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Landfill aeration: review of technical issues and effectiveness

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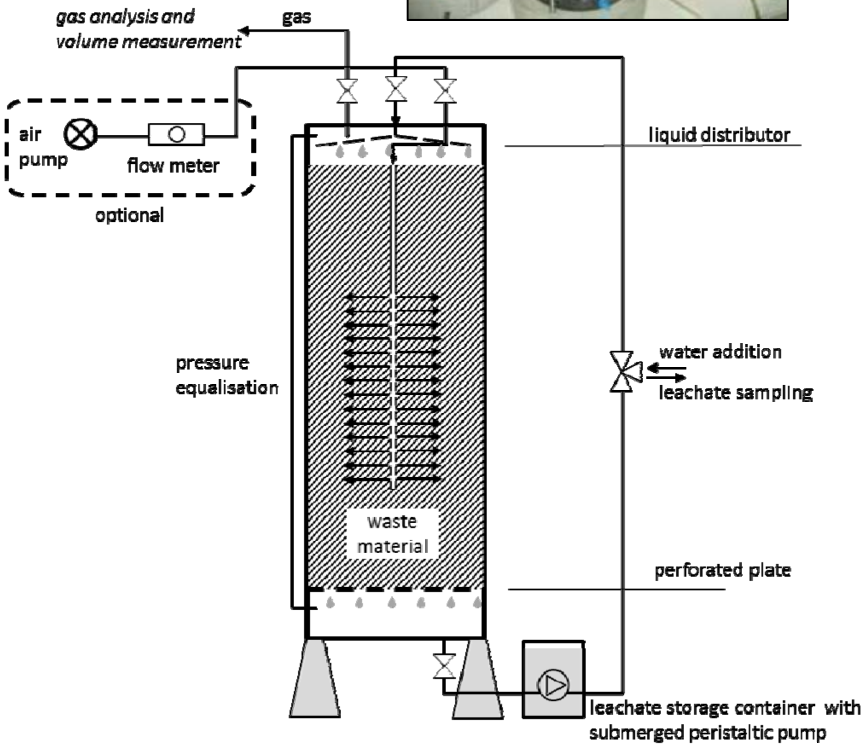
Engineering and the Environment

Introduction

- **Studies into landfill aeration since early 1990s, full scale early 2000s:**
  - Main players in its development: Germany, Austria, Italy, USA
- **What might be the main drivers for landfill aeration in the UK?**
  - reduce gas emissions to within the capacity of passive control systems
  - reduce leachate NH_4-N to within the capacity of passive control systems
  - currently no strong financial incentive to further reduce GHG emissions
- **Content of presentation:**
  - what can be achieved under optimized conditions (lysimeters)
  - what has been achieved in full scale projects
  - factors leading to reduced efficiency in full scale projects to date
  - aeration system design
  - fate of leachate nitrogen
  - other aspects e.g. fire/high temperature, settlement, metal mobility
  - challenges, limitations, cost context

Lysimeters* show what is possible:

- **Conditions are generally optimized:**
  - **shredded homogenized waste; no barriers to flow**
  - **controlled temperature and moisture regime**
  - **often high aeration rates**
  - **likely to be good, uniform distribution of air**
  - **often include high rate leachate recirculation, which aids mixing and liquid/air contact**
  - **often flushed at high rate**
  - **easier to do gas and liquid mass balance**
  - **Typical LSR , 40cm ϕ, 120cm tall, ~70kg/100 litres waste**



* Landfill Simulation Reactors, or LSRs

Lysimeters: results summary

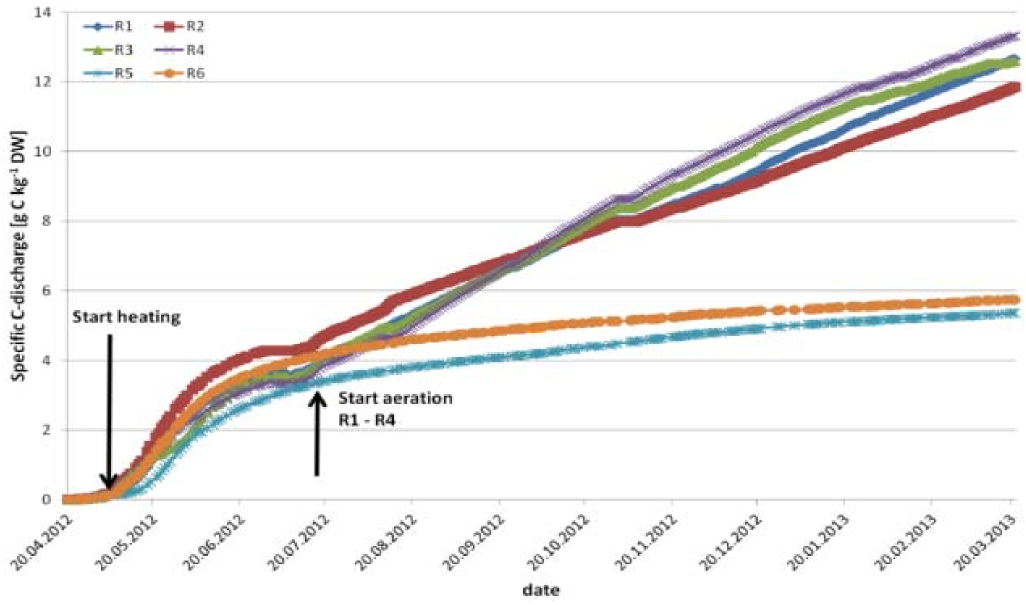
- **Acceleration of carbon flux**
  - mainly as CO_2
  - reductions in solids organic content (RA_4, GP_{21}, BMP, Cellulose, LoI etc.
- **Rapid removal of leachate NH_4-N to near zero**
- **Some reduction of leachate hard COD**
- **Post aeration: low C-flux, low NH_4-N**
  - fewer data on post-aeration phase emissions

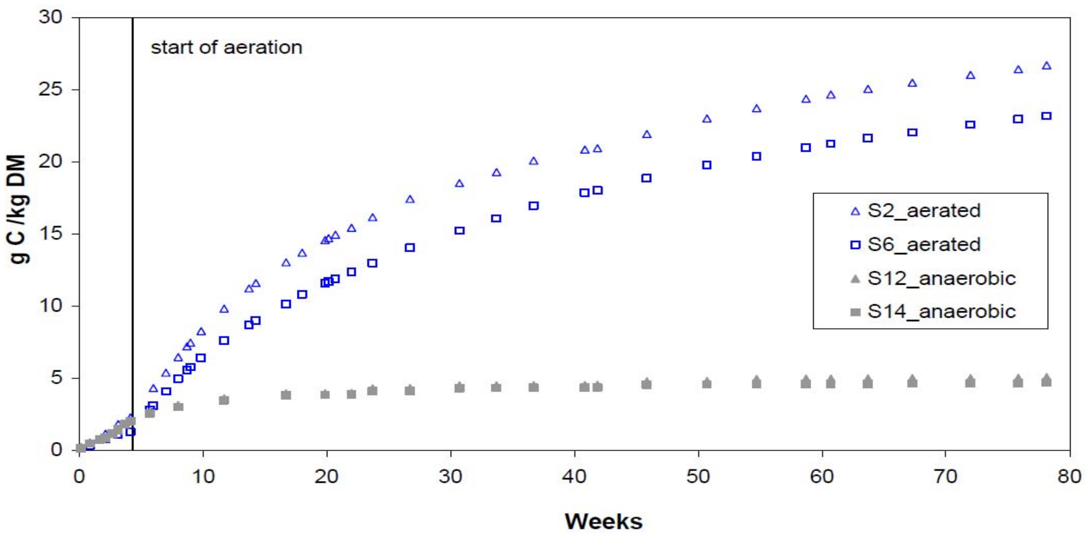
		units	Leikam et al, Germany 1997	Klingenthal, Germany	Kuhstedt, Germany	USA, Berge et al	Heferlbach, Austria	Mannersdorf, SE of Vienna, Austria	Mannersdorf, SE of Vienna, Austria	Mannersdorf, Austria	Austria, unidentified	Laogang, China	Canada, Calgary
Site/waste details	Filling period of study zone			1977 - 1998	mid 60s - 1987		1965 - 1973	(ii) 1986-1995	(ii) 1986-1995	(i) 1976-1985 (ii) 1986-1995	1979 - 2004		
	Years since closure		8 - 14	pre-1990; post-1992; mixtures	11 and 13; (1998 and 2000 expts)		39	8	8	13	6	"5 - 8 years since landfilled"	>30
	Age of waste studied	years		>12; 4-10; mix							~12		
	Quantity of waste in lysimeter(s)	kg		70	70		70kgDM	15kgDM	15kgDM	120	12	3,100	
		litres		120	120		120			70	20		
	In situ waste density	t/m3								1.6		1.4 (high)	0.3 (low)
	Diameter of lysimeter	mm		400	400		400	200	200	400	200	1,000	
	Area of lysimeter top surface	m2		0.126	0.126		0.126	0.031	0.031	0.126	0.031	0.785	
	Waste depth in lysimeter	cm		~100	~100			65	65		52	200	
	Temperature controlled?			yes	yes		yes	yes	yes	yes	yes	no	
	Temperature	C		35	35		36	35	35	40		-2 to +37	
Aeration/ irrigation details	Initial moisture content	% WM		40			23 - 28						
	Water irrigation rate	litre/d		6	4		~1						
		mm/d		48	32								
		mm/a		17,380	~12,000						1000	1200?	
	Clean water flushing rate	litre/week		not clear	1		~0.5			1.2	0.55		
	Aeration rate(s)	litre/day		Zero x 12wks, 20 x 12 weeks, 70 x 6 weeks, 320 x 6 weeks	not reported	3988 i.e. massive rate		12/24		72	24	720 - 1440	
		m3/t.a		104, 365, 1668	88	104,000	174	175 & 350	185	219	730	85 - 170	
	Aeration period	d		280	640/930/1350		731	513 & 270	514	740	545	4.5years	
	Aeration strategy				from below		central lance	from below	from below	from below	from below	via 3 levels	
Effects	Pre-aeration carbon flux	m3/t.a											
	Carbon flux during aeration	m3/t.a	2.6 - 34	no data on carbon flux or gas comp.	(i) 41 (ii) 8 (iii) 6.4		AW 22.5 AD 22.5, cf AN 7, so 3x accel'n		11.6	10.6	(i) overall 18.2 (ii) final rate 7.3	0.6	
	Carbon flux overall effect		3 - 5x acceleration				3x accel'n; TOC loss of ~2.2%DM			flux remained low after stop aeration, noCH4 detected		2x acceleration cf "anaerobic"	
	Gas composition										all CO2, no CH4		
	Removal of NH4-N	rate		Yes: ~3 to 6mg/l.d	Yes: ~4mg/l.d	33mg/l.d	2.7mg/l.d in wet aerated (AW)	yes; 25mg/l.d			yes: 22 mg/l.d	yes; ~6mg/l.d	
		lag (d)		45 - 85	~35-40	no					35		
	Impact on metal mobility			no data	Increase, mainly Cu, Cd, Pb. Slight increase Ni, Cr.	Exponential decline, consider air stripping role?	no data	no metals data	no metals data	no metals data			

Lysimeters: acceleration of carbon flux

- **Benchmark**
  - Starting point is the gas curve for real landfills:
  - ~1m³/t.a +/-, with 50-75 m³/t potential remaining.
  - Looking for acceleration compared with that.

