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Comparison of different systems for classification of seven podzolized, sandy soils in southern Norway

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The 1975 and 1992 versions of Soil Taxonomy, the 1988 version of the FAO-Unesco system, and the 1987 version of the Canadian System of Soil Classification were used to classify seven sandy soils with different degrees of podzolization. None of the soils were classified as Spodosols according to the 1975 version of Soil Taxonomy, three were classified Spodosols according to the Keys to Soil Taxonomy 1992, five as Podzols according to the FAO-Unesco system and two were classified as Podzolic according to the Canadian system. The exclusion of soils from the Podzol (Spodosol) orders was due to depth or thickness requirements for the podzolic (spodic) horizon. Indexes based on properties of the mineral soil were used to evaluate the degree of podzolization. Cluster analyses of these indexes were used to group the soils. Comparisons between these groups and the different classifications suggested that the difference in soil development were reflected best by the 1992 version of Soil Taxonomy. A cluster analysis based on the upper podzol B subhorizon properties suggested that the difference in podzol development were best reflected by the Canadian classification.

Key words: Podzol, podzol morphology, podzolic order, soil classification, soil taxonomy, spodic material, spodosols.

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In this study podzolization refers to translocation of amorphous organic matter, aluminium and iron from the O, A and E horizons to the B horizon. The mechanism of the podzolization process will not be discussed as it is beyond the scope of this study. Podzolization is the dominant soil-forming process in sandy soils under coniferous forests in cool humid climates. Sandy soils need less iron and carbon to obtain the same colours than more loamy-textured soils (Evans & Manly 1983). Consequently, sandy soils will develop a podzol morphology more rapidly than the more loamy textured soils. However, with regard to classification, many of the sandy soils with a podzol morphology fail to meet the chemical criteria for Podzols (Spodosols) given in the 1975 version of Soil Taxonomy and in the FAO/Unesco system (Evans & Cameron 1985). The limited correlation between field morphology and chemical classification criteria has complicated field classification of podzols. Stanley & Ciolkosz (1981);

McKeague et al. (1983) and Padley et al. (1985) among others have criticized this lack of correlation in the Spodosol criteria of the 1975 version of Soil Taxonomy. Some of this has been taken into account in the revised Spodosol criteria of the 1992 version of Keys to Soil Taxonomy. The classification criteria of the Canadian System of Soil Classification has been criticized, e.g., by Evans & Cameron (1985) who suggested that the morphological criteria were too broad and poorly defined.

In this study seven sandy soils with a podzolic morphology were investigated. The soils were all from a small area but showed differences in degree of development. The soils were classified according to FAO-Unesco, Soil Map of the World, revised legend (FAO 1988), the Canadian Soil Classification System (Agr. Can. Exp. Com. Soil Survey 1987), the 1975 version of Soil Taxonomy (Soil Survey Staff 1975) and the 1992 version of Keys to Soil Taxonomy (Soil Survey Staff, 1992). Based on characteristics resulting from the podzolization process, such as the distribution of organic matter, poorly crystalline Al- and Fe-rich compounds, and the colour pattern of the soils, an evaluation has been undertaken to determine how well the classification systems account for the differences in the development observed.

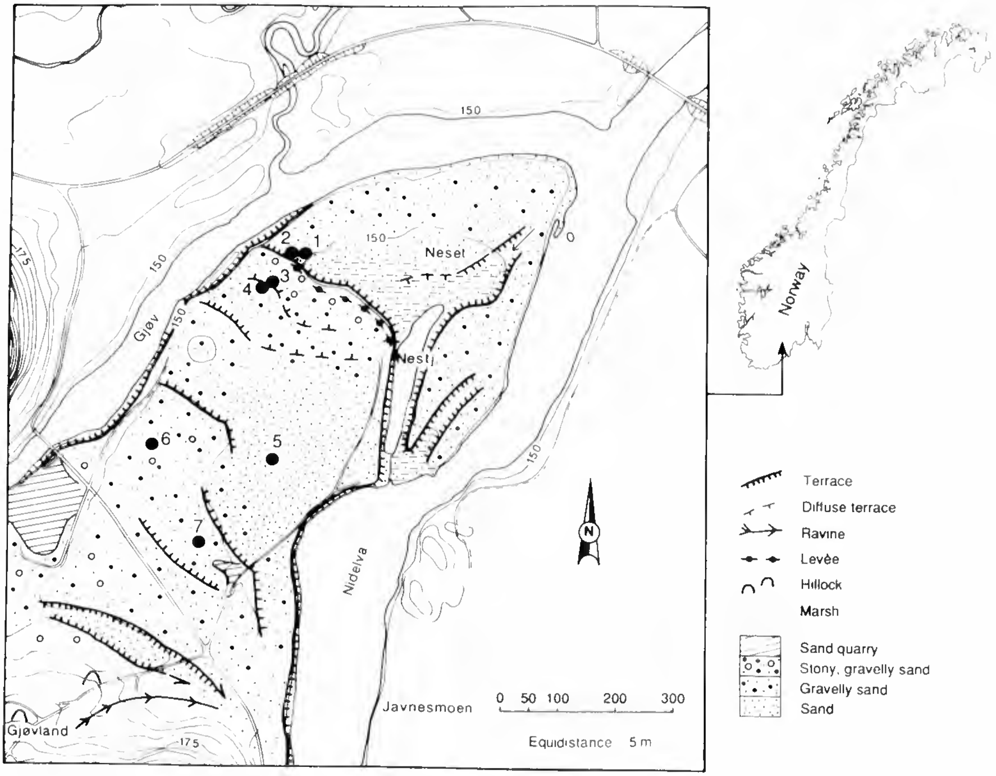

Figure 1. Map of the study area showing the profile sites 1-7.

Material and methods

Study area

The study area was located on the peninsula where the river Gjøv joins the river Nidelv, (8°30'E, 58°48'N) in Åmli, Aust Agder county in southern Norway (Fig. 1). Seven soils with a podzol morphology were selected and were labelled from 1 to 7. The soils were subjectively selected to represent the widest range in podzol development observed in the study area.

The study area is a glacifluvial deposit derived mainly from Precambrian crystalline bedrock and influenced by changing sedimentation conditions.

The vegetation in the area is a Scots pine (*Pinus sylvestris* L.) stand of varying age. The ground vegetation, determined according to Kielland-Lund (1967), is the *Vaccinio-pinetum* type the dominating species being *Vaccinium vitis-idaea*, *Deschampsia flexuosa* , *Calluna vulgaris* and *Vaccinium myrtillus*. The old Scots pine forest in the area where profiles 6 and 7 are situated was clear-cut in the late 1980s.

A high water level in the rivers, especially after snowmelt causes waterlogging for shorter periods in profile 1. The other soils are well to excessively well drained. There were no climatic data for the study area but climatic data from the two nearest meterological stations are presented in Table 1. This suggests that according to Soil Taxonomy (Soil Survey Staff 1975) the soil moisture regime is udic and the soil temperature regime is frigid. This equals the humid soil moisture class and the cold soil temperature class of the Canadian system of soil classification (Agr. Can. Exp. Com. Soil Survey 1987).

The soils were described and sampled following the FAO, guidelines for soil profile description (FAO 1977).

Laboratory methods

Laboratory analyses were carried out on the fine earth fraction. Particle size distribution was determined by the pipette method after destruction of organic matter with H_2O_2 (Elonen 1971). Particle size classes were determined according to Sveistrup & Njøs (1984).

Total carbon was measured by dry combustion. The CEC was determined by the 1M NH_4OAc pH 7 method using 3 g soil to 250 ml NH_4OAc (Schollenbergen & Simon 1945). The pH was determined

Table 1. Climatic data for the study area

	J	F	M	A	M	J	J	A	S	O	N	D	Year
						Temperature (°C)							
Nelaug	-3.5	-3.7	-0.2	3.8	9.7	14.1	15.5	14.5	10.5	6.7	1.5	-1.5	5.6
Tveitsund	-4.0	-4.8	-0.9	3.2	8.9	13.6	15.1	14.0	9.9	6.0	1.0	-2.0	5.0
						Precipitation (mm)							
Nelaug	108	71	81	60	86	78	99	109	140	163	139	96	1230
Tveitsund	71	51	54	48	77	71	89	109	118	127	110	69	994

in a 1:2.5 v/v ratio of soil/distilled water and soil/0.01 M $CaCl2$.

Pyrophosphate extractable Fe and Al (Fe_p and Al_p) were determined according to Bascomb (1968) using sodium pyrophosphate instead of potassium pyrophosphate. Dithionite-citrate extractable Fe and Al (Fe_d and Al_d) were determined according to Holmgren (1967) using 2 g crushed soil to 100 ml extraction solution. Oxalate extractable Fe and Al (Fe_o and Al_o) were determined according to Saunders (1965) using 2 g soil to 100 ml extraction solution.

Statistical analyses

Analyses of variance were performed using a general linear model, GLM-procedure on a 5% probability level and LSD-tests were used to differ among groups (SAS Institute Inc. 1987).

A clustering method based on nonparametric probability density linkage and the distance between the k-th nearest neighbours was used to group the soils by morphological and chemical properties. Density linkage clustering does not place any constraint on the shapes of the clusters and is capable of recovering clusters with elongated or irregular shapes. Density linkage clustering is less effective at recovering compact clusters from small samples than most other methods (SAS Institute Inc. 1987).

Results and discussion

Physical properties

The seven soils had a gravel and stone content of between 5 and 50%, with marked differences within the profiles as a result of stratification. The clay content was low, with the highest amounts generally found in the upper podzol B subhorizon. The sand content in the fraction < 2 mm was generally greater than 70%, and increased with depth. The silt content was similarly higher in the upper horizons (Table 2). Nørnberg (1977) described the same trend for some sandy podzolic soils in Denmark and suggested that the silt-rich surface layers were attributable to *in situ* physical weathering. This was also suggested by Teveldal et al. (1990) for some sandy podzolic soils in southern Norway. In the present study the higher silt content in the upper horizons was most likely due to variations in the parent material.

Morphological properties

All soils displayed a morphology typical for podzolic soils (Table 2). An increasing soil development was observed towards the north/east (Fig. 1). This was reflected in the depth to the C horizon (Fig. 2).

Colour indexes based on the mineral soil were made for each profile. The reddest hue, 2.5 YR, was given the highest numerical value, 5, and the yellowest hue, 2.5 Y, was given the lowest numerical value, 1. Each of these was multiplied by the thickness of the horizon it represented. These values were then added down to a depth of one metre. The same procedure was applied for the values and chromas. The highest indexes indicate the soils with the overall reddest hue, the highest value or the highest chroma. The soils in the north/east have the reddest hue indexes indicating more developed podzols. The colour indexes of the value showed a gradual increase from profile 1 to 7. This was related to the increasing proportion of lighter-coloured C horizon material in the value indexes, suggesting that the value indexes also reflected the difference in soil development. No particular trend was found for the chroma (Fig. 3).

Table 2. Some chemical and morphological data of the soils

	cm	g/100g	pH		cmol(+)/kg	g/100g						g/100g			Colour (moist)		
Design.	Thick.	Tot. C	H2O	CaCl2	CEC	Fep	Alp	Fed	Ald	Feo	Alo	Clay	Silt	Sand	Hue	Value	Chorma
Profile 1																	
Olf	8	37.4	4.1	3.3	93.9	-	-	-	-	-	-	-	-	-	-	-	-
Oh	6	27.1	4.0	3.3	164.1	-	-	-	-	-	-	-	-	-	-	-	-
E	3	2.3	4.3	3.7	30.0	0.24	0.10	0.53	0.10	0.26	0.09	1	32	67	5YR	4	2
Bs1	5	3.2	4.9	4.3	34.7	0.65	0.66	1.84	0.72	1.05	0.77	3	28	69	5YR	3	4
Bs2	16	1.8	5.1	4.9	23.8	0.18	0.51	1.42	0.94	0.84	1.09	3	21	76	5YR	4	6
Bs3	15	0.8	5.1	5.1	11.2	0.05	0.25	0.48	0.35	0.21	0.60	1	25	74	7,5YR	4	4
BC	61	0.4	5.2	4.9	9.3	0.04	0.08	0.52	0.24	0.14	0.34	0	7	93	10YR	5	4
Profile 2																	
Olfh	7	40.8	3.7	3.1	119.1	-	-	-	-	-	-	-	-	-	-	-	-
E	4	1.4	4.1	3.5	13.3	0.09	0.08	0.21	0.04	0.07	0.05	1	24	75	10YR	5	2
Bs1	7	2.3	4.7	4.2	14.8	0.41	0.36	1.14	0.46	0.61	0.40	1	21	78	7,5YR	4	4
Bs2	16	1.2	5.0	4.9	10.7	0.06	0.31	1.54	0.72	0.74	0.85	1	20	79	5YR	4	6
Bs3	21	0.6	5.2	5.1	7.5	0.01	0.12	0.97	0.40	0.42	0.54	2	15	83	5YR	4	6
BC	12	0.1	5.1	5.2	6.3	< 0.01	0.07	0.26	0.12	0.16	0.13	0	2	98	10YR	5	8
C	40	0.1	5.2	5.1	6.0	< 0.01	< 0.04	0.15	0.07	0.11	0.12	0	1	99	2,5Y	6	4
Profile 3																	
Olf	5	53.5	3.6	2.9	188.7	-	-	-	-	-	-	-	-	-	-	-	-
Oh	5	54.8	3.5	2.9	194.4	-	-	-	-	-	-	-	-	-	-	-	-
E	2	1.9	4.0	3.1	14.1	0.05	< 0.04	0.17	0.03	0.05	0.01	1	18	81	10YR	4	2
Bhs	3	3.0	4.2	3.7	23.7	0.60	0.28	1.24	0.33	0.81	0.28	4	20	76	5YR	3	3
Bs	24	1.1	4.9	4.9	11.5	0.03	0.24	1.52	0.68	0.66	1.13	1	20	79	7,5YR	4	6

Tabell 2 forts.

	cm	g/100g	pH		cmol(+)/kg	g/100g						g/100g			Colour (moist)		
Design.	Thick.	Tot. C	H2O	CaCl2	CEC	Fep	Alp	Fed	Ald	Feo	Alo	Clay	Silt	Sand	Hue	Value	Chorma
BC	21	0.1	5.0	4.9	8.6	< 0.01	0.06	0.23	0.11	0.14	0.20	0	5	95	10YR	5	6
C	50	0.1	5.0	5.0	7.8	< 0.01	< 0.04	0.12	0.06	0.08	0.13	0	2	98	10YR	6	3
Profile 4																	
Olf	4	55.4	3.4	2.8	184.7	-	-	-	-	-	-	-	-	-	-	-	-
Oh	2	38.5	3.5	2.7	135.9	-	-	-	-	-	-	-	-	-	-	-	-
E	5	1.3	4.0	3.3	16.4	0.02	<0.04	0.08	0.03	0.06	0.03	1	23	76	10YR	4	2
Bs1	4	1.9	4.5	4.1	19.2	0.46	0.39	1.13	0.37	0.81	0.39	4	23	73	7,5YR	3	4
Bs2	12	1.0	4.9	5.0	15.8	0.03	0.23	1.08	0.63	0.63	1.18	2	19	79	7,5YR	4	6
BC	12	0.1	4.9	5.0	11.2	< 0.01	< 0.04	0.23	0.11	0.20	0.27	0	7	93	10YR	5	6
C1	13	0.0	5.0	5.1	10.5	< 0.01	< 0.04	0.07	0.04	0.08	0.10	0	2	98	10YR	6	3
C2	54	0.2	5.1	5.0	13.0	< 0.01	< 0.04	0.26	0.13	0.13	0.35	1	82	17	10YR	5	2
Profile 5																	
Olf	3	55.3	3.8	3.1	158.3	-	-	-	-	-	-	-	-	-	-	-	-
Oh	5	46.0	3.7	2.9	166.2	-	-	-	-	-	-	-	-	-	-	-	-
E	3	1.3	4.1	3.2	12.2	< 0.01	< 0.04	0.05	0.02	0.02	0.03	0	13	87	10YR	5	2
Bhs	3	4.1	4.5	3.9	28.0	0.30	0.61	0.79	0.74	0.51	0.90	3	18	80	2,5YR	2.5	2
Bs	18	1.2	4.9	4.8	14.6	0.06	0.24	0.78	0.49	0.48	1.33	1	14	85	7,5YR	4	6
BC	20	0.3	4.9	4.9	10.6	0.04	< 0.04	0.13	0.08	0.08	0.26	0	2	98	10YR	5	6
C	56	0.2	5.0	5.0	10.3	< 0.01	< 0.04	0.10	0.05	0.06	0.16	0	1	99	2,5Y	6	6

Tabell 2 forts.

	cm	g/100g	pH		cmol(+)/kg	g/100g						g/100g			Colour (moist)		
Design.	Thick.	Tot. C	H2O	CaCl2	CEC	Fep	Alp	Fed	Ald	Feo	Alo	Clay	Silt	Sand	Hue	Value	Chorma
Profile 6																	
Olf	7	54.1	3.6	2.9	137.9	-	-	-	-	-	-	-	-	-	-	-	-
Oh	5	43.8	3.5	2.8	145.4	-	-	-	-	-	-	-	-	-	-	-	-
E	4	2.0	4.0	3.2	11.3	0.02	0.05	0.09	0.03	0.03	0.04	1	15	84	10YR	5	2
Bs1	3	3.0	4.3	3.8	18.1	0.31	0.35	0.64	0.37	0.43	0.46	3	11	86	7,5YR	3	4
Bs2	11	0.8	5.1	5.2	9.1	< 0.01	0.15	0.60	0.34	0.34	1.00	1	19	80	7,5YR	4	6
BC	14	0.3	5.1	5.0	7.3	< 0.01	< 0.04	0.42	0.16	0.18	0.41	0	9	91	10YR	5	6
C	68	0.2	5.2	5.0	7.8	< 0.01	< 0.04	0.15	0.06	0.11	0.10	0	7	93	10YR	6	3
Profile 7																	
Olf	3	56.3	3.7	2.9	203.6	-	-	-	-	-	-	-	-	-	-	-	-
Oh	3	49.2	3.6	2.8	193.9	-	-	-	-	-	-	-	-	-	-	-	-
E	4	1.9	4.0	3.2	19.2	0.06	< 0.04	0.15	0.04	0.06	0.08	0	16	83	10YR	4	1
Bs1	3	3.3	4.3	3.7	28.0	0.42	0.24	0.74	0.30	0.55	0.39	3	17	80	5YR	3	4
Bs2	9	1.7	4.9	4.7	19.1	0.02	0.28	1.08	0.73	0.62	1.22	1	18	81	7,5YR	4	6
BC	9	0.4	4.9	4.9	13.8	< 0.01	< 0.04	0.25	0.12	0.25	0.53	0	11	89	10YR	5	6
C1	20	0.4	4.9	4.9	14.0	< 0.01	0.09	0.26	0.12	0.18	0.36	0	24	76	2,5Y	5	4
C2	55	0.2	5.1	5.0	11.3	<0.01	<0.04	0.07	0.03	0.03	0.08	0	1	99	2.5Y	6	4

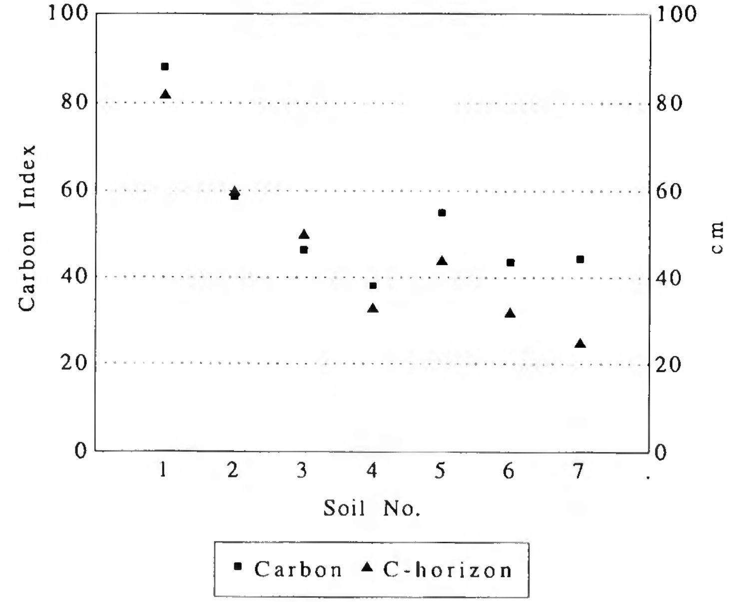

Figure 2. Carbon indexes of the soils down to 1 metre depth combined with depths to the C horizon

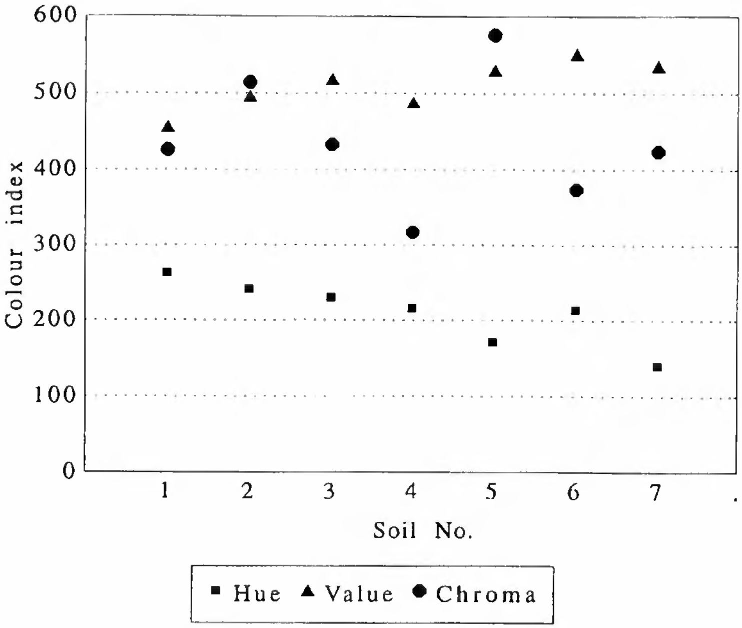

Figure 3. Colour indexes based on hues, values and chromas of the soils down to 1 metre depth.

Chemical properties

All the soils showed a distribution of carbon, Fe and Al indicating that these elements were translocated from the E horizons to the B horizons (Table 2). These patterns of distribution are typical of podzols (Bascomb 1968; Blume & Schwertmann 1969; Mokma & Buurman 1982). The greatest amounts of carbon, Fe and Al were found in the soils towards the north/east (Fig. 1). The distribution patterns indicate that there is a good correlation between the chemical properties of the soils, colour and other field-based morphological attributes.

To facilitate an evaluation of the differences in degree of development, indexes for carbon, iron and aluminium were calculated for each soil. The indexes were calculated by multiplying the results from the chemical analyses of each mineral soil horizon by the horizon thicknesses. The horizon data were then summed, giving one index per property, for each soil. Since there were only minor differences in bulk density between the soils for horizons with the same horizon designation, the bulk density was therefore disregarded when calculating the indexes. Higher values of the profile indexes denote stronger soil development. Because the soils were described to different depths, the deepest soil may have a higher index based on this factor alone. To avoid this, all indexes were calculated for a depth of one metre. The indexes cannot be used to differentiate soils exposed to different soil-forming processes but may be used to indicate degree of development in soils exposed to the same soil-forming processes.

The carbon indexes decreased gradually from soils 1 to 4 following the observed trend in podzol development. An increase in the carbon indexes was observed from soils 4 to 5 (Fig. 2) and soils 6 and 7 had higher carbon indexes than soil 4. Figure 2 also suggests that the carbon index follows the observed differences in soil development indicated by the depth to the C horizons.

A comparison between the profile indexes revealed that the amount of Fe_d and Fe_o decreased from soils 1 to 5, while the decrease levelled off for soils 5, 6, and 7 (Fig. 4). This indicates that the degree of soil development decreased from soils 1 to 5 and that there was little difference in soil development between soils 5, 6, and 7. Fe_p is assumed to be representative of the iron in complexes with organic material and therefore closely connected to podzolization (Bascomb 1968). Soil 1 and 2 had the highest Fe_p indexes while there was little difference between the other soils, which suggests that soils 1 and 2 were the most podzolized. In general, soil 1 had the highest Al index and soil 6 had the lowest index for all Al-extracts. It would seem from the Al_p indexes that podzolization was most pronounced in soils 1 and 2 (Fig. 5). Although there was a decrease from soils 1 to 7, the Al_o indexes were irregular compared to the Al_p and Ald indexes. Farmer et al. (1980) proposed a theory on podzolization involving inorganic migration of Al and its precipitation as allophane or imogolite. Wang et al. (1986) suggested that this process was particularly important for the podzol formation in cold areas. Oxalate is considered a good extractant of inorganic amorphous Al such as poorly crystalline Al-oxyhydroxides, allophane and imogolite, and it also extracts Al from Al-organic complexes (Farmer et al. 1983). A maximum of Al_o and inorganic amorphous Al, (Al_o-Al_p) was found in the second podzol B subhorizons of the studied soils, which suggests that imogolite or allophanic material may be present. The fact that Al_o did not follow

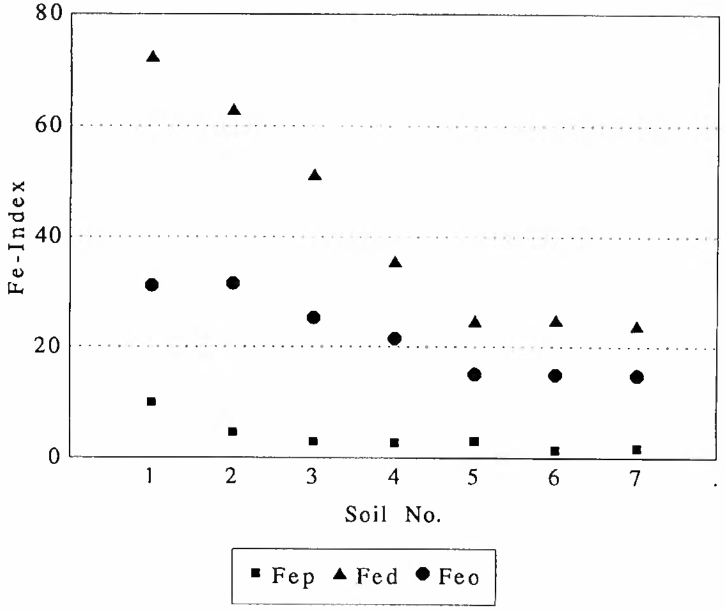

Figure 4. Iron indexes based on pyrophosphate, dithionite and oxalate extractable iron of the soils down to 1 metre depth.

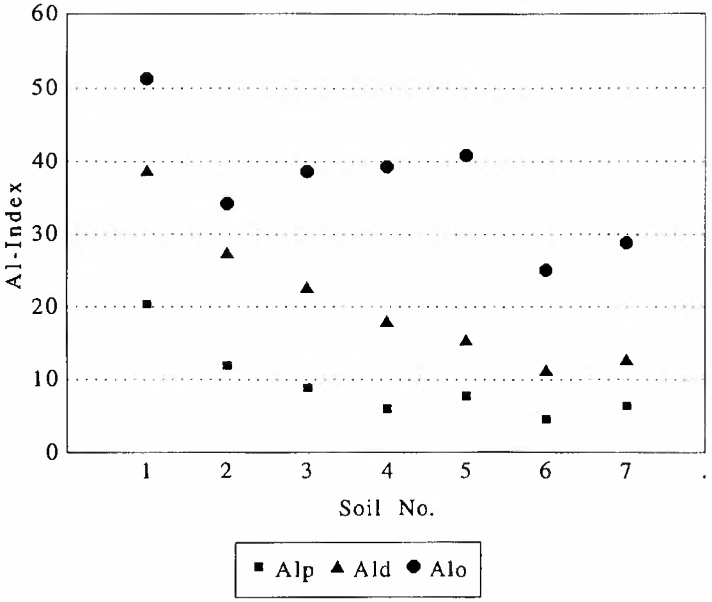

Figure 5. Aluminium indexes based on pyrophosphate, dithionite and oxalate extractable aluminium of the soils down to 1 metre depth.

the other Al extracts may indicate that the accumulation of inorganic amorphous Al represents a process that does not correspond to the podzolization processes that result in the typical podzolic morphology.

Classification

The 1975 and 1992 versions of Soil Taxonomy, The 1988 version of the FAO/Unesco system, and the 1987 version of the Canadian System of Soil Classification were used to investigate how well they reflect the differences in soil development. Analyses necessary for classification are presented in Table 2. The classifications according to the different schemes can be found in Table 3 and the family level classifications according to Soil Taxonomy and the Canadian System of Soil Classification in Table 4.

The main reason for excluding soils from the Podzol (Spodosol) orders was that the B horizons that fulfil the chemical and morphological criteria were either too thin or did not fulfil the depth requirements of the classification schemes in question.

The soils that did not qualify as Podzols (Spodosols) were placed in the Soil Taxonomy and the FAO-Unesco orders that emphasize the sandiness of the soils; Entisols and Arenosols respectively. The soils that did not qualify for the Podzolic order were placed in the Brunisolic order, by the Canadian Soil Classification System.

The podzol morphology of the soils was sometimes indicated at lower levels of classification. This was not the case for the soils classified according to Soil Taxonomy version 1975 (Table 3). According to the 1992 version of Keys to Soil Taxonomy two of the soils were classified in the Spodic subgroup of the Udipsamments while two other soils were classified as Typic Udorthents (Table 3). The only difference between the Spodic Udipsamments and the Typic Udorthents in the present study is the sandy skeletal particle size class (Table 4). The podzol morphology was not reflected in the soil unit classification of the two soils that were Arenosols according to the FAO-Unesco system (Table 3). The five soils that were classified in the Brunisolic order of the Canadian system all have a subgroup classification of Eluviated Dystric Brunisols, which suggests a

Table 3. Classification of the seven soils according to the different classification systems and versions

	Soil Taxonomy		FAO-Unesco	Canadian Soil Classification
Soil No.	1975	1992	1988	1987
1	Typic Udipsamment	Oxyaquic Haplorthod	Haplic Podzol	Orthic Humo-Ferric Podzol
2	Typic Udipsamment	Typic Haplorthod	Haplic Podzol	Orthic Humo-Ferric Podzol
3	Typic Udorthent	Typic Haplorthod	Cambic Podzol	Eluviated Dystric Brunisol
4	Typic Udorthent	Typic Udorthent	Haplic Podzol	Eluviated Dystric Brunisol
5	Typic Udipsamment	Spodic Udipsamment	Haplic Podzol	Eluviated Dystric Brunisol
6	Typic Udipsamment	Spodic Udipsamment	Cambic Arenosol	Eluviated Dystric Brunisol
7	Typic Udorthent	Typic Udorthent	Cambic Arenosol	Eluviated Dystric Brunisol

Table 4. Family level classification of the seven soils

Soil No.	Soil Taxonomy (1975, 1992)	Canadian Soil Classification (1987)
1	Sandy, mixed, frigid	Sandy, mixed, acid, cold humid
2	Sandy, mixed, frigid	Sandy, mixed, acid, cold humid
3	Sandy skeletal, mixed, frigid	Sandy skeletal, mixed, acid, cold humid
4	Sandy skeletal, mixed, frigid	Sandy skeletal over coarse silty, mixed, acid, cold humid
5	Sandy, mixed, frigid	Sandy, mixed, acid, cold humid
6	Sandy, mixed, frigid	Sandy, mixed, acid, cold humid
7	Sandy skeletal, mixed, frigid	Sandy skeletal, mixed, acid, cold humid

podzol morphology by indicating both an eluviated horizon and acidic properties.

Cluster analyses

Cluster analyses were used to group the soils by morphological and chemical properties. The clusters were compared with the different classifications of the soils. The properties used for the cluster analyses were the profile indexes of carbon, Fe_p, Al_p, Fe_d, Al_d, Fe_o, Al_o, hue, value and chroma.

Density linkage clustering based on the distance between three or more nearest neighbours, k=>3, resulted in the formation of one modal cluster. The results of this clustering procedure were comparable to classifications according to the 1975 version of Soil Taxonomy and revealed nothing about the differences in the observed soil development (Table 5). With so few soils as in this study, the

Table 5. Results from the cluster analyses (1, 2) combined with the results of the classification separating the podzols (p) from the non-podzols (n)

	Soil No.							
	1	2	3	4	5	6	7	
Density Linkage								Classification
k > 2	1	1	1	1	1	1	1	
	n	n	n	n	n	n	n	ST 1975
k = 2 (-Alo)	2	2	2	1	1	1	1	
	p	p	p	n	n	n	n	ST 1992
k = 2 (+Alo)	2	2	2	2	2	1	1	
p	p	p	p	p	n	n		FAO 1988
k = 2 (Bhs)	2	2	1	1	1	1	1	
	p	p	n	n	n	n	n	Canada 1987

chances of finding clusters using k=>3 would be minimal even if they were present.

Basing the analysis on the distance between two nearest neighbours, k=2, suggested two modal clusters (Table 5). The two clusters were soils 6 and 7 in one group and soils 1, 2, 3, 4 and 5 in the other. An analysis of variance between the two clusters show that the only variable dividing the clusters was Al_o, which was significantly lower ($p<0.05$) for soils 6 and 7. This cluster analysis gave groups similar to the FAO-Unesco classification.

As the Al_o index displayed an irregular behaviour compared to the observed trends in soil profile development (Fig. 5), elimination of Al_o from the cluster analysis seemed reasonable. When Al_o was excluded soils 1, 2 and 3 made up the first cluster and soils 4, 5, 6 and 7 made up the second (Table 5). The two clusters are similar to the classification obtained by the 1992 version of Soil Taxonomy. An analysis of variance revealed that the first cluster had a significantly ($p<0.05$) higher amount of Fe_d, Al_d, Fe_o and redder hue than the second cluster.

Neither the cluster analysis including the Al_o index nor the one excluding the index showed significant differences between the groups based on properties generally assumed to be the most closely related to podzolization such as Fe_p, Al_p and carbon. This perhaps suggests that by using the indexes for the soil down to one metre, too much emphasis may have been placed on the sometimes very thick C horizons.

The upper podzol B subhorizon, is generally assumed to be the horizon with the most pronounced podzolic properties and is the horizon most emphasized in the classification of the podzols. Therefore a cluster analysis was applied to the weighted upper podzol B subhorizon properties in the assumption that this would more closely reflect the degree of podzolization. The cluster analysis (k=2) suggested two clusters. Soils 1 and 2 made up the first cluster and soils 3, 4, 5, 6 and 7 made up the second (Table 5). The first cluster had a significantly ($p<0.05$) higher Fe_p, Al_p, Fe_d, Al_d, Fe_o, Al_o and carbon content as well as having a significantly ($p<0.05$) redder hue, higher value and higher chroma. These two groups were similar to those obtained by the Canadian classification, which suggests that the degree of podzolization was well reflected by the Canadian system.

These cluster analyses show how important it is to know which properties to emphasize when evaluating the suitability of different classification systems for specific purposes. The purpose of the present study was to examine the ability of the classification systems to reflect the soil development in some podzolized soils. Many mechanisms for podzolization processes have been suggested and are still subject to discussion, therefore it is difficult to know exactly which properties to emphasize when evaluating a classification system for podzols. This is clearly demonstrated in the different results of the cluster analyses.

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Effects of long-term crop rotations, fertilizer, farm manure and straw on soil productivity

II. Mineral composition of plants, nutrient balances and effects on soil

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Mineral composition of crop species, nitrogen and mineral balances and the effects on soi conditions for a 12-year period in a crop rotation-fertilizer experiment on clay loam at Ås Norway are reported. Four six-course rotations were used: Spring grain only (I); 3 years of grain crops and 3 years of row crops (II); 4 years of grain and 2 years of clover-timothy ley (III); 2 years of grain and 4 years of ley (IV). The crop rotations were in a split block design with 4-8 fertilizer rates including farm manure every sixth year and also in arable rotations with yearly ploughed-in straw. The nitrogen concentration in grain was found to be higher after ley than in the all-grain rotations, also in relation to obtained yields. Nitrogen balances were negative in all four rotations when only moderate amounts of mineral fertilizers were applied. Total-N in topsoil in 1990 was 0.9 and 1.1 tons higher per hectare in ley rotation IV than in rotations I and II. Differences in soil nitrogen mineralization and leaching losses are likely explanations. In 37 years the increased N-uptake in crops amounted to only 25-30% of the N added to farm manure (FYM), and 60-75% and for additional doses of N in calcium nitrate, increasing after a higher proportion of ley in the rotation (I versus IV). The amount of N left in the soil of the total addition since 1954 was about 20% for farm manure, almost the same for fertilizer N in all arable rotations, and somewhat less in the ley rotation. Unaccounted-for losses of N were large for FYM and for ploughed-in cereal straw. Only one-third of the surplus additional P was found as readly soluble P in soil. Exchangeable K in soil increased from 1972 to 1990 despite large negative balances. It was found that by using calcium nitrate pH was maintained without liming in the period 1978-90. The lime status of soil could be assessed fairly well also by excess bases/N in the crop removals.

Key words: Leys versus arable crops, N-utilization, plant nutrient contents, soil N and C.

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The experimental design and the yields of different crops in a long-term crop rotation-fertilizer experiment conducted at Ås, Norway were recently reported (Uhlen et al. 1994). The results showing changes in soil nitrogen and carbon content, (1954-84), as influenced by leys, fertilizer, farm manure and straw were also published (Uhlen 1991) as well as the effects upon soil aggregation and aggregate stability (Skøien 1993).

In this report the results of the chemical analysis of plant and soil samples will be dealt with.

In rotation experiments the chemical composition of different crop species grown on the same plots can be exactly compared, as well as the effect of crop rotation upon total uptake of nitrogen and minerals. Changes in the soil content of some elements are evaluated, although no complete accounts of losses, such as gaseous and leaching losses of nitrogen, are available.

Materials and mothods

An experiment with four six-course rotations and eight fertilizer treatments was started at Ås, Norway in 1953 on a clay loam high in organic matter. The clay content averaged 25% in the topsoil and somewhat more in the subsoil. Relatively high spatial variability, in both a vertical and a horizontal direction was shown in a comprehensive study of the experimental area (Stensby Høstmark 1994). Nevertheless, the variations in yield between the two real replicates in the experimental fields were not above normal, giving coefficients of variation of 7-10% as averages for the different crops (Uhlen et al. 1994).

The experimental treatments have been subject to some changes during the 40 years; – fertilizer rates have been increased in accordance with the common trends in agriculture, and also the crop sequences have been somewhat adjusted. In 1954-77 only one year our of six in rotation II was allotted to row crops (potatoes).

The following plan was used from 1978 to 1992:

Crop sequences in the six-course rotations:
Sequence no. = block no. in 1982, 1988

	1	2	3	4	5	6
I	Barley	Spring wheat	Barley	Oats	Spring wheat	Oats
II	Potatoes	Swedes	Barley	Beet	Spring wheat	Oats
III	Barley	Spring wheat*	1st year ley	2nd year ley	Spring wheat	Oats
IV	Barley	Spring wheat*	1st year ley	2nd year ley	3rd year ley	4th year ley

*Timothy and red clover seeded in with the spring wheat.

All crops were represented every year and duplicated (= 48 rotation plots) and placed in blocks of four plots.

Fertilizer and manure treatments:

a. Moderate rates of N, P and K in fertilizer. Same amounts for rotations I-IV in the period 1953-80. Later on, rates were differentiated to some extent between crop species.

b. Normal rates of N-, P- and K-fertilizers to different crops.

c. Farm manure, 60 tons/hectare in the year with potatoes and barley (sequence no. 1) + NPK in fertilizer to commensurate with treatment b.

d. I and II. As for b + all cereal straw ploughed in.
d. III and IV. As for c + additional fertilizer for grassland.

In order to assess higher N-rates, half of all the respective grain plots were given an additional 80 kg N per hectare after sprouting. This topdressing of N, in calcium nitrate, was applied alternately on the left- and right-hand sides of the subplots.

The rotation treatments I-IV and the fertilizer treatments a, b and c were of complete factorial design, whereas treatment d was not. A split-block field design was used, with rotation and fertilizer treatments crosswise on rows or columns, thus affording the highest precision for determining the rotation x fertilizer interactions.

Farm manure (FYM) in treatments I-IV-c and III-IV-d was incorporated in spring by harrowing before planting.

In the plan the N, P and K values of 60 tons FYM were set to 140, 90 and 200 kg respectively. The N, P and K in fertilizers applied in treatment c were reduced by these amounts in contrast to treatment b. This reduction was apportioned over the rotation period, although the largest correction was made for N and K in the year of FYM application. Some additional adjustment had to be made in the year after the FYM treatment based on chemical analysis. For nitrogen, the reduction in N-fertilizer over six years in treatment c is greater than the applied 108 kg NH_4-N, but much less than the total-N in FYM (234 kg).

In treatments Id and IId the potassium rate was reduced by 20 kg K per hectare in all years after ploughing-in the straw.

The analytical programme has not been complete and therefore analyses are missing for barley III in sequence no. 1, spring wheat in sequence no. 2 and oats II in sequence no. 6. In an earlier publication (Uhlen et al. 1994) yield results from 1980 to 1992 were assessed. No chemical analyses were carried out in 1990 and 1991 because of lack of resources. For many of the crops it was possible to include results from 1979 and 1980, giving two complete 6-year courses in Table 1.

Results and discussion

Mineral composition of different crop species

The mineral content is reported as a percentage of dry matter. The figures presented in Table 1 for two fertilizer treatments are repectively from rotation I for grain, rotation II for row crops, III-IV for first- and second-year clover and timothy and rotation IV for mixed grasses. N, P and K concentrations were determined also in samples from most of the fertilizer x rotation treatments, for instance in barley and spring wheat in the first year after 4-year ley (IV) and a 2-year ley (III) respectively and in oats the second year after a 2-year ley (III). For the other elements the analytical program-

Table 1. Nitrogen and mineral content of crop species in a rotation experiment 1979-90. Percentage of dry matter yield.

	N		P		K		S		Cl		Ca		Mg		Na	
N-applications	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Barley, grain	1.96	2.31	0.40	0.41	0.54	0.54	0.16	0.19	0.13	0.13	0.06	0.06	0.11	0.11	(0.01)	
" straw	0.70	0.94	0.10	0.12	1.46	1.69	0.16	0.18	0.85	0.76	0.34	0.37	0.06	0.06	0.03	0.04
Oats, grain	1.90	2.25	0.39	0.41	0.46	0.48	0.18	0.19	0.08	0.09	0.09	0.10	0.10	0.11	(0.01)	
" straw	0.63	0.83	0.13	0.13	2.07	2.28	0.13	0.16	0.97	1.05	0.31	0.35	0.05	0.07	0.04	0.06
Wheat, grain	2.29	2.64	0.44	0.46	0.46	0.46	0.17	0.19	0.06	0.06	0.04	0.04	0.12	0.13	(0.02)	
" straw	0.71	0.85	0.11	0.10	1.03	1.13	0.14	0.15	0.50	0.47	0.22	0.24	0.06	0.06	(0.01)	
Swedes, root	1.45	1.61	0.30	0.30	2.13	2.16	0.35	0.38	0.27	0.25	0.34	0.37	0.09	0.10	0.06	0.08
" top	2.71	2.96	0.35	0.33	3.67	3.18	0.81	0.78	2.99	2.28	2.70	2.66	0.15	0.18	0.07	0.10
Beet root	0.85	1.01	0.19	0.19	1.75	1.82		0.08		0.35		0.12		0.09		0.09
" top	2.40	2.91	0.29	0.29	6.28	5.64		0.43		2.77		1.68		0.52		0.90
Potato,tubers	1.28	1.50	0.28	0.27	2.42	2.33		0.15		0.28		0.05		0.11		0.02
Clover 1. yr 1. cut	2.67	2.80	0.26	0.27	2.86	3.16		0.19		0.87		1.46		0.23		0.02
" 1. yr 2. cut	2.83	2.82	0.25	0.26	2.45	2.70		0.19		0.81		1.68		0.28		0.02
" 2. yr 1. cut	2.67	2.78	0.28	0.29	2.90	3.07		0.19		0.84		1.40		0.22		0.02
" 2. yr 2. cut	3.00	2.92	0.25	0.25	2.44	2.60		0.20		0.79		1.74		0.27		0.02
Timothy 1. yr 1. cut	1.65	1.86	0.27	0.27	2.58	2.71		0.16		1.34		0.39		0.09		0.02
" 1. yr 2. cut	1.87	1.89	0.28	0.26	2.49	2.38		0.18		1.12		0.45		0.10		0.02
" 2. yr 1. cut	1.59	1.95	0.25	0.26	2.49	2.63		0.18		1.29		0.40		0.09		0.02
" 2. yr 2. cut	1.70	1.80	0.27	0.25	2.26	2.20		0.18		1.05		0.52		0.10		0.02
Grasses 3. yr 1. cut	1.68	2.03	0.26	0.27	2.55	2.61		0.18		1.15		0.47		0.08		0.02
" 3. yr 2. cut	1.73	1.90	0.26	0.25	1.98	2.12		0.17		0.98		0.63		0.11		0.02
" 4. yr 1. cut	1.46	1.98	0.23	0.24	2.50	2.53		0.19		1.15		0.47		0.09		0.02
" 4. yr 2. cut	1.75	1.80	0.30	0.25	2.46	2.11		0.17		0.99		0.72		0.12		0.02

N-application rates 1 and 2 were 80 and 160 kg N per hectare and year in calcium nitrate. P and K, equal for N rates 1 and 2 for grain, were 35 kg P in superphosphate (9% P) and 100 kg K in potassium chloride (49% K). For ley and row crops K additions were increased from 120 to 160 kg K at N-rates 1 and 2 respectively. For grain increased N (2-1) was given as topdressing and for other crops also as increased spring application.

me was restricted to the two levels of nitrogen fertilizer treatment as shown in Table 1.

