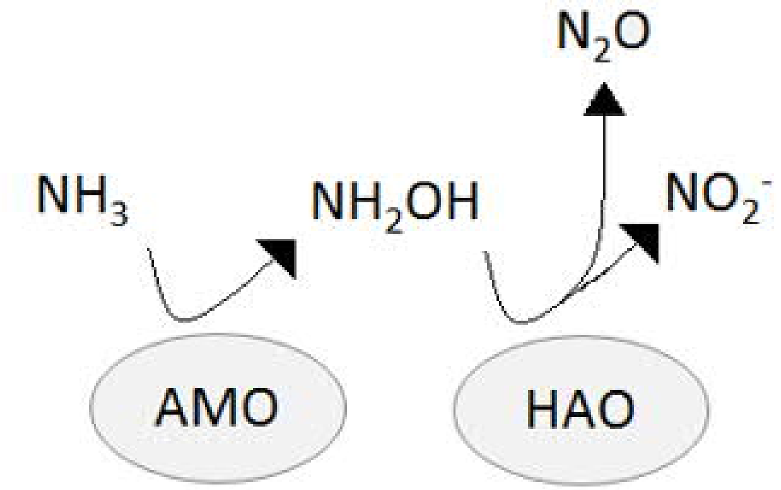
Denitrification



Two pathways related to nitrifiers:
Hydroxylamine pathway and nitrifier denitrification

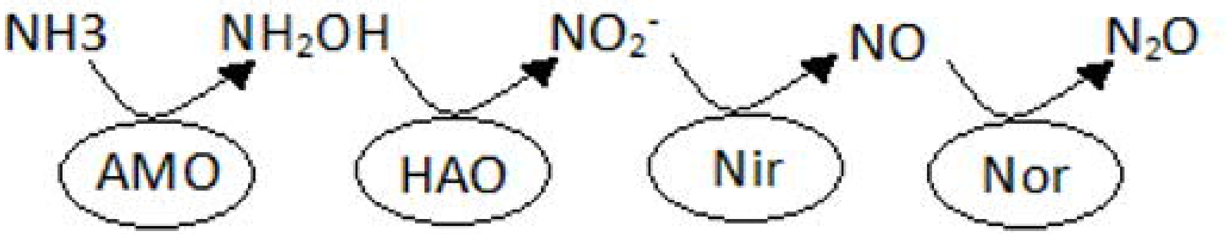


Hydroxylamine oxidation



Strong correlation to ammonium concentration
Increase in ammonium leads to accumulation of intermediate components

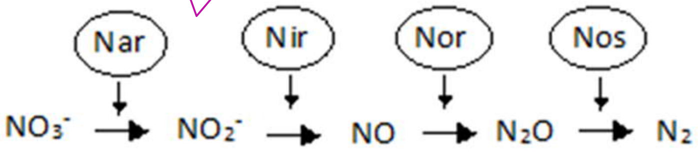
Nitrifier denitrification



Strong correlation to low DO and/or to high nitrite concentrations
A way for microbes to avoid high toxic nitrite concentrations

Heterotrophic denitrification

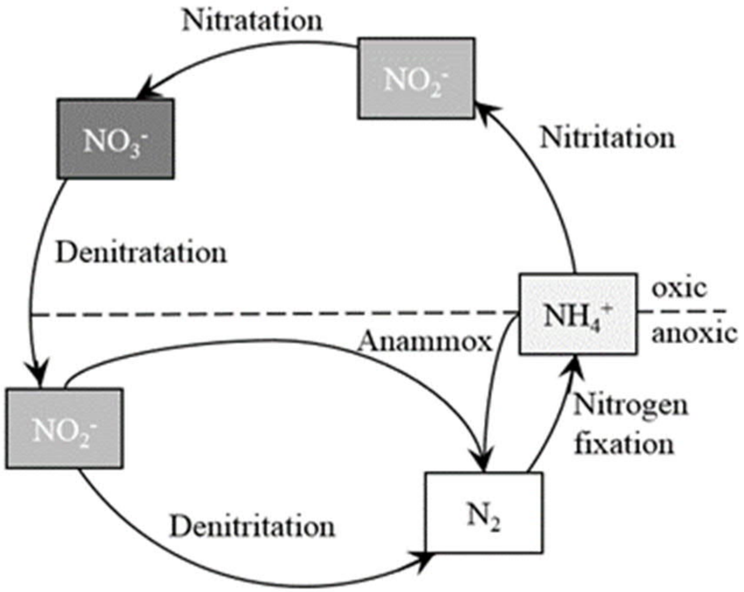
A source or a sink?