Lysimeters: acceleration of carbon flux cf anaerobic





- aerobic 3-5x anaerobic
- sometimes get initial burst then slows down
- still significant rates after prolonged aeration period

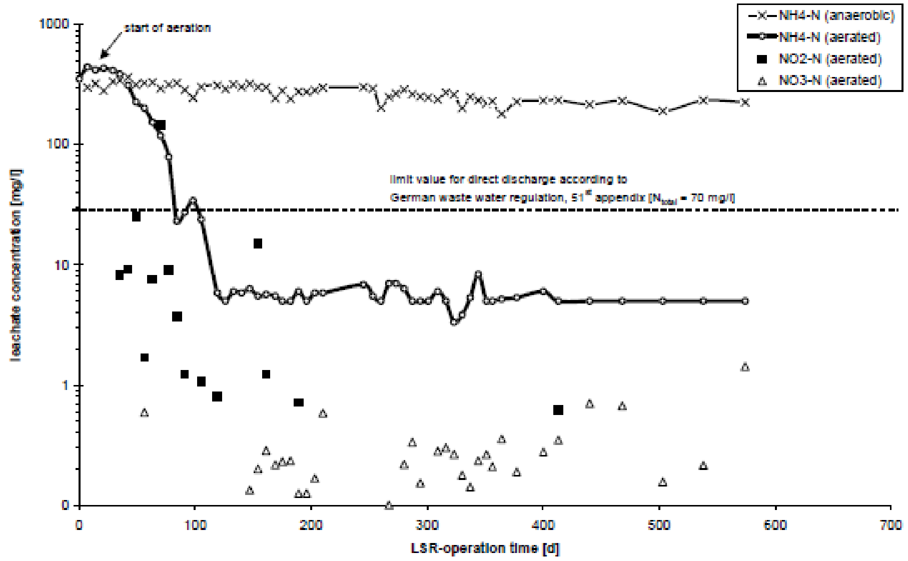
Sources shown: Brandstatter, Heferlbach lysimeters (2015);; Huber-Humer et al, Mannersdorf lysimeters, 2013

Lysimeters: acceleration of carbon flux

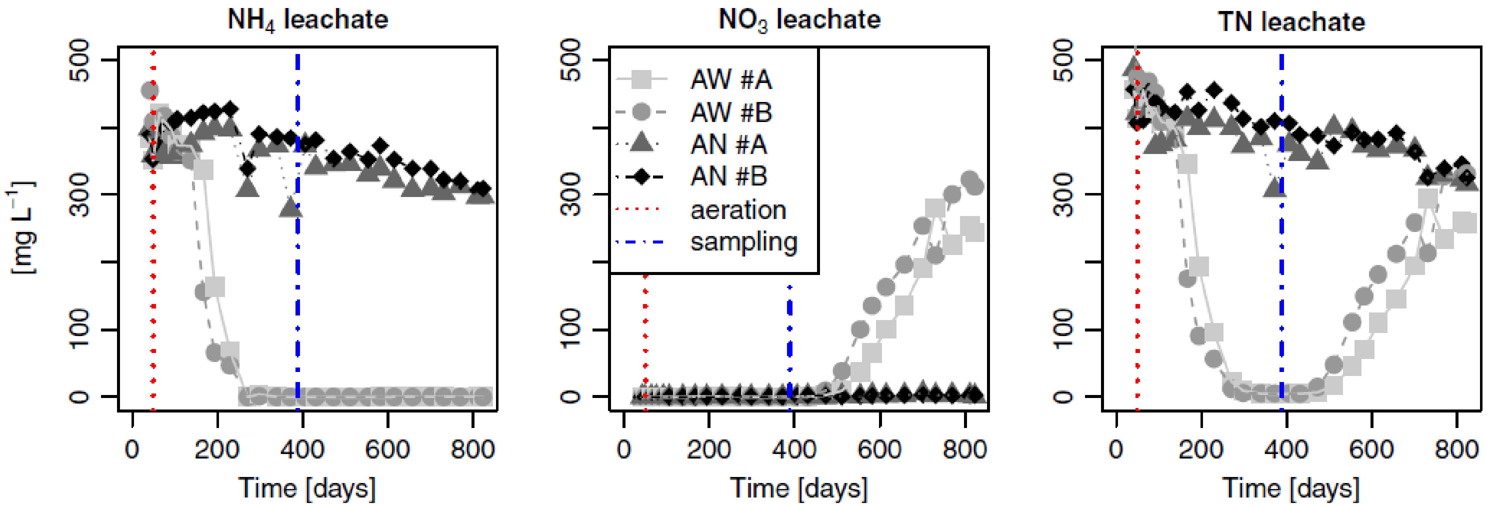
- table shows carbon flux in a range of aerated lysimeters
- shown as equivalent LFG flow (50% CH_4/ 50% CO_2) in $m^3/t.a$
- compare with 'tail' rates of 1 $m^3/t.a$:

Various lysimeters	2.6 - 34	Leikam et al, 1997
Initial rate, Days 1-40	41	Ritzkowski et al, 2003
Steady rate, Day 40-250	8	
Aerated, wet	22.5	Brandstatter et al
Aerated, dry	22.5	
Anaerobic control	7	
Aerated, wet	11.6	Prantl et al, 2005
Aerated, wet	10.6	Hrad et al, 2013
Average over whole study	18.2	Huber-Humer et al, 2013
Rate at end of study	7.3	

Lysimeters: removal of ammonia from leachate

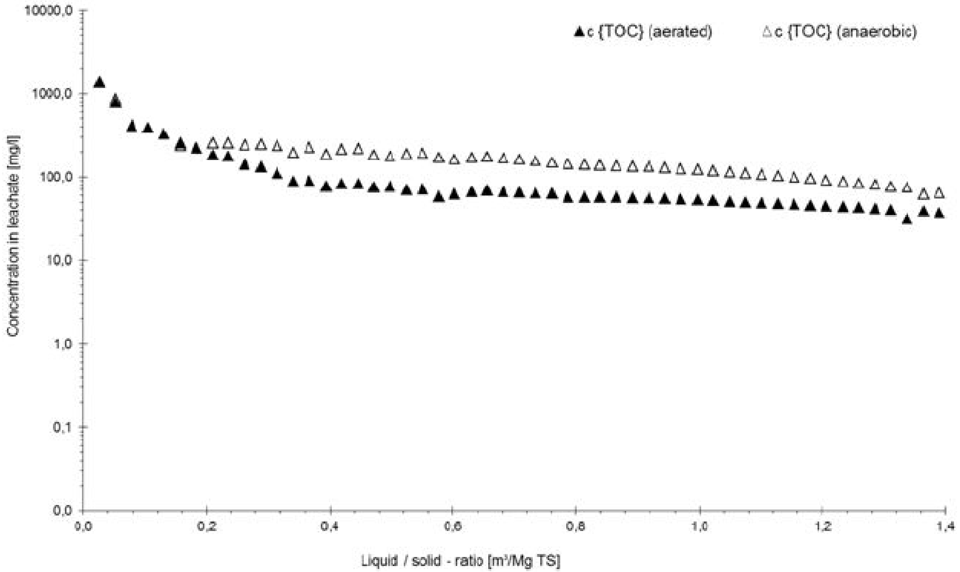


- Examples shown from two studies
- Rapid removal cf flushed anaerobic LSRs
- Range 2.7 – 25 $mgNH_4$-N/l.d
- short lag period 35-45 days
- late appearance of nitrate



Sources: 2003 Ritzkowski et al; 2003 Hantsch et al; 2015 Brandstatter et al

Lysimeters: impact on leachate hard COD



Source: 2011 #751, Fig 3. Kuhstedt lysimeters

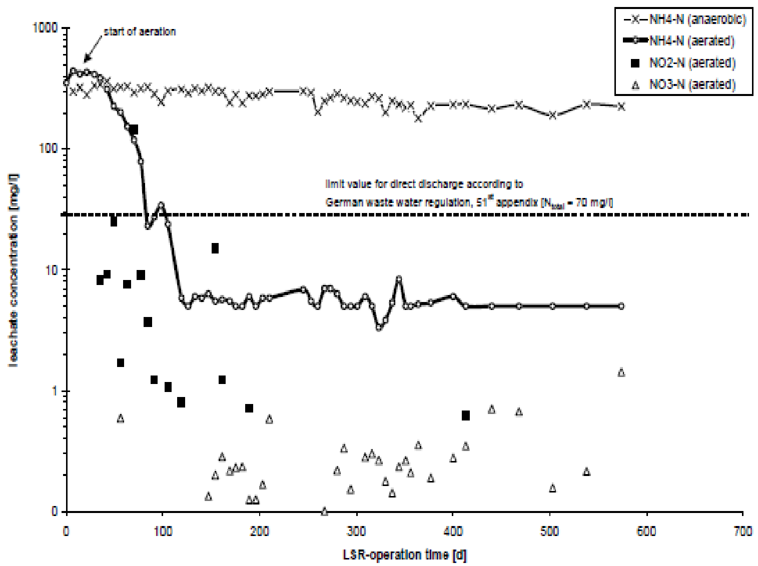
- graph shows aerated cf. anaerobic
- table shows aerated wet/dry cf anaerobic wet
- modest reductions in COD or TOC
- not solely due to flushing