The application of 80 kg N per hectare in calcium nitrate after sprouting in addition to 80 kg per hectare at sowing increased the N-content in cereals. In relation to the yield levels obtained, the N2-level represents a surplus amount of N for spring grain.

The total-P content in dry matter did not vary greatly between the different crops. If we consider grain + straw, total-P would be in the range of 0.25-0.30% of dry matter for most crop species. The variations in total-P between the years were very small (standard deviation ± 0.03%) compared with the yearly variations in total-N and K content.

Confidence limits, based on yearly variations, are not given in Table 1. These variations are likely to be much smaller than the variation in mineral composition found by comparing crops grown on different soils. The average contents reported here, however, are in fairly good agreement with results reported earlier from Denmark (Henriksen 1965) Finland (Jaakkola & Vogt 1972) and Norway (Njøs 1964, Ekeberg 1984). The result in Table 1 also revealed some rather striking similarities to a US compilation of plant compositions (Beeson 1941).

The composition of clover and grasses will also depend on the stage of development at harvest, in both the first and second cuts. Since all the potassium fertilizers were applied in early spring, high yields in the first cut have left less potassium for the regrowth, as indicated in the K-content in the second harvest, especially in the third and fourth ley years. We found that the higher N application rate increased K-content of cereal straw, and also that oat straw contained 40% more K than barley straw and twice as much as the wheat straw.

The Cl-content follows the K-content in the comparison between crop species and also among years. The Cl- content of straw, grasses and root crops was about half that of K. Since Cl was added in almost the same amount as K, in KCl, large proportions of the added Cl were lost through leaching. In an 8-year field lysimeter study on the same soil, 50% of the added Cl was leached out, and 50% taken up in the different crops (Uhlen 1989a). The correlation between K and Cl in grasses was relatively high, giving correlation coefficients from +0.6 to +0.9 for different ley years and cuts. This also applies to barley and oat straw (r = +0.6) affected not only by yield levels, but also by the fact that K and Cl are elements that are readily leached from straw after ripening in some wet autumn seasons.

The familiars picture of high concentration of K, Cl and Ca in cereal straw and higher concentrations of N, P and Mg in grain is demonstrated in the table. The variations from year to year are, for most elements, larger in straw than in grain. The standard deviations (SD) for samples collected between the 12-years were 0.03% for S in grain and 0.06 for S in straw. For Ca, SD values were 0.015% for oat grain and 0.07% for oat straw. High yearly variations were found for K and Cl in cereal straw, especially for oats, with SD values of 0.8% for K and 0.4% for Cl. The corresponding SD values for timothy were 0.35% for K, and 0.2% for Cl, for both the first and second cuts, and also almost the same for the first and second ley years.

The nitrogen content of cereal grain was correlated with yield levels in the different years (Table 2) and the residual variance corresponded to a standard deviation of 0.2% N for yearly observations as an average of the three grain species.

Table 2. The relationship between grain yield levels and N-per centages in grain at different fertilizer and rotational treatments (1979/1962-90)

Treatment combination N in kg/ha/yr			No. of years	N-percentage Y=c-bx	r	Estimated grain N (%) at yield levels 3t/ha	5t/ha
Ib	80	Barley	29	2.78 - 0.215 X	-0.77	2.13	1.71
IbN	160	"	12	3.12 - 0.165 X	-0.82	2.62	2.29
IVb	80	"	10	3.11 - 0.246 X	-0.83	2.37	1.88
IVbN	160	"	10	3.40 - 0.201 X	-0.61	2.80	2.40
Ib	80	Oats	29	2.71 - 0.180 X	-0.95	2.17	1.81
IbN	160	"	12	2.88 - 0.137 X	-0.70	2.47	2.19
IIIb	80	"	10	2.52 - 0.114 X	-0.86	2.18	1.95
IIIbN	160	"	10	2.88 - 0.129 X	-0.63	2.49	2.23
Ib	80	Spring wheat	12	3.18 - 0.282 X	-0.83	2.33	1.77
IbN	160	" "	12	3.16 - 0.148 X	-0.74	2.72	2.42
IIIb	80	" "	10	3.28 - 0.239 X	-0.82	2.56	2.09
IIIbN	160	" "	10	3.09 - 0.100 X	-0.50[1]	2.79	2.59

Y = N-percentages of grain dry matter
X = Grain dry matter yields in tons per hectare
I = Continuously grain, alternating barley, oats and wheat
IV = Barley 1st year after a 4-year ley
III = Spring wheat 1st year after a 2 year-ley
III = Oats 2nd year after a 2 year-ley
bN = The additional N given after sprouting
[1] Not significant.

The yields of the other crop species correlated less closely with the yearly yield figures, although the variations in N-content from year to year were substantial, corresponding to a standard deviation of 0.33-0.45% N for timothy and 0.25-0.45% for clover.

In this experiment as much as 40-50 kg S was added in superphosphate per hectare and year. The S-content of the crops seems rather high, and with N:S ratios of 10 or less. The variations in S-content were, like the content of P, small between crop species. Swedes are exceptional with the well-known high sulphur demand. Also, the content of Mg did not differ much between plant species, with the exception of a high content in clover and beet leaves.

Beet roots contained less N, P and K

than the roots of swedes, whereas the tops of both beet and swedes had a very high mineral content. The K-percentages for beet leaf dry matter of 6.3 and 5.4% are outstanding. The average dry matter yields of beet tops were 2.8 and 3.8 tons per hectare and those of beet roots 6.3 and 7.2 tons for the two fertilizer levels. The withdrawals of K per hectare in the beet year in rotation II were 270 and 330 kg and the addition K in fertilizers 120-160 kg K. Beet plants were also remarkable in the uptake of Na, almost 1% of dry matter leaves. Na is no doubt present in large quantities in the soil solution in this soil (Uhlen 1989a), and therefore apparently excluded in root uptake by most crops, such as cereals, timothy and also clover.

Treatment effects on mineral composition

The relationship between grain yields of barley, oats, and spring wheat and percentage of N in dry matter grain is shown in Table 2 for the two N-fertilizer levels and for rotations with and without ley in previous years. Data from the earlier period (1962-79) are included for barley and oats at low N-fertilizer levels.

Variation in grain crop yields from year to year can largely explain ($R^2 = 0.5$-0.9) the variation in total-N in grain in the all grain-rotation (I). Grain grown after ley (rotations III and IV) has a markedly higher N-content in relation to the attained grain yields than that grown in the all-grain rotation. These results indicate, therefore, that the additional nitrogen mineralized in soil as a consequence of ley in rotation may be taken up by the cereal crops too late in the season for the maximum yield to be effected. This is analogous to the fact that split application of N at flowering stage in cereals increases N-content more than grain yields (Skorge & Sogn 1988, Stabbetorp & Dæhlin 1993, Bänziger et al. 1994).

From the regression formulae the expected N-content in grain dry matter at two yield levels (3 and 5 tons dry matter per hectare) and at the two actual N-fertilizer additions is calculated (Table 2). As we can also see from the regression coefficients, there was a more marked decline in the N-content of grain with increasing yields when N-applications were moderate (80 kg) than when they were high (160 kg). The effects of ley in rotation upon the N-content of grain at increasing yield are somewhat more variable at the highest N-rate (non-significant correlation for spring wheat). As reported in publication I (Uhlen et al. 1994), cereal lodging reduced the positive after-effect of ley at high grain yields. The effect of lodging upon N-content of grain cannot be further evaluated in this experiment.

The effect of farm manure on N, P and K percentages in different crop species was small. In the year of FYM application, the N-content and N-uptake in barley and potatoes were a little higher after FYM + 80 kg fertilizer N than after 160 kg N in fertilizers (sequence no. 1 in Table 3). In the second to fourth years the after-effects of FYM tended to be a little less than the 20 kg N reduction in fertilizer rate on plots without FYM. This is in accordance with the yields reported earlier (Uhlen et al. 1994).

The P-content of the different crops was scarcely affected by differences in rotations or by application rates in farm manure or superphosphate. Only total uptake of P and K in crops for the different rotations I-IV is reported (Table 5).

On average for all comparisons between the treatments with and without straw, the N-contents of both grain and

Table 3. Nitrogen in crops in relation to inputs. Means for two 6-year periods, 1980 - 92. Kg N/hectare

	Added N		In crops, sequence no						Averages	
	Range	Mean	1	2	3	4	5	6	per year	
			Bar.	Sp.wh.	Bar.	Oats	Sp.wh.	Oats		
Ia	40-120	80	87	81	85	95	81	86	86	- 6
Ib	80-160	120	111	100	112	109	100	108	107	+13
Ic	0-160									
+ FYM	234	136	119	102	109	110	102	113	109	+27
Id	80-160	120	111	101	116	113	101	108	108	
In straw			23	21	26	25	21	22	23	+35
			Pot.	Swe.	Bar.	Beet	Sp.wh.	Oats		
IIa	40-120	80	72	125	90	120	78	91	96	-16
IIb	80-200	140	92	173	115	182	99	109	128	+12
IIc	80-180	156	97	176	114	179	102	112	130	+26
+ FYM	234									
IId	80-200	140	91	176	118	190	101	111	131	
In straw					24		20	23	11	+20
			Bar.	Sp.wh.	Ley 1	Ley 2	Sp.wh.	Oats		
IIIa	40-120	80	94	80	113	124	100	102	102	-22
IIIb	80-160	130	121	101	153	189	116	120	133	- 3
IIIc	0-160	146	128	102	148	179	121	124	134	+12
+ FYM	234									
IIId	0-220	169	125	102	178	220	122	122	145	+24
+FYM	234									
			Bar.	Sp.wh.	Ley 1	Ley 2	Ley 3	Ley 4		
IVa	40- 80	80	107	94	113	124	152	125	119	-39
IVb	80-240	143	127	116	153	189	215	200	167	-24
IVc	0-160	159	137	114	148	179	208	199	164	-5
+ FYM	234									
IVd	0-240	209	136	121	178	220	259	234	192	+17
+ FYM	234									
					1 year ley:	2 year ley:				
In clover		III+IV a			86	78			27	
		" b			62	51			19	
		" c			64	54			20	
		" d			59	41			17	

Bar. = barley Sp.wh. = spring wheat. Pot. = potatoes. Swe. = swedes.

Values for leys 1 and 2 are averages for rotations III and IV.

Table 4. Total-C and total-N in topsoil 1984 and 1990. Percentage of dry matter

	Tot.-C		Tot.-N[1]		C/N	Tons N/hectare[2]
	1984	1990	1984	1990	1990	1990
Ia	3.34	3.35	0.296	0.323	10.37	7.27
Ib	3.41	3.46	0.304	0.330	10.48	7.43
Ic	3.56	3.62	0.318	0.343	10.55	7.72
Id	3.57	3.62	0.311	0.338	10.71	7.61
IIa	3.28	3.26	0.284	0.312	10.44	7.02
IIb	3.35	3.38	0.294	0.325	10.40	7.31
IIc	3.52	3.48	0.306	0.330	10.54	7.43
IId	3.47	3.42	0.301	0.327	10.46	7.36
IIIa	3.34	3.52	0.300	0.341	10.32	7.67
IIIb	3.60	3.69	0.313	0.350	10.54	7.88
IIIc	3.69	3.86	0.326	0.359	10.74	8.08
IIId	3.48	3.68	0.318	0.358	10.28	8.06
IVa	3.65	3.88	0.326	0.362	10.72	8.14
IVb	3.81	4.00	0.336	0.373	10.72	8.39
IVc	3.96	4.13	0.349	0.383	10.78	8.62
IVd	4.00	4.21	0.349	0.384	10.96	8.64
LSD	0.16	0.12	0.014	0.011	0.27	0.25

[1] Total-N analyses in 1984 and 1990 are not directly comparable due to changes in analytical methods.

[2] In 2250 tons of soil.

Table 5. Phosphorus and potassium balances for 1980-92 in kg per hectare and year in relation to soil analysis

	Added		Crop removals				In topsoil 0-20 cm				
	P	K	P		K		P-AL		K-AL		
							1984	1990	1972	1984	1990
Ia	25	80	16.3	+ 8.7	52	+28	11.2	10.7	12	13.0	17.3
Ib	35	100	19.1	+15.9	63	+37	13.2	14.7	12	14.1	18.7
Ic	35	100	19.7	+15.3	64	+36	13.0	13.9	13	14.0	18.4
Id	35	80	19.8	+19.2	67	+61	13.1	14.5	16	17.8	21.7
Straw	+4	+48									
IIa	25	100	17.5	+7.5	120	-20	10.6	10.8	11.7	11.3	13.4
IIb	35	130	20.4	+14.6	144	-14	12.9	13.6	12	11.5	13.5
IIc	35	130	21.1	+13.9	146	-16	12.0	13.0	12.7	11.0	12.2
IId	35	120	21.1	+15.9	151	-7	13.1	13.5	14.7	12.9	13.7
Straw	+2	+24									
IIIa	25	93	20.7	+4.3	117	-24	9.2	11.4	8.7	9.2	11.4
IIIb	35	120	23.2	+11.8	136	-16	10.1	11.5	9.8	10.1	11.5
IIIc	35	120	23.5	+11.5	137	-17	10.1	12.2	10	10.1	12.2
IIId	38	133	24.0	+14.0	144	-11	10.7	12.8	9.6	10.7	12.8
IVa	25	107	22.6	+2.4	167	-60	8.3	10.2	9.6	8.3	10.2
IVb	35	140	25.9	+9.1	198	-58	9.1	11.1	9.7	9.1	11.1
IVc	35	140	25.8	+9.2	197	-57	9.2	11.3	9.4	9.2	11.3
IVd	42	167	26.5	+15.5	211	-44	10.9	11.7	10.7	10.9	11.7
							LSD 1.2			LSD 1.4	

In the period 1980-92 7 kg and 34 kg P and K respectively were added in farm manure for treatment combination Ic, IIc, IIIc, IIId, IVc and IVd.

For the whole period 1954-92 the P and K contents in farm manure were 12 and 36 kg calculated per hectare and year. P-AL and K-AL represent readily soluble P and K in mg/100 g soil according to the AL-method (Egnér et al. 1960) straw were identical, 2.24% N in grain and 0.78-79% N in straw yields. The K-content of the straw yields in the ploughed-in straw treatment, however, was consistently higher than that in the treatment without straw, despite of an additional application of 20 kg K per hectare and year in that treatment.

Effects of farm manure, straw and rotations on the contents of S, Cl, Ca, Mg and Na in crops were not investigated.

The nitrogen balances

The inputs of nitrogen in fertilizer, farm manure and straw and the output in crops are calculated in Table 3 for the last 12-year period. As already noted, the analytical programmes were not complete, and some missing data had to be taken from analytical figures of the same crop in other sequences. The average figures for N, P and K in crops for the whole period were used for 1991 and 1992 also when chemical analyses were not carried out. Since only analysis of one composite sample from each individual treatment was available, an analysis of variance was not carried out.

Nitrogen in precipitation (about 10 kg N per hectare and year) was not included in Table 3. A very important question, however, is how the nitrogen in clover should be taken into account. In ley rotations III and IV (Table 3), N in clover was left out in the input-output figures. The amounts of N in the clover yields in the first and second ley years can, however, be found at the foot of Table 3. In the third and fourth ley years there was practically no clover.

The balance calculation for nitrogen is based on the assumption that the quantities of N in clover taken from the soil and fertilizers were about the same as the biological fixed N in clover residues, root and stubble left in the soil. The harvested nitrogen in clover was only about 20 kg N per hectare and year on average for the rotation period. The clover has no doubt also taken up nitrogen added in fertilizer. As can be seen from Table 1, the N-content of clover increased in the first, but not in the second cut, after the high rate of N-application.

In their review work La Rue & Patterson (1981) point out that only part of the nitrogen in leguminous plants originates from the symbiotic fixation. For soybeans, Johnson et al (1975) reported that the fraction of N from dinitrogen fixation declined from 46 to 10% as fertilizer N increased. More recent reports indicate that measurement of N fixed by legumes is often overestimated by the so called fertilizer replacement value method compared with direct measurements (Bullock 1992).

If we assume that 50% of the clover nitrogen yield, as well as that of the residues left behind, were fixed nitrogen, the above assumption and calculated balances would be correct only if the N-content in residues were as large as the N-content in harvested clover hay. The additional N-uptake in spring wheat following a 2-year ley with clover was about 20 kg N per hectare, and, likewise, the effect on oats in the second year was 12-15 kg N (Table 3). Only part of this nitrogen can be accredited to clover and, on the other hand, only part of the residue will have an effect of N in the subsequent years.

If mineral fertilizers only were applied, the N-balances would be more negative in ley rotations than in all-grain rotations. This is unlikely, however, because of an underestimated contribution of fixed N in clover and clover residues. It should be noted again that, in relation to the attained yield, the N-application rates were larger for the grain crops than for the leys in this experiment.

When 60 ton of farm manure per hectare was applied to barley and potatoes in sequence year no. 1, the N-balances for the 6-year periods became positive and likewise for ploughed-in straw in treatments Id and IId.

The input-output figures are only part of the situation. Leaching and other losses were not measured, and the rate of mineralization of soil nitrogen has apparently been very different in ley rotations compared with all-arable cropping.

The utilization of added N was calculated as additional N-uptake in crops in percentages of added N. The results are presented in Fig. 1 for three periods and for the whole 37-year period, for both mineral fertilizer and farm manure. For cereal crops the additional N doses were ½ (b + bN - a - aN) = 120 - 80 = 40 kg for the last period and only 73 - 52 = 21 kg N per hectare and year in earlier periods. Likewise, the N doses (b-a) for ley were much higher after 1978, + 80 kg for leys 2-4 against + 42 kg in the earlier period. The high utilization percentages of fertilizer nitrogen in the period 1962-79 were partly caused by the low N-fertilizer rates. The analytical programme was not complete and some missing data had to be estimated. In the period 1962-79 clover and grasses were not separated for the second cut yields. The clover yields in kilograms of dry matter per hectare did not differ much between the N-treatments in the first cut, and therefore the N-percentages in Fig. 1 would not have been greatly influenced if the N in clover had been included also in the first cut hay yields.

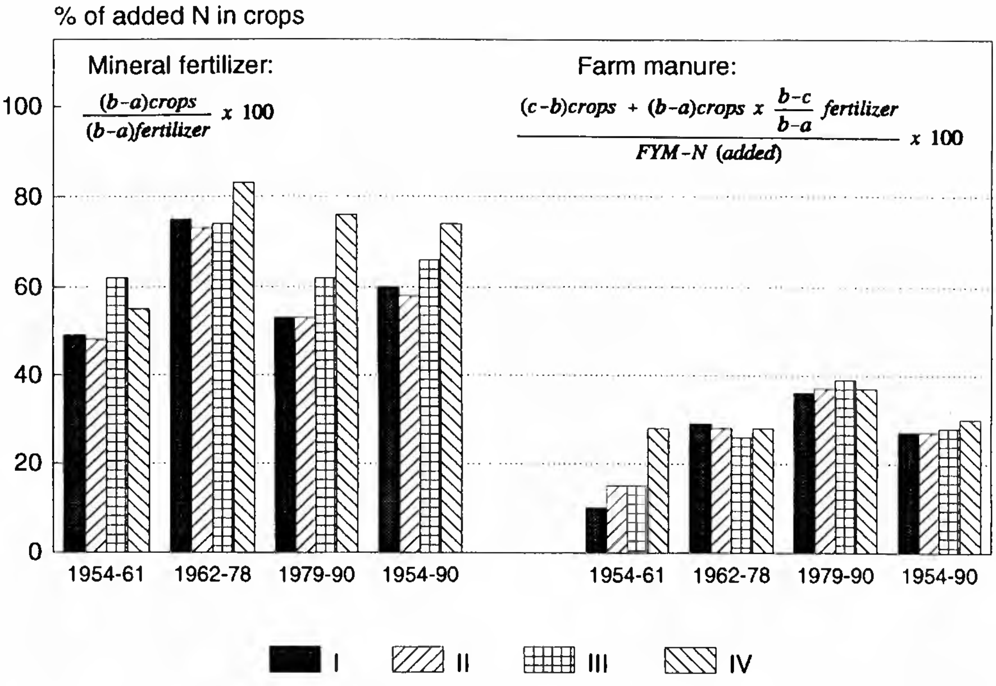

Figure 1. Utilization percentages of nitrogen in mineral fertilizer and farm manure

The uptake figures of nitrogen from farm manure had to be corrected for differences in mineral-N addition between the treatments with (c) and without FYM (b), as shown in Fig. 1. The results demonstrate that the utilization of N in FYM was only 40-45% of that of mineral fertilizers, even after including all residual effects during 37 years.

The increased utilization of FYM from 15-20 to 35-40% in the three periods are in accordance with another long-term experiment at Ås (Uhlen 1989b), where the utilization of N in FYM increased from 20 to 35% of added N in 30-40 years. In that experiment the effect of farm manure was measured against a treatment without any nutrient being applied, and, an 8-year residual period was also included.

Organic matter and nitrogen in soil

Total-C and total-N were determined in topsoil samples from all subplots (192) every sixth year. A change in analytical method from Kjeldahl to a direct combustion method (Tabatabai & Bremner 1990) brought about a change in the level of total N. It was possible to compare the methods for some stored samples taken out in 1954, which revealed differences between the two methods similar to those found for 1990 compared with 1984 in Table 4. Both methods, however, demonstrated the reduction in soil nitrogen during the 37 years' arable cropping. Owing to change in ploughing depth, no exact comparison can be made between 1954 and 1990. The effect of the different treatment combinations seemed to be much the same in 1990 as in 1984. Positive effects upon total-N and total-C in soil of ley farming, farm manure, and N-fertilizer rates were demonstrated. The small gains in total-C and total-N after ploughed-in straw, demonstrated by earlier analyses (Uhlen 1991), were less convincing for the 1990 samples. Prior to 1977 straw was ploughed in for five out of six years in rotation no. II, against three out of six years in 1978-90.

A high proportion of ley in the rotations (four out of six years rotation in IV) led to an increase in total-C also and to a significant increase in the C/N ratios for the last period. Very high yields of hay crops in 1978-90 might have influenced the storage of soil carbon.

Despite the fact that nitrogen balances (added N in fertilizer N in harvested crops) were as negative in the ley rotations III and IV as in the all-arable rotations I and II, total-N in tons per hectare in 0-20 cm of the topsoil demonstrate the opposite result. The difference in soil N after 37 years of arable cropping compared with the 4-year ley rotation was roughly 1000 kg N per hectare, in addition to an extra withdrawal of 30 kg N per hectare and year in rotation IV in the last 12-year period compared with rotation I.

The main factors responsible for the lower soil N after all-arable crops were no doubt reduced mineralization rates under leys and, to some extent, also higher leaching losses in the first case. In field lysimeters with the same soil, leaching losses were 20 kg N per hectare and year higher in an all-grain rotation than for perennial grassland in 1974-81 (Uhlen 1989a). The differences in leaching losses from ley and all-arable plots were about the same at moderate and very high N-application rates in the field lysimeters.

In calculations based on several long-term fertilizer experiments a half-life of 14 years was indicated for the residual N in soil after use of mineral N fertilizers (Uhlen 1991). The half-life refers to a rough average for nitrogen left in the soil. The breakdown rate will vary for diffe-

Table 6. Cation-anion relationship in crop uptake 1980-92, pH 1984-1990 and cations in topsoil 1984

	Excess cations/N kg eq.v./hectare/year	pH (H_2O)		Exchangeable cations[1] mg/100 g			Sum cations kg eq.v./hectare
		1984	1990	Ca	Mg	Na	(2250 tons)
Ia		5.9	6.0	217	5.7	2.3	
Ib	0.57/7.62=0.075	5.9	6.1	227	5.3	2.3	276
Ic		6.0	6.1	232	7.6	2.5	
Id		5.9	6.1	226	5.3	2.3	
IIa		5.8	5.8	204	5.3	2.1	
IIb	3.26/9.14 = 0.36	5.8	5.9	217	4.8	2.1	261
IIc		5.9	5.9	222	6.7	2.3	
IId		5.9	5.9	215	4.6	2.2	
IIIa		5.7	5.7	207	5.3	2.3	
IIIb	2.40/10.37 = 0.23 (9.04)[2] = (0.27)	5.8	5.8	226	4.8	2.3	271
IIIc		5.8	6.0	233	7.3	2.8	
IIId		5.9	6.0	238	7.1	2.7	
IVa		5.7	5.8	223	5.7	2.7	
IVb	3.84/12.85 = 0.30 (11.50)[2] (0.33)	5.8	5.9	248	5.3	2.8	296
IVc		5.8	5.9	246	7.7	3.1	
IVd		5.9	6.0	258	6.9	3.0	
	LSD	0.1		11	0.8	0.2	

[1] Cations in accordance with the AL-method. Sums also include K-AL.

[2] N in clover not included.

rent fractions of soil nitrogen (Parton et al. 1982). For applied cereal straw, it was found that most of the organic matter disappeared in less than one year (Christensen 1986).

The higher amount of nitrogen in the soil in treatment b than that in treatment a corresponded to about 20% of the added N during 37 years in rotations I and II and only 15% in the ley rotations. The somewhat small soil N residues in ley rotations could be due to the higher utilization percentages of N removed by the grass crops. It should be noted, however, that the differences in soil N were subject to a relatively high error rate. Lyngstad (1991) found higher 15N-residues of N applied to grass than those found for spring grain.

Of the farm manure N added during the 37 years, no more than 20% was left in the soil. Since the corresponding uptake from FYM was less than 30%, half the amount of added N was lost in other ways. Loss of ammonia after spreading may have been substantial, although incorporation in the soil took place mostly within a day. The unaccounted-for N added in mineral fertilizers came to about 20% in the all-arable plots and only to 10% in the ley rotation (IV). Larger leaching losses in arable cropping than in ley cropping can perhaps explain this difference in the fate of the added mineral nitrogen.

The amount of N added to straw during the 37 years was about 750 kg per hectare. In addition to straw nitrogen, a certain quantity of N taken from the soil might have been assimilated in the first breakdown phase because of the high C/N ratio of straw. A reduction in mineral N in soil of 10 kg N per hectare and year has been found (Lyngstad 1978). Nevertheless, the non-significant increase in soil N after 37 years represented only 25%, and additional uptake in cereal yields 8% of the added straw N in rotation I. Scherer & Mengel (1981) advocated that the reduced nitrate content in straw-treated soil was caused by an increased denitrification. Also, farm manure nitrogen may be susceptible to large denitrification losses (Paul & Beauchamp 1989).

One possible source of error in long-term experiments is transportation of soil from one plot to another (Sibbesen 1986). In this rotation experiment the fate of the fertilizer N seemed realistic, but, the question can perhaps be raised whether organic residues from the straw and farm manure applied earlier are more susceptible to horizontal transportation than soil particles and fertilizers.

Phosphorus and potassium balances

The differences between added and removed P and K in crops can be found in Table 5 for all treatment combinations, as well as the contents of readily soluble P and K in the soil.

The same quantities of P and K were applied either in FYM + mineral fertilizers (treatment c) or in mineral fertilizers only (treatment b). The tendency toward a slightly increased uptake of P and K in treatment c compared with treatment b for three out of four rotations was also indicated for N in Table 3. It is highly likely that this results from yield differences in the year of FYM application, where the cereal straw yields in particular were higher in treatment c than in treatment b. The effect of FYM after long-term application may also be caused by a variety of other factors.

The phosphorus added represent surplus applications in this experiment, and large positive balances occurred. Changes in P-AL in the soil from 1984 to 1990 point in the same direction, but, it should be mentioned that the results from 1990, contrary to those from 1984, were for only one composite sample per treatment combination. Comparison of results of samples collected and analysed in different years are liable to errors. A large increase in P-AL-values was found in the 1970s in this experiment, most likely caused by lime applications in this period.

The increases in P-AL in the period from 1984 to 1990, like the differences in P-AL between treatments, are small in comparison to the balance differences. An increase in P-AL of 1-2 units in the 0-20 cm top layer is equivalent to 20-40 kg P per hectare, whereas the calculated positive balances per 6-year period may be in the range of 100 kg P per hectare. The P-AL values appear to be highly buffered.

The potassium balances are positive in the all grain rotation I and largely negative when row crops or ley were included in the crop rotation. The K-AL values, which give a fairly good estimate of exchangeable K in the soil, increased in the period from 1984 to 1990 in all cases. In ley rotation IV, for instance, more than 50 kg K per hectare and year has been taken from the plough layer without reducing the amount of exchangeable K. Acid-soluble potassium (K-HNO_3), which is considered to be an estimate of soil potassium reserves, is moderate in this soil, only 60-70 mg K per 100 g dry soil (Stensby Høstmark 1994).

Effects on the lime status of soil

The experimental area had not been limed since 1975. However, the lime status was maintained when calcium nitrate was used as the only N-fertilizer source, as can be seen from the pH values reported in Table 6. pH values in 1978 (not reported) were almost the same as those in 1984. In 1990 only one composite sample from each treatment combination was analysed. According to these measurements, soil pH in fact increased to some extent during the last 6 years in the rotation with spring grains only.

For fertilizer treatment b, a more complete analytical programme for all plant species was performed (see Table 1). From the plant mineral composition and yields the total cations and anions in kilogram equivalents per hectare were calculated for each crop and rotation. The excess cations in plants divided by the corresponding N equivalents in accordance with Pierre & Banwart (1973) are presented in Table 6. Excess cations are the sum of (K + Ca + Mg + Na) (P + S + Cl). If the excess cation/N relationship is less than unity, a physiological alkaline effect of nutrient uptake is to be expected. Even though some modifications to this statement might be appropriate, the comparison between crops and rotations should be quite realistic.

Since monocotyledons, suchs as grains and grasses, were the dominant crop species in most rotations, base uptake was small and the lime status was not negatively affected. If nitrogen in clover originates from biological fixation, the acidifying effect of clover will correspond to the excess cation uptake. The excess bases in crop yields in rotation II over rotation I are 3.26-0.57 = 2.69 kg eq.v per year or 32 kg eq.v in 12 years. Calculated as CaO, the difference will be 0.9 ton per hectare. In this type of soil it is commonly experienced that 1 ton of CaO is needed to raise pH 0.2 units (Stabbetorp 1978).

The soil content of cations in AL-solution exchangeable cations was determined in 1984 only, about 6 years after the introduction of 50% row crops in rotation II. Nevertheless, a reduction in exchangeable cations occurred in rotation II in relation to rotation I. The reduction was 15 kg eq.v per hectare, again in fairly good agreement with the above excess base calculations and pH measurements.

When comparing base status in the ley rotations with that of arable cropping, we must also consider the long-term after-effects of ley from the preceding rotation periods. We found that pH values were much the same in rotation II, III and IV, whereas the respective contents of exchangeable cations in 1984 were higher, especially in rotation IV. Since organic matter content was about 1% higher in IV than in II, an increase in the exchange capacity of the soil after ley farming could have contributed to this result.

We note also from Table 6 that farm manure gave a comparatively large increase in Mg-AL and that the high uptake of Na in beet crops in rotation II most likely reduced Na-AL in soil also.

The effects of farm manure and straw on pH are small as has also been demonstrated in other long-term experiments (Uhlen 1979).

Concluding remarks

The intensive monoculture cropping frequently practised in today's agriculture has caused some concern (Mitchell et al. 1991, Bullock 1992), although in a new summary by Karlen et al. (1994) it is suggested that this concern is likely to be less pressing in the future.

From the yield results of the long-term rotation experiment reported here, as well as from practical experience, it was concluded (Uhlen et al. 1994) that under Nordic conditions an all-arable grain-growing system was sustainable also without farm manure or other organic amendments. The organic matter content of the soil was maintained after a downward trend for some decades, although an increased proportion of row crops in the past 12-15 years (50% row crops and 50% spring grain) resulted in a further decrease in soil total-N and total-C in this experiment.

The rather comprehensive analytical programmes provide us with data for comparison of the mineral composition of different plant species grown on the same plots. The results also reveal that if a high protein content of grain is needed, much higher rates of fertilizer nitrogen must be added in all-arable rotation than in cereals in rotation with ley crops. However, in relation to the obtained yields, the N-content of grain crops after ley periods was superfluous.

The unaccounted-for losses of nitrogen, including leaching, were not unexpectedly large for the increased N added in mineral fertilizers, about 20% in all-arable rotations and 10% of the somewhat higher dose added in ley rotation IV (4 years of ley and 2 years of cereals). The very high level of unaccounted-for nitrogen that occurred during the 37 years in farm manure and straw treated soil cannot be satisfactorily explained.

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N fertilizer value of cabbage residues

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Three experiments were carried out on a loam soil in Southeast Norway to determine the N fertilizer value of cabbage residues for subsequent crops. In an initial trial in 1987 the effect of residue incorporation (without fertilizer) was compared with that of residue removal (at three levels of NPK fertilizer), and the effects of various timings and depths of tillage were also compared. In the second trial in 1990 the effects of prior cropping with cabbage and wheat at four levels of NPK fertilizer were compared, again with various timings and depths of tillage. In the third trial, performed on different sites in 1992 and 1993, the effects of prior cropping with cabbage and barley at five levels of N fertilizer were compared. The test crops were wheat in the first two trials, and wheat, barley and potatoes in the third trial. The nitrogen content of the cabbage residues used varied between 90 and 250 kg/ha. The fertilizer value of the residues ranged from 50 to 100 kg N/ha, roughly in relation to the amount of residue used, and was approximately the same for all crop types. Timing and depth of tillage had little effect on the fertilizer responses in these trials. There was, however, some evidence to show that autumn ploughing gave the highest level of soil mineral N in the following spring. An effect of cabbage residues on soil mineral N was observed during the subsequent growing season at all levels of fertilization, and the effect persisted until after harvest in some cases.

Key words: Cabbage, cereals, crop residues, fertilizer responses, potatoes, soil mineral nitrogen, tillage depth, tillage timing.

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Cabbage and other brassica crops normally have a harvest index of only 40-60%, which means that large amounts of nitrogen-rich residue are left in the field. Values of 100-200 kg N/ha are commonly cited for the residues of cabbage, cauliflower and Brussels sprouts (Scharpf & Schrage 1988; Alt & Wiemann 1990; Dragland 1991; Everaarts 1993a). This may be a valuable N source for subsequent crops, as demonstrated by Rahn et al. (1992). However, mineralisation of nitrogen from such material is often rapid, because of its low C:N ratio, so that the released nitrogen may be leached from the soil before the subsequent crop is established, especially when residues are incorporated by tillage (Schrage & Scharpf 1987).

The use of catch crops to prevent such losses has limited potential in Norway because of low autumn temperatures. On the other hand, long periods with frozen ground probably reduce winter losses. Nevertheless, a recent survey in SE Norway indicated that autumn levels of soil mineral N, measured to a depth of 60 cm, were about 40 kg/ha higher after vegetable crops than after cereals or grass, but only 15 kg/ha higher the following spring

(Riley et al. 1993). Current recommendations in Norway suggest that fertilizer rates may be reduced by 20-40 kg N/ha following brassica crops, but there is much uncertainty about this figure. There is clearly a need to develop methods for predicting the release of nitrogen from crop residues, and estimating its availability to subsequent crops.

This article presents the results of fertilizer trials performed in the inland area of SE Norway, to assess the N fertilizer value of cabbage residues for spring cereals and potatoes.

Materials and methods

Various experimental designs were used in three trials performed on loamy, well-drained soils with a high organic matter content (ca. 6%) in different years between 1986 and 1993. In the first two trials, the effects of timing and depth of crop residue incorporation on N fertilizer requirements of spring wheat were investigated. In the third trial, which was performed at two sites in consecutive years, the effects of cabbage residues on N fertilizer requirements of barley, wheat and potatoes were compared. These crops are known to have different nitrogen uptake patterns.

Trial no. I

All plots in this initial investigation were established on the site of a cabbage variety trial performed at Kise in 1986. The site comprised two 12 x 19 m blocks, on which varieties for processing and fresh consumption had been grown, respectively.

The blocks differed in plant density and harvest date, which led to differences in the amount and nutrient content of crop residues remaining after harvest. The following data are means of three samples of leafy material (excluding stems):

Block	DM Mg/ha	%N	%P	%K	%Ca	kg N/ha
"Processing"	6.9	1.3	0.20	2.2	4.4	91
"Fresh consumption"	9.7	2.1	0.22	2.5	5.1	150

The following treatments were established in a split-plot arrangement, using the above-mentioned blocks as replicates:

Main plots (5 x 12 m)	Split plots (5 x 3 m)	
A. Ploughed to	1. With residues.	0 kg N/ha
30 cm in autumn	2. No residues.	40 kg N/ha
B. Rotary tilled to	3. No residues.	80 kg N/ha
10 cm in autumn	120 kg N/ha	
C. Rotary tilled to		
10 cm in spring		
4. No residues.		

Leaves, stems and attached roots were removed in autumn in treatments 2-4. Fertilizer was applied as a 21-4-10 NPK compound and spring wheat was sown in early May 1987.

Soil mineral N (nitrate and ammonium) was measured to a depth of 20 cm soon after crop emergence and two weeks after harvest. Dry matter (DM) weight and N, P and K concentrations were measured in plants sampled after tillering (15 June) and at heading (15 July) and in the grain at harvest (24 September).

Trial no. II

This trial was established in the spring of 1990, on either side of a 96 m border between blocks on which wheat and cabbage had been grown in 1989 on a farmer's field near Kise. Straw was removed from the wheat area and residues retained on the cabbage area. The arrangement did not give randomization of the crop residue treatment, but there was thought to be little systematic soil variation between the blocks. Mean data for four samples of cabbage leaf residue were as follows:

DM Mg/ha	%N	%P	%K	kg N/ha
9.2	1.3	0.15	1.5	120

Four tillage treatments and three levels of N fertilizer were included in a split plot arrangement with four replicates:

Main plots (6 x 18 m)	Split plots (6 x 4.5 m)
A. Ploughed to 30 cm in autumn	1. 0 kg N/ha
B. Ploughed to 30 cm in spring	2. 42 kg N/ha
C. Rotary tilled to 10 cm in autumn	3. 84 kg N/ha
D. Rotary tilled to 10 cm in spring	4. 168 kg N/ha

Fertilizer was applied as a 21-4-10 NPK compound, and spring wheat was sown on 27 April 1990. Soil mineral N was sampled on 24 plots at depths of 0-25 and 25-40 cm on 26April, and on all 128 plots at a depth of 0-20 cm on 6 June and 5 Sept. DM weight and N, P and K concentrations were measured in plants sampled during tillering (6 June) and in grain at harvest (4 September).

Trial no. III

Three randomized 16 x 20 m blocks of barley and of cabbage were grown in the initial year at each site. Mean data for six samples of cabbage residue were as follows:

	DM Mg/ha	%N	%P	%K	kg N/ha
1991/92 site	7.6	3.3	0.52	3.1	249
1992/93 site	6.8	2.0	0.36	3.4	134

A high proportion of unharvested summer cabbage residues was responsible for the high N concentration in 1991. Straw was removed from the barley blocks in both years.

Five 3 x 5 m plots (two with spring wheat, two with spring barley and one with potato) were established on each block. These were further subdivided into five split plots, which were treated with 0, 40, 80, 120 and 160 kg N/ha as calcium nitrate. Part of the dressing (40 kg N) was withheld until just before heading on half of the cereal plots, whilst the other half and the potato plots received the whole amount in early May. Heavy dressings of P and K were applied following barley and of P following cabbage, in order to mask any possible inequalities which might have have been caused by the cabbage residues with respect to these nutrients.

Dates of sowing, fertilizing, irrigation and harvesting, and of soil and plant sampling are presented in Table 1.

Weather conditions

Mean air temperatures and accumulated precipitation for the winter preceding each trial and for the growing season of the trial are reported in Table 2, together with long-term normals.

In trial I a colder than normal winter was followed by a cool and very wet summer. In the other trials, winter conditions were much milder, with slightly less precipitation than normal, and growing season conditions were close to normal.

Analysis of mineral nitrogen in soil

Nitrate and ammonium were analysed after extraction with 0.1 N KCl from soil which had been frozen after sampling. Taken together, these fractions designated as soil mineral nitrogen (N-MIN). Results are expressed as concentrations (mg/100 g soil) on a dry-weight basis. No attempt

Table 1. Dates of field operations and soil/plant sampling performed in 1992 and 1993 in trial III.

	1992	1993	Remarks
Soil sampling (N-min.)	14 April	14 April	0-20 cm
" "	5 May	6 May	"
Spring fertilization	5 May	7 May	
Sowing/planting	14 May	12/18 May	
Plant & soil sampling	11 June	10 June	0-20 cm
Top-dressing (cereals)	18 June	23 June	
Irrigation	18 June	23 June	ca. 25 mm
"	29 June	ca. 25 mm	
Harvest (barley)	27 Aug.	23 Sept.	
" (wheat)	4 Sept.	14 Oct.	
Soil sampling (barley)	9 Sept.	27 Sept.	0-20 cm
" (wheat)	9 Sept.	14 Oct.	"
Harvest (potato)	22 Sept.	14 Sept.	
Soil sampling (")	"	15 Sept.	0-20 cm
Final soil sampling	14 Oct.	2 Nov.	0-25, 25-60 cm (1993 only)

Table 2. Mean air temperatures (°C) and accumulated precipitation (mm) for the winter period (Oct.-March) and growing season (April -Sept.) of the trials, compared with normal values at Kise.

	Winter period		Growing season	
	Temp.	Precip.	Temp.	Precip.
Trial no. I (1986/87)	-5.0	213	9.5	518
Trial no. II (1989/90)	1.2	186	11.6	349
Trial no. III (1991/92)	0.2	181	11.3	358
Trial no. III (1992/93)	-1.1	224	10.3	404
Normal values (1961-90)	-3.3	242	10.5	343

has been made to convert these figures to absolute amounts of nitrogen per hectare, because of variations in sampling depth between trials. Furthermore, uncertainties in such a conversion arise from variations in both soil bulk density and soil stone and gravel content, neither of which was measured in these trials. The stone content of these soils is often 20-40%.

Results

Trial I

There was no significant effect of the type of cabbage grown ("processing" versus "fresh consumption") or of the subsequent tillage treatment (timing and depth) on the soil mineral N content or on the growth, nutrient concentration and final grain yield of the wheat crop in this trial. All these variables were significantly affected by fertilizer use, however.

The effect of residue incorporation (with no additional N) on growth and yield approximated to the use of about 50 kg N/ha in compound fertilizer (Fig. 1). The incorporation of residues had the effect of maintaining plant nutrient concentrations at comparable levels in most cases, except in early summer, when the nitrogen concentration was somewhat lower (Table 3). This may be explained by the somewhat lower content of soil mineral N found at that time in the presence of residues:

	Residues	40 kg N/ha	80 kg N/ha	120 kg N/ha
Soil min. N	1.45	2.03	3.83	4.29 mg/100g

There was no effect of residues or fertilizer level on soil mineral N after harvest.