Production related to DO in the anoxic zones, COD limitation and low pH
Nos is more sensible and suffering from the competition

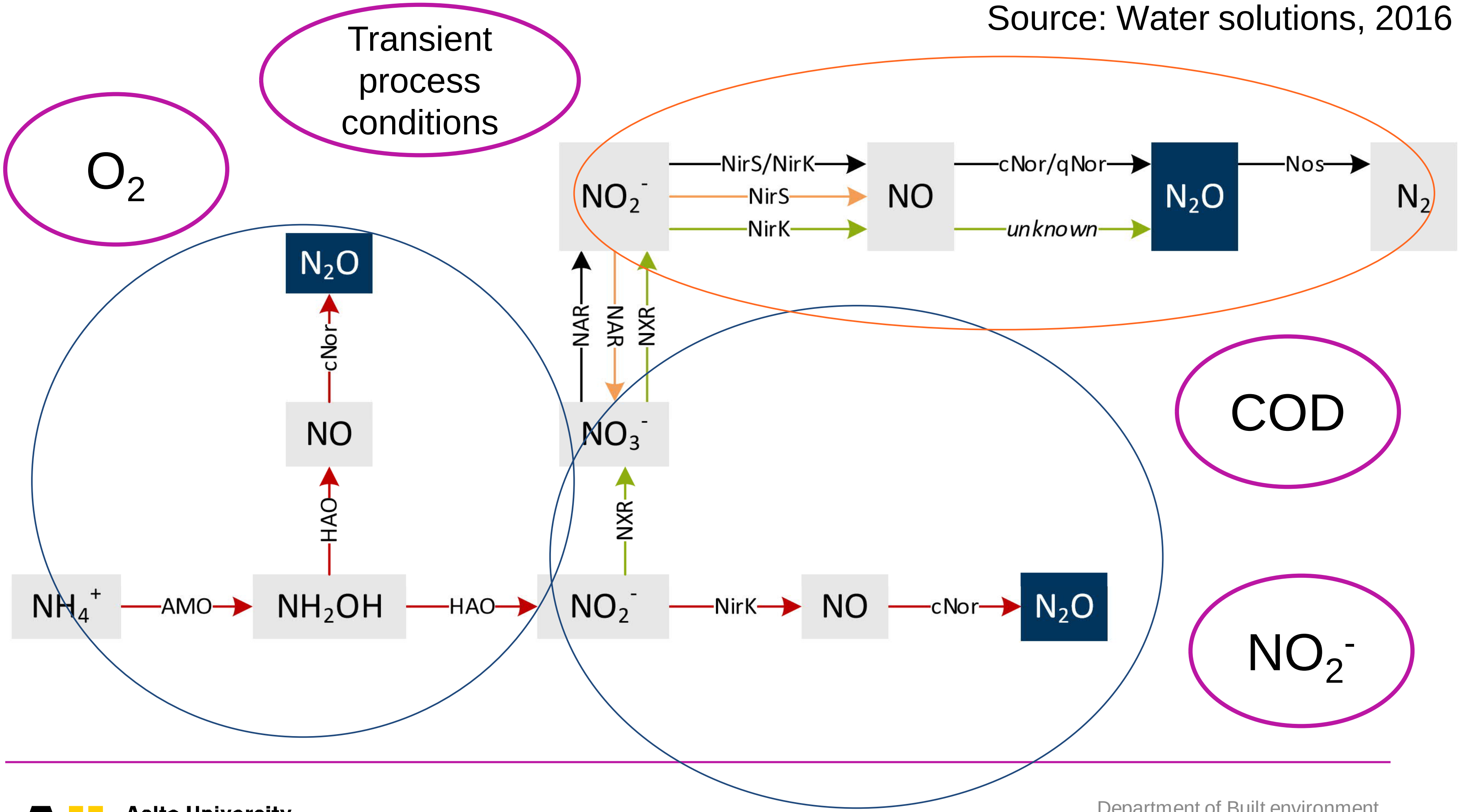
Short-cut nitrogen removal processes

- Short-cut nitrogen removal processes have been developed mainly to decrease the energy consumption (and CO_2 footprint)
- Nitritation + denitritation and deammonification by anammox bacteria
- Reported N_2O emissions vary between 0 – 15% of the nitrogen load



Production of N_2O in the wastewater treatment

Source: Water solutions, 2016



Reading material

Biological wastewater treatment (Course book):

Chapters

4.2-4.3

4.11

Nitrogen removal

5.1

6.1

6.3-6.6

Activated sludge process from the other course book (Environmental Biotechnology)

Pages 213-222