AW &AD = aerated wet/dry; AN = anaerobic, wet

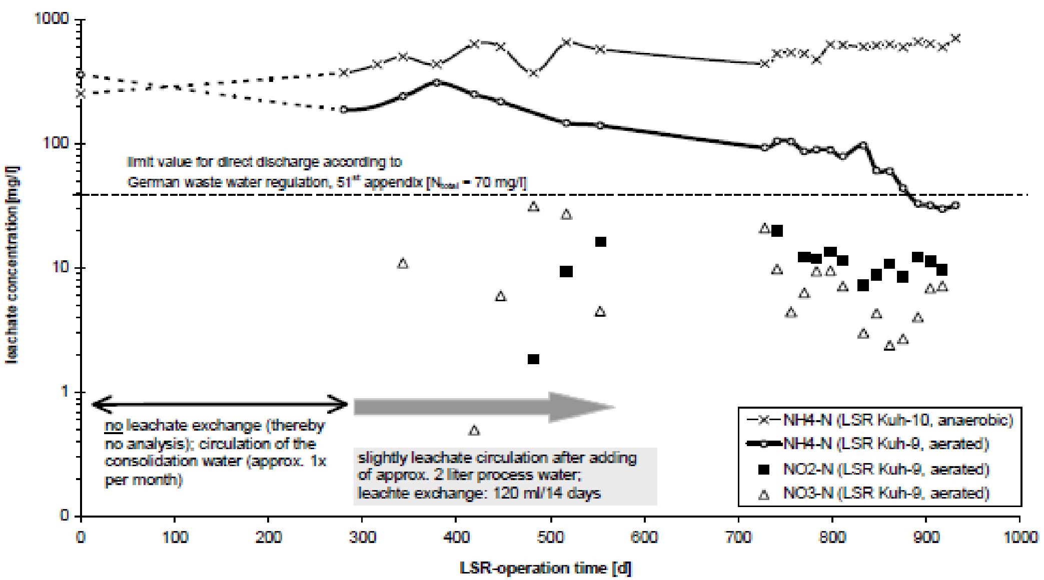
	AW start	AD start	AN start	AW finish	AD finish	AN finish
COD, mg/l	342	384	399	14.4	58.6	112
BOD, mg/l	195	225	229	1.2	2.4	37.5

Source: 2015 Brandstatter, Heferlbach lysimeters

‘Wet’ vs ‘dry’ operation



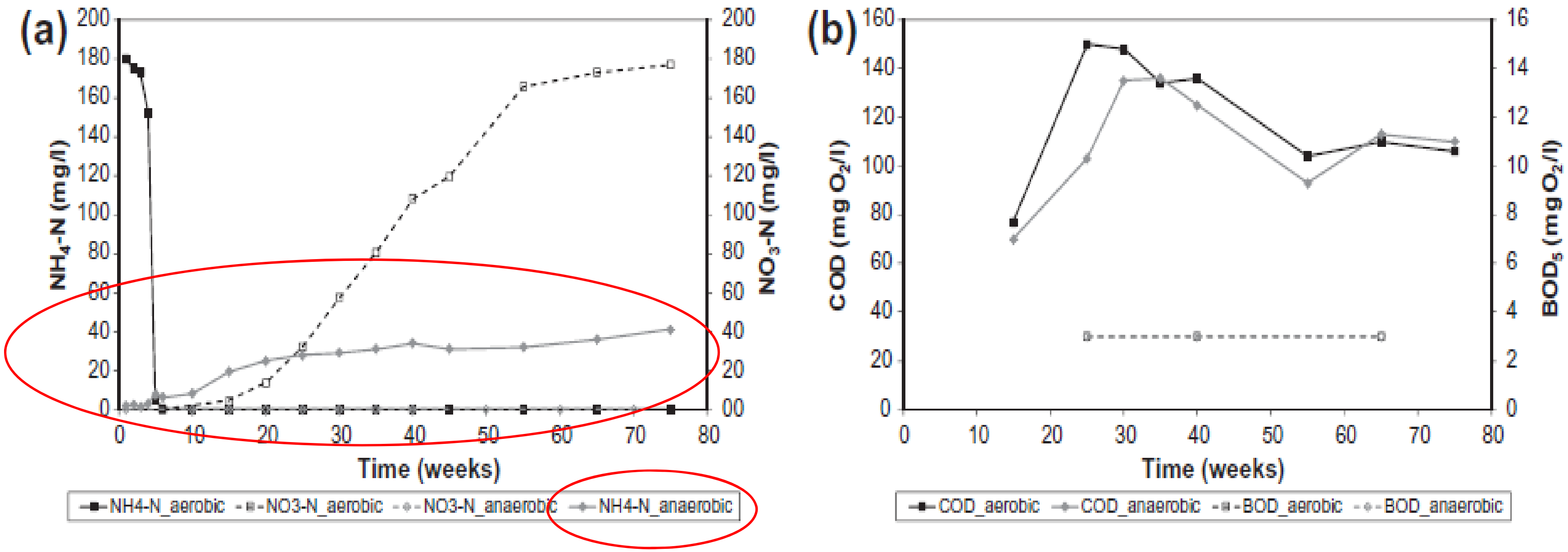
- Comparison of ‘wet’ (upper chart) and ‘dry’ (lower chart) lysimeters at Kuhstedt
- ‘Wet’: recirculation HRT ~1 week; clean water HRT ~27 weeks;
- ‘Dry’: HRTs ~13 weeks & 450 wks resp.
- NH_4-N removed in Dry LSR but at a slower rate (~900d vs ~120d)
- possible role of irrigation/recirculation at full scale
  - similar effect in Austrian lysimeters (Brandstatter et al)



Source: Ritzkowski et al, Sardinia 2003 #056 Figs 2 and 3

Lysimeters: behaviour post-aeration

- Gradual return of some NH_4-N but only to still quite low concentrations
- No change in COD
- No CH_4 detected in Hrad et al. up to 75 weeks post-aeration
- No longer term post-aeration data found

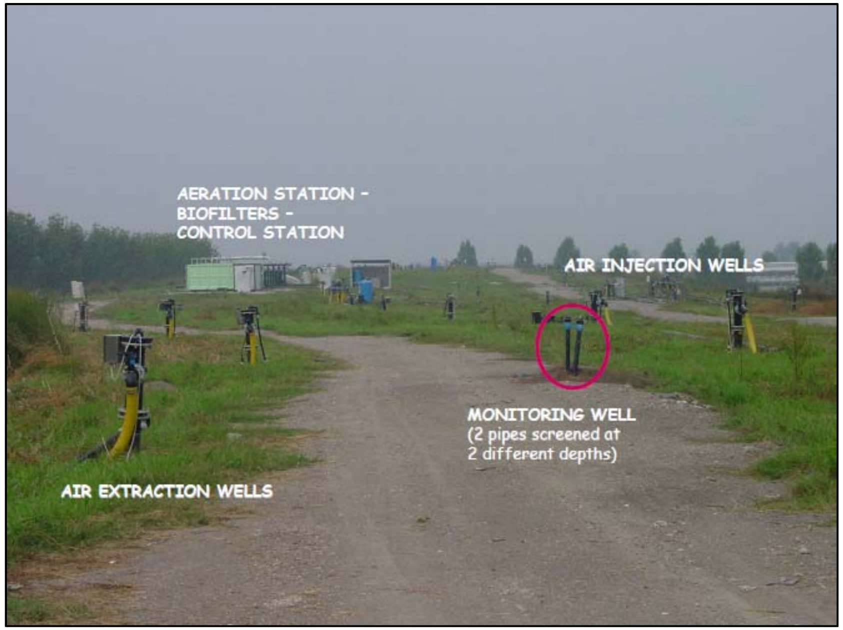


"Anaerobic" = formerly aerated lysimeter; "Aerobic" = formerly anaerobic lysimeter

Source: WM 2013 Hrad et al. "Anaerobic" = formerly aerated lysimeter; "Aerobic" = formerly anaerobic lysimeter

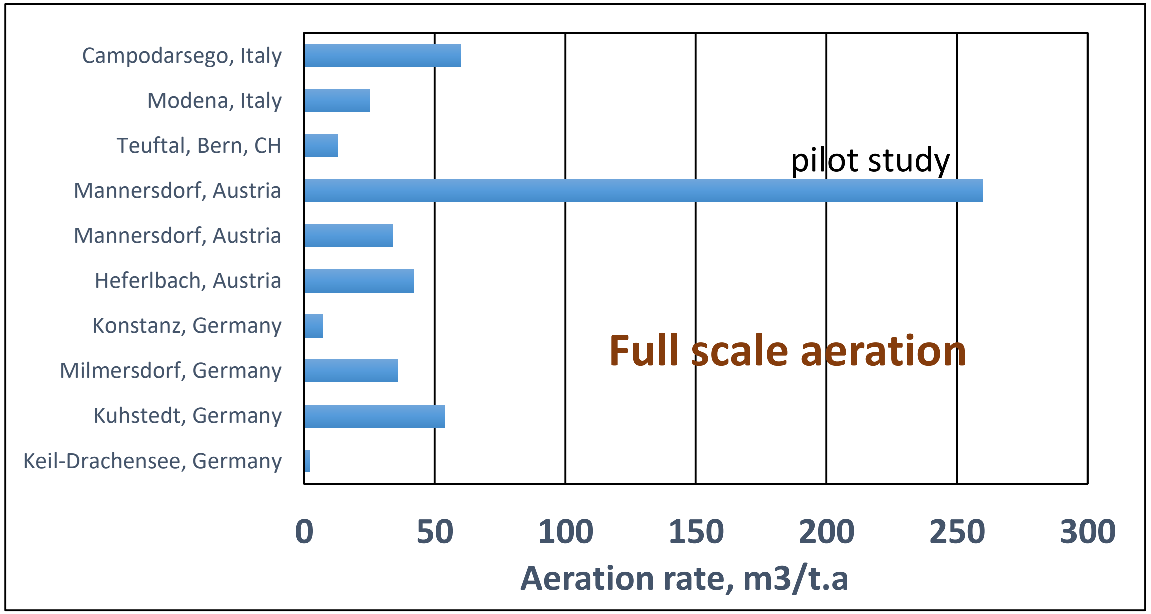
Field scale studies: basic operational features