Trial II

Wheat plant weights in early summer were unaffected by tillage depth, but on average were 13% higher after tillage in autumn than after tillage in spring and 33% higher after prior cropping with cabbage than after prior cropping with wheat. On average the final grain yield was 3% higher with autumn tillage than

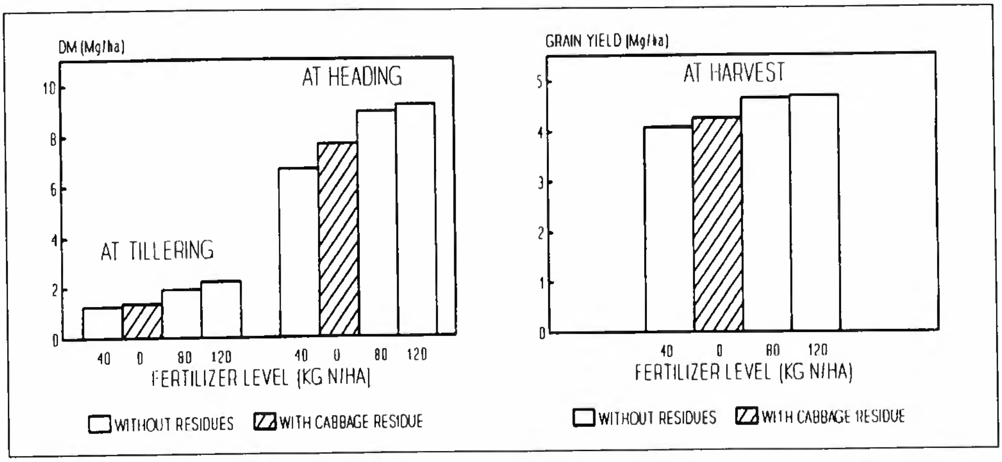

Figure 1. The effect of incorporating cabbage residues (without fertilizer) compared with the effect of fertilizer alone on the growth of wheat in trial I, 1987.

Table 3. The effect of three levels of NPK fertilizer and of cabbage residues alone on nutrient concentrations of wheat plants and grain, as percentages of dry matter (trial I, 1986).

Date of sampling[1]		Fertilizer level (kg/ha)			With Cabbage residues (no fert.)	LSD 5%[2]	
		N 40	80	120			
		P 8	15	23			
		K 19	38	57			
%N	15 June	3.31	3.61	4.16	3.09	0.38	***
	15 July	0.81	1.02	1.26	0.87	0.19	**
	24 Sept.	1.63	1.66	1.70	1.70	0.06	ns
%P	15 June	0.62	0.59	0.60	0.63	0.03	*
	15 July	0.26	0.29	0.32	0.26	0.03	*
	24 Sept.	0.48	0.48	0.45	0.48	0.03	ns
%K	15 June	4.26	4.52	4.78	4.07	0.26	**
	15 July	1.35	1.79	2.17	1.40	0.19	**
	24 Sept.	0.49	0.51	0.48	0.50	0.03	ns

[1] Concentrations in whole plant at tillering (15 June) and at heading (15 July), and in grain at harvest (24 Sept.)

[2] * = $p<0.05$, ** = $p<0.01$, *** = $p<0.001$, ns = not significant

with spring tillage, 6% higher after ploughing than after rotary tillage and 20% higher after cabbage than after wheat.

There was no interaction between tillage and prior cropping, but there was a significant interaction in both plant growth and nutrient concentrations between fertilizer level and prior cropping (Fig. 2, Table 4). This interaction suggests, as in the previous trial, that the fertilizer value of cabbage residues was approxi-

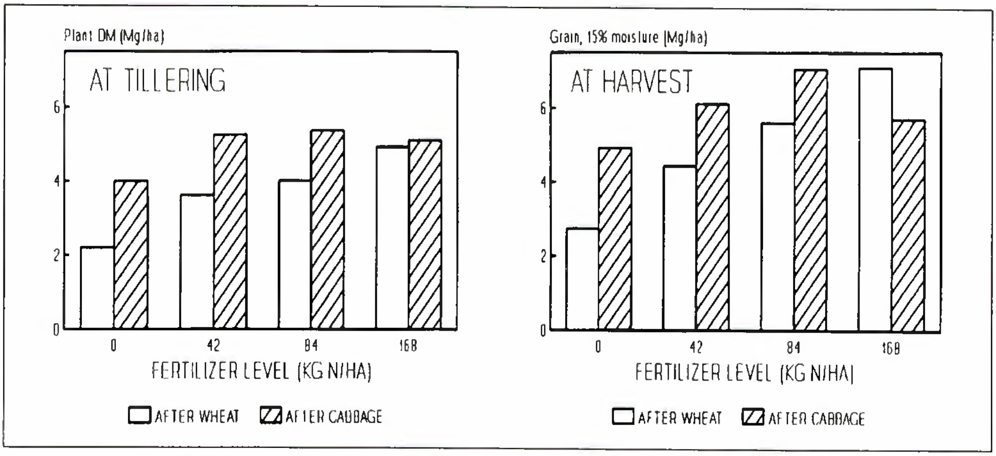

Figure 2. The effect of four levels of nitrogen applied as compound fertilizer on the growth of wheat in trial II, 1990, following prior cropping with wheat and cabbage.

Table 4. The effect of different levels of NPK fertilizer and of prior cropping with cabbage or wheat on the nutrient concentrations of wheat plants grown in trial II, 1990.

		At tillering				At harvest			
	Prior	Level of 21:4:10 NPK compound fertilizer (kg/ha)							
	cropping	0	20	40	80	0	20	40	80
%N	Cabbage	2.68	3.20	3.40	3.09	2.20	2.19	2.28	2.27
	Wheat	2.49	3.01	3.54	3.82	2.16	1.93	1.97	2.24
		Interaction p<0.001				Interaction p<0.001			
%P	Cabbage	0.38	0.41	0.42	0.40	0.42	0.40	0.40	0.39
	Wheat	0.38	0.40	0.45	0.45	0.43	0.43	0.43	0.41
		Interaction p<0.01				Interaction p<0.001			
%K	Cabbage	3.38	3.87	4.12	3.75	0.42	0.41	0.41	0.42
	Wheat	2.89	3.29	3.82	4.02	0.53	0.51	0.47	0.48
		Interaction p<0.001				Interaction p<0.1			

mately equivalent to that obtained with the use of 50 kg N/ha in compound fertilizer.

The positive effect of cabbage residues was clear at the first three fertilizer levels, but a negative effect was observed in combination with the highest level. Lower than expected nutrient contents were also found early in the growing season in the case of the latter treatment. The reason for this anomaly is not known. There was no lodging of the wheat crop in this trial.

In early spring there were significantly higher concentrations of mineral N in the soil on plots which had been tilled the previous autumn than on untilled plots. This was found in both topsoil and subsoil, and particularly where cabbage residues had been incorporated (Table 5). Mineral N in the topsoil at tillering was not affected by the time or method of tillage, but was significantly higher at the highest level of fertilizer, especially on the plots previously cropped with wheat. Levels of mineral N in the topsoil were generally low in autumn. There was at that time no significant effect of tillage, and only minor effects of previous cropping and fertilizer level.

Trial III

The effect of prior cropping on crop growth was marked in both years (Table 6). Average cereal plant weights at tillering were considerably higher after cabbage than after barley. This effect was much more evident than that of N fertilizer level during early growth. Plant concentrations of nitrogen, particularly those of nitrate N, were significantly higher after cabbage in these young plants, but, on the whole, there was little

Table 5. Concentrations of mineral nitrogen (mg/100g dry soil) in topsoil and subsoil before fertilization in spring, and in the topsoil in summer and autumn in trial II, 1990.

	Prior cropping	Autumn tillage		
		Untilled	Rotavated	Ploughed
Spring (26 April)				
Topsoil	Cabbage	0.63	1.16	1.26
(0-25 cm)	Wheat	0.59	0.65	0.68
Subsoil	Cabbage	0.59	0.99	1.06
(25-40 cm)	Wheat	0.51	0.66	0.59

Tillage $p<0.01$ Prior cropping x tillage $p<0.05$ Depth $p<0.01$

		Fertilizer level (kg N/ha)			
		0	42	84	168
Summer (6 June)					
Topsoil	Cabbage	2.5	2.3	3.1	3.6
(0-25 cm)	Wheat	1.4	1.8	2.2	5.2

Fertilizer level $p<0.001$ Prior cropping x fert. level $p<0.01$

		0	42	84	168
Autumn(5 Sept.)					
Topsoil	Cabbage	0.8	0.8	0.9	0.8
(0-25 cm)	Wheat	1.0	1.0	1.1	1.0

Fertilizer level $p<0.05$ Prior cropping $p<0.05$ Interaction n.s.

Table 6. Dry matter mass and nutrient concentrations in cereal plants sampled at tillering, as affected by prior cropping in trial III. Mean data over years and fertilizer levels.

	Barley plants			Wheat plants		
Prior cropping:	Cabbage	Barley		Cabbage	Barley	
Dry matter (Mg/ha)	1.30	0.75	***	1.46	0.86	**
Total N (% of DM)	4.92	4.79	ns	4.87	4.31	**
Nitrate N (ppm)	708	320	***	445	162	**
Total P (% of DM)	0.59	0.60	ns	0.60	0.58	ns
Total K (% of DM)	4.86	4.82	ns	4.42	4.03	**

*** = $p<0.001$ ** = $p<0.01$ ns = not significant effect of prior cropping on the concentrations of phosphorus and potassium.

Concerning final yields, for all crops there was a significant interaction between the effect of prior cropping and the effect of N fertilizer level. This interaction indicated that yields increased with increasing levels of N fertilizer following barley, but that the responses were in general much smaller, and sometimes negative, following cabbage.

The optimum N fertilizer level for wheat and barley was 120 kg/ha when grown after barley, in terms of both grain and straw yield (Fig. 3). When grown after cabbage, the optimum N fertilizer levels were 0 and 40 kg/ha for barley and wheat grain, respectively, and 40 and 80 kg/ha in the case of straw. The negative effect of higher N levels was to some

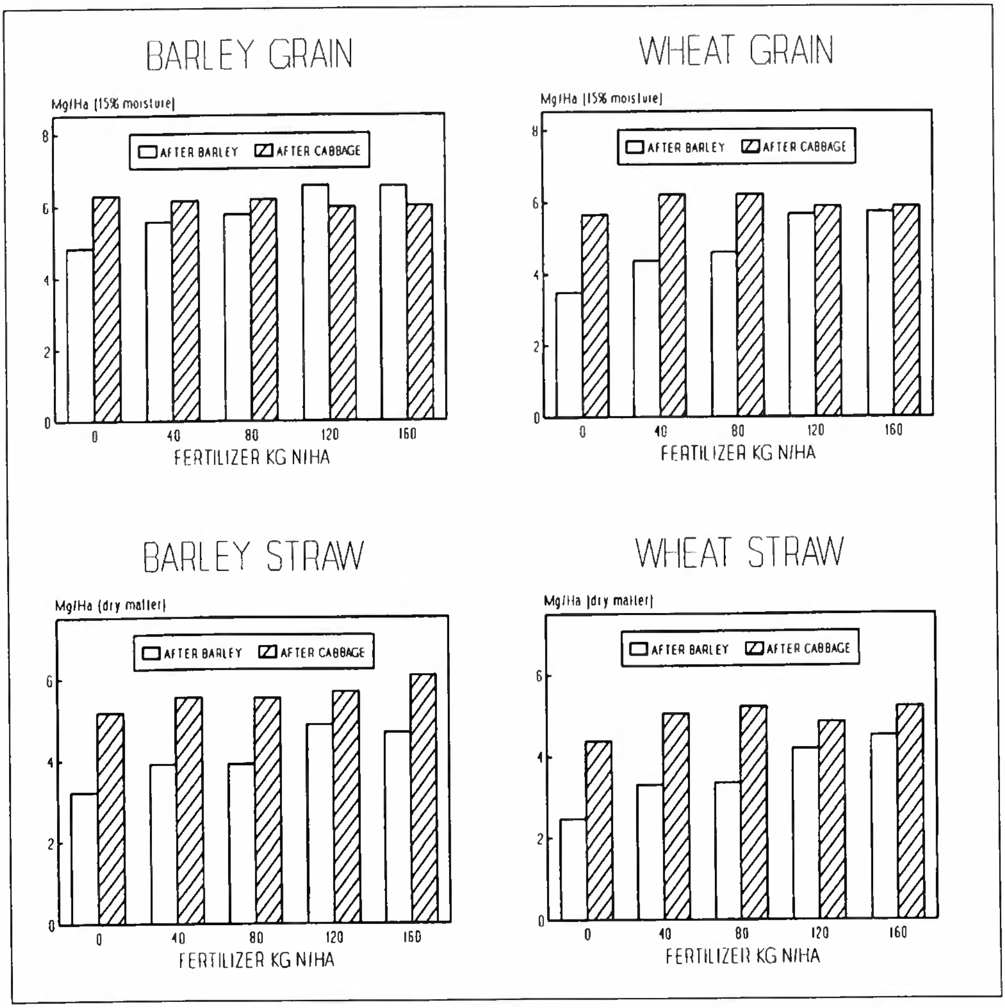

Figure 3. The effect of prior cropping with cabbage or with barley on the yield response of cereals to N fertilizer in trial III. Mean data for 1992 and 1993.

extent, but not wholly, attributable to lodging.

Potato yields increased up to the highest level of N fertilizer when grown after barley (Fig. 4), although the marginal response at the highest levels was relatively small. When grown after cabbage, there was a slight increase in total and saleable tuber yields between 0 and 40 kg N/ha, and a slight but steady decline at higher fertilizer levels. Potato dry matter concenration was significantly higher after barley than after cabbage in one year, and was highest at an intermediate level of N fertilizer (80 kg/ha) irrespective of prior cropping (Table 7). Tuber quality, as judged by shape and splitting, showed little consistent effect of prior cropping or N fertilizer level.

Prior cropping with cabbage resulted in considerably higher N concentrations in both barley and wheat grain and in

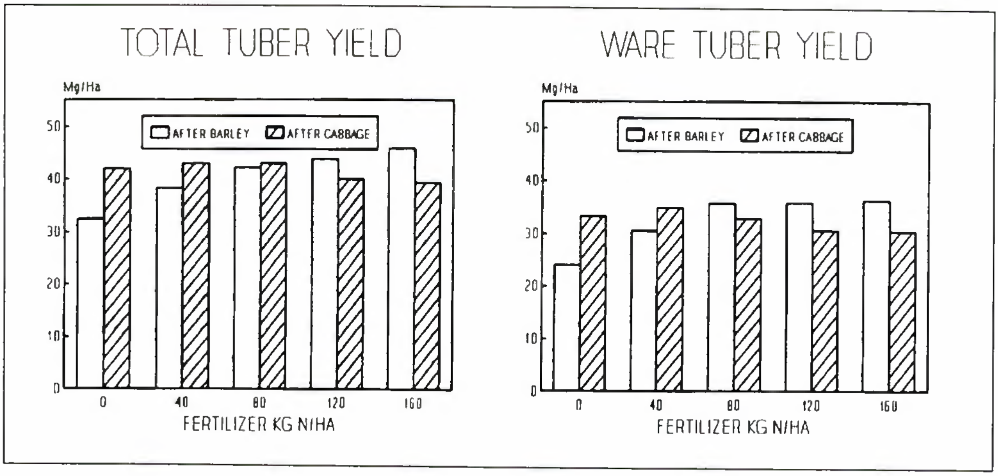

Figure 4. The effect of prior cropping with cabbage or with barley on the yield response of potatoes to N fertilizer in trial III. Mean data for 1992 and 1993.

Table 7. Dry matter concentration (%) of potato tubers in trial III, as affected by prior cropping and N fertilizer.

		Prior cropping		
		Cabbage	Barley	
Year	1992	23.6	25.1	Prior cropping p<0.05
	1993	23.4	23.2	Interaction w. year p<0.05
N level	0	23.4	24.8	N level p<0.02
(kg/ha)	40	23.1	24.7	Interaction n.s.
	80	24.6	25.0	
	120	22.8	23.9	
	160	22.7	23.4	

potato tubers, irrespective of N fertilizer level, than prior cropping with barley (Table 8). The concentration in crops grown after cabbage without any N fertilizer was in all cases higher than in crops grown after barley with 160 kg/ha N fertilizer. Nitrate concentrations, on the other hand, were hardly affected at all by prior cropping or N fertilizer. This was also the case for the concentrations of P and K.

In both years, the concentration of mineral N in the topsoil in spring (before fertilization) was significantly higher following cabbage than following barley (Table 9). A greater proportion of the nitrogen was present as ammonium in the case of prior cropping with cabbage. Levels of mineral N rose markedly between mid-April and early May, especially after prior cropping with cabbage.

The effect of prior cropping on mineral N levels in the topsoil was found once again, both early in the growing season and at harvest, at all levels of subsequent fertilization (Fig. 5). Concentrations following cabbage were often almost twice as high as those following barley. The levels measured in June were about ten times higher than those measured at harvest. The latter were highest for plots on which barley had been grown in the trial year, and lowest on plots with potatoes. A residual effect of fertilizer level was found in both cereals, but this effect was less marked in potatoes.

The effect of prior cropping on soil mineral-N could still be observed in late autumn, just before the soil froze for the winter (Fig. 6). This could be seen in both topsoil and subsoil, though the latter was sampled in only one year. At this time the effect of fertilizer level was appreciable only for the highest application rate. Levels of mineral N in the topsoil had increased somewhat since harvest, but the amount of mineralization at this time did

Table 8. The effect of prior cropping and of N fertilizer level on total N concentration in cereal grain and potato tubers at harvest in trial III, means of both years.

	Prior cropping	N fertilizer level (kg/ha) 0	40	80	120	160
Barley	Cabbage	2.45	2.59	2.56	2.67	2.69
Grain	Barley	1.92	2.04	2.25	2.22	2.25
		Prior cropping $p<0.01$ Fert. level $p<0.001$ Interaction n.s.				
Wheat	Cabbage	2.66	2.73	2.76	2.96	2.89
Grain	Barley	2.14	2.12	2.34	2.57	2.58
		Prior cropping $p<0.01$ Fert. level $p<0.001$ Interaction n.s.				
Potato	Cabbage	1.10	1.16	1.25	1.29	1.37
Tubers	Barley	0.75	0.87	0.83	1.03	1.02
		Prior cropping $p<0.002$ Fert. level $p<0.001$ Interaction n.s.				

Table 9. Topsoil concentrations of mineral nitrogen (mg/100g dry soil) measured in mid-April and early May (before fertilization) of 1992 and 1993 in relation to prior cropping in trial III.

Prior	1992		1993	
cropping	Mid-April	Early May	Mid-April	Early May
Cabbage	1.7	2.9	0.7	1.0
Barley	0.5	0.7	0.4	0.5
		Prior cropping $p<0.05$	Sampling date $p<0.02$	Year $p<0.1$

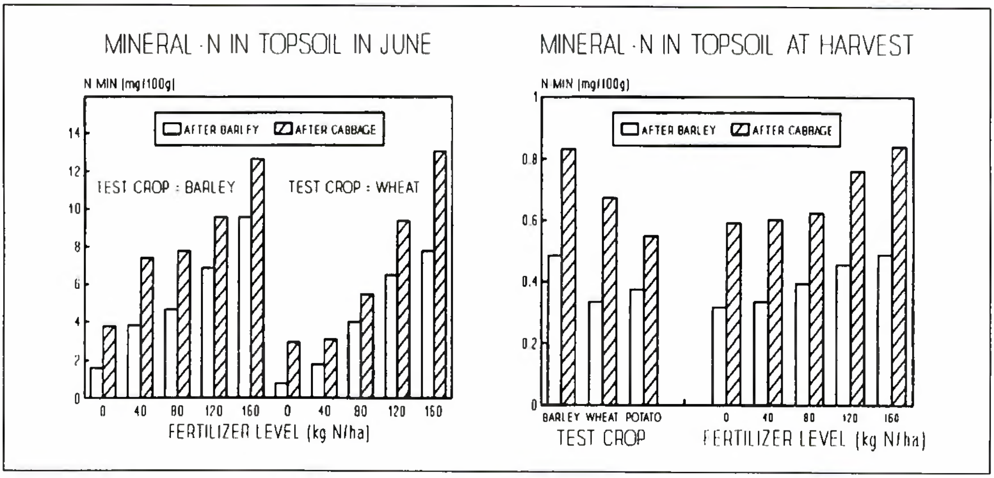

Figure 5. The effect of prior cropping with cabbage r with barley on mineral N concentrations in the topsoil under various crops in early summer and at harvest. Mean data for 1992 and 1993.

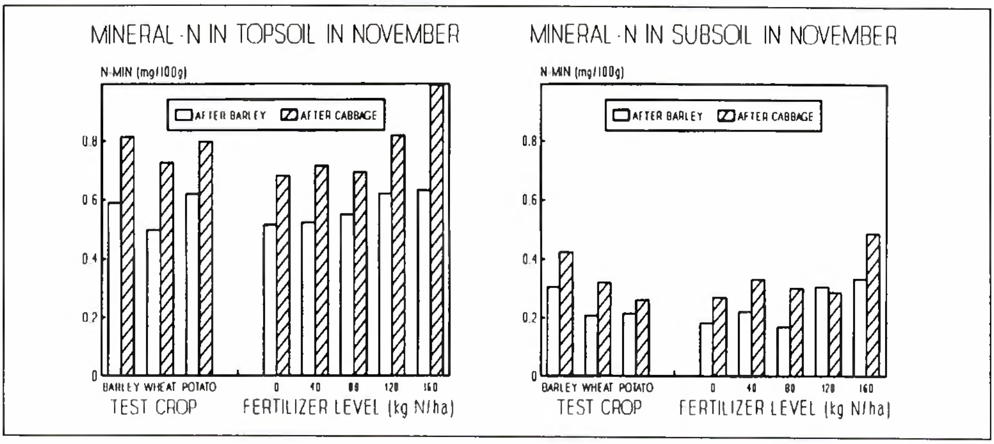

Figure 6. The effect of prior cropping with cabbage or with barley on mineral N concentrations in the topsoil and subsoil in late autumn of the following year. Topsoil data are means of 1992 and 1993, whilst subsoil data are from 1993 only.

not appear to have been affected by prior cropping.

Discussion and conclusions

A considerable N fertilizer effect of cabbage residues was found in all years, and for all crops studied. The absolute value varied within the range 50-100 kg N/ha, which is higher than the previously assumed norm in Norway, but is of the same order as values reported from Denmark, where the nitrogen effect of cabbage residues was found to be equivalent to 50 kg/ha in leeks and 90 kg/ha in cabbage (Nygaard Sørensen 1993).

The level of response was to some extent related to the amount of nitrogen present in the residues. Responses were equivalent to 50 kg N/ha in trials I and II and to 100 kg N/ha in trial III, where the average N contents in cabbage residues were 120 and 190 kg/ha, respectively. This suggests that about 40-50% of the nitrogen in the residues becomes available to crops in the following growing season. This figure should nevertheless be treated as somewhat tentative, since similar yield responses were found in individual trials, despite considerable variation in the amounts of residues present (viz. trials I and III).

The timing and method of incorporation did not appear to affect the fertilizer value of residues in the present trials, although there was an indication that autumn tillage resulted in more rapid nutrient release (trial II). Preliminary results from a field incubation study performed under similar conditions to those in these trials (Henriksen 1995) have shown that about 20% of the DM in cabbage residues is broken down during the first month after incorporation in October, 70% after the winter period and 85% by the following autumn. If nitrogen release is roughly proportional to DM breakdown, this would mean that incorporation in early autumn increases the risk of leaching. However, previous incubation trials performed at Kise suggest that some nitrogen immobilization takes place when fresh cabbage residues are incorporated (Dragland, unpublished).

A good strategy may be to leave plant residues undisturbed for as long as possible (Everaarts 1993b; Sanderson and MacLeod 1994). This reduces soil mineral N levels because of slower residue breakdown and continued uptake of nitrogen by plants in autumn (Hoel & Eltun 1995). However, there is still the question of whether incorporation should take place in late autumn or in spring. Uhlen (1989) found a surface runoff loss of 13 kg N/ha, with an appreciable amount of phosphorus as well, when cauliflower residues were left on the surface during winter in SE Norway.

In the case of clover, in which the initial breakdown pattern is similar to that of cabbage, it was found that ploughing in October gave 44% nitrogen release by the following May, as opposed to 27% for residues remaining on the soil surface (Breland 1989). The choice of incorporation timing may therefore be guided by the planting time and expected uptake pattern of the subsequent crop. In the case of cereals, which have a high uptake of nutrients early in the season, incorporation in late autumn is probably necessary. For potatoes and root crops, incorporation in spring may be better, in order to minimize the risk of leaching. However, there are other agronomic considerations which favour autumn incorporation, since residues left on the surface in winter may harbour plant pathogens and hinder weed control.

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Sorption of cadmium, zinc, copper and lead by soils developed on alum shales and other materials

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A laboratory experiment was conducted to study the adsorption of cadmium, zinc, copper and lead by four different soils developed on alum shale and other mineral materials. Equilibration time was determined and it was found that half an hour shaking time was sufficient for near complete equilibration. The adsorption data were very well fitted to the nonlinear Freundlich equation, the R^2 value ranging from 0.966 to 0.999. The Freundlich adsorption isotherms showed that the curves are very steep at low concentrations and became less steep when the concentration of metals in equilibrium solution increased. For all soils, with the exception of sandy loam, the adsorption capacity was very high and the order of adsorption capacity was alum shale > peat soil> organic soil> sandy loam. The desorption of adsorbed amount of metals by 0.005M $CaCl_2$ was very low from all soils except for sandy loam. The order of desorption of metals was Cu < Pb < Zn < Cd. Desorption of all metals was least from alum shale, which indicates that metals are strongly adsorbed by this soil. The desorption of metals increased significantly when the concentration of desorbing solution ($CaCl_2$) was increased from 0.005M to 0.5M.

Key words: Adsorption, desorption, heavy metals, ionic strength, soil types.

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The behaviour of heavy metals in the terrestrial environment has gained greater attention during the last two decades because of the increasing burden of metals on this environment from anthropogenic activities such as dumping of industrial effluents and agricultural applications of sewage sludge, fertilizers and pesticides (Adriano 1986; Tiller 1989; Jensen & Bro-Rasmussen 1992; Singh & Steinnes 1994). A quantitative interpretation of soil contamination with heavy metals in terms of possible effects on crop and ground water needs insight into the combined effects of chemical, physical, and biological processes. The chemical behaviour of heavy metals is primarily governed by retention and release reactions of solute with the soil matrix. Retention and release reactions in soils include precipitation/dissolution, ion exchange, and adsorption/desorption reactions (Amacher et al. 1986). Retention may be due to precipitation and/or adsorption (involving several molecular mechanisms) and depends on factors such as the nature of the metal, the nature of the mineral and organic constituents of the soil, and the composition of the soil solution. For adsorption, cations are held either through electrostatic attraction, thus giving rise to ion exchange with the surrounding ions, or by specific adsorption through surface complexation on organic and mineral substrates. Whatever the mechanism may be, retention in soils greatly determines the mobility and the bioavailability of heavy metals, and it is therefore essential to improve our knowledge of this process in soils of varying properties. Hence, the adsorption and mobility of heavy metals in soils of different compositions is of potential interest for determining the heavy metals loading capacity of a given soil and the distribution in the soil profile. These studies can be used for predicting the environmental impact of pollution by heavy metals, as well for drawing up guidelines for government policies on the usage and disposal of materials containing metals in agricultural soils.

The study was planned with the following objectives : (1) To determine the adsorption capacity of four soils with widely differing properties using a wide range of Cd, Zn, Cu and Pb concentrations; (2) to prepare adsorption isotherms using adsorption models and; (3) to determine the desorption of adsorbed metals at increasing ionic strength of calcium chloride.

Materials and methods

Four surface soils (0-20 cm), alum shale, sandy loam, organic soil and peat soil, were used for this study. The soils were air-dried, ground and passed through a 2 mm plastic sieve before use. Soil classification and some physical and chemical characteristics of these soils are presented in Table 1. Soil pH was measured in a 1:2.5 soil/water suspension. The soil suspension was allowed to stand overnight prior to pH determination. Soil organic carbon was measured by combustion in an EC-12 LECO-carbon analyser. Cation exchange capacity (CEC) was determined in accordance with the procedure described by Page et al. (1982). The soil particle size distribution was measured by the pipette method (Elonen 1971). Total Cd, Zn, Cu and Pb was extracted with aqua regia and estimated by atomic absorption spectrophotometer (PYE UNICAM SP9 Series).

(a) Equilibration time

The time- dependence adsorption of Cd, Zn, Cu and Pb from 0.005M $CaCl_2$ electrolyte was determined for two soils, an alum shale and a sandy loam. The

Table 1. Characteristics of the soil used in this study

Soil	Classification	pH (1:2.5)	Org. C (g kg^{-1})	CEC (cmol(+)kg^{-1})	Sand (%)	Silt (%)	Clay (%)	Total metal (μg g^{-1}) Cd	Zn	Cu	Pb
Alum shale	Typic Cryoboroll	6.4	64.3	44.4	31	41	28	3.0	200	99	27.2
Sandy loam	Humaquept	5.4	24.2	12.5	56	25	19	0.8	101	11	21.8
Organic soil	Typic Humaquept	5.8	159.0	46.1	24	47	29	0.9	74	23	22.0
Peat soil	Histic Cryaquept	5.8	342.0	93.0	29	67	4	1.3	75	26	14.8

equilibration time for the two soils with each metal (Cd, Zn, Cu and Pb) was determined by shaking 1 g soil with 10 cm^3 of 0.005M CaCl2 containing either 10 μg cm^{-3} Cd or 50 μg cm^{-3} Zn, Cu or Pb for periods of up to 120 h. Soil suspension contained in a 50 cm^3 centrifuge tube was shaken end-over-end at 100 osc min^{-1}. The tubes were then centrifuged at 5000 rpm for 10 min followed by filtration of the supernatant through Schleicher and Schull 5892 filter paper to remove any particulate materials. The amount of Cd, Zn, Cu and Pb in the aliquots was estimated by atomic absorption spectrophotometer. The quantities of Cd, Zn, Cu and Pb retained by the soils were calculated as the decrease in metal concentration in the solution.

(b) Adsorption studies

For the adsorption study 1 g soil sample was placed in 50 cm^3 plastic centrifuge tubes. Ten cm^3 of solutions with varying concentrations of Cd, Zn, Cu or Pb in a 0.005M $CaCl_2$ background electrolyte were added to the tube. The Cd concentrations ranged from 0.1 to 50 μg cm^{-3} but those of Zn, Cu and Pb ranged from 1 to 200 μg cm^{-3}. This wide range of initial concentrations was used because different wastes vary greatly in heavy metal concentrations. Furthermore, some of these soils have a high initial content of heavy metals and it was important to determine their maximum adsorption capacity. The preliminary study of varying equilibration times showed no significant changes in solution concentrations of Cd, Zn, Cu and Pb after 4-h of equilibration. Accordingly, a 4-h shaking time was adopted in this study. The soil suspension was shaken end-over-end for 4-h at 100 osc min^{-1}. Following the equilibration period, the samples were centrifuged at 5000 rpm for 10 min and filtered. The Cd, Zn, Cu, and Pb concentrations were estimated in the respective aliquots. The amount of each element adsorbed by the soil was calculated as:

$$X = (Co - C) * V/W$$

where X is the amount of metal retained by the soil (μg g-1); Co is the initial concentration in solution (μg cm^{-3}); C is the final concentration in solution (μg cm^{-3});

V is solution volume (10 cm^3); and W is the weight of soil (1 g).

(c) Desorption studies

Desorption studies were conducted on the soil left in the centrifuge tubes after removing the supernatant liquid of the adsorption study. Ten cm^3 of 0.005M $CaCl_2$ was added to each tube and samples were shaken for 2 h at 100 osc min^{-1}. The suspensions were centrifuged at 5000 rpm and the supernatant liquid was withdrawn. The amount of metals desorbed was estimated in the aliquots. The amount of metals retained in the entrapped solution was calculated by weighing the centrifuge tube before shaking for adsorption and after removing the equilibrium solution. This amount was deducted from the amount desorbed.

(d) Effect of ionic strength

To see the effect of ionic strength of the extractant, three concentrations of $CaCl_2$, i.e 0.005M, 0.05M and 0.5M, were compared in all soils. The concentrations of metals used for this study were 10 μg cm^{-3} for Cd and 25 μg cm^{-3} for Zn, Cu and Pb, respectively. The same procedure was followed as described for desorption study. The amount of metals desorbed by $CaCl_2$ of different concentrations was estimated and compared.

All adsorption and desorption studies were run in duplicate at room temperature

(20°C) but only mean values are reported here.

(e) Model description

All adsorption data from the soils were fitted to Langmuir and Freundlich models but this data were best fitted to the Freundlich equation. The Freundlich equation is the oldest nonlinear sorption equation and has been used widely to describe solute retention by soils (Helfferich 1962; Travis & Etnier 1981; Sposito 1984; Buchter et al. 1989).The nonlinear Freundlich equation is

$$X = K\,C^n$$

where X is the amount of metal retained by the soil ($\mu g\ g^{-1}$), C is the equilibrium concentration ($\mu g\ cm^{-3}$), K is the Freundlich adsorption constant ($cm^3\ g^{-1}$), and n is the Freundlich exponential term. The term K and n are correlated with adsorption capacity and adsorption intensity , respectively.

The parameters K and n were estimated for each metal in each soil using nonlinear regression analysis (JMP programme).

Results and discussion

Equilibration time

The amount of Cd, Zn, Cu and Pb adsorbed as a percentage of that added was plotted against shaking time (Fig. 1). In the alum shale soil all added Pb was adsorbed and thus it is not seen in the figure. The results indicated that a quasi-stationary state was achieved within half an hour of shaking in both soils for all metals, but in order to give sufficient contact time to ensure equilibrium for the system, a 4-h shaking time was adopted for all the adsorption studies. The adsorption of metals from suspension of adsorbent materials is rapid in the beginning and generally takes place within a few minutes. Later on the rate of adsorption slows down and this might be due to diffusion in soil aggregates. The observations of this study concur well with those reported by other workers (Cavallaro & McBride 1978; Christensen 1984; Aringhieri et al. 1985; Ghanem & Mikkelsen 1988).

Adsorption isotherms

The results of Cd, Zn, Cu and Pb adsorption obtained for four different soils are presented in Figs. 2 and 3. The

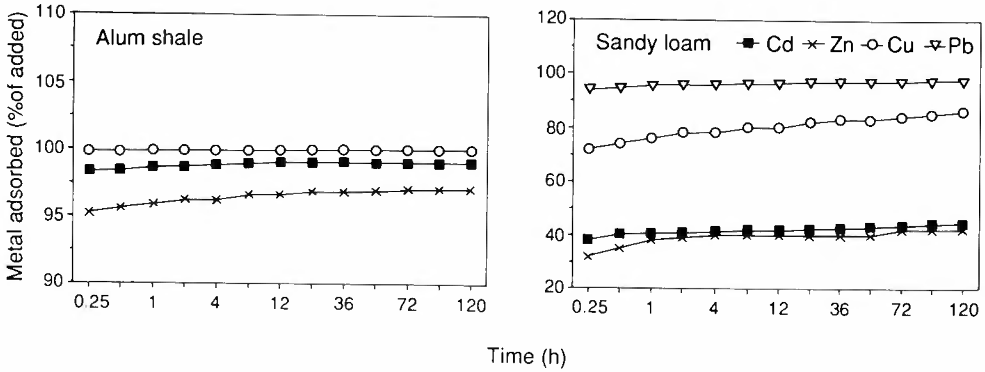

Figure 1. Dependence of adsorption of Cd, Zn, Cu and Pb on time in alum shale and sandy loam soils.

adsorption data were fitted to either Langmuir or Freundlich equations. Fit of the data of this study to the Langmuir equation was not good but the same data fitted very well to the nonlinear Freundlich equation. Often, the logarithmic form of the Freundlich equation is used rather than the exponential form. In this study the exponential form of the equation was used and the K and n parameters were estimated by nonlinear regression analysis (Figs. 2 and 3). Kinniburgh (1986) and Buchter et al. (1989) have also recommended this approach. Freundlich isotherms for different metals and soils were drawn using equilibrium concentrations (µg cm^{-3}) and the amount of metal retained by the soil (µg g^{-1}). K and n, two parameters of metal adsorption by the soils and goodness-of-fit (R^2), were calculated. The distribution coefficient (Kd), viz., the ratio between the amount of metal adsorbed in the soil and the equilibrium solution concentration at a given equilibrium concentration (Ce = 0.5 µg cm^{-3}), was also calculated. The distribution coefficient (Kd) is regarded as a measure of the adsorption capacity of Cd, Zn, Cu and Pb by a soil.

Adsorption isotherms for Cd in different soils showed that at the initial concentration of equilibrium solution the curves were very steep (Fig. 2) in all soils. The curves became less steep as the concentration of solution increased. In the alum shale almost 100% of the added Cd was retained by the soil up to 2.5 µg Cd cm^{-3} solution concentration. In this soil even at the highest concentration (50 µg Cd cm^{-3}), 98% of Cd was retained. The corresponding adsorption rates in the sandy loam, organic soil and peat soil were 27, 93 and 97%, respectively. The adsorption constant (K) of the Freundlich equation was also highest in the alum shale soil (531.5) followed by peat soil (311.8), organic soil (167.5) and sandy loam (14.7) soils. This suggests that the adsorption capacity of these soils was in the order alum shale> peat soil> organic soil> sandy soil. The value of n was higher in the alum shale, peat and organic soils than in the sandy soil, indicating a higher affinity in the former soils. The same trend was followed by the distribution coefficient (Kd). The Kd value was 630 cm^3 g^{-1} for alum shale, 19 for sandy loam, 187 for organic soil and 335 for peat soil.

The visual comparison of the isotherms for Zn in different soils showed that the curves were not so steep as in the case of Cd (Fig. 2). The adsorption rates of Zn at the highest equilibrium solution concentration (200 µg Zn cm^{-3}) were 92% in peat soil, 90% in alum shale, 83% in organic soil and 23% in sandy loam soil. This indicates that the soil containing the highest amount of organic matter retained the maximum concentration of Zn. The values of the adsorption constant (K) decreased in the order alum shale > peat soil> organic soil> sandy loam soil. Likewise, the Kd value was highest for alum shale (483 cm^3 g^{-1}) and lowest for sandy loam (13 cm^3 g^{-1}).

The Freundlich isotherms for Cu showed that the shape of the curve depended on the concentration of equilibrium solution and the soil types (Fig. 3). In the alum shale soil almost all of the Cu concentration was retained and this was also the case for the peat soil and organic soil. In the sandy loam soil only 49% Cu of the added Cu was adsorbed. The Kd values for Cu for alum shale, sandy loam, organic soil and peat soil were 5043, 233, 1484 and 2075 cm^3 g^{-1}, respectively. Like Cd and Zn, the K and Kd values for Cu were also higher in the alum shale, peat soil and organic soils than in the sandy loam soil.

Lead adsorption in the alum shale soil

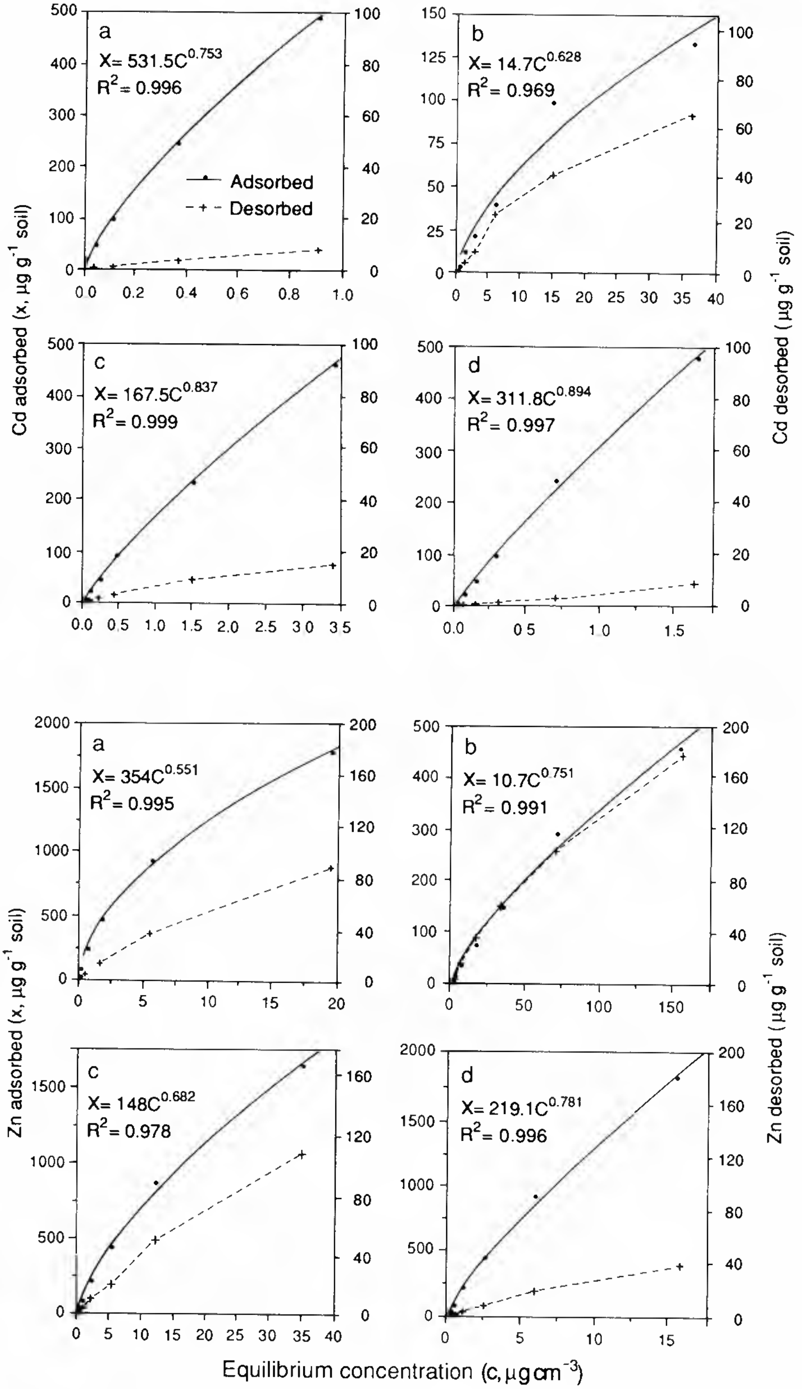

Figure 2. Freundlich isotherms for Cd and Zn adsorption and desorption by soils, (a) alum shale; (b) sandy loam; (c) organic soil; (d) peat soil. The solid lines indicate adsorption and hatched lines desorption.

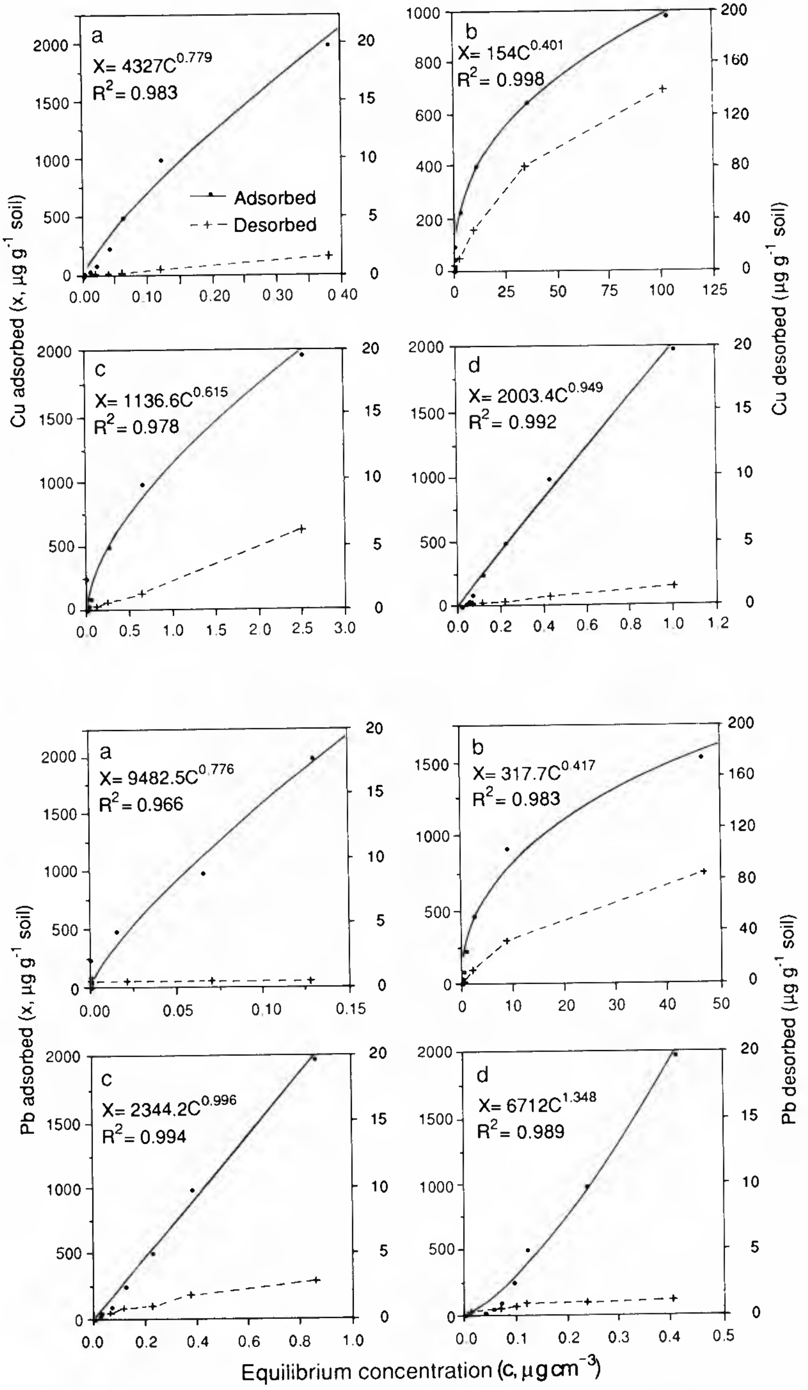

Figure 3. Freundlich isotherms for Cu and Pb adsorption and desorption by soils,(a) alum shale; (b) sandy loam; (c) organic soil; (d) peat soil. The solid lines indicate adsorption and hatched lines desorption.

was almost 100% of the amount added to the equilibrium solution (Fig. 3), and the same result was found for organic soil and sandy loam, but in peat soil at higher equilibrium concentrations it was precipitation rather than adsorption. The order of adsorption was alum shale > peat soil> organic soil> sandy loam. The adsorption constant (K) and distribution coefficient (Kd) values also followed the same trend.