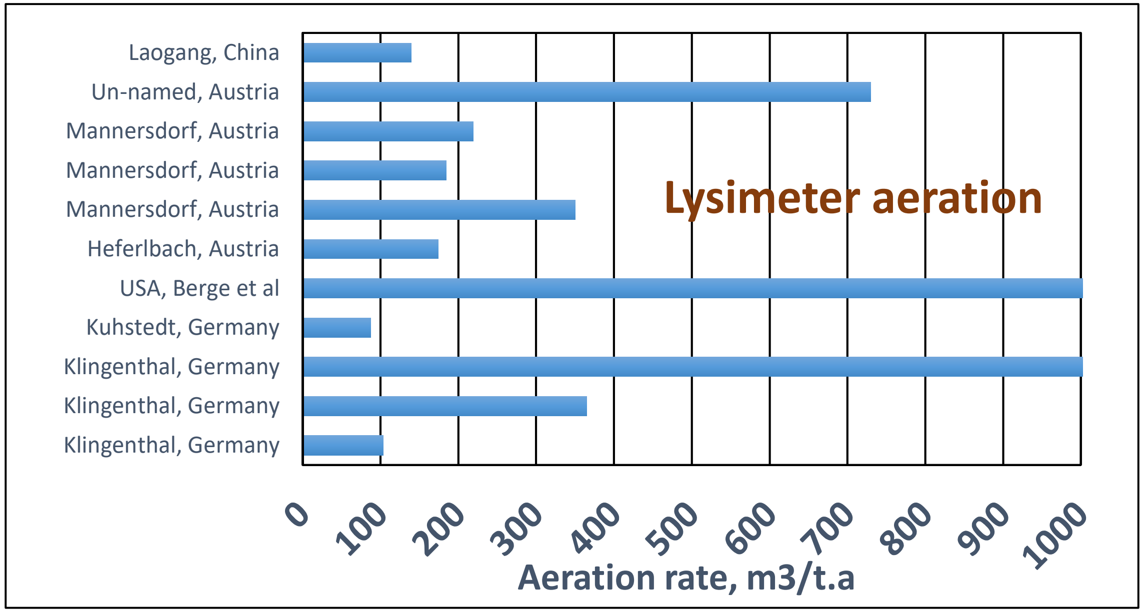
- Mostly done at landfills <20m deep
- Areas from 1 to 6ha
- Years since closure: 4 to 39
- Reported data periods mostly <2 years
  - range ~1yr to ~6 yrs



Field scale studies: aeration rates

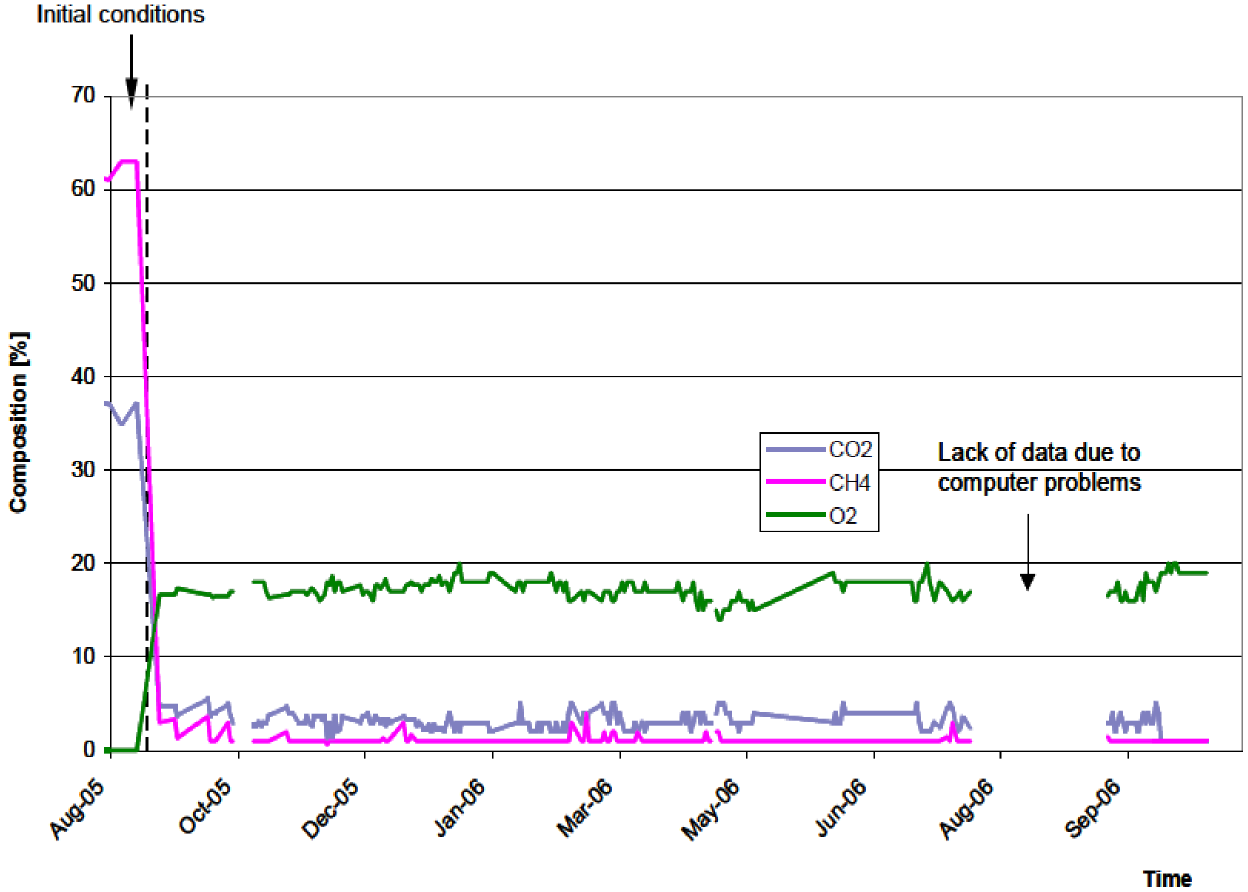
- Well spacings typically from 10m to 50m
- Aeration rates much lower than in lysimeters
  - often only ~10-20%
- But still high cf normal rates of LFG generation





Field scale results: biochemistry

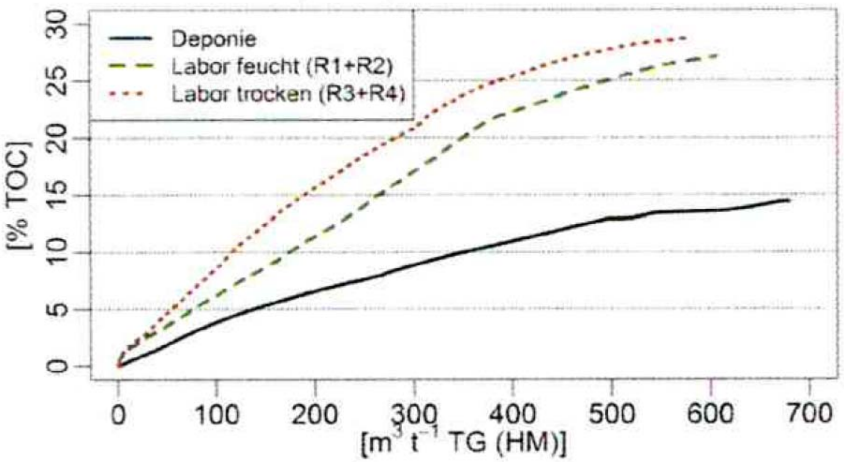
- Rapid change in biochemistry (1-2 weeks) evident from gas composition
  - change to CO_2 >> CH_4
  - continued presence of some methane indicates anaerobic zones remain



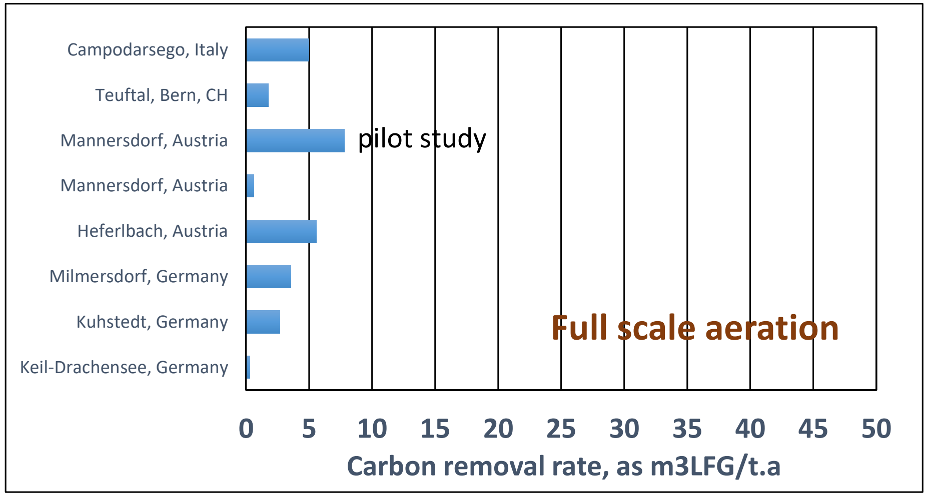
Source: Cossu et al 2007
Shows rapid change to CO2 > CH4

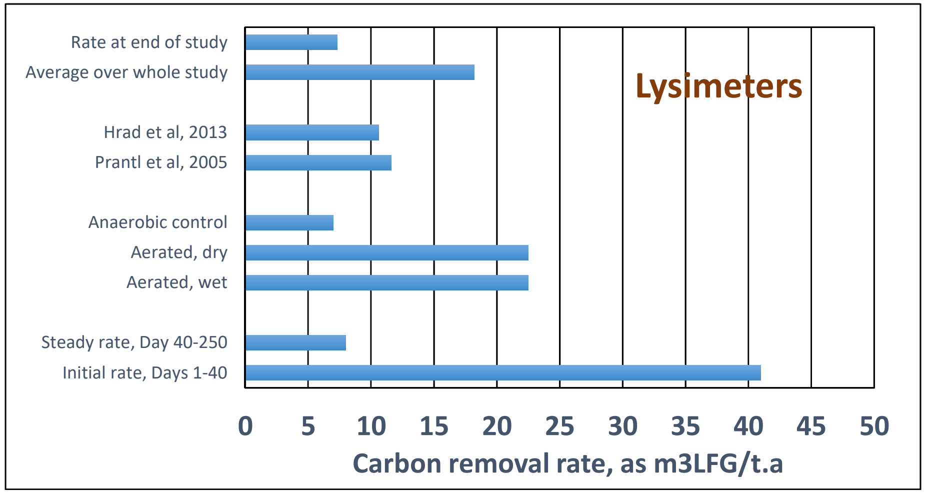
Field scale results: carbon flux

- Acceleration of carbon release as gas
  - significant cf ‘tail’ rate of $1m^3/t.a$
  - slower by ~5 to 10x cf lysimeters