A general look at the isotherms and values of K, n, and R^2 for all metals in different soils revealed a good fit to the Freundlich nonlinear equation. The value of n is <1 in all cases with the exception of Pb in peat soil, which contained a very high amount of organic matter. The values of R^2 are highly significant and varied from 0.966 to 0.999. The Kd values followed the same trend as that for K values in all four soils for Cd, Zn, Cu and Pb. The Freundlich adsorption constant (K) is a convenient parameter for comparing the sorbing tendencies of soils. This parameter may be useful in assessment of the metal contamination of ground waters and the uptake of metals by plants. Among the four metals tested, Zn displayed the lowest K value for all soils and the order of metals was Zn < Cd < Cu < Pb. Basta & Tabatabai (1992) found that the order of adsorption of these metals in their study was similar to that in the present study. From these results one may conclude that Pb and Cu form much stronger complexes with soil colloids than do Cd and Zn. Among soils the alum shale soil generally retained the maximum amount of metals, despite its higher initial metal content, lower amount of organic matter and lower CEC. This perhaps suggests that in the alum shale soil some other sites than those occupying the total CEC may be responsible for retaining the metals. This soil contained sulphide, which can associate metals. The second reason may be its high lime content and high Ca saturation (85%) of the CEC. This Ca^{2+} in the exchange complex favours the adsorption process to a greater extent. The high affinity of this soil with metal adsorption may prevent the loss of metals by leaching from the upper layers and may elevate the concentration of metals in the longer run.

Desorption

The results of the reversibility experiments, i.e. the adsorption and desorption isotherms for Cd, Zn, Cu and Pb drawn between equilibrium concentration vs amount of metal adsorbed or desorbed, are presented in Figs. 2 and 3. The extractant $CaCl_2$ (0.005M) could not desorb any Cd from the alum shale and silt loam soil at the initial concentration of added Cd (up to 1 μg cm^{-3}). Even at the highest concentration (50 μg cm^{-3}) only < 2% of the adsorbed Cd was desorbed in these soils. In the clay loam soil the maximum desorption was 4%. In the sandy loam soil the desorption was much higher than that in other soils, up to 60% of the adsorbed Cd (Fig. 2). Near irreversibility of the adsorbed Cd in alum shale, peat soil and organic soil may imply that Cd in these soils formed such compounds which were either co-precipitated with other compounds or diffused into soil particles, rendering the adsorbed Cd less soluble in desorbing electrolyte. Amacher et al. (1986) reported that the irreversible retention of Cd may be the result of formation of Cd compounds which are extremely slowly soluble, co-precipitated with other compounds and retained by carbonates in the high pH soil, whereas Mayor (1978) observed full reversibility in an acid forest soil loaded with low Cd concentrations and Christensen (1984) found partial reversibility in a sandy loam soil.

Zinc desorption generally followed the trend similar to that for Cd (Fig. 2). In the alum shale soil < 5% of adsorbed Zn was desorbed by 0.005M CaCl2. The extent of Zn desorption increased to about 8% in the clay loam and silt loam soils and to about 48% in the sandy loam soil.

Desorption of Cu by 0.005M $CaCl_2$ was < 1% in the alum shale, organic soil and peat soil even at the highest level of adsorption but in the sandy loam soil the maximum amount desorbed was 14% (Fig. 3). These results suggest a near complete irreversibility of adsorbed Cu in all soils with the exception of the sandy loam.

Similar to Cu, a very small amount (< 0.4 per cent) of adsorbed Pb was desorbed from the alum shale and clay loam soil (Fig. 3). In the sandy loam soil the maximum amount desorbed was 6%.

O,Connor et al. (1983) for Zn and Ni and O,Connor et al. (1984) for Cd reported that as the loading of metals increases, the specific sites approach saturation and reversibility of metals increases. In our study the desorption of metals was generally very low in the alum shale, organic soil and peat soil even at the highest levels of metal loading, which suggests that Cd, Zn, Cu and Pb were adsorbed almost irreversibly on highly specific sites. This may have been caused by sorption sites possessing higher free energy than the average sites. This observation implies that these soils having very high irreversibility of metals may work as a permanent sink rendering added metals environmentally unavailable.

Effect of ionic strength on metal desorption

The comparison of three different concentrations of $CaCl_2$ for desorption of adsorbed metals from the soil is presented in Table 2. In the alum shale soil, the amount of Cd desorbed increased from 1.1 to 65% when the electrolyte concentration was increased from 0.005M to 0.5M. A 100-fold increase in the ionic strength of $CaCl_2$ resulted in a 60-fold increase in desorption. Although the extent of desorption varied, the trend in the sandy loam, organic soil and peat soil remained similar to that observed in the alum shale soil. Jarvis & Jones (1980) and Christensen (1984) found that increasing the concentration of $CaCl_2$ in the desorbing solution resulted in the increased amount of Cd desorbed. This seemes to be caused by the ionic competition between Ca and Cd ions for the exchange sites, where an increased Ca concentration resulted in increased Cd desorption. This statement was supported by Homann and Zasoski (1986, unpublished data). They reported a strong competition between Ca and Cd for adsorption sites in acid soils.

The desorption of Zn and Pb by the increasing strength of $CaCl_2$ solutions generally followed the same trend as that observed above for Cd. Copper desorption, on the other hand, was not affected by the increasing strengths of $CaCl_2$ solutions. Only small increases in metal desorption by increasing strength of the electrolyte were observed for all soils except for the sandy loam where a significant amount of these metals was desorbed (Table 2). Based on these results one might suggest that in these soils the binding strength of the adsorbed metals was in the order Cu > Pb > Zn > Cd.

Conclusion

The investigations have shown that adsorption of metals in four soils varying in physico-chemical properties was different. Adsorption data were fitted very

Table 2. Effect of Ca ion concentration on the desorption of Cd, Zn, Cu and Pb

Soil	Amount adsorbed ($\mu g\ g^{-1}$ soil)	Amount desorbed ($\mu g\ g^{-1}$soil)		
		0.005M	0.05M	0.5M
		Cadmium		
Alum shale	99	1.09	17.9	63.9
Sandy loam	40	23.82	32.4	35.3
Organic soil	95	2.65	29.0	66.5
Peat soil	97	1.07	16.2	63.9
		Zinc		
Alum shale	244	4.87	35.4	119.3
Sandy loam	75	35.73	52.0	64.7
Organic soil	229	8.96	60.8	150.9
Peat soil	239	4.47	33.4	127.3
		Copper		
Alum shale	250	0.10	0.4	2.0
Sandy loam	223	10.56	38.1	66.1
Organic soil	249	0.29	0.7	4.4
Peat soil	249	0.26	0.5	2.7
		Lead		
Alum shale	250	0.25	3.6	27.7
Sandy loam	244	2.92	32.4	165.0
Organic soil	249	0.71	5.6	46.7
Peat soil	249	0.79	3.3	28.6

well to the Freundlich equation and gave highly significant R^2 values. The highest value of adsorption constant K for all metals was observed in the alum shale soil, while the peat soil showed the highest value of affinity term n. This perhaps implies that although the alum shale soil adsorbed the maximum amounts of metals, it did not show the highest affinity for metal adsorption. The order of metal adsorption among the soils was alum shale > peat soil> organic soil> sandy loam. Among metals, Pb was adsorbed in the highest quantity by all soils followed by Cu, Cd and Zn. The Freundlich adsorption constant (K) and distribution coefficient (Kd) were found to be good indicators of the metal adsorbing capacity of these soils.

The desorption of metals from all the soils with the exception of the sandy loam was generally low at the lowest concentration of the desorbant but increased with increasing concentration of the desorbing solution.

This study suggests that, from an environmental point of view, the metal adsorbed by these soils excluding the sandy loam, may not leach down to contaminate the ground water and may be less available to plants.

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An interdisciplinary approach for studying greenhouse gases at the landscape scale

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Soil and land use are the main variables that control fluxes of greenhouse gases at landscape scale. An experimental approach is described that examines the influence of landscape terrain and land use on fluxes of important greenhouse gases (CH_4, N_2O and CO_2) in soil. The landscape is gridded into "field" units (cells), and each cell is characterized. For example, a 500 X 500 m rolling landscape, consisting of forest and croplands, is gridded into 400 field units (25 X 25 m cells). Cell gridding and classification of the slope, elevation and land use are partially automated using photogrammetric techniques. An analytical plotter locates 400 sample points on (1:5000 scale) aerial photographs and issues X,Y ground coordinates, then determines elevation (Z), and computes slope for each cell. Through photo interpretation, each cell is classified by landform, land use, and vegetation. These data are superimposed on soil maps. Each cell is classified by the soil characteristics that conceptually regulate the microbial processes and the gas fluxes in question (at proximal level). Geostatistics (e.g. semivariograms) allows examination of the spatial relationships of the factor(s) that control the gas fluxes in question. Based on the study's objective, appropriate cells can be statistically selected (identified) by an experimental designed (e.g. factorial). The gas fluxes and other soil and environmental factors of potential explanatory importance (e.g. NH_4^+, NO_3^-, C, N content of soil, soil moisture and temperature) should be measured simultaneously in selected cells. The number of sample measurements required within each cell depends on the methods of measurements and spatial variability of the variable in question. This experimental approach appears feasible for semi-automated investigations of gas fluxes at the landscape scale.

Key words: Carbon dioxide, greenhouse gases, landscape, methane, nitrous oxide

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The atmospheric concentration of greenhouse gases CH_4, N_2O and CO_2 continues to increase (Houghton et al. 1992). The atmospheric CO_2 is currently 353 ppmv and increasing by 0.5% per year (Eriksson 1991). The atmospheric

CH_4 is currently at 1.8 ppmv, and is increasing by about 1% per year, whereas N_2O concentration is 315 ppbv and is increasing by 0.25% per year (Denmead 1991). The causes of these increases are not fully understood. They may be due to increased emissions or decreased terrestrial sinks. For example, increase in atmospheric N_2O and decrease in CH_4 uptake may be linked to different land use -- increased nitrogen fertilization, irrigation and soil compaction in agriculture (Hansen et al. 1993) -- and increased atmospheric deposition of nitrogen on forest soils (Sitaula & Bakken 1993; Brumme & Beese 1992).

There is also considerable uncertainty in many of the source-sink estimates, because the net annual flux, determined by subtracting total sink strength from total source strength, does not balance the observed rate of increase in atmospheric content for any of the gases (Duxbury et al. 1993). The annual budget for N_2O and CH_4 appears to underestimate sources and for CO_2 underestimates the sink (Duxbury et al. 1993). The uncertainties in many of the source-sink estimates for trace gas fluxes are often linked to high spatial and temporal variability which makes it difficult to estimate source - sink over a larger area (Matson et al. 1989). Generally speaking, soil source and sink estimates are based on fragmented information collected over small areas during short monitoring times (Davidson 1991). More work is, therefore, needed on a larger scale (e.g. landscape scale) in order to update the current estimates. One of the major obstacles for monitoring a large landscape is the selection of sampling units used to characterize the range of conditions at the site. Even though the variation within field plots with specific land use or forest types at any time may be high, the annual fluxes between a distinct landform element or land use across the landscape can be estimated -- provided that adequate methods are used. Soil factors at the landscape may provide effective predictors for fluxes of CH_4 and N_2O which are poorly known.

This article presents an overview of the regulating factors for the production and consumption of greenhouse gases N_2O, CH_4 and CO_2 at landscape scale. Special attention is given to describing a conceptual research methodology outlining the application of three semi-automated systems that can aid in the capture, analysis and location of empirically based spatial units -- topography, land use, and soil -- for studying the fluxes of greenhouse gases at the landscape scale. The techniques of field flux measurement, detailed scheme for sampling and subsampling of gases and regulating factors (e.g. moisture, temperature, mineral N) and, also, the statistical approach for studying the fluxes of greenhouse gases at the landscape scale are presented.

Controlling factors

Bouwman (1990) estimated that soils might contribute some 90% of N_2O emission. In soils, N_2O is formed by microbial processes during nitrification, i.e. the oxidation of NH_3 to NO_3^-, and denitrification, the reduction of NO_3^-. The first is an aerobic process, which is probably the dominating source of N_2O in moderately moist soils. The latter is an anaerobic process, which is the dominating N_2O source when soil moisture is high (Firestone & Davidson 1989).

One of the approaches for dealing with the high variability of these gas fluxes is to increase the scale of investigation in both time and area (Groffman & Tiedje

1989). Soil factors at the landscape scale may provide more effective predictors for gas fluxes. At the small plot scale, soil variables that control N_2O release are water content, NH_4^+ availability (as measured by nitrification rate) and temperature (Sitaula & Bakken 1993). In a landscape-scale study in Michigan, Groffman & Tiedje (1989) found 86% of the annual denitrification-induced N_2O loss was explained by incorporating soil texture and soil drainage into their model variables that regulate denitrification only indirectly.

Denitrification N_2O

At the landscape scale, work reported is mainly associated with denitrification N_2O (Kessel et al. 1993; Pennock et al. 1992; Groffman & Tiedje 1989). Within a landscape, seasonal rates of denitrification are controlled by a variety of soil and environmental factors. Denitrification is also strongly controlled by the presence of NO_3^- and NO_2^- and by the presence of organic compounds, since most denitrifying organisms are heterotrophic. The partitioning of the gaseous products of denitrification (N_2O/N ratio), which is of particular interest as far as atmospheric chemistry is concerned, has been shown to be related to a variety of factors including the level of available NO_3^- and NO_2^-, organic C supply, O_2 level, and pH (Groffman 1991).

Field-scale control of denitrification is affected primarily by N supply (NO_3^-) and by soil water (which controls O_2 supply). Numerous studies have attempted to quantify rates of denitrification in relation to moisture status, fertilizer additions, cropping systems, and other field-scale variables. Most of these studies have been hindered by high spatial and temporal variability in activity, with coefficients of variation frequently exceeding 100% (Groffman 1991). Hence, applying that knowledge to explain and predict variation in denitrification N_2O exchange within and across landscapes, or even in small plot studies, remains troublesome. However, soil type and plant community type are useful conceptual regulators of denitrification at the landscape scale (Groffman 1991).

Kessel et al. (1993) found distinctly different rates of denitrification associated with various landform elements, indicating a strong topographic influence on the variables that regulate denitrification. The role of topography corresponds to what Robertson (1989) terms a distal control on denitrification. That is, although topography itself is not the controlling factor, it has a strong influence on the more basic hydrologic and pedologic processes that directly control denitrification at the cellular level (i.e., the proximal controls). A similar interpretation can be given of the results reported by Groffman & Tiedje (1989), in which there was a strong relationship between denitrification and soil texture and drainage class across a forested landscape in Michigan. It should be noted, however, that soil drainage and, to a lesser extent, texture are influenced strongly by topography. Bottom-slope positions routinely may have relatively fine-textured soils, with higher soil moisture and plant productivity and more dynamic N cycles than top-slope or hillside positions (Groffman 1991).

Other factors, in addition to topography, are also found to be important controllers of N_2O fluxes. Rates of denitrification and ambient N_2O evolution were found to be very low when the soil was cool and dry (Kessel et al. 1993). Increased soil temperatures, the application of fertilizer N, and adequate rain all tended to increase denitrification rates and to be strongly correlated to N_2O evolution in a landscape-scale study (Kessel et al. 1993).

Nitrification N_2O

Studies on nitrification at landscape scale are scarce. Groffman (1991) discussed that to address ecological control of nitrification at scales above the field level, one needs to identify the factors that control the variability of NH_4^+ and O_2 supply in soil at the scale in question. Soil type (texture and drainage), which is a strong controller of organic matter levels, moisture dynamics, and N mineralization, is an important landscape-scale controller of nitrification. If the landscape is viewed as an aggregate of "field"-scale units consisting of distinct soil types, landscape-scale patterns of nitrification can be systematically evaluated. Groffman (1991) also discussed that another approach for evaluating nitrification at the landscape scale is to focus on plant community type. Plant community patterns are often strongly related to N availability (Pastor et al. 1984), and different plant communities should thus exhibit distinct patterns of nitrification. Consideration of plant community type can be extended to encompass different agricultural production systems, which often differ in the nature and extent of N enrichment and should thus have distinct patterns of nitrification and associated N_2O flux.

CH_4 uptake

The largest biological sink for CH_4 is micro-organisms (methanotrophs) in aerobic soil (Topp & Hanson 1991). CH_4 oxidizing bacteria are ubiquitous and diversity between different environments is low (e.g., Hayer et al. 1984). However, the effect of environmental factors differs greatly between ecosystems, e.g. agriculture or forest. CH_4 oxidation activity observed in soil is highly influenced by changes in the physical condition of soil, e.g. mixing and compaction (Hansen et al. 1993) or chemical changes, e.g. increased nitrogen loading and increased moisture content (King & Adamsen 1992; Mosier et al. 1991; Steudler et al. 1989). All these factors are influenced by different land use and management practices in the agricultural ecosystem.

Forest soils are also thought to be an important sink for atmospheric CH_4 (Yavitt et al. 1990; Steudler et al. 1989). CH_4 oxidation in soils is apparently being suppressed by inputs of nitrogen (Hansen et al. 1993, Denmead 1991; Steudler et al. 1989). CH_4 uptake in forest soil needs to be investigated since forest soil occupies significant areas of land, and these soils may be losing their capacity to act as a sink for atmospheric CH_4 as a result of disturbances such as increased input of airborne N. Other interacting soil factors controlling CH_4 fluxes are soil texture and soil moisture. In a lysimeter scale experiment (Bonilla et al. in prep.), more than 80% of variation in CH_4 fluxes was explained by moisture content in the range of 7 to 33 (% v/v) and apparently this soil moisture was related to soil texture. Average CH_4 uptake rate in silty clay soil (18-23% clay) was significantly higher (38%) compared to sandy soil (2-4% clay) (Bonilla et al., in prep).

Carbon dioxide

CO_2 is the most abundant greenhouse gas and the release of CO_2 from terrestrial biota, including soil emission, contributes significantly to the present atmospheric CO_2 concentration (Bouwman 1990). Its atmospheric concentration (353 ppmv) is about 25% higher than the preindustrial value (280 ppmv) and is currently increasing by 0.5% per year accounting for about 60% of the current increase in the greenhouse effect (Eriksson 1991). Soil may either be a net sink or a net source of atmospheric CO_2. In periods where there is a net accumulation of organic matter, soil will be a significant sink. The opposite is true for periods with net decrease in soil organic C. The balance is determined by several factors, including the "history" of the soil and the weather conditions. Global warming may result in a further increase in CO_2 concentrations due to a temperature-dependent net decrease in soil organic matter by mineralization (see Schimmel 1995 for ref.).

The organic C content of well-drained soils does not accumulate indefinitely (Eriksson 1991). An equilibrium level between litter supply and decomposition is attained with time, depending on soil-forming factors such as climate, topography, vegetation, organisms and parent material. Human activities affect all these factors in different ways. The two activities causing the greatest increases in decomposition rates inducing high CO_2 fluxes from forest land are probably artificial drainage and site preparation. Forest drainage work in Sweden covering about 10,000-20,000 ha yr^{-1} induced CO_2 emissions, roughly estimated to about 1 Mton C yr^{-1} (Eriksson 1991).

Characterizing a landscape

Defining the landscape system

Our understanding of ecological systems is not predicated on the presumption that we can understand all basic chemical and physical laws that influence the fluxes of greenhouse gases; rather our goal is to understand the behaviour of systems within appropriate levels of organization. A "system", as defined by Forrester (1968) is merely a grouping of parts that operate together for a common purpose. The precise definition or model of a system, however, will depend on the objective of any given study (with a well-defined problem), because no natural system can be described in complete detail. Furthermore, the understanding of a system at any conceived level of organization requires knowledge of the levels immediately above and below that level.

In this study, the theoretical construct of a landscape system is based on Woodmansee's (1990, p. 59) assumption that all levels within the ecological hierarchy are models that must be defined in space and time: "When matter is exchanged between components within one level in the hierarchy, that exchange must take place through some vector or medium of transport." The levels and components are abstractions that represent real entities. The modelled matter also represents real exchanges and can be quantified in terms of matter moved per unit area per unit time.

Woodmansee (1990) integrates the concepts of Anderson et al. (1983), MacMahon et al. (1978) and Rowe (1961) to produce a hierarchical diagram, with the focal system being a site - sometimes called a landscape element or local ecosystem (Fig. 1). A site can be, for example, a polypedon: a group of contiguous pedons with similar characteristics. A polypedon is bounded on all sides either by non-soil or pedons of significantly different characteristics (Soil Survey Staff 1975). The boundary between polypedons may be sharp, as with a vertical scarp, or may be gradual and extended to a distance of kilometres; and, generally, the boundary will extend over a few metres (Woodmansee 1990). This is the unit from which individual soil samples are taken and in which process-level measurements are made.

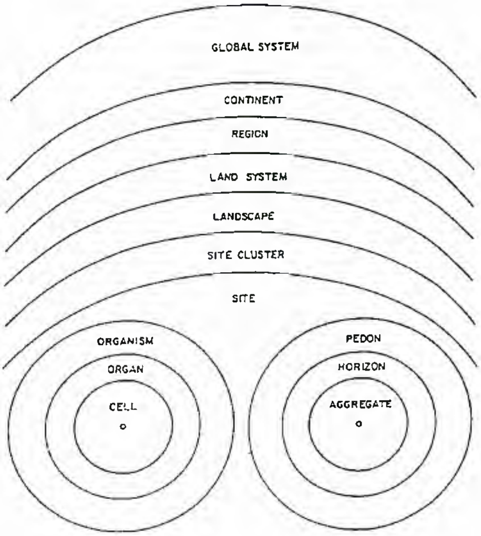

Figure 1. Diagram indicating the integration of concepts from biological and pedological hierarchies. Within each level of organization, energy or matter is the currency of exchange between components (Woodmansee 1990, p. 60).

Since gas flux is partially dependent on living organism (e.g. vegetation), the site should also be defined from an ecosystem perspective. Within the context of Woodmansee's (1990) hierarchy, a local ecosystem is equivalent to a site: a unit composed of a biotic community growing in association with a soil polypedon (and with associated parent material and atmosphere). Since soil and plants are fixed in space, if not in time, and are relatively easy to measure, it is convenient to use this relationship to define the boundaries of a site.

The next level in the hierarchy is the site cluster. The concept of the site cluster is important for two reasons: (i) it describes a series of sites connected by a significant exchange of matter; and (ii) it includes the concept of a catena, traditionally used by soil scientists to describe a connected series of soils on a slope (Fig. 2). The connective element in a soil catena is typically the downward slope movement of water that follows distinct flow paths. Since soil development and productivity are generally enhanced at the bottom of the slope, a soil catena conveys an inherent concept of size, or length, characteristics of an ecological flow path (a series of sites related to one another via a transported substance or object). Keep in mind, however, that a flow path is not merely a linear down-slope concept: it is a two-dimensional area concept where short-range atmospheric and animal transport of material also takes place among the cluster of neighbouring sites (Woodmansee 1990).

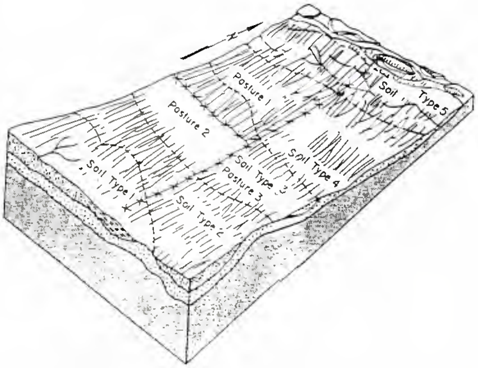

Figure 2. Three pastures superimposed on a catena of five soil types (Woodmansee 1990, p. 62).

A landscape is a hierarchical level whose component parts are site clusters. Processes and agents of material transport common to this level of organization are presented by Woodsmansee (1990), though the flux rates between site clusters are essentially unknown and represent an ecological frontier. Matter can be directly exchanged between site clusters by animals (e.g., that forage in one site and defecate in another), by wind transport of soil particles and organic debris, and by water where dissolved or suspended nutrients are transported from upstream site clusters to downstream bottom-land clusters.

Woodmansee's (1990) hierarchy of ecological systems is useful in building a conceptual framework for organizing many related or seemingly unrelated facts and observations about fluxes of greenhouse gases. It organizes information and is based on tangible entities or objects that can be described in time and space and can be measured, albeit sometimes with difficulty. Consequently, the various levels of the hierarchy lend themselves to mapping and aggregation. By georeferencing measurable phenomena, this scheme allows the placement of processes at meaningful levels within the hierarchy. For example, though soil and land use are assumed to be the main variables that control fluxes of greenhouse gases at the landscape scale, the fluxes are traditionally measured at the site or smaller scale. Processes at one level of organization must not be inappropriately applied to another level ((see Woodmansee 1990 for ref.). But by proper sampling and by aggregating information we can vastly improve our understanding of higher-order ecological systems.

One of the major obstacles to research at the landscape scale is the selection of sampling units used to characterize the range of conditions at the site (Groffman 1991). Sampling units must be chosen such that they reflect spatial differences in the factors that control the process in question, e.g. quantitative classification of slope form to assess patterns of denitrification (Pennock et al. 1992). Although gas flux is also time-dependent (e.g., Kessel et al. 1993), assessing temporal variations does not fall within the scope of this study. However, assessment of temporal/seasonal variation in gas fluxes is needed for selecting the duration and frequency of gas measurement to obtain precise annual estimates.

Our objective is to describe a semi-automated method that examines the influence of terrain variation and land use on fluxes of important greenhouse gases (CH_4, N_2O and CO_2) at the landscape level.

Methodological approach

Research design

The development of a landscape-based estimate for gas fluxes requires that spatial variability inherent to the processes is adequately assessed. Although our experimental approach is theoretical, the initial stage of stratifying a hypothetical landscape into meaningful spatial units is based upon empirical investigations: landform elements, soil type, and land use. For example, slope is quantified according to Kessel et al.'s (1993) landscape scale study; land use is stratified using maps and photo interpretation; and soil units based on 1:5000 scale soil maps.

The objective of this experimental design is to outline the application of three semi-automated systems that can aid in the capture, analysis and location of empirically based spatial units -- topography, land use, and soil -- for studying the fluxes of greenhouse gases at the landscape scale.

Theoretical field description and sampling

For this study, let us assume a one square kilometre landscape consisting of ten soil units. Land use includes forest, cultivated crops, and pasture; and we assume that each soil within each land use has a unique associated biota. Thus, each soil/plant community combination represents a unique site or local ecosystem (Fig. 3).

The rolling landscape has significant elevation difference (30 m), such that each soil catena -- or site cluster -- conveys an inherent size (Fig. 4). In order to define the site clusters, we superimpose landform elements (i.e. slopes) with soil types and land uses. Technically speaking, superimposing these elements is rather straightforward, because these data can be manipulated by a digital mapping system.

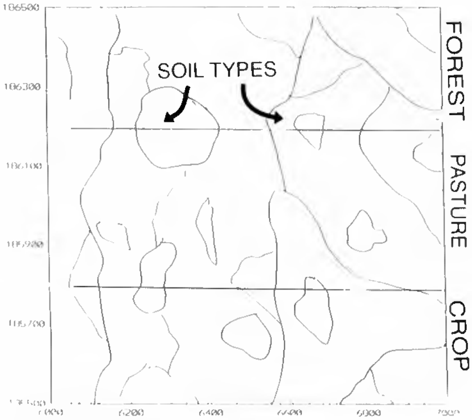

Figure 3. The site or local ecosystem represented by the combination of soil type and plant community.

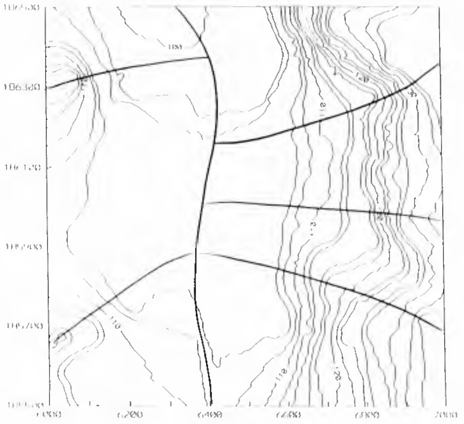

Figure 4. Site clusters within the landscape.

Although many soil maps are already in digital form, land use and topographic data are more troublesome for two reasons. First, due to the inherent changing nature of agricultural landscapes, land use maps are often outdated. Second, elevation data from rural topographic maps are generally inadequate for our site-specific slope classification. So our first task is to capture slope and land use data so that we can assemble them with soil data and structure a suitably scaled sampling strategy. To do this, we implement our first semi-automated system.

System 1: data capture

One of the most accurate methods to capture land use and elevation data is by photogrammetry -- the science of making reliable measurements from photographs. For example with conventional aerial survey photography (1:15,000 scale), elevations can be recorded with an accuracy of about 20 cm. And when metric photography is used in conjunction with semi-automated analytical instruments, photogrammetry proves to be a most efficient method for data capture (Warner et al. 1991).

The procedure consists of the following operations: A stereomodel (two overlapping photographs) is placed in an analytical stereoplotter and photogrammetrically oriented to the ground (i.e., scaled and levelled).

Land use units (polygons) are delineated off the photographs and the data (X, Y, Z coordinates) are entered directly into a geographical information system (GIS). Next, the analytical plotter is switched to a drive-to-point mode. That is, the instrument is programmed to collect elevation data at given points over the landscape area. Specifically, the instrument drives along a grid, separated by

10 m spacing, and as the operator records the elevation of each point, the X, Y, Z coordinates of each point are registered in the GIS. The 10,000 elevation points can be captured in about 4-5 hours.

System 2: Selecting sample locations

The heart of the semi-automated sampling strategy is the GIS. It serves three basic functions. First, it generates a 10-m grid digital elevation model (DEM) based upon the 10 000 elevation points. The DEM is used to classify each 10 X 10 m cell of the surface into one of six landform element classes, described by van Kessel et al. (1993): upper level, divergent shoulders, convergent shoulders, divergent foot slopes, convergent foot slopes, and lower level.

Second, the GIS identifies sites and site clusters. By layering land-use and soil-type polygons on the DEM, the GIS can geo-reference sites and quantify their characteristics. Specifically, the geometric characteristics of each site (size, slope, aspect, and elevation) are integrated with soil and land use data (Fig. 5).

Third, the GIS determines an optimal spatial sampling technique. Since it is impractical to sample all 10, 000 grid cells across the landscape, it is important to design a robust sampling scheme. To do this, each grid cell is classified by the soil characteristics that conceptually regulate the microbial processes and the gas fluxes in question (at proximate level). The spatial relationships of the factors that control the gas fluxes in question are evaluated by Geostatistics (e.g. semi-variograms).

System 3: locating sample sites

Based upon the study's objective, appropriate cells can be statistically selected by an experimental design (e.g. factorial), and identified with X, Y ground coordinates. The gas fluxes and other soil and environmental factors of potential explanatory importance (e.g. nitrogen content of soil, soil moisture and temperature) should be measured in selected cells. The locating of specific cells in the landscape can be accomplished quite efficiently by entering the cells' X, Y coordinates into a global

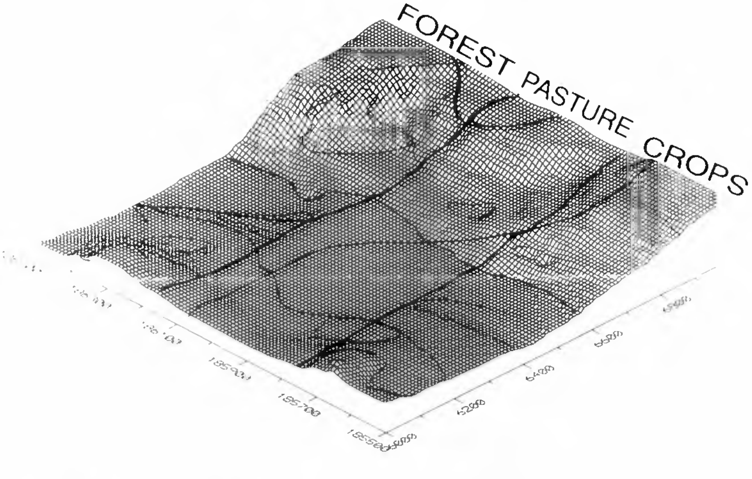

Figure 5. Digital elevation model of the landscape showing land use and soil type superimposed.

position system (GPS). The hand-held GPS is then taken into the field and the operator merely navigates to each cell by following the directional finder. When the cell centre is located, field instruments are installed to measure gas fluxes. Used in the differential mode, a hand-held GPS has a position ground accuracy of about 5 m. The number of sample measurements required within each cell depends on the spatial variability of the variable in question and on methods of field flux measurement, described below.

Techniques of field flux measurements

Traditionally, flux measurements of N_2O and CH_4 are usually conducted by using field chambers, from which gas samples are collected and analysed by gas chromatography (Smith et al. 1994a). There are a number of drawbacks with the traditional techniques, but the temporal and spatial variability in the emissions render the method unsuitable for flux measurements at a landscape scale (Sörensen et al., submitted). For CO_2, chamber methods cannot be used as they affect the photo assimilation of CO_2 by plants and algae. To measure the emissions on a landscape scale one needs an integrating spectroscopic or infra-red absorption approaches in combination with micrometeorological techniques (Zahniser et al. 1995, Galle et al. 1994; Hargreaves et al. 1994; Wienhold et al. 1994; Fowler & Duyzer 1989). The micrometeorological methods can not, however, be used for all systems, in particular for heterogeneous sites (Fowler & Duyzer 1989). For such sites one can use the megachamber method, which integrates the emissions at a scale of about 60 m^2 (Galle et al. 1994; Smith et al. 1994b).

Megachamber method

The megachamber ([from Galle et al. 1994]) is a hemicylindrical chamber, an elongated camping tent. It consists of two end sections and a 24-m mid-section. The chamber covers an area of 64 m^2 (Galle et al. 1994). The chamber used by Smith et al. (1994b) had a similar design but was constructed of plastic hoops and polyethylene sheet, that was weighted down by water- or sand-filled bags. The advantage of the tent used by Smith et al., (1994b) is that it is cheaper than the one used by Galle et al. (1994) and that it can be changed in size more readily.

The production of the gases can be measured with an instrument placed within the megachamber. Two different instruments have been used to measure gas production/consumption in megachambers. Galle et al. (1994) used a Long Path Fourier Transformed Infra-red Spectroscopy (LPFTIR, Bomem MB100) in combination with a 1 km optical path a multiple reflection mirror arrangements (White cells) with a base of 25 m. Smith et al. (1994b) used a long path infra-red instrument (Hawk, Siemens Plessey Controls Limited) and a retro-reflector system (the beam covers two paths compared with the 40 for the LPFTIR system). The LPFTIR with an open path White cell can measure lower emission rates than the Hawk, at sub-ppb levels. It can also compensate for changes in gas concentrations resulting from changes in the water vapour as the H_2O is measured. Furthermore, the LPFTIR can measure multiple gases (N_2O, CH_4, CO_2, H_2O and CO) simultaneously. The Hawk is, however, easier to work with, is a more robust field instrument than the LPFTIR system and costs less. However, one Hawk can only measure a single gas species.

The FTIR instrument was also placed

outside the megachamber and air pumped from the megachamber for analysis (Fig. 6). The benefit of this arrangement is that the size of the tent is flexible, depending on the site studied. Several different tents can easily be measured at a site. This is important, as it was shown by Smith et al. (1994a) that several different placements of the megachamber have to be conducted to achieve a correct integration of the fluxes from the field.

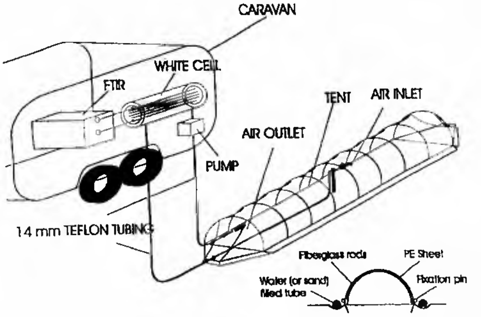

Figure 6. Schematic view of the megachamber configuration, with the FTIR and 96 m closed optical path White system (the base path 25-m). (Source: Klemedtsson L.)

The advantages of the megachamber method is that it integrates over a larger area (64 m^2) than the conventional field chambers (0.01 to 1 m^2), at sites where micrometeorological methods are unsuitable either because of topographical limitations, inhomogeneous flux or very small fluxes below the detection limit of the technique.

The disadvantages are similar to those of the small field chambers. The megachamber alters the micro-climate during the measurements and the leak rate of gases from the chambers has to be measured.

Micrometeorological techniques

The techniques described here all share a common requirement of an adequate upwind distance (fetch) of representative surface. The area over which the flux is integrated is a function of instrument measurement height, wind speed, surface roughness and atmospheric stability, and as a general rule of thumb an adequate ratio of fetch:height is 100:1. Thus a measurement made at a height of 5 m requires a fetch of at least 500 m upwind. (See, for example, Monteith & Unsworth 1990; Fowler & Duyzer 1989).

Flux-gradient techniques

Using the flux-gradient techniques, the flux, Fx, is indicated by:

$$F_x = -K^2 \frac{dw}{dln(z-d)} \bullet \frac{d\chi}{dln(z-d)} \phi_m^{-1} \phi_h^{-1}$$

where k = von Karmann's constant, w = windspeed (m s^{-1}) at height z (m), $\div$ = gas concentration ($\mu g\ m^{-3}$) at height z (m), d = zero plane displacement (m) and ϕ_m and ϕ_h are dimensionless stability corrections. Therefore, measurements of vertical profiles of windspeed, temperature and gas concentration are all that is required to calculate landscape scale fluxes using this method. The most important constraint on the method is the need for a sufficiently sensitive instrument capable of measuring very small differences in gas concentration. In the case of N_2O, for example, a difference of less than 1 ppb in a background concentration of 310 ppb is typical. An autosampling GC system has been successfully employed for measuring N_2O fluxes from grassland (Arah et al. 1994; Hargreaves et al. 1994; Smith et al 1994a). FTIR systems have also been used for gradient measurements (Galle et al. 1994). In this configuration the gas has been pumped from mast to closed White cells with an optical path length variable between 3 and 139 m. The benefit of this instrument for gradient measurements is that several species, including N_2O, CH_4, CO_2, H_2O, and CO, can be monitored simultaneously. Tuneable diode laser (TDL) spectrometers can also be used, but are very expensive, and the rapid response time which they are capable of is unnecessary for gradient measurements.

Eddy covariance

This is conceptually the simplest and most elegant micrometeorological technique with the flux, indicated by

$$F_\chi = \overline{W'\chi'}$$

where w' = instantaneous deviation of vertical windspeed, w, from the mean (m s^{-1}), χ' = instantaneous deviation of gas concentration, χ, from the mean (µg m-3). Thus, although only two parameters require to be measured, it is necessary to measure them at high frequency (e.g. 5 Hz or faster) with high precision. Windspeed is easily measured using an ultrasonic anemometer having a response frequency of 21 Hz. For CO_2 and H_2O, instruments are also available commercially which have adequate response times. However, for gases such as CH_4 and N_2O, the only technique currently available is TDL spectroscopy. These instruments are now becoming available, and have been successfully applied in several field experiments (e.g. Hargreaves et al. 1995; Fowler et al. 1995; Wienhold et al. 1995).

Conditional sampling

This technique (also known as relaxed eddy accumulation) has the elegance and simplicity of the eddy covariance method, but eliminates the need for fast-response gas analysers. The flux is given by

$$F_\chi = \beta\sigma_w(\chi_u - \chi_d)$$

where β = dimensionless coefficient determined from heat flux measurements, σ_w = standard deviation of the vertical windspeed (m s^{-1}), χ_u = gas concentration in updraughts (µg N m^{-3}), and χ_d = gas concentration in downdraughts (µg N m^{-3}). σ_w is measured by an ultrasonic anemometer, and gas concentrations can either be measured using a dual channel instrument (e.g. a GC) or the samples can be accumulated in bags over a period of 30 min to 1 h then stored for subsequent analysis by GC, FTIR or TDL. FTIR techniques are especially suitable for application to this method because of the large suite of gases they can measure simultaneously. CH_4 and N_2O fluxes measured using this method are described in Beverland et al. (1995) and Hargreaves et al. (1995).

Detailed sampling and subsampling within the field (cell)

If the experimental area is to be sampled so that an estimate of the spatial scale of variability of emissions is required, then the field should be split into plots with samples taken at random locations within each plot. The following scheme is similar to one used by Ball et al. (1995) for this purpose. We suggest that a 24 m x 24 m field could be split into, for example, 64 square plots of sides 3 m. A sampling position could be located within each square, with the x and y coordinates of each position determined as random fractions of the side length of each plot. We recommend that, in addition to gas flux measurements, the concentrations of gas in the soil air and relevant soil physical, chemical and biological properties of potential explanatory importance be measured. We also recommend that sampling positions be measured to within a few centimetres in the x, y and z planes in order to provide accurate locations for geostatistical analysis and for isolating the effect of variations in microtopography on emissions.

Fluxes of N_2O and CH_4 and CO_2 are measured at each position using, preferably, closed chambers, e.g. the design described by Clayton et al. (1994). These are 20 cm tall polypropylene cylinders of diameter 40 cm enclosing an area of 0.126 m2. The chambers are closed with aluminium lids, fitted with an injection port and three-way tap and sealed with a rubber draught excluder. The chambers are inserted 5 cm into the soil. This can be facilitated by cutting circular slots in the soil with a sharpened metal cylinder driven vertically by a mechanical hammer. An alternative is to use chambers of a smaller diameter (7.3 cm) enclosing an area of 41.8 cm^2. These are metal sleeves 5 cm joined by a 3.5 cm long section of rubber cut from a motorcycle inner tube. These mini-chambers are closed with close-fitting plastic caps containing a rubber septum injection port. Mini-chambers are inserted to a depth of approximately 4 cm. Sixty minutes after closing the lid, duplicate air samples (1 ml) are taken from the chambers using airtight, greased glass syringes suitable for sample storage. Gas concentrations in the samples are measured soon after sampling.

Gas concentrations in the soil atmosphere can be determined using, for example, 4-mm ID, 6-mm OD brass tubes, length 30 cm, inserted to 10 (and 20) cm depths close to the wall of the chamber. These are sealed at the top with a rubber/Teflon septum. Duplicate 1 ml samples were taken and analysed as above.