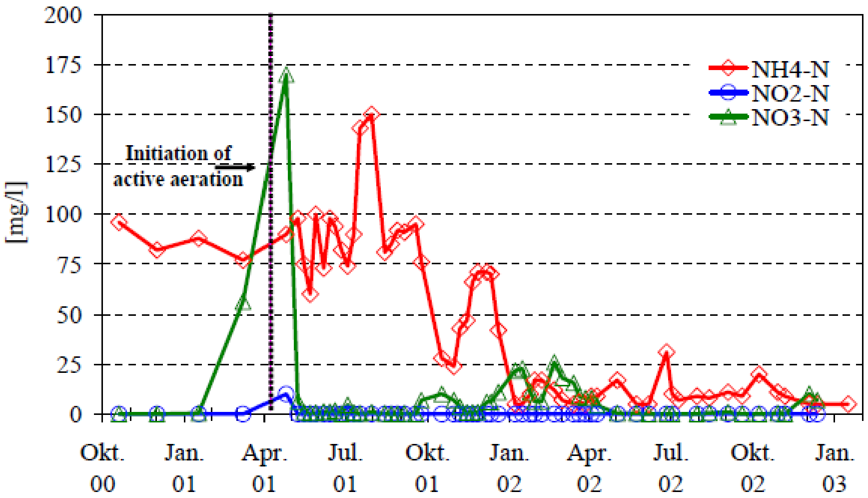
Source: Brandstatter et al 2016, Heferlbach, Austria
Shows carbon release as % waste TOC content in full scale (‘Deponie’) and two LSRs, wet and dry (‘Labor’)



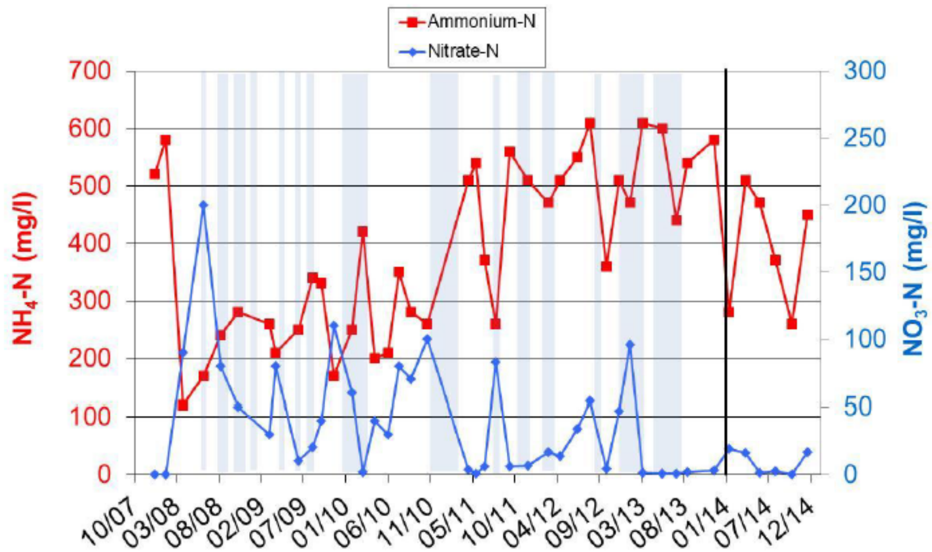


Field scale results: leachate NH_4-N

- **NH_4-N removal from leachate achieved only occasionally, and incomplete**
- **Examples show one that worked, one that did not**



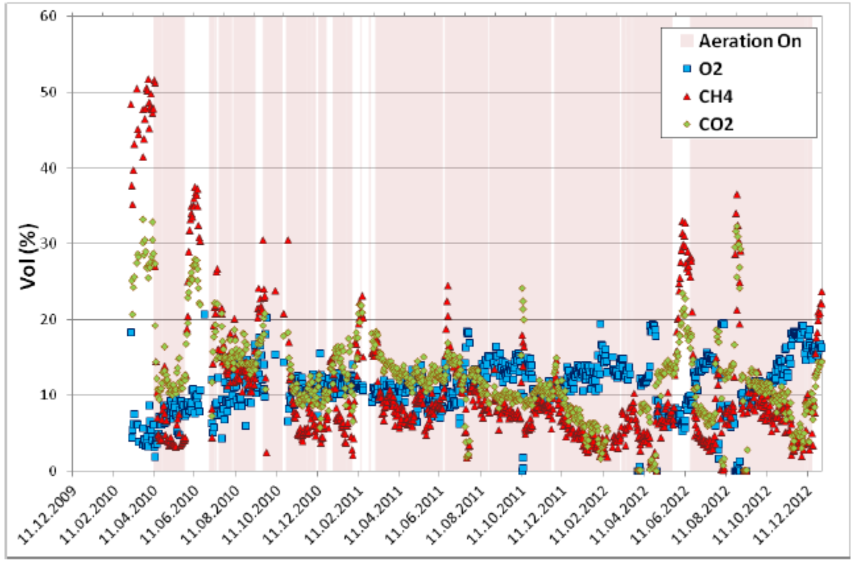
Source Ritzkowski et al, 2003: Kuhstedt, closed 1987, aerated 2001-2007.
Nitrogen species at leachate/groundwater well adjacent to toe of wastes.



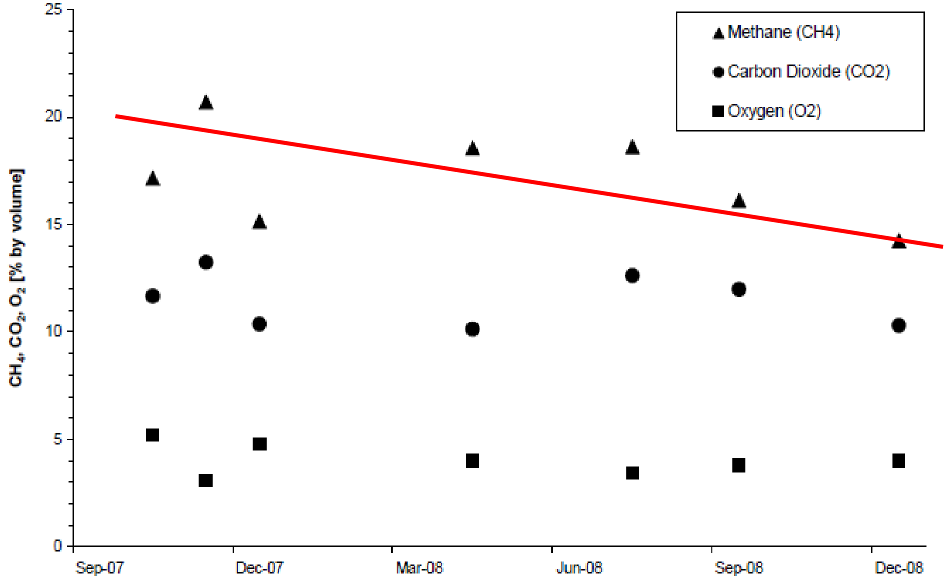
Source Hrad et al 2015 #200, Mannersdorf, Austria. Aerated at 20-30 m3/t.a

Field scale results: post-aeration

- **Few post-aeration data**
  - rapid reversion to $CH_4 > CO_2$
  - oxygen remains > zero



Source: Oncu et al, Sardinia 2013, Fig 4

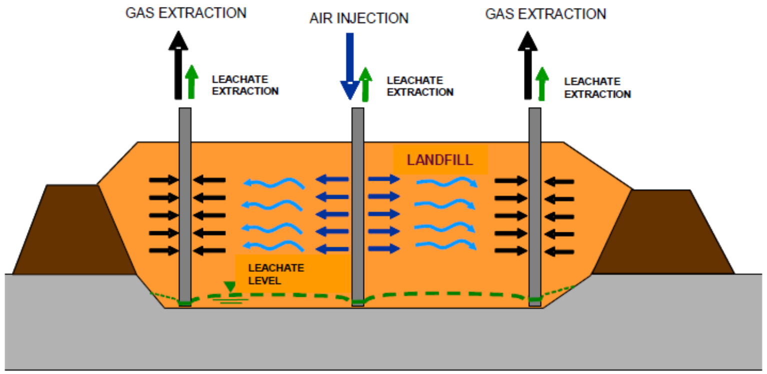


Source Ritzkowski et al, 2009: Kuhstedt, closed 1987, aerated 2001-2007.
Mean in situ gas composition following cessation of aeration in June 2007

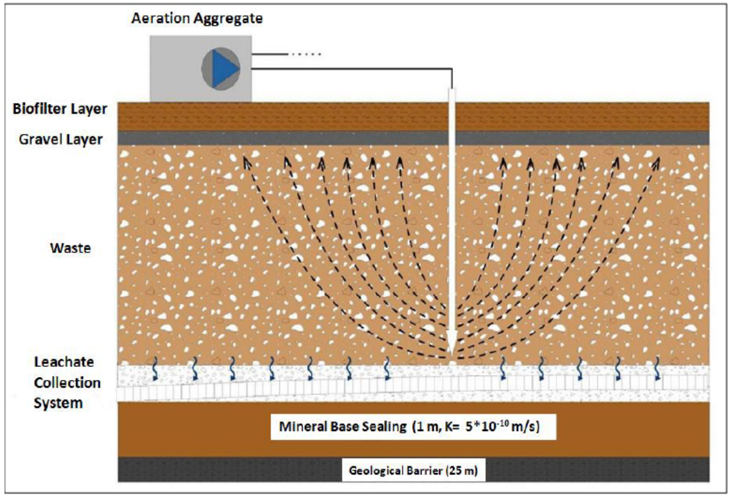
Factors affecting performance at full scale

- **Why full scale systems may perform worse than lysimeters**
  - Aeration rates generally much lower
  - Well spacing and well-field design highly variable
  - Air distribution uneven, localised
  - Limited control of moisture regime: zones may be too wet or too dry:
    - *lysimeters often irrigated at high rates by recirculation + flushing*
  - High leachate levels
  - Heterogeneity of the wastes and barriers to flow
    - *e.g. cover, low K wastes, leachate lenses*
    - *preferential flow paths, leakage of air through surface and side slopes*
    - *continued presence of anaerobic zones and anaerobic processes*
  - No control of temperature: e.g. very high T may inhibit nitrifiers

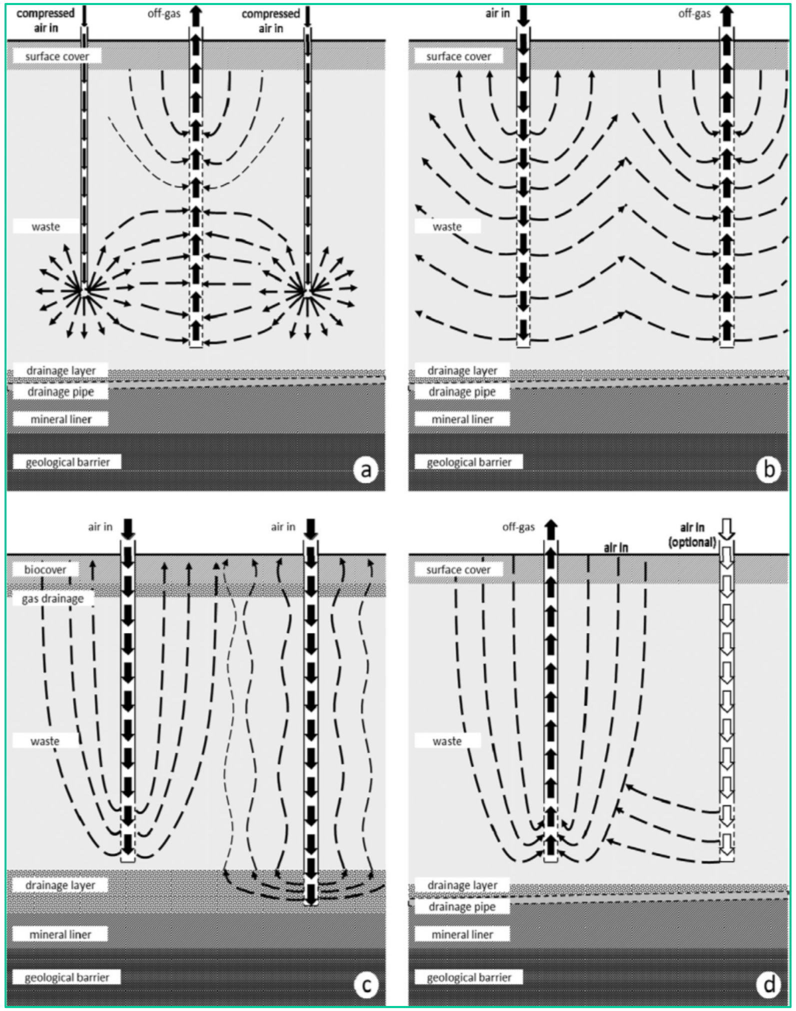
Aeration systems: huge variations in conceptual design



Source: Raga et al, Legnano, Italy



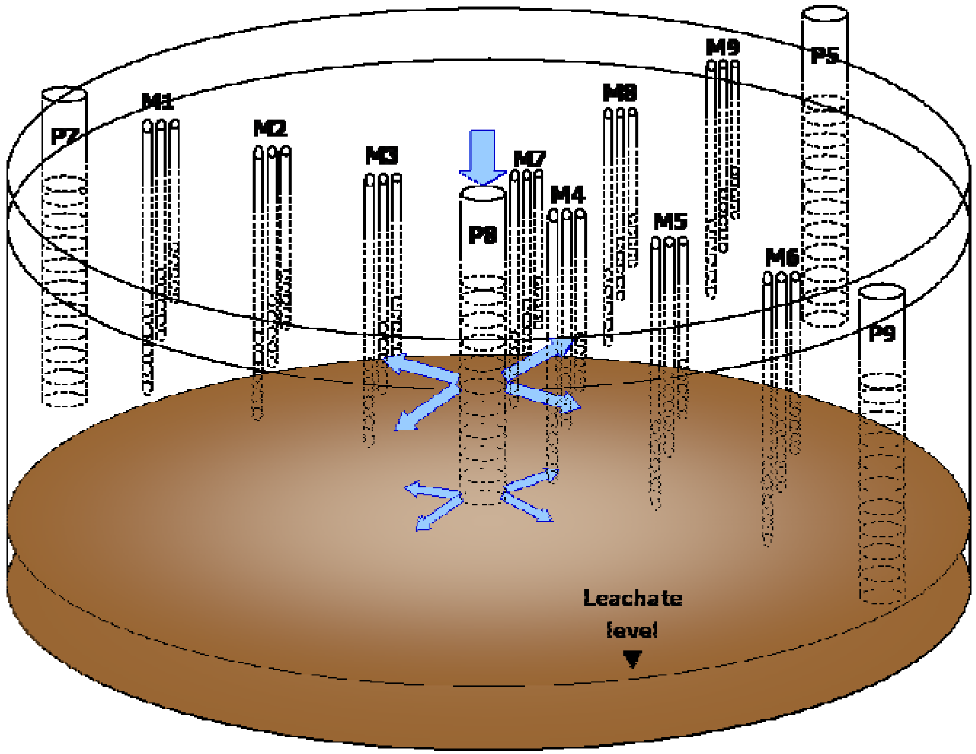
Source: Oncu et al, 2011, Konstanz-Dorfweiher, Germany



Source: Ritzkowski and Stegmann, 2012

Aeration systems and effectiveness

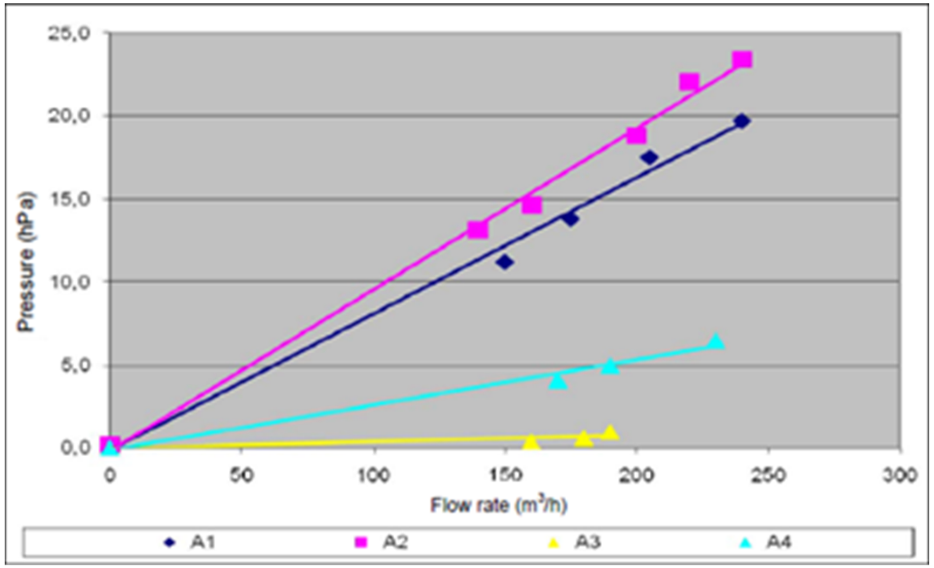
- **Aeration pilot studies by University of Padua**
  - injection wells at e.g. ~20m spacing
  - monitoring wells at three depths
  - varied injection flow/pressure
  - determine radius of influence



Source: Italy, Cestaro et al, 2003 #571, Fig 2

Aeration systems and effectiveness

- **Aeration pilot studies by University of Padua, example of results:**
  - wide variation in flow vs pressure relationships over short distances
  - O_2 distribution shows clear evidence of short-circuiting
  - radius of influence range from 20m at Q=50m³/h to 10-15m at Q= 160-230m³/h



Source: Italy, Cossu et al, 2009 #699, Fig 3,
Flow-pressure relationships for different wells

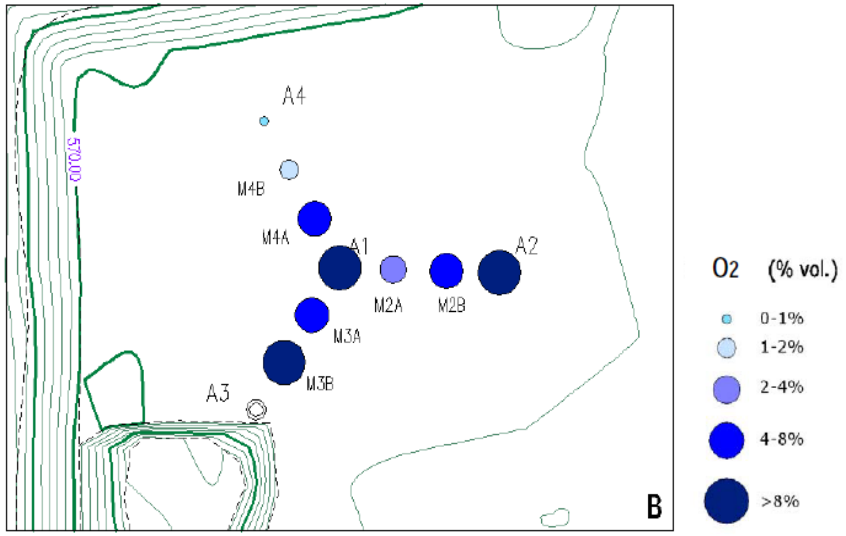
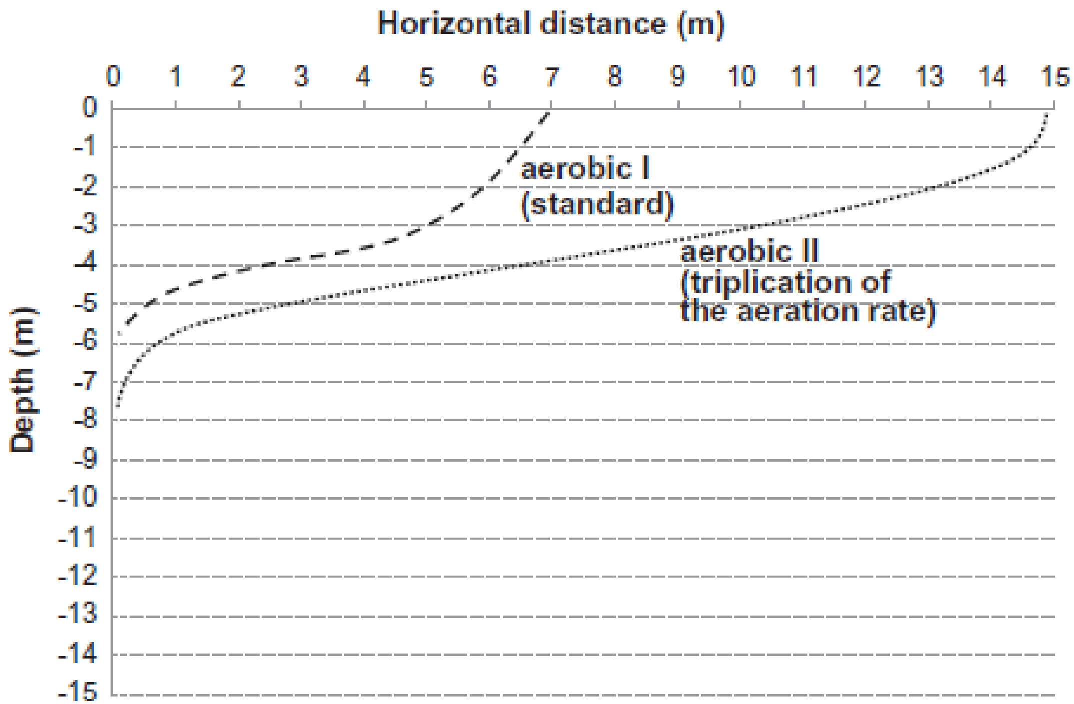


Figure 4: O_2 concentration (% vol.) in the monitoring wells 11 m deep in the landfill and in wells A1, A2 and A4 after a 6-hour air injection test from well A3.