In order to measure the soil physical, chemical and biological properties likely to be governing the emissions of gases, it is necessary to take soil samples. Intact cores are required for measurement of soil physical properties, whereas disturbed cores are satisfactory for chemical properties. If physical properties include gas diffusion measurements, then the core size should be chosen to accommodate the measuring apparatus. Here we recommend 5-cm deep and 7.3-cm diameter cores which can be used in the methods of measurement of relative gas diffusivity and air permeability of Ball et al. (1981). Measurement at field water content only is recommended. Pore continuity can be calculated as the quotient of relative diffusivity divided by air-filled porosity (Ball et al. 1988). Air-filled porosities and volumetric water contents are estimated from measured particle and bulk densities. The cores can be taken from the centre of the chamber positions from 0-5 and 5-10 cm depths. Cores for the measurement of soil chemical properties can be taken using a gouge auger from 0-10 cm and 10-20 cm depths. Field measurements of soil physical properties are also possible, for example gaseous diffusion can be measured in the field (Ball et al. 1994) or cone resistance to indicate soil compaction and how it varies with soil depth (Anderson et al. 1980). If it is not determined from sampling, measurement of volumetric water content is also essential. We recommend the TDR probe (Cassel et al. 1994) because it samples soil near the surface better than the common alternative, the neutron moisture meter. An assessment of soil temperature is also useful in that it plays an important role in determining emission. Spatial variability of temperature is likely to be low, therefore, few measurements are required.

We recommend measurement of soil chemical properties as follows: Nitrogen in NO_3^-, NO_2^- and NH_4^+ forms is measured by continuous flow colorimetric analysis of 1M KCL extracts prepared from field-moist soil using a soil:solution ratio of 15 g:50 ml. Soil pH is determined on suspensions of 10 ml fresh soil in 25 ml water. Soil organic matter content can be calculated from measurements of total organic carbon by oxidation with potassium dichromate. If possible, soluble organic carbon should be measured instead of total organic carbon as this is a more relevant measure of the microbial energy source. Other assessments of microbial activity include respiration rate and microbial biomass.

If there are insufficient resources and time available to measure everything in one day, measurements can be split over two days, by choosing fewer plots and two sampling locations within each plot. On the first day one of the positions is sampled, and on the second day the other position is sampled. If this scheme is followed, gas samples should be taken at the same time on each day (e.g. late morning) in order to avoid the possibility of diurnal variations in concentration contributing to the variability of the results. By combining measurements over two days, a geostatistical grid of at least 80 positions was secured. Ideally, the minimum should be about 100 as recommended by Webster & Oliver (1992) for computation of a satisfactory variogram.

After sampling is finished, we recommend that the locations of the closed chamber positions and of a grid of points surrounding them are determined using an electronic distance-measuring theodolite. This yields x, y and z positions to an accuracy of one cm. From this, the overall slope at each site and the deviation of the z location of the chamber from this overall slope can be determined.

The degree of autocorrelation among the sample points within each grid can be analysed by isotropic semivariograms (Cresseie & Hawkins 1980). The semivariogram describes the average variance of pairs of points a given distance apart (Oliver & Webster 1991). The semivariograms can be fitted to curves by a spherical model. Geostatistical analyses can be made using GENSTAT. More detailed information on application of geostatistics and data analysis are described below.

Data analysis : application of geostatistics

Variations in soil properties tend to be correlated over space. That is, two values taken close together tend to be more alike than two samples taken far apart. Geostatistics offers an approach to quantify spatial correlations of soil properties including fluxes of gases produced and/or consumed by organisms in the soil. Thereby, values at unrecorded locations can be estimated with greater precision with the kriging interpolation method than by using averages of values at recorded places.

The semivariogram is the central tool of geostatistics. It can quantify the scale and intensity of spatial variation and it provides the essential information for estimation of unknown values by kriging (Burgess & Webster 1980a, 1980b) and for optimizing sample intensity (Burgess et al. 1981; McBratney et al. 1981). It can also be used in an exploratory manner in order to discover the underlying causes of the variation (Robertson et al. 1988; Oliver 1987).

Semivariograms are created using data from measurement points located along a transect or in a regular grid as describe earlier. The basic idea in the present study of making a grid in the landscape, thereby creating regular "field" units, provides a potential for using geostatistics to analyse spatial variability of the gas fluxes in question.

The semivariogram describes the average variance of pairs of points at a given distance apart. The steepness of the initial slope of the semivariogram indicates the degree of spatial correlation of a property. Many semivariograms of soil variables show a positive intercept with the ordinate. This is the *nugget* variance, which includes the variation that remains unresolved by the smallest sampling distance, the variability attributable to sampling and analysing errors, as well as any purely random variation. With increasing distance between measurement points the semivariance may approach an upper limit, and remain constant for larger distances. This constant value is called the *sill* and the corresponding distance is called the *range*, which denotes the limit of spatial dependency, or autocorrelation of the measurements. Points closer together than the *range* are spatially dependent while points farther apart are not related to one another.

Previous studies (Ambus & Christensen 1994; Priemé et al. 1994; Priemé, *in prep.*) showed a marked difference in semivariograms on N_2O and CH_4 fluxes. Most notably, the *range* for CH_4 uptake in two Danish forest systems was much smaller than the *range* for N_2O emission on a fertilized grassland. This is in all likelihood due to the different nature of the microbial processes involved.

There are no general rules governing the minimum number of measurement points needed to create a semivariogram as this is related to the requirements of the study and the nature of the spatial variation in question. In the studies by Ambus & Christensen, (1994) and Priemé et al. (1994) on N_2O and CH_4 fluxes in soils, 35-72 measurement points within regular grids were employed. In these, small (0.0078 m^2) chambers were used and minimum distances within the grids ranged from 0.11 to 10 m while maximum distances were 1.1-71 m. In the study at landscape scale, much larger sample units will be used because another sampling technique is used, as described earlier. This will, of course, mask any spatial variability on a smaller scale.

With the kriging method, interpolated values can be used to make isarithmic ("contour") maps of the soil property, e.g. gas fluxes. The accuracy of the kriged estimates depends, of course, on the goodness of the computed variogram, and usually more data points are needed to create an isarithmic map than to create a semivariogram.

Application of the geostatistical techniques described above to determine the distance between sites in the grid is needed to sample a new reliable and independent data set that can be used for classical statistics such as mean and standard deviation. Semivariogram ranges will enable the obtaining of distance between sampling points where gas fluxes are uncorrelated to the soil variable in question. The effects of distinct soil variables and landform elements can be tested with analyses of variance (ANOVA). Multiple comparisons among means in the ANOVA models can be tested using the Newman-Keuls test. Studentized residuals of the data sets can be used to test the normality of the distributions with residual plots and procedure UNIVARIATE (SAS Institute 1988). If data are not normally distributed, which is often the case for N_2O fluxes, data transformations should be carried out to obtain a normal distribution before the statistical analyses. If N_2O or CH_4 data have a highly skewed distribution and data transformation does not approximate a normal distribution, the non-parametric statistics can be used. In such cases the differences between sample points grouped by land properties or landform elements can be assessed using the Kruskal-Wallis one-way analysis of variance by ranks corrected for ties (Siegel & Castellan 1988). The temporal variation of the gas fluxes associated with different landform elements can be assessed using the Kendall coefficient of concordance, W (Siegel and Castellan 1988). Further tests by non-parametric statistics of the data collected at landscape scale are suggested by Kessel et al. (1993). The statistical approaches to assess spatial and temporal variability of gas fluxes and processes at landscape scale are as suggested by Pennock et al. (1992) and Parkin (1993).

In summary, this experimental approach appears feasible for semi-automated investigations of gas fluxes at the landscape scale. The present study holds the potential for geostatistic analyses of trace gas fluxes. The analyses can not only provide valuable information on the spatial variability of the gas fluxes, but also increase our understanding of the underlying causes of this variability and help to visualize the fluxes on a map.

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Host plant preferences of *Chromatomyia fuscula* (Zett.) (Dipt., Agromyzidae) and the attack rate on various commercially grown cereal and grass species

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Andersen, A. Host plant preferences of *Chromatomyia fuscula* (Zett.) (Dipt., Agromyzidae) and the attack rate on various commercially grown cereal and grass species. Norwegian Journal of Agricultural Sciences 9: 211-216. ISSN 0801-5341.

In four experimental series performed outdoors at Ås, Norway, in May-July 1987-92, it was observed that *Chromatomyia fuscula* displayed a broad host spectrum by laying eggs in all 14 cereal and grass species offered. The most preferred/attacked species were *Avena sativa* L., *Phleum pratense* L., *Secale cereale* L. and *Festuca pratensis* Hudson. In all four experimental series, these plant species were significantly more preferred/attacked than the least preferred species *Bromus inermis* Leysser, *Festuca rubra* L. and *Phalaris arundinacea* L. No simple correlation could be found between known nutrient contents in the different plant species and the preference/attack rates measured. *Hordeum vulgare* L. among the cereals and *Dactylis glomerata* L., *B.inermis* and *P. arundinacea* among the grasses were considered the most suitable species for growing in areas susceptible to heavy attack by *C. fuscula*.

Key words: Agromyzidae, attack rates, cereals, *Chromatomyia fuscula*, Gramineae, grasses, host plant preferences, pest insects

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The agromyzid fly *C. fuscula* attacks a large number of wild and cultivated cereal and grass species in more than 20 genera (Griffiths 1980; Spencer 1990), and is therefore considered to be a major pest in cereals and grasses in parts of Fennoscandia (Andersen 1989, 1991). However, from observations in the field, the attack rate on different plant species was thought to differ. The present investigation was performed mainly with the aim of discovering which plant species were the least attacked, as they would be the most promising species for commercial growing in areas susceptible to heavy attack by *C. fuscula*.

Materials and methods

The experiments were conducted outdoors at the Norwegian Plant Protection Institute at Ås in 1987-92. In experiment 1 the host plant preferences of the flies were measured in no-choice tests in 40 cm broad, 40 cm deep and 55 cm high cages covered with gauze. Each cage contained one plant species planted in two flower pots, with seven cereal plants (Zadoks stage 21-22 (Zadoks et al. 1974)), or three grass plants (two months old) in each pot. Twenty-five females and three males of *C. fuscula*, netted in a nearby cereal field shortly before the start of the experiment, were kept in the cage for 24 h on a sunny day toward the end of May, then removed. The total number of eggs laid in the leaves was counted, using a stereomicroscope with light from underneath. A total of nine plant species were tested in four replicates.

In experiment 2 the host plant preferences were measured in choice tests in 154 cm broad, 65 cm deep and 80 cm high cages covered with gauze. Each cage was treated as one replicate, and contained six 65 cm long, parallel plant rows 22 cm apart. Each row had six plants of one cereal species (Zadoks stage 22) or grass species (2 months old). The six plant species in each cage were randomly distributed. Two-hundred flies netted in a nearby cereal field shortly before the start of the experiment were kept in the cage for 24 h on a sunny day at the end of May, then removed. The number of eggs laid per plant species was counted, as in experiment 1. Six plant species were tested in four replicates.

In experiment 3 the attack rate was measured in choice tests by exposing plants to the naturally occurring fly population in the area. The plant species were grown separately in concrete rings of diameter 50 cm filled with a commercial soil mixture. The rings within each replicate were spaced about 50 cm apart, while the replicates were spaced at 220 cm intervals. The area around the rings was covered with gravel. In each ring ten 2-month-old plants were planted (grass species) or directly sown (cereal species with the exception of *Secale cereale*) in the beginning of May. *S. cereale* was sown in pots the previous autumn and kept outdoors until planted in the rings in the beginning of May. The plant species were randomly distributed within each replicate. The experiment contained 14 plant species in four replicates and was laid out each year in the period 1987-92, but the attack rates were measured only in 1987-89 and in 1992, the four years with the highest attacks. The number of *C. fuscula* individuals in the leaves (mainly larvae and pupae) was counted on ten randomly chosen shoots from each ring in the beginning of July, after the oviposition period.

In experiment 4, as in experiment 3, the attack rate was measured in choice tests by exposing plants to the naturally occurring fly population in the area. Eight plant species from experiment 3 were tested in larger plots (5 x 5 m) with three replicates. The grass species were sown in the plots once, in August 1989, while the cereal species were sown in April/May each year. The species distribution between plots was drawn at random in the first year, but in the later years the same plant species was always grown in the same plot. The experiment was set up each year in the period 1990-93, but the attack rates were measured only in 1991 and 1993, the two years with the highest attacks. The number of *C. fuscula* individuals in the leaves was counted on ten randomly chosen shoots from each plot. In 1991 mostly pupae were counted in the beginning of July, while in mid-June 1993 both larvae and pupae were counted.

Phleum pratense (species no. 2), *Hordeum distichum* (species no. 5), *Dactylis glomerata* (species no. 9) and *Bromus inermis* (species no. 13) were included in all four experimental series.

The data in all the experiments were tested statistically by analysis of variance. In Table 1 there is a list of the plant species tested in one or more experiments, and each species is given a number that is used in all the figures.

Results and discussion

The results from experiments 1-4 are presented in Figs. 1-4, respectively. *C. fuscula* laid eggs in all the cereal and grass species offered. This confirms that the fly species has a very broad host spectrum

Table 1. General information about the 14 cereal and grass species used in the experiments.

Spec. no.	Scientific name	Common name	Variety
1	*Avena sativa* L.	Oat	Mustang
2	*Phleum pratense* L.	Timothy	Grindstad
3	*Secale cereale* L.	Rye	Norderås
4	*Festuca pratensis* Hudson	Meadow fescue	Løken
5	*Hordeum distichum* L.	Two-row barley	Gunilla
6	*Hordeum vulgare* L.	Six-row barley	Bamse
7	*Triticum aestivum* L.	Wheat	Runar
8	*Lolium perenne* L.	Perennial rye-grass	Svea
9	*Dactylis glomerata* L.	Cocksfoot	Apelsvoll
10	*Agrostis tenuis* Sibthorp	Common bent	Leikvin
11	*Phalaris arundinacea* L.	Reed-grass	Vantage
12	*Festuca rubra* L.	Red fescue	Leik
13	*Bromus inermis* Leysser	Smooth brome	Løfar
14	*Poa pratensis* L.	Smooth meadow-grass	Leikra

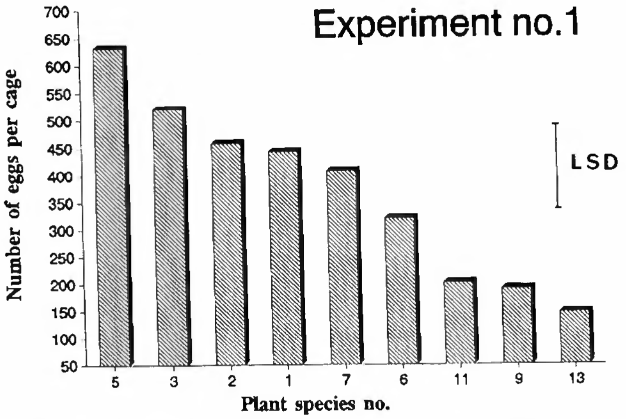

Fig. 1. Host plant preferences of C. fuscula *on five cereal and four grass species in experiment 1. (p=0.01, LSD=153). The plant species numbers are given in Table 1.*

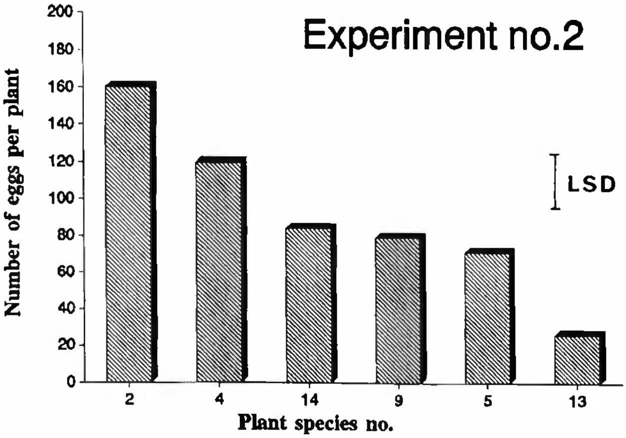

Fig. 2. Host plant preferences of C. fuscula *on five cereal and one grass species in experiment 2. (p=0.01, LSD=31). The plant species numbers are given in Table 1.*

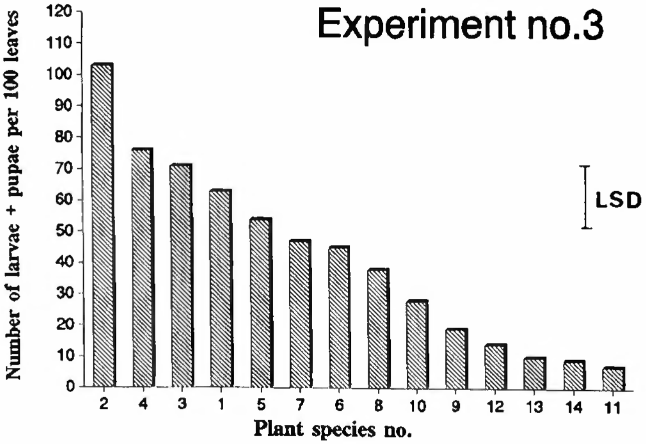

Fig. 3. Attack rates of C. fuscula *on five cereal and nine grass species in experiment 3. (p=0.001, LSD=19). The plant species numbers are given in Table 1.*

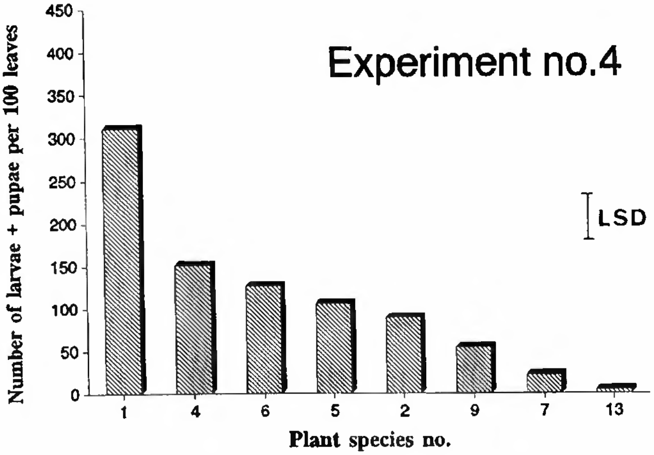

Fig. 4. Attack rates of C. fuscula *on four cereal and four grass species in experiment 4. (p=0.001, LSD=55). The plant species numbers are given in Table 1.*

among the Gramineae (Spencer 1990).

There were no systematic differences between the results in the experiments measuring only the host plant preferences of the fly (experiments 1-2) and the ones measuring naturally occurring attack rates (experiments 3-4). As the preferences for oviposition were assumed to be similar in all the experiments, this result suggests that the mortality of eggs and larvae caused by plant resistance is of similar magnitude in all the tested plant species. The only possible exception was *Poa pratensis* (species no. 14), which was strongly preferred in experiment 2, but had a very low attack rate in experiment 3.

The most preferred/attacked species were *Avena sativa* (species no. 1), *P. pratense* (species no. 2), *S. cereale* (species no. 3) and *F. pratensis* (species no. 4). The least preferred/attacked species were *B. inermis* (species no. 13), *Festuca rubra* (species no. 12) and *Phalaris arundinacea* (species no. 11). In all four experimental series, all the species in the preferred group were significantly more preferred/attacked than all the species in the least preferred group.

P. pratense was most preferred in experiment 2 and had the highest attack rate in experiment 3, the two series where many grass and cereal species were grown close together and offered to the flies (Figs. 2 and 3). This indicates that for *C. fuscula*, *P. pratense* is the most preferred and attacked among the tested plant species.

Among the cereals, *Triticum aestivum* and *Hordeum vulgare* were the two least preferred/attacked species. For climatic reasons, *T. aestivum* is normally not grown in the areas with large fly populations. Consequently, *H. vulgare* is the cereal species most suitable for these areas. Among the grass species, *D. glomerata*, *B. inermis* and *P. arundinacea* are the most suitable alternatives to *P. pratense* and *F. pratensis* for growing in areas with high fly populations.

Tscharntke & Greiler (1995) claim that insect host plant preferences within

Gramineae are mostly due to nutritional factors. In the present investigation it was not possible to find a simple correlation between known nutrient contents (proteins, carbohydrates or minerals) in the different plant species and the preference/attack rates measured. Generally, however, the preference/attack rates were highest in those plant species that are used in farming for their qualities as fodder crops. This certainly is an area that needs further investigation.

Acknowledgements

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Plum tree nutrition: effects of phosphorus, liming and some other elements on vigour, yield, fruit weight and fruit quality of 'Mallard' plum (*Prunus domestica* L.) grown on a virgin, acid soil

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Ystaas, J. & O. Frøynes 1995. Plum tree nutrition: effects of phosphorus, liming and some other elements on vigour, yield, fruit weight and fruit quality of 'Mallard' plum (*Prunus domestica* L.) grown on a virgin, acid soil. Norwegian Journal of Agricultural Sciences 9: 217-229. ISSN 0801-5341.

In a 13-year field trial carried out on a virgin, acid soil low in plant available P, exchangeable K, Ca and Mg it was found that 'Mallard' plum trees responded positively to phosphorus fertilization. Application of 30 kg P ha^{-1} per year resulted in significant increases in tree size as measured by trunk girth, cumulative yield, yield efficiency and fruit size. The plum trees had a sufficient supply of P when soil plant available P was above 4 mg P/100 g soil and leaf P was in the range 0.20-0.30% P. Liming with ground limestone and dolomitic limestone (4000-8000 kg ha^{-1}) at the start of the experiment raised pH from 4.5 to 5.3-6.0 in the 0-30 cm soil layer. Liming, partly by dolomitic limestone, was essential in order to overcome severe magnesium deficiency of unlimed control trees and was found to exert a favourable effect on the plum trees by significantly improving vigour, cumulative yield, yield efficiency, fruit size and fruit quality. Application of 80 kg K ha^{-1} per year resulted in a larger than optimum K uptake.

Key words: Prunus domestica, fertilizer, fruit quality, P, K, Ca, Mg, yield.

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A virgin, acid soil on a morainic deposit in the experimental orchard of the Norwegian Crop Research Institute, Ullensvang Research Centre, western Norway, offered an interesting opportunity to study how young plum trees reacted to differential rates of liming material, phorphorus and potassium fertilizers when the 0-20 cm soil-layer was very low in phosphorus (1 mg P/100 g soil) and exchangeable calcium, magnesium and potassium (11, 2 and 6 mg/100 g soil, respectively) and was strongly acid (pH 4.5).

Plum trees do not usually show any response to phosphorus fertilization (Benson et al. 1966). In California where stone fruits were grown on soils that were markedly deficient in P and where annual crops showed a marked increase in growth following application of phosphate fertilizer, stone fruits showed no indication of disturbance of P nutrition and failed to respond to additional phosphate fertilizers (Lilleland 1932). Plum trees have a higher demand for potassium than for phosphorus, because the fruit has a relatively high K content (Westwood 1978). In heavily cropping prune trees, potassium accumulation in the fruits has been shown to accompany K depletion from leaves and perennial tree parts (Hansen et al. 1982; Weinbaum et al. 1994). A positive response of potassium fertilization to plum trees has been demonstrated by Sandvad (1962) and Ystaas (1966). In acid soil, liming with ground limestone and dolomitic limestone is the most economical source of calcium and magnesium. Regulation of soil pH through liming is also necessary to achieve optimal response of other nutrient elements (Stiles 1994). The objectives of this study were to determine the long-term effects of differential application of P, Ca, Mg and K on major nutrient uptake, vigour, productivity, fruit size, and fruit quality of young trees of the 'Mallard' European plum (*Prunus domestica* L.) grown on a virgin, acid soil low in major nutrients.

Materials and methods

During the years 1982-94 a fertilizer trial with young plum trees was carried out at Ullensvang Research Centre, western Norway, on a loamy sand high in organic matter (6.9%). The soil was a morainic deposit under deciduous forest until it was cleared in 1979. The virgin soil was acid (pH 4.5) and had very low levels of plant available P and exchangeable Ca, Mg and K. No fertilizers had ever been applied to the soil prior to the experiment.

One-year-old trees without feathers of the cultivar 'Mallard' on St. Julien A rootstock were planted in spring 1982 at spacing 5.5 x 3 m. Each experimental tree was surrounded by guard trees of the cultivar 'Opal', which also served as a pollinator. The trees were trained with a central leader and given the form of free spindle. Tree height was kept at 2.5 m by pruning.

A split-plot experimental design was used. On small plots three levels of phosphorus applied as granular superphosphate (8.8% P) at rates 0, 30 and 60 kg P ha^{-1} were combined with three levels of calcium: (1) no calcium, (2) 2000 kg ground limestone (50% CaO)ha^{-1} and 2000 kg dolomitic limestone (50% CaO-13% Mg) ha^{-1}; and (3) 6000 kg ground limestone ha^{-1} and 2000 kg dolomitic limestone ha^{-1}. On the large plots two concentrations of potassium were applied as muriate of potash (49% K) at rates 80 kg and 160 kg K ha^{-1}. All of the ground limestone and dolomite treatments were applied to the soil surface at the start of the experiment. The experiment had four replications and included 36 one-tree plots. Soil management was a combination of frequently mown grass in the alleyways with 1-m-wide herbicide strips along tree rows. Nitrogen applied as calcium nitrate (15.5% N, 0.3% B) at a rate of 80 kg N ha^{-1} per year was broadcast over the entire experimental area in early spring.

Trunk circumference 25 cm above the graft union was recorded annually in the autumn and total yield was also recorded annually. Fruit weight and fruit quality as measured by the content of soluble solids were determined on random samples of 50 fruits from each tree. Concentration of soluble solids was measured by an Atago digital refractometer from free-run fruit juice from 10 mature fruits of the 50-fruit sample.

In order to obtain data for the distribution pattern of the major nutrients in the soil profile of an orchard under permanent grass when the fertilizers and liming material were applied to the ground surface, soil samples from every plot of the soil layers 0-5 cm, 5-20 cm and 20-30 cm were collected annually for the first three years and later biannually. In addition soil samples of the 0-20 cm layer were collected biannually from the fourth year, providing soil samples from the experiment every year throughout the experimental period. Exchangeable cations and soil phosphorus were extracted in accordance with the method described by Egnér et al. (1960).

Leaf samples were collected during the last week of August every year; 25 leaves from the middle of the current year's shoots of each tree were sampled and dried at 60°C until constant weight. For determination of K, Mg, Ca and P in the leaves, the plant material was digested in a 1:2 mixture of perchloric and nitric acids (Oland & Opland 1956). The determination of cations was achieved by atomic absorption spectrophotometry. Determination of phosphorus in plant material and soil extract was carried out in accordance with methods proposed by Michelsen (1957) and Murphy & Riley (1962), respectively.

Statistical analysis of all data was performed by the SAS statistical package (SAS Institute, Cary, N. C., USA) using the PROC GLM procedure.

Results

Main effects on tree vigour, productivity and fruit quality

Phosphorus

Annual applications of 30 kg P ha^{-1} over 13 years had a favourable effect on the vegetative growth of 'Mallard' plum trees, increasing the tree size significantly (Table 1). Phosphorus fertilization likewise exerted a positive influence on cumulative yield and yield efficiency. Fruit weight was increased by P application, while fruit quality as measured by the content of soluble solids was negatively affected by P fertilization. The favourable responses of phosphorus fertilization were obtained by the lower amount of P applied. No positive, additional effect was obtained by increasing the phosphorus fertilization from 30 to 60 kg ha^{-1}.

Calcium and magnesium

Liming the very acid soil (pH 4.5) low in calcium and magnesium brought about a significantly positive reaction in 'Mallard' plum trees: improved vegetative growth as measured by the trunk circumference (Table 1), increased cumulative yield and yield efficiency, larger fruit weight and increased content of soluble solids were obtained. These effects were obtained by the lower level of liming materials (4000 kg ha^{-1}) only; no additional effect was obtained by increasing the liming materials to 8000 kg ha^{-1}, apart from an increase in the content of soluble solids of the fruit.

Potassium

The constraints of the experimental design limited the potassium fertilization to two levels of K, omitting the control without any K application. Increasing the annual K application from 80 to 160 kg K ha^{-1} resulted in a positive response of the 'Mallard' plum trees with an increase in cumulative yield and fruit weight. The effect, however, was significant for the fruit weight only.

Table 1. Main effects of phosphorus, calcium, magnesium and potassium application to 'Mallard' plum on tree size as measured by trunk girth of 13-year-old trees, cumulative yield, cumulative yield efficiency, fruit weight and soluble solids, average figures.

Fertilizer application kg ha^{-1}	Trunk girth, cm	Cumulative yield, kg/tree	Cumulative yield efficiency, kg/cm^2	Fruit weight, g	Soluble solids, %
Phosphorus					
0	21.9	29.7	0.72	26.8	14.9
30	24.9	45.7	0.88	30.7	14.7
60	25.0	43.0	0.85	30.9	14.0
LSD P = 0.05	2.7	9.0	0.11	2.3	0.5
Calcium + Magnesium					
0	21.4	27.3	0.72	26.9	13.7
4000[1)]	24.5	44.8	0.87	29.8	14.7
8000[2)]	25.9	46.3	0.85	31.6	15.2
LSD P = 0.05	2.7	9.0	0.11	2.3	0.5
Potassium					
80	23.1	35.4	0.78	28.7	14.4
160	24.8	43.6	0.85	30.2	14.6
LSD P = 0.05	NS	NS	NS	0.3	NS

[1)] Applied as 2000 kg ground limestone and 2000 kg dolomite

[2)] Applied as 6000 kg ground limestone and 2000 kg dolomite

Effects of major nutrients on soil and trees

As no significant interaction between treatments was found, the effects of differential supply of P, Ca, Mg and K will be dealt with separately.

Phosphorus

The phosphorus application had a rapid and consistent effect on plant available P in the 0-5 cm soil layer (Fig. 1); a significant increase in soil P was obtained in the second year by applying 30 kg P ha^{-1}. Doubling the P application increased plant available P significantly and consistently over the lower rate for the rest of the experimental period (12 years). In this experiment the time-lag from the soil surface application of phosphorus fertilizer to the phosphorus penetration into the deeper soil layers was four years (Fig. 1). The increase in plant available P in the deeper layers (5-20 cm, 20-30 cm) reflected the situation in the surface layer (0-5 cm) and became more evident over time. Phosphorus fertilization increased the uptake of P by the 'Mallard' plum trees and significantly affected the leaf content of P (Fig. 2). No additional effect on leaf P was found by increasing the P application from 30 to 60 kg P ha^{-1}, maintaining the leaf P level between 0.20 and 0.30% P of leaf dry matter.

Over the experimental period, tree

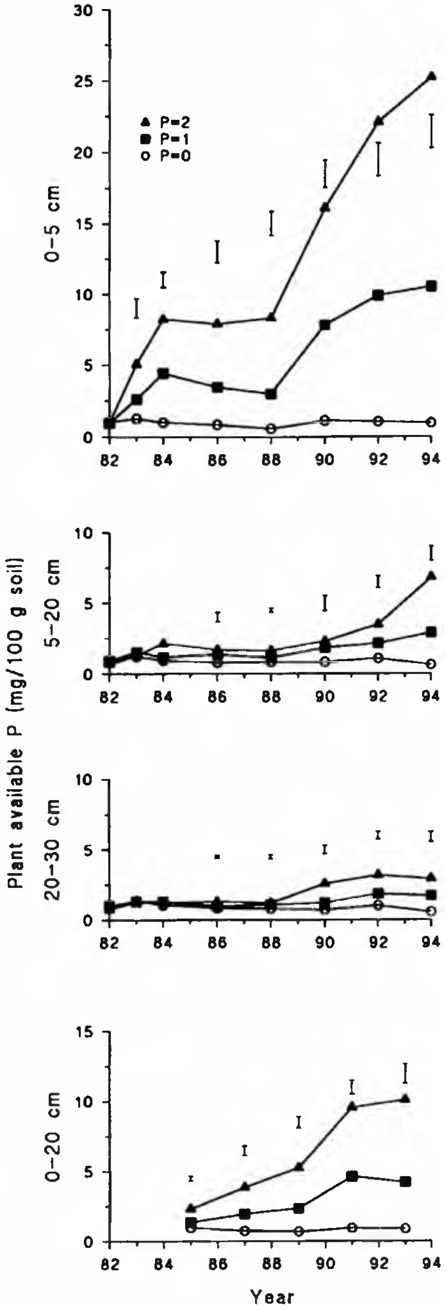


Fig. 1. Plant available P in different soil layers as affected by phosphorus fertilization over 13 years. P0 = no P, P1 = 30 kg P ha^{-1}, P2 = 60 kg P ha^{-1} per year. Vertical bars represent LSD, P = 0.05

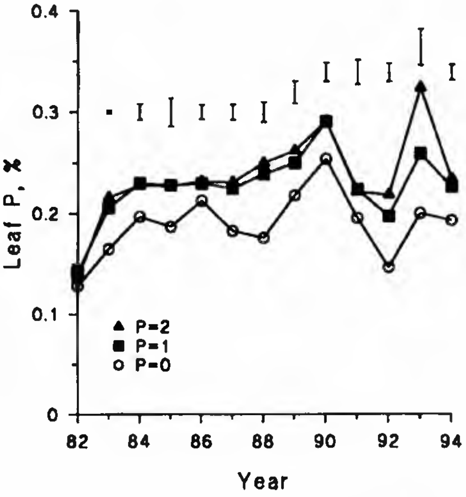


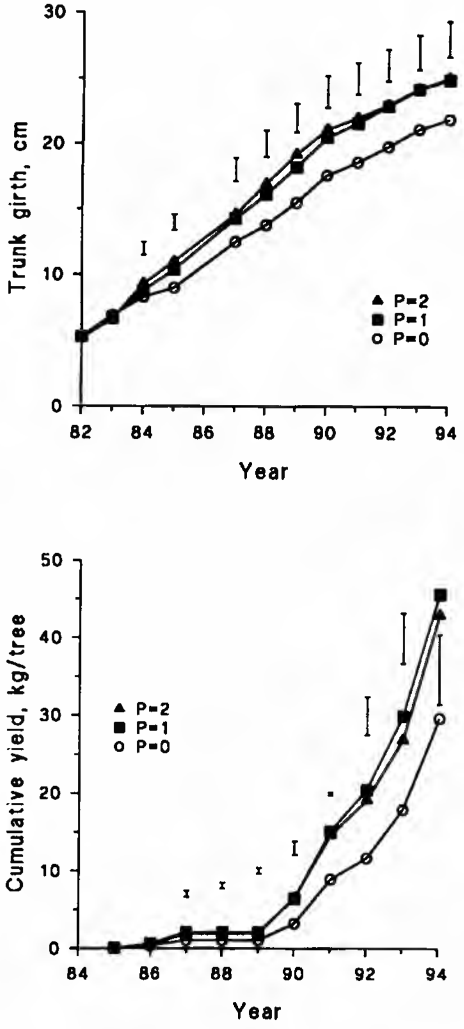
Fig. 2. Leaf P (per cent of leaf dry matter) as affected by phosphorus fertilization over 13 years. P0 = no P, P1 = 30 kg P ha^{-1}, P2 = 60 kg P ha^{-1} per years. Vertical bars represent LSD, P = 0.05

vigour as measured by trunk girth was increased by annual application of 30 kg P ha^{-1} (Fig. 3). No additional effect was obtained by doubling the rate of P fertilization.

Cumulative yield was positively affected by application of 30 kg P ha^{-1} per year (Fig. 4); however, increasing the P fertilization to 60 kg P ha^{-1} did not have any additional effect.

Calcium and magnesium

Liming the orchard floor with ground limestone and dolomitic limestone at rates 4000 and 8000 kg ha^{-1} at the start of the experiment affected exchangeable Ca and Mg strongly at different soil depths over the years (Figs 5 and 6). As indicated in Fig. 5, the maximum content of exchangeable Ca in the 0-5 cm soil layer was reached in the second year after application. Significant differences between control and rates of liming were maintained throughout the rest of the experimental period (11 years). The influence



Figs. 3 - 4. Effects of P fertilization on tree size as measured by trunk girth (cm) and cumulative yield (kg/tree) over the years. P0 = no P, P1 = 30 kg P ha^{-1}, P2 = 60 kg P ha^{-1} per year. Vertical bars represent LSD, P = 0.05

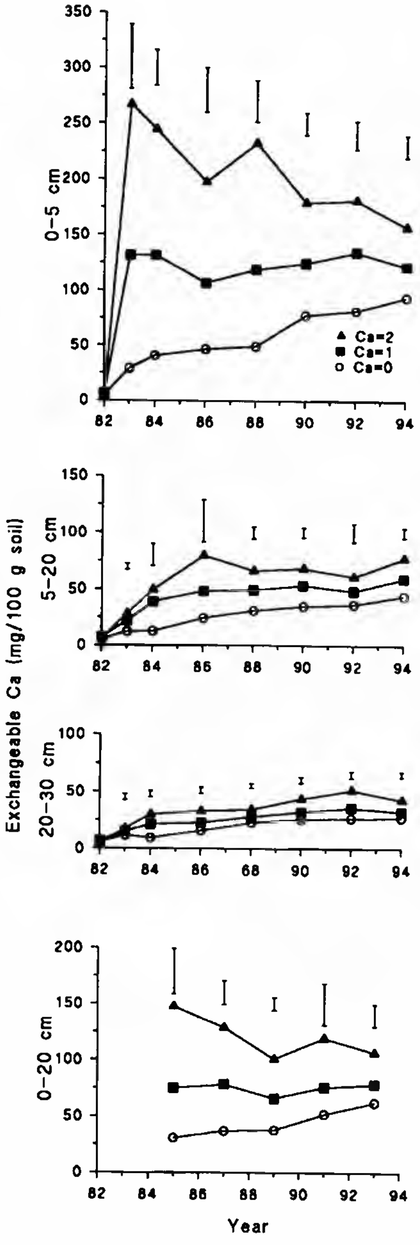


Fig. 5. Effects of ground limestone and dolomite on exchangeable Ca (mg/100 g soil) in different soil layers over 13 years. Ca0 = no lime, Ca1 = 2000 kg ground limestone + 2000 kg dolomitic limestone ha^{-1}, Ca2 = 6000 kg ground limestone + 2000 kg dolomitic limestone ha^{-1} applied at the start of the trial. Vertical bars represent LSD, P = 0.05

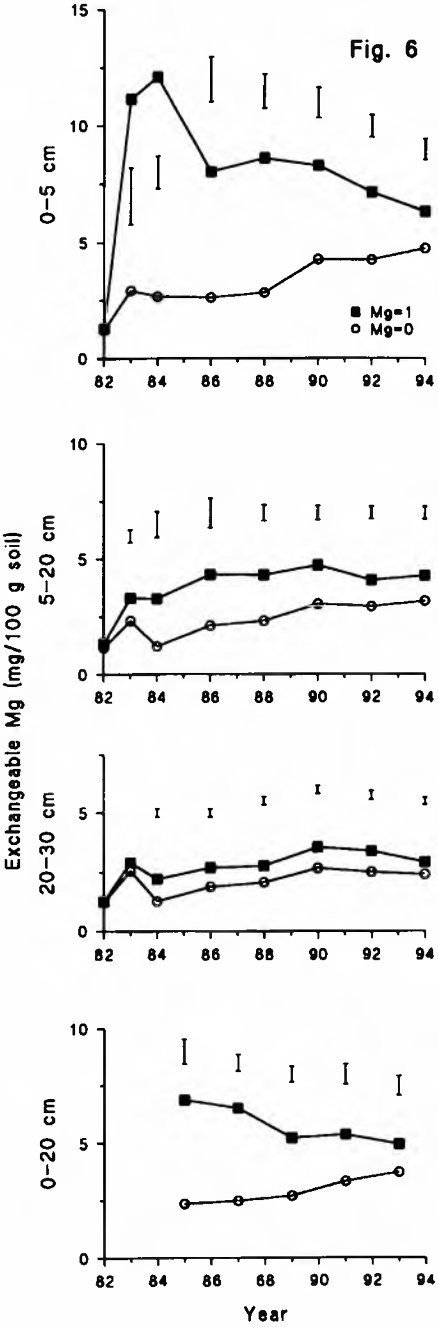


Fig. 6. Effects of ground dolomitic limestone on exchangeable Mg (mg/100 g soil) in different soil layers over 13 years. Mg0 = no Mg, Mg1 = 2000 kg dolomitic limestone ha^{-1} applied at the start of the trial. Vertical bars represent LSD, P = 0.05

of liming on the content of exchangeable Ca was apparent even in the deeper soil layer as early as the second year; three significant levels of exchangeable Ca were established over the years in accordance with the rates of liming material applied.

The application of 2000 kg ha^{-1} of dolomitic limestone established a significantly higher level of exchangeable Mg in different soil layers (Fig. 6). This effect lasted throughout the experimental period (11 years).

Liming effectively reduced soil acidity in the second year in the upper soil layers (0-5 cm, 5-20 cm) as shown in Fig. 7. In the 20-30 cm soil layer a significant effect of liming was established from the fifth year, and was maintained throughout the experimental period. The reduction in soil acidity found in the unlimed control plots can partly be accounted for by the annual use of calcium nitrate (19% Ca) as the source of nitrogen fertilizer.

Liming significantly affected the leaf Ca content (Fig. 8). The lower rate of liming (4000 kg Ca ha^{-1}) raised leaf Ca consistently to a level significantly higher than that of the control trees, while no additional effect of increasing the liming rate to 8000 kg Ca ha^{-1} was obtained.

Application of dolomitic limestone (2000 kg ha-1) significantly increased the leaf Mg of the 'Mallard' plum trees compared with that of the control trees in the second year and for the rest of the experimental period (Fig. 9).

Over the experimental period liming based on ground limestone and dolomitic limestone exerted a significant influence on tree vigour as measured by trunk girth (Fig. 10). The positive effect on vegetative growth was obtained by the lower rate of liming (4000 kg Ca ha^{-1}); no further increase in trunk girth by doubling the amount of liming material was found.