Source: Italy, Cossu et al, 2009 #699, Fig 4,
O2 distribution at 11mbg when aerating through A3

Aeration systems and effectiveness

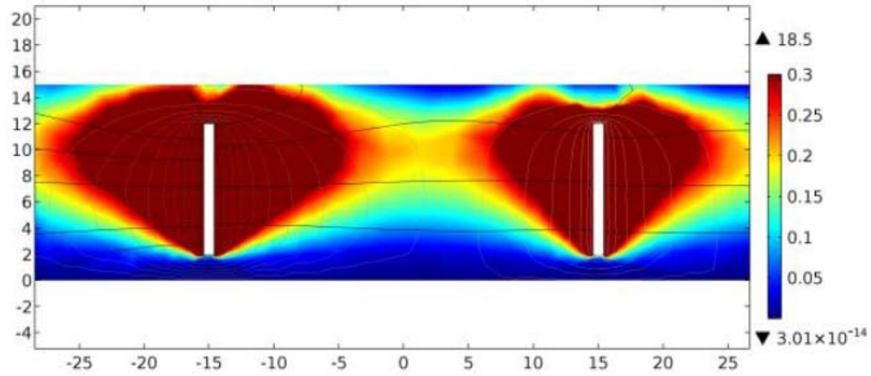
- distribution of injected air, from detailed monitoring study
- average waste depth 8-10m
- large areas unreached by aeration at ~22 and 65 m^3/t.a via wells at ~25m spacing



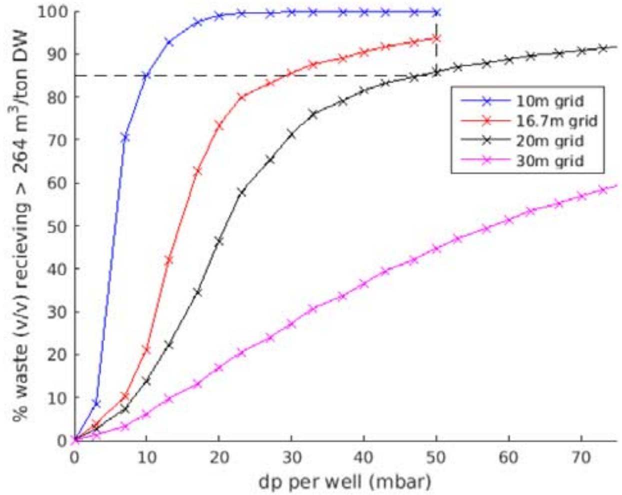
Source: Austria, Hrad et al 2013, Mannersdorf, 13 years post-closure. Shows boundary of O2 > 5%; waste 8-10m deep average, range 3-18m..

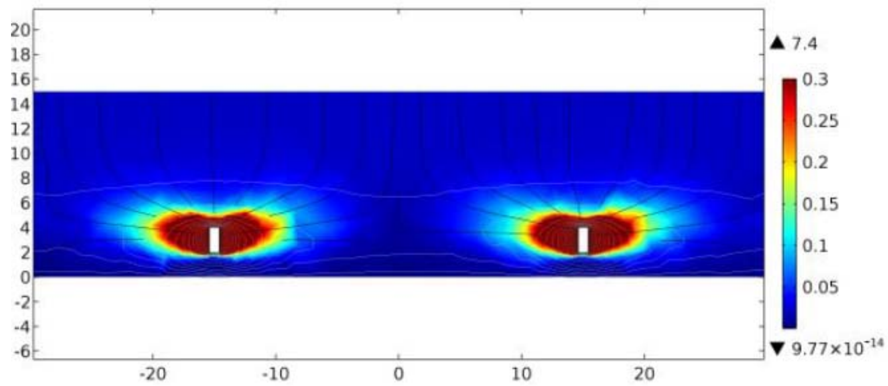
Air distribution – Timo Heimovaara modelling

Air flux in $m^3/m^2.h$



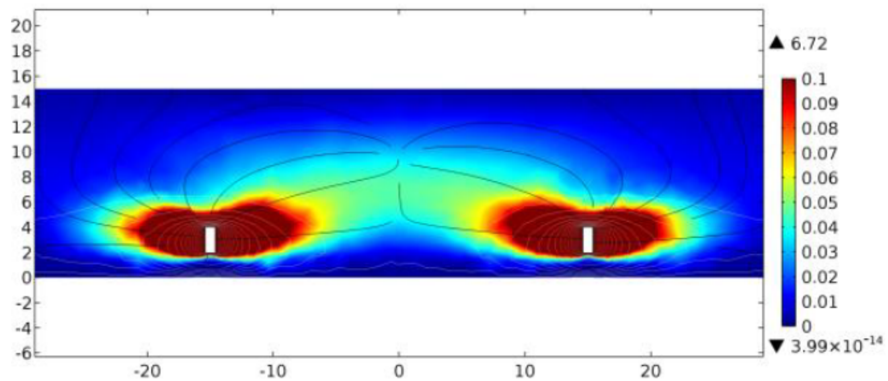
Low pressure injection and extraction via long wells





Over-extraction via deep 2m wells

- **Waste 15m deep**
- **0.5m leachate**
- **Wells to 2m above base**
- **Wells 30m apart**
- **Injection +30mb**
- **Extraction -60mb**
- **Trade-off: well-spacing vs ΔP (=energy cost)**

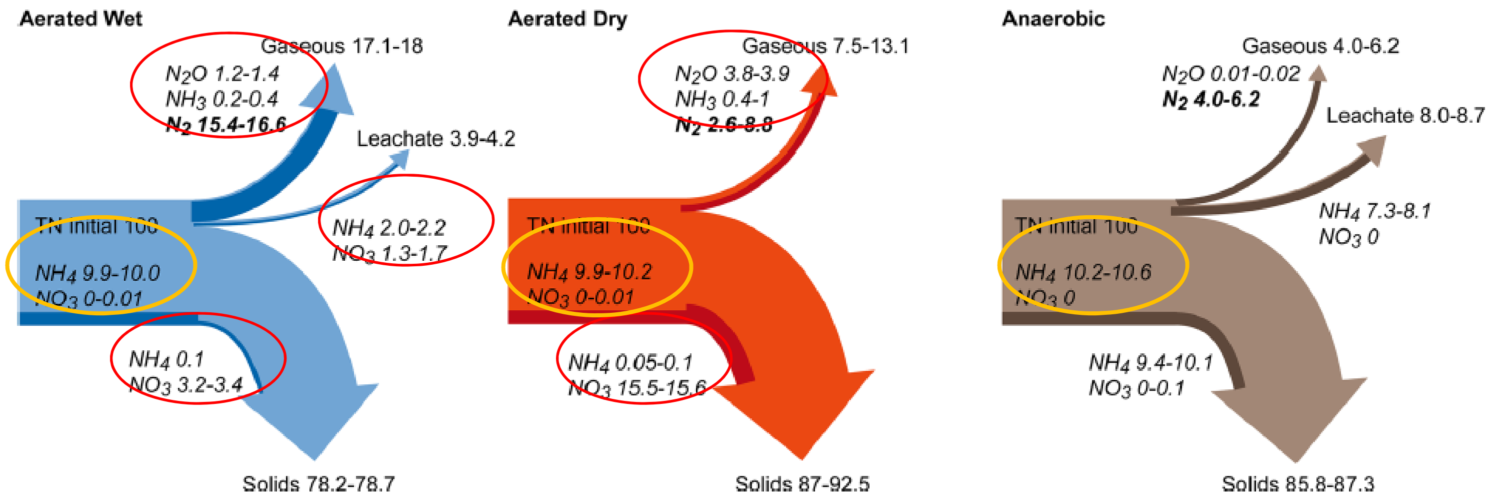


Hybrid: low pressure injection through long well at 0,0 and extraction via deep wells

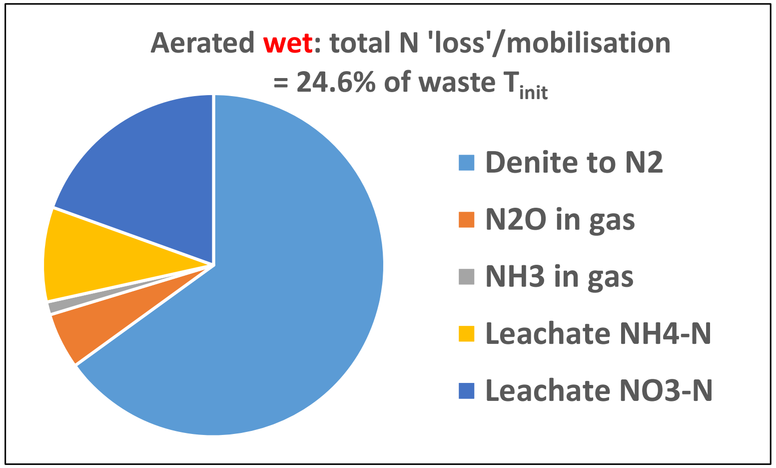
Sources: Sardinia 2015 #578 Heimovaara et al.
Heimovaara presentation to LANDSS Forum June 2016

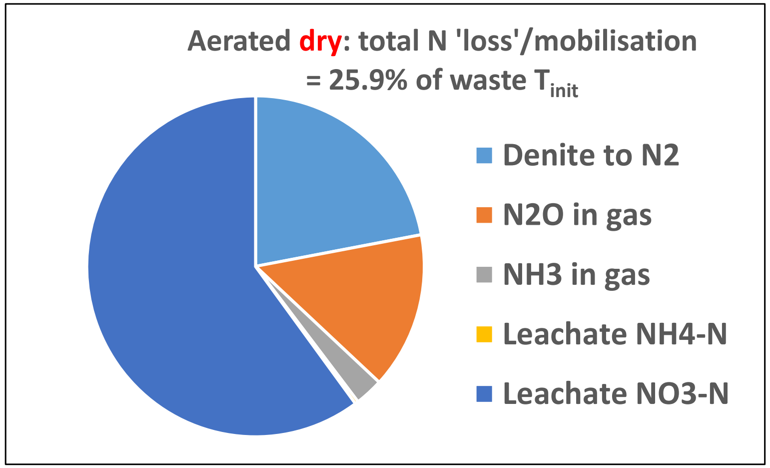
Fate of Nitrogen during aeration: mass balance

- **Quantification of NH_3, N_2O and N_2 in off gases; NH_4-N and TON in leachate phase**
- **Evidence that both nitrification and denitrification occur**
- **Austrian lysimeters: shows % of initial total N content, TN_{init}, after 2+ years aeration**
- **Overall: 'Dry' N mobilisation similar to 'Wet' but gaseous loss smaller and greater % as nitrate**



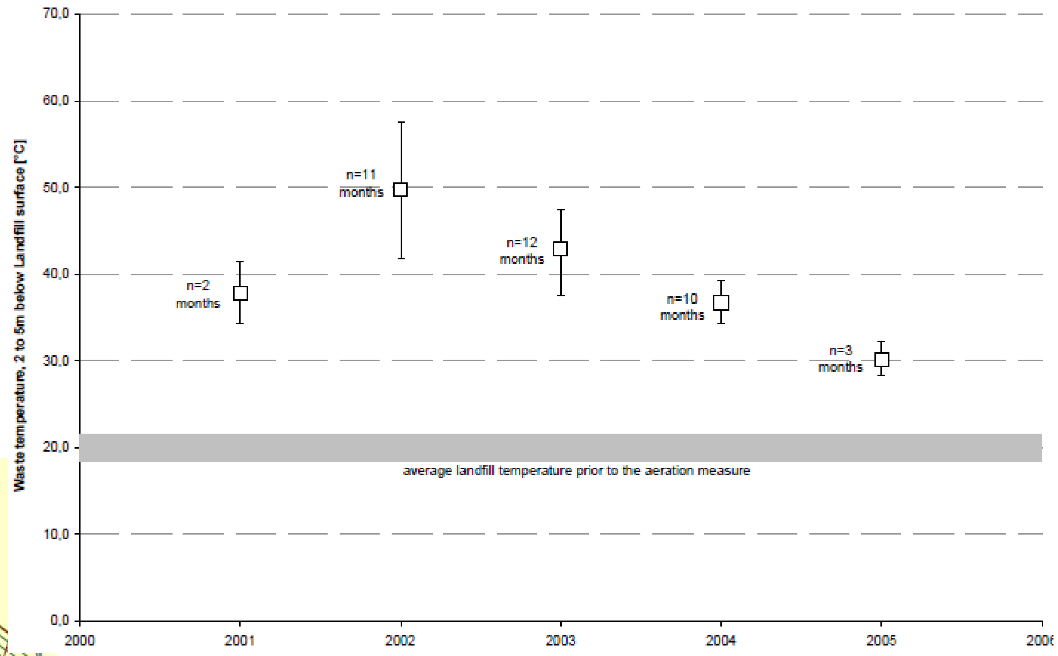
Source: Biodeg 2015 (26):399-414,



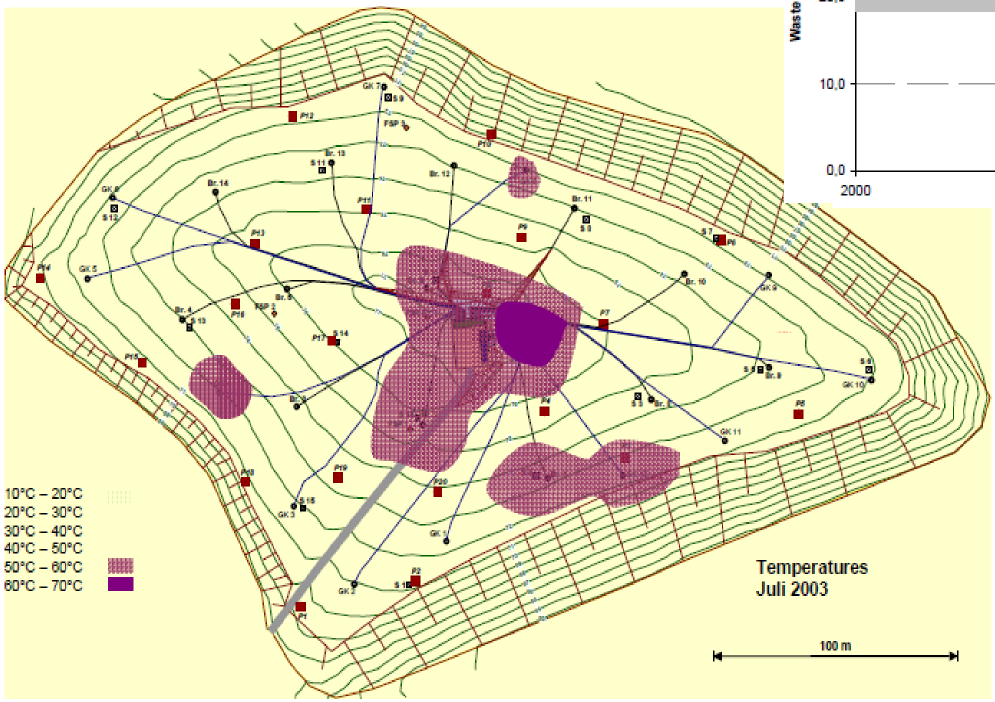


Other issues: temperature

Kuhstedt, 14 years post-closure: temperature peaked during second year of aeration, then steady decline from ~50°C to ~30°C over the next 3 years



Source: Ritzkowski and Stegmann, Sardinia 2005 #180 Fig6

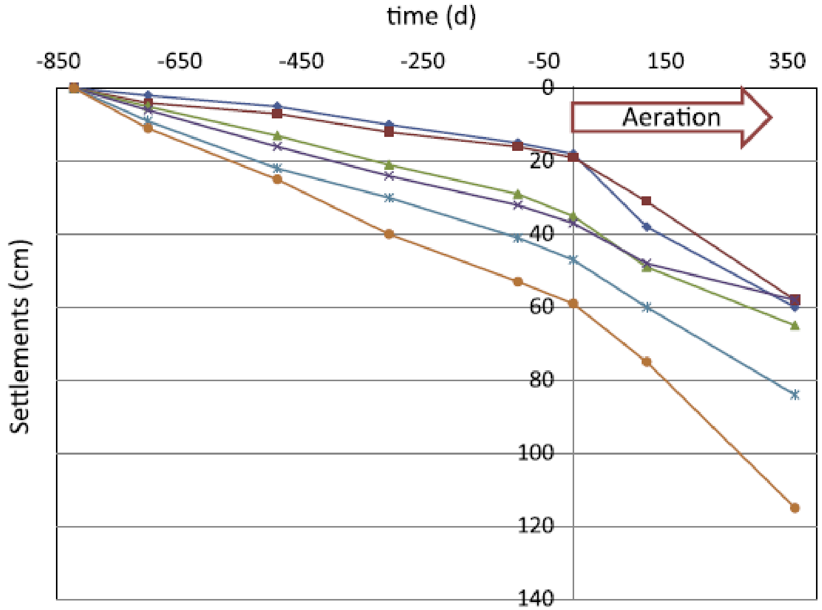


Milmersdorf, 4 years post-closure: temperatures reached >60°C within one year of aeration

Source: Heyer et al, Sardinia 2003 #723

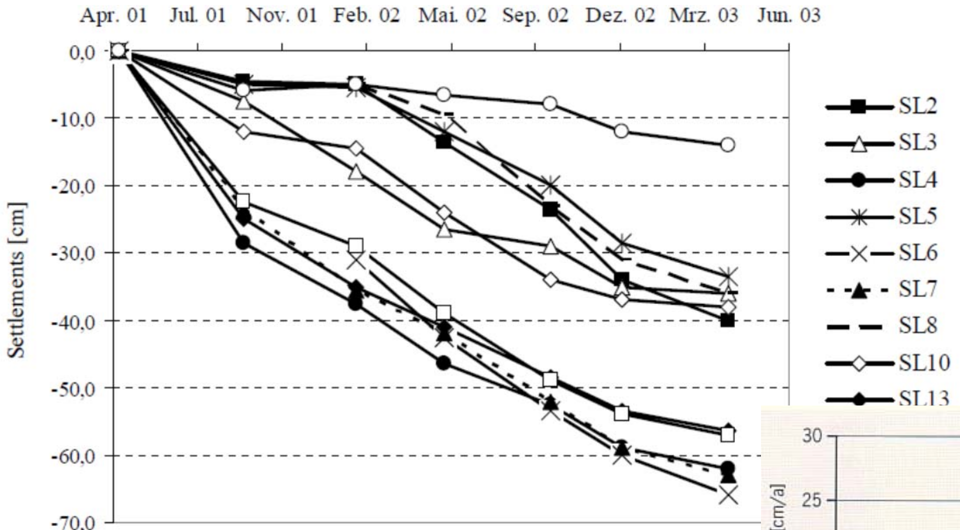
Other issues: accelerated settlement

- **Campodarsego data:**

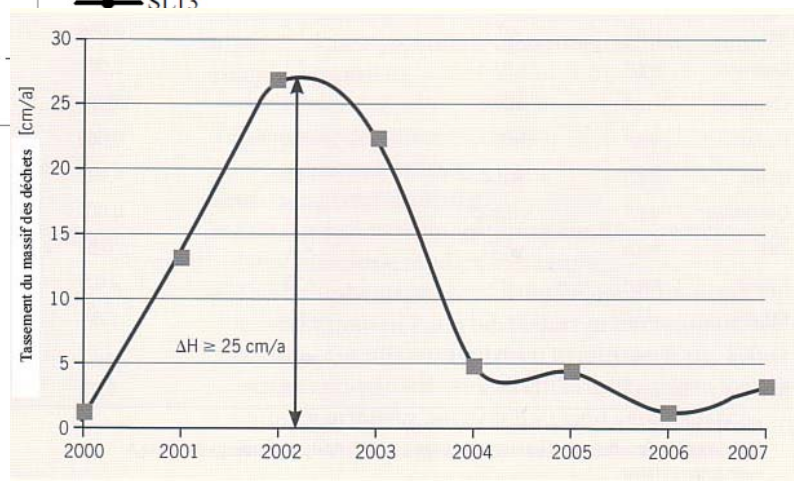


Source WM 2014 Fig 6. Settlement measurements at six locations
12m waste; 22 years since closure

- **Kuhstedt data:**



Source: Ritzkowski et al 2003 #570, Fig5
~10m waste; 14+ years since closure.



Source: Gisbert 2010, Kuhstedt data

Challenge for in situ aeration

- Get sufficient air to a high % of the waste mass
  - combination of deep and shallow wells?
  - use closer well spacing?
  - use higher pressures?
  - aim for the most cost-effective combination of well field design, well spacing and blower sizing
- Create optimum moisture regime for nitrification and especially for denitrification
  - possible need for leachate recirculation
  - how to achieve optimum moisture in unlined landfills
- Mass balance monitoring to improve understanding of N removal mechanisms
- Quantify cost/benefit elements
  - Capex: wells, blowers, pipework, control systems, off-gas treatment
  - Opex: power, staffing, loss of gas revenue, etc
  - Reduced gas and leachate management costs; subsidies/incentives