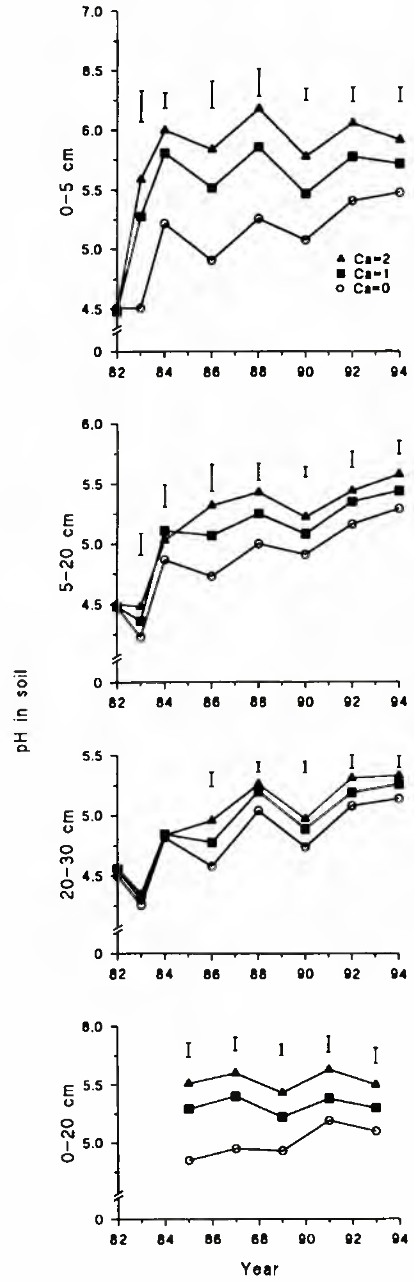
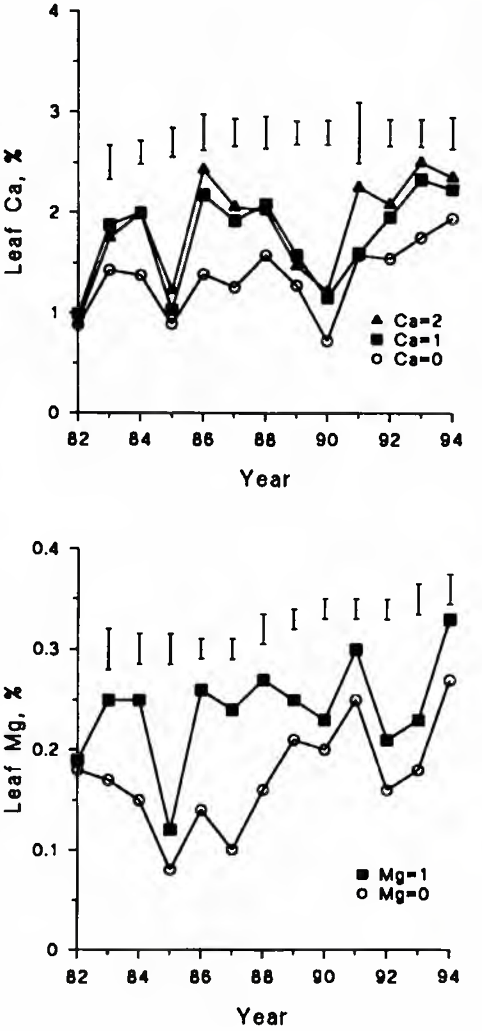
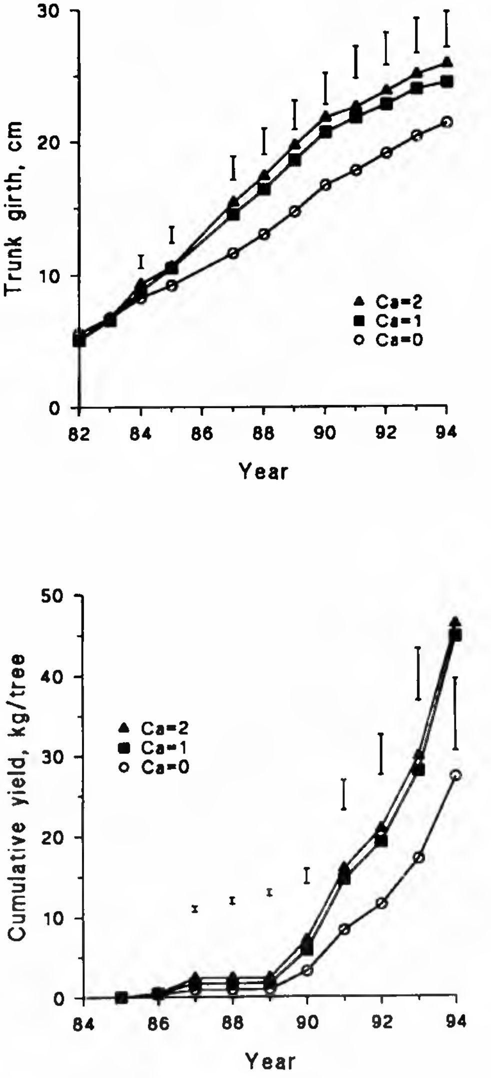


Fig. 7. The effect of liming on soil pH in different soil layers over 13 years. Ca0 = no lime, Ca1 = 2000 kg ground limestone + 2000 kg dolomitic limestone ha^{-1}, Ca2 = 6000 kg ground limestone + 2000 kg dolomitic limestone ha^{-1} applied at the start of the trial. Vertical bars represent LSD, P = 0.05



Figs. 8 - 9. Leaf Ca and leaf Mg as affected by liming over 13 years. Ca0 = no lime, Ca1 = 2000 kg ground limestone + 2000 kg dolomitic limestone ha^{-1}, Ca2 = 6000 kg ground limestone + 2000 kg dolomitic limestone ha^{-1}. Mg0 = No Mg, Mg1 = 2000 kg dolomitic limestone ha^{-1}. Vertical bars represent LSD, P = 0.05

Cumulative yield was significantly affected by liming (Fig. 11). No additional positive effect on yield was found by increasing the lime application from 4000 to 8000 kg Ca ha^{-1}.



Figs. 10 - 11. Effects of liming on tree size as measured by trunk girth (cm) and cumulative yield (kg/tree) over years. Ca0 = no lime, Ca1 = 2000 kg ground limestone + 2000 kg dolomitic limestone ha^{-1}, Ca2 = 6000 kg ground limestone + 2000 kg dolomitic limestone ha^{-1} applied at the start of the trial. Vertical bars represent LSD, P = 0.05

Potassium

Differential potassium fertilization affected exchangeable K in different soil layers over time (Fig. 12). The annual application of 80 and 160 kg K ha^{-1} increased exchangeable K substantially in all soil layers examined over time. No significant differences (with the exception of in one year) were found, however, between the differential rates of K applied. The differential K fertilization did not cause any significant difference in leaf K levels with the exception of in three out of 13 years (Fig. 13). A positive trend toward improving cumulative yield by the higher rate of K fertilization was not substantiated statistically (Fig. 14).

Discussion

Under normal orchard conditions it has generally been found that there is no response of phosphorus fertilization to plum trees (Lilleland 1932; Sandvad 1962; Johansson 1962; Benson et al. 1966). This is in contrast to the results obtained in this experiment. In a soil that can be characterized as phosphorus-deficient, containing only 1 mg plant available P/100 g soil, annual application of 30 kg P ha^{-1} resulted in an increase in the soil plant available P over the years to 4 mg P/100 g soil in the 0-20 cm layer (Fig. 1). This had a beneficial effect on the 'Mallard' plum trees; significantly improved vigour as indicated by trunk girth, higher yields, and yield efficency and improved fruit size were obtained. No additional effects were obtained on the performance of the plum trees by increasing the annual phosphorus application to 60 kg P ha^{-1}. On this background the leaf phosphorus data (Fig. 2) indicated that the optimal range of leaf P for plums should be adjusted to 0.20-0.30% P of dry matter. This is somewhat higher than the optimal range of 0.15-0.20% P recommended for plum trees in England (Greenham 1976) and is more in

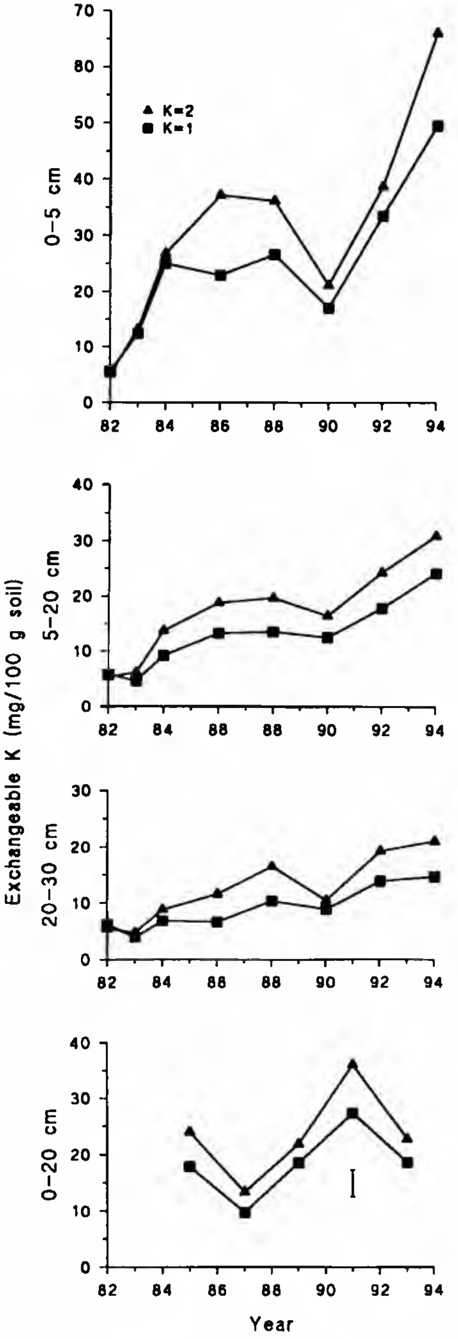
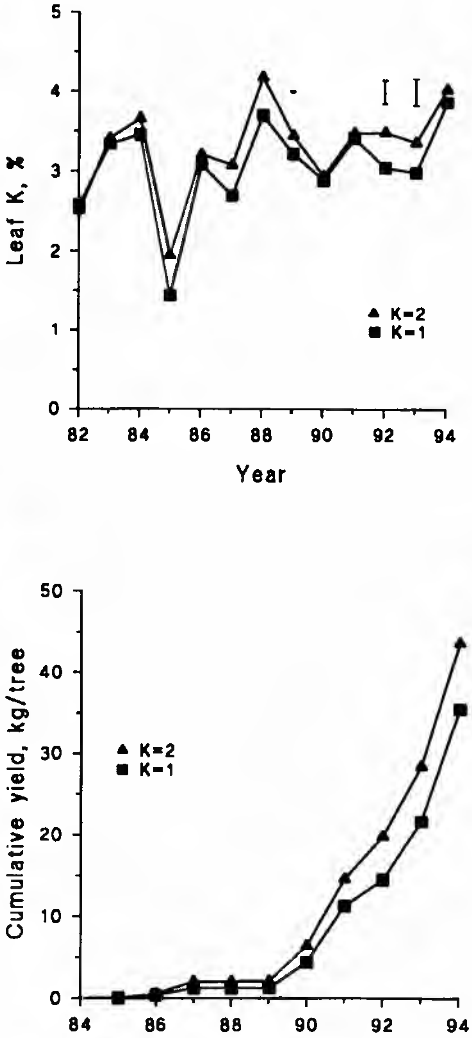


Fig. 12. Exchangeable K (mg/100 g soil) in different soil layers as affected by potassium fertilization over 13 years. K1 = 80 kg K ha^{-1}, K2 = 160 kg K ha^{-1} per year. Vertical bars represent LSD, P = 0.05



Figs. 13 - 14. Effects of potassium fertilization on leaf K (per cent of leaf dry matter) and cumulative yield (kg/tree) over years. K1 = 80 kg K ha^{-1}, K2 = 160 kg K ha^{-1} per year. Vertical bars represent LSD, P = 0.05

agreement with the American recommendation of 0.13-0.33% P for all fruit crops; stating that leaf samples from stone fruits are generally higher in P content than those from apples and pears (Stiles & Shaw Reid 1991). The optimal ranges of leaf P for plums recommended in

Scandinavia are 0.15-0.30% P (Vang-Petersen 1989) and 0.15-0.25% P (Ystaas 1981).

The positive effect of phosphorus on the tree vigour of plum trees was in agreement with the results obtained by Neilsen (1994) who used phosphorus fertilization to overcome replant disorders by improving establishment and early growth of young fruit trees. Östlind (1956), working with 'Oullins Gage' plum trees on a morainic soil low in plant available P in Sweden, found no effect of phosphorus fertilization on tree vigour, but reported an increase in yield by P application. The results were, however, not analysed statistically. Significantly positive responses of phosphorus fertilization to sweet cherries were recently reported by Ystaas & Frøynes (1995); 'Kristin' sweet cherry trees grown on a soil very low in P produced a significant increase in tree size, cumulative yield, yield efficiency and fruit size after P application.

Owing to the poor quality of the experimental trees, the onset of cropping was delayed by several years. In contrast to the very productive 'Opal' guard trees, the 'Mallard' experimental trees were shy croppers which was the reason for the low cumulative yield obtained in the experiment.

The unlimed control trees developed mineral deficiency symptoms (Fig. 15). These appeared every year throughout the experimental period. By comparing the scores of deficiency symptoms and the leaf Mg, Ca and P content (Table 2), it was evident that magnesium deficiency was the main cause of the inferior performance of the control trees. Application of 2000 kg ground dolomitic limestone ha^{-1} supplied the plum trees with sufficient magnesium to keep the leaf Mg content within the optimal ranges proposed by Greenham (1976): 0.20-0.25%, Ystaas (1981): 0.20-0.30%, and Vang-Petersen (1989): 0.20-0.40% Mg.

Fig. 15. Typical magnesium deficiency symptoms on 'Mallard' plum tree; "Christmas tree effect": the silhouette of a Christmas tree is seen on the leaf lamina

Although liming established three different levels of exchangeable Ca in the soil, the leaves of the 'Mallard' plum trees revealed only two significantly different levels of leaf Ca, both within the optimal ranges proposed by Ystaas (1981): 1.0-1.5%, Vang-Petersen (1989): 1.6-2.1%, and Stiles & Shaw Reid (1991): 1.3-2.0% Ca, which demonstrated that doubling the liming rate had no effect on the calcium content of the plum leaves.

The leaf potassium content (Fig. 13) indicated that the plum trees had a higher K uptake than was considered advisable. One possible reason for this may be the poor cropping performance, since opti-

Table 2. Mineral deficiency symptoms and leaf content of major nutrients in relation to liming; average figures of 13 years.

Liming material kg ha^{-1}	Deficiency symptoms, scores 1-9[1]	Per cent of leaf dry matter				
		N	P	K	Ca	Mg
0	5.0	2.39	0.22	3.28	1.36	0.17
4000	1.4	2.44	0.22	3.15	1.77	0.24
8000	1.2	2.41	0.22	3.09	1.87	0.24
LSD, P=0.05	1.0	NS	NS	0.15	0.13	0.01

[1] Observation of one year only (1991); scores of deficiency symptoms: 1 - green, healthy leaves, 5 = shoot and spur leaves yellow with marginal scorch; whole canopy affected, 9 = whole tree without healthy leaves. Scores for deficiency symptoms for the rest of the experimental period are missing, but the 1991 observation can be considered as representative for the whole period.

mum ranges are normally referring to trees with at least average crop loads. The optimal range of leaf K of plum trees as proposed by Greenham (1976) was 1.5-2.0%, while 2.0-2.5% and 2.2-2.8% K were put forward by Ystaas (1981) and Vang-Petersen (1989), respectively. The soil, initially low in exchangeable K, had a high potassium-supplying power (Ystaas & Frøynes 1995). In addition, the annual application of 80 and 160 kg K ha^{-1} evidently provided the plum trees with more potassium than was needed; a luxury consumption of potassium was indicated by the overoptimal leaf K content.

Conclusion

Liming and application of phosphorus to an acid, virgin soil resulted in positive effects of phosphorus and magnesium on young plum trees by increasing vigour, yield, yield efficiency and fruit size. Liming, partly by dolomitic limestone, was helpful in overcoming severe magnesium deficiency.

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Short-term efficiency and peak pH values of soft-burnt limes of dolomite and limestone in a silty loam

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Erstad, K.-J., E. Enge & A. Erstad 1995. Short-term efficiency and peak pH values of soft-burnt limes of dolomite and limestone in a silty loam. Norwegian Journal of Agricultural Sciences 9: 231-248. ISSN 0801-5341.

Burnt liming materials are widely used in Norway to combat clubroot disease (*Plasmodiophora brassicae* Wor.). A pot experiment on a barren soil was carried out in order to study the short-term efficiency of particle size classes and commercial products of burnt dolomite and burnt calcitic limestone on a chemical basis. The burnt-lime flash during the first week was marked for both limes, but generally a little stronger for the calcitic lime. The pH peaks were very distinct and regular in the soil for the finest particles <0.063 mm and 0.063-0.2 mm, and then the burnt dolomite was slightly superior. However, it was found that with increasing particle size, burnt limestone was the more favourable material. Coarse particles >2.0 mm demonstrated spotwise pH effects. With application of 0-3.15 mm graded commercial products, burnt dolomite was inferior compared with burnt limestone in the immediate short term, but more sustainable in the long term. It is recommended that burnt dolomite should be delivered in the 0-0.2 mm grading and burnt limestone in the 0-1 mm grading. Then both limes account for their total chemical contents, and a 14.3% reduction in burnt dolomite mass can be applied compared with burnt limestone.

Key words: Calcitic lime, dolomitic lime, fineness, liming materials, *Plasmodiophora brassicae* Wor., reactivity, rock carbonates, soft-burnt limes, soil incubation.

Abbreviations: ENV: Effective Neutralizing Value = Neutralizing Value * Dissolution in soil during a defined period

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The interest in agricultural burnt lime in the Nordic countries is partly related to improvement of the soil aggregation and the P retention in soil, but in Norway the main interest is in combatting clubroot disease (*Plasmodiophora brassicae* Wor.).

Burnt lime is not defined as a plant protection agent within the frames of legislation, but it is considered to be a valuable tool in preventing severe damage when there is likely to be very little crop rotation.

Among plant and soil scientists there are discussions on whether or not burnt lime has any advantage over ground limestone. Balvoll (1974, 1981, 1991) claimed that finely ground limestone was equally as good as burnt lime, because pH and Ca^{2+} (divalent cation) concentration in soil were most decisive for the effect. Too high a pH could also depress the yields.

Fletcher et al. (1982) tested up to 60 tons finely ground limestone * ha^{-1} during 3 years. pH was then stabilized at 8.0. $CaSO_4$ was also examined for this purpose, and it was found that even with no soil pH impact, it counteracted the clubroot disease.

Flønes (1988) raised the pH in a silty loam rich in organic matter from 5.4 to 7.2 and 7.9 by adding 20 tons CaO equivalents*ha^{-1} of finely ground limestone and burnt lime respectively. The latter was the more efficient in combatting the disease, which attacked different varieties of cabbages and swedes.

Boynton (1980), who described the importance of fineness for carbonate liming materials, gave few details of the particle size efficiency of burnt lime, only stating that this quicklime acts rapidly, like a fertilizer. In the USA, as in Europe, ground carbonates have replaced burnt limes to a large extent. In some regions, however, as in the eastern seaboard areas of the USA, soils are often deficient in magnesium, and this element is most efficiently restored with dolomitic lime.

In field experiments Singh & Singh (1984) tested the effectiveness of liming materials (calcite, dolomite, burnt lime and basic slag), their doses and fineness on yield and nutrient uptake by Frenchbean (*Phaseolus vulgaris* L.) in Uttar Pradesh. The yields increased with an increase in the fineness of all liming materials up to a particle size of 0.25-0.6 mm. Smaller particle sizes had no significant additional yield effects. Burnt lime was inferior to calcite applied in equivalent doses, which was attributed to its caustic and hygroscopic nature, causing the soil to deflocculate (peptization). The liming materials were most efficient in the order calcite > dolomite = burnt lime > basic slag, results in agreement with those reported by Chakraborty et al. (1961).

In industry burnt limes are sometimes converted to the hydroxide form (hydrated or slaked limes):

$CaO + H_2O \text{ ----> } Ca(OH)_2$ Burnt limestone

$CaO{*}MgO + 2H_2O \text{ ----> } Ca(OH)_2{*}\ Mg(OH)_2$ Burnt dolomite

In tests comparing four calcitic and four dolomitic liming materials in different chemical states and particle sizes at the rate of 2 tons*$acre^{-1}$ (5 tons*ha^{-1}), Gamble & Kenworthy (1961) found that dolomitic materials in the hydroxide form showed the greatest efficiency and remained more effective as acid neutralizers than carbonate materials after 3-5 years. At a 0-6 inch depth, 3 years after liming, hydrated dolomitic lime (98% <0.075 mm) yielded a pH level of 7.0, and hydrated calcitic lime (98%<0.045 mm) a pH level of 6.8. Dolomitic hydrate was recommended as a liming material and a magnesium source for orchards.

Erstad (1990) investigated the qualities of burnt limestones delivered to farmers in Lier (Buskerud county, Norway) in 1990. Some of the products delivered were accidentally hydrated before delivery, others were too coarse (up to 2-4 mm particles). These products were inferior with respect to an even soil pH increase and possible thermic effects, generating too little protection against the clubroot disease. It was recommended that burnt lime for this purpose should be finer than 1-2 mm.

Kawamura & Diamond (1975) studied in laboratory the stabilization of clay soils against erosion loss by adding small percentages of hydrated lime or Portland cement to the soils. The pH level of the saturated soil-lime solution was decisive. The flocculation process was highly pH-dependent. The untreated acid clay was in fact strongly acid flocculated, and increasing the pH level to the 8-10 range disaggregated the flocs. Exceeding this isoelectric point, a pH level of 11.5 was sufficient to give resistance to raindrop impact erosion. In order to establish mechanical strength for use in a highway subgrade, Eades & Grim (1966) concluded that pH 12.4 was necessary.

A commercially available product (0-3.15 mm) of burnt dolomite has already been produced for different customers in Norway and Sweden, mostly in industry. The producer wanted to know if this grading was satisfactory for farmers specializing in horticulture, who require a highly reactive burnt lime demonstrating the typicalflash during the first hours in the soil.

The effects of possible modifications in particle size distribution have to be verified, and burnt dolomite should be directly compared with competing burnt products of calcitic limestone. In this report we present the conclusions from experiments designed to deal with these questions.

Moreover, it was intended to develop a pH prediction model for PC.

Materials and methods

For this experiment, which was carried out at Fureneset in 1994, we received burnt dolomite in the particle sizes 0-3.15 mm and 0-6.3 mm, and burnt limestone in the particle size 0-6.3 mm.

Concerning the crude carbonate materials, the dolomite was delivered by Norwegian Holding/Hammerfall Dolomitt AS from Seljeli dolomite quarry, Elsfjord in Vefsn, Nordland county, and the limestone from Verdalskalk AS (Franzefoss Bruk AS), Hylla in Nord-Trøndelag county.

The calcination was performed at the kilns of Mo Industripark AS in Mo i Rana, Nordland county, the earlier Norsk Jernverk. In production, dolomite and limestone were alternately calcined. The qualities were checked daily as an internal routine control. In burnt limes, Ca and Mg contents were analysed by EDTA complexometric titration, and recalculated to oxide form. By multiplying the MgO figures by 1.4 and adding the amounts of CaO, the neutralizing value (NV) digits were calculated as the sum of CaO equivalents. Undissolved residues were determined gravimetrically after dissolution in conc. HCl:water 1:1 v/v. S and C were examined by means of a LECO apparatus, including a combustion method followed by infrared (IR) absorption. C was recalculated to CO_2. Reactivity was tested according to a pH-stat method (pH 7), developed as an internal laboratory procedure (SINTEF MoLab doc. no. 30101402). By stirring 50 g 2-10 mm burnt lime in 2 l H_2O (313 K - 40°C), 4N HCl was added, and consumption during 1, 5 and 10 min. recorded. Table 1 presents the chemical data, and shows good quality burnt limes, low in CO_2 residues and S, and highly reactive in mineral acids.

The 0-6.3 mm burnt limes were divided into particle size classes for fractionwise soil incubation, whereas the 0-3.15 mm burnt dolomite was tested as delivered. The particle size distribution, dry sieved at Fureneset, is presented in Table 2. In order to make a comparison, fractions of the burnt lime were also mixed to create a product of exactly the same particle size distribution.

Table 1. Chemical analyses of burnt liming materials analysed at SINTEF Molab (SM), 5th-6th weeks 1994, delivered for soil incubation tests.

Liming material	%CaO	%MgO	NV	%S	% undis-solved	$\%CO_2$ residual	Reactivity, ml 4N HCl 1 ---	Reactivity, ml 4N HCl 5 min.	Reactivity, ml 4N HCl 10 ---
Burnt dolomite 0-3.15 mm, j.no. SM D10/94	58.8	37.7	111.6	0.028	1.4	1.25	145	230	280
Burnt dolomite 0-6.3 mm, j.no. SM D11/94	58.6	37.7	111.4	0.019	1.1	1.86	125	200	235
Burnt limestone 0-6.3 mm, j.no. SM D12/94	96.0	1.2	97.7	0.012	0.4	1.59	230	380	420

Table 2. Particle size distribution of the 0-3.15 mm burnt dolomite as delivered, dry sieved at Fureneset

Particle size class (mm)	Distribution (in percent)
<0.063	2.8
0.063-0.2	23.6
0.2-0.4	48.6
0.4-0.6	8.5
0.6-0.8	2.6
0.8-1.0	2.1
1.0-1.4	3.1
1.4-1.6	1.3
1.6-2.0	2.8
2.0-3.15	4.5
3.15-6.3	0.1
>6.3	0

A loamy soil from Strømmen in Askvoll, Sunnfjord, was selected as a reference soil in the incubation method. This mineral soil was analysed mechanically using the pipette method, after oxidation of the organic material with H_2O_2, following the procedure by Elonen (1971). The results are presented in Table 3, together with the soil class name, in accordance with the classification of the Soil Survey of England and Wales (Hodgson 1974).

A set of soil characteristics was analysed. The soil density values were obtained following the procedure described by Bondorff (1950). Loss on ignition was measured at 823 K (550°C) for 12 h, and organic matter found by subtracting the hygroscopic water kept in the clay minerals of the soil, obtained from standard tables of correction. $pH(H_2O)$ was achieved from the ratio soil:distilled water 1:2.5 v/v.

Exchangeable cations H, Ca, Mg, K and Na were extracted using the NH_4OAc method pH 7.00, as described by Thomas (1982). The acidity was assessed by back titration to pH 7.00, and Ca, Mg, K and Na by atomic absorption spectrometry. The results together with the calculated base saturation are listed in Table 4.

The soil incubation method used with the above-mentioned reference soil is a laboratory method intended to resemble reactivity of liming materials under agricultural conditions. Because the experiment was conducted in the laboratory at a constant 293 K (20°C), the incub-

Table 3. Mechanical analysis (Elonen 1971) of the mineral material <2 mm of the soil used in the laboratory incubation experiment. Numbers in parentheses represent subdivisions for sand and silt fractions: Sand: (2-0.6 mm - 0.6-0.2 mm - 0.2-0.06 mm); Silt: (0.06-0.02 mm - 0.02-0.006 mm - 0.006-0.002 mm)

Soil	% sand	% silt	% clay	Soil class
Strømmen, *Askvoll*	11.3 (1.3-2.4-7.6)	73.2 (40.2-23.5-9.5)	15.5	Silty loam

Table 4. Chemical analyses of the soil used in the laboratory incubation experiments

Soil density kg*dm^{-3}	Loss on ignition %	Organic matter %	pH(H_2O)	EXCHANGEABLE CATIONS Ca^{2+}	Mg^{2+}	K$^+$	Na$^+$	H$^+$	Base saturation, %
				meq*100g^{-1}					
0.91	12.7	10.7	5.1	1.26	0.54	0.19	0.19	20.0	9.8

ation period was half of that in the field. (For a detailed description, see Erstad 1992). When working with burnt lime, the experiments deviated from the standard method with respect to elevated soil water saturation and sampling frequency. Dried soil and the liming materials to be tested were mixed and water added to a defined percentage of field capacity at free drainage. The percentage was increased from 70%, as prescribed by Erstad (1992), to 90% for mineral soils. This was done in order to simulate the conditions of irrigating vegetable fields in the first hours and days after burnt-lime application. At each sampling time 10 cm^{-3} soil was collected separately from each pot with a miniauger, mixed and stirred with 1:2.5 v/v distilled water. During the first 24 h of incubation, pH was measured within 15-30 min after soil-water stirring, for later measurements after standing overnight.

The 0-6.3 mm burnt liming materials were sieved and the following fractions were kept separate: <0.063, 0.063-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0 1.0-1.4, 1.4-1.6, 1.6-2.0, 2.0-3.15 and 3.15-6.3 mm. Dosages of limes were added to the soil fractionwise, and as delivered or mixed 0-3.15 mm sized products in the amounts 1,500-50,000 kg CaO equivalents*ha^{-1} (20 cm plough layer) in accordance with Table 5. The incubation was performed on a barren soil.

The treatments that included liming materials had two replicates, while the treatment without liming was replicated 18 times, subdivided and accompanied by smaller series of lime treatments. The pots were covered with a parafilm during the 24-week incubation period, and this was removed 5-7 days before each sampling when the intervals became longer. First, the samples were hastily taken out 1, 3, 6 and 24 h after soil-lime mixing, and then 1, 3, 6, 12 and 24 weeks after liming.

The equipment used for pH measurements was a METROHM 654 digital pH meter with separate electrodes.

Table 5. Levels of burnt liming materials as fractions and mixed products added to the soil, kg CaO equiv.*ha^{-1} (20 cm plough layer)

Levels (dosages)	kg CaO equiv.*ha^{-1}	Burnt dolomite 0-3.15 mm As delivered	Burnt dolomite 0-6.3 mm Fractions	Burnt limestone 0-6.3 mm Fractions	Burnt limestone 0-3.15 mm Mixed
0					
Ia	1,500	x			
I	3,000	x	x	x	
II	6,000	x	x	x	
III	9,000	x	x	x	
IV	12,000	x	x	x	
V	15,000	x			
VI	18,000	x			
VII	21,000	x			
VIII	24,000	x			x
IX	27,000	x			
X	30,000	x			
XI	40,000	x			
XII	50,000	x			x

The net pH increase effects (ΔpH) were calculated by subtracting the pH values of the zero treatment from those of the limedtreatments.

Owing to linearity between liming and pH in the range 4.5-6.5(7.0), conversion of pH increments on a kg CaO equivalent basis to masses of liming materials was performed. This was practical for commercial use.

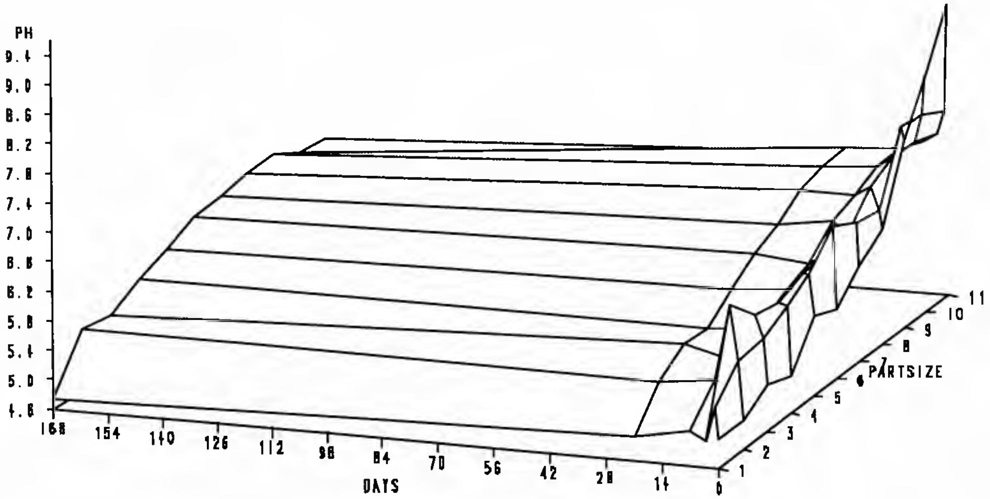
Calculations above pH 7.0 had to be made with the utmost care. The figures for 24 weeks were equivalent to ENV 1 year, in accordance with Erstad (1992), when multiplying by results from NV analyses. In addition, relative peak values during the first hours and days for burnt dolomite and burnt limestone respectively were also established. This was done relating their efficiency to pH increase.

All analyses of variance were effected using the Statistical Analysis System (SAS), Release 6.03 (SAS INSTITUTE 1985, 1987a & 1988). The analytical procedure PROC ANOVA was applied when data sets were even, and, if not, then the PROC GLM procedure was applied. The means of the variables (treatments) were compared using the Ryan-Einot-Gabriel-Welsch Multiple F Test (REGWF) at the 5% level (type I experimentwise error rate). Means with same letter indicated no significant difference.

All graphs were produced by the means of the SAS Graph (SAS INSTITUTE 1987b) and the procedures applied were PROC G3GRID and PROC GPLOT.

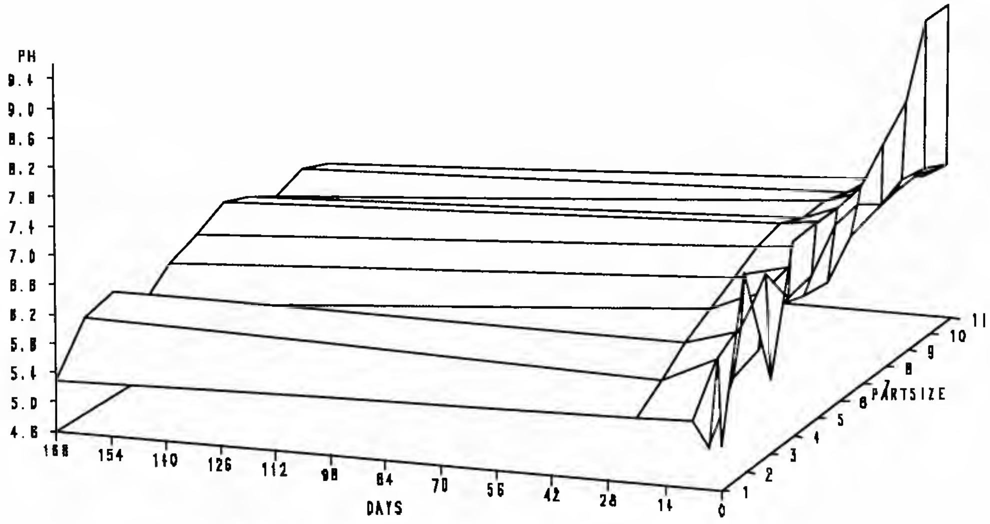
Results and discussion

Figures 1-2 present the effects on soil reaction of burnt dolomite and burnt limestone during 24 weeks, when adding dosages of 6,000 kg CaO equivalents * ha^{-1}, which show a very representative pH



Partsize 1=3.15–6.3 mm, 2=2.0–3.15 mm, 3=1.6–2.0 mm, 4=1.4–1.6 mm, 5=1.0–1.4 mm, 6=0.8–1.0 mm, 7=0.6–0.8 mm, 8=0.4–0.6 mm, 9=0.2–0.4 mm, 10=0.063–0.2 mm, 11=<0.063 mm.

*Fig. 1. Soil pH values of particle size classes of burnt dolomite during 24 weeks (168 days). 6,000 kg CaO equiv.*ha^{-1} added to a silty loam from Askvoll, Norway.*



Partsize 1=3.15–6.3 mm, 2=2.0–3.15 mm, 3=1.6–2.0 mm, 4=1.4–1.6 mm, 5=1.0–1.4 mm, 6=0.8–1.0 mm, 7=0.6–0.8 mm, 8=0.4–0.6 mm, 9=0.2–0.4 mm, 10=0.063–0.2 mm, 11=<0.063 mm.

Fig. 2. Soil pH values of particle size classes of burnt limestone during 24 weeks (168 days). 6,000 kg CaO equiv. ha^{-1} added to a silty loam from Askvoll, Norway*

development.

Burnt dolomite showed slightly lower pH peaks compared with burnt limestone when the lime supplies were increased. On the other hand, concerning the extreme pH range, burnt dolomite demonstrated a much more sustained pH course (up to 3 days), whilst burnt limestone exhibited a marked reduction in pH within a few hours to 1 day. Burnt dolomite was more sustainable in the long run, too.

Table 6 presents the analyses of variance for the soil pH effects when adding burnt limes on a chemical equivalent basis. For all particle size classes, burnt limestone was superior to burnt dolomite on a chemical basis, the differences decreased with incubation time. For particle size classes, there were no significant differences between the lime materials for particles <0.4 mm, whilst medium and coarser particles of burnt limestone raised the soil pH more efficiently than burnt dolomite. For coarser particle sizes (>2.0 mm) the burnt-lime effect was very uneven and casual, yielding spotwise pH effects in the soil. Considering the effects of lime incre-

Table 6. Analyses of variance for soil pH effects when adding burnt dolomite and burnt limestone on chemical equivalent basis, divided into main effects (types of lime) and effects by incubation time, fractions and lime increments.

Source of variation	DF tot.	MS	F value	Model Pr>F	C.V. %
Overall model	1551	237.52	254.72	0.001	15.0
Effects by incubation time					
1 hour	193	53.24	29.59	0.001	19.9
3 hours	193	40.38	37.54	0.001	15.7
6 hours	193	46.05	44.10	0.001	15.2
24 hours	193	26.62	33.36	0.001	14.1
3 days	193	24.81	39.97	0.001	12.2
1 week	193	21.00	37.76	0.001	11.7
3 weeks	193	21.75	43.23	0.001	11.3
24 weeks	193	20.17	53.20	0.001	10.4
Effects by fractions					
<0.063 mm	127	0.06	0.06	0.813	13.5
0.063-0.2 mm	127	0.20	0.21	0.651	13.2
0.2-0.4 mm	127	0.72	0.97	0.325	11.9
0.4-0.6 mm	127	3.47	5.74	0.018	11.3
0.6-0.8 mm	127	5.38	9.60	0.002	11.1
0.8-1.0 mm	127	7.74	12.94	0.001	11.7
1.0-1.4 mm	127	12.67	20.52	0.001	12.1
1.4-1.6 mm	127	13.24	17.05	0.001	13.8
1.6-2.0 mm	127	16.32	22.42	0.001	13.7
2.0-3.15 mm	127	12.95	17.09	0.001	14.5
3.15-5.0 mm	127	10.93	14.93	0.001	15.3
Effects by lime increments					
3,000 kg CaO equiv.	351	3.89	13.73	0.001	9.3
6,000 kg CaO equiv.	351	17.09	26.41	0.001	12.5
9,000 kg CaO equiv.	351	29.25	34.39	0.001	13.2
12,000 kg CaO equiv.	351	18.17	23.31	0.001	12.0

ments, the largest pH gap between burnt limestone and burnt dolomite was found at 9,000 kg CaO equivalents*ha^{-1}. Burnt limestone approached its soil pH equilibrium resulting from hydroxide saturation at a higher pH level than burnt dolomite.

Interactions between parameters that raised soil pH were tested by analyses of variance. Most interactions were significant, with the exception of incubation time*fractions, the three-factor interactions lime * incubation time * fractions, lime increments * incubation time * fractions, and, ultimately, the four-factor interaction.

In order to adapt the results for a prediction model, non-significant interactions were dropped, yielding the variance data in Table 7.

The resulting prediction model was:

Soil pH = μ+ **a**(lime) + **b**(incubation time) + **c**(fraction) + **d***lime increment + lime increment * [**e**(lime) + **f**(fraction) + **g**(incubation time) + **h**(lime*fraction) + **i**(lime*incubation time)]

The constants **a-i** are related to class variables in parentheses. Lime increment is a continuous variable in the range 0-12,000 kg CaO equivalents*ha^{-1}.

Table 8 presents the complete list of constants for calculations of predicted soil pH values. These data are based on this tested silty loam, but could, by straight conversion, be considered as relative figures of lime efficiency, because a standard reference soil is applied.

The model was used to develop a PC program in Turbo Pascal, readily adapted for DOS, but requiring a mathematical co-processor. This program is available from the authors.

The program enabled us to predict pH levels in soil of burnt limes of different particle size distributions during 24 weeks. The predicted pH values are valid only for this reference soil, but simultaneously they presented lime efficiency relative to the finest grading. Furthermore, the program was used to compare measured values, as presented in a subsequent section, with the predicted ones. The program will soon be extended to cover ENV calculations for the burnt limes in the period 1 h-24 weeks.

Table 7. Analyses of variance for an overall interaction test of experimental parameters raising soil pH levels when adding burnt dolomite and burnt limestone on chemical equivalent basis. Non-significant interactions deleted. Lime increments=kg CaOequ. R^2(model)=0.823

Source of variation	DF total	MS	F value	Model Pr>F
Lime	1	2.43	11.10	0.001
Incubation time	7	0.88	4.03	0.001
Fractions	10	3.12	14.26	0.001
KgCaOequiv	1	526.88	2409.85	0.001
KgCaOequiv*Lime	1	3.32	15.17	0.001
KgCaOequiv*Fractions	10	1.30	5.94	0.001
KgCaOequiv*Incubation time	7	1.58	7.24	0.001
KgCaOequiv*Lime*Fractions	10	2.35	10.73	0.001
KgCaOequiv*Lime*Incubation	7	4.68	21.39	0.001

Table 8. Constants for the soil pH prediction model when adding burnt dolomite and burnt lime, depending on lime, particle size distribution and incubation time. Lime increments in the range 0-12,000 kg CaO equiv.$*ha^{-1}$

Parameter	Variable	Constant estimate	T for H0	Pr>F	Standard error estimate
Intercept	**μ**	**5.01**	67.24	0.001	0.075
Lime	**a**				
	Zero treatment	**0**	-	-	-
	Dolomite	**0.890**	7.90	0.001	0.113
	Limestone	**1.094**	9.70	0.001	0.113
Incubation time	**b**				
	1 hour	**-0.123**	-1.28	0.200	0.096
	3 hours	**-0.125**	-1.30	0.195	0.096
	6 hours	**0**	-	-	-
	24 hours	**-0.115**	-1.19	0.23	0.096
	3 days	**-0.146**	-1.52	0.130	0.096
	1 week	**-0.121**	-1.25	0.210	0.096
	3 weeks	**-0.265**	-2.75	0.006	0.096
	24 weeks	**-0.457**	-4.75	0.001	0.096
Fraction	**c**				
	Zero treatment	**0**	-	-	-
	<0.063 mm	**0**	-	-	-
	0.063-0.2 mm	**-0.0124**	-0.09	0.931	0.143
	0.2-0.4 mm	**-0.200**	-1.40	0.162	0.143
	0.4-0.6 mm	**-0.430**	-3.01	0.003	0.143
	0.6-0.8 mm	**-0.546**	-3.81	0.001	0.143
	0.8-1.0 mm	**-0.670**	-4.68	0.001	0.143
	1.0-1.4 mm	**-0.735**	-5.13	0.001	0.143
	1.4-1.6 mm	**-0.924**	-6.45	0.001	0.143
	1.6-2.0 mm	**-0.938**	-6.55	0.001	0.143
	2.0-3.15 mm	**-0.824**	-5.75	0.001	0.143
	3.15-5.0 mm	**-1.125**	-7.86	0.001	0.143
Lime increment * **d**	**d**	**0.000219**	13.31	0.001	0.0000165
Lime increment * lime	**e**				
	Dolomite	**-0.0000072**	-0.49	0.621	0.0000146
	Limestone	**0**	-	-	-
Lime increment * fraction	**f**				
	<0.063 mm	**0**	-	-	-
	0.063-0.2 mm	**0.0000170**	0.91	0.365	0.0000188
	0.2-0.4 mm	**0.0000200**	1.06	0.289	0.0000188
	0.4-0.6 mm	**0.0000180**	0.96	0.338	0.0000188
	0.6-0.8 mm	**0.0000177**	0.94	0.348	0.0000188

Table 8. cont.

Parameter	Variable	Constant estimate	T for H0	Pr>F	Standard error estimate
	0.8-1.0 mm	**0.0000254**	1.35	0.177	0.0000188
	1.0-1.4 mm	**0.0000266**	1.41	0.158	0.0000188
	1.4-1.6 mm	**0.0000381**	2.02	0.043	0.0000188
	1.6-2.0 mm	**0.0000231**	1.23	0.220	0.0000188
	2.0-3.15 mm	**-0.0000203**	-1.08	0.281	0.0000188
	3.15-5.0 mm	**-0.0000403**	-2.14	0.033	0.0000188
Lime increment* incubation time	*g*				
	1 hour	**0.0000300**	2.19	0.029	0.0000137
	3 hours	**0.0000051**	0.37	0.711	0.0000137
	6 hours	**0**	-	-	-
	24 hours	**-0.0000346**	-2.53	0.012	0.0000137
	3 days	**-0.0000505**	-3.69	0.001	0.0000137
	1 week	**-0.0000651**	-4.76	0.001	0.0000137
	3 weeks	**-0.0000634**	-4.63	0.001	0.0000137
	24 weeks	**-0.0000898**	-6.55	0.001	0.0000137
Lime increment* lime * fraction	**h**				
	IF DOLOMITE				
	<0.063 mm	**0**	-	-	-
	0.063-0.2 mm	**-0.0000131**	-0.92	0.356	0.0000142
	0.2-0.4 mm	**-0.0000219**	-1.54	0.124	0.0000142
	0.4-0.6 mm	**-0.0000429**	-3.02	0.003	0.0000142
	0.6-0.8 mm	**-0.0000485**	-3.41	0.001	0.0000142
	0.8-1.0 mm	**-0.0000610**	-4.28	0.001	0.0000142
	1.0-1.4 mm	**-0.0000796**	-5.59	0.001	0.0000142
	1.4-1.6 mm	**-0.0000825**	-5.80	0.001	0.0000142
	1.6-2.0 mm	**-0.0000882**	-6.20	0.001	0.0000142
	2.0-3.15 mm	**-0.0000960**	-6.75	0.001	0.0000142
	3.15-5.0 mm	**-0.0000802**	-5.63	0.001	0.0000142
	IF LIMESTONE	**0**	-	-	-
Lime increment* lime * incubation time	**i**				
	IF DOLOMITE				
	1 hour	**-0.0000244**	-2.01	0.045	0.0000121
	3 hours	**-0.0000128**	-1.05	0.292	0.0000121
	6 hours	**0**	-	-	-
	24 hours	**0.0000580**	6.11	0.001	0.0000121
	3 days	**0.0000571**	4.71	0.001	0.0000121
	1 week	**0.0000509**	4.19	0.001	0.0000121
	3 weeks	**0.0000695**	5.73	0.001	0.0000121
	24 weeks	**0.0000742**	6.11	0.001	0.0000121
	IF LIMESTONE	**0**	-	-	-

Table 9 provides data of relative dissolution efficiency of particle sizes of the burnt limes during 24 weeks. Some very slight interpolations were performed in order to smooth extreme peaks of burnt-lime flash.

Table 10 presents *modified* ENV *figures* for the lime products, i.e. modified in the sense of a shortened soil incubation time. Normally ENV is presented in correspondence with 1 and 5 years in the field. The ENV figures were established by simply multiplying their CaO equivalent contents by the relative dissolution figures.

These results proved that the burnt dolomite was equally as efficient as the burnt limestone with respect to the finest particles, whereas burnt limestone was superior in the intermediate and coarse particle size range. With respect to the ENV figures, the burnt dolomite obviously could profit from its substantially higher content of CaO equivalents.

Figures 3A and 3B demonstrate the pH-enhancing effects of the 0-3.15 mm lime products, including very high lime dosages. Mainly dolomite treatments were involved, but a few limestone treatments were also included (24,000 and

Table 9. Relative dissolution efficiency of particle sizes of burnt limes of dolomite and limestone during 24 weeks in the reference silty loam. 100 = dissolution of limestone <0.063 mm

BURNT DOLOMITE

	1 hour	3 hours	6 hours	24 hours	3 days	1 week	3 weeks	24 weeks
<0.063 mm	87	100	100	100	100	100	100	100
0.063-0.2 mm	80	96	97	100	100	100	100	100
0.2-0.4 mm	64	78	85	100	100	100	100	100
0.4-0.6 mm	42	56	75	83	85	88	95	100
0.6-0.8 mm	38	48	63	75	77	78	86	98
0.8-1.0 mm	32	40	52	65	71	74	80	93
1.0-1.4 mm	32	36	42	59	66	67	68	80
1.4-1.6 mm	32	34	37	59	60	60	60	74
1.6-2.0 mm	23	25	36	39	42	46	54	65
2.0-3.15 mm	13	17	28	29	35	43	46	57
3.15-5.0 mm	7	16	18	19	24	33	36	45

BURNT LIMESTONE

	1 hour	3 hours	6 hours	24 hours	3 days	1 week	3 weeks	24 weeks
<0.063 mm	100	100	100	100	100	100	100	100
0.063-0.2 mm	99	100	100	100	100	100	100	100
0.2-0.4 mm	83	90	96	96	98	100	100	100
0.4-0.6 mm	67	79	84	89	90	92	97	100
0.6-0.8 mm	59	76	79	86	88	90	96	100
0.8-1.0 mm	59	71	75	81	84	86	93	97
1.0-1.4 mm	57	69	73	78	84	85	86	86
1.4-1.6 mm	52	65	68	73	80	80	81	86
1.6-2.0 mm	46	56	64	73	77	79	79	85
2.0-3.15 mm	46	48	49	50	55	67	67	69
3.15-5.0 mm	22	46	46	46	46	49	49	50

Table 10. *Modified ENV figures* of burnt limes of dolomite and limestone during 24 weeks in the reference silty loam.

BURNT DOLOMITE

	1 hour	3 hours	6 hours	24 hours	3 days	1 week	3 weeks	24 weeks
<0.063 mm	97	112	112	112	112	112	112	112
0.063-0.2 mm	89	107	108	112	112	112	112	112
0.2-0.4 mm	71	87	95	112	112	112	112	112
0.4-0.6 mm	47	62	84	93	95	98	106	112
0.6-0.8 mm	42	54	70	84	86	87	96	109
0.8-1.0 mm	36	45	58	72	79	83	89	104
1.0-1.4 mm	36	40	47	66	74	75	76	89
1.4-1.6 mm	36	38	41	66	67	67	67	83
1.6-2.0 mm	26	28	40	43	47	51	60	72
2.0-3.15 mm	14	19	31	32	39	48	51	64
3.15-5.0 mm	8	18	20	21	27	37	40	50

BURNT LIMESTONE

	1 hour	3 hours	6 hours	24 hours	3 days	1 week	3 weeks	24 weeks
<0.063 mm	98	98	98	98	98	98	98	98
0.063-0.2 mm	97	98	98	98	98	98	98	98
0.2-0.4 mm	81	88	94	94	96	98	98	98
0.4-0.6 mm	65	77	82	87	88	90	95	98
0.6-0.8 mm	58	74	77	84	86	88	94	98
0.8-1.0 mm	58	69	73	79	82	84	91	95
1.0-1.4 mm	56	67	71	76	82	83	84	84
1.4-1.6 mm	51	64	66	71	78	78	79	84
1.6-2.0 mm	45	55	63	71	75	77	77	83
2.0-3.15 mm	45	47	48	49	54	65	65	67
3.15-5.0 mm	21	45	45	45	45	48	48	49

50,000 kg CaO equivalents*ha^{-1}). As known from the original carbonate products (Boynton 1980), the calcium-magnesium oxide exhibited an incipient soil saturation and pH levelling surpassing to some extent that of the pure calcium oxide. By increasing the lime doses, the pH graphs of the two lime products run apart. At extremely high lime doses to this soil, 50,000 kg CaO equivalents*ha^{-1}, a pH level of 12.4 could be reached with burnt limestone, whilst pH 10.5-10.8 would be the level of burnt dolomite reached during the first hours. The pH differences diminished with time, as can be observed from Figures 3A and 3B and Table 11. The lime products were gradually recarbonatized and approached soil carbonate equilibria.

Table 11 presents the analyses of variance for the soil pH effects of these 0-3.15 mm graded lime products, first testing the main effects and then subdividing into incubation time and two high lime increments.

Despite its initial lower reactivity,

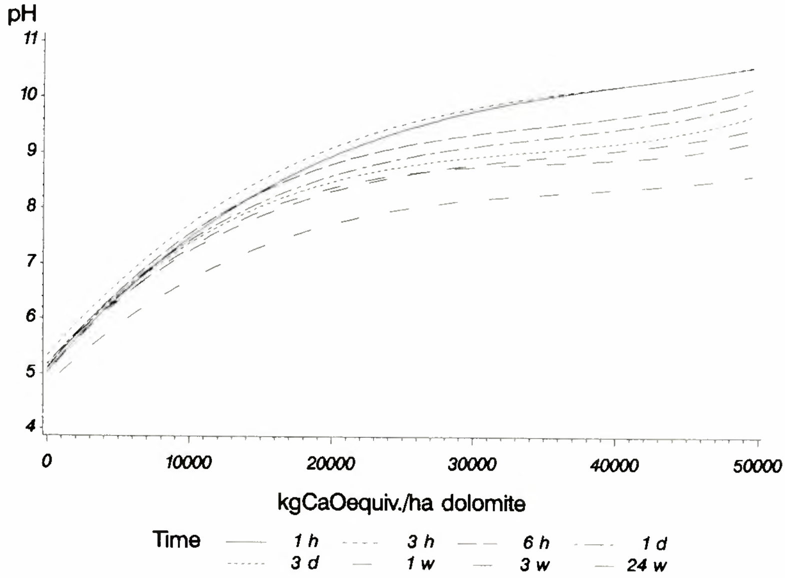


Fig. 3A. Burnt dolomite

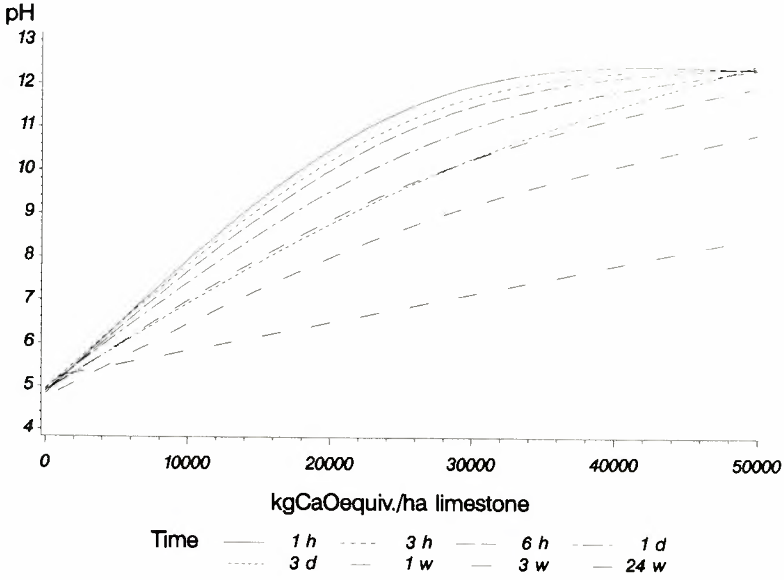


Fig. 3B. Burnt limestone

*Fig. 3. Soil pH values of 0-3.15 mm products of burnt dolomite and burnt limestone during 24 weeks. 1,500-50,000 kg CaO equiv.*ha^{-1} added to a silty loam from Askvoll, Norway.Note different scales on the pH axis.*

Table 11. Analyses of variance for soil pH effects when adding 0-3.15 mm products of burnt dolomite and burnt limestone on chemical equivalent basis, divided into main effects (types of lime) and effects by incubation time and lime increments

Source of variation	DF tot.	MS	F value	Model Pr>F	C.V. %
24,000 kg CaO equiv.*ha^{-1}					
Overall model	31	9.54	11.89	0.002	9.7
50,000 kg CaO equiv.*ha^{-1}					
Overall model	31	27.32	19.39	0.001	11.2
Effects by incubation time					
24,000 kg CaO equiv.*ha^{-1}					
1 hour	3	3.22	20.31	0.046	3.9
3 hours	3	3.49	52.45	0.019	2.6
6 hours	3	3.89	38.19	0.025	3.3
24 hours	3	2.11	58.80	0.017	2.0
3 days	3	0.51	13.12	0.069	2.2
1 week	3	1.05	2.17	0.279	7.8
3 weeks	3	0.002	0.06	0.836	2.5
24 weeks	3	0.002	1.09	0.406	0.5
50,000 kg CaO equiv.*ha^{-1}					
1 hour	3	3.20	12.35	0.072	4.4
3 hours	3	3.87	22.41	0.042	3.7
6 hours	3	5.38	40.24	0.024	3.3
24 hours	3	5.93	33.25	0.029	3.8
3 days	3	7.61	71.94	0.014	2.9
1 week	3	6.28	115.38	0.009	2.2
3 weeks	3	2.78	29.55	0.032	3.1
24 weeks	3	0.43	20.69	0.045	1.8

burnt dolomite was more sustained in maintaining pH levels than burnt limestone. At 1-3 weeks of incubation there were no significant differences between the studied 0-3.15 mm lime products of dolomite and limestone at a dose of 24,000 kg CaO equivalents*ha^{-1}. Adding 50,000 kg CaO equivalents*ha^{-1} burnt dolomite was found to be superior after 24 weeks of incubation. The statistical analyses revealed that the coefficient of variation was very low.

The model developed was used to compare measured pH values and predicted ones up to lime increments of 12,000 kg CaO equivalents*ha^{-1}.

Table 12 presents data for 0-3.15 mm burnt dolomite from this experiment. The model fitted quite well, with only a few apparent deviations from the experimental results for the commercially available products. The peak values were observed after 3 hours of incubation, whereas the model predicted 6-24 h. This was probably due to some suppression of the intermediate-sized fractions when mixed with the finest particles. On the other, this effect could presumably delay

Table 12. Measured pH values of 0-3.15 mm burnt dolomite and predicted pH figures by the model for burnt lime efficiency. Predicted figures in italic fonts. The silty loam from Askvoll, Norway, as a standard reference soil

kg CaO equiv.* ha^{-1}	1 hour	3 hours	6 hours	24 hours	3 days	1 week	3 weeks	24 weeks
0	4.776	5.029	4.898	4.982	4.880	4.835	4.747	4.598
	4.867	4.841	4.856	4.914	4.915	4.920	4.720	4.561
1,500	5.500	5.603	5.495	5.595	5.580	5.707	5.573	5.162
	5.472	5.533	5.495	5.539	5.552	5.744	5.534	5.118
	5.82	*5.80*	*5.93*	*5.85*	*5.80*	*5.79*	*5.68*	*5.45*
3,000	6.047	6.553	6.084	6.186	6.223	6.081	5.934	5.723
	5.983	6.497	6.152	6.168	6.176	6.102	6.089	5.679
	6.13	*6.08*	*6.23*	*6.19*	*6.11*	*6.07*	*5.99*	*5.73*
6,000	6.674	7.143	6.786	6.680	6.698	6.570	6.632	6.063
	6.999	7.328	6.949	6.939	6.797	6.617	6.708	6.245
	6.74	*6.66*	*6.83*	*6.85*	*6.72*	*6.62*	*6.60*	*6.28*
9,000	7.184	7.585	7.294	7.171	7.066	6.980	6.997	6.546
	7.548	7.781	7.581	7.314	7.153	7.368	7.110	6.733
	7.35	*7.28*	*7.42*	*7.52*	*7.34*	*7.18*	*7.21*	*6.83*
12,000	7.663	7.936	7.926	7.634	7.476	7.466	7.636	6.933
	7.898	8.375	8.110	8.006	7.593	7.508	7.693	6.993
	7.96	*7.80*	*8.02*	*8.19*	*7.95*	*7.73*	*7.83*	*7.38*

the pH decline at the end of the incubation period (24 weeks). A certain overestimation was also predicted for lime increments below 3,000 kg CaO equivalents*ha^{-1}, the fractionwise start level.

A more extensive report on this project can be found in Erstad et al. (1995).

Conclusions

The burnt-lime flash was distinct for both lime products, but a little sharper for burnt limestone than for the burnt dolomite. The pH peaks were particularly strong and equally distributed in the soil when fine particles were applied, i.e. <0.063 mm and 0.063-0.2 mm. By increasing particle sizes, burnt limestone was more efficient than burnt dolomite. For coarser particle sizes (>2.0 mm), the burnt-lime effect was very uneven and casual, yielding random pH effects in soil. The burnt lime particles are in general exposed to gradual recarbonatization, due to chemical instability.

By application of 0-3.15 mm graded commercial products burnt dolomite was inferior in the immediate short term. At extreme levels of 24,000 and 50,000 kg CaO equivalents*ha^{-1} soil pH at an incubation of one hour was 9.5-10.6 for burnt dolomite and 11.3-12.3 for burnt limestone respectively. The differences diminished with time, but burnt limestone still showed the highest reactivity for coarser particles.

It is recommended that burnt dolomite should be delivered as a 0-0.2 mm powder for horticultural use. It would then be highly reactive and account for its entire chemical contents (112% CaO equivalents). Compared with burnt limestone, the amounts applied could be reduced by 14,3% on the basis of mass commercial products.

The burnt-lime flash is expected to last for at least 3 days, and, despite irrigation following lime mixing into the soil, the farmer should wait for at least these 3 days before planting in order to avoid damaged root tips of *Brassica* spp.

Burnt dolomite is a concentrated magnesium source (22.7% Mg). To the best of our knowledge from soil and plant fertility management in this part of the world, we have not experienced any danger of overdosing with the readily displaced Mg^{2+} ion. On the other hand, it sometimes happens that long-term use of burnt limestone can implement Mg deficiency. For burnt limestone it is recommended that finer gradings than those previously used in horticulture should be used. A particle size range of 0-1 mm, maximum 0-2 mm, is advised.

Acknowledgements

The producer of the burnt dolomite, Hammerfall Dolomitt AS, situated in Sørfold in Nordland county, a company in Norwegian Holding AS, Bergen, is thanked for practical and financial support of this research work. The assistance given by technical assistant Asmund Hovland, Særheim Agricultural Research Station, Division Fureneset, who carefully managed the conditions for the experiment, is greatly appreciated. We also thank Ådne Håland for comments and adjustments to this article.

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The influence of ozone pollution on growth of young plants of *Betula pubescens* Ehrh. and *Phleum alpinum* L. Dose-response relations

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Mortensen, L.M. 1995. The influence of ozone pollution on growth of young plants of *Betula pubescens* Ehrh. and *Phleum alpinum* L. Dose-response relations. Norwegian Journal of Agricultural Sciences 9: 249-262. ISSN 0801-5341.

Seedlings of *Betula pubescens* Ehrh. and *Phleum alpinum* L. were grown in six growth chambers in a greenhouse for 6 weeks, during which time the plants were exposed to 60 or 80 nmol mol^{-1} O_3 for 0, 1, 2, 3, 4, 5 or 6 weeks. The different O_3 exposures (up to 6 weeks) at 60 nmol mol^{-1} O_3 did not significantly affect the shoot dry weight, leaf:stem dry weight ratio or plant height of *Betula pubescens*; however, the 80 nmol mol^{-1} O_3 exposures decreased the dry weight and height, and increased the leaf:stem ratio. Regression analysis indicated that an accumulated O_3 dose over 40 nmol mol^{-1} (AOT40 where 1 nmol mol^{-1} = 1 ppb) of 5.4 ppm-h decreased the dry weight by 10%. Increasing the exposure duration at both 60 and 80 nmol mol^{-1} O_3 increased the percentage of main leaves with O_3 injury as well as leaf drop. An AOT40 dose of 3.0-3.3 ppm-h was estimated to cause 10% O_3 injury. In *Phleum alpinum*, an AOT40 dose of 3.2 and 3.6 ppm-h at 80 and 60 nmol mol^{-1} respectively was estimated to decrease the dry weight by 10%. AOT40 doses of 4.0 ppm-h at 60 nmol mol^{-1} O_3 and 2.1 ppm-h at 80 nmol mol^{-1} O_3 were estimated to increase the amount of necrotic leaves by 10%. The effect of O_3 pollution on *Betula pubescens* and *Phleum alpinum* is discussed on the basis of O_3 monitoring data from different locations in Norway, and the use of 40 ppb O_3 as a threshold concentration for calculations of O_3 doses is also discussed.

Key words: *Betula pubescens*, growth, leaf injury, ozone doses, *Phleum alpinum*.

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Tropospheric ozone (O_3) is recognized as being an air pollutant that might cause growth and yield decreases in sensitive plant species in Scandinavia, e.g. wheat (Skärby et al. 1993), timothy (Mortensen 1992, 1993a) and birch (Mortensen & Skre 1990). Today, much attention is focused on how to define the critical O_3 dose for plant growth (UNECE 1994). It has been proposed that the long-term critical level for O_3 should be expressed as the cumulative exposure over the threshold concentration of 40 nmol mol-1 (40 ppb) for both agricultural crops and forest trees (UNECE 1994). This exposure index is referred to as AOT40 (accumulated exposure over 40 ppb).

Betula pubescens, *Phleum pratense* and *Phleum alpinum* have been shown to be among the most O_3 sensitive species of the approximately 60 species tested in Norway (Mortensen & Skre 1990; Mortensen 1992; Mortensen & Nilsen 1992; Mortensen 1993a, 1994a, b). *Phleum alpinum* has an O_3 sensitivity comparable to or somewhat higher than that of *Phleum pratense*, the most important agricultural grass species in Norway. The sensitivity of *Betula pubescens* and *Phleum alpinum* to O_3 has been shown to be relatively independent on the site of origin in Norway (Mortensen 1994c, d). Because of its general high sensitivity to O_3, *Phleum alpinum* was chosen to represent the most sensitive Norwegian grass species. *Betula pubescens* is the most widespread deciduous tree species in Scandinavia, and this species as well as *Phleum alpinum* can be found growing up to a latitude of about 70°N. These two species were therefore used in an attempt to determine the critical O_3 dose causing growth reductions and leaf injuries. Different O_3 doses were obtained by combining different O_3 concentrations with different exposure durations. The results were compared with the O_3 doses measured in different parts of Norway.

Material and methods

Seeds of *Betula pubescens* Ehrh. (Maudal, 59°N) and *Phleum alpinum* L. (Jotunheimen, 61.5°N) were sown on 15 March 1994 in a mixture of 75% standard fertilized peat (Floralux, Nittedal industrier Ltd., Norway) and 25% perlite at 18°C in a greenhouse compartment. After germination the seedlings were placed at a temperature of about 10°C until 1 May when they were potted in the same substrate in 0.4 l pots, two seedlings of *Betula* or three of *Phleum* per pot. The O_3 concentration in the greenhouse was <25 nmol mol^{-1}. On 10 May the pots were placed in six growth chambers (2.5 m^2 growth area) previously described by Mortensen & Nilsen (1992). The pots were watered regularly with a complete nutrient solution in order to maintain the electrical conductivity at about 2.0 mS cm^{-1} (Mortensen 1992). The start dry weight of *Betula pubescens* was 0.04 g per plant, and that of *Phleum alpinum* 0.15 g per pot.

Three O_3 concentrations were established, two chambers per concentration (Fig. 1, Table 1): Low (control), medium (about 60 nmol mol^{-1}) and high (about 80 nmol mol^{-1}) in 8 h day^{-1} (10.00-18.00 h). The control O_3 concentration depended on the outside O_3 concentration (Fig. 2), but was lower than this because of the O_3 absorption inside the chambers. Ozone was generated from dry air using a high-voltage generator (Nomizon, Normiljø ab, Sweden). The effect of O_3 produced by air has recently been compared with O_3 produced by oxygen on *Phleum pratense* at the same O_3 concentration (Mortensen 1994d). The two treatments resulted in the same amount of foliar injury, and it was concluded that no toxic by-products were produced by the generator when air was used instead of oxygen. The O_3 concentration was measured twice an hour in each chamber using a scanner that switched the air flows from the chambers sequentially to an O_3 analyser (Monitor Labs. Inc., Model 8810). Measurements indicated that there were no O_3 concentration gradients inside the chambers. The CO_2 concentration was 350±20 μmol mol^{-1} as measured by an infra-red gas analyser.

The supplementary light level was 175 μmol m^{-2} s^{-1} during 20 h day^{-1} (12.6 mol m^{-2} day^{-1}) and was supplied by high-

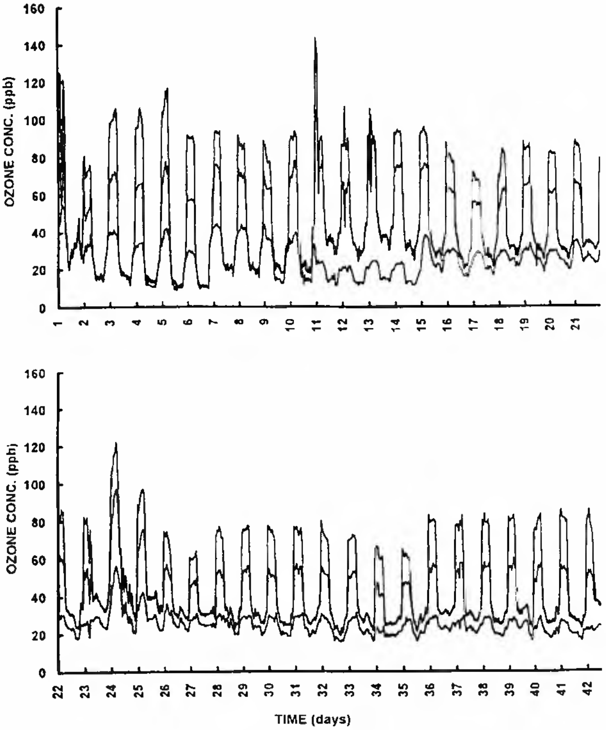


Fig. 1. The O_3 concentrations during the experiment at low (control), medium and high O_3 levels presented as hourly means. 1 nmol mol^{-1} = 1 ppb

Table 1. Mean O_3 concentrations during the 6-week experimental period, and the accumulated O_3 doses over 0 (AOTO), 30 (AOT30), 40 (AOT40), 50 (AOT50) and 60 ppb O_3 (AOT60). The range of O_3 doses in exposure durations of 1-6 weeks are given at medium and high O_3 concentrations. In the control treatment the O_3 concentration was low for the whole period, therefore only one value is given.

O_3 level	Replicate	Mean O_3 conc. (ppb)	Accumulated O_3 doses (ppm-h)				
			AOT0	AOT30	AOT40	AOT50	AOT60
Low	1	29±4	24.4	1.13	0.201	0.018	0.000
(control)	2	31±3	25.0	1.21	0.237	0.043	0.001
Medium	1	60±6	25.9-40.4	2.57-12.4	1.40-7.39	0.766-3.98	0.321-1.74
	2	59±7	26.8-39.6	2.82-11.8	1.56-6.99	0.895-3.71	0.411-1.63
High	1	81±7	30.3-47.3	4.35-19.5	3.19-14.7	2.53-11.2	1.99-7.97
	2	78±6	28.2-45.9	4.20-18.1	2.95-13.4	2.27-9.93	1.71-6.73

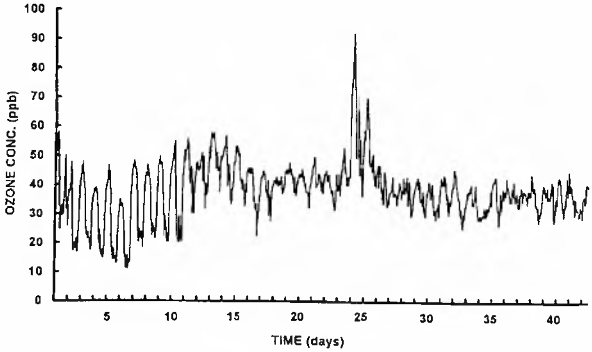


Fig. 2. The O_3 concentration as measured in outside air during the 6-week experimental period

pressure sodium lamps (Philips SON-T Plus). The light was measured by means of a Lambda LI-185B instrument with quantum sensor (400-700 nm). The contribution of daylight inside the chambers was on average 23.2 mol m^{-2} day^{-1}. This value was based on measurements taken at the Meteorolgical Station at Særheim, which were reduced by 50% owing to the light reduction caused by the greenhouse and growth chamber constructions. The total number of photosynthetic active photons inside the chambers was therefore 35.8 mol m^{-2} day^{-1}, which was comparable with the average daylight conditions in May-July (35-45 mol m^{-2} day^{-1}) in Norway. The air temperature was 14/9°C at 12/12 h intervals, giving a mean temperature varying from 12.0±0.4 to 12.2±0.3°C (continuously measured by thermocouples) in the six chambers. The relative humidity was continuously measured by humidity sensors, and was maintained at 85-90% during the experiment.

In *Betula pubescens*, the plants were first grown at 60 or 80 nmol mol^{-1} O_3 for 0, 1, 2, 3, 4, 5 or 6 weeks, and then at low O_3 (30 nmol mol^{-1}) for rest of the 6-weeks' experimental period. In *Phleum alpinum*, the plants were first grown at low O_3 concentration and then at 60 or 80 nmol mol^{-1} for 0-6 weeks. The experimental period lasted from 10 May until 21 June 1994. In addition to these treatments, *Phleum alpinum* was also exposed to 60 or 80 nmol mol^{-1} for 2 weeks either at the beginning, in the middle or at the end of the experimental period. Each treatment comprised five pots of each species which was replicated twice. The *Betula pubescens* plants were spaced at 1 plant/2 dm^2, and the *Phleum alpinum* at 1 pot/3 dm^2. The two species were divided into two plant stands inside the chambers.

The plants were harvested after 6 weeks from start of the experiment, and shoot fresh weight and dry weight of leaves and stems, plant height, number of branches, number of dropped and intact main leaves and number of intact main leaves with O_3 injuries (yellow stipples/ necrosis) were recorded in *Betula pubescens*. In *Phleum alpinum*, plant fresh and dry weights (the roots not included), plant height and percentage of necrosis of the total leaf area per pot were recorded. The injury was visually determined in intervals of 10%.

The accumulated O_3 doses (AOT) over 0, 30, 40, 50 and 60 ppb (nmol mol^{-1}) were calculated on the basis of hourly mean values for all treatments (Table 1). The AOT40 values were used in the presentation of dose-response curves of the different growth variables as previously proposed (UNECE 1994). Linear regression and correlation analyses between the accumulated doses over the different O_3 concentration and the values of the different growth variables were also performed (SAS Inc., Carey NC, USA).

Results

Betula pubescens

Increasing the exposure duration (0 to 6 weeks) at 60 nmol mol^{-1} O_3 did not significantly affect the shoot dry weight, whereas increasing the duration at 80 nmol mol^{-1} O_3 caused a dry weight decrease (Fig. 3A). In the figure the dry weights at the different treatments are plotted against the AOT40 values of the respective treatments. The regression for the dry weight at an increasing exposure duration to 60 nmol mol^{-1} O_3 (AOT40 doses from 0.2 to 7.4 ppm-h) was not significant, whereas the regression at 80 nmol mol^{-1} O_3 exposures (AOT40 doses from 0.2 to 14.7 ppm-h) was significant at $p<0.1$ level.

From the regression equation it was calculated that an AOT40 dose of 5.4 ppm-h caused a 10% dry weight decrease.

The leaf:stem dry weight ratio as well as plant height were unaffected by increasing the AOT40 dose at 60 nmol mol^{-1} O_3 level (Fig. 3A and 3B). Increasing the exposure duration at 80 nmol mol^{-1} caused an increase in the ratio and a decrease in the height. An AOT40 dose of 3.6 ppm-h caused a 10% increase in leaf:stem ratio, while a dose of 6.6 ppm-h caused a 10% decrease in plant height, as calculated by the regression equations. The total number of main leaves (14 in number) and the percentage of nodes which developed branches (80-90%) were unaffected by the O_3 treatments (data not presented).

Increasing the AOT40 dose by increasing the exposure duration at 60 or 80 nmol mol^{-1} enhanced the percentage of main leaves with O_3 injury as well as leaf drop (Fig. 4A and 4B). At an AOT40 dose of 3.0 and 3.3 ppm-h, at 60 and 80 nmol mol^{-1} O_3 respectively, the amount of leaf injury was calculated to be enhanced by 10%. The leaf drop was increased by 10% at an AOT40 dose of 6.3 and 10.0 ppm-h at 60 and 80 nmol mol^{-1}, respectively, as calculated by the regression equation.

The correlation between the value of the different growth variables and the accumulated O_3 dose over different threshold concentrations was analysed (Table 2). All exposure treatments were included in this analysis. The analysis revealed that the threshold concentration which gave the highest correlation between accumulated O_3 dose (AOT) and the effect on growth depended on the growth character measured (Table 2). Shoot dry weight, leaf:stem dry weight ratio and plant height were best correlated with AOT60, the percentage main leaves with O_3 injury was best correlated with AOT40 and the percentage dropped main leaves was best correlated with AOT0 or AOT30. However, it is important to be aware of the high intercorrelations between any two of the AOT0, AOT30, AOT40, AOT50 and AOT60, which varied from $r=0.857$ ($p<0.001$) to $r=0.992$ ($p<0.001$) (analysis not presented). This was so because any increase in the O_3 concentration or in exposure time increased the O_3 dose irrespective of the threshold concentration used.

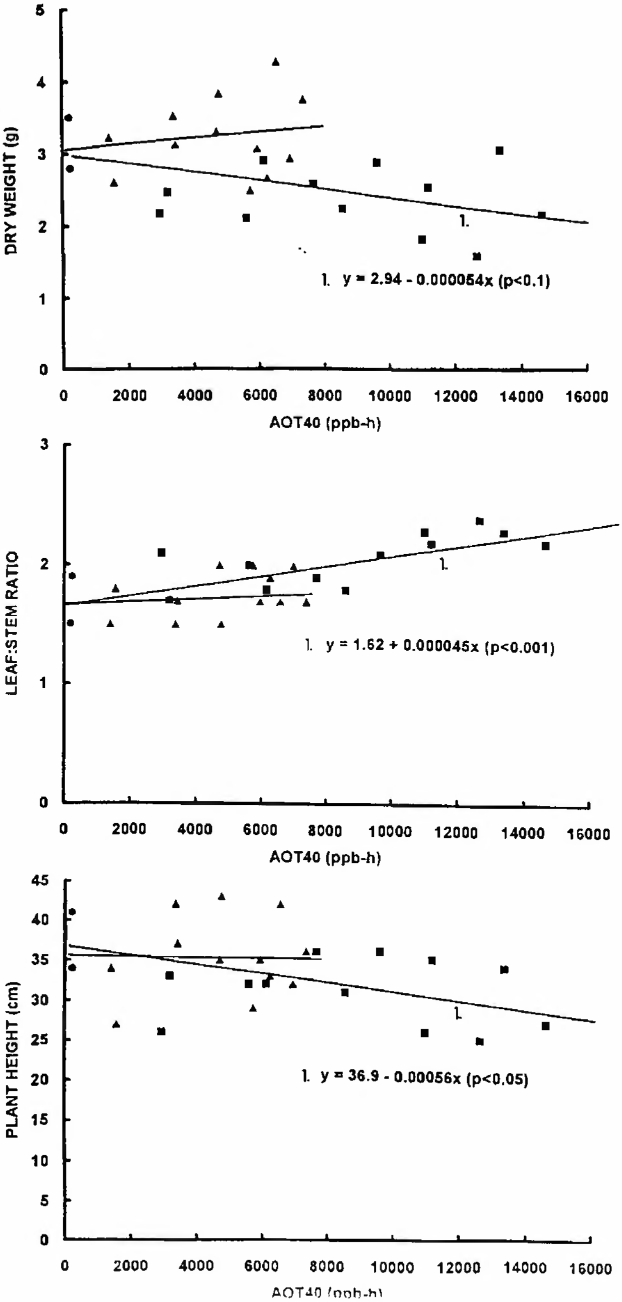


Fig. 3. Shoot dry weight, leaf:stem dry weight ratio and plant height of Betula pubescens as plotted against the AOT40 dose (O_3 dose over 40 nmol mol^{-1} = 40 ppb) in the different treatments. Linear regression equations are given in the cases when the regressions are significant. ● = low control; ▲ = O_3 exposures at 60 nmol mol^{-1}; ■ = O_3 exposures at 80 nmol mol^{-1} O_3.

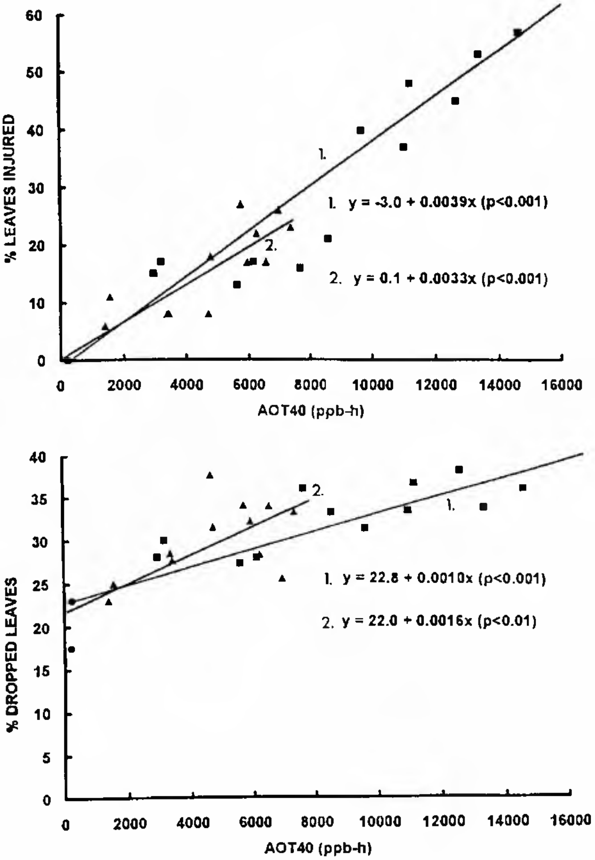


Fig. 4. The percentage of main leaves with O_3 injury of the total number of intact main leaves, and the percentage number dropped main leaves of the total in Betula pubescens, as plotted against AOT40 in the different O_3 treatments. See Fig. 3 text.

Table 2. Correlations (r) between the O_3 dose above 0, 30, 40, 50 and 60 ppb O_3 and measured values of different growth variables in *Betula pubescens*. Significance levels: ns, not significant; *,p<0.05, **,p<0.01; ***,p<0.001

	O_3 dose (ppb-h)				
Growth variable	AOT0	AOT30	AOT40	AOT50	AOT60
Shoot d.w.	-0.366*	-0.354*	-0.444**	-0.523**	-0.593***
Leaf:stem d.w.ratio	0.644***	0.661***	0.698***	0.726***	0.732***
Height (cm)	-0.332^{ns}	-0.314^{ns}	-0.372*	-0.425*	-0.472**
% of main leaves with O_3 injury	0.842**	0.875***	0.880***	0.868***	0.825***
% dropped main leaves of total	0.704***	0.704***	0.694***	0.664***	0.606***

Phleum alpinum

Shoot dry weight of this species was significantly decreased by increasing the exposure duration in 60 or 80 nmol mol^{-1} O_3 (Fig. 5A). The dry weight of the plants grown continuously at low O_3 (30 nmol mol^{-1}, AOT40 of 0.2 ppm-h) was excluded from the results because of reduced growth resulting from a period of very dense spacing. From the regression equations it was calculated that a 10% dry weight decrease was reached at 3.6 ppm-h AOT40 when exposed to 60 nmol mol^{-1} O_3, and at 3.2 ppm-h when exposed to 80 nmol mol^{-1} O_3 (Fig. 5A).

The percentage necrotic leaf area increased with increasing AOT40 doses at both 60 and 80 nmol mol^{-1} O_3 (Fig. 5B).

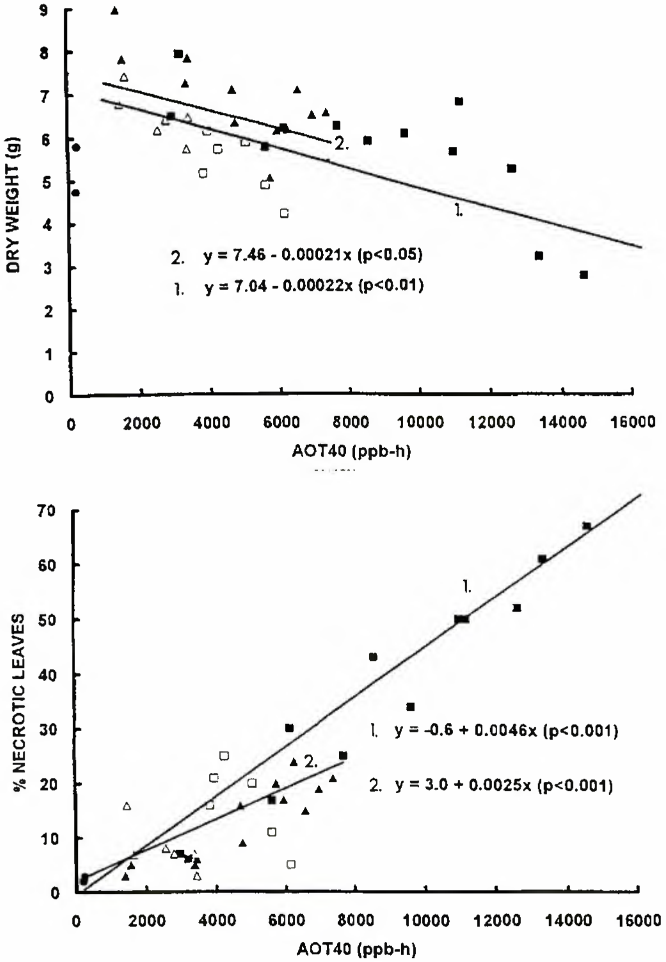


Fig. 5. The shoot dry weight and percentage necrotic leaves in Phleum alpinum as plotted against AOT40 in the different O_3 treatments. The regression equations are given ● = low control; ▲ = O_3 exposures at 60 nmol mol^{-1}; ■ = O_3 exposures at 80 nmol mol^{-1}; Δ = 2 weeks' exposure at 60 nmol mol^{-1}; □ = 2 weeks' exposure at 80 nmol mol^{-1}.

AOT40 doses of 4.0 and 2.1 ppm-h were calculated to increase the leaf necrosis by 10% at 60 and 80 nmol mol^{-1} exposures, respectively. In this species, 2-week O_3 exposures were given at the beginning, middle and at the end of the growth period in order to analyse the O_3 effect at different growth stages. However, the O_3 doses in the different 2-week treatments were very different, making a comparison impossible. The results of these treatments are presented in the figures and are used in the dose-response analysis (Fig. 5).

An analysis of correlations between O_3 doses at different threshold levels and the dry weight indicated that the shoot dry weight was best correlated with AOT60, and the percentage necrotic leaf area best correlated with AOT40 (Table 3). The plant height was unaffected by the O_3 treatments.

Discussion

Betula pubescens as well as *Phleum alpinum* were shown to be relatively sensitive to O_3, particularly with respect to the development of leaf injuries, in accordance with previous studies on the same species (Mortensen & Skre 1990; Mortensen 1993a). However, contrary to previous results it was found that the exposure to 60 nmol mol^{-1} did not significantly decrease the dry weight of *Betula pubescens* (Mortensen 1995). This might be explained by the closer spacing (1 plant/2 dm^2) and higher leaf area index in the present experiment compared with that in the previous one (1 plant/3 dm^2) (Mortensen 1995). Ozone exposure caused the development of leaf injuries and enhanced senescence of leaves, as was previously found in the present species (Mortensen & Skre 1990). However, at the time this took place the leaves were shaded by the leaves above and therefore, particularly in a very close plant stand, no longer contributed much to plant growth in any case.

In the present experiment an AOT40 of 5.4 ppm-h was estimated to decrease the shoot dry weight of *Betula pubescens* by 10%, compared with 9 or 13 ppm-h previously found in *Betula pendula* (Matyssek et al. 1992). A similar decrease in the dry weight of beech was found with 6-7 ppm-h AOT40 (Küppers et al. 1994; Braun & Flückiger 1994), and 12 ppm-h in Norway spruce and Scots pine during one growing season (Küppers et al. 1994). *Betula pubescens* seems therefore to be one of the most O_3 sensitive forest tree species so far studied. This is also in accordance with the conclusion from previous studies carried out with nine conifer species (Mortensen 1994b), Quercus robur and *Acer pseudoplanta-*

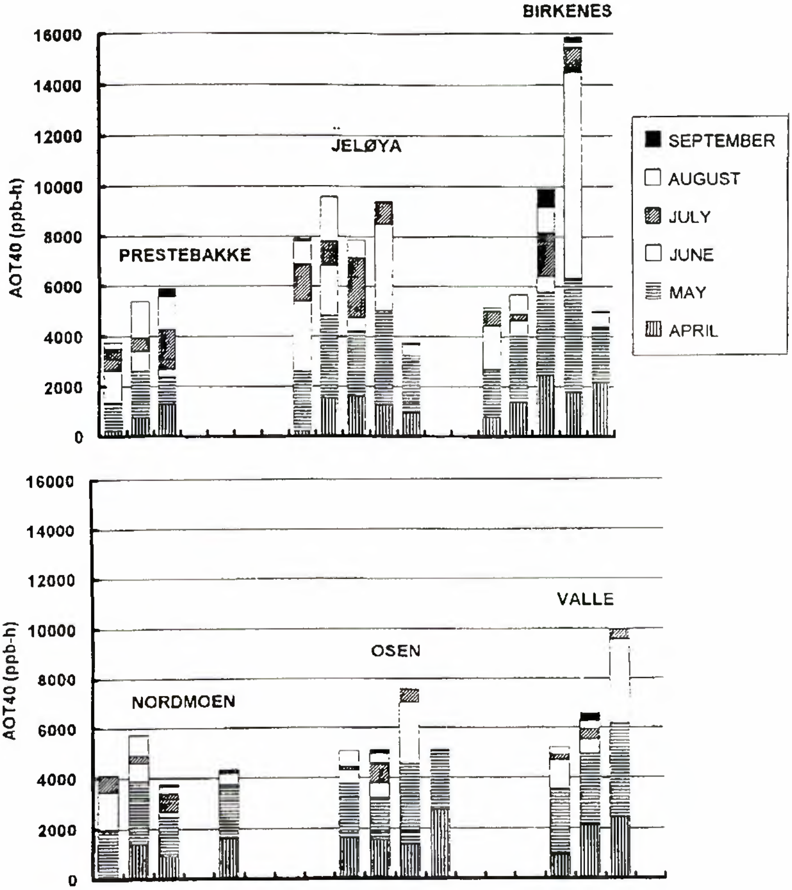
Table 3. Correlations (r) between the O_3 dose above different O_3 concentrations and measured values of two growth variables in *Phleum alpinum*. See Table 2 text.

Growth variable	AOT0	AOT30	AOT40	AOT50	AOT60
Shoot d.w. (g)	-0.476^{**}	-0.543^{***}	-0.597^{***}	-0.645^{***}	-0.672^{***}
% necrotic leaves	0.864^{***}	0.894^{***}	0.900^{***}	0.897^{***}	0.872^{***}

noides (Mortensen, unpublished results) and *Betula pubescens* (Mortensen 1994c, d) grown in the same growth chambers under similar climatic conditions.

In the present experiment, *Phleum alpinum appeared* to have a slightly higher O_3 sensitivity than *Betula pubescens*. Fuhrer (1994) estimated that an AOT40 of 5.3 ppm-h would decrease the wheat yield by 10%. This estimation was based on results from different open-top chamber experiments in Europe. In comparison, an AOT40 dose of 3.2-3.6 ppm-h was estimated to cause a 10% dry weight decrease in *Phleum alpinum*.

On the basis of data from the Norwegian Air Research Institute (Tørseth & Mortensen 1995), accumulated O_3 doses over 40 ppb (AOT40) are presented from 12 locations ranging from 58 to 79°N in Norway (Fig. 6). Based on monthly AOT40 data during 1989-93, it appears that the O_3 doses are much higher at the lower than at the higher latitudes. When the measured AOT40 doses in the field are compared with the O_3 dose causing a specific growth decrease in a species, it is important to relate the accumulated O_3 doses to the growth season of the species. In Norway, *Betula pubescens* generally starts to produce new leaves in the middle of May in the lowlands in South Norway,



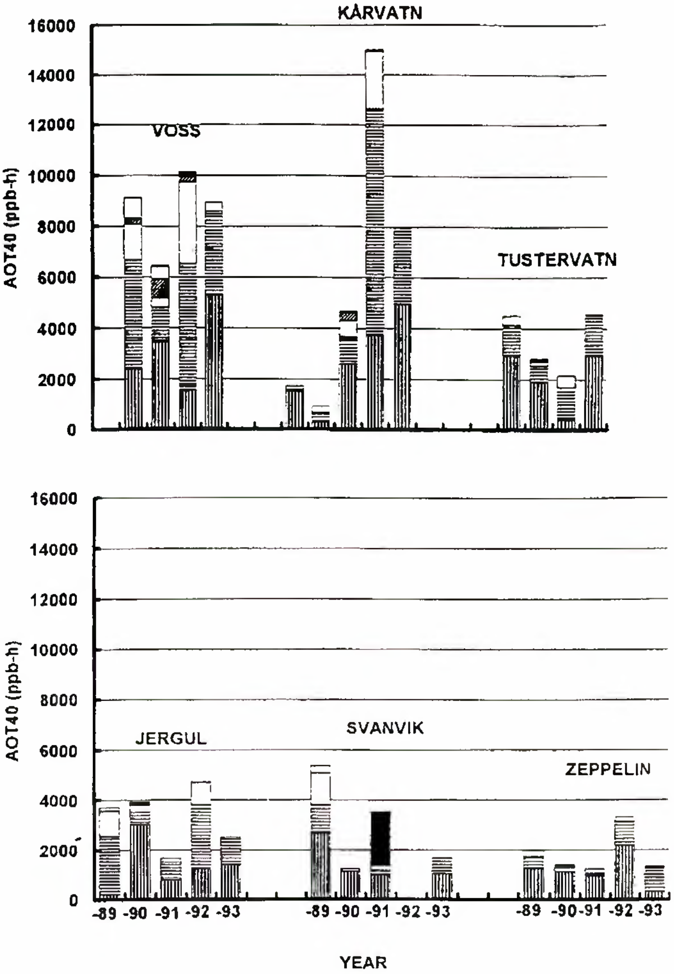


Fig. 6. The accumulated O_3 doses over 40 ppb (AOT40) during 24 h day^{-1} in different locations in Norway as expressed on a monthly basis (April-September) in 1989-93. The presentation is based on data from Tørseth & Mortensen (1995). The following locations are included: Prestebakke (59°00"N/11°32"E, 160 m asl, Jeløya (59°26"N/10°36"E, 5 m asl), Birkenes (58°23"N/8°15"E, 190 m asl), Nordmoen (60°16"N/11°06"E, 200 m asl), Osen (61°15"N/11°47"E, 440 m asl), Valle (59°03"N/7°34"E, 250 m asl), Voss (60°36"N/6°32"E, 500 m asl), Kårvatn (62°47"N/8°53"E, 210 m asl), Tustervatn (65°50"N/13°55"E, 439 m asl), Jergul (69°27"N/24°36"E, 255 m asl), Svanvik (69°27"N/30°02"E, 30 m asl) and Zeppelin (78°54"N/11°53"E, 474 m asl)

and in June in the mountain areas and in northern parts of Norway. This means that the O_3 pollution in April, as well as at least in parts of May, is of no relevance for this tree species or for any other deciduous tree species in Norway. It is very important to bear this in mind since it is in April-May that the highest AOT40 doses occur (Fig. 6). In the generally most polluted locations (Jeløya, Birkenes and Voss) 50-

80% of the AOT40 dose in the period April-September occurs in April-May. In *Betula pubescens*, 5.4 ppm-h was estimated to decrease the biomass production by 10%. This value was slightly exceeded during the growth season in the most polluted locations in southern parts of Norway, but, in the northern parts the O_3 dose was much lower than this value. With respect to *Phleum alpinum*, this species does not appear to be exposed to very high O_3 doses in general, since it grows in the mountain areas in South Norway or in North Norway and its growth season does not begin before June. However, its relative *Phleum pratense* has also been shown to be very sensitive to O_3 (Mortensen 1992). This species as well as other grasses start to grow in the middle of April in the lowland of South Norway, and might therefore be exposed to O_3 doses ranging from 5 to 10 ppm-h. Therefore, it seems likely that agricultural as well as other grasses are much more exposed to high O_3 concentrations than different deciduous tree species during a growth season in Norway.

So far, the proposed critical AOT40 doses for crops and trees have not taken into account the potential influence of the climatic conditions. In *Betula pubescens*, it has been shown that decreasing the temperature strongly increases the effect of a particular O_3 dose due to increased leaf absorption of O_3 (Mortensen 1993b). The relatively low O_3 dose (5.4 ppm-h AOT40) needed to decrease the biomass production by 10% in *Betula pubescens* at 12°C (the present experiment) will most probably be significantly higher if the temperature is increased. The air humidity and light conditions may also influence the O_3 effect. Increasing the water-vapour deficit or the photosynthetic active radiation has been shown to decrease the injurious effect of O_3 in wheat (Mortensen 1990) as well as in clover (Sanders et al. 1994). Obviously, the climatic conditions are a critical factor which needs much more attention in any further work on critical levels.

The threshold concentration which gave the best correlations between AOT and the effects on the plants, depended on the growth variable measured. For both species the development of leaf injuries was better correlated with lower threshold concentrations (40 nmol mol^{-1}) than was the biomass (50-60 nmol mol^{-1}). However, the high positive intercorrelations between any two of the AOT0, AOT30, AOT40, AOT50 and AOT60 doses make it difficult to decide whether the proposed 40 nmol mol^{-1} threshold (UNECE 1994) is the best choice. In order to evaluate this, more than one O_3 concentration below 40 nmol mol^{-1} as well as more than one exposure period per day should be included in the experiment. Recently, Krupa et al. (1995) concluded that the crop response appeared to be best explained statistically by the cumulative frequency of hourly O_3 concentrations between 50 and 90 nmol mol^{-1}. Skärby (1994), however, suggested that a threshold concentration of 30 is perhaps more relevant than 40 nmol mol^{-1} for forest trees. However, choosing a threshold concentration lower than 40 nmol mol^{-1} will include concentrations which are very close to the background O_3 concentration.

Adknowledgements

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The influence of raised atmospheric CO_2 concentration on morphology of the grasses *Lolium perenne* and *Phleum pratense* in the cool and maritime climate of southwestern Norway

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Sæbø, A. & L.M. Mortensen 1995. The influence of raised atmospheric CO_2 concentration on morphology of the grasses *Lolium perenne* and *Phleum pratense* in the cool and maritime climate of southwestern Norway. Norwegian Journal of Agricultural Sciences 9: 263-269. ISSN 0801-5341.

Lolium perenne and *Phleum pratense* were grown at ambient and elevated CO_2 concentrations in field chambers through the growth season on the southwest coast of Norway. The dry weight of the above-ground plant mass was not significantly affected by the CO_2 concentration. At elevated CO_2 concentrations the number of tillers increased by 38% in *P. pratense* and by 26% in *L. perenne*. The leaf area per leaf was significantly smaller (22%) in *P. pratense* at the elevated CO_2 concentration, probably causing no effect of elevated CO_2 level on dry matter despite an increase in tillering. The plant height was significantly decreased in plants in the early phase of growth at high CO_2 concentration. However, at harvest time (at shooting) there was no difference in plant height between the two treatments. Shooting occurred significantly earlier in *P. pratense* at elevated CO_2 concentrations than at ambient CO_2 level. The results are discussed in relation to production and competition.

Key words: Carbon dioxide, fodder, grasses, morphology, yield.

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Grasses for fodder production constitute the main crop in many parts of Norway, and it is therefore important to predict the influence of the current rise in atmospheric CO_2 concentration on these grasses. Elevated atmospheric CO_2 concentrations have been shown to increase photosynthesis (Kendall et al. 1985), decrease photorespiration and respiration (Bunce & Caulfield 1991; Ziska & Buce 1993) and increase tillering (Ryle et al. 1992). Poorter (1993) suggests that the response of monocotyledons may be smaller than that of dicotyledons.

A positive contribution to growth by an increase in CO_2 concentration may be offset by the effect of high temperatures. Through a stress-induced premature development of the crops, a smaller dry matter accumulation may thus be expected (Rosenzweig & Parry 1994). In some regions the effect of increased CO_2 concentration on photorespiration and water-use efficiency may be small, owing to low temperatures (Idso et al. 1987; 1993; Drake 1992). The increase in dry matter production at elevated CO_2 is probably realized mainly through an increase in the number of tillers, as shown in *Lolium perenne* (Ryle et al. 1992).

In the cool climate of the west coast of Norway the yield of vegetable species in general was shown to be little affected by elevated CO_2 concentrations (Mortensen 1994); grass yields also showed little response, but a significant decrease in plant height was found (Sæbø & Mortensen 1995). In clover, the yield increased by about 30%. Sæbø & Mortensen (1995) emphasized the possible change in competitiveness between plant species with different responses to elevated CO_2 when growing in the same habitat.

The aim of the present research was to study the dynamics of the effect of elevated CO_2 concentration on the morphology of *Lolium perenne* and *Phleum pratense* grown in the coastal climate of southwestern Norway.

Materials and mothods

Plant material

Lolium perenne 'Tove' and *Phleum pratense* 'Forus' were sown in boxes (40 x 60 cm in area and 20 cm deep) on 20 April, with 30 g seeds per box, and the seedling number was reduced to 20 plants per box after germination. The plants were grown in peat (Floralux, Nittedal torvindustrier A/S).

Field chamber units

Ten field plots (3.0 x 3.0 m), surrounded by 1.8 m high transparent plastic foil (0.2 mm polyethylene), mounted on wooden frames, were established at Særheim Research Centre (59°N, 6°E). Perforated (1 mm holes) tubes (4 mm diameter) were placed on the ground in five of the field chambers (13 holes per m^2), and pure CO_2 gas from a container was supplied through the tubes at a flow rate of 150 l m^{-2} (chamber area) h^{-1} when a solenoid valve was opened for the CO_2 supply. The remaining chambers were not supplied with CO_2. The CO_2 concentration in the chambers with elevated CO_2 was continuously measured: air from the chambers was sampled from a perforated (5 mm holes 10 cm apart) tube (50 mm) which ensured that air samples for analysis represented the chamber atmosphere. The mean CO_2 concentration was maintained between 590 and 743 μmol mol^{-1} by the solenoid valve on the CO_2 supply to the enriched chambers. The CO_2 supply to the other four CO_2-enriched chambers was controlled in parallel with this chamber. The CO_2 concentration was measured in the five chambers with elevated CO_2, in three of the chambers with ambient concentrations, and at one point outside the chambers. This was done by using a scanner which switched the air streams sequentially from each measure point to the gas analyser (ADC, Model 25 MK3, UK). No forced ventilation was used in the field chambers and, therefore, the wind significantly influenced the accuracy of CO_2 regulation. The CO_2 concentration above the boxes varied continuously by about ±100 μmol mol^{-1} at wind speeds of 0-1 m s^{-1} and about ±200 μmol mol^{-1} at wind speeds of 2-4 m s^{-1}. At higher wind speeds the variation in CO_2 concentration increased, and at wind speeds above 10 m s^{-1} it was difficult to maintain a high CO_2 concentration. However, such high wind speeds are rare in the growth season of the experimental site.

The air temperature at plant level was measured by thermocouples (Table 1). The mean relative air humidity, number of hours with sunshine, number of photosynthetically active photons, precipitation and wind speed were recorded at the Meteorological Station of Særheim (Table 1).

The boxes were placed in the five field chambers, before sowing, at ambient CO_2 and in the five chambers with high CO_2 concentrations, one box for each species per chamber. In addition, three boxes per species were placed outside the chambers in order to study the 'chamber effect'. Water, enriched with nutrients at an electrical conductivity of 2.0 mS cm^{-1} was applied through drip-irrigation, two drips per box. The plants were harvested at the usual stage for good forage quality, at the beginning of shooting.

During the growth season the following characters were recorded: plant height, recorded as three measurements per box, leaf length, leaf width, leaf area and the number of tillers. At harvest dry matter of the above-ground plant material and shooting were also recorded. The data were subjected to analysis of variance using the SAS-GLM procedure (SAS Inc., Carey NC, USA). Data from field chambers with ambient CO_2 were compared with data from field plots to analyse "the chamber effect", and field chambers containing ambient CO_2 were compared with elevated CO_2 chambers.

Results

The dry weights were not significantly affected by the CO_2 concentrations (Table 2). The number of tillers was enhanced (significant only at 10% level of probability), by 34% in *Phleum* and 25% in *Lolium*. A significant decrease in plant height was observed in both species at elevated CO_2 concentrations (Fig. 1a, 1b). However, the difference in height disappeared at harvest, when shooting was in progress. The elongation of individual leaves also lagged behind at elevated CO_2, significant at 10% level of probability in *P. pratense*, but the difference was not great (Table 2). Leaf width was not affected by the CO_2 concentration. The leaf area per leaf (Fig. 2) was significantly smaller at elevated CO_2 in *P. pratense*, but was not significantly affected in *L. perenne*.

The percentage of flowering was significantly larger (27%) at elevated CO_2 in *P. pratense* but was not significantly affected in *L. perenne*.

Table 1. Monthly mean values for precipitation, air temperature inside and outside of the field chambers and daily mean radiation during the experimental period.

Month	Precipitation, mm	Air temperature, °C		Radiation, mol m^{-2} day^{-1}	CO_2conc., (µmol mol^{-1})		Wind speed, m s^{-1}
		inside	outside		Low	High	
May	57	10.1	9.7	47.3	372	653	2.6
June	120	10.7	10.5	36.3	364	716	3.0
July	39	16.2	16.2	42.9	370	743	1.9
Aug	155	14.4	14.0	29.9	364	590	2.3

Table 2. Accumulated dry weight, number of tillers, leaf length and leaf width on 13 July and the percentage of shoots flowering at the harvest (20 August) in boxes with *Phleum pratense* and *Lolium perenne* grown at normal CO_2 concentrations in field plots (FP) and field chambers (Low) and at elevated CO_2 in field chambers (High). Mean values ± standard deviation

Species	CO_2	Dry weight per box, g	No of tillers per plant	Leaf length, cm	Leaf width, cm	Flowering plants, %
Phleum pratense	Low	633±25	13±3	34±3	13±1	44±9
	High	655±29	18±4	31±2	12±1	56±6
	FP	468±24	15±2	32±3	13±1	43±6
Level of significance						
	CO_2	ns	+	+	ns	*
	Chamber	*	ns	ns	ns	ns
Lolium perenne	Low	476±25	23±3	50±5	9±1	58±11
	High	523±29	29±6	46±3	8±3	66±9
	FP	502±24	29±4	46±1	9±1	37±23
Level of significance						
	CO_2	ns	+	ns	ns	ns
	Chamber	ns	*	ns	ns	ns

*: statistically significant at 5% level of probability. +: significant at 10% level of probability.

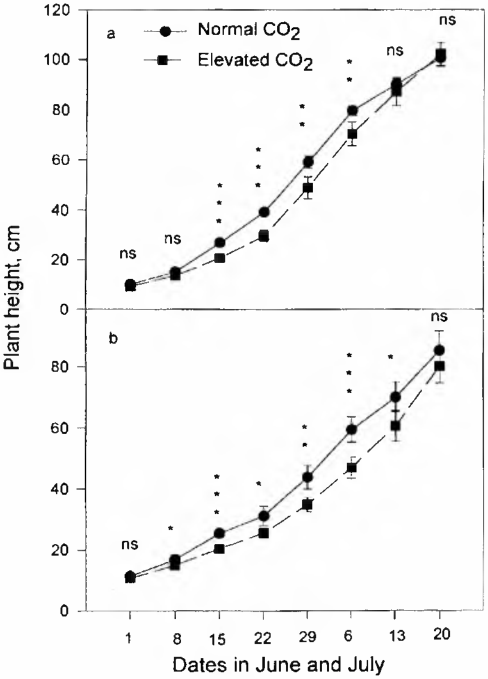

Fig. 1. Plant height (± standard deviation, n=5) during the growth season of P. pratense (a) and L. perenne (b) at normal and elevated CO_2 concentrations.

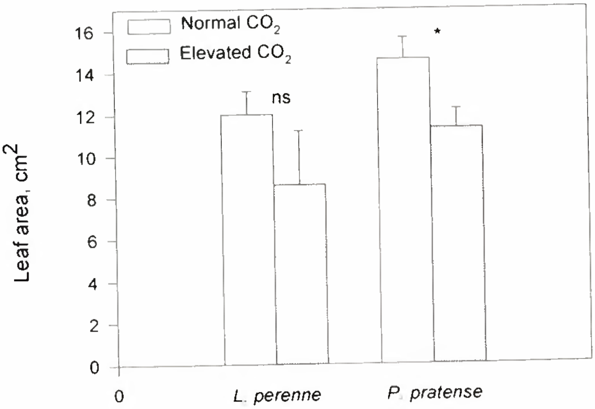

Fig. 2. Leaf area (± standard deviation, n=5) of L. perenne and P. pratense at normal and elevated CO_2 concentrations.

Discussion

An increase in dry matter production is often found in grasses subjected to high CO_2 concentrations (Hocking & Meyer 1991; Nicolas et al. 1993; Delgado et al. 1994). However, only a small response to elevated CO_2 was found in dry matter yield of timothy and ryegrass under the growth conditions of southwestern Norway (Sæbø & Mortensen 1995). In the present study, dry matter of *L. perenne* and *P. pratense* tended to increase by only 4 and 10% respectively, owing to the CO_2 enrichment, the small response probably caused by the low temperature. The photorespiration is little affected by elevated CO_2 at low temperature. A more efficient water use in plants at elevated CO_2 concentrations may not be important when the water supply does not limit growth (which was probably the case in the present experiment).

There was an increase in tillering at elevated CO_2, in agreement with observations in several grasses (Hocking & Meyers 1991). Ryle et al. (1992) suggest that there may be little response in biomass production unless tillering is affected. The results of the present study indicate that an increase in biomass depends also on the development of each tiller. The plant height was mainly affected through a decrease in the stem elongation, and only to a lesser extent was leaf elongation affected. In order to compensate for less elongation in the vegetative stage, elongation must have been much faster in the generative phase at high CO_2 concentrations. Plants may accumulate more dry matter in roots at elevated CO_2 compared with at ambient CO_2 levels (Stulen & Hertog 1993). These root reserves may have played a role in the fast elongation at the shooting phase in plants at elevated CO_2, which was observed in the present study. The lack of significant dry matter accumulation at elevated concentrations of CO_2 may also in part be a result of the smaller leaf areas in this treatment. In previous experiments a decrease in plant height was found in timothy and ryegrass but not in clover (Sæbø & Mortensen 1995). A decrease in elongation at elevated CO_2 concentrations was found in barley and oats, but not in wheat (Sæbø & Mortensen, in press). The observations indicate that a change in competitiveness between species may occur in the field. There may also be a change in the competition and interaction between the crops and weeds. The competition from weeds in wheat was strong when the individual competitor plants were large, and weak when the competitor plants were small (Thompson & Woodward 1994). The present experiment suggests that a change in the relative size of crop plants and weed plants is possible in the phase when the grasses are being established in the field, and in the phase before shooting. Thus, even if a decrease in elongation does not persist throughout the growth season, negative effects from competition may be severe during the period when elongation is affected.

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Autumn application of chlormequat chloride (CCC) in seed production of *Bromus inermis*

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The short photoperiod combined with high temperature required for primary flower induction has a limiting effect on seed yields of *Bromus inermis* Leyss. at high latitudes. Since the long-day inhibition of induction is mediated by gibberellins, this research examines the effect of autumn applications of the gibberellin biosynthesis inhibitor CCC (2 kg a.i. ha^{-1}) at various locations in SE Norway (58-61°N). It was found that CCC increased first year seed yields by up to 50% when applied to spring-sown crops in August, whereas spraying in September had a less stimulatory effect at 58°N and a negative effect at 61°N. Spraying in autumn had no effect when applied to a crop established by transplanting (4.8 plants m^{-2}). There was a negative interaction between CCC applied in autumn and in spring, the highest seed yield being obtained with CCC in spring only. Ethephon applied in spring also increased seed yield, both with and without CCC in autumn. Seed yields in the second harvest year were not affected by CCC after the first seed harvest, but were greatly increased by stubble removal.

Key words: *Bromus inermis*, chlormequat chloride (CCC), ethephon, gibberellin, growth regulation, plant height, seed production, temperature, tillering.

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Several chemical plant growth regulators have the potential to increase herbage seed yields (Hebblethwaite 1987). However, many of the most promising products have never reached commercial markets, because either they are too expensive or high soil persistency precludes official registration.

Because of its widespread use in cereal production, chlormequat chloride (CCC) is readily available in most temperate countries. While this growth regulator had no effect or a very limited one on seed yields of *Lolium perenne* L. in British, Oregonian, Danish and Canadian experiments (Hebblethwaite & Burbidge 1976; Young et al. 1984; Fuglsang 1990; Mares Martins & Gamble 1993), Hampton (1986) reported yield increases of 35-44% as a result of improved survival of fertile tillers in trials in New Zealand. In Scandinavian experiments, CCC application had a positive effect on seed yields of *Dactylis glomerata* L. and *Phleum pratense* L., whereas *Festuca pratensis* Huds. showed little response. Results in *Festuca rubra* L. and *Poa pratensis* L. were inconsistent (Fuglsang 1990; Nordestgaard 1990; Järvi 1990; Skuterud 1990).

Species within the genus Bromus are very responsive to CCC treatment. In experiments carried out in New Zealand, application of 750 g a.i. ha-1 at spikelet initiation increased seed yields of *Bromus willdenowii* Kunth. by 13-18% (Hampton et al. 1989). Whereas this increment was associated with higher seed number per spikelet, delayed leaf senescence and reductions in plant height, lodging and vegetative tiller number, higher levels of CCC produced no further increase in seed yield. On average for nine Norwegian experiments, CCC at the rate 2 kg a.i. ha^{-1} at Zadok 31 (first node visible) increased seed yields of *Bromus inermis* Leyss. from 370 to 520 kg ha^{-1} and reduced lodging from 61 to 26% (Skuterud 1990).

On the basis of a temporary permission, CCC has been used in commercial seed production of *Bromus inermis* in Norway since 1989. In 1994, the chemical was officially approved for application in seed crops of *Phleum pratense*, *Dactylis glomerata* and *Bromus inermis*, with no restrictions regarding the use of straw as feed.

In the experiments cited above, CCC was always applied in spring. With the exception of *Bromus willdenowii* and *Phleum pratense*, the species mentioned have dual flower induction requirements, i.e. they require a certain exposure to low temperature and/or short photoperiod (primary induction) before inflorescence development in long days (secondary induction (Heide 1994a). Since gibberellins are inhibitory to primary induction (Heide et al. 1987), CCC, which is a gibberellin biosynthesis inhibitor, has the potential to increase seed yields also when applied in autumn (Heide 1994a). This effect was demonstrated by Heide (1994b) in *Phalaris arundinacea* L. and has earlier been documented by Buettner et al. (1976) in field experiments with *Poa pratensis*. However, the results were not consistent in Danish experiments with autumn application of CCC to *Poa pratensis*, *Festuca rubra* and *Lolium perenne* (Nordestgaard 1990).

Unlike in most temperate grasses, low temperature can not substitute for short photoperiod during primary induction in *Bromus inermis*. Norwegian cultivars have an absolute requirement for at least 4-6 weeks at photoperiods shorter than 13-14 h, i.e. after the beginning of September. The optimum temperature during this period is as high as 15-21°C, induction being completely inhibited at temperatures below 6°C (Heide 1984). These requirements are scarcely met at high latitudes, and remedies to improved primary induction are therefore desirable. Moreover, when spring sown without cover crop, *Bromus inermis* often develops elongated, vegetative tillers (culms) which will never be receptive to primary induction; this tendency can also be prevented by autumn application of CCC.

The objective of the present research was to examine the effect of autumn applications of CCC to seed stands of *Bromus inermis* in the marginally inductive climate of Norway.

Materials and methods

During 1990-93 seven experimental fields with seed crops of *Bromus inermis* were established; cv. Løfar in six and cv. Manchar in one experiment. The locations ranged from Birkeland and Landvik on the Norwegian south coast (58°N – three experiments) to Hellerud and Apelsvoll in the inland north of Oslo (60-61°N – three experiments); with one experiment at an intermediate location in Våle, Vestfold (59°N). The trials followed three different experimental plans:

Plan 1: Autumn application of CCC in the establishment year

A. Stand cut to 5 cm on 1 August. No CCC.
B. Stand cut to 5 cm on 1 August. CCC on 15 August.
C. Stand cut to 5 cm on 1 August. CCC on 15 August and on 15 September.
D. Stand cut to 5 cm on 1 August. CCC on 15 September.
E. Stand cut to 5 cm on 1 September. No CCC.
F. Stand cut to 5 cm on 1 September. CCC on 1 September.
G. Stand cut to 5 cm on 1 September. CCC on 15 September.
H. Stand cut to 5 cm on 1 September. CCC on 1 October.

This plan was used in one experiment at each of the locations Landvik, Våle and Apelsvoll. One experiment at Birkeland comprised treatments E-H only. With the exception of the experiment in Våle, which was laid out in a crop transplanted on 27 June at a row spacing of 60 cm and plant spacing within rows of 35 cm, all experiments had been sown without cover crop at 12-15 cm row spacing in late May or June.

Plan 2: CCC in the autumn of the establishment year combined with CCC or ethephon in the spring of the first harvest year

Factor 1:	Factor 2:
A. No CCC in autumn.	X. No growth regulator in spring.
B. CCC on 6 September.	Y. CCC on 13 May.
	Z. Ethephon on 13 May.

This plan, which was laid out in a randomized complete block design with three replicates, was used only in one experiment at Hellerud. After sowing without cover crop and at 13 cm row spacing on 22 June, the crop had been cut to 5 cm on 30 August.

Plan 3: Stubble removal and CCC-application after the first seed harvest

Factor 1:	Factor 2:
A. No stubble removal after seed harvest.	X. No CCC.
B. Stubble cut to 5 cm after seed harvest.	Y. CCC just after seed harvest/stubble removal.
	Z. CCC on 20 September.

One experiment at Birkeland and another at Hellerud were laid out in a split-plot design, with stubble removal on main plots and chemical growth regulation on subplots. Stubble height after the first seed harvest was 15-25 cm.

General

The areas of the gross plots and harvest plots were usually 10 m • 3 m and 8.5 m •1.5 m, respectively. CCC was always applied at the rate 2 kg a.i.ha^{-1}, with the addition of 0.04% etoxylated ethylphenol (Extravon) in order to improve leaf absorption. Ethephon (plan 2) was applied at the rate 0.5 kg a.i.ha^{-1}. With the exception of autumn cutting and chemical growth regulation, crops were managed in accordance with Norwegian practice, including fertilizer application at 30-40 kg N ha^{-1} in autumn and 60-100 kg N ha^{-1} in spring. The experiments were harvested by direct combining at 20-30% seed moisture content, usually in late August. In addition to seed yield, data on plant height and lodging were recorded, and in some cases vegetative and reproductive tillers were counted and thousand seed weight and germination determined after seed cleaning.

Results

Plan 1: Autumn application of CCC in the establishment year

The effect of autumn cutting and CCC application on seed yield varied according to location and method of establishment (Table 1). Cutting on 1 September tended to produce higher seed yields than cutting on 1 August in non-regulated plots established by ordinary sowing (Landvik and Apelsvoll), but the effect was the opposite in the field established by transplanting in Våle. While CCC increased seed yield only when applied after cutting on 1 August at Apelsvoll, positive tendencies were noted also after cutting on 1 September at Landvik and Birkeland. No effect of CCC on seed yield was detectable in Våle.

Neither CCC application nor date of autumn cutting affected lodging, thousand seed weight or germination in the following season. In Våle, plant height on non-sprayed plots cut on 1 August was 137 cm compared with 122 cm on non-sprayed plots cut on 1 September; this character was unaffected by CCC application.

On average for three experimental fields, panicle number on plots cut on 1 August tended to be higher after CCC application on 15 August than after later, double or no application (data not shown in table). On average for treatments, the proportion of reproductive to vegetative tillers was much higher in the transplanted crop in Våle (344 reproductive vs. 24

Table 1. Seed yields (kg ha^{-1}, 100 % purity, 15 % moisture content) of *Bromus inermis* in four experimental fields as affected by various combinations of cutting and CCC application in the autumn of the year of establishment.

Cutting, date	CCC[1], date	Landvik	Våle	Apelsvoll	Mean, 3 expt.	Birkeland
1 Aug.	Nil	494	743	372	536	-
1 Aug.	15 Aug	657	690	542	630	-
1 Aug.	15 Aug + 15 Sep	569	717	586	624	-
1 Aug.	15 Sep	571	701	458	577	-
1 Sep.	Nil	536	559	450	515	1161
1 Sep.	1 Sep	626	566	387	526	1343
1 Sep.	15 Sep	611	594	347	517	1300
1 Sep.	1 Oct	534	594	325	484	1376
LSD ($p<0.05$)		ns	ns($p=0.06$)	86	ns($p=0.13$)	ns

[1] 2 kg a.i. ha^{-1} at each application

vegetative tillers m^{-2}) than in any of the sown crops.

Plan 2: CCC in the autumn of the establishment year combined with CCC or ethephon in the spring of the first harvest year

CCC stimulated seed yield both when applied in autumn and in spring. The two applications were not additive, however, the highest yield being obtained on plots receiving CCC in spring only (Table 2). Ethephon was less effective than CCC when applied in spring to plots which had not received CCC in autumn, and its effect was mainly additive to that of CCC in autumn.

Significant or almost significant interactions between growth regulators in spring and autumn were found for vegetative and reproductive tiller numbers (Table 3). The proportion of vegetative to reproductive tillers was rather high in this experiment, but it was reduced after ethephon application in spring and, most notably, by CCC in either autumn or spring. However, CCC applications in both autumn and spring were less effective than just one application.

Table 2. Yield of cleaned seed (kg ha^{-1}) of *Bromus inermis* as affected by growth regulators in autumn and spring.

Growth regulation in autumn	Growth regulation in spring Nil	CCC[1]	Ethe-phon[2]	Mean	LSD (p<0.05)	LSD (p<0.05) (interaction)
Nil	513	835	697	681		
CCC1	742	777	815	778	63	109
Mean	627	806	756			
LSD (p<0.05)		83				

[1] 2 kg a.i. ha^{-1} [2] 0.5 kg a.i. ha^{-1}

Table 3. Reproductive and vegetative tillers at seed harvest as affected by growth regulators in autumn and spring.

	Reproductive tillers, m^{-2} Growth regulation in spring			Vegetative tillers, m^{-2} Growth regulation in spring		
Growth regulation in autumn	Nil	CCC	Ethe-phon	Nil	CCC	Ethe-phon
Nil	167	229	227	584	341	481
CCC	248	197	164	359	473	437
LSD (p<0.05) (interaction)	ns (p=0.09)				94	

Chemical growth regulation in autumn had no effect on plant height, but CCC and ethephon applied in spring reduced the average height from 128 (control plots) to 110 and 117 cm, respectively (data not shown in table).

Plan 3. Stubble removal and CCC application after the first seed harvest

Stubble removal after the first seed harvest significantly reduced plant height and lodging and increased reproductive tiller number and seed yield in the second harvest year (Table 4). CCC application had no effect on any of these characters (data not shown).

Discussion

Spring-sown crops of *Bromus inermis* used in these experiments established rapidly and developed dense canopies within a couple of months. While the increase in crop dry weight during June and July was mainly due to leaf extension, August was also characterized by elongation of vegetative culms. Such culms are detrimental to seed yields in the first harvest year, partly because they have no reproductive potential by themselves (Heide 1994a), and partly because they aggravate light competition and thus the mortality of primary-induced tillers during the subsequent spring (Meijer & Vreeke 1988). Non-sprayed plots in the experiments at Landvik and Apelsvoll (Table 1) tended to produce more seed after cutting on 1 September than on 1 August probably because more redundant material, in particular elongated tillers, was removed on the latter date.

The rapid elongation of vegetative culms in August suggests that there there were high levels of endogenous gibberellins at this time of the year at both Landvik and Apelsvoll. Since gibberellins are inhibitory to primary induction in *Bromus inermis*, it is not surprising that CCC had the most positive effect on seed yields when applied shortly after cutting on 1 August. By counteracting the effect of long days, cutting on 1 August followed by CCC application on 15 August prevented many culms from becoming elongated and shifted the critical induction period into late summer when temperatures were still high. Bearing in mind that *Bromus inermis* has a high temperature

Table 4. Seed yield, panicle number, lodging and plant height in the second harvest year as affected by cutting and removal of stubble after the first seed harvest.

	Seed yield, kg ha^{-1} (15 % moisture)		Panicle number m^{-2}	Lodging %	Plant height, cm	
	Birkeland[1]	Hellerud[2]	Hellerud	Birkeland	Birkeland	Hellerud
Uncut	480	806	350	61	128	106
Cut	596	1093	530	1	113	99
LSD ($p<0.05$)	54	128	31	54	12	7

[1]Cleaned seed [2]Corrected to 100% purity

optimum for primary induction (15-21°C – Heide 1984), the warmer climate during autumn (average normal for September and October 9.9°C at Landvik and Birkeland vs. 6.9°C atApelsvoll) explains why applications after cutting on 1 September enhanced yields only at the southern locations. At Apelsvoll, CCC applied to plots cut on 1 September probably suppressed the content of endogenous gibberellins to suboptimal levels, causing a reduction in seed yield.

Earlier experiments have shown that seed production of *Bromus inermis* is stimulated by low plant densities (Jonassen & Torskenæs 1994). Raising plants in pots and transplanting them into the field is an expensive, but efficient way of establishing an optimal plant density. The lack of effect of CCC application in the experiment in Våle can be explained as a result of less growth and slower biosynthesis of gibberellins in transplanted plants, probably associated with less competition for light in the more open stand. Unlike in the sown experiments, almost all tillers were induced to flowering, and cutting on 1 September only had a negative effect because it reduced the accumulation of underground reserves before winter. Experiments with transplanted stands of *Phalaris arundinacea*, which in many ways resembles *Bromus inermis* in its responses (Heide 1994b), reveal that cutting in September is detrimental to seed production (Jonassen 1994).

The highly positive effect of CCC applied in spring (Table 2) is in good agreement with earlier experiments in *Bromus inermis* (Skuterud 1990) and in *Bromus wildenowii* (Hampton et al. 1989). Unlike autumn applications, CCC applied in spring caused a significant reduction in plant height, thus directing more assimilates to the developing panicle. Spring application of CCC therefore probably had a positive effect both on the development of marginally induced inflorescence primordia and on seed yield per panicle. This was also the case for ethephon, although the effect of this ethylene-releasing compound was inferior to that of CCC in both the present and earlier trials (Skuterud 1990). Ethephon may also interfere with gibberellin biosynthesis, but the mechanism seems less defined than for CCC (Van Andel 1973; Buettner et al. 1976).

Buettner et al. (1976) explained the positive effect of autumn-applied CCC on panicle formation in *Poa pratensis* as being due to increased tillering in autumn. On the other hand, spring-applied CCC reduced tillering in *Bromus wildenowii* (Hampton et al. 1989), whereas the effect of CCC on tiller number in *Lolium perenne* differed between years (Hampton 1986). In the present research, CCC reduced vegetative tiller number and increased panicle number when applied in either autumn or spring, but chemical growth regulation in both seasons almost reversed these effects (Table 3). It therefore seems that the concentration of endogenous gibberellins must follow an optimal course from the early autumn until seed harvest in order to maximize panicle formation and seed production in *Bromus inermis*.

The experiment with combined autumn and spring application of CCC was conducted in the rather chilly autumn climate at Hellerud, and CCC was applied as late as 6 September. Bearing in mind the results from Apelsvoll (Table 1), future experiments should investigate whether an earlier application of CCC in autumn could have a positive effect on seed yield in addition to that of spring application. Moreover, the possibility of using spilt applications with lower concentrations of CCC ought to be explored, particularly as Hampton et al. (1989) found 0.75 kg a.i. ha^{-1} to be equally effective as 3.0 kg a.i. ha^{-1} in *Bromus wildenowii*.

Unlike in the year of establishment, CCC had no effect when applied after the first seed harvest. As far as spraying immediately after combining or stubble removal is concerned, this is not surprising since very few green leaves were receptive to chemical growth regulators at this stage. Some effect could possibly have been expected from the application on 20 September at Birkeland, but, at this point, photoperiods were apparently short enough to give an optimal concentration of gibberellins even without CCC application.

Since Norwegian seed crops of *Bromus inermis* are normally harvested toward the end of August, it appears that applying CCC to such crops will normally be too late to have any effect on subsequent seed yields. On the other hand, stubble removal after seed harvest is clearly critical in order to obtain strong autumn tillers which can undergo flower induction and survive until seed harvest in the second year (Table 4); this seems to be a general situation in most perennial grasses (e.g. Chilcote et al. 1980; Heide 1994a).

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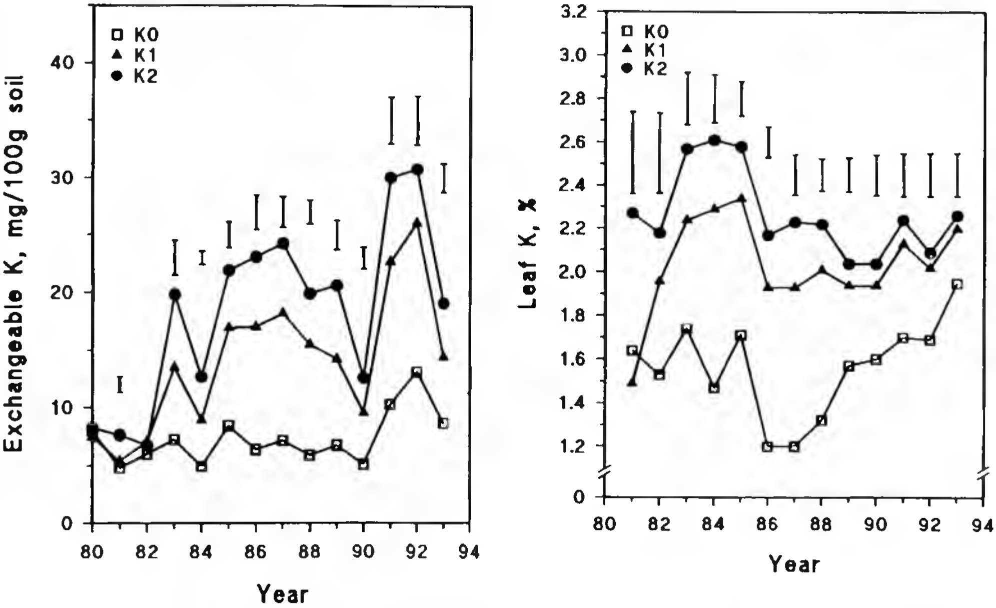
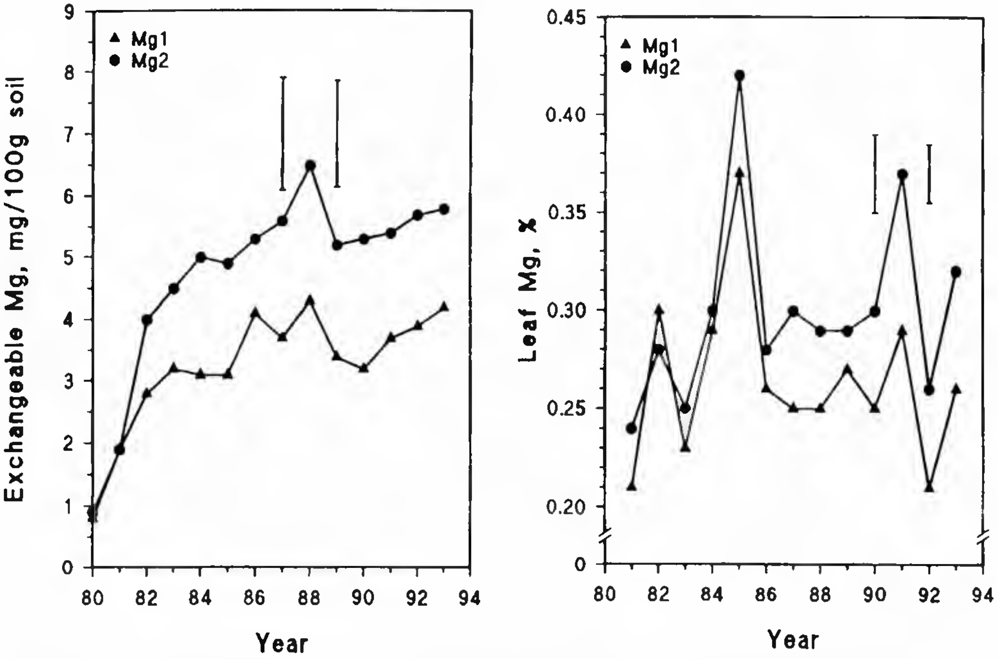
Correction: NJAS Vol. 9 1-2 1995, Sweet cherry nutrition, by Jonas Ystaas & Oddmund Frøynes p. 105-114



Figs. 5 - 6. Effects of K fertilization on soil exchangeable K (mg K/100 g soil) and leaf K (per cent of leaf dry matter) over 13 years. K0 = no K; K1 = 60 kg K ha^{-1}; K2 = 120 kg K ha^{-1} per year. Vertical bars represent LSD, P = 0.05



Figs. 7 - 8. Effects of ground dolomitic limestone on soil exchangeable Mg (mg Mg/100 g soil) and leaf Mg (per cent of leaf dry matter) over 13 years. Mg1 = 1000 kg dolomite ha^{-1}. Mg2 = 2000 kg dolomite ha^{-1} applied at the start of the trial. Vertical bars represent LSD. P = 0.05

Table 1. Main effects of phosphorus, potassium, calcium and magnesium application to 'Kristin' sweet cherries on tree size as measured by trunk girth of 13-year old trees, cumulative yield, cumulative yield efficiency, fruit weight and soluble solids, average figures

Fertilizer application kg ha^{-1}	*Trunk girth cm*	*Cumulative yield kg/tree*	*Cumulative yield efficiency kg/cm^2*	*Fruit weight g*	*Soluble solids %*
Phosphorus					
0	42.1	38.6	2.88	7.7	18.5
20	50.0	67.0	4.24	8.0	18.0
40	49.5	63.4	4.04	8.0	17.9
LSD, P=0.05	2.1	11.8	0.80	0.2	0.4
Potassium					
0	48.0	47.1	3.05	7.8	18.4
60	47.4	63.1	4.11	7.9	18.1
120	46.2	58.8	4.00	8.0	17.9
LSD, P=0.05	NS	11.8	0.80	NS	0.4
Calcium + magnesium					
2000[1)]	47.2	56.9	3.79	7.9	18.3
6000[2)]	47.2	55.8	3.66	7.9	17.9
LSD, P=0.05	NS	NS	NS	NS	NS

[1)] *Applied as 1000 kg ground limestone and 1000 kg dolomite*
[2)] *Applied as 4000 kg ground limestone and 2000 kg dolomite*

Table 2. The effects of different potassium applications on non-exchangeable K in the 0-20 cm soil layer

Potassium applications kg K ha^{-1}	*K, mg per 100 g soil*		
	Year 1	*Year 13*	*Mean*
0	*175*	*177*	*176*
60	*182*	*184*	*183*
120	*176*	*194*	*185*
LSD, P=0.05	*NS*	*NS*	*NS*